

1196051157

**INNOVATIVE CLEAN COAL TECHNOLOGY (ICCT)**

DOE/PC/89652--T19-Vol.1

DE-FC22-890 PC89652

**DEMONSTRATION OF SELECTIVE CATALYTIC REDUCTION (SCR)  
TECHNOLOGY FOR THE CONTROL OF NITROGEN OXIDE (NO<sub>x</sub>)  
EMISSIONS FROM HIGH-SULFUR COAL-FIRED BOILERS**

**Final Report**

**Volume 1 of 3**

**October 1996**

**DOE Contract  
DE-FC22-90PC89652**

**SCS Contract  
C-91-000026**

**Prepared by:**

**Southern Company Services, Inc.  
600 North 18th Street  
P.O. Box 2625  
Birmingham, AL 35202-2625**

**MASTER**

*Cleared by DOE Patent Counsel on Oct. 22, 1996*

**DISCLAIMER**

**Portions of this document may be illegible  
in electronic image products. Images are  
produced from the best available original  
document.**

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

## DISCLAIMER

This report was prepared by Southern Company Services, Inc. pursuant to a cooperative agreement partially funded by the U.S. Department of Energy and neither Southern Company Services, Inc., nor any of its subcontractors, nor the U.S. Department of Energy, nor any person acting on behalf of either:

- (a) Makes any warranty or representation, express or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or
- (b) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Department of Energy. The views and opinion of authors expressed herein do not necessarily state or reflect those of the U.S. Department of Energy.

## ABSTRACT

The objective of this project is to demonstrate and evaluate commercially available Selective Catalytic Reduction (SCR) catalysts from U.S., Japanese and European catalyst suppliers on a high-sulfur U.S. coal-fired boiler. SCR is a post-combustion nitrogen oxide ( $\text{NO}_x$ ) control technology that involves injecting ammonia into the flue gas generated from coal combustion in an electric utility boiler. The flue gas containing ammonia is then passed through a reactor that contains a specialized catalyst. In the presence of the catalyst, the ammonia reacts with  $\text{NO}_x$  to convert it to nitrogen and water vapor.

Although SCR is widely practiced in Japan and Europe on gas-, oil-, and low-sulfur coal-fired boilers, there are several technical uncertainties associated with applying SCR to U.S. coals. These uncertainties include: 1) potential catalyst deactivation due to poisoning by trace metal species present in U.S. coals that are not present in other fuels. 2) performance of the technology and effects on the balance-of-plant equipment in the presence of high amounts of  $\text{SO}_2$  and  $\text{SO}_3$ . 3) performance of a wide variety of SCR catalyst compositions, geometries and methods of manufacturer under typical high-sulfur coal-fired utility operating conditions. These uncertainties were explored by operating nine small-scale SCR reactors and simultaneously exposing different SCR catalysts to flue gas derived from the combustion of high sulfur U.S. coal.

Results of the study showed that catalyst deactivation was similar to that experienced in Europe and Japan. Deactivation for the coals tested is considered to be manageable and thus would not preclude the use of SCR technology on U.S. coals. The test program also showed that all of the catalysts tested were able to meet design specifications. These design specifications required that 80%  $\text{NO}_x$  reduction be achieved while maintaining slip (unreacted ammonia) at less than 5 ppm and  $\text{SO}_2$  oxidation at less than 0.75% through the end of the test program. The study of balance-of-plant concerns focused on air preheater performance in conjunction with SCR technology and the detrimental effect that the technology could have on plant waste streams. The results of the study demonstrate that increased air preheater maintenance, including wash frequency and corrosion mitigation steps (possibly requiring use of specialized basket materials) may be required with the use of SCR technology.

The test facility operating experience provided a basis for an economic study investigating the implementation of SCR technology. The conclusion shows the 250-MW base case (60%  $\text{NO}_x$  removal) unit capital and first year O&M (in 1996 dollars) are \$13,415,000 (\$54/kW) and \$1,045,000, respectively. Levelized cost for the base case unit is \$2,500/ton on a current dollar basis and \$1,802/ton on a constant dollar basis. Busbar cost is 2.57 mills/kWh on a current dollar basis and 1.85 mills/kWh on a constant dollar basis.

## ACKNOWLEDGMENTS

Southern Company Services, Inc. would like to acknowledge the following individuals and their respective organizations for their contributions to the writing of this report.

---

*Dr. W.S. Hinton*      *Mr. B.D. Eller*      *Ms. J.A. French*      *Mr. C.A. Powell*  
*Mr. J.D. Maxwell*      *Mr. E.C. Healy*      *Mrs. D.B. Hill*      *Mr. G.F. Bandura*

Southern Company Services, Inc.  
600 North 18th Street  
P.O. Box 2625  
Birmingham, Alabama 35202-2625

---

*Mr. A.L. Baldwin*

U.S. Department of Energy  
Building 920  
Wallace Road  
P.O. Box 10940  
Pittsburgh, PA 15236

---

*Mr. K.M. Cushing*      *Dr. E.B. Dismukes*      *Mr. R.F. Heaphy, Jr.*

Southern Research Institute  
2000 Ninth Avenue South  
P.O. Box 55303  
Birmingham, Alabama 35255

---

*Mr. J.D. Seebald*      *Mr. S.F. Harding*      *Mr. W.S. Counterman*

ABB Air Preheater, Inc.  
Andover Road  
P.O. Box 372  
Wellsville, New York 14895

## ACKNOWLEDGMENTS (Cont'd)

We would like to also thank the following individuals for their contribution to the project, making this report possible; *Mr. Randy Hinton, Mr. Jimmy Garrett, Mr. Richard Jacaruso*, and *Ms. Wynema Kimbrough* whose diligent work with Southern Research Institute allowed the collection of manual research data, *Mr. James Gibson* of Spectrum Systems, Inc. for his responsibilities in the continuous monitoring of test facility gas concentrations, *Mr. Ken Pathak* and *Mr. Bill Zimmer* for their devotion to data analysis, collection, and archiving, *Mr. Danny Mabire* of Instrumental Control Services, Inc. for his continuous efforts in maintaining the facility's instrumentation and controls equipment, all of the personnel at the Gulf Power Crist Plant, especially the SCR operators; *Mr. Steve Clark, Mr. Dave Davis, Mr. Frank Enfinger, Mr. Marcus Farmer, Mr. Lee Gunter, Mr. Guy Jensen, Mr. Carl Jordan, Mr. Gordon Powers, Mr. Miguel Puentes, Mr. Earl Roberts*, and *Mr. Tommy Tidwell*. We would also like to give special thanks to *Mrs. Katie Carroll, Mrs. Nancy Miller*, and *Mrs. Carrie Noland* for their immense efforts in the preparation of this report. Also, special thanks to *Mrs. Toby Whatley* and *Ms. Ann Jones* of Southern Company Services, Inc. for their help throughout the life of the project.

## POINT OF CONTACT

For further information on the project or SCR technology, please use the following contacts.

***Mr. Robert R. Hardman***  
Southern Company Services, Inc.  
P.O. Box 2625  
Birmingham, AL 35202  
205-870-5212

***Mr. Arthur L. Baldwin***  
U.S. Department of Energy  
Office of: Clean Coal Technology  
P.O. Box 10940  
Pittsburgh, PA 15236  
412-892-6011

***Dr. W. Scott Hinton***  
W.S. Hinton & Associates  
2708 Woodbreeze Drive  
Cantonment, FL 32533  
904-478-2400

## NOTE TO THE READER

This report is divided into two volumes. The first volume contains the body of the report with the subsequent volume containing appendices. In most cases, data summaries are contained in the body of the report with detailed data contained in the appendices. The report body has been written in such a way as to provide meaningful data discussions and presentations without the use of the appendices. However, the appendices contain detailed data and data discussions which can be used if the reader chooses to examine a particular subject in-depth. In many cases, the appendices contain stand-alone reports and are therefore numbered as originally written and may include sub-appendices. These sub-appendices should not be confused with the overall final report appendices.

# TABLE OF CONTENTS

|  |            |
|--|------------|
| List of Tables .....                       | xiv        |
| List of Figures .....                      | xvii       |
| List of Appendices.....                    | xxxvii     |
| List of Abbreviations .....                | xxxviii    |
| List of Units .....                        | xxxix      |
| Executive Summary.....                     | xi         |
| Bibliography.....                          | xliii      |
| <b>1.0 INTRODUCTION.....</b>               | <b>1-1</b> |
| 1.1 ICCT Program.....                      | 1-1        |
| 1.1.1 Role of the Program .....            | 1-1        |
| 1.1.2 Program Implementation.....          | 1-4        |
| 1.1.3 Funding .....                        | 1-5        |
| 1.1.4 Commercial Realization .....         | 1-6        |
| 1.1.5 Southern Company Participation.....  | 1-7        |
| 1.2 SCR Description/Status .....           | 1-9        |
| 1.2.1 Overview of Process Development..... | 1-9        |
| 1.2.2 Process Description .....            | 1-10       |
| 1.3 Project Objectives/Goals.....          | 1-14       |
| <b>2.0 PROJECT DESCRIPTION .....</b>       | <b>2-1</b> |
| 2.1 Site Characteristics .....             | 2-1        |
| 2.2 SCR Catalysts.....                     | 2-2        |
| 2.2.1 Material Safety Data Sheets.....     | 2-3        |
| 2.2.2 Catalyst Module Dimensions.....      | 2-4        |
| 2.3 Test Facility Design.....              | 2-5        |
| 2.3.1 Test Facility Layout .....           | 2-5        |
| 2.3.2 Process Description .....            | 2-9        |
| 2.3.2.1 Reactor Train Designation .....    | 2-9        |
| 2.3.2.2 Process Flow Diagram.....          | 2-9        |
| 2.3.2.3 Operational Philosophy.....        | 2-12       |
| 2.3.2.3.1 Temperature .....                | 2-12       |

|       |            |  |      |
|-------|------------|--|------|
|       | 2.3.2.3.2  | Space Velocity.....  | 2-13 |
|       | 2.3.2.3.3  | Ammonia-to-NO <sub>x</sub> Ratio .....                                       | 2-14 |
|       | 2.3.2.3.4  | Control Precision .....  | 2-14 |
|       | 2.3.2.4    | Air Preheater Testing .....  | 2-15 |
|       | 2.3.2.5    | Start-up and Shut-down Requirements.....                                     | 2-17 |
|       | 2.3.2.6    | Economizer Bypass Vapor Phase--Trace Metal<br>Concentration Effects .....    | 2-18 |
| 2.3.3 |            | Facility Description.....  | 2-19 |
|       | 2.3.3.1    | Area 100: Flue Gas Extraction Scoop to Flue Gas<br>Distribution Header ..... | 2-19 |
|       | 2.3.3.2    | Area 200: Flue Gas Distribution Header to Reactor<br>Inlet.....              | 2-23 |
|       | 2.3.3.2.1  | Electric Flue Gas Heaters and Air Purge .....                                | 2-24 |
|       | 2.3.3.2.2  | Electric Heater Size .....   | 2-24 |
|       | 2.3.3.2.3  | Electric Heater Location .....   | 2-25 |
|       | 2.3.3.2.4  | Electric Heater Control .....  | 2-25 |
|       | 2.3.3.2.5  | Electric Heater Process Concerns.....  | 2-26 |
|       | 2.3.3.2.6  | Electric Heater Electrical Design.....                                       | 2-27 |
|       | 2.3.3.2.7  | Miscellaneous Heater Requirements.....                                       | 2-27 |
|       | 2.3.3.2.8  | Venturi .....  | 2-28 |
|       | 2.3.3.2.9  | Design Flue Gas Composition .....  | 2-28 |
|       | 2.3.3.2.10 | Reactor Inlet Ducting.....   | 2-29 |
|       | 2.3.3.3    | Area 300: Ammonia Storage to Reactors.....                                   | 2-31 |
|       | 2.3.3.3.1  | Ammonia/Air Flow Measurement and Control .....                               | 2-32 |
|       | 2.3.3.3.2  | Ammonia Dilution Air Supply and Electric<br>Heater .....                     | 2-35 |
|       | 2.3.3.3.3  | Ammonia Injection Grid.....  | 2-37 |
|       | 2.3.3.4    | Area 400: SCR Reactors.....  | 2-38 |
|       | 2.3.3.5    | Area 500: SCR Reactors Outlet to Pilot APH<br>Outlet.....                    | 2-41 |
|       | 2.3.3.5.1  | Rotary Air Heaters.....  | 2-42 |
|       | 2.3.3.5.2  | Heat Pipe Air Preheater .....  | 2-46 |
|       | 2.3.3.6    | Area 600: Cyclones to Host Boiler Duct .....                                 | 2-47 |
|       | 2.3.3.7    | Area 700: Pilot-Plant Air Compressor Station.....                            | 2-52 |
|       | 2.3.3.8    | Area 800: Dilution/Extractive Gas Sampling System.....                       | 2-53 |
|       | 2.3.3.8.1  | O <sub>2</sub> Analysis .....  | 2-53 |
|       | 2.3.3.8.2  | CO, CO <sub>2</sub> , SO <sub>2</sub> , and NO <sub>x</sub> Analysis.....    | 2-54 |
|       | 2.3.3.8.3  | Gas Analyzers.....   | 2-55 |
|       | 2.3.3.9    | Area 900: Control Room .....   | 2-57 |
|       | 2.3.3.10   | Area 1000: Utility Systems.....  | 2-58 |
|       | 2.3.3.10.1 | Electric Service.....  | 2-58 |
|       | 2.3.3.10.2 | Potable Water .....  | 2-59 |
|       | 2.3.3.10.3 | Service Water .....  | 2-59 |
|       | 2.3.3.10.4 | Steam .....  | 2-60 |
|       | 2.3.3.10.5 | Fire Protection System.....  | 2-60 |

|            |   |            |
|------------|---|------------|
|            | 2.3.3.10.6 Heating, Ventilation, and Air Conditioning System .....  | 2-60       |
| 2.3.4      | Initial Site Characterization.....  | 2-60       |
| 2.3.4.1    | Particulate Concentrations .....  | 2-60       |
| 2.3.4.2    | Particle Size Distributions .....   | 2-61       |
| 2.3.4.3    | Chemical Species Concentrations.....  | 2-62       |
| 2.3.4.4    | Schedule.....   | 2-62       |
| 2.3.4.5    | Results.....  | 2-62       |
| <b>3.0</b> | <b>TEST PROGRAM.....</b>  | <b>3-1</b> |
| 3.1        | SRI Test Plan .....   | 3-1        |
| 3.1.1      | Start-up & Commissioning Tests .....  | 3-1        |
| 3.1.1.1    | TASK 1 - Commissioning Without Catalyst and Without Ammonia Injection.....                                    | 3-3        |
| 3.1.1.2    | TASK 2 - Commissioning Without Catalyst and With Ammonia Injection.....                                       | 3-6        |
| 3.1.1.3    | TASK 3 - Commissioning With Catalyst, Without Ammonia Injection and With Ammonia Injection .....              | 3-7        |
| 3.1.1.3.1  | TASK 3A. Commissioning With Catalyst and Without Ammonia Injection .....                                      | 3-8        |
| 3.1.1.3.2  | TASK 3B. Commissioning With Catalyst and With Ammonia Injection: [Preliminary Parametric Test Sequence] ..... | 3-8        |
| 3.1.2      | Parametric Tests .....  | 3-9        |
| 3.1.2.1    | Ammonia Measurement .....   | 3-10       |
| 3.1.2.2    | SO <sub>2</sub> Oxidation Measurements .....  | 3-11       |
| 3.1.2.3    | N <sub>2</sub> O Formation .....  | 3-11       |
| 3.1.2.4    | Ammonia to NO <sub>x</sub> Distribution.....  | 3-11       |
| 3.1.2.5    | Fly Ash Composition and Loading .....   | 3-12       |
| 3.1.2.6    | Velocity and Particulate Distributions .....  | 3-12       |
| 3.1.3      | Long Term Tests .....   | 3-13       |
| 3.2        | Air Heater Evaluation.....  | 3-14       |
| 3.3        | Catalyst Supplier Laboratory Tests .....  | 3-15       |
| 3.4        | Coal Testing.....   | 3-16       |
| 3.4.1      | Coal Supply.....  | 3-16       |
| 3.4.2      | Samples.....  | 3-17       |
| 3.4.3      | Analytical Methods.....   | 3-18       |
| 3.5        | Waste Stream Impacts .....  | 3-18       |

|            |   |            |
|------------|---|------------|
| 3.6        | Miscellaneous Other Tests .....                         | 3-19       |
| 3.7        | Data Acquisition/Analyses (Standard Methods/QA/QC)..... | 3-20       |
| <b>4.0</b> | <b>OPERATIONS/HISTORICAL HIGHLIGHTS.....</b>            | <b>4-1</b> |
| 4.1        | Design/Construction .....                               | 4-1        |
| 4.1.1      | Fourth Quarter 1991 .....                               | 4-1        |
| 4.1.2      | First Quarter 1992 .....                                | 4-3        |
| 4.1.3      | Second quarter 1992.....                                | 4-6        |
| 4.1.4      | Third Quarter 1992.....                                 | 4-8        |
| 4.1.5      | Fourth Quarter 1992.....                                | 4-11       |
| 4.1.6      | Design/Construction Synopsis.....                       | 4-14       |
| 4.2        | Start-up/Commissioning .....                            | 4-18       |
| 4.2.1      | First Quarter 1993 .....                                | 4-18       |
| 4.2.2      | Second Quarter 1993.....                                | 4-22       |
| 4.2.3      | Start-up/Commissioning Synopsis.....                    | 4-24       |
| 4.3        | Long Term Operations.....                               | 4-26       |
| 4.3.1      | Third Quarter 1993.....                                 | 4-26       |
| 4.3.2      | Fourth Quarter 1993.....                                | 4-30       |
| 4.3.3      | First Quarter 1994 .....                                | 4-36       |
| 4.3.4      | Second Quarter 1994.....                                | 4-39       |
| 4.3.5      | Third Quarter 1994.....                                 | 4-43       |
| 4.3.6      | Fourth Quarter 1994.....                                | 4-45       |
| 4.3.7      | First Quarter 1995 .....                                | 4-46       |
| 4.3.8      | Second Quarter 1995.....                                | 4-47       |
| 4.3.9      | Operational Phase Synopsis .....                        | 4-48       |
| 4.4        | Availability .....                                      | 4-54       |
| <b>5.0</b> | <b>PERFORMANCE EVALUATION .....</b>                     | <b>5-1</b> |
| 5.1        | Commissioning Tests.....                                | 5-2        |
| 5.1.1      | Task 1 .....  | 5-2        |
| 5.1.1.1    | Venturi Calibration .....                               | 5-2        |
| 5.1.1.2    | Particulate Measurements .....                          | 5-3        |
| 5.1.1.3    | Flue Gas Chemistry.....                                 | 5-7        |
| 5.1.1.4    | Fly Ash and Coal Chemistry, Fly Ash Resistivity .....   | 5-9        |

|           |  |       |
|-----------|--|-------|
| 5.1.1.5   | Trace Metal Analysis .....   | 5-10  |
| 5.1.1.6   | Trace Elements Determined by Method 29 and<br>Series Cyclones .....  | 5-12  |
| 5.1.1.7   | Mercury Concentrations Determined from Iodated<br>Carbon Traps ..... | 5-16  |
| 5.1.2     | Task 2 .....   | 5-18  |
| 5.1.2.1   | Ammonia Distribution.....  | 5-18  |
| 5.1.2.2   | Ammonia Loss in the Absence of Catalyst.....                         | 5-20  |
| 5.1.2.3   | Conclusions .....  | 5-22  |
| 5.1.3     | Task 3 .....   | 5-22  |
| 5.2       | Long Term Tests .....  | 5-23  |
| 5.2.1     | Flue Gas Composition.....  | 5-23  |
| 5.2.2     | Test Facility Inlet Gas Temperature .....                            | 5-25  |
| 5.2.3     | Reactor Pressure Drops .....   | 5-26  |
| 5.2.4     | Long-term NO <sub>x</sub> Reduction.....                             | 5-36  |
| 5.3       | Parametric Tests - Sequential.....                                   | 5-39  |
| 5.3.1     | First Parametric Sequence (Preliminary).....                         | 5-39  |
| 5.3.2     | Second Parametric Sequence .....                                     | 5-67  |
| 5.3.3     | Third Parametric Sequence .....                                      | 5-113 |
| 5.3.4     | Fourth Parametric Sequence .....                                     | 5-150 |
| 5.3.5     | Fifth Parametric Sequence (Abbreviated).....                         | 5-200 |
| 5.4       | Parametric Tests - Summary .....                                     | 5-235 |
| 5.5       | Air Preheater Evaluation.....  | 5-281 |
| 5.5.1     | Manual Air Preheater Test Series Evaluation .....                    | 5-281 |
| 5.5.1.1   | First Manual Air Preheater Test Series .....                         | 5-281 |
| 5.5.1.1.1 | Ammonia Concentrations.....  | 5-282 |
| 5.5.1.1.2 | SO <sub>2</sub> and SO <sub>3</sub> Concentrations.....              | 5-282 |
| 5.5.1.1.3 | HCl Concentration.....   | 5-282 |
| 5.5.1.1.4 | Mass Concentration .....   | 5-283 |
| 5.5.1.1.5 | Particle Size Distributions .....                                    | 5-283 |
| 5.5.1.1.6 | Ash Mineralogy .....   | 5-283 |
| 5.5.1.1.7 | Ash Resistivity .....  | 5-284 |
| 5.5.1.2   | Second Manual Air Preheater Tests Series .....                       | 5-284 |
| 5.5.1.2.1 | Ammonia Concentrations.....  | 5-285 |
| 5.5.1.2.2 | SO <sub>2</sub> and SO <sub>3</sub> Concentrations.....              | 5-285 |
| 5.5.1.2.3 | HCl Concentrations .....   | 5-286 |
| 5.5.1.2.4 | Mass Concentrations.....   | 5-287 |
| 5.5.1.3   | Third Manual Air Preheater Test Series.....                          | 5-287 |

|       |           |   |       |
|-------|-----------|---|-------|
|       | 5.5.1.3.1 | Ammonia Concentrations.....                                     | 5-287 |
|       | 5.5.1.3.2 | SO <sub>2</sub> and SO <sub>3</sub> Concentrations.....         | 5-289 |
|       | 5.5.1.3.3 | HCl Concentrations .....  | 5-289 |
|       | 5.5.1.3.4 | Particulate Mass Concentrations .....                           | 5-289 |
|       | 5.5.1.3.5 | Fly Ash Resistivity .....                                       | 5-290 |
|       | 5.5.1.3.6 | Fly Ash Mineral Analysis.....                                   | 5-290 |
|       | 5.5.1.3.7 | Metals Extractions .....  | 5-290 |
| 5.5.2 |           | Continuous Long-Term Air Preheater Evaluation.....              | 5-290 |
| 5.5.3 |           | Air Preheater Evaluation by ABB Air Preheater, Inc. ....        | 5-318 |
| 5.6   |           | Catalyst Supplier Laboratory Test Results.....                  | 5-319 |
| 5.6.1 |           | W.R. Grace & Co. - Reactors A and D .....                       | 5-330 |
|       | 5.6.1.1   | General Advertised Information .....                            | 5-330 |
| 5.6.2 |           | Nippon Shokubai Company, Ltd. - Reactor B .....                 | 5-331 |
|       | 5.6.2.1   | General Advertised Information .....                            | 5-331 |
|       | 5.6.2.2   | Laboratory Testing Results .....                                | 5-332 |
| 5.6.3 |           | Siemens - Reactor C .....                                       | 5-333 |
|       | 5.6.3.1   | General Advertised Information .....                            | 5-333 |
| 5.6.4 |           | Cormetech, Inc. - Reactors E and J.....                         | 5-336 |
|       | 5.6.4.1   | General Advertised Information.....                             | 5-336 |
|       | 5.6.4.2   | Laboratory Testing Results .....                                | 5-337 |
|       | 5.6.4.2.1 | Reactor E - High-Dust.....                                      | 5-337 |
|       | 5.6.4.2.2 | Reactor J - Low-Dust .....                                      | 5-338 |
| 5.6.5 |           | Haldor Topsoe - Reactor F .....                                 | 5-338 |
|       | 5.6.5.1   | General Advertised Information .....                            | 5-338 |
| 5.6.6 |           | Hitachi Zosen - Reactor G .....                                 | 5-341 |
|       | 5.6.6.1   | General Advertised Information .....                            | 5-341 |
|       | 5.6.6.2   | Laboratory Testing Results .....                                | 5-343 |
| 5.7   |           | Coal Analysis.....  | 5-344 |
| 5.8   |           | Waste Stream Impacts .....                                      | 5-348 |
|       | 5.8.1     | Ammonia Extractability and Volatilization from SCR Fly Ash..... | 5-349 |
|       | 5.8.2     | Metals Extractability from SCR Fly Ash.....                     | 5-350 |
| 5.9   |           | Miscellaneous Test Results .....                                | 5-350 |
|       | 5.9.1     | TCLP Analysis.....  | 5-350 |
|       | 5.9.2     | Ammonia Partitioning .....                                      | 5-353 |
|       | 5.9.2.1   | First Test Series.....  | 5-353 |
|       | 5.9.2.2   | Second Test Series.....   | 5-355 |
|       | 5.9.2.3   | Third Test Series .....   | 5-357 |
|       | 5.9.3     | Fly Ash Resistivity .....                                       | 5-359 |
|       | 5.9.4     | High Velocity Catalyst Tests - Reactor H.....                   | 5-360 |

|            |  |            |
|------------|--|------------|
| <b>6.0</b> | <b>ECONOMIC EVALUATION.....</b>                      | <b>6-1</b> |
| 6.1        | Base Case Economics.....                             | 6-4        |
| 6.1.1      | Base Case Definition.....                            | 6-5        |
| <b>7.0</b> | <b>CONCLUSIONS .....</b>                             | <b>7-1</b> |
| 7.1        | SCR Technology Evaluation.....                       | 7-1        |
| 7.1.1      | SCR Catalyst.....                                    | 7-1        |
| 7.1.1.1    | SCR Catalyst deNO <sub>x</sub> Activity.....         | 7-2        |
| 7.1.1.2    | SCR Catalyst SO <sub>2</sub> Oxidation Activity..... | 7-3        |
| 7.1.1.3    | SCR Catalyst Pressure Drop.....                      | 7-3        |
| 7.1.1.4    | SCR Catalyst Fouling Characteristics.....            | 7-4        |
| 7.1.1.5    | SCR Catalyst Physical Strength/Durability.....       | 7-5        |
| 7.1.2      | SCR Reactor Design.....                              | 7-6        |
| 7.1.2.1    | NH <sub>3</sub> /NO <sub>x</sub> Distribution.....   | 7-6        |
| 7.1.2.2    | Velocity Distributions.....                          | 7-6        |
| 7.1.2.3    | Particulate Distributions.....                       | 7-7        |
| 7.1.3      | Commercial SCR Operational Recommendations.....      | 7-7        |
| 7.1.3.1    | Flue Gas Operation.....                              | 7-8        |
| 7.1.3.2    | Ammonia Injection.....                               | 7-9        |
| 7.1.3.3    | Sootblowing.....                                     | 7-10       |
| 7.2        | SCR Downstream Effects.....                          | 7-10       |
| 7.2.1      | Air Preheater Performance.....                       | 7-10       |
| 7.2.2      | Environmental Impacts.....                           | 7-11       |
| 7.3        | Low/High-Dust SCR Configuration.....                 | 7-12       |

## LIST OF TABLES

| Table Number | Description   | Page Number |
|--------------|---|-------------|
| Table 2.1-1  | Characteristics of Plant Crist Units 1-7                                      | 2-1         |
| Table 2.1-2  | Site Specific Design Conditions   | 2-1         |
| Table 2.2-1  | Catalysts in the DOE/SCS SCR Project  | 2-2         |
| Table 2.2-2  | SCR Catalyst Design Specifications  | 2-3         |
| Table 2.2-3  | Catalyst Module Dimensions  | 2-4         |
| Table 2.3-1  | Fly ash Settling in Test Facility Ducts at 60fps                              | 2-21        |
| Table 2.3-2  | Heater Inlet Conditions (High Dust)   | 2-27        |
| Table 2.3-3  | Design Flue Gas Composition at Maximum Flow Conditions                        | 2-28        |
| Table 2.3-4  | Velocity Profile Test Results Summary for Selected Model Reactor Inlet Design | 2-30        |
| Table 2.3-5  | Ljungstrom <sup>®</sup> Air Heater Performance                                | 2-45        |
| Table 2.3-6  | Rotary Air Heater Rotor Designs   | 2-45        |
| Table 2.3-7  | Specifications/Performance of Heat Pipe Heat Exchanger                        | 2-47        |
| Table 2.3-8  | Large Reactor Steady State Operating Conditions                               | 2-49        |
| Table 2.3-9  | Large Reactor Off-Design Operating Matrix                                     | 2-49        |
| Table 2.3-10 | Small Reactor Steady State Operating Conditions                               | 2-49        |
| Table 2.3-11 | Small Reactor Off-Design Operating Matrix                                     | 2-50        |
| Table 2.3-12 | Cumulative Particle Size Distribution   | 2-51        |
| Table 2.3-13 | Flue Gas Composition at Steady State Operation                                | 2-51        |
| Table 2.3-14 | Fly Ash Particle Size Comparison  | 2-64        |
| Table 3.1-1  | Start-up and Commissioning Tests  | 3-2         |
| Table 3.1-2  | SCR Reactor Preliminary Parametric Test Sequence                              | 3-9         |
| Table 3.1-2  | General Base-line and Parametric Conditions                                   | 3-10        |
| Table 3.2-1  | Original Proposed Air Heater Test Schedule                                    | 3-15        |
| Table 3.2-2  | Tests Performed by Catalyst Suppliers   | 3-16        |
| Table 4.2-1  | Catalyst Suppliers and Reactor Designation                                    | 4-23        |
| Table 4.3-1  | Sootblowing Schedule and Procedures   | 4-29        |
| Table 5.2-1  | Test Facility Gas Concentrations  | 5-23        |
| Table 5.2-2  | Test Facility Inlet Gas Temperature (°F)                                      | 5-26        |
| Table 5.2-3  | Reactor A - Long Term NO <sub>x</sub> Reduction                               | 5-36        |
| Table 5.2-4  | Reactor B - Long Term NO <sub>x</sub> Reduction                               | 5-36        |
| Table 5.2-5  | Reactor C - Long Term NO <sub>x</sub> Reduction                               | 5-37        |
| Table 5.2-6  | Reactor D - Long Term NO <sub>x</sub> Reduction                               | 5-37        |
| Table 5.2-7  | Reactor E - Long Term NO <sub>x</sub> Reduction                               | 5-37        |
| Table 5.2-8  | Reactor F - Long Term NO <sub>x</sub> Reduction                               | 5-37        |
| Table 5.2-9  | Reactor G - Long Term NO <sub>x</sub> Reduction                               | 5-38        |

## LIST OF TABLES (Cont'd)

|                |  |       |
|----------------|--|-------|
| Table 5.2-10   | Reactor J - Long Term NO <sub>x</sub> Reduction                    | 5-38  |
| Table 5.3.1-1  | Parametric Test Conditions (1st Test Sequence)                     | 5-41  |
| Table 5.3.1-2  | Reactor A Data (1st Parametric Sequence)                           | 5-43  |
| Table 5.3.1-3  | Reactor B Data (1st Parametric Sequence)                           | 5-44  |
| Table 5.3.1-4  | Reactor C (1st Parametric Sequence)                                | 5-45  |
| Table 5.3.1-5  | Reactor D (1st Parametric Sequence)                                | 5-46  |
| Table 5.3.1-6  | Reactor E (1st Parametric Sequence)                                | 5-47  |
| Table 5.3.1-7  | Reactor F (1st Parametric Sequence)                                | 5-48  |
| Table 5.3.1-8  | Additional Base-line Measurements                                  | 5-51  |
| Table 5.3.2-1  | Parametric Test Conditions (2nd Test Sequence)                     | 5-68  |
| Table 5.3.2-2  | Reactor A (2nd Parametric Sequence)                                | 5-70  |
| Table 5.3.2-3  | Reactor B (2nd Parametric Sequence)                                | 5-71  |
| Table 5.3.2-4  | Reactor C (2nd Parametric Sequence)                                | 5-72  |
| Table 5.3.2-5  | Reactor D (2nd Parametric Sequence)                                | 5-73  |
| Table 5.3.2-6  | Reactor E (2nd Parametric Sequence)                                | 5-74  |
| Table 5.3.2-7  | Reactor F (2nd Parametric Sequence)                                | 5-75  |
| Table 5.3.2-8  | Reactor G (2nd Parametric Sequence)                                | 5-76  |
| Table 5.3.2-9  | Additional Base-line Measurements                                  | 5-81  |
| Table 5.3.3-1  | Parametric Test Conditions (3rd Test Sequence)                     | 5-113 |
| Table 5.3.3-2  | Reactor A Data (3rd Parametric Sequence)                           | 5-115 |
| Table 5.3.3-3  | Reactor B Data (3rd Parametric Sequence)                           | 5-116 |
| Table 5.3.3-4  | Reactor C Data (3rd Parametric Sequence)                           | 5-117 |
| Table 5.3.3-5  | Reactor D Data (3rd Parametric Sequence)                           | 5-118 |
| Table 5.3.3-6  | Reactor E Data (3rd Parametric Sequence)                           | 5-119 |
| Table 5.3.3-7  | Reactor F Data (3rd Parametric Sequence)                           | 5-120 |
| Table 5.3.3-8  | Reactor G Data (3rd Parametric Sequence)                           | 5-121 |
| Table 5.3.3-9  | Reactor J Data (3rd Parametric Sequence)                           | 5-122 |
| Table 5.3.3-10 | Additional Base-line Measurements                                  | 5-126 |
| Table 5.3.4-1  | Parametric Test Conditions (4th Test Sequence)                     | 5-150 |
| Table 5.3.4-2  | Reactor A Data (4th Parametric Sequence)                           | 5-152 |
| Table 5.3.4-3  | Reactor B Data (4th Parametric Sequence)                           | 5-153 |
| Table 5.3.4-4  | Reactor C Data (4th Parametric Sequence)                           | 5-154 |
| Table 5.3.4-5  | Reactor D Data (4th Parametric Sequence)                           | 5-155 |
| Table 5.3.4-6  | Reactor E Data (4th Parametric Sequence)                           | 5-156 |
| Table 5.3.4-7  | Reactor F Data (4th Parametric Sequence)                           | 5-157 |
| Table 5.3.4-8  | Reactor G Data (4th Parametric Sequence)                           | 5-158 |
| Table 5.3.4-9  | Reactor J Data (4th Parametric Sequence)                           | 5-159 |
| Table 5.3.4-10 | Additional Base-line Measurements                                  | 5-164 |
| Table 5.3.5-1  | Parametric Test Conditions (5th Parametric Sequence - Abbreviated) | 5-201 |
| Table 5.3.5-2  | Reactor A Data (5th Parametric Sequence)                           | 5-203 |

## LIST OF TABLES (Cont'd)

|                |  |       |
|----------------|--|-------|
| Table 5.3.5-3  | Reactor B Data (5th Parametric Sequence)   | 5-204 |
| Table 5.3.5-4  | Reactor C Data (5th Parametric Sequence)   | 5-205 |
| Table 5.3.5-5  | Reactor D Data (5th Parametric Sequence)   | 5-206 |
| Table 5.3.5-6  | Reactor E Data (5th Parametric Sequence)   | 5-207 |
| Table 5.3.5-7  | Reactor F Data (5th Parametric Sequence)   | 5-208 |
| Table 5.3.5-8  | Reactor G Data (5th Parametric Sequence)   | 5-209 |
| Table 5.3.5-9  | Reactor J Data (5th Parametric Sequence)   | 5-210 |
| Table 5.3.5-10 | SO <sub>2</sub> Oxidation  | 5-213 |
| Table 5.3.5-11 | Additional Base-line Measurements  | 5-214 |
| Table 5.4-1    | Average Intermediate NO <sub>x</sub> Reduction   | 5-238 |
| Table 5.4-2    | Average Ammonia Slip   | 5-241 |
| Table 5.4-3    | Average SO <sub>2</sub> Oxidation  | 5-243 |
| Table 5.5-1    | Average Air Preheater Operational Parameters   | 5-291 |
| Table 5.6-2    | Total Catalyst Exposure Time   | 5-320 |
| Table 5.6-3    | Laboratory Test Conditions   | 5-320 |
| Table 5.7-1    | Alabama Power/SCS Coal Analysis Data - As Burned Composites  | 5-345 |
| Table 5.7-2    | Plant Crist Unit 5 Coal Analyses - 1993-95 Quarterly, As-Burned Composites INAA Results from the University of Missouri-Columbia, Research Reactor Center, Dry Basis | 5-346 |
| Table 5.7-3    | Comparison of APC Analyses Versus INAA Analyses, Dry Basis   | 5-347 |
| Table 5.9-1    | TCLP Analysis - 6/21/93  | 5-351 |
| Table 5.9-2    | TCLP Analysis - 6/28/93  | 5-351 |
| Table 5.9-3    | TCLP Analysis - 8/25/94  | 5-351 |
| Table 5.9-4    | TCLP Analysis - 7/12/95  | 5-352 |
| Table 5.9-5    | Analyzing Laboratory Reporting Limits  | 5-352 |
| Table 5.9-6    | Ammonia Partitioning Test - First Series   | 5-355 |
| Table 5.9-7    | Ammonia Partitioning - Second Series   | 5-357 |
| Table 5.9-8    | Ammonia Partitioning - Third Series  | 5-359 |
| Table 6.1-1    | 250 MW Base Case Design and Capital Requirement  | 6-8   |

## LIST OF FIGURES

| Figure         | Description  | Page<br>Number |
|----------------|--|----------------|
| Figure 1.2-1   | Flow Diagram of Typical SCR Installation   | 1-15           |
| Figure 2.3-1   | Basic Layout of SCR Test Facility  | 2-6            |
| Figure 2.3-2   | Photograph of West Side of Completed SCR Facility  | 2-7            |
| Figure 2.3-3   | Photograph of South Side of Completed SCR Facility   | 2-8            |
| Figure 2.3-4   | Prototype SCR Demonstration Facility-Process Flow Diagram  | 2-11           |
| Figure 2.3-5   | Basic Design of Ammonia Injection System   | 2-34           |
| Figure 5.2-1   | Pressure Drop vs Time - 3rd Quarter 1993   | 5-28           |
| Figure 5.2-2   | Pressure Drop vs Time - 4th Quarter 1993   | 5-29           |
| Figure 5.2-3   | Pressure Drop vs Time - 1st Quarter 1994   | 5-30           |
| Figure 5.2-4   | Pressure Drop vs Time - 2nd Quarter 1994   | 5-31           |
| Figure 5.2-5   | Pressure Drop vs Time - 3rd Quarter 1994   | 5-32           |
| Figure 5.2-6   | Pressure Drop vs Time - 4th Quarter 1994   | 5-33           |
| Figure 5.2-7   | Pressure Drop vs Time - 1st Quarter 1995   | 5-34           |
| Figure 5.2-8   | Pressure Drop vs Time - 3rd Quarter 1995   | 5-35           |
| Figure 5.3.1-1 | First (Abbreviated) SCR Parametric Test Plan   | 5-42           |
| Figure 5.3.1-2 | First Bed NO <sub>x</sub> Red. vs NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Grace Noxeram<br>Preliminary Parametric Sequence       | 5-52           |
| Figure 5.3.1-3 | First Bed NO <sub>x</sub> Red. vs NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>NSKK<br>Preliminary Parametric Sequence                | 5-52           |
| Figure 5.3.1-4 | First Bed NO <sub>x</sub> Red. vs NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Siemens<br>Preliminary Parametric Sequence             | 5-53           |
| Figure 5.3.1-5 | First Bed NO <sub>x</sub> Red. vs NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Grace Synox<br>Preliminary Parametric Sequence         | 5-53           |
| Figure 5.3.1-6 | First Bed NO <sub>x</sub> Red. vs NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Cormetech High-Dust<br>Preliminary Parametric Sequence | 5-54           |
| Figure 5.3.1-7 | First Bed NO <sub>x</sub> Red. vs NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Haldor Topsoe<br>Preliminary Parametric Sequence       | 5-54           |
| Figure 5.3.1-8 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Grace Noxeram: 750 F<br>Preliminary Parametric Sequence                                  | 5-55           |

## LIST OF FIGURES (Cont'd)

|                 |  |      |
|-----------------|--|------|
| Figure 5.3.1-9  | SO <sub>2</sub> Oxidation vs Flow Rate<br>NSKK: 750 F<br>Preliminary Parametric Sequence   | 5-55 |
| Figure 5.3.1-10 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Siemens: 750 F<br>Preliminary Parametric Sequence  | 5-56 |
| Figure 5.3.1-11 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Grace Synox: 750 F<br>Preliminary Parametric Sequence  | 5-56 |
| Figure 5.3.1-12 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Cormetech High-Dust: 750 F<br>Preliminary Parametric Sequence  | 5-57 |
| Figure 5.3.1-13 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Haldor Topsoe: 750 F<br>Preliminary Parametric Sequence  | 5-57 |
| Figure 5.3.1-14 | SO <sub>2</sub> Oxidation vs Temperature<br>Grace Noxeram: 0.6 NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Preliminary Parametric Sequence       | 5-58 |
| Figure 5.3.1-15 | SO <sub>2</sub> Oxidation vs Temperature<br>NSKK: 0.6 NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Preliminary Parametric Sequence                | 5-58 |
| Figure 5.3.1-16 | SO <sub>2</sub> Oxidation vs Temperature<br>Siemens: 0.6 NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Preliminary Parametric Sequence             | 5-59 |
| Figure 5.3.1-17 | SO <sub>2</sub> Oxidation vs Temperature<br>Grace Synox: 0.6 NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Preliminary Parametric Sequence         | 5-59 |
| Figure 5.3.1-18 | SO <sub>2</sub> Oxidation vs Temperature<br>Cormetech High-Dust: 0.6 NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Preliminary Parametric Sequence | 5-60 |
| Figure 5.3.1-19 | SO <sub>2</sub> Oxidation vs Temperature<br>Haldor Topsoe: 0.6 NH <sub>3</sub> /NO <sub>x</sub> Ratio<br>Preliminary Parametric Sequence       | 5-60 |
| Figure 5.3.1-20 | Mass Concentration Profile<br>Reactor D<br>Preliminary Parametric Sequence   | 5-61 |
| Figure 5.3.1-21 | Mass Concentration Profile<br>Reactor E<br>Preliminary Parametric Sequence   | 5-62 |
| Figure 5.3.1-22 | Mass Concentration Profile<br>Reactor F<br>Preliminary Parametric Sequence   | 5-63 |

## LIST OF FIGURES (Cont'd)

|                 |   |      |
|-----------------|---|------|
| Figure 5.3.1-23 | Flue Gas Velocity Profile<br>Reactor D<br>Preliminary Parametric Sequence   | 5-64 |
| Figure 5.3.1-24 | Flue Gas Velocity Profile<br>Reactor E<br>Preliminary Parametric Sequence   | 5-65 |
| Figure 5.3.1-25 | Flue Gas Velocity Profile<br>Reactor F<br>Preliminary Parametric Sequence   | 5-66 |
| Figure 5.3.2-1  | Second SCR Parametric Test Plan   | 5-69 |
| Figure 5.3.2-2  | Ammonia Slip vs Flow Rate<br>Grace Noxeram: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Second Parametric Sequence      | 5-82 |
| Figure 5.3.2-3  | Ammonia Slip vs Flow Rate<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F<br>Second Parametric Sequence                | 5-82 |
| Figure 5.3.2-4  | Ammonia Slip vs Flow Rate<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F<br>Second Parametric Sequence             | 5-83 |
| Figure 5.3.2-5  | Ammonia Slip vs Flow Rate<br>Grace Synox: $\text{NH}_3/\text{NO}_x = 0.95$ , 700 F<br>Second Parametric Sequence        | 5-83 |
| Figure 5.3.2-6  | Ammonia Slip vs Flow Rate<br>Cormetech High-Dust: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F<br>Second Parametric Sequence | 5-84 |
| Figure 5.3.2-7  | Ammonia Slip vs Flow Rate<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F<br>Second Parametric Sequence       | 5-84 |
| Figure 5.3.2-8  | Ammonia Slip vs Flow Rate<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F<br>Second Parametric Sequence       | 5-85 |
| Figure 5.3.2-9  | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace Noxeram: 620 F, High Flow<br>Second Parametric Sequence        | 5-85 |
| Figure 5.3.2-10 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>NSKK: 620 F, High Flow<br>Second Parametric Sequence                 | 5-86 |
| Figure 5.3.2-11 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Siemens: 620 F, High Flow<br>Second Parametric Sequence              | 5-86 |
| Figure 5.3.2-12 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace Synox: 620 F, High Flow<br>Second Parametric Sequence          | 5-87 |

### LIST OF FIGURES (Cont' d)

|                 |  |      |
|-----------------|--|------|
| Figure 5.3.2-13 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Cormetech High-Dust: 620 F, High Flow<br>Second Parametric Sequence           | 5-87 |
| Figure 5.3.2-14 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Haldor Topsoe: 620 F, High Flow<br>Second Parametric Sequence                 | 5-88 |
| Figure 5.3.2-15 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Hitachi Zosen: 620 F, High Flow<br>Second Parametric Sequence                 | 5-88 |
| Figure 5.3.2-16 | Ammonia Slip vs Temperature<br>Grace Noxeram: $\text{NH}_3/\text{NO}_x = 0.8$ , High Flow<br>Second Parametric Sequence          | 5-89 |
| Figure 5.3.2-17 | Ammonia Slip vs Temperature<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.8$ , High Flow<br>Second Parametric Sequence                   | 5-89 |
| Figure 5.3.2-18 | Ammonia Slip vs Temperature<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.8$ , High Flow<br>Second Parametric Sequence                | 5-90 |
| Figure 5.3.2-19 | Ammonia Slip vs Temperature<br>Grace Synox: $\text{NH}_3/\text{NO}_x = 0.9$ , High Flow<br>Second Parametric Sequence            | 5-90 |
| Figure 5.3.2-20 | Ammonia Slip vs Temperature<br>Cormetech High-Dust: $\text{NH}_3/\text{NO}_x = 0.8$ , High<br>Flow<br>Second Parametric Sequence | 5-91 |
| Figure 5.3.2-21 | Ammonia Slip vs Temperature<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.8$ , High Flow<br>Second Parametric Sequence          | 5-91 |
| Figure 5.3.2-22 | Ammonia Slip vs Temperature<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.8$ , High Flow<br>Second Parametric Sequence          | 5-92 |
| Figure 5.3.2-23 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Grace Noxeram: $\text{NH}_3/\text{NO}_x = 0.8$ , 750 F<br>Second Parametric Sequence     | 5-92 |
| Figure 5.3.2-24 | $\text{SO}_2$ Oxidation vs Flow Rate<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.8$ , 750 F<br>Second Parametric Sequence              | 5-93 |
| Figure 5.3.2-25 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.8$ , 750 F<br>Second Parametric Sequence           | 5-93 |
| Figure 5.3.2-26 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Grace Synox: $\text{NH}_3/\text{NO}_x = 0.98$ , 750 F<br>Second Parametric Sequence      | 5-94 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.2-27 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Cormetech High-Dust: NH <sub>3</sub> /NO <sub>x</sub> =0.8, 750 F<br>Second Parametric Sequence         | 5-94  |
| Figure 5.3.2-28 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Haldor Topsoe: NH <sub>3</sub> /NO <sub>x</sub> =0.8, 750 F<br>Second Parametric Sequence               | 5-95  |
| Figure 5.3.2-29 | SO <sub>2</sub> Oxidation vs Flow Rate<br>Hitachi Zosen: NH <sub>3</sub> /NO <sub>x</sub> =0.8, 750 F<br>Second Parametric Sequence               | 5-95  |
| Figure 5.3.2-30 | SO <sub>2</sub> Oxidation vs Temperature<br>Grace Noxeram: NH <sub>3</sub> /NO <sub>x</sub> =0.8, Low Flow<br>Second Parametric Sequence          | 5-96  |
| Figure 5.3.2-31 | SO <sub>2</sub> Oxidation vs Temperature<br>NSKK: NH <sub>3</sub> /NO <sub>x</sub> =0.8, Low Flow<br>Second Parametric Sequence                   | 5-96  |
| Figure 5.3.2-32 | SO <sub>2</sub> Oxidation vs Temperature<br>Siemens: NH <sub>3</sub> /NO <sub>x</sub> =0.8, Low Flow<br>Second Parametric Sequence                | 5-97  |
| Figure 5.3.2-33 | SO <sub>2</sub> Oxidation vs Temperature<br>Grace Synox: NH <sub>3</sub> /NO <sub>x</sub> =0.98, Low Flow<br>Second Parametric Sequence           | 5-97  |
| Figure 5.3.2-34 | SO <sub>2</sub> Oxidation vs Temperature<br>Cormetech High-Dust: NH <sub>3</sub> /NO <sub>x</sub> =0.8, Low<br>Flow<br>Second Parametric Sequence | 5-98  |
| Figure 5.3.2-35 | SO <sub>2</sub> Oxidation vs Temperature<br>Haldor Topsoe: NH <sub>3</sub> /NO <sub>x</sub> =0.8, Low Flow<br>Second Parametric Sequence          | 5-98  |
| Figure 5.3.2-36 | SO <sub>2</sub> Oxidation vs Temperature<br>Hitachi Zosen: NH <sub>3</sub> /NO <sub>x</sub> =0.8, Low Flow<br>Second Parametric Sequence          | 5-99  |
| Figure 5.3.2-37 | Mass Concentration Profile<br>Reactor A<br>Second Parametric Sequence   | 5-100 |
| Figure 5.3.2-38 | Mass Concentration Profile<br>Reactor B<br>Second Parametric Sequence   | 5-101 |
| Figure 5.3.2-39 | Mass Concentration Profile<br>Reactor C<br>Second Parametric Sequence   | 5-102 |
| Figure 5.3.2-40 | Mass Concentration Profile<br>Reactor D<br>Second Parametric Sequence   | 5-103 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.2-41 | Mass Concentration Profile<br>Reactor E   | 5-104 |
| Figure 5.3.2-42 | Second Parametric Sequence<br>Mass Concentration Profile<br>Reactor F   | 5-105 |
| Figure 5.3.2-43 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor A  | 5-106 |
| Figure 5.3.2-44 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor B  | 5-107 |
| Figure 5.3.2-45 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor C  | 5-108 |
| Figure 5.3.2-46 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor D  | 5-109 |
| Figure 5.3.2-47 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor E  | 5-110 |
| Figure 5.3.2-48 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor F  | 5-111 |
| Figure 5.3.2-49 | Second Parametric Sequence<br>Flue Gas Velocity<br>Reactor G  | 5-112 |
| Figure 5.3.3-1  | Third SCR Parametric Test Plan  | 5-114 |
| Figure 5.3.3-2  | Ammonia Slip vs Flow Rate<br>NSKK: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$                                     | 5-127 |
| Figure 5.3.3-3  | Third Parametric Sequence<br>Ammonia Slip vs Flow Rate<br>Siemens: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$     | 5-127 |
| Figure 5.3.3-4  | Third Parametric Sequence<br>Ammonia Slip vs Flow Rate<br>Grace Synox: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$ | 5-128 |
| Figure 5.3.3-5  | Third Parametric Sequence<br>Ammonia Slip vs Flow Rate<br>CORM HD: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$     | 5-128 |

## LIST OF FIGURES (Cont'd)

|                 |  |       |
|-----------------|--|-------|
| Figure 5.3.3-6. | Ammonia Slip vs Flow Rate<br>Haldor Topsoe: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence      | 5-129 |
| Figure 5.3.3-7  | Ammonia Slip vs Flow Rate<br>Hitachi: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence            | 5-129 |
| Figure 5.3.3-8  | Ammonia Slip vs Flow Rate<br>CORM LD: 700 F, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence            | 5-130 |
| Figure 5.3.3-9  | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace NXRМ: Design Flow, 620 F<br>Third Parametric Sequence       | 5-130 |
| Figure 5.3.3-10 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>NSKK: Design Flow, 620 F<br>Third Parametric Sequence             | 5-131 |
| Figure 5.3.3-11 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Siemens: Design Flow, 620 F<br>Third Parametric Sequence          | 5-131 |
| Figure 5.3.3-12 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace Synox: Design Flow, 620 F<br>Third Parametric Sequence      | 5-132 |
| Figure 5.3.3-13 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>CORM HD: Design Flow, 620 F<br>Third Parametric Sequence          | 5-132 |
| Figure 5.3.3-14 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Haldor Topsoe: Design Flow, 620 F<br>Third Parametric Sequence    | 5-133 |
| Figure 5.3.3-15 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Hitachi Zosen: Design Flow, 620 F<br>Third Parametric Sequence    | 5-133 |
| Figure 5.3.3-16 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>CORM LD: Design Flow, 620 F<br>Third Parametric Sequence          | 5-134 |
| Figure 5.3.3-17 | Ammonia Slip vs Temperature<br>Grace NXRМ: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence | 5-134 |
| Figure 5.3.3-18 | Ammonia Slip vs Temperature<br>NSKK: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence       | 5-135 |

## LIST OF FIGURES (Cont'd)

|                 |  |       |
|-----------------|--|-------|
| Figure 5.3.3-19 | Ammonia Slip vs Temperature<br>Siemens: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence                  | 5-135 |
| Figure 5.3.3-20 | Ammonia Slip vs Temperature<br>Grace Synox: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence              | 5-136 |
| Figure 5.3.3-21 | Ammonia Slip vs Temperature<br>CORM HD: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence                  | 5-136 |
| Figure 5.3.3-22 | Ammonia Slip vs Temperature<br>Haldor Topsoe: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence            | 5-137 |
| Figure 5.3.3-23 | Ammonia Slip vs Temperature<br>Hitachi Zosen: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence            | 5-137 |
| Figure 5.3.3-24 | $\text{SO}_2$ Oxidation vs Temperature<br>Grace NXRM: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence    | 5-138 |
| Figure 5.3.3-25 | $\text{SO}_2$ Oxidation vs Temperature<br>NSKK: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence          | 5-138 |
| Figure 5.3.3-26 | $\text{SO}_2$ Oxidation vs Temperature<br>Siemens: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence       | 5-139 |
| Figure 5.3.3-27 | $\text{SO}_2$ Oxidation vs Temperature<br>Grace SNX: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence     | 5-139 |
| Figure 5.3.3-28 | $\text{SO}_2$ Oxidation vs Temperature<br>CORM HD: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence       | 5-140 |
| Figure 5.3.3-29 | $\text{SO}_2$ Oxidation vs Temperature<br>Haldor Topsoe: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence | 5-140 |
| Figure 5.3.3-30 | $\text{SO}_2$ Oxidation vs Temperature<br>Hitachi Zosen: Design Flow, $\text{NH}_3/\text{NO}_x = 0.8$<br>Third Parametric Sequence | 5-141 |
| Figure 5.3.3-31 | Flue Gas Velocity<br>Reactor A<br>Third Parametric Sequence  | 5-142 |
| Figure 5.3.3-32 | Flue Gas Velocity<br>Reactor B<br>Third Parametric Sequence  | 5-143 |

## LIST OF FIGURES (Cont'd)

|                 |  |       |
|-----------------|--|-------|
| Figure 5.3.3-33 | Flue Gas Velocity<br>Reactor C<br>Third Parametric Sequence  | 5-144 |
| Figure 5.3.3-34 | Flue Gas Velocity<br>Reactor D<br>Third Parametric Sequence  | 5-145 |
| Figure 5.3.3-35 | Flue Gas Velocity<br>Reactor E<br>Third Parametric Sequence  | 5-146 |
| Figure 5.3.3-36 | Flue Gas Velocity<br>Reactor F<br>Third Parametric Sequence  | 5-147 |
| Figure 5.3.3-37 | Flue Gas Velocity<br>Reactor G<br>Third Parametric Sequence  | 5-148 |
| Figure 5.3.3-38 | Flue Gas Velocity<br>Reactor J<br>Third Parametric Sequence  | 5-149 |
| Figure 5.3.4-1  | Fourth SCR Parametric Test Plan  | 5-151 |
| Figure 5.3.4-2  | Ammonia Slip vs Flow Rate<br>Grace NXR: $\text{NH}_3/\text{NO}_x = 0.80$ , 620 F<br>Fourth Parametric Sequence     | 5-165 |
| Figure 5.3.4-3  | Ammonia Slip vs Flow Rate<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence          | 5-165 |
| Figure 5.3.4-4  | Ammonia Slip vs Flow Rate<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence       | 5-166 |
| Figure 5.3.4-5  | Ammonia Slip vs Flow Rate<br>Grace SNX: $\text{NH}_3/\text{NO}_x = 0.80$ , 620 F<br>Fourth Parametric Sequence     | 5-166 |
| Figure 5.3.4-6  | Ammonia Slip vs Flow Rate<br>CORM HD: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence       | 5-167 |
| Figure 5.3.4-7  | Ammonia Slip vs Flow Rate<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence | 5-167 |
| Figure 5.3.4-8  | Ammonia Slip vs Flow Rate<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence | 5-168 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.4-9  | Ammonia Slip vs Flow Rate<br>CORM LD: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence            | 5-168 |
| Figure 5.3.4-10 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace NXRM: Design Flow, 620 F<br>Fourth Parametric Sequence         | 5-169 |
| Figure 5.3.4-11 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>NSKK: Design Flow, 620 F<br>Fourth Parametric Sequence               | 5-169 |
| Figure 5.3.4-12 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Siemens: Design Flow, 620 F<br>Fourth Parametric Sequence            | 5-170 |
| Figure 5.3.4-13 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace SNX: Design Flow, 620 F<br>Fourth Parametric Sequence          | 5-170 |
| Figure 5.3.4-14 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>CORM HD: Design Flow, 620 F<br>Fourth Parametric Sequence            | 5-171 |
| Figure 5.3.4-15 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Haldor Topsoe: Design Flow, 620 F<br>Fourth Parametric Sequence      | 5-171 |
| Figure 5.3.4-16 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Hitachi Zosen: Design Flow, 620 F<br>Fourth Parametric Sequence      | 5-172 |
| Figure 5.3.4-17 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>CORM LD: Design Flow, 620 F<br>Fourth Parametric Sequence            | 5-172 |
| Figure 5.3.4-18 | Ammonia Slip vs Temperature<br>Grace NXRM: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence | 5-173 |
| Figure 5.3.4-19 | Ammonia Slip vs Temperature<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence       | 5-173 |
| Figure 5.3.4-20 | Ammonia Slip vs Temperature<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence    | 5-174 |
| Figure 5.3.4-21 | Ammonia Slip vs Temperature<br>Grace SNX: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence  | 5-174 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.4-22 | Ammonia Slip vs Temperature<br>CORM HD: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence              | 5-175 |
| Figure 5.3.4-23 | Ammonia Slip vs Temperature<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence        | 5-175 |
| Figure 5.3.4-24 | Ammonia Slip vs Temperature<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence        | 5-176 |
| Figure 5.3.4-25 | Ammonia Slip vs Temperature<br>CORM LD: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence                    | 5-176 |
| Figure 5.3.4-26 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Grace NXRM: $\text{NH}_3/\text{NO}_x = 0.80$ , Design Flow<br>Fourth Parametric Sequence  | 5-177 |
| Figure 5.3.4-27 | $\text{SO}_2$ Oxidation vs Flow Rate<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence              | 5-177 |
| Figure 5.3.4-28 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence           | 5-178 |
| Figure 5.3.4-29 | $\text{SO}_2$ Oxidation vs Flow Rate<br>CORM HD: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence           | 5-178 |
| Figure 5.3.4-30 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence     | 5-179 |
| Figure 5.3.4-31 | $\text{SO}_2$ Oxidation vs Flow Rate<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence     | 5-179 |
| Figure 5.3.4-32 | $\text{SO}_2$ Oxidation vs Flow Rate<br>CORM LD: $\text{NH}_3/\text{NO}_x = 0.80$ , 700 F<br>Fourth Parametric Sequence           | 5-180 |
| Figure 5.3.4-33 | $\text{SO}_2$ Oxidation vs Temperature<br>Grace NXRM: Design Flow, $\text{NH}_3/\text{NO}_x = 0.80$<br>Fourth Parametric Sequence | 5-180 |
| Figure 5.3.4-34 | $\text{SO}_2$ Oxidation vs Temperature<br>NSKK: Design Flow, $\text{NH}_3/\text{NO}_x = 0.80$<br>Fourth Parametric Sequence       | 5-181 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.4-35 | SO <sub>2</sub> Oxidation vs Temperature<br>Siemens: Design Flow, NH <sub>3</sub> /NO <sub>x</sub> = 0.80<br>Fourth Parametric Sequence       | 5-181 |
| Figure 5.3.4-36 | SO <sub>2</sub> Oxidation vs Temperature<br>Grace SNX: Design Flow, NH <sub>3</sub> /NO <sub>x</sub> = 0.80<br>Fourth Parametric Sequence     | 5-182 |
| Figure 5.3.4-37 | SO <sub>2</sub> Oxidation vs Temperature<br>CORM HD: Design Flow, NH <sub>3</sub> /NO <sub>x</sub> = 0.80<br>Fourth Parametric Sequence       | 5-182 |
| Figure 5.3.4-38 | SO <sub>2</sub> Oxidation vs Temperature<br>Haldor Topsoe: Design Flow, NH <sub>3</sub> /NO <sub>x</sub> = 0.80<br>Fourth Parametric Sequence | 5-183 |
| Figure 5.3.4-39 | SO <sub>2</sub> Oxidation vs Temperature<br>Hitachi Zosen: Design Flow, NH <sub>3</sub> /NO <sub>x</sub> = 0.80<br>Fourth Parametric Sequence | 5-183 |
| Figure 5.3.4-40 | SO <sub>2</sub> Oxidation vs Temperature<br>CORM LD: Design Flow, NH <sub>3</sub> /NO <sub>x</sub> = 0.80<br>Fourth Parametric Sequence       | 5-184 |
| Figure 5.3.4-41 | Mass Concentration Profile<br>Reactor A<br>Fourth Parametric Sequence   | 5-185 |
| Figure 5.3.4-42 | Mass Concentration Profile<br>Reactor B<br>Fourth Parametric Sequence   | 5-186 |
| Figure 5.3.4-43 | Mass Concentration Profile<br>Reactor C<br>Fourth Parametric Sequence   | 5-187 |
| Figure 5.3.4-44 | Mass Concentration Profile<br>Reactor D<br>Fourth Parametric Sequence   | 5-188 |
| Figure 5.3.4-45 | Mass Concentration Profile<br>Reactor E<br>Fourth Parametric Sequence   | 5-189 |
| Figure 5.3.4-46 | Mass Concentration Profile<br>Reactor F<br>Fourth Parametric Sequence   | 5-190 |
| Figure 5.3.4-47 | Mass Concentration Profile<br>Reactor G<br>Fourth Parametric Sequence   | 5-191 |
| Figure 5.3.4-48 | Flue Gas Velocity<br>Reactor A<br>Fourth Parametric Sequence  | 5-192 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.4-49 | Flue Gas Velocity<br>Reactor B<br>Fourth Parametric Sequence  | 5-193 |
| Figure 5.3.4-50 | Flue Gas Velocity<br>Reactor C<br>Fourth Parametric Sequence  | 5-194 |
| Figure 5.3.4-51 | Flue Gas Velocity<br>Reactor D<br>Fourth Parametric Sequence  | 5-195 |
| Figure 5.3.4-52 | Flue Gas Velocity<br>Reactor E<br>Fourth Parametric Sequence  | 5-196 |
| Figure 5.3.4-53 | Flue Gas Velocity<br>Reactor F<br>Fourth Parametric Sequence  | 5-197 |
| Figure 5.3.4-54 | Flue Gas Velocity<br>Reactor G<br>Fourth Parametric Sequence  | 5-198 |
| Figure 5.3.4-55 | Flue Gas Velocity<br>Reactor J<br>Fourth Parametric Sequence  | 5-199 |
| Figure 5.3.5-1  | Fifth (Final) SCR Parametric Test Plan  | 5-202 |
| Figure 5.3.5-2  | Ammonia Slip vs Flow Rate<br>Grace NXR: $\text{NH}_3/\text{NO}_x = 0.90$ , 630 F<br>Fifth Parametric Sequence     | 5-215 |
| Figure 5.3.5-3  | Ammonia Slip vs Flow Rate<br>NSKK: $\text{NH}_3/\text{NO}_x = 1.00$ , 700 F<br>Fifth Parametric Sequence          | 5-215 |
| Figure 5.3.5-4  | Ammonia Slip vs Flow Rate<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.60$ , 700 F<br>Fifth Parametric Sequence       | 5-216 |
| Figure 5.3.5-5  | Ammonia Slip vs Flow Rate<br>Grace SNX: $\text{NH}_3/\text{NO}_x = 1.00$ , 620 F<br>Fifth Parametric Sequence     | 5-216 |
| Figure 5.3.5-6  | Ammonia Slip vs Flow Rate<br>CORM HD: $\text{NH}_3/\text{NO}_x = 0.65$ , 625 F<br>Fifth Parametric Sequence       | 5-217 |
| Figure 5.3.5-7  | Ammonia Slip vs Flow Rate<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.70$ , 700 F<br>Fifth Parametric Sequence | 5-217 |
| Figure 5.3.5-8  | Ammonia Slip vs Flow Rate<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.65$ , 700 F<br>Fifth Parametric Sequence | 5-218 |

### LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.5-9  | Ammonia Slip vs Flow Rate<br>CORM LD: $\text{NH}_3/\text{NO}_x = 0.55$ , 700 F<br>Fifth Parametric Sequence           | 5-218 |
| Figure 5.3.5-10 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace NXRМ: Design Flow, 620 F<br>Fifth Parametric Sequence        | 5-219 |
| Figure 5.3.5-11 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>NSKK: Design Flow, 700 F<br>Fifth Parametric Sequence              | 5-219 |
| Figure 5.3.5-12 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Siemens: Design Flow, 700 F<br>Fifth Parametric Sequence           | 5-220 |
| Figure 5.3.5-13 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Grace SNX: Design Flow, 620 F<br>Fifth Parametric Sequence         | 5-220 |
| Figure 5.3.5-14 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>CORM HD: High Flow, 700 F<br>Fifth Parametric Sequence             | 5-221 |
| Figure 5.3.5-15 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Haldor Topsoe: High Flow, 700 F<br>Fifth Parametric Sequence       | 5-221 |
| Figure 5.3.5-16 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>Hitachi Zosen: High Flow, 700 F<br>Fifth Parametric Sequence       | 5-222 |
| Figure 5.3.5-17 | Ammonia Slip vs $\text{NH}_3/\text{NO}_x$ Ratio<br>CORM LD: Design Flow, 620 F<br>Fifth Parametric Sequence           | 5-222 |
| Figure 5.3.5-18 | Ammonia Slip vs Temperature<br>Grace NXRМ: Design Flow, $\text{NH}_3/\text{NO}_x = 0.60$<br>Fifth Parametric Sequence | 5-223 |
| Figure 5.3.5-19 | Ammonia Slip vs Temperature<br>NSKK: Design Flow, $\text{NH}_3/\text{NO}_x = 1.00$<br>Fifth Parametric Sequence       | 5-223 |
| Figure 5.3.5-20 | Ammonia Slip vs Temperature<br>Siemens: Design Flow, $\text{NH}_3/\text{NO}_x = 0.80$<br>Fifth Parametric Sequence    | 5-224 |
| Figure 5.3.5-21 | Ammonia Slip vs Temperature<br>Grace SNX: Design Flow, $\text{NH}_3/\text{NO}_x = 0.80$<br>Fifth Parametric Sequence  | 5-224 |

## LIST OF FIGURES (Cont'd)

|                 |   |       |
|-----------------|---|-------|
| Figure 5.3.5-22 | Ammonia Slip vs Temperature<br>CORM HD: Design Flow, $\text{NH}_3/\text{NO}_x = 0.70$<br>Fifth Parametric Sequence            | 5-225 |
| Figure 5.3.5-23 | Ammonia Slip vs Temperature<br>Haldor Topsoe: Design Flow, $\text{NH}_3/\text{NO}_x = 0.70$<br>Fifth Parametric Sequence      | 5-225 |
| Figure 5.3.5-24 | Ammonia Slip vs Temperature<br>Hitachi Zosen: Design Flow, $\text{NH}_3/\text{NO}_x = 0.55$<br>Fifth Parametric Sequence      | 5-226 |
| Figure 5.3.5-25 | Ammonia Slip vs Temperature<br>CORM LD: Design Flow, $\text{NH}_3/\text{NO}_x = 0.50$<br>Fifth Parametric Sequence            | 5-226 |
| Figure 5.3.5-26 | Flue Gas Velocity<br>Reactor A<br>Fifth Parametric Sequence   | 5-227 |
| Figure 5.3.5-27 | Flue Gas Velocity<br>Reactor B<br>Fifth Parametric Sequence   | 5-228 |
| Figure 5.3.5-28 | Flue Gas Velocity<br>Reactor C<br>Fifth Parametric Sequence   | 5-229 |
| Figure 5.3.5-29 | Flue Gas Velocity<br>Reactor D<br>Fifth Parametric Sequence   | 5-230 |
| Figure 5.3.5-30 | Flue Gas Velocity<br>Reactor E<br>Fifth Parametric Sequence   | 5-231 |
| Figure 5.3.5-31 | Flue Gas Velocity<br>Reactor F<br>Fifth Parametric Sequence   | 5-232 |
| Figure 5.3.5-32 | Flue Gas Velocity<br>Reactor G<br>Fifth Parametric Sequence   | 5-233 |
| Figure 5.3.5-33 | Flue Gas Velocity<br>Reactor J<br>Fifth Parametric Sequence   | 5-234 |
| Figure 5.4-1    | Intermediate $\text{NO}_x$ Reduction vs Exposure Time<br>Grace Noxeram: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 5000<br>SCFM | 5-244 |
| Figure 5.4-2    | Intermediate $\text{NO}_x$ Reduction vs Exposure Time<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 5000 SCFM             | 5-245 |

## LIST OF FIGURES (Cont'd)

|               |  |       |
|---------------|--|-------|
| Figure 5.4-3  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>Siemens: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 5000 SCFM               | 5-246 |
| Figure 5.4-4  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>Grace Synox: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 400 SCFM            | 5-247 |
| Figure 5.4-5  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>Cormetech High-Dust: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F,<br>400 SCFM | 5-248 |
| Figure 5.4-6  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>Haldor Topsoe: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 400<br>SCFM       | 5-249 |
| Figure 5.4-7  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>Hitachi Zosen: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 400<br>SCFM       | 5-250 |
| Figure 5.4-8  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>Cormetech Low-Dust: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F,<br>400 SCFM  | 5-251 |
| Figure 5.4-9  | Intermediate NO <sub>x</sub> Reduction vs Exposure Time<br>At Base-Line Conditions<br>Values are for the combination of all reactors       | 5-252 |
| Figure 5.4-10 | Average NO <sub>x</sub> Reduction (Base-Line)<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.8, Design Temp, Design Flow Rate                     | 5-253 |
| Figure 5.4-11 | Average NO <sub>x</sub> Reduction (Base-Line)<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.8, Low Temp, Design Flow Rate                        | 5-254 |
| Figure 5.4-12 | Average NO <sub>x</sub> Reduction<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.8, Design Temp, High Flow  | 5-255 |
| Figure 5.4-13 | Average NO <sub>x</sub> Reduction<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.6, Design Temp, Design Flow                                      | 5-256 |
| Figure 5.4-14 | Ammonia Slip vs Time<br>Grace Noxeram: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 5000<br>SCFM   | 5-257 |
| Figure 5.4-15 | Ammonia Slip vs Time<br>NSKK: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 5000 SCFM   | 5-258 |
| Figure 5.4-16 | Ammonia Slip vs Time<br>Siemens: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 5000 SCFM  | 5-259 |
| Figure 5.4-17 | Ammonia Slip vs Time<br>Grace Synox: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 400<br>SCFM  | 5-260 |
| Figure 5.4-18 | Ammonia Slip vs Time<br>Cormetech High-Dust: NH <sub>3</sub> /NO <sub>x</sub> = 0.8,<br>700 F, 400 SCFM                                    | 5-261 |
| Figure 5.4-19 | Ammonia Slip vs Time<br>Haldor Topsoe: NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 400<br>SCFM  | 5-262 |

### LIST OF FIGURES (Cont'd)

|               |   |       |
|---------------|---|-------|
| Figure 5.4-20 | Ammonia Slip vs Time<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 400<br>SCFM   | 5-263 |
| Figure 5.4-21 | Ammonia Slip vs Time<br>Cormetech Low-Dust: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F,<br>400 SCFM  | 5-264 |
| Figure 5.4-22 | Ammonia Slip vs Exposure Time At Base-Line<br>Conditions<br>Values are for the Combination of all Reactors<br>$\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 100% Design Flow | 5-265 |
| Figure 5.4-23 | Average Base-Line Ammonia Slip<br>$\text{NH}_3/\text{NO}_x = 0.8$ , Design Temp, Design Flow  | 5-266 |
| Figure 5.4-24 | Average Base-Line Ammonia Slip<br>$\text{NH}_3/\text{NO}_x = 0.8$ , Low Temp, Design Flow   | 5-267 |
| Figure 5.4-25 | Average Ammonia Slip<br>$\text{NH}_3/\text{NO}_x = 0.8$ , Design Temp, High Flow  | 5-268 |
| Figure 5.4-26 | Average Ammonia Slip<br>$\text{NH}_3/\text{NO}_x = 1.0$ , Design Temp, Design Flow Rate   | 5-269 |
| Figure 5.4-27 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Grace Noxeram: $\text{NH}_3/\text{NO}_x = 0.8$ , Design Temp,<br>Design Flow  | 5-270 |
| Figure 5.4-28 | $\text{SO}_2$ Oxidation vs Exposure Time<br>NSKK: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 5000 SCFM  | 5-271 |
| Figure 5.4-29 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Siemens: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 5000 SCFM   | 5-272 |
| Figure 5.4-30 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Grace Synox: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 400<br>SCFM   | 5-273 |
| Figure 5.4-31 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Cormetech High-Dust: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F,<br>400 SCFM   | 5-274 |
| Figure 5.4-32 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Haldor Topsoe: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 400<br>SCFM   | 5-275 |
| Figure 5.4-33 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Hitachi Zosen: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F, 400<br>SCFM   | 5-276 |
| Figure 5.4-34 | $\text{SO}_2$ Oxidation vs Exposure Time<br>Cormetech Low-Dust: $\text{NH}_3/\text{NO}_x = 0.8$ , 700 F,<br>400 SCFM  | 5-277 |

## LIST OF FIGURES (Cont'd)

|               |  |       |
|---------------|--|-------|
| Figure 5.4-35 | SO <sub>2</sub> Oxidation vs Exposure Time At Base-Line Conditions<br>Values are for the combination of all Reactors<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.8, 700 F, 100% of Design Flow | 5-278 |
| Figure 5.4-36 | Average SO <sub>2</sub> Oxidation (Base-Line)<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.8, Design Temp, Design Flow  | 5-279 |
| Figure 5.4-37 | Average SO <sub>2</sub> Oxidation<br>NH <sub>3</sub> /NO <sub>x</sub> = 0.8, High Temp, Design Flow  | 5-280 |
| Figure 5.5-1  | Air Preheater Trend Data for 3rd Quarter 1993<br>Train A   | 5-294 |
| Figure 5.5-2  | Air Preheater Trend Data for 3rd Quarter 1993<br>Train B   | 5-295 |
| Figure 5.5-3  | Air Preheater Trend Data for 3rd Quarter 1993<br>Train C   | 5-296 |
| Figure 5.5-4  | Air Preheater Trend Data for 4th Quarter 1993<br>Train A   | 5-297 |
| Figure 5.5-5  | Air Preheater Trend Data for 4th Quarter 1993<br>Train B   | 5-298 |
| Figure 5.5-6  | Air Preheater Trend Data for 4th Quarter 1993<br>Train C   | 5-299 |
| Figure 5.5-7  | Air Preheater Trend Data for 1st Quarter 1994<br>Train A   | 5-300 |
| Figure 5.5-8  | Air Preheater Trend Data for 1st Quarter 1994<br>Train B   | 5-301 |
| Figure 5.5-9  | Air Preheater Trend Data for 1st Quarter 1994<br>Train C   | 5-302 |
| Figure 5.5-10 | Air Preheater Trend Data for 2nd Quarter 1994<br>Train A   | 5-303 |
| Figure 5.5-11 | Air Preheater Trend Data for 2nd Quarter 1994<br>Train B   | 5-304 |
| Figure 5.5-12 | Air Preheater Trend Data for 2nd Quarter 1994<br>Train C   | 5-305 |
| Figure 5.5-13 | Air Preheater Trend Data for 3rd Quarter 1994<br>Train A   | 5-306 |
| Figure 5.5-14 | Air Preheater Trend Data for 3rd Quarter 1994<br>Train B   | 5-307 |
| Figure 5.5-15 | Air Preheater Trend Data for 3rd Quarter 1994<br>Train C   | 5-308 |
| Figure 5.5-16 | Air Preheater Trend Data for 4th Quarter 1994<br>Train A   | 5-309 |
| Figure 5.5-17 | Air Preheater Trend Data for 4th Quarter 1994<br>Train B   | 5-310 |

## LIST OF FIGURES (Cont'd)

|               |  |       |
|---------------|--|-------|
| Figure 5.5-18 | Air Preheater Trend Data for 4th Quarter 1994<br>Train C | 5-311 |
| Figure 5.5-19 | Air Preheater Trend Data for 1st Quarter 1995<br>Train A | 5-312 |
| Figure 5.5-20 | Air Preheater Trend Data for 1st Quarter 1995<br>Train B | 5-313 |
| Figure 5.5-21 | Air Preheater Trend Data for 1st Quarter 1995<br>Train C | 5-314 |
| Figure 5.5-22 | Air Preheater Trend Data for 2nd Quarter 1995<br>Train A | 5-315 |
| Figure 5.5-23 | Air Preheater Trend Data for 2nd Quarter 1995<br>Train B | 5-316 |
| Figure 5.5-24 | Air Preheater Trend Data for 2nd Quarter 1995<br>Train C | 5-317 |
| Figure 5.6-1  | K/Ko vs Exposure Time ( Grace Noxeram )                  | 5-323 |
| Figure 5.6-2  | K/Ko vs Exposure Time ( NSKK)                            | 5-323 |
| Figure 5.6-3  | K/Ko vs Exposure Time ( Siemens)                         | 5-324 |
| Figure 5.6-4  | K/Ko vs Exposure Time ( Grace Synox )                    | 5-324 |
| Figure 5.6-5  | K/Ko vs Exposure Time ( Cormetech HD)                    | 5-325 |
| Figure 5.6-6  | K/Ko vs Exposure Time ( Haldor Topsoe)                   | 5-325 |
| Figure 5.6-7  | K/Ko vs Exposure Time ( Hitachi Zosen)                   | 5-326 |
| Figure 5.6-8  | K/Ko vs Exposure Time ( Cormetech LD)                    | 5-326 |
| Figure 5.6-9  | Composite K/Ko vs Time for Cond. #1                      | 5-327 |
| Figure 5.6-10 | Composite K/Ko vs Time for Cond. #2                      | 5-327 |
| Figure 5.6-11 | Composite K/Ko vs Time for Cond. #3                      | 5-328 |
| Figure 5.6-12 | Composite K/Ko vs Time for Cond. #4                      | 5-328 |
| Figure 5.6-13 | Composite K/Ko vs Time for Cond. #5                      | 5-329 |
| Figure 5.6-14 | Composite K/Ko vs Time for Cond. #6                      | 5-329 |

## LIST OF APPENDICES

|                             |   |
|-----------------------------|---|
| Appendix A (Volume 2) ..... | Example Material Safety Data Sheet            |
| Appendix B .....            | Initial Site Characterization Test Results    |
| Appendix C .....            | Testing Proposal, Southern Research Institute |
| Appendix D .....            | Example Laboratory Catalyst Test Protocol     |
| Appendix E .....            | Detailed Coal Analysis Data                   |
| Appendix F .....            | Standard Methods - QA/QC Document             |
| Appendix G .....            | Task #1 Commissioning Tests                   |
| Appendix H .....            | Task #2 Commissioning Tests                   |
| Appendix I .....            | First Parametric Sequence Spreadsheets        |
| Appendix J .....            | Second Parametric Sequence Spreadsheets       |
| Appendix K .....            | Third Parametric Sequence Spreadsheets        |
| Appendix L .....            | Fourth Parametric Sequence Spreadsheets       |
| Appendix M .....            | Fifth Parametric Sequence Spreadsheets        |
| Appendix N .....            | First Series - Manual APH Tests               |
| Appendix O .....            | Second Series - Manual APH Tests              |
| Appendix P .....            | Third Series - Manual APH Tests               |
| Appendix Q .....            | ABB Analysis of Air Preheaters - Final Report |
| Appendix R .....            | ABB Corrosion Analysis Study                  |
| Appendix S .....            | SRI Waste Stream Impacts Study                |
| Appendix T .....            | Economic Evaluation                           |

## LIST OF ABBREVIATIONS

|                   |  |
|-------------------|--|
| $\Delta P$        | Pressure Drop  |
| $\Delta P_a$      | Air-Side Pressure Drop   |
| $\Delta P_g$      | Gas-Side Pressure Drop   |
| AB                | Analyzer Bank  |
| ABB               | ABB Air Preheater, Inc.  |
| ABS               | Ammonium Bisulfate   |
| ABS/AS            | Ammonium Bisulfate/Ammonium Sulfate                                    |
| AC                | Alternating Current  |
| AMCA              | Air Moving and Conditions Association                                  |
| APC               | Alabama Power Company  |
| APH               | Air Preheater  |
| ASHRAE            | American Society of Heating, Refrigeration, Air Conditioning Engineers |
| ASME              | American Society of Mechanical Engineers                               |
| ASTM              | American Society for Testing and Materials                             |
| AV                | Area Velocity  |
| CAAA              | Clean Air Act Amendments   |
| cal.              | Calibration  |
| CCT               | Clean Coal Technology  |
| CE                | Combustion Engineering   |
| CRT               | Cathode Ray Tube (Monitor)   |
| DC                | Direct Current   |
| DCS               | Digital Control System   |
| deNO <sub>x</sub> | Nitrogen Oxides Removal  |
| DOE               | U.S. Department of Energy  |
| DU                | Undulating Design  |
| EPA               | U.S. Environmental Protection Agency                                   |
| EPRI              | Electric Power Research Institute                                      |
| ESP               | Electrostatic Precipitator   |
| EV <sub>a</sub>   | Air Side Euler Number  |
| EV <sub>g</sub>   | Gas Side Euler Number  |
| FD                | Forced Draft   |
| FW                | Foster Wheeler   |
| HAPs              | Hazardous Air Pollutants   |
| HVAC              | Heating, Ventilation and Air Conditioning                              |
| I & C             | Instrumentation and Controls   |
| ICAP              | Inductively Coupled Argon Plasma                                       |
| ICCT              | Innovative Clean Coal Technology                                       |
| ID                | Induced Draft  |
| IEEE              | Institute of Electrical and Electronics Engineers                      |
| INAA              | Instrumental Neutron Activation Analysis                               |
| INT.              | Intermediate   |

### LIST OF ABBREVIATIONS (Cont'd)

|                  |  |
|------------------|--|
| k/k <sub>o</sub> | Relative Catalyst Activity                               |
| LSMCC            | Lear Siegler Measurement Controls Corporation            |
| MCC              | Motor Control Center                                     |
| MMD              | Mass Median Diameter                                     |
| MSDS             | Material Safety Data Sheet                               |
| MWe              | Megawatts electrical                                     |
| NA               | Not Available  |
| NEMA             | National Electrical Material Association                 |
| NEPA             | National Environmental Policy Act                        |
| NF               | Notched-Flat Design                                      |
| NO <sub>x</sub>  | Nitrogen Oxides (Combination of NO and NO <sub>2</sub> ) |
| o.d.             | Outer Diameter   |
| Oxid.            | Oxidation  |
| PEIS             | Programmatic Environmental Impact Statement              |
| QA               | Quality Assurance  |
| QC               | Quality Control  |
| RMS              | Root Mean Square   |
| rsd              | Relative Standard Deviation                              |
| SCR              | Selective Catalytic Reduction                            |
| SCS              | Southern Company Services, Inc.                          |
| SRI              | Southern Research Institute                              |
| SS               | Stainless Steel  |
| SV               | Space Velocity   |
| TCLP             | Toxicity Characteristic Leaching Procedure               |
| TVA              | Tennessee Valley Authority                               |
| w.c.             | Water Column   |

## LIST OF UNITS

|              |   |
|--------------|---|
| %            | Percent                                       |
| μ            | Microns                                       |
| acfm         | Actual Cubic Feet Per Minute                  |
| atm          | Atmosphere                                    |
| BTU          | British Thermal Unit                          |
| dscf         | Dry Standard Cubic Foot                       |
| fps          | Feet Per Second                               |
| ft or f      | Feet  |
| gpm          | Gallons Per Minute                            |
| gr           | Grains  |
| h or hr      | Hour  |
| Hz           | Hertz   |
| in           | Inches  |
| kg           | Kilogram                                      |
| KVA          | Kilo Volt - Amperes                           |
| kW           | Kilowatt                                      |
| lb           | Pounds  |
| m            | Meter   |
| ma           | Milliamperes                                  |
| mg           | Milligram                                     |
| mm           | Millimeter                                    |
| MMBtu        | Million British Thermal Units                 |
| N            | Normal (1 atm, 0 °C)                          |
| °C           | Degrees Celsius                               |
| °F           | Degrees Fahrenheit                            |
| ppm          | Parts-per-million                             |
| ppm(v)       | Parts-per-million by volume                   |
| psig         | Pounds Per Square Inch Gage                   |
| s            | Seconds                                       |
| SCFM or scfm | Standard Cubic Feet Per Minute (1 atm, 32 °F) |
| Sq. ft.      | Square Feet                                   |
| T            | Temperature                                   |
| V            | Volt  |
| VAC          | Volts Alternating Current                     |
| W            | Watt  |
| WSCFM        | Wet Standard Cubic Feet Per Minute            |

## EXECUTIVE SUMMARY

### Introduction/Process Description.

This project, titled "Demonstration of Selective Catalytic Reduction (SCR) technology for the control of Nitrogen Oxides (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers" is part of the Department of Energy's Innovative Clean Coal Technology Program. The project had a total budget of approximately \$23 million.

The Innovative Clean Coal Technology Demonstration Program (also referred to as the CCT Program) is a \$7.14 billion cost-shared industry/government technology development effort. The program is to demonstrate a new generation of advanced coal-based technologies, with the most promising technologies being moved into the domestic and international marketplace.

SCR technology involves the catalytic reaction of ammonia (NH<sub>3</sub>), which is injected into the flue gas, and NO<sub>x</sub> to produce molecular nitrogen (N<sub>2</sub>) and water vapor. These reactions take place in the SCR reactor using a solid phase catalyst to help promote the reaction. The catalyst is housed in a reactor located downstream of the boiler economizer and normally operates at approximately 700 °F. Ductwork may be provided to bypass some flue gas around the economizer during periods when the boiler is operating at reduced load to insure that the catalytic reactor is operating at a sufficiently high temperature.

Current formulations of SCR catalysts are typically comprised of vanadium pentoxide (V<sub>2</sub>O<sub>5</sub>) as the active material deposited on or incorporated with a substrate. The catalyst substrate is typically composed of pure titanium dioxide (TiO<sub>2</sub>), although some manufacturers use modifications to this standard material. The catalyst is offered commercially in two basic geometric shapes: honeycomb and plate.

DeNO<sub>x</sub> efficiency is nearly directly proportional to the ratio of NH<sub>3</sub> to NO<sub>x</sub> up to NO<sub>x</sub> removal (deNO<sub>x</sub>) levels for which an installation has been designed. At higher removal levels, however, unreacted NH<sub>3</sub> passing through the SCR reactor becomes appreciable (referred to as NH<sub>3</sub> slip). Minimization of NH<sub>3</sub> slip is a major operational and design concern as discussed below due to its potential to form by-products such as ammonium bisulfate (NH<sub>4</sub>HSO<sub>4</sub>) which are detrimental to down-stream equipment.

### Project Objective/Goals

The project objective was to demonstrate the applicability of SCR technology to provide a cost-effective means of reducing NO<sub>x</sub> emissions from power plants burning U.S. high-sulfur coal. The process was demonstrated on flue gases containing both high and low concentrations of particulate matter. The performance of eight commercially available

SCR catalysts were evaluated from suppliers selected from throughout the world. These catalysts were evaluated under various operating conditions while achieving NO<sub>x</sub> reduction as high as 98%.

Specifically, the project addressed several technical uncertainties which are associated with applying SCR technology to U.S. coals. These include:

1. Potential catalyst deactivation due to poisoning by trace metal species in U.S. coals that are not present in other fuels.
2. Performance of the technology and effects on the balance-of-plant equipment including three air preheater designs in the presence of high amounts of SO<sub>2</sub> and SO<sub>3</sub>.
3. Performance of a wide variety of SCR catalyst compositions, geometries, and methods of manufacture under these new operating conditions.
4. Performance of and requirements for auxiliary equipment associated with SCR technology.

## Results

The test facility was operated for a period of two years to provide adequate exposure time to determine important long-term catalyst operating parameters. Actual exposure time on most catalysts was 10,000 to 12,000 hours.

### Catalyst Deactivation

The results of laboratory tests have shown that for all catalysts, deactivation rates are similar to those noted in European and Japanese installations. No unusual deactivation trends were noted and it appears that at least for the coals tested at this facility, catalyst poisoning and deactivation are similar in significance to other world-wide installations.

### Catalyst SO<sub>2</sub> Oxidation

Unfortunately, the catalytic reactions that result in deNO<sub>x</sub> activity also contribute to SO<sub>2</sub> oxidation activity. Since increased SO<sub>2</sub> oxidation is detrimental to equipment downstream of the SCR, the competing reactions tend to bound the catalyst design. In general, as requirements to minimize SO<sub>2</sub> oxidation relax, deNO<sub>x</sub> activity per volume of catalyst can be increased. The upper bound for SO<sub>2</sub> oxidation for the test facility catalysts was set at 0.75%. While all catalyst designs essentially met this maximum oxidation requirement, some exceeded (improved upon) it greatly. In practice, all suppliers would likely be able to meet a customer's specific SO<sub>2</sub> oxidation requirements.

### Air Preheater Performance

As measured by the drop in number of transfer units (Ntu) from the initial values to the final values, the thermal performance of the test facility's air preheaters declined an average of 14%. In general, all three air preheaters showed generally steady increases in gas-side pressure drop during the test period. In general, the high  $\Delta P$ 's could be reduced by aggressive cleaning methods, including sootblowing at 4 hour intervals, thorough water washing, and occasional increases in the gas outlet temperature. It was not possible, however, to maintain the original, clean  $\Delta P$  of any of the air preheaters. Corrosion tests on various heat transfer surfaces showed that enameled heat transfer surfaces should be used when both sulfur and ammonia compounds are present in the gas stream.

### SCR Technology Economics

The test facility operating experience provided a basis for an economic study investigating implementation of SCR technology. This study reports the results of a commercial-scale capital and O&M costs evaluation of SCR technology applied to a new, coal-fired boiler utilizing high-sulfur, U.S. indigenous coal. The information reported reflects a macro-economic analysis of SCR technology based on historical data measured at the test facility, empirical laboratory data generated as a result of the test program, and consolidation of operational lessons learned tempered with the knowledge of the current commercial market trends.

The conclusion shows the 250-MW base case (60%  $\text{NO}_x$  removal) unit capital and first year O&M (in 1996 dollars) are \$13,415,000 (\$54/kW) and \$1,045,000, respectively. Levelized cost for the base case unit is \$2,500/ton on a current dollar basis and \$1,802/ton on a constant dollar basis. Busbar cost is 2.57 mills/kWh on a current dollar basis and 1.85 mills/kWh on a constant dollar basis.

For the new plant applications, total capital requirement for a 60 percent  $\text{NO}_x$  removal design ranged from \$45/kW for a 700-MW unit to \$61/kW for a 125-MW unit. Associated current dollar levelized cost ranged from \$2,165/ton to \$2,811/ton for the 700-MW unit and 125-MW unit, respectively.

Capital cost variation as a function of  $\text{NO}_x$  removal for a 250-MW unit ranged from \$57/kW for an 80 percent design to \$52/kW for a 40 percent removal design. Corresponding current dollar levelized cost ranged from \$2,036/ton to \$3,502/ton for the 80 percent and 40 percent removal cases, respectively.

Retrofit applications for a 60 percent removal design show a range of capital requirements from \$59/kW for an 880-MW unit size to \$87/kW for a 100-MW units size. There are two plants having capital requirements of \$130/kW and \$112/kW due to balanced draft conversion of the units. Levelized costs range from \$1,848/ton to \$5,108/ton on a current dollar basis.

## BIBLIOGRAPHY

### *Papers*

1. Hinton, W.S., Maxwell, J.D., Healy, E.C., Hardman, R.R., (Southern Company Services, Inc.), *Demonstration of SCR Technology for the control of NO<sub>x</sub> Emissions from High-Sulfur Coal-Fired Boilers*, EPRI Workshop on NO<sub>x</sub> controls for Utility Boilers, Cincinnati, Ohio, August 6-8, 1996.
2. Hinton, W.S., Maxwell, J.D. (Southern Company Services, Inc.), and Baldwin, A.L., (Pittsburgh Energy Technology Center), *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers at Plant Crist-SCR Test Facility*, Fourth Annual Clean Coal Technology Conference: The Global Opportunity. Technical Papers. Report No. CONF-9509170. U.S. Department of Energy, The Center for Energy and Economic Development, and National Mining Association, September 1995
3. Hinton, W.S., Powell, C.A., Maxwell, J.D. (Southern Company Services, Inc.), Baldwin, A.L., (Pittsburgh Energy Technology Center), *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers at Plant Crist SCR Test Facility*, EPRI/EPA 1995 Joint Symposium on Stationary Combustion NO<sub>x</sub> Control, Kansas City, Missouri, May 16-19, 1995.
4. Hinton, W.S., Powell, C.A., Maxwell, J.D. (Southern Company Services, Inc.), et al., *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers at Plant Crist SCR Test Facility*, Third Annual Clean Coal Technology Conference: Technical Papers. U.S. Department of Energy and The Center for Energy & Economic Development. September 1994.
5. Powell, C.A., Hinton, W.S., Maxwell, J.D. (Southern Company Services, Inc.), *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers*, EPRI's NO<sub>x</sub> Controls for Utility Boilers Workshop, May 11-13, 1994.
6. Hinton, W.S., Powell, C.A., Maxwell, J.D. (Southern Company Services, Inc.), *Demonstration of Selective Catalytic Reduction Technology for the Control of Nitrogen Oxide Emissions from High-Sulfur Coal-Fired Boilers*, Proceedings - Second Annual Clean Coal Technology Conference. Report No. CONF-9309152. U.S. Department of Energy and the Southern States Energy Board. September 1993.

7. Maxwell, J.D., Ranhotra, G.S., (Southern Company Services, Inc.), *Demonstration of Selective Catalytic Reduction Technology for the control of Nitrogen Oxide Emissions from High-Sulfur Coal-Fired Boilers*, 86th Annual Meeting and Exhibition - Air and Waste Management Association, Denver, Colorado, June 13-18, 1993.
8. Maxwell, J.D. (Southern Company Services, Inc.), Baldwin, A.L., (Pittsburgh Energy Technology Center), *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers*, 1992 International Joint Power Generation Conference and Exposition, October 18-22, 1992, Atlanta, Georgia.
9. Maxwell, J.D. (Southern Company Services, Inc.), Baldwin, A.L., (Pittsburgh Energy Technology Center), *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers*, Ninth Annual international Pittsburgh Coal Conference, October 12-16, 1992.
10. Maxwell, J.D. (Southern Company Services, Inc.), Baldwin, A.L., (Pittsburgh Energy Technology Center), *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers*, First Annual Clean Coal Technology Conference, Cleveland, Ohio, September 1992.

### ***Project Publications***

11. *Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers: Environmental Monitoring Program (EMP) Final Report.* This report prepared by Radian International LLC for Southern Company Services, Inc. Submitted to the U.S. Department of Energy on September 30, 1996.
12. *United States Department of Energy's and Southern Company Services, Inc.'s September 28 - October 12, 1991, Visit to Japanese (Hitachi Zosen, Nippon Shokubai K.K., and Mitsubishi Heavy Industries) Selective Catalytic Reduction Catalyst Suppliers.* Baldwin, A.L., (Pittsburgh Energy Technology Center), Maxwell, J.D., (Southern Company Services, Inc.).
13. *United States Department of Energy's and Southern Company Services, Inc.'s August 24 - September 1, 1991, Visit to European (Haldor Topsoe A/S, Siemens AG, and Simmering - Graz - Pauker VA) Selective Catalytic Reduction Catalyst Suppliers.* Baldwin, A.L., (Pittsburgh Energy Technology Center), Maxwell, J.D., (Southern Company Services, Inc.).

14. *Design Bases, Volume 1 and 2, Demonstration of Selective Catalytic Reduction (SCR) Technology for the control of Nitrogen Oxide (NO<sub>x</sub>) Emissions from High-Sulfur Coal-Fired Boilers, (Preliminary and Final) Public Design Report, June 1991. (Southern Company Services, Inc.).*
15. Quarterly Technical Progress Reports. (Southern Company Services, Inc.). Reports covering the third Quarter 1990 through the Fourth Quarter 1995.



## **1.0 INTRODUCTION**

### **1.1 ICCT Program**

#### **1.1.1 Role of the Program**

The Innovative Clean Coal Technology Demonstration Program (also referred to as the CCT Program) is a \$7.14 billion cost-shared industry/government technology development effort. The program is to demonstrate a new generation of advanced coal-based technologies, with the most promising technologies being moved into the domestic and international marketplace.

Coal is a major contributor to the energy and economic well-being of the United States, accounting for almost one-quarter of the primary energy consumed. Nearly 53 percent of all electricity generated in 1993 came from coal. It is forecast that coal will continue to dominate as a fuel for U.S. electric power production at least through 2010, with a significant need for additional baseload capacity starting about the middle of the first decade (nominally 2005). Coal is also an important source of energy for the industrial sector, particularly in the generation of heat and power and in the production of iron, steel, and cement. Coal is a vital contributor to the U.S. economy, making a \$21-billion direct annual contribution and accounting for over one million jobs. Additionally, coal exerts a positive influence on the nation's trade deficit with annual exports valued at nearly \$5 billion leaving U.S. ports to Canada and overseas destinations.

Technology has a vital role in ensuring that coal can continue to serve U.S. energy interests and enhance opportunities for economic growth and employment while meeting the national commitment to a clean and healthy global environment. These technologies are being advanced through the CCT Program, with the most promising moving into the marketplace.

The CCT Program has been committed to commercial realization since its inception. The emphasis on commercialization reflects the strategic importance of coal to the U.S. economy and the commitment to sound environmental policies. The CCT Program plays a major role in

advancing the U.S. Department of Energy's (DOE) vision of the future by being a major contributor in ensuring that the United States leads the world in developing, applying, and exporting sustainable, clean, and economically competitive coal utilization technologies. As such, the CCT Program has a key role in advancing three goals of the DOE Strategic Plan under the Energy Resource business line:

- \* Reduce adverse environmental impacts associated with energy production, delivery, and use;
- \* Ensure reliable energy services with reduced vulnerability to energy price and supply volatility; and
- \* Enhance energy productivity to strengthen the U.S. economy and improve living standards.

The technologies being demonstrated under the CCT Program reduce the emissions of sulfur oxides, nitrogen oxides, greenhouse gases, hazardous air pollutants, solid and liquid wastes, and other emissions resulting from coal use or conversion to other fuel forms. These emissions reductions are achieved with efficiencies equal to or greater than currently available technologies.

Clean coal technologies being demonstrated under the CCT Program are creating the technology base that allows the nation to meet its energy and environmental goals efficiently and reliably. The fact that most of the demonstrations are being conducted at commercial scale, in actual user environments, and under conditions typical of commercial operations, allows the potential of the technologies to be evaluated in their intended commercial applications. The technologies are categorized into four market sectors:

- \* Advanced electric power generation systems,
- \* Environmental control devices,
- \* Coal processing equipment for clean fuels, and
- \* Industrial technologies.

Approximately 78 percent, or about \$5.5 billion, of the total CCT Program cost is directed toward enhancing efficiency and reliability of electric power production by addressing the advanced electric power generation systems and environmental control devices market applications. Over 1,200 MWe of new capacity and over 800 MWe of repowered capacity are represented by 15 advanced electric power generation projects valued at \$4.8 billion. There are 19 environmental control device projects valued at more than \$686 million. These projects include NO<sub>x</sub> controls, SO<sub>2</sub> controls, and combined SO<sub>2</sub>/NO<sub>x</sub> controls.

Participation in the projects mentioned above involves over 55 investor-owned utilities, non-utility power generators, municipals, and cooperatives. These electric power generators represent approximately 50 percent of the coal-fired capacity in the United States and almost 70 percent of the Phase-I-affected units under Title IV of the Clean Air Act Amendments (CAAA) of 1990.

There are five coal processing projects for clean fuels valued at over \$521 million. These projects produce solid, high-energy-density compliance fuels and coal-derived liquids that can be used as electric power generation fuel and as chemical or transportation fuel feedstock. One project is demonstrating a method to allow optimum matching of the boiler's performance to coal feedstock.

The final market application category is industrial technologies, encompassing the iron, steel, and cement industries and industrial boilers. There are six projects in this category valued at over \$1.12 billion.

The contribution of the \$7.4 billion CCT Program to direct employment in the 21 states where projects are located is significant. Each advanced electric power generation project can create more than 1,000 construction jobs and 50-130 permanent operator jobs, while a typical retrofit emissions control project employs 100-200 construction workers. Thus, the 45 clean coal projects are estimated to create, for the years 1995 through 1999, an average of 29,000 construction and service jobs (direct and indirect), up to 2,000 permanent operating jobs, and over 500 jobs in coal mining and related industries.

### 1.1.2 Program Implementation

The CCT Program has been implemented through a series of five nationwide competitive solicitations (CCT I-V) conducted over a period of nine years, with each competition associated with a specific level of government funding and program objectives. The first three solicitations were aimed primarily at technologies that could mitigate the potential impacts of acid rain. The fourth and fifth solicitations addressed the post-2000 energy supply and demand situation with SO<sub>2</sub> emissions capped under the CAAA of 1990, increasing need for electric power, and continuing concerns over global climate change--a situation which translates into a need for technologies with very high efficiencies and extremely low emissions.

The completion of the original plans for five solicitations provided the framework to examine the lessons learned from the planning and implementation of the program and to analyze its future needs. In June 1994, DOE published the report, *Clean Coal Technology Program Lessons Learned*. This report summarized the programmatic and procedural lessons learned in conducting the program. Comments from the industrial participants are quoted to highlight the important aspects of the program from their viewpoint.

In planning for the future, two additional reports were issued in 1994. In February 1994, the National Coal Council released a report requested by the Secretary of Energy on the future directions for the CCT Program. The thrust of the report, *Clean Coal Technology for Sustainable Development*, was recommendations to enhance commercial deployment of demonstrated technologies. The second report, *Clean Coal Technology Program Completing the Mission*, was issued by DOE in May 1994 in response to a congressional request that the Secretary report on available funds appropriated but not used in the solicitations. The report stated "the highest priority for DOE is the completion of the 45 projects currently in the program."

Critical factors in implementing the CCT Program involve complying with the requirements of the National Environmental Policy Act (NEPA), executing the environmental monitoring plans (EMP), and monitoring hazardous air pollutants (HAPs).

The CCT Program complies with NEPA through a process which includes (1) preparation in 1989 of a programmatic environmental impact statement (PEIS); (2) preparation of pre-selection, project-specific environmental reviews; and (3) preparation of post-selection, site-specific NEPA documents.

By the end of 1994, NEPA reviews had been completed for 33 of the 45 projects. Additionally, during 1994, four public meetings were held on draft environmental impact statements for two projects.

Sponsors of CCT projects are required to develop and implement an EMP which is intended to ensure collection and dissemination of the significant technology, project, and site-specific environmental data. At the end of 1994, EMPs had been completed for 30 projects.

The CAAA of 1990 calls for the eventual establishment of HAPs emissions standards for various source categories. The CCT Program recognizes that HAPs emissions from clean coal technologies will become part of the characterization of environmental performance used to evaluate commercial deployment potential. Therefore, DOE established a HAPs monitoring program which is being implemented in 25 active projects. These data are being shared with the U.S. Environmental Protection Agency, which is responsible for evaluating HAPs emissions.

### **1.1.3 Funding**

Congress has appropriated nearly \$2.75 billion as a federal budget for the CCT Program. These funds have been committed to demonstration projects through five competitive solicitations. Cooperative agreement awards have been negotiated for each project selected in the five solicitations, with the exception of one project which is in negotiation.

The five solicitations have resulted in a combined commitment by the federal government and the private sector of about \$7.14 billion. DOE's share of the project cost is \$2.42 billion, or approximately 34 percent of the total. The project participants (i.e., the non-federal government participants) are providing the remainder -- nearly \$4.72 billion, or approximately 66 percent of the total estimated cost.

Although all funds necessary to implement the entire CCT Program were appropriated by Congress prior to fiscal year (FY) 1990, the legislation directs that these funds be made available (i.e., apportioned) to DOE on a time-phased basis. Total funding has been apportioned for the first three solicitations. Funding for the projects selected under the fourth solicitation (\$566 million) were apportioned for FY 1991 through FY 1997. The \$564 million for projects selected in the fifth solicitation are apportioned for FY 1992 through 1997.

In 1994, repayments to the government were received from the Nucla CFB Demonstration Project (Tri-State Generation and Transmission Association, Inc.), Full-Scale Demonstration of Low-NO<sub>x</sub> Cell Burner Retrofit (The Babcock & Wilcox Company), and the Development of the Coal Quality Expert (ABB Combustion Engineering, Inc., and CQ, Inc.).

#### **1.1.4 Commercial Realization**

The success of the CCT Program ultimately will be measured by the degree to which the technologies are commercialized and by their contribution to the resolution of energy, economic, and environmental issues. This contribution can be maximized best if those in the public and private sectors appreciate that clean coal technologies increase the efficiency of energy use and enhance environmental quality at costs which are competitive with alternative energy options.

In 1994, an active program was expanded to define and understand the potential domestic and international markets for clean coal technologies. This program involved interviews with electric utility executives, public utility commissioners, and financiers. Analyses were made of utility

integrated resource plans, environmental compliance strategies, state regulations, and legislation that impact commercial deployment.

A highlight of the continuing CCT Program outreach effort was the Third Annual Clean Coal Technology Conference attended by about 400 persons from 23 nations. The theme of the conference was "The Investment Pays Off." The conference participants reviewed the status and success of the program, the role of the program in meeting domestic and global energy and environmental needs, the opportunities for commercialization in the United States and abroad, and the challenges which are being encountered. Highlights included the Eastern Europe/NIS and the Asia/Pacific Rim Reverse Trade Missions. These reverse trade missions provided the opportunity for U.S. industry to gain an understanding of the business opportunities for clean coal technologies in the countries represented. Three issues of the *Clean Coal Today* newsletter were prepared for distribution to 3,700 domestic and international readers. The CCT Program staff participated in 12 major domestic and international events involving users and vendors of the technology, state institutions, state regulators, and environmental groups.

International activities centered on developing a summary of the potential markets in developing countries for exporting clean coal technologies and the financing mechanisms and/or levels of government support necessary to assist U.S. industry participation in these markets. A report to the United States Congress, *Clean Coal Technology Export Markets and Financing Mechanism*, was distributed in May 1994. In November 1994, DOE solicited statements of interest in commercial projects employing CCTs in foreign countries projected to have significant growth in greenhouse gas emissions. DOE's report to Congress described the results of the informational solicitation and identified the extent to which various types of federal incentives would accelerate the commercial availability of CCTs in an international context.

#### **1.1.5 Southern Company Participation**

In 1988, in response to the second ICCT solicitation, Southern Company Services, Inc. (SCS), on behalf of the Southern electric system, submitted proposals, and was awarded four Innovative

Clean Coal Technology projects. Funding for the projects was primarily provided by operating utilities of The Southern Company, DOE, and the Electric Power Research Institute. One project demonstrated the significant cost savings of the Chiyoda Thoroughbred-121 (CT-121) flue gas desulfurization (FGD) process and consisted of constructing and operating a 100-MW scrubber at Georgia Power's Plant Yates. Two other projects focused on full-scale demonstration of seven advanced combustion techniques for reduction of nitrogen oxides (NO<sub>x</sub>). One of the two low NO<sub>x</sub> combustion projects was a demonstration of low-NO<sub>x</sub> burners (LNB) and advanced over-fire air (AOFA) on a 500-MW, pulverized coal, wall-fired unit at Georgia Power's Plant Hammond. The second low NO<sub>x</sub> combustion project demonstrated various low-NO<sub>x</sub> combustion techniques for pulverized coal, corner-fired boilers. This demonstration was conducted at Gulf Power's Plant Smith on a 180-MW unit.

The fourth project (and subject of this report) was a demonstration of selective catalytic NO<sub>x</sub> reduction (SCR) on an 8.7 MW slip-stream from one unit at Gulf Power's Plant Crist. The performance of this project recognized that combustion modification alone might not be sufficient to comply with proposed NO<sub>x</sub> emissions limits. These four projects are part of an integrated strategy by the Southern electric system to demonstrate lower cost, retrofit emission control options for sulfur dioxide and nitrogen oxides.

## 1.2 SCR Description/Status

### 1.2.1 Overview of Process Development

The selective catalytic reduction of  $\text{NO}_x$  using  $\text{NH}_3$  as the reducing gas was first discovered and patented by Engelhard Corporation in 1957. The original catalyst consisted of platinum or other platinum group metals. The catalytic activity of these early catalysts was high, requiring low operating temperatures which were near the temperature range at which explosive ammonium nitrate forms. Other base metal catalysts (Fe, Co, and Ni) were evaluated in the 1960s, but rejected due to their low activity. Building upon this work and responding to severe environmental regulations imposed by the government in their country, the Japanese discovered the vanadium/titanium combination as an effective  $\text{NO}_x$  reduction catalyst. This combination forms the basis of current SCR catalysts. Several primary U.S. patents control this basic vanadium pentoxide/titanium oxide ( $\text{V}_2\text{O}_5/\text{TiO}_2$ ) catalyst technology. One was issued to Mitsubishi Petrochemical Corporation and another was issued to Sumitomo Chemical Company. An additional patent assigned to NGK Insulators for Japan claims the use of the honeycomb shape for vanadium/titanium SCR catalyst for use in flue gas processing. Mitsubishi Heavy Industries has been granted an exclusive license to the NGK patent. By the late 1970s, vanadium/titanium-based SCR catalysts were being applied commercially in Japan to natural-gas and low-sulfur oil-fired industrial boilers. Also, in the late 1970s and early 1980s, three pilot-scale SCR tests (two on coal, one on natural gas) were carried out in the U.S. The first utility applications of SCR catalyst technology started in Japan in 1977 for oil- and gas-fired boilers and subsequently in 1979 for coal-fired boilers.

In addition to Japan, several countries in western Europe (most notably West Germany and Austria) have passed stringent  $\text{NO}_x$  emission regulations that have all but mandated the installation of SCR. Prior to commercial SCR installations in West Germany, utility companies demonstrated several types of SCR facilities in prototype demonstration programs similar to this ICCT project. Over 50 SCR pilot plants were built and operated in western Europe. These pilot plants ranged

from 19 to 6200 SCFM and provided the database that led to commercialization of the SCR technology in western Europe.

The word-wide SCR experience on utility boilers follows in Table 1.2-1. The data are categorized according to fuel type and country/region.

Table 1.2-1 Word-Wide SCR Experience  
Megawatts of Installed Capacity<sup>1</sup>

| Country/Region | Coal          | Gas <sup>2</sup> | Oil           | TOTAL         |
|----------------|---------------|------------------|---------------|---------------|
| Japan          | 7700          | 1,500            | 35,800        | 45,000        |
| Germany        | 33,000        | 0                | 7,500         | 40,500        |
| Canada         | 0             | 900              | 0             | 900           |
| Netherlands    | 1,000         | 0                | 0             | 1,000         |
| Austria        | 1,200         | 0                | 0             | 1,200         |
| Scandinavia    | 1,100         | 0                | 0             | 1,100         |
| USA            | 2,000         | 5,000+           | 0             | 7,000+        |
| <b>TOTAL</b>   | <b>46,000</b> | <b>7,000+</b>    | <b>43,300</b> | <b>96,700</b> |

1. Does not include industrial installations equipped with SCR.
2. Does not include HRSG's and/or combustion turbines.

### 1.2.2 Process Description

The basic process flow diagram and equipment are shown in Figure 1.2-1. The SCR technology involves the catalytic reaction of  $\text{NH}_3$  which is injected into the flue gas with  $\text{NO}_x$  to produce molecular nitrogen ( $\text{N}_2$ ) and water vapor. These reactions take place in the SCR reactor.

In theory, the SCR reactor can be placed in nearly any configuration desired, downstream of the boiler. In practice, however, this can present some difficulties due to the relatively high required

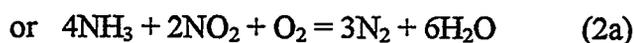
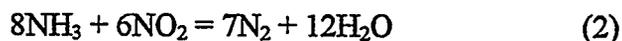
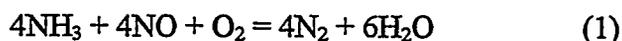
operating temperature (approximately 700 °F) of the SCR reactor. Configurations downstream of air preheaters require gas reheating, adding significantly to the cost of the installation and often resulting in a substantial heat-rate penalty. Configurations downstream of particulate control or flue gas desulfurization offer some benefits due to low dust concentrations. Costs, however, of this type of configuration usually outweigh the low-dust benefit. As a result, most SCRs are located prior to the unit's air preheater, either upstream of particulate control devices (high-dust) or downstream of particulate control devices (low-dust, assuming "hot-side" particulate control is in place).

Specifically, hot flue gas leaving the economizer section of the boiler is ducted to the SCR reactor. Prior to entering the reactor,  $\text{NH}_3$  is injected into the flue gas at a sufficient distance upstream of the reactor to provide for complete mixing of the  $\text{NH}_3$  and flue gas. The quantity of  $\text{NH}_3$  can be adjusted as it reacts with the  $\text{NO}_x$  in the presence of the catalyst to remove  $\text{NO}_x$  from the flue gas. The flue gas leaving the catalytic reactor enters the air preheater where it transfers heat to the incoming combustion air. Provisions are made for ash removal from the bottom of the reactor since some fallout of fly ash is expected. Ductwork is also provided to bypass some flue gas around the economizer during periods when the boiler is operating at reduced load. This is required to maintain the temperature of the flue gas entering the catalytic reactor at the optimum reaction temperature of about 700 °F. The flue gas leaving the air preheater goes to the electrostatic precipitator (ESP) where fly ash is removed. The ESP is part of the existing plant and is generally unaffected by the SCR system except as higher  $\text{SO}_3$  content affects the electrical resistivity of the fly ash or if  $\text{NH}_4\text{HSO}_4$  co-precipitates with the fly ash.

Current formulations of SCR catalysts are typically comprised of  $\text{V}_2\text{O}_5$  as the active material deposited on or incorporated with a substrate. The  $\text{V}_2\text{O}_5$  composition typically ranges between one and five weight percent depending upon the flue gas  $\text{SO}_2$  content. Tungsten trioxide ( $\text{WO}_3$ ) is often added as a co-catalyst/promoter in cases where additional catalyst activity is needed. But, the  $\text{V}_2\text{O}_5$  concentration does not typically exceed 2% when using high-sulfur fuel due to concerns about the oxidation of  $\text{SO}_3$ . The catalyst substrate is typically composed of pure  $\text{TiO}_2$ , although

some manufacturers use modifications to this standard material. The catalyst is offered commercially in Europe and Japan in two basic geometric shapes: honeycomb and plate.

Theoretically, the  $\text{NO}_x$  and  $\text{NH}_3$  react in the presence of these catalysts according to the following equations:



However side reactions which produce undesirable by-products can occur between  $\text{NH}_3$  and  $\text{SO}_3$  in the flue gas. These reactions are:



Since the  $\text{NO}_x$  contained in flue gas derived from coal-fired boilers is typically composed of 90% to 98%  $\text{NO}$ , reaction (1) dominates. Inspection of these reactions reveals two major points:

- \* Oxygen must be present in the flue gas for the reactions to proceed, and
- \*  $\text{H}_2\text{O}$  partial pressure (high concentration) in the flue gas can inhibit the forward reaction.

Under typical operating conditions of utility boilers, lack of oxygen should not occur since utility boilers are never operated below approximately 2% excess oxygen.  $\text{DeNO}_x$  efficiency is nearly directly proportional to the ratio of  $\text{NH}_3$  to  $\text{NO}_x$  up to maximum  $\text{deNO}_x$  levels for which a particular installation was designed. Above this  $\text{deNO}_x$  level,  $\text{NH}_3$  passing through the SCR reactor (referred to as  $\text{NH}_3$  slip) can become appreciable. (Ammonia slip is theoretically defined as the ammonia fed minus consumption by the  $\text{deNO}_x$  reaction and consumption by by-product formation and oxidation.) Minimization of  $\text{NH}_3$  slip is a major operational and design concern as

discussed below. Also, as a practical matter, some deNO<sub>x</sub> inhibition by H<sub>2</sub>O is unavoidable since the combustion reaction will result in approximately 8% to 10% H<sub>2</sub>O by volume. Otherwise, H<sub>2</sub>O has little additional effect on deNO<sub>x</sub> efficiency.

Slip NH<sub>3</sub> is a concern in the application of SCR to coal-fired boilers due to the formation of ammonium bisulfate (NH<sub>4</sub>HSO<sub>4</sub>), according to reaction (4), and its subsequent condensation on downstream equipment. The condensed NH<sub>4</sub>HSO<sub>4</sub> is a sticky, corrosive material that can cause corrosion problems unless more costly, corrosion resistant materials of construction are used.

Factors that contribute to NH<sub>4</sub>HSO<sub>4</sub> formation are temperature, catalyst composition, and the concentrations of NH<sub>3</sub> and NO<sub>x</sub> in the flue gas. The influence of temperature and catalyst composition are interdependent. The quantity of NH<sub>3</sub> available can be controlled by the plant operator. The amount of SO<sub>3</sub> present is determined by two factors: the amount formed in the boiler itself and the amount that is formed by the catalytic oxidation of SO<sub>2</sub> to SO<sub>3</sub> in the SCR unit. The combustion of low-sulfur coal typically results in very little SO<sub>3</sub> formation in the boiler. In addition, the SO<sub>2</sub> concentration in the flue gas is also very low, resulting in less SO<sub>2</sub> to SO<sub>3</sub> conversion. Thus, NH<sub>3</sub> slip is of less concern when burning low-sulfur coals. However, U.S. high-sulfur coal may form much more SO<sub>3</sub> in the boiler. Moreover, the higher flue gas SO<sub>2</sub> content will likely cause more SO<sub>2</sub> to be converted to SO<sub>3</sub> in the SCR reactor, thereby aggravating the NH<sub>4</sub>HSO<sub>4</sub> formation problems.

Complete resolution of these questions regarding NO<sub>x</sub> destruction and NH<sub>3</sub> slip cannot be made until actual operating experience with SCR on U.S. high-sulfur coal is obtained. However, certain design and operating changes can be made to minimize any problems.

The SCR test facility was designed, installed and operated for this demonstration project to help to determine the levels to which NO<sub>x</sub> can be reduced while minimizing the production of NH<sub>4</sub>HSO<sub>4</sub> and problems associated with NH<sub>4</sub>HSO<sub>4</sub>.

### 1.3 Project Objectives/Goals

The project objective was to demonstrate the applicability of SCR technology to provide a cost-effective means of reducing NO<sub>x</sub> emissions from power plants burning U.S. high-sulfur coal. The process was demonstrated on both high and low-dust loading of flue gas. The performance of commercially available SCR catalysts was evaluated from suppliers selected from throughout the world. These catalysts were evaluated under various operating conditions while achieving NO<sub>x</sub> reduction as high as 98%.

Specifically, the project addressed several technical uncertainties which are associated with applying SCR technology to U.S. coals. These include:

1. Evaluation of the performance of SCR catalysts when applied to operating conditions found in U.S. pulverized coal utility boilers firing U.S. high-sulfur coal;
2. Identification and quantification of operational changes that will be required for both boilers and SCR processes when SCR is retrofit to a boiler;
3. Demonstration of NO<sub>x</sub> removal performance of SCR catalysts under various operating conditions consistent with acceptable levels of NH<sub>3</sub> slip;
4. Documentation of the potential of various SCR catalysts to cause NH<sub>4</sub>HSO<sub>4</sub> to form when exposed to high levels of SO<sub>2</sub> and SO<sub>3</sub>, and to determine the process operating conditions under which this formation occurs;
5. Evaluation of the ability of modifications to conventional utility air preheater and new air preheater designs to accommodate NH<sub>4</sub>HSO<sub>4</sub> formation;
6. Assessment of the potential impact of an SCR retrofit on the balance of utility plant equipment;
7. Documentation of the deactivation rates of SCR catalysts when exposed to flue gas from high sulfur U.S. coal in order to determine accurate process economics; and
8. Provision of information for public consumption which will serve to document the SCR process capabilities and cost.

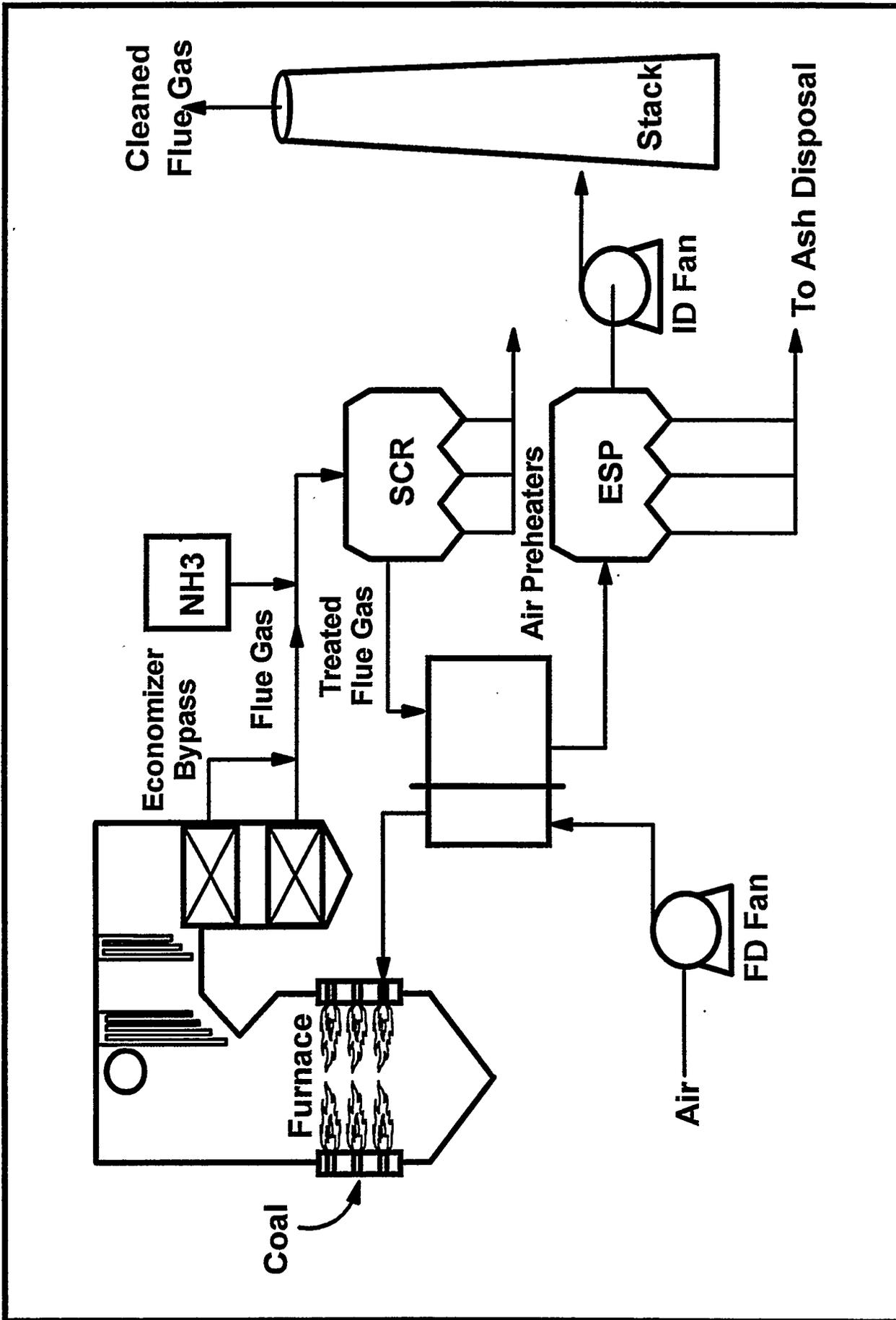
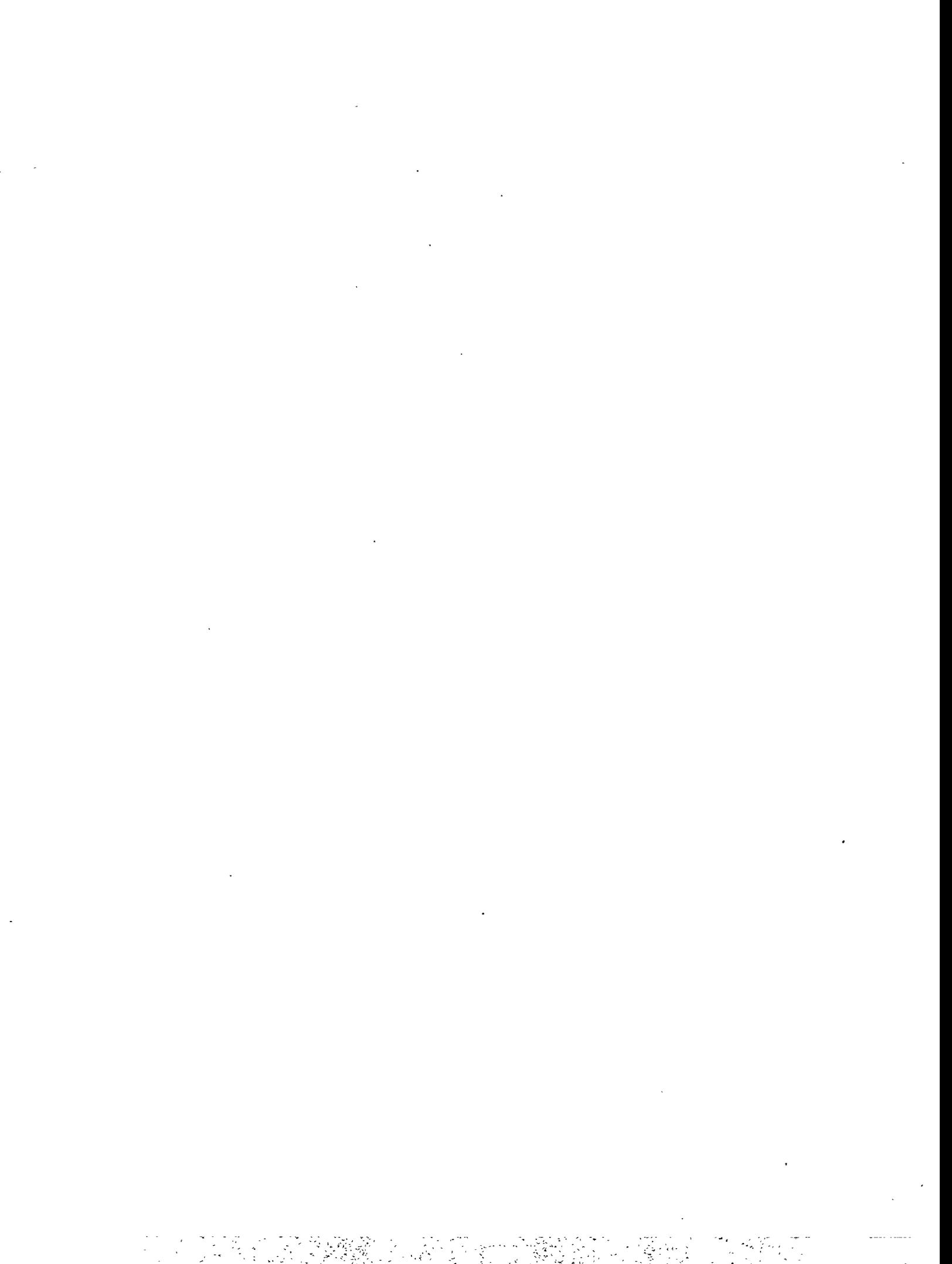


Figure 1.2-1 Flow Diagram of Typical SCR Installation.



## 2.0 PROJECT DESCRIPTION

### 2.1 Site Characteristics

Plant Crist consists of seven fossil generating units that are designed to utilize a variety of fuels. Units 1, 2, and 3 are small natural gas and oil-fired, and consequently do not have a high utilization factor. The remaining units, 4 through 7, are coal-fired. A brief description of the Crist units and site specific design conditions are shown in Tables 2.1-1 and 2.1-2 respectively.

The prototype SCR facility was built in and around the ductwork on Unit 5, with the ability to extract flue gas from Unit 5 either upstream of the hot-side ESP (high-dust), or downstream of the hot-side ESP (low-dust). Eight of the SCR reactors operated with high-dust levels while one small reactor operated with the low-dust loading.

Table 2.1-1 Characteristics of Plant Crist Units 1 - 7

| Unit Number                 | 1           | 2           | 3           | 4                          | 5             | 6             | 7             |
|-----------------------------|-------------|-------------|-------------|----------------------------|---------------|---------------|---------------|
| Size, MW                    | 22.5        | 22.5        | 30          | 75                         | 75            | 320           | 500           |
| Boiler Manufacturer         | Riley       | Riley       | Riley       | CE                         | CE            | FW            | FW            |
| Boiler Capacity, klbs/hr    | 230         | 230         | 320         | 582                        | 582           | 2,337         | 3,626         |
| Steam Pressure, psig        | 850         | 850         | 850         | 1800                       | 1800          | 2400          | 2400          |
| Steam Temperature, °F       | 900         | 900         | 910         | 1000/<br>1000 <sup>a</sup> | 1000/<br>1000 | 1000/<br>1000 | 1000/<br>1000 |
| Start-up Month              | 6/45        | 6/49        | 9/52        | 6/59                       | 4/61          | 5/70          | 5/73          |
| Fuels Capable               | Gas/<br>Oil | Gas/<br>Oil | Gas/<br>Oil | Gas/<br>Coal               | Gas/<br>Coal  | Gas/<br>Coal  | Coal          |
| Cooling Source <sup>b</sup> | OT/H        | OT/H        | OT/H        | OT/H                       | OT/H          | CT/CL         | CT/CL         |

<sup>a</sup> Superheat/Reheat Temperature

<sup>b</sup> OT/H = Once Through cooling with helper tower during summer; CT/CL = Cooling Tower, closed loop.

Table 2.1-2 Site Specific Design Conditions

|                            |                                 |
|----------------------------|---------------------------------|
| Elevation above sea level  | 0' - 0"                         |
| Grade datum elevation      | 90' - 0"                        |
| Design ambient temperature | Summer - 100 °F, Winter - 32 °F |
| Design ambient pressure    | 29.92" Hg                       |
| Design relative humidity   | 95%                             |
| Seismic load zone          | VBC Zone 0                      |

## 2.2 SCR Catalysts

The SCR test facility evaluated commercially available SCR catalysts obtained from world-wide suppliers. It was the intent of SCS to select catalysts that provided an evaluation of process chemistry and balance of plant integration effects when applying SCR to high-sulfur U.S. coal.

Evaluation agreements were signed with six catalyst suppliers. The suppliers, applicable test facility reactor size, and catalyst configuration are listed in Table 2.2-1. The SCR catalyst specifications for each catalyst are reported in Table 2.2-2. Due to the early withdrawal of Engelhard as a catalyst supplier participant, one reactor was idled for the majority of the test program and thus only eight reactors are described in Tables 2.2-1 and 2.2-2. Engelhard originally agreed to provide catalyst for one small high-dust reactor and for the small low-dust reactor. After their withdrawal, solicitations were made and Cormetech was chosen as the supplier for the low-dust reactor. The remaining small high-dust reactor was idled since no high-dust catalysts significantly different from those already in the test program were available from project participants. Catalyst suppliers external to the program were not solicited due to contractual requirements which would have caused significant delays in the testing program.

Table 2.2-1 Catalysts in the DOE/SCS SCR Project

| Reactor | Catalyst Supplier    | Reactor Size | Catalyst Configuration |
|---------|----------------------|--------------|------------------------|
| A       | W.R. Grace           | Large        | Honeycomb              |
| B       | Nippon Shokubai K.K. | Large        | Honeycomb              |
| C       | Siemens AG           | Large        | Plate                  |
| D       | W.R. Grace           | Small        | Honeycomb              |
| E       | Cormetech            | Small        | Honeycomb (high-dust)  |
| F       | Haldor Topsoe        | Small        | Plate                  |
| G       | Hitachi Zosen        | Small        | Plate                  |
| J       | Cormetech            | Small        | Honeycomb (low-dust)   |

Table 2.2-2 SCR Catalyst Design Specifications

| Parameter  | Grace Noxeram     | NSKK      | Siemens         | Grace Synox       | Cornetech \ High-Dust | Haldor Topsoe       | Hitachi Zosen   | Cornetech Low-dust |
|--|-------------------|-----------|-----------------|-------------------|-----------------------|---------------------|-----------------|--------------------|
| Reactor  | A                 | B         | C               | D                 | E                     | F                   | G               | J                  |
| Dust Level                                       | High              | High      | High            | High              | High                  | High                | High            | Low                |
| Composition                                      | V-W/Ti            | V-W/Ti/Si | V/Ti            | V/Ti/Si           | V-W/Ti                | V/Ti                | V/Ti            | V-W/Ti             |
| Type <sup>5</sup>                                | HC                | HC        | Plate           | HC                | HC                    | Plate               | Plate           | HC                 |
| Pitch, mm (opening/wall thick.)                  | 7.5 (6.1/1.4)     | 7.0       | 5.0             | 7.5 (6.1/1.4)     | 7.1 (6.0/1.1)         | DNX-16 6.4 hyd.dia. | 5.5             | 3.7 (3.2/0.5)      |
| Void Fraction, %                                 | 65                | 70        | 81              | 65                | 71                    | 73                  | 90              | 72                 |
| Density, lb/ft <sup>3</sup>                      | 39±3.5            | 25        | 37 <sup>1</sup> | 18±1.5            | 37                    | 16                  | 23 <sup>2</sup> | 32                 |
| Geom. Surf. Area, m <sup>2</sup> /m <sup>3</sup> | 430               | 470       | 383             | 430               | 470                   | 455                 | 420             | 910                |
| Gas Flow, Nm <sup>3</sup> /hr                    | 8500              | 8500      | 8500            | 680               | 680                   | 680                 | 680             | 680                |
| Catalyst Volume, m <sup>3</sup>                  | 3.1               | 3.026     | 2.30            | 0.19              | 0.245                 | 0.189               | 0.27            | 0.097              |
| GHSV @ 0°C, hr <sup>-1</sup>                     | 2742              | 2809      | 3692            | 3579              | 2776                  | 3600                | 2500            | 7033               |
| Parametric Range Min. (as % of design) Max.      | 63% 126%          | 91% 127%  | 60% 150%        | 66% 131%          | 60% 150%              | 50% 100%            | 66% 150%        | 60% 150%           |
| Cross Sec. Area, m <sup>2</sup>                  | 1.080             | 1.08      | 1.106 (1.164)   | 0.09              | 0.081                 | 0.094               | 0.09            | 0.081              |
| Super.Lin.Veloc., Nm/s <sup>3</sup> Min. Max.    | 2.186 2.76        | 2.186 2.5 | 2.135 3.203     | 2.10 2.76         | 2.34 3.0              | 2.00 2.5            | 2.1 2.5         | 2.34 3.5           |
| No. of Beds                                      | 3                 | 3         | 2               | 3                 | 3                     | 3                   | 3               | 2                  |
| Temperature, °F                                  | 700               | 700       | 700             | 700               | 700                   | 700                 | 700             | 700                |
| Parametric Range Min. Max.                       | 625 750           | 572 752   | 644 779         | 625 750           | 625 750               | 617 770             | 608 752         | 625 750            |
| Continuous Oper. Min. Max.                       | 660 750           | 644 842   | 617 806         | 660 750           | 644 790               | 617 752             | 626 752         | 644 790            |
| % SO <sub>2</sub> Oxidation                      | 0.75              | 0.5       | <0.6            | <0.75             | <0.75                 | 0.68                | 0.7             | <0.75              |
| Inlet NO <sub>x</sub> , ppmv (wet)               | 400               | 400       | 417             | 400               | 400                   | 400                 | 400             | 400                |
| NH <sub>3</sub> /NO <sub>x</sub>                 | 0.813             | 0.811     | 0.817           | 0.813             | 0.81                  | 0.81                | 0.81            | 0.81               |
| Parametric Range Min. Max.                       | 0.6 1.0           | 0.6 1.0   | 0.6 1.2         | 0.6 1.0           | 0.6 1.2               | 0.6 1.2             | 0.7 1.1         | 0.6 1.2            |
| % deNO <sub>x</sub> Activity                     | 80                | 80        | 80              | 80                | 80                    | 80                  | 80              | 80                 |
| NH <sub>3</sub> Slip, ppmv (wet)                 | < 5               | 5         | 5               | < 5               | < 5                   | < 5                 | < 5             | < 5                |
| Particulates, g/Nm <sup>3</sup>                  | 6 - 8             | 6 - 8     | NA <sup>6</sup> | 6 - 8             | 6-8                   | 6-8                 | 6 - 8           | NA                 |
| Pressure Drop, in. H <sub>2</sub> O              | 3.85 <sup>4</sup> | 2.62      | 1.28            | 2.60 <sup>4</sup> | 2.6                   | 1.73                | < 4             | 3.5                |

1. Includes basket, otherwise catalyst density only.
2. Catalyst only. Value in parentheses includes basket.
3. Superficial linear velocity based on cross-sectional area of catalyst, not basket.
4. For Grace, the pressure drop includes baskets.
5. HC = Honeycomb.
6. NA = Not applicable

### 2.2.1 Material Safety Data Sheets

A material safety data sheet (MSDS) is included in Appendix A for handling the types of SCR catalysts used in the SCS/DOE program. This data sheet would generally apply to all eight of the project's vanadium-based catalysts.

## 2.2.2 Catalyst Module Dimensions

Tables 2.2-3 shows the catalyst module dimensions and catalyst number of layers and volumes. The SCS recommended dimensions according to facility design are also noted.

Table 2.2-3 Catalyst Module Dimensions

### Large Reactor Module Dimensions

| Reactor            | Catalyst | Length (clearance) | Width (clearance) | Depth   | No. of Layers | Eff. Volume          |
|--------------------|----------|--------------------|-------------------|---------|---------------|----------------------|
| SCS Recomm.        | --       | 1.354 m            | 1.048 m           | --      | --            | --                   |
| Supplier Responses |          |                    |                   |         |               |                      |
| A                  | Noxeram  | 1.354 m (0.010 m)  | 1.048 m (0.010 m) | 1.150 m | 3             | 3.026 m <sup>3</sup> |
| B                  | NSKK     | 1.354 m            | 1.048 m           | 1.170 m | 3             | 2.3 m <sup>3</sup>   |
| C                  | Siemens  | 1.354 m (0.010 m)  | 0.954 m (0.003 m) | 1.100 m | 2             | 3.026 m <sup>3</sup> |

### Small Reactor Module Dimensions

| Reactor                    | Catalyst      | Length (clearance) | Width (clearance) | Depth                                  | No. of Layers | Eff. Volume          |
|----------------------------|---------------|--------------------|-------------------|--|---------------|----------------------|
| <b>SCS Recommendations</b> |               |                    |                   |  |               |                      |
|                            | --            | 0.318 m            | 0.318 m           | --                                     | --            | --                   |
| <b>Supplier Responses</b>  |               |                    |                   |  |               |                      |
| D                          | Synox         | 0.318 m (0.010 m)  | 0.318 m (0.010 m) | 1.150 m                                | 3             | 0.19 m <sup>3</sup>  |
| E                          | Cormetech     | 0.325 m            | 0.330 m           | 1.115 m                                | 3             | 0.245 m <sup>3</sup> |
| F                          | Haldor Topsoe | 0.321 m (0.002 m)  | 0.321 m (0.002 m) | 0.650 m for 1st & 3rd<br>1.207 m - 2nd | 3             | 0.189 m <sup>3</sup> |
| G                          | Hitachi Zosen | 0.318 m (0.003 m)  | 0.318 m (0.003 m) | 1.130 m                                | 3             | 0.25 m <sup>3</sup>  |
| J                          | Cormetech     | 0.325 m            | 0.308             | 0.740                                  | 2             | 0.097 m <sup>3</sup> |

## **2.3 Test Facility Design**

The test facility design follows nearly identically the original detailed design set forth in the Public Design Report for the project. Only very minor (detailed engineering) changes were made between the final as-built test facility and the original facility design. The following sections give an overview of the test facility design following a format similar to that of the Public Design Report.

### **2.3.1 Test Facility Layout**

The basic layout of the SCR test facility at Plant Crist is shown in Figure 2.3-1. Figures 2.3-2 and 2.3-3 show photographs of the west and south sides of the completed facility, respectively. Plant Crist is located approximately at sea level. However, the plant site datum elevation for grade elevation is 90'0".

Plant Crist Unit 5 operates retrofitted hot-side ESPs in series with cold-side ESPs. Due to the difficulty of retrofitting the hot-side ESPs, flue gas exits the boiler in a split flow configuration. Consequently, the Unit 5 hot-side ESP has two inlet ducts and two outlet ducts. The high-dust extraction location is on the west side of the hot-side ESP inlet duct. The low-dust extraction location is on the east side of the hot-side ESP outlet duct. This configuration was chosen to prevent any bias of the low-dust sample being extracted downstream of the high-dust sample.

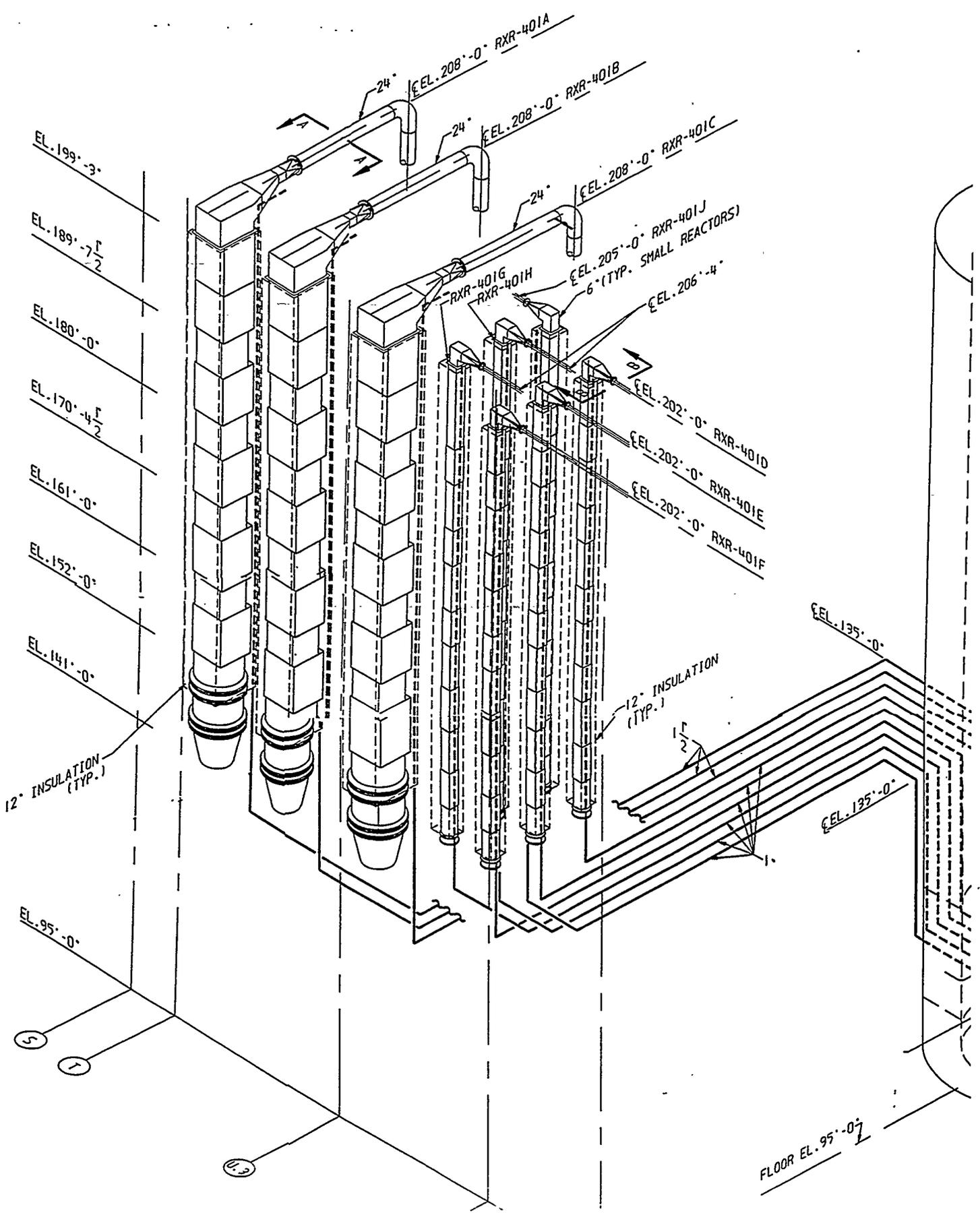


Figure 2.3-1 Basic Layout of SCR Test Facility

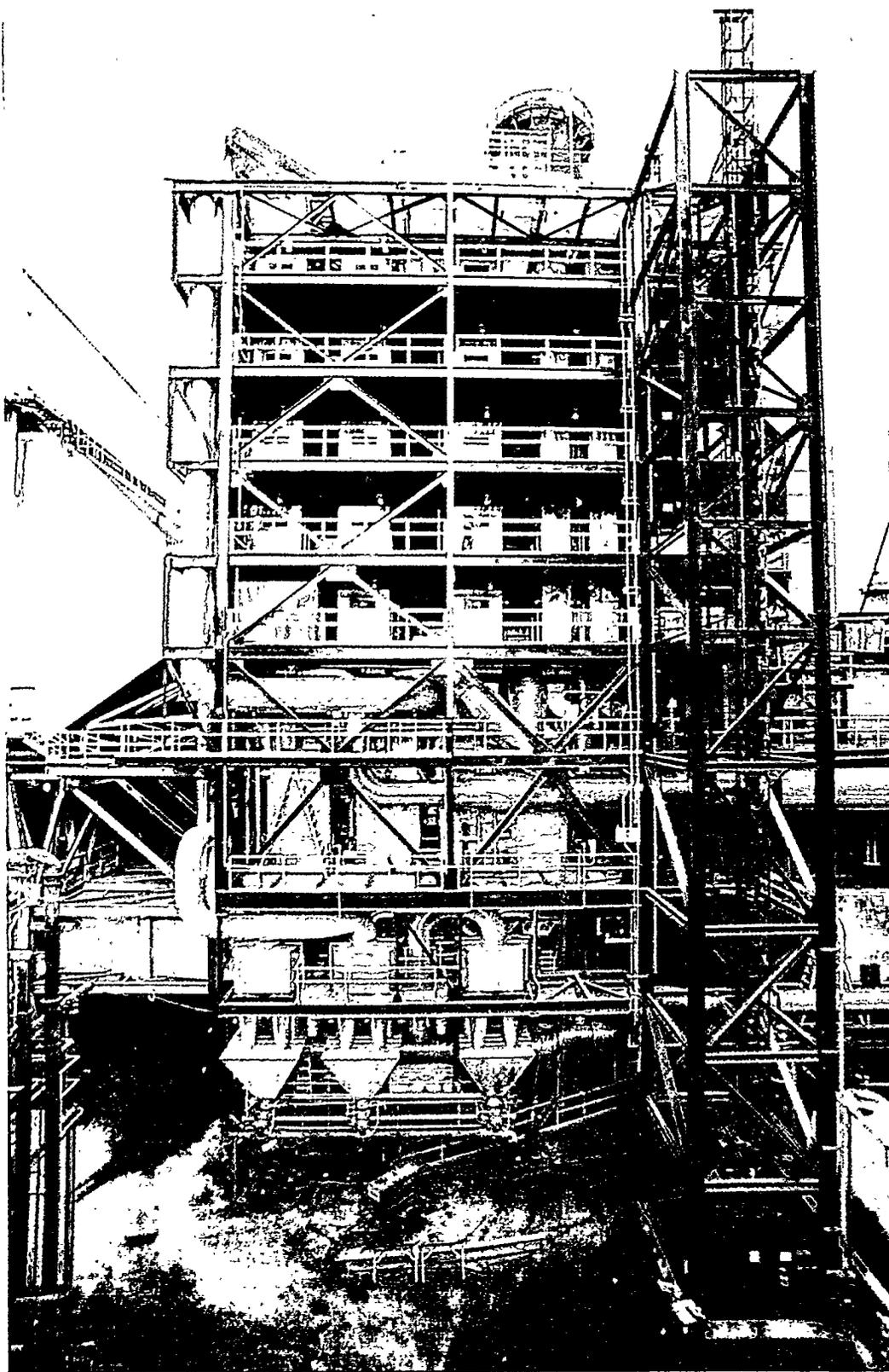
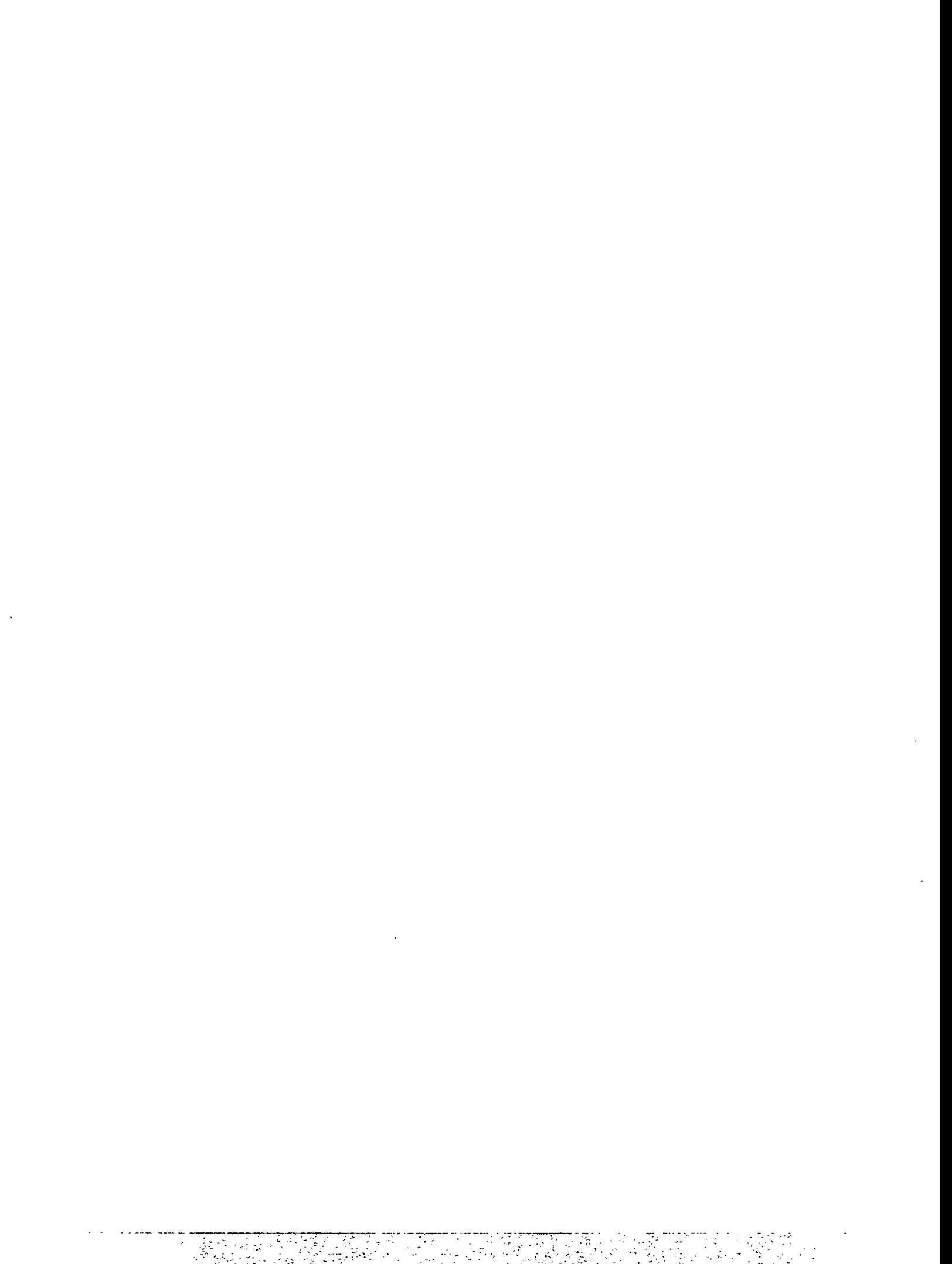


Figure 2.3-2 Photograph of West Side of Completed SCR Facility



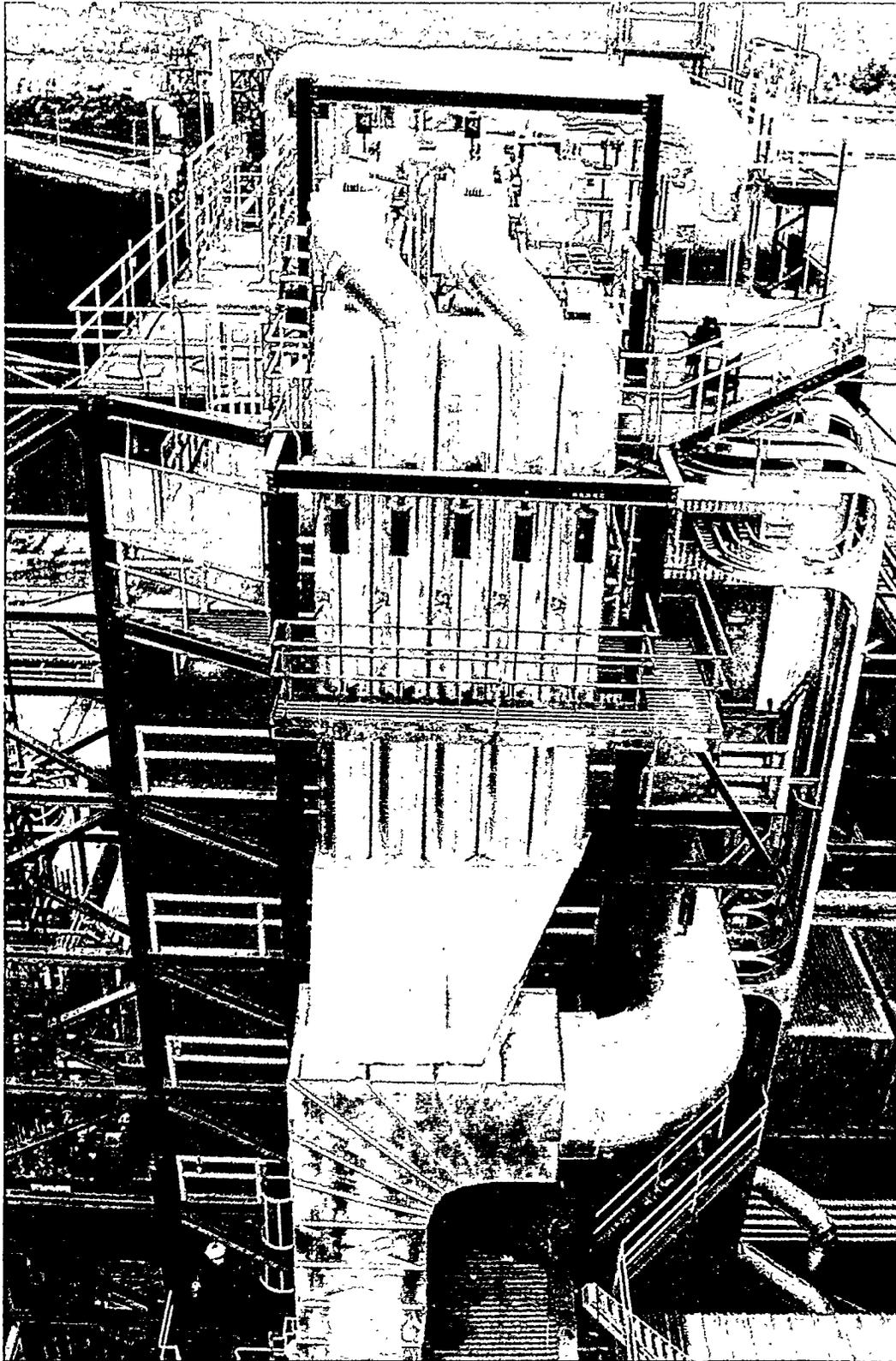


Figure 2.3-3 Photograph of South Side of Completed SCR Facility



## 2.3.2 Process Description

### 2.3.2.1 Reactor Train Designation

Each SCR catalyst was assigned to a separate reactor. The designation of the different reactor trains, which reflects the assignment of SCR catalysts, is as follows:

| Reactor Train | Reactor Size | Unit | Dust Loading | Catalyst Supplier     |
|---------------|--------------|------|--------------|-----------------------|
| A             | Large        | 5    | High         | W.R. Grace - Noxeram  |
| B             | Large        | 5    | High         | Nippon Shokubai       |
| C             | Large        | 5    | High         | Siemens               |
| D             | Small        | 5    | High         | W.R. Grace - Synox    |
| E             | Small        | 5    | High         | Cormetech - High-Dust |
| F             | Small        | 5    | High         | Haldor Topsoe         |
| G             | Small        | 5    | High         | Hitachi Zosen         |
| J             | Small        | 5    | Low          | Cormetech - Low-Dust  |

### 2.3.2.2 Process Flow Diagram

The process flow diagram for the SCR test facility is shown in Figure 2.3-4. High-dust flue gas was extracted from the inlet duct on the west side of Unit 5's hot-side ESP. The high-dust flue gas was equally distributed to the three large reactors, 5000-scfm each, and five of the small reactors, 400-scfm each. One small reactor was operated with low-dust extracted from the east side hot-side ESP outlet duct for Unit 5. Each reactor train had electric duct heaters to control the temperature of the flue gas and a venturi flow meter to measure the flue gas flow to the reactors. Anhydrous ammonia was independently metered to a stream of dilution air that injected the ammonia via nozzles into the flue gas stream prior to each SCR reactor. An economizer bypass line to the SCR test facility maintained a minimum flue gas temperature of 620 °F supplied to the test facility.

The flue gas and ammonia passed through the SCR reactors, which had the capacity to contain up to four catalyst layers. There is a flow straightening grid (dummy layer) at the top of the SCR

reactors to prevent swirling of the flue gas which could cause erosion problems when catalysts are operated under high-dust conditions. Each catalyst layer was housed in a metal frame commonly referred to as a basket. The catalyst basket was constructed so that the catalyst could be easily loaded into each SCR reactor.

For the large reactor trains, the flue gas exited the reactor and entered a pilot-scale air preheater (APH). The APHs were incorporated to evaluate the effects on downstream equipment using SCR process on flue gas from a high-sulfur coal and consisted of two Ljungstrom<sup>®</sup> rotary air preheaters and one heat pipe (ABB Q-Pipe). The two rotary air preheaters were slightly different, with one having a two-layer design and one having a three-layer design. The small reactors did not have air preheaters following the SCR reactors. All reactor trains, except the low-dust train J, had a cyclone downstream of the SCR reactors to protect the ID fans from particulate erosion. The small reactors were grouped into three reactors per ID fan.

The exhaust for all the SCR reactors was combined into a single manifold and routed back to the host boiler for re-injection ahead of the cold-side ESP. The preheated air from the APH on the large reactors was also combined into a single manifold and returned to the host boiler draft system at the air outlet of the existing APH. All the particulates removed from the flue gas with the cyclones were combined and sent to an ash disposal area.

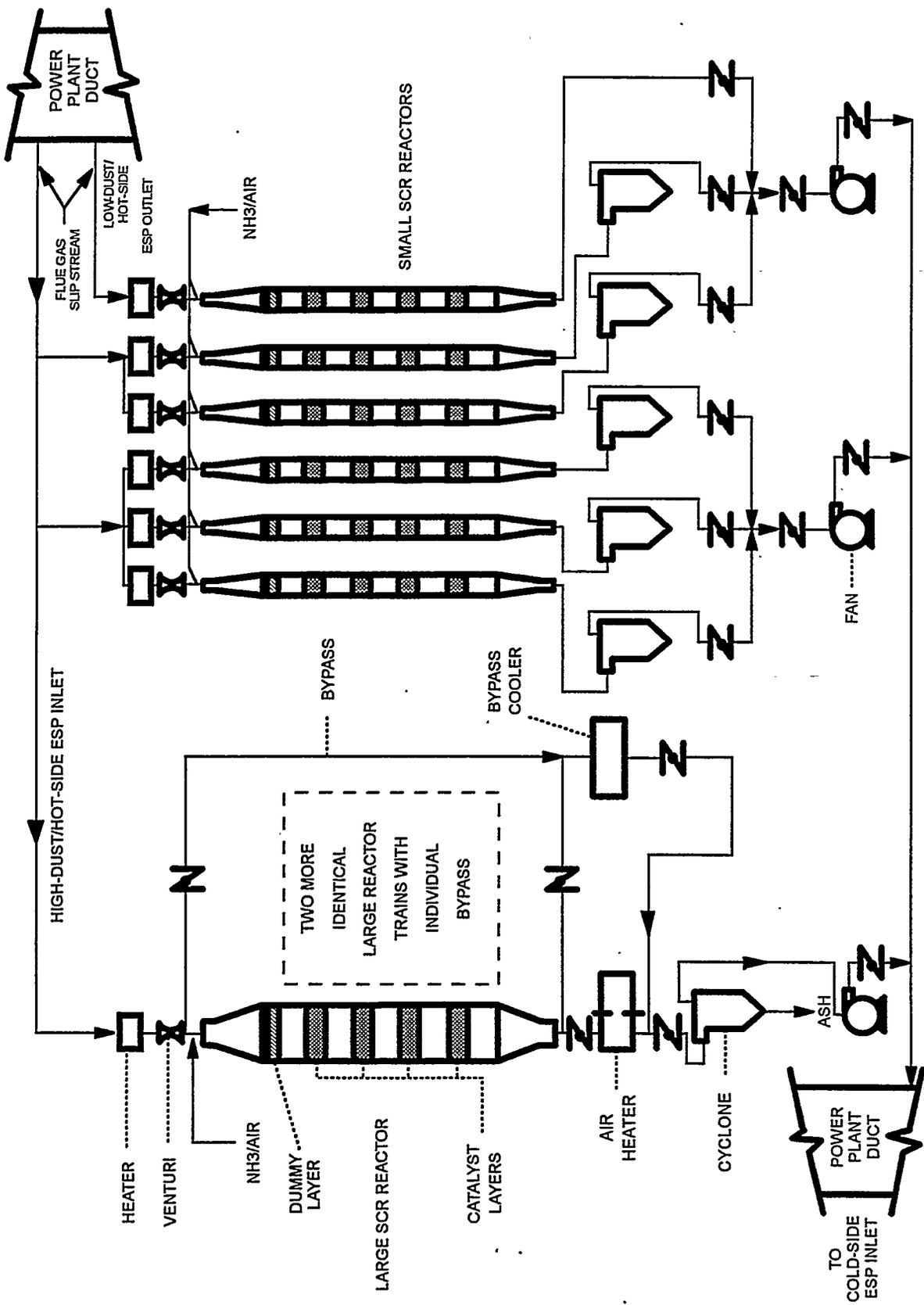


Figure 2.3-4 Prototype SCR Demonstration Facility-Process Flow Diagram

### 2.3.2.3 Operational Philosophy

One primary purpose of the SCR demonstration facility was to determine deactivation rates of commercially available SCR catalysts under exposure to flue gas from high-sulfur U.S. coals. This was determined by evaluating catalyst deNO<sub>x</sub> efficiency and other performance variables as a function of three main process variables:

- \* ammonia-to-NO<sub>x</sub> ratio,
- \* temperature, and
- \* space velocity.

The philosophy of operation was to determine base-line performance of each catalyst under design conditions immediately after successful start-up. Once base-line conditions were established, each catalyst was sequenced through a test matrix that varied each of the above variables around the design point. Appropriate deNO<sub>x</sub> efficiency, pressure drop, SO<sub>2</sub> oxidation, and ammonia slip were determined at each test condition. Once each parametric test was completed, each reactor was returned to base-line design conditions, allowing for steady-state operation over a three-month period, for aging of the catalyst. The parametric test matrix was repeated for each reactor train once every three to six months.

#### 2.3.2.3.1 Temperature

The operating temperature range for the test facility reactors is shown below. The Unit 5 host boiler-economizer outlet temperature ranges between 590 °F at low load to 680 °F at high load. The test facility maintained a minimum flue gas temperature of 620 °F through the use of an economizer bypass.

The following range of operating temperature was adopted for design purposes:

| Minimum | Base-line<br>(Design Point) | Maximum |
|---------|-----------------------------|---------|
| 620 °F  | 700 °F                      | 750 °F  |

At full boiler load, the economizer bypass line was closed and the temperature of the flue gas to the SCR test facility was equivalent to the boiler-economizer exit temperature minus any heat loss. As boiler load decreases, the boiler-economizer outlet temperature also decreases. When the boiler-economizer exit temperature dropped below 620 °F, the economizer bypass line opened to allow hotter gas extracted from the superheater section of the boiler to blend with the boiler outlet gas. The lower the boiler load, the more bypass gas was required to maintain the 620 °F temperature in the SCR test facility.

The temperature of the flue gas in each reactor train was independently controlled, using electric in-duct heaters located upstream of the venturi. The heaters were designed to boost the flue gas temperature from a minimum of 620 °F to the maximum design temperature of 750 °F. A detailed discussion of the electric heaters is contained in Section 2.3, Area 200.

#### 2.3.2.3.2 Space Velocity

Space velocity is defined as the volumetric flue gas flow rate divided by the catalyst volume. SCS did not actually set space velocity. Instead, each catalyst supplier was required to achieve targeted NO<sub>x</sub> removal levels for design flue gas flow rates and inlet NO<sub>x</sub> levels. Each supplier specified the amount of catalyst required to achieve the targeted reductions, which established the base-line space velocities. With catalyst volumes thus fixed, variations in flue gas flow rates altered the space velocity around the design point. Additional gas measurements at intermediate catalyst layers allowed testing of different space velocities while operating at the same linear velocity for a given flow rate.

The following are the design ranges for flue gas flow rates for the small and large test facility reactors:

#### Large Reactors

| Minimum   | Base-line | Maximum   |
|-----------|-----------|-----------|
| 3000 SCFM | 5000 SCFM | 7500 SCFM |

### Small Reactors

| Minimum  | Base-line | Maximum  |
|----------|-----------|----------|
| 240 SCFM | 400 SCFM  | 600 SCFM |

The flow rate in the reactors was varied by adjusting the ID fan speed, using a variable speed motor. With the small reactors grouped three per ID fan, an adjustment to the flow rate for one reactor using flow control dampers resulted in some balancing of flue gas flow through the bank of reactors, thus obtaining the proper flue gas flow rates in each reactor.

#### 2.3.2.3.3 Ammonia-to-NO<sub>x</sub> Ratio

The ammonia-to-NO<sub>x</sub> ratio design range is shown below:

#### NH<sub>3</sub>/NO<sub>x</sub> Molar Ratio

| Minimum | Base-line | Maximum |
|---------|-----------|---------|
| 0.6     | 0.85      | 1.0     |

The base-line value of 0.85 was selected as a design basis. Moreover, the maximum value of 1.0 specified that the design of the ammonia delivery system had the capacity to deliver this quantity of condition for long periods of time. However, this NH<sub>3</sub>/NO<sub>x</sub> value was used for only short duration testing of the performance of the catalyst under extreme conditions.

#### 2.3.2.3.4 Control Precision

It was sufficient for the SCR test facility design to specify only the above ranges of the process variables. It was also necessary to maintain close control over the precision of the process variables at each test condition. The following describes the required process precision.

Temperature - control to within  $\pm 2$  °F at any given operating point.

- Flue gas flow - control to within  $\pm 2$  percent of flow on the large reactors (i.e., control to within 100 scfm). On small reactors, control to within  $\pm 5$  percent of flow (i.e., 20 scfm). Since the flow was much smaller, this was actually harder to accomplish.
- Ammonia-to-NO<sub>x</sub> - control to within 0.005 NH<sub>3</sub>/NO<sub>x</sub>. For the design base-line, this means that NH<sub>3</sub>/NO<sub>x</sub> should range between 0.845 and 0.855.
- Gas flow distribution - not more than 10 percent deviation (+ or -) in flow velocity or mass flow of flue gas across the cross-section of an individual reactor.
- Ammonia distribution - not more than  $\pm 5$  percent deviation in ammonia distribution. Note however, that ammonia distribution closely controlled at this level is of no value if NO<sub>x</sub> distribution is also not controlled at this level. The point is that the ammonia and the NO<sub>x</sub> must match each other, even if the NO<sub>x</sub> is maldistributed.
- To ensure proper catalyst aging, the uniformity of fly ash loading and particle size distributions must be controlled, and thus the following limits were set:
- Fly ash loading balance - Not more than  $\pm 5$  percent deviation between total mass loading in mg/Nm<sup>3</sup> between individual reactors, and not more than 10 percent deviation in fly ash particle size distribution, as determined by cumulative mass versus particle diameter plots.

#### 2.3.2.4 Air Preheater Testing

The overall objective of the pilot-scale air preheater operation was to adequately simulate the response of existing, full-scale utility APHs if exposed to a post-SCR environment. Proper simulation of full-scale equipment associated with the rotary air preheaters required maintenance of the following:

- \* Similar gas-side axial temperature profiles, including exit gas temperature;
- \* Identical metal surface temperatures and temperature variations;
- \* Equal pressure drops on both air and gas sides;
- \* Identical rates of air leakage from air to gas side;
- \* Similar fluid mechanics of gas flow and cleaning medium; and
- \* Equal air and gas velocities.

Many of these factors were determined by the design and configuration of the pilot-scale rotary APHs and associated equipment. However, some of the operational characteristics of full-scale units must be modified in smaller-scale equipment. The SCR rotary APHs were equipped with variable speed drives in order to vary rotational speed and, therefore, to properly match surface temperatures and temperature variations. Metal surface temperatures were matched to within  $\pm 5$  °F. Although it was desirable to maintain air in-leakage below 10 percent of the flue gas flow, this was deemed unfeasible by APH suppliers with pilot-scale APHs. The air in-leakage approached 20 percent for this test facility, but was minimized as much as possible by varying air-side flow static pressure to not more than 1 inch of H<sub>2</sub>O differential between the gas-side and air-side pressure at the hot-end of the pilot-scale APH. This required that the APH air flow be under induced draft.

The APHs were operated under these conditions while the associated large reactor was operating. During operation, gas air flows were determined, as were inlet SO<sub>3</sub> and NH<sub>3</sub> concentrations, particulate mass loadings, and size distributions. The APH pressure drop and inlet and outlet temperatures were also monitored. Outlet O<sub>2</sub> was measured to determine air leakage (rotary APHs only). Sootblowing was performed as required to maintain proper static pressure differentials across the APH. APH solid deposits were sampled periodically to determine the nature of such deposits. The original facility design bypassed the APHs during parametric testing so that above design ammonia-to-NO<sub>x</sub> values, which could cause excessive ammonium bisulfate formation, would not contaminate long-term deposit formation in the APH. However, the inoperability of the by-pass heat exchangers required that the APHs be operated at all times that the reactor was in operation.

The heat pipe APH had no corresponding gas/air flow and pressure drop concerns since it was a zero leakage device. It was sized according to the heat transfer duties needed to simulate a full-scale air preheater and monitored during reactor operation. Like the rotary units, the original facility design called for APH bypass during parametric testing.

### 2.3.2.5 Start-up and Shut-down Requirements

The SCR reactors required operation over a period of time prior to the loading of the catalyst, for proper seasoning of the ductwork and reactor walls. In addition, the SCR test facility commissioning tests were first performed without catalysts, both with and without ammonia, followed by commissioning tests with catalysts and without ammonia.

Start-up of the SCR reactors required that the reactors be heated above the acid dew point, approximately to 300 °F, before introducing flue gas into the reactors. This was accomplished by using ambient air purge heated by the electric flue gas heater for each reactor train. The ambient air inlet for each reactor train was located ahead of the flue gas heaters, and was also used to purge the reactors during shut-down. Once the temperature of the reactors was above the acid dew point, flue gas could then be introduced into the reactors, heating them to the desired operating temperature. To avoid ammonia-sulfur compound deposition, ammonia injection began only after the entire catalyst bed reached the minimum operating temperature of 620 °F.

Although the flue gas temperatures were monitored, proper catalyst surface temperature was most important for start-up and shut-down to identify whether the temperature was sufficient for operations with ammonia. Therefore, thermocouples were mounted on the catalyst surface, on the inlet side of the first catalyst layer, and on the outlet surface of the last layer. Measurements were made near the corners due to higher possible heat loss.

The SCR reactors were purged before shutting down for the removal of ammonia. The air purge occurred above the condensation temperature of the ammonium sulfate compounds, approximately 450 °F. Reactors were also purged when process upsets occurred and the flue gas had to be diverted to the reactor bypass. This was accomplished by using the air dilution system associated with ammonia injection, since the ammonia injection point was located between the reactor bypass take-off and the reactor inlet. Both low and high temperature alarms were located on the reactor inlets as well as the host boiler duct to prevent damage to the SCR catalysts. At high temperatures (>750 °F), sintering of SCR catalysts can occur, which could greatly reduce the

catalytic activity of the catalyst. At low temperatures, catalytic activity is reduced, thus causing higher ammonia slip, which can lead to high deposition of ammonium sulfate compounds in the downstream equipment and on the catalyst surface.

#### **2.3.2.6 Economizer Bypass Vapor Phase -- Trace Metal Concentration Effects**

Some SCR vendor development experience indicates that catalyst activity loss may vary with the extraction location of the flue gas from the host boiler. Flue gas extracted and treated immediately at the economizer wall can show higher trace metal concentrations and can lead to higher catalyst poisoning. Extracting and treating flue gas, after long duct runs with cooler gas temperatures, may allow vapor phase metal condensation. If extracted in this manner for a test facility, it is possible that the catalyst may not be exposed to the actual trace metal concentration that the catalyst would see on a commercial system. SCR developers operating a test facility with an extraction point, and reheat with electric heaters similar to our preliminary conceptual design, noticed relatively low catalyst activity loss. However, commercial plant catalysts, located nearer the economizer and with an economizer bypass, were experiencing rapid catalyst activity loss. They eventually added heat tracing to their test facility ductwork. This has been primarily noticed on wet bottom boilers with fly ash recycle, which may allow rather high trace metal concentration build-up in the flue gas. Reheating the flue gas, once it has cooled, does not solve this problem. Once the trace metals deposit on the ash, the temperature required to re-vaporize these compounds is much higher than the SCR operating temperature.

As a result of the above, it was proposed to maintain the original main flue gas extraction point, while adding an economizer bypass line. The economizer bypass allowed gas from the economizer/superheater region to mix with the main gas slipstream being taken off between the economizer and hot-side ESP for the SCR test facility. The economizer bypass was used only as needed to maintain a minimum temperature of 620 °F for the total flue gas entering the SCR test facility, usually at low loads. At full load, the bypass was usually closed. This mode of operation more closely resembles that of a commercial system, which normally has an economizer bypass,

allowing the exposure of the catalysts to potential poisons. Thus, the test facility more accurately reflected the catalyst deactivation which would be experienced on a full-scale SCR system.

### **2.3.3 Facility Description**

#### **2.3.3.1 Area 100: Flue Gas Extraction Scoop to Flue Gas Distribution Header**

Area 100 included the area from the flue gas extraction scoop to the flue gas distribution header. The high-dust extraction scoop was located in the west side hot-ESP inlet duct of the host boiler (unit 5) near the duct sampling ports. The high-dust extraction scoop removed flue gas from the main duct to supply flue gas to the three large reactors and five of the small reactors, for a nominal capacity of 17,000 scfm. The low-dust extraction scoop supplied nominally 400 scfm to one of the small reactors, and utilized a penetration on the east side hot-ESP exit duct.

Results from Southern Research Institute (SRI) ductwork testing indicated that the boiler ducts are well varied on Unit 5, both at the ESP inlet and outlet. Particulate mass loading, ductwork gas velocity, flue gas temperature, and NO<sub>x</sub> distributions were fairly uniform across the duct cross section at high and low loads. The flue gas extraction scoop had a rectangular geometry and was located in the center of the boiler duct. The center of the duct was chosen for several reasons: 1) the center gave the most representative sample at all loads since the sample was drawn equally from the top and bottom of the duct, thereby minimizing sample bias; 2) the flue gas flow around the scoop, when not in use, gave a better streamline effect, causing the flow disturbance to dampen out quicker; 3) installation and support of the scoop was easier; and 4) the scoop inlet could be adequately characterized using the existing sample ports. The height dimension of the scoop was a function of the final face velocity needed to approach isokinetic operation.

The measured velocity in the boiler duct ranged between 30 to 35 fps at low load, to 45 to 50 fps at high load. Based on a scoop face velocity of about 46.6 fps, the scoop design was 6 ft. wide x 2 ft. 2in. high and blocked approximately 18 percent of the boiler duct area when not in use. The

extraction scoop was designed with turning vanes, accelerating flue gas from the extracted velocity to the design test facility ductwork velocity of 60 fps. Additional design recommendations for the scoop included: (1) all edges of the scoop should be sharpened; (2) no horizontal stiffener plates in between guide vanes; and (3) guide vanes were designed as in the *Handbook of Hydraulic Resistance* (Idelchik).

Flow modeling of the main flue gas duct and the effect on the scoop in the main duct was done on a 1/9 scale model. Iso-velocity contours of the Unit 5 duct model showed that the model represented the actual plant duct very well, usually  $\pm 2$  to 3 percent variation. The increased pressure drop from adding the scoop was only about a one-half duct velocity head, or 0.11 in. of water gauge pressure loss.

The distance between the scoop and hot ESP inlet was sufficient to allow almost equivalent velocity profiles at the ESP inlet with or without the scoop. Thus, changes in flow introduced by the scoop were dampened out by the time the flue gas entered the downstream ESP, and the scoop did not have any deleterious effects on the main flue gas flow patterns.

Data presented in Table 2.3-1 indicates that there was not a problem in dust stratification in test facility ducts. However, by taking gas from the main duct with the scoop and reducing the main gas velocity, the potential for fallout in the main duct between the scoop and ESP inlet was increased, primarily at low boiler loads. Inspection of this portion of the main flue gas duct was done during Unit 5 downtime periods, and if needed, any ash build-up was removed.

Table 2.3-1 Fly ash Settling in Test Facility Ducts at 60fps

| Weight % | Less than $\mu$<br>(Microns) | Terminal Velocity<br>fps | Downward Movement<br>In 1 Second or 60 ft. |
|----------|------------------------------|--------------------------|--|
| 95       | 90                           | 1.10                     | 13.2"                                      |
| 90       | 57                           | 0.44                     | 5.3"                                       |
| 80       | 38                           | 0.196                    | 2.35"                                      |
| 60       | 21                           | 0.060                    | 0.72"                                      |
| 50       | 16                           | 0.035                    | 0.42"                                      |
| 40       | 13                           | 0.023                    | 0.28"                                      |
| 20       | 6.6                          | 0.0059                   | 0.071"                                     |
| 10       | 3.4                          | 0.0016                   | 0.019"                                     |
| 1        | 1.1                          | 0.00016                  | 0.0019"                                    |

Other potential consequences of introducing the scoop into the main flue gas duct included the following:

- \* Dust accumulation in the scoop at no flow -- During periods when the test facility was not operating but Unit 5 remained on-line, ash build-up could occur in the scoop.
- \* Vibration of downstream vanes in main duct -- There was a slight increase in forces acting on the vanes; stiffeners were added for additional support.
- \* Scoop location -- If it became necessary to reduce pressure loss of unsteady forces on the vanes, the scoop could be moved upstream 9 to 12 ft., which would produce equivalent velocity profiles. This action was not necessary.

As noted above, the difference between high and low load main flue gas duct velocities was about 15 fps. The extraction velocity during low load was about 50 percent higher than the duct velocity. The ash concentration was less during low load, and thus there was no significant increase in ash to the test facility. However, the effect had to be considered when determining  $\text{NH}_3$  slip by using the method of analyzing for  $\text{NH}_3$  on fly-ash. Thus, during commissioning, ash measurement was conducted at various loads for  $\text{NH}_3$  mass balance calculations.

The extraction of the flue gas for eight of the SCR reactor trains from the west ESP inlet duct was estimated to potentially exacerbate an existing problem with the Unit 5 APH cold-end

temperatures. (See the text under Area 500, Section 2.3.3.5, SCR reactor outlet to pilot APH outlet, for discussion of the problems and resolution for flue gas/air disposition.)

The materials of construction for the piping ductwork and reactors on the pilot-scale SCR facility were low carbon steels. Either ASTM A53 or ASTM A106 was used for the piping ductwork, while the steel plate for the reactors was constructed of ASTM A516 or ASTM A204.

The insulation was a non-asbestos material. A calcium silicate material was used for piping ductwork while mineral wool was used with the reactors. Both materials are typical of normal power plant insulators. Theoretical calculations indicated a drop in the flue gas temperature of only 2 °F from the extraction scoop to the reactors. However, because of non-ideal conditions, losses through test ports, flanges, expansion joints, and dampers, etc., the actual expected temperature loss was about five times the theoretically-calculated loss. As a result, a thickness of about one foot of insulation was used for the ductwork to the reactor inlet.

As discussed in Section 2.3.2.6, the vapor phase trace metal composition in the flue gas may decrease as a result of (1) temperature drop between the boiler-economizer outlet and extraction scoop and between the scoop and heater or pilot SCR reactor; (2) flue gas residence time in the duct; and (3) heater surface temperature. A change in this vapor phase metal composition resulting from temperature drops can lead to different, possibly improved, catalyst deactivation rates than would normally be achieved on a full-scale facility. As a result, maintaining temperatures and minimizing heat loss was of major importance. In addition to the thicker insulation and heat tracing on the inlet ductwork to the reactor mentioned in the preceding paragraphs, the project scope was increased to include an economizer bypass.

The temperature of the test facility flue gas being extracted and sent to the distribution header for the SCR reactors was monitored. This measurement was used to control a flow control damper on the economizer bypass line to maintain a minimum temperature of 620 °F for the flue gas entering the test facility system. As the boiler load decreased from full load, the temperature of the extracted flue gas from above the boiler-economizer region was allowed to mix with and raise

the temperature of the flue gas entering the SCR system. Trace metal vapor phase condensation was minimized, and the catalyst was exposed to a level of potential poisons more similar to that expected in a commercial system. Sizing of the economizer bypass line was completed upon finalizing tie-in locations and temperature profiles for Unit 5. Preliminary results from a computer model were used for initial estimates.

### **2.3.3.2 Area 200: Flue Gas Distribution Header to Reactor Inlet**

Area 200 was the area from the flue gas header to the SCR reactor inlet. This area included the flue gas extraction header, reactor train isolation dampers, electric flue gas heaters, flow venturi, air purge for start-up and shut-down, and reactor inlet ducting.

Two alternatives were considered for the take-offs from the flue gas manifold for the small reactors on high-dust service. Originally each reactor would have its own take-off. However, the alternative which was used was a common extraction scoop for all five of these small reactors as well as the large reactors. The flue gas manifold decreased in size after each large reactor take-off from the manifold. This was at an angle less than 90 degrees (i.e., 45 degrees). Therefore, standard Y piping components were used for the large reactor manifolds. Long radius elbows were used for 90 degree turns in all the duct work to the reactors.

Common round pipe was utilized for the flue gas ductwork, from the extraction scoop to the reactor inlets. Transition pieces also were used where necessary for connecting to equipment on ductwork with rectangular interfaces.

A positive shutoff damper was installed in each reactor train duct to allow for routine maintenance and to isolate the system from the host boiler during system upsets. Air in-leakage for the isolation dampers was minimized, particularly for the large reactor trains.

### 2.3.3.2.1 Electric Flue Gas Heaters and Air Purge

Nine electric flue gas heaters were used to control the temperature of the flue gas entering each SCR reactor. Each reactor train utilized an independently operated heater, or bank of heaters, to control the flue gas temperature for that particular reactor. The flue gas temperature exiting the electric heaters ranged from 620 °F with heaters out of service to 750 °F when operating at the maximum flow rate, 7500 scfm for large reactors, and 600 scfm for small reactors.

The flue gas electric heaters also provided a heat source to heat ambient air when purging the reactor of combustion gases or heating the reactor up during cold start-ups. The ambient air purge allowed controlled start-up and shut-down of the catalyst, particularly when passing through the moisture and acid dew points. The flue gas electric heaters were required to heat ambient air from a temperature of 30 °F to 300 °F when operating at the minimum reactor flow rate, 3000 scfm for large reactors, and 240 scfm for small reactors.

### 2.3.3.2.2 Electric Heater Size

The electrical heater loads were grossly estimated using the following formula:

$$\text{kW} = \{\text{CFM} \times \text{Delta T}\} / 3000$$

Where: CFM is the flow rate of gas at standard conditions (70 °F and 1 atm.)

The large reactor flow ranged from a maximum of 7500 scfm to 3000 scfm with the design flow rate at 5000-scfm. Therefore, maximum electrical load for the large reactor heaters when heating flue gas was approximately:

$$(7500) ((460+70)/(460+32))(750-620)/3000 = 350 \text{ kW}$$

Maximum heater loads for heating ambient air for large reactor purge were approximately:

$$(3000)((460+70)/(460+32))(300-30)/3000 = 291 \text{ kW}$$

The small reactor flow ranged from a maximum of 600 scfm to 260 scfm with the design flow rate at 400 scfm. Therefore, maximum electrical load for the small reactor heater when heating flue gas was approximately:

$$(600)((460+70)/(460+32))(750-620)/3000 = 28 \text{ kW}$$

#### **2.3.3.2.3 Electric Heater Location**

The electrical heaters were located in the ductwork upstream of the SCR test facility reactors. The inlet ductwork consisted of round carbon steel pipe and ranged in size from 24 inches in diameter for the large reactors to 6 inches in diameter for the small reactors. Provisions were made for round mounting through custom or standard type flanges. The heaters were mounted in a horizontal duct run with flue gas contact perpendicular to the heater elements. There were 10 linear feet of duct run in which the heaters were required to fit. The small reactor heaters were also located in horizontal duct runs.

The location of the heaters was downstream of the air purge connection and upstream of the ammonia injection grid. This allowed ambient air to be drawn across the heaters to allow reactor purging and heat up. Also, the ammonia was injected downstream of the heater where it would not be subjected to high surface temperature elements and hence thermally degrade to form NO<sub>x</sub>.

#### **2.3.3.2.4 Electric Heater Control**

The flue gas electric heater controls were required to be capable of maintaining the bulk gas temperature to within  $\pm 2$  °F of the desired set point. The test facility Digital Control System (DCS) provided one (1) 4-20 ma DC signal to the heater controls. The heaters used silicon

control rectifiers to control heat output based on the value of the 4-20 ma DC signal (4 ma = zero heater output and 20 ma = maximum heater output). The heater controls were equipped with overload protection, flow detection, and over temperature protection.

#### **2.3.3.2.5 Electric Heater Process Concerns**

There were two process concerns related to the flue gas electric heaters. The first concern was the tendency of the heaters to oxidize  $\text{SO}_2$  to  $\text{SO}_3$ . This side reaction takes place due to the catalytically active metallic surface of the heater element operating at high temperature. The surface temperature of the heater element is much higher than the bulk gas temperature. Since  $\text{SO}_3$  is undesirable to the test facility and downstream equipment, minimizing the conversion across the heaters was desired. The expected  $\text{SO}_2$  and  $\text{SO}_3$  concentrations in the flue gas are shown below.

Sulfur Dioxide ( $\text{SO}_2$ ) 2000 - 3000 ppmv

Sulfur Trioxide ( $\text{SO}_3$ ) 15 - 20 ppmv

One option which was explored was the ability of suppliers to furnish ceramic type heater elements rather than metallic alloy type heater elements. This would reduce the conversion rate of  $\text{SO}_2$  to  $\text{SO}_3$  since ceramic is less catalytically active than metal. A second option would limit the watt-density of the individual heater elements to less than 20 watts per square inch. Ceramic type heater elements were not available, thus metallic elements were used and commissioning tests were performed to determine the  $\text{SO}_2$  oxidation across the heaters.

The other concern was fly ash erosion of the heater elements since the heater was subjected to a fly-ash-laden flue gas. Design of the heating elements attempted to take this into account to provide a reasonable heater life.

### 2.3.3.2.6 Electric Heater Electrical Design

The test facility had 480 volt, 3-phase, 60 Hz power available for the electric heaters. The heaters utilized high temperature cables to protect from overheating of wires and/or melting insulation. Over temperature control was incorporated into the heater design to prevent the heaters from burning out when no flow conditions occur. External heater components were enclosed in a NEMA 4 enclosure for weather protection. The number of multiple heaters (or heater banks) was divisible by three to minimize phase distortions. Heater design conditions are shown below in Table 2.3-2.

Table 2.3-2 Heater Inlet Conditions (High Dust)

| FLOW RATE     | LARGE REACTOR | SMALL REACTOR |
|---------------|---------------|---------------|
| Maximum       | 17378 acfm    | 1390 acfm     |
| Design        | 10975 acfm    | 878 acfm      |
| Minimum       | 6585 acfm     | 527 acfm      |
| ASH LOADING   |               |               |
| Maximum       | 225 lb/hr     | 18 lb/hr      |
| Design        | 150 lb/hr     | 12 lb/hr      |
| Minimum       | 90 lb/hr      | 7 lb/hr       |
| GRAIN LOADING |               |               |
| Maximum       | 1.59 gr/acf   | 1.59 gr/acf   |
| Design        | 1.59 gr/acf   | 1.59 gr/acf   |
| Minimum       | 1.51 gr/acf   | 1.51 gr/acf   |

### 2.3.3.2.7 Miscellaneous Heater Requirements

The flue gas electric heaters were designed for changeable heater elements (vs. welded elements) so that an entire heater replacement was not necessary. Provisions were made to minimize the occurrence of ceramic insulator damage due to moisture or overheating. Flue gas electric heaters were furnished with a flanged connection on each end to allow easy lifting into place.

### 2.3.3.2.8 Venturi

DynaGen concurred that a venturi type flowmeter was a good choice for flow measurement for a high fly ash environment. Turning vanes were installed ahead of the venturi flow meter to eliminate any swirls in the flue gas. These flow straighteners were designed per ASME, AMCA and ASHRAE guidelines. Pressure taps were provided by a piezometer ring, or averaging annulus, to increase accuracy. The rings had an automatic air blow back system to periodically clean the taps of fly ash.

### 2.3.3.2.9 Design Flue Gas Composition

The predicted flue gas composition for the large and small reactors at maximum flow conditions is shown in Table 2.3-3.

Table 2.3-3 Design Flue Gas Composition at Maximum Flow Conditions

| COMPONENT        | Large Reactors<br>(High-Dust)<br>Reactors A,B,C |             | Small Reactors<br>(High-Dust)<br>Reactors D,E,F,G,H |         | Small Reactors<br>(Low-Dust)<br>Reactor J |             |
|------------------|---|-------------|---|---------|---|-------------|
|                  | lb/hr   | WEIGHT<br>% | lb/hr   | WEIGHT% | lb/hr                                     | WEIGHT<br>% |
| CO <sub>2</sub>  | 7643  | 20.57       | 611   | 20.55   | 611                                       | 20.69       |
| O <sub>2</sub>   | 1190  | 3.20        | 95  | 3.20    | 95  | 3.21        |
| N <sub>2</sub>   | 25730   | 69.24       | 2058  | 69.22   | 2058                                      | 69.64       |
| SO <sub>2</sub>  | 178   | 0.48        | 14  | 0.47    | 14  | 0.47        |
| SO <sub>3</sub>  | 2.01  | 0.01        | 0.16  | 0.01    | 0.16                                      | 0.01        |
| NO               | 14.28   | 0.04        | 1.14  | 0.04    | 1.14                                      | 0.04        |
| NO <sub>2</sub>  | 1.15  | 0.0003      | 0.09  | 0.0003  | 0.09                                      | 0.0003      |
| HCl              | 4.75  | 0.01        | 0.38  | 0.01    | 0.38                                      | 0.01        |
| H <sub>2</sub> O | 2173  | 5.85        | 174   | 5.85    | 174                                       | 5.89        |
| Ash              | 225   | 0.61        | 18  | 0.61    | 0.11                                      | 0.004       |
| Total            | 37161   | 100         | 2973  | 100     | 2955                                      | 100         |

### 2.3.3.2.10 Reactor Inlet Ducting

For the reactor inlet ducting design, DynaGen performed flow modeling tests with a 1/2 scale model of the inlet ducting for two alternative designs. Each alternative reflected the following changes from the original reactor inlet concept: a) change from a vertical inlet duct run to a horizontal duct run with round to rectangular duct transitions; b) addition of a diffuser, equipped with internal baffle plates and expansion in only one dimension; and c) transition from horizontal to vertical flow into the reactor inlet equipped with turning vanes.

The model design achieving the best velocity uniformity results and requiring the minimum space called for a transition from round to square duct and expansion on the horizontal of roughly 50%. Four equally spaced baffles were included on the horizontal expansion, generating a diffuser arrangement. A 90° turn then followed with eleven turning vanes which expanded parallel to the turn, generating dimensions equivalent to the reactor. The velocity profile data for the inlet geometry in the round piping ductwork was shown to be uniform and symmetric. However, in initial flow model testing, the velocity profile uniformity at the diffuser outlet was poor and had high velocities, about 50 percent above average in the center, and low velocities at the walls. This phenomena resulted from the flow area expansion from a 1 foot circle to a 1 foot square, followed by the expansion across the diffuser to a 1.5 foot x 2 foot cross-section. To reduce the velocities and distribute the flow more uniformly, a set of resistance pipes was located immediately at the outlet of the circle to square transition (which also corresponded to an ammonia injection grid).

Slight modifications in detail geometry of the resistance pipes progressively improved the diffuser outlet uniformity from 16.7 percent of data within  $\pm 10$  percent to 87.5 percent of data within  $\pm 10$  percent as shown in Table 2.3-4 for the final resistance pipe design selected. The velocity profile test results for the optimum design tested are summarized in Table 2.3-4. About 96 percent of the results were within  $\pm 10$  percent of the average velocity and 99 percent of the results were within  $\pm 15$  percent of the average.

**Table 2.3-4 Velocity Profile Test Results Summary for  
Selected Model Reactor Inlet Design**

| Geometry Description                                | Location Description | RMS <sup>a</sup> | ± 10% (%) <sup>b</sup> | ± 15% (%) <sup>c</sup> |
|---|----------------------|------------------|------------------------|------------------------|
| Open design with elbow and diffuser vanes           | Diffuser Outlet      | 0.066            | 87.5                   | 97.9                   |
| No space between elbow and core                     | Dummy Layer Inlet    | 0.074            | 86.1                   | 95.5                   |
| Five 1" dowels unequally spaced, 58.3% open average | Dummy Layer Outlet   | 0.049            | 95.5                   | 99.0                   |

a) RMS = Standard deviation of velocity about an average velocity, expressed as a fraction of the average velocity. For a value of zero, the flow would be perfectly uniform with all data points equal.

b) Percentage of data within ± 10% band about the average.

c) Percentage of data within ± 15% band about the average.

The following are conclusions from the above DynaGen flow modeling.

1. The proposed design was the minimum height and length design and was a more practical field unit configuration.
2. The initial base design, with elbow vanes and diffuser baffles but no resistance pipes, was very poor.
3. Resistance pipes were needed at the outlet of the circle to square transition to improve velocity profile uniformity.
4. The best velocity uniformity results achieved for test 17 were RMS = 0.049, 95.5 percent of data with ± 10 percent of average, and 99.0 percent of data within ± 15 percent.
5. This velocity uniformity could be improved by:
  - a. adding more dummy core length;
  - b. using unequally spaced vanes; or
  - c. adding a second resistance at the diffuser outlet or the elbow outlet.
6. The pipe resistance could be used as the grid for the ammonia injection nozzles.
7. The use of a 12 inch model spacer between the elbow outlet and dummy core inlet gave better results above the dummy core but worse results at the dummy core outlet.

8. The pressure loss from prior to the turning vanes to downstream of the resistance pipes was roughly 0.69 in. of water at field operating conditions.

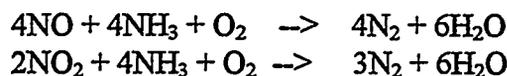
In follow-up testing to evaluate vertical versus the previously-tested horizontal arrangements for resistance pipes, it was concluded that the horizontal arrangement provided the best velocity uniformity results and so the final design incorporated the horizontal resistance pipe configuration.

### **2.3.3.3 Area 300: Ammonia Storage to Reactors**

Area 300 was from the ammonia storage tanks to reactor injection nozzles, and included the ammonia injection skid. Refrigeration grade anhydrous ammonia was stored in one 1,200 gallon tank that was provided by the ammonia supplier. The ammonia storage tank was located on the north side of an abandoned de-mineralizer building. A relatively constant vapor pressure of ammonia gas was maintained in the top of the storage tank, utilizing an electric heater system to vaporize the liquid ammonia to maintain pressure of nominally 175 psig. Gaseous ammonia was fed to an ammonia header via a flow control valve that maintained the header at a pressure of nominally 30 psig. Ammonia from the header was metered to each of the SCR reactor trains. A single speed fan provided a constant flow of dilution air to a manifold to assist in maintaining proper ammonia injection into the ductwork preceding the SCR reactors. The air and ammonia were combined and passed through an in-line static mixer, providing proper mixing before going to the ammonia injection grid.

#### **2.3.3.3.1 Ammonia/Air Flow Measurement and Control**

Ammonia consumption depends upon the flue gas flow,  $\text{NO}_x$  concentration, and  $\text{NH}_3/\text{NO}_x$  ratio. For a  $\text{NH}_3/\text{NO}_x$  range of 0.6 to 1.1, the ammonia consumption ranges for the large and small reactors were 2.12 to 10.9 lb/hr, and 0.20 to 0.90 lb/hr, respectively. The following reactions, which were shown previously, describe the chemistry of the SCR process.



Based on these reactions, the equation for the calculation of ammonia consumption is given by:

$$m \text{ NH}_3 = \frac{\Delta \text{NO}_x}{46.005} * \frac{\epsilon \text{NO} + \epsilon \text{NO}_2 * 2}{100} * 17.031 + \text{NH}_3\text{-slip} * V * 10^{-6}$$

Where:

|                           |  |
|---------------------------|--|
| $m \text{ NH}_3$          | ammonia mass flow (kg/h)   |
| $\Delta \text{NO}_x$      | $\text{NO}_x$ in - $\text{NO}_x$ out ( $\text{mg}/\text{m}^3\text{N}$ , dry, standard $\text{O}_2$ ), as $\text{NO}_2$ |
| $\epsilon \text{NO}$      | $\text{NO}$ - share on $\text{NO}_x$ content (%)   |
| $\epsilon \text{NO}_2$    | $\text{NO}_2$ - share on $\text{NO}_x$ content (%)   |
| $\text{NH}_3\text{-slip}$ | ( $\text{mg}/\text{m}^3\text{N}$ )   |
| $V$                       | flue gas flow ( $\text{Nm}^3/\text{h}$ , dry, standard $\text{O}_2$ )  |

Mass flow measurement devices are recommended for accurately metering ammonia vapor because of the following advantages:

- temperature independent,
- pressure independent,
- wide measurement ranges, and
- electric output signal.

Mass flow meters are sensitive to small amounts of liquid water and oil, which decreases the accuracy. A coalescing filter was used upstream of the mass flow meter to collect water and oil. Mass flow meter measurements are also sensitive to the meter orientation.

The ammonia dilution air flow was measured to determine the amount of air/ $\text{NH}_3$  added to the reactor. Since the air/ $\text{NH}_3$  injection was downstream of the reactor inlet venturi, the total gas flow through the reactor was not known without the dilution air flow being measured. The dilution air supply was always in operation, even with no ammonia injection, to avoid injection nozzle plugging by fly ash.

Maintaining a relatively low value for ammonia slip is a major consideration in SCR operations. Ammonia slip is governed by the catalyst design and volume, and the effectiveness of the ammonia injection system. The basic design of the ammonia injection system, from the ammonia flowing from the header to the  $\text{NH}_3$ /air injection into the reactor inlet ducting, is shown in

Figure 2.3-5. This injection system comprised the control and stop valves for ammonia, dilution air supply and heaters, static mixer, the isolation, throttling and adjusting valves, and the array of pipes with nozzles in the flue gas duct. The original design as shown called for individual pressure drop measurements across the individual nozzle pipes. This was not incorporated in the final installed design.

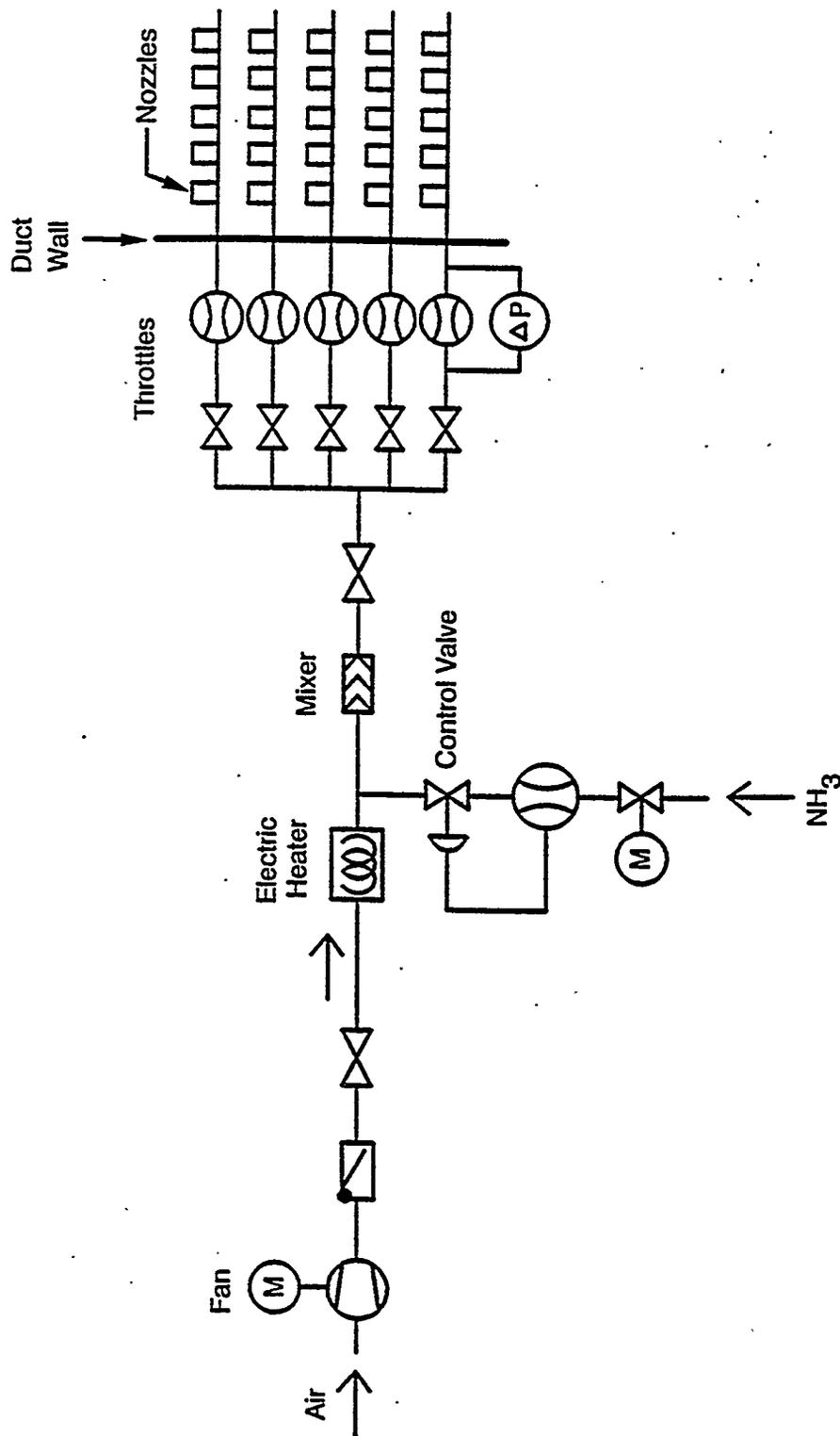


Figure 2.3-5 Basic Design of Ammonia Injection System

### 2.3.3.3.2 Ammonia Dilution Air Supply and Electric Heater

The ammonia dilution air utilized a common centrifugal fan with a common dilution air heater to furnish heated dilution air for all reactors. The heater utilized a silicon control rectifier to adjust heater power output with any combination of reactors in or out of service and was similar to the small reactor flue gas heaters.

The ammonia dilution air heater was used to heat the ambient dilution air above the ammonium bisulfate (ABS) dew point, approximately 500 °F, to prevent formation of ABS and pluggage of the ammonia injection nozzles. By raising the temperature of the dilution air above the ABS dew point, the heaters also raised the temperature of the air above the acid dew point, which minimized corrosion.

The ammonia dilution air electrical heater load was grossly estimated using the following formula:

$$kW = \{CFM \times \Delta T\} / 3000$$

Where: CFM is the flow rate of air at standard conditions, 70 °F and 1 atm.

The large reactor ammonia dilution air flow was approximately 32 CFM. Therefore, maximum electrical load for the large reactor dilution air was approximately:

$$(32) (500-30) / 3000 = 5 \text{ kW}$$

The small reactor ammonia dilution air flow was approximately 2.5-CFM. Therefore, maximum electrical load for the small reactor dilution air was approximately:

$$(2.5) (500-30) / 3000 = 0.4 \text{ kW}$$

The common ammonia dilution air heater load would be the sum of the above calculated loads:

$$(3) (5) + (6) (.4) = 17.5 \text{ kW}$$

The common ammonia dilution air heater was required to have controls capable of accommodating any combination of reactors in or out of service.

The ammonia dilution air heater control was capable of maintaining the ammonia dilution air temperature to within  $\pm 2$  °F of the desired set point. The test facility distributed control system (DCS) used a single output 4-20 ma DC signal to control the heater. Heater control was staged into service based on the value of the 4-20 ma DC signal (4 ma = zero heater and 20 ma = maximum heater output). The heater control was provided with overload protection, flow detection, and over-temperature protection.

The test facility had 480-volt, 3-phase, 60-Hz power, available for the ammonia dilution air electric heater. The heater utilized high temperature cables to protect from overheating of wired and/or melting insulation. Over temperature control was incorporated into the heater design to prevent the heaters from burning out when no flow conditions occur. External heater components were enclosed in a NEMA 4-type enclosure for weather protection. The number of heater banks was divisible by three to minimize phase distortions.

#### **2.3.3.3.3 Ammonia Injection Grid**

The ammonia injection grid was a set of pipes installed horizontally across the duct cross-section at the outlet of the transition from circle to square transition, which also served as resistance pipes to improve flue gas velocity profiles. This was located so as not to interfere with the venturi flow reading, while allowing ample distance for proper mixing of the ammonia in the flue gas.

The injection grid for the small SCR reactors consisted of four horizontal pipes across the duct with a four by four array of nozzles, for a total of 16 nozzles. For the large reactors, the grid

consisted of five horizontal pipes across the duct, with a five by five array of nozzles, for a total of 25 nozzles.

The ammonia was injected at a velocity as near that of the flue gas flow as possible. The pressure drop in the nozzle also assisted in minimizing differences in volumetric flow over the length of the injection pipe. Injection was parallel to the flue gas flow direction. Injection against the flue gas flow should be avoided, especially in high-dust cases where the ash loading may plug the nozzle openings, particularly upon loss of the dilution air supply.

It was recommended by some suppliers that the deviation of the  $\text{NH}_3/\text{NO}_x$  molar ratio at the catalyst inlet not exceed 5 percent. Subsequently, the reduction rate over the reactor cross-section should also not deviate by more than 5 percent. This was also required in order to minimize the residual ammonia content downstream of the reactor throughout the catalyst life. The system was planned so that it was possible to adjust the  $\text{NH}_3/\text{NO}_x$  ratio in individually defined areas.

Air purge connections were furnished on the ammonia system piping, allowing several pipe volumes of air to purge the lines before maintenance was performed on the ammonia system.

#### **2.3.3.4 Area 400: SCR Reactors**

Area 400 consisted of the three large, 5000-scfm and six small, 400-scfm SCR reactors. The original facility concept included a common bypass for all three large reactors. This concept was changed in favor of individual reactor bypasses to simplify the flow control and operation of the test facility. Each large reactor bypass was capable of sending flue gas to the APH or a bypass heat exchanger.

There were five small reactors for high-dust service (i.e., ahead of the hot-side ESP) and one small reactor for low-dust service (i.e., after the hot-side ESP). The small reactors were grouped in banks of three for fan service. There was no bypass of small reactors.

The transition piece at the reactor inlet was designed to reduce the gas flow from 60 fps down to 15 fps and assure that the velocity components of flow were uniformly distributed across the reactor cross-section. DynaGen responded to SCS with recommendations on reactor transition pieces that allowed uniform expansion and contraction of gas into the reactors. Each reactor was equipped with a dummy layer of inert ceramic at the reactor inlet to provide some gas pressure drop and help to redistribute the gas flow.

Each reactor was identical in design, requiring catalyst suppliers to match their catalyst configuration to the common design. The large reactors had internal dimensions of about 1.37m x 1.06m, about 4.5 ft. x 3.5 ft., allowing for both the module dimensions and clearance. The small reactors had internal dimensions of about 330mm x 330mm, about 1 ft. x 1 ft. The catalyst was housed in movable structures called baskets. The dimensions of the catalyst modules for each catalyst supplier were given in Table 2.2-2. The baskets were made of carbon steel. Each catalyst supplier provided the basket for its catalyst.

Preliminary heat transfer calculations showed that 6-inch thick mineral fiber insulation (normal ductwork insulation at these temperatures) provided an acceptable heat loss (less than 55 Btu/sq. ft.) and provided a safe surface temperature (less than 140 °F) for personnel protection. The calculations showed the gas temperature drops 0.5 °F for the large reactors and 2 °F for the small reactors, assuming negligible heat of reaction. However, based on field experience, actual heat loss is typically four to five times greater than that calculated. Therefore, insulation thickness of 1 foot was used on the reactors and inlet ductwork.

Thermocouples were directly inserted into the catalyst for permissives on start-up and temperature measurement. According to previous test facility experience, there can be as much as 60 to 70 °C difference between the bulk gas and catalyst surface temperatures. This measurement also provided some indication of the thermal inertia of the catalyst during start-up and shut-down. In addition, bulk gas temperature measurement was included in the final design of the reactor. The use of catalyst bed heaters was not included in the reactor design. During

cold shut-downs, the heated ammonia dilution air provided a warm air purge to prevent water condensation and sulfuric acid formation, which would accelerate catalyst poison migration from the fly ash.

The large reactors had a bolted door design very similar to the Electric Power Research Institute (EPRI) test facility at the Tennessee Valley Authority (TVA) Shawnee Station. Minimum door and flange thickness of 1/2 inches provided adequate protection against deformation, thereby minimizing air in-leakage through the doors. Braided fiberglass gaskets were used to provide an adequate seal.

Sampling ports for the large and small reactors were located between the flow straightening grid and the first catalyst layer, at the outlet of the reactor, and in between each catalyst layer. This included three horizontally aligned sampling ports on the 3-ft reactor door of the large reactors at each door location. The small reactors had only two sample ports at each location which were vertically aligned. In practice, the small reactor ports were used for more than one purpose, such as sootblowing and manual testing.

Materials of construction for reactors were ASTM A516 carbon steel structural plate. Utility stations for steam, air, and electrical were installed on each reactor level to allow easy hookup for servicing the reactors.

Fly ash buildup on the reactor walls and the catalyst surface was a concern for the pilot scale reactors. Previous test facility experience suggested that fly ash deposition was due to small recirculation zones at the entrance and exit of the catalyst modules. SCS attempted to minimize the re-circulation zones, and hence the fly ash buildup on the catalyst modules, by minimizing the distance which the catalyst support structure protrudes into the gas path of the reactor.

Obviously, the optimum situation is to have the reactor inner walls as smooth as possible without flow disturbances.

The reactor design also allowed approximately 5 to 6 feet between catalyst modules to allow flow patterns to become more streamlined before entering the next catalyst module. The flue gas incident angle to the surface of the catalyst should never be more than 30 degrees, as measured from the vertical, to prevent the formation of stalagmites of fly ash from growing upon the surface of the catalyst. Fly ash buildup is not generally a problem on plate-type catalyst due to the irregular leading edges. A wire mesh screen cover was also placed over the catalyst surface. This mesh screen caught large ash particles, preventing them from lodging on the catalyst surface and physically blocking channels.

In addition to the above mentioned items, each reactor had provisions for sootblowing on each catalyst layer and the dummy layer. The large reactors used a traversing-type, retractable sootblower to deliver superheated steam from the Unit 5 boiler to the surface of the catalyst. The small reactor sootblowers used air from the service air system and were stroked manually across catalyst layers by plant personnel. Sootblowing was sequenced from the top to the bottom of the reactors and controlled by the test facility control system on the large reactors.

Sootblowers were the primary concern for air in-leakage into the reactors. All possible precautions to minimize air in-leakage were incorporated into the final reactor design. The sootblower could fully retract out of the gas path to provide as smooth an inner reactor surface as possible.

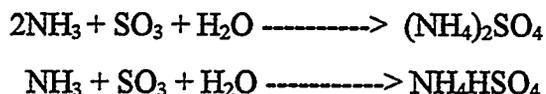
### 2.3.3.5 Area 500: SCR Reactor Outlet to Pilot APH Outlet

Area 500 was from the outlet of the large SCR reactors to the pilot-scale air preheater (APH) outlets. The objective of Area 500 was to simulate full scale APH operation downstream of an SCR unit.

The three air preheaters (APH) consisted of two rotary designs and one heat pipe design. In the original design, each APH could be isolated and the gas flow bypassed around the APH during high ammonia slip testing and water washing of the unit, while the SCR reactors were on-line. A water cooled tube-in-shell heat exchanger was used in the bypass of the APH, reducing the temperature of the flue from 700 °F to 200 °F and preventing damage to the flue gas ID fans. In practice, however, these heat exchangers fouled after a short period of use and were subsequently not operated. The APH could be isolated with dampers at both the inlet and outlet. The fan for the air side of the APHs was induced-draft, thereby reducing the differential pressure across the hot-end of the APH and minimizing the air in-leakage.

Extracting flue gas from in front of the Unit 5 air heater was calculated to potentially exacerbate an existing problem with average cold-end temperatures on the plant air heater. After reviewing many alternatives with Gulf Power Company, the decision was made to extract air downstream of the units' forced draft fan and to return air just upstream of the unit's boiler wind box.

Slip  $\text{NH}_3$  is a concern in the application of SCR to coal-fired boilers. The combined presence of  $\text{NH}_3$ ,  $\text{SO}_3$ , and  $\text{H}_2\text{O}$  may lead to the formation and condensation of ammonium bisulfate [ $\text{NH}_4\text{HSO}_4$  (ABS)] and ammonium sulfate  $(\text{NH}_4)_2\text{SO}_4$  on downstream equipment. The chemistry of these reactions are shown below:



Because it contains  $V_2O_5$ , SCR catalyst has a tendency to promote  $SO_2$  conversion to  $SO_3$ , as a function of temperature for a particular catalyst formulation. The effect of temperature is also influenced by the quantity of vanadium, tungsten, and other catalytically active metals in the catalyst. Space velocity also influences  $SO_2$  to  $SO_3$  conversion. The combustion of low-sulfur coal typically results in less than 3 to 8 ppm  $SO_3$  formation in the boiler. Moreover, the  $SO_2$  concentration in the flue gas is often less than 600 ppm. Thus,  $NH_3$  slip is of less concern, since the total  $SO_3$  content of the flue gas leaving the SCR is also relatively low (i.e., 3 to 8 ppm). However, U.S. high-sulfur coal with high  $Fe_2O_3$  content may form as much as 30 ppm  $SO_3$  in the boiler. This, combined with as much as  $\frac{1}{10}$  percent conversion of the  $SO_2$  in the flue gas to  $SO_3$  over the SCR catalyst, can lead to substantial problems with ammonium bisulfate formation if the  $NH_3$  slip is not kept to the lowest values practicable.  $NH_4HSO_4$  will form as a sticky condensate and will deposit in the intermediate sections of the power plant air preheater. Once deposited, the  $NH_4HSO_4$  may corrode the underlying metal, or contribute to pressure losses.

#### 2.3.3.5.1 Rotary Air Heaters

The design features that must be maintained to achieve a good simulation for a rotary air heater are listed below:

- \* Identical mass flow rate of flue gas per unit frontal area of air heater surface;
- \* Identical heating element basket design, spacing, and materials; and
- \* Identical element depth, or the length of air heater in the direction of flow.

A specially modified size 9 Ljungstrom<sup>®</sup> vertical shaft air heater manufactured by ABB Air Preheater Inc., formerly C-E Air Preheater Company, was used for the two rotary APHs. The size 9 APH is similar in basic design to the large Ljungstrom<sup>®</sup> APH that exists in many coal-fired power plants. With a wheel diameter of 5 feet, the mass flow rate of flue gas per rotor frontal area is in the same range as that of typical large electric utility boilers. The element depth of the size 9 heater is 72 inches, which compares favorably with the 90- to 96-inch basket depth found in larger Ljungstrom<sup>®</sup> APHs. The size 9 heater will also accept the same types of baskets that are

used in large APHs. Therefore, aspects of deposition and cleaning related to basket geometry and materials can be readily duplicated.

One aspect of simulation that was not considered adequate in the standard size 9 APH was the fluid mechanics of gas flow entering the APH. Because of the large ratio of shaft diameter to wheel diameter for the size 9 APH, versus a large APH, the entrance flange openings on the size 9 unit are somewhat more constricted. This could have a significant effect on gas-side inlet flow distributions and deposition patterns. In order to mitigate this potential problem, the entrance flanges were widened and extended, providing a larger opening and a more direct path for the flue gas entering and exiting the APH. The requirements for matching element metal temperatures in the size 9 APH with those in large APHs required a change in the typical operation of the APH. Normally, small rotary air heaters rotate at a faster rate than larger air heaters due to mechanical considerations. This means that the elements of smaller APH experience a smaller temperature swing as the baskets rotate. The size 9 APH was equipped with a variable speed drive to allow temperature swings to match typical large APH, which were  $\pm 30$  °F. The variable speed feature also allowed the rotor speed to be increased as necessary for test facility sootblowing conditions to be representative of full scale.

APH leakage of air into the gas stream is a function of the area of the seal opening and the static pressure differential across the seals. Small APHs have more sealing length per unit volume than large rotary APHs. The estimated air in-leakage for the size 9 rotary APH was nominally 20 percent. Most of the air leakage was across the cold-end radial seal, and therefore did not affect  $\text{NH}_4\text{HSO}_4$  deposition. However, hot-end leakage was significant, and this leakage could affect the  $\text{NH}_4\text{HSO}_4$  deposition as a result of either concentration or temperature effects. In order to provide flexibility in setting the quantity of air in-leakage, the air handling systems for each APH were designed for air-side static pressure to be varied to within approximately 1 inch  $\text{H}_2\text{O}$  of the gas-side static pressure by utilizing an induced draft fan.

Design and performance details for the two rotary APH are shown in Table 2.3-5. The major APH issues with the SCR test facility were deposition, corrosion, and cleanability which impact

the segmentation, design, and materials of the APH rotor baskets. Each of the two rotary APHs had a different rotor selection, as shown in Table 2.3-6.

The first selection (APH A) is used extensively in Europe and had two layers of elements rather than the conventional three. The hot-end layer was of conventional undulating design (DU), fabricated from low alloy steel. This type of element has superior heat transfer characteristics, but is more prone to deposition because of tighter passages and increased turbulence, and is difficult to clean. The second layer in the first selection was a notched-flat (NF) design, and was fabricated from Corten or enamel coated carbon steel. The NF element has lower turbulence and large openings and is less apt to form deposits than the DU-type. The NF elements were more easily cleaned by the cold-end sootblower. The cleanability was enhanced by using one deep cold-end layer for the two layers, rather than one intermediate and one cold, typically installed in utility APH. The continuous element ensured that sootblowing steam penetrated to the deposit and did not lose effectiveness by expanding into a gap between elements. The use of two layers in the region of  $\text{NH}_4\text{HSO}_4$  deposition has been shown to result in deposit buildup at the junction between elements.

The second selection (APH B), shown in Table 2.3-6, consisted of three layers. The hot-end layer was of conventional DU design, and was manufactured from low alloy steel. The intermediate layer of 42 inch NF design was fabricated from Corten. The cold layer had a typical depth of 12 inches NF design, and was also fabricated from Corten.

Both of the rotary APHs had access on the air-side of the APH for side removal of the elements. Each APH incorporated steam sootblowers at the hot-end and the cold-end of the APH, with steam conditions specified at 250-psi and 650 °F. Precautions were taken to ensure that the sootblowing of a full-scale APH was simulated and thus the small APHs were rotated at several times the rate of a full-scale unit. This brought about the desired rate of steam flow per unit area, at the frontal surface of the element. Therefore, it was necessary to increase the rotational rate of the small-scale APH prior to sootblowing and reduce the rate afterwards.

Water washing of the rotary APH was required more frequently with the SCR test facility than for a typical power plant. Each APH was equipped with water-wash manifolds at both the hot-end and the cold-end of the heater for removal of soluble deposits such as  $\text{NH}_4\text{HSO}_4$ . Drains were installed in the exit ductwork to remove wash water from each of the APHs.

Table 2.3-5 Ljungstrom® Air Heater Performance

|   |                                       |   |
|---|---------------------------------------|---|
| Air heater manufacturer                     | C-E Air Preheater                     |   |
| Air heater size/type                        | Size 9/VI (vertical, gas flow down)   |   |
| Number of element sectors                   | 12                                    |   |
|   | Selection 1<br>(APH A)<br>(two-layer) | Selection 2<br>(APH B)<br>(three-layer) |
| <b>Flows (1b/hr):</b>                       |                                       |   |
| Air Entering                                | 23,850                                | 27,757                                  |
| Air Leaving                                 | 18,250                                | 22,357                                  |
| Gas Entering                                | 24,934                                | 24,934                                  |
| Gas Leaving                                 | 30,534                                | 30,334                                  |
| <b>Temperatures (°F):</b>                   |                                       |   |
| Air Entering                                | 100                                   | 100                                     |
| Air Leaving                                 | 633                                   | 579                                     |
| Gas Entering                                | 700                                   | 700                                     |
| Gas Leaving Uncorrected                     | 334                                   | 298                                     |
| Gas Leaving Corrected                       | 293                                   | 264                                     |
| <b>Pressure Diff. (in. H<sub>2</sub>O):</b> |                                       |   |
| Air-side Pressure Drop                      | 1.60                                  | 1.80                                    |
| Gas-side Pressure Drop                      | 2.85                                  | 2.50                                    |
| Hot-end Differential                        | 1.00                                  | 1.00                                    |
| Cold-end Differential                       | 5.45                                  | 5.30                                    |

Table 2.3-6 Rotary Air Heater Rotor Designs

|                     |       |        |                                     |
|---------------------|-------|--------|-------------------------------------|
| <b>Selection 1:</b> |       |        |                                     |
| Layer               | Depth | Design | Material                            |
| Hot-end             | 30"   | DU     | Low alloy corrosion resistant steel |
| Cold-end            | 42"   | NF-3.5 | Corten                              |
| <b>Selection 2:</b> |       |        |                                     |
| Layer               | Depth | Design | Material                            |
| Hot-end             | 18"   | DU     | Low alloy corrosion resistant steel |
| Intermediate        | 42"   | NF-3.5 | Corten                              |
| Cold-end            | 12"   | NF-3.5 | Corten                              |

### 2.3.3.5.2 Heat Pipe Air Preheater

Heat pipe APHs have recently entered the utility market as an alternative to rotary APHs. A heat pipe APH consists of bundles of individual, sealed heat pipes which conduct heat from flue gas in one passage to air in an adjacent passage. The specifications of the heat pipe APH designed by ABB Air Preheater Inc. (formerly C-E Air Preheater Company) are given in Table 2.3-7. The unit consisted of 328 individual heat pipes with an in-line arrangement to facilitate cleaning. The heat pipes were arranged on a square pitch of 3.75 inches. The heat pipes were finned to ensure effective heat transfer. The heat pipe was fabricated from Corten. The working fluids in the heat pipe were naphthalene in the hot-end and toluene in the cold-end.

The heat pipe APH design was equipped with five sootblower cavities, with a total of ten sootblowers provided. The heat pipe APH was also equipped with cold-end and hot-end manifolds for water washing. Drains were provided in the exit ductwork for drainage of the APH wash water.

One hot air fan was used to pull ambient air through the two Ljungstrom<sup>®</sup> air heaters and the single heat pipe air heater. This heated air was reinjected into the main unit secondary air supply after the main unit air heater.

Table 2.3-7 Specifications/Performance of Heat Pipe Heat Exchanger

|                                       |                         |                       |
|---------------------------------------|-------------------------|-----------------------|
| <b>DESIGN:</b>                        |                         |                       |
| Total Number of Heat Pipes            | 328                     |                       |
| Pipe O.D. (in.)                       | 2.0                     |                       |
| Fin Density (fins per inch)           | 3.0 gas/3.0 air         |                       |
| Fin Type                              | Solid                   |                       |
| Tube Arrangement                      | In-Line                 |                       |
| Transverse Pitch (in.)                | 3.75                    |                       |
| Longitudinal Pitch (in.)              | 3.75                    |                       |
| Total Gas-side Surface Area (sq. ft.) | 10,057                  |                       |
| Total Air-side Surface Area (sq. ft.) | 4,076                   |                       |
| Total Unit Approximate Weight (lb.)   | 54,000 with transitions |                       |
| <b>PERFORMANCE:</b>                   | <b>FLUE GAS</b>         | <b>COMBUSTION AIR</b> |
| Flow Rate (lb/hr)                     | 24,934                  | 21,759                |
| Entering Temp. (°F)                   | 700                     | 100                   |
| Leaving Temp. (°F)                    | 300                     | 588                   |
| Pressure Drop (in. H <sub>2</sub> O)  | 1.60                    | 3.00                  |
| Avg. Specific Heat (Btu/lb°F)         | 0.263                   | 0.247                 |
| Heat Recovered (MMBtu/hr)             | 2.69                    |                       |
| Minimum Metal Temp. (°F)              | 277                     |                       |

### 2.3.3.6 Area 600: Cyclones to Host Boiler Duct

Area 600 was from the cyclones to the host boiler duct and included the cyclones, flow control dampers, fan and fan motors, isolation damper for each reactor train for the large reactors, and the exhaust gas heaters.

The process configuration in Area 600 was different for the large reactor compared to the small reactors, due to the APH (Area 500) used in the large reactor train configuration. The flow control concept for the small reactors used a fan with a variable speed motor, in conjunction with a flow control damper, since a single fan was used for three of the reactors; whereas the large reactors used only a variable speed fan for flow control.

The cyclones were included for particulate removal to help protect downstream equipment such as the fan and control dampers. During normal operation, the large reactors were operated at

steady state around a set of design conditions. Once the gas passed through the reactor, it entered the air heater and was cooled to approximately 300 °F. The predicted flue gas conditions at the large reactor cyclone inlet follows in Table 2.3-8.

The test facility periodically operated at various off-design conditions to stress the catalyst performance, and quantify the deactivation rate. These off-design conditions involved variations of flue gas flow and temperature as well as NO<sub>x</sub> removal. The large reactor trains were equipped with an air preheater bypass, which was designed to operate when the reactor was operated at any condition other than the design point. Each bypass line was equipped with a finned-tube heat exchanger, which cooled the gas to approximately 300 °F when entering the cyclones. In practice, these bypass heat exchangers plugged after a short period of use and were subsequently not used. Table 2.3-9 shows the variations in flue gas flow and ash loading that were expected at the large reactor cyclones.

Similar to the large reactors, the small reactors were operated at steady state around a set of design conditions. Because there were no air preheaters cooling the flue gas on the small reactors, the cyclones were operated at the full temperature of the flue gas. The small reactors were arranged into groups of three, each with its own cyclone. The predicted flue gas conditions at the small reactor cyclone inlet are shown below in Table 2.3-10.

Temperature variation ranged between 620 °F and 750 °F during off-design conditions. The flue gas flow ranged from 60 percent of design flow to 150 percent of design flow for each reactor. The range of off-design operation is shown below in Table 2.3-11.

Table 2.3-8 Large Reactor Steady State Operating Conditions

| Parameter                            | Ljungstrom® APH | Heat Pipe APH |
|--------------------------------------|-----------------|---------------|
| Number of Cyclones Per Reactor Train | 1               | 1             |
| Flue gas flow rate                   | 9642 acfm       | 8195 acfm     |
| Flue gas temperature                 | 300 °F          | 300 °F        |
| Inlet gas velocity                   | 60 ft/sec       | 60 ft/sec     |
| Ash flow rate                        | 150 lb/hr       | 150 lb/hr     |
| Grain loading                        | 1.81 gr/acf     | 2.14 gr/acf   |

Table 2.3-9 Large Reactor Off-Design Operating Matrix

| Nominal Flow rate |                     |                     |                    |
|-------------------|---------------------|---------------------|--------------------|
|                   | 7500 SCFM<br>(150%) | 5000 SCFM<br>(100%) | 3000 SCFM<br>(60%) |
| FLOW:             | 14354 ACFM          | 9297 ACFM           | 5500 ACFM          |
| TEMP:             | 400 °F              | 400 °F              | 400 °F             |
| VELOCITY:         | 95 f/s              | 64 f/s              | 38 f/s             |
| ASH:              | 225 lb/hr           | 150 lb/hr           | 90 lb/hr           |
| Gr LOAD:          | 1.83 gr/acf         | 1.88 gr/acf         | 1.91 gr/acf        |
| FLOW:             | 12635 ACFM          |                     | 4851 ACFM          |
| TEMP:             | 300 °F              | Steady State        | 300 °F             |
| VELOCITY:         | 80 f/s              | Operating Point     | 32 f/s             |
| ASH:              | 225 lb/hr           | (see Table 2.3-8)   | 90 lb/hr           |
| Gr LOAD:          | 2.08 gr/acf         |                     | 2.16 gr/acf        |
| FLOW:             | 11752 ACFM          | 7638 ACFM           | 4526 ACFM          |
| TEMP:             | 250 °F              | 250 °F              | 250 °F             |
| VELOCITY:         | 74 f/s              | 50 f/s              | 30 f/s             |
| ASH:              | 225 lb/hr           | 150 lb/hr           | 90 lb/hr           |
| Gr LOAD:          | 2.23 gr/acf         | 2.29 gr/acf         | 2.32 gr/acf        |

Table 2.3-10 Small Reactor Steady State Operating Conditions

|                      |             |
|----------------------|-------------|
| Number of cyclones   | 5           |
| Flue gas flow rate   | 984 acfm    |
| Flue gas temperature | 700 °F      |
| Inlet gas velocity   | 60 ft/sec   |
| Ash flow rate        | 12 lb/hr    |
| Grain loading        | 1.42 gr/acf |

Table 2.3-11 Small Reactor Off-Design Operating Matrix

|           | 600 SCFM<br>(150%) | 400 SCFM<br>(100%) | 240 SCFM<br>(60%) |
|-----------|--------------------|--------------------|-------------------|
| FLOW:     | 1527 ACFM          | 1027 ACFM          | 611 ACFM          |
| TEMP:     | 750 °F             | 750 °F             | 750 °F            |
| VELOCITY: | 80 f/s             | 54 f/s             | 32 f/s            |
| ASH:      | 18 lb/hr           | 12 lb/hr           | 7 lb/hr           |
| Gr LOAD:  | 1.38 gr/acf        | 1.36 gr/acf        | 1.34 gr/acf       |
| FLOW:     | 1462 ACFM          |                    | 585 ACFM          |
| TEMP:     | 700 °F             | Steady State       | 700 °F            |
| VELOCITY: | 77 f/s             | Operating Point    | 31 f/s            |
| ASH:      | 18 lb/hr           | (see Table 2.3-11) | 7 lb/hr           |
| Gr LOAD:  | 1.44 gr/acf        |                    | 1.4 gr/acf        |
| FLOW:     | 1363 ACFM          | 915 ACFM           | 545 ACFM          |
| TEMP:     | 620 °F             | 620 °F             | 620 °F            |
| VELOCITY: | 72 f/s             | 48 f/s             | 29 f/s            |
| ASH:      | 18 lb/hr           | 12 lb/hr           | 7 lb/hr           |
| Gr LOAD:  | 1.54 gr/acf        | 1.53 gr/acf        | 1.5 gr/acf        |

\*NOTE: Nominal flow rates are at standard conditions of 0 °F (32 °F) at 1 atm.

An average of 80 to 85 percent removal efficiency was desired at the steady state design point for large and small reactors. While it is possible to obtain higher removal efficiencies with cyclones, it was not needed, since the flue gas was returned ahead of the cold side ESP.

Realizing that the trade-off between removal efficiency and pressure drop across the cyclone was important, SCS generally had some flexibility, within reason, to compensate for higher than normal cyclone pressure drop from the 150 percent flow case, with the design of the booster fans. After the cyclone had been sized for the steady state operating point, the high and low removal efficiencies and pressure drops were calculated, using any of the off-design conditions for both the large and small reactor cyclones. The performance of the cyclone was bracketed between a best removal, highest pressure drop case, and a worst removal, lowest pressure drop case, with the steady state operating case somewhere in between.

Cumulative particle size distributions of the fly ash are shown in Table 2.3-12. These data are reproduced from Southern Research Institute duct testing. Table 2.3-13 shows the predicted flue gas composition for the large and small reactors at the steady state design point.

Table 2.3-12 Cumulative Particle Size Distribution

| WEIGHT<br>% | PARTICLE SIZE<br>LESS THAN ( $\mu$ ) |
|-------------|--------------------------------------|
| 95          | 90                                   |
| 90          | 57                                   |
| 80          | 38                                   |
| 60          | 21                                   |
| 50          | 16                                   |
| 40          | 13                                   |
| 20          | 6.6                                  |
| 10          | 3.4                                  |
| 1           | 1.1                                  |

Table 2.3-13 Flue Gas Composition at Steady State Operation

| Component        | Large Reactor Cyclone Inlet |            | Small Reactor Cyclone Inlet |            |
|------------------|-----------------------------|------------|-----------------------------|------------|
|                  | lb/hr                       | Weight %   | lb/hr                       | Weight %   |
| CO <sub>2</sub>  | 5095                        | 17.33      | 408                         | 20.45      |
| O <sub>2</sub>   | 1870                        | 6.36       | 66                          | 3.31       |
| N <sub>2</sub>   | 20709                       | 70.43      | 1382                        | 69.27      |
| SO <sub>2</sub>  | 118                         | 0.40       | 9.44                        | 0.47       |
| SO <sub>3</sub>  | 2.23                        | 0.01       | 0.02                        | 0.01       |
| NO               | 1.90                        | 0.01       | 0.15                        | 0.01       |
| NO <sub>2</sub>  | 0.15                        | 0.0005     | 0.01                        | 0.00       |
| HCl              | 3.16                        | 0.01       | 0.25                        | 0.01       |
| H <sub>2</sub> O | 1456                        | 4.95       | 117                         | 5.86       |
| NH <sub>3</sub>  | 0.012                       | 0.00       | 0.0048                      | 0.00       |
| Ash              | 150                         | 0.51       | 12                          | 0.60       |
| <b>Total</b>     | <b>29405</b>                | <b>100</b> | <b>1955</b>                 | <b>100</b> |

The flue gas for the large reactor train was taken out of the main unit gas stream, upstream of the main unit hot side precipitator. Each of the large reactor trains required one exhaust gas fan. The gas stream from each large reactor air heater then passed through the cyclone dust collector before entering each fan. At various time intervals, the test facility underwent parametric testing,

where the flow rate varied between 60 and 150 percent of the design flow. During these periods on each reactor, the Ljungstrom® air heater, or the heat pipe heat exchanger, was planned to be bypassed. A water-cooled heat exchanger was provided in the bypass line to cool the gas to approximately the same temperature as the Ljungstrom®, or heat pipe exit gas temperature, at design flow. As previously discussed, the bypass heat exchangers were not adequate for this application which resulted in the air preheater being in operation whenever its corresponding reactor was in operation. The exhaust gas fan re-injected the flue gas into the gas flow upstream of the main unit cold side precipitator.

The small reactors were grouped in banks of three. Each small reactor on high-dust service had its own cyclone for particulate control. The small reactor on low-dust service did not have a cyclone. Damper control was used for the small reactors for flow control of the flue gas. Each bank of three small reactors had one variable speed fan.

The flue gas from the test facility was re-injected ahead of the cold-side ESP. Advantages of this arrangement included: 1) injecting the flue gas ahead of the particulate control device gave the ESP an opportunity to remove any particulate that passed by the cyclones; 2) injecting after the APH removed any risk of increased cold-end corrosion caused by SO<sub>3</sub> concentration, ammonium bisulfate formation, and localized temperature reduction brought on by inadequate mixing; 3) any SO<sub>3</sub> which leaked out of the SCR reactors potentially would improve the performance of the cold side ESP; and 4) flue gas temperatures from the test facility and the host plant were compatible.

#### **2.3.3.7 Area 700: Test Facility Air Compressor Station**

Area 700 was the air compression station that supplied pressurized air to the SCR test facility. Compressed air was utilized for instrumentation on a continuous basis and various services, such as sootblowing of the small SCR reactors, on a periodic basis. The compressed air station was self-contained and separate from Plant Crist. This area included the air filter, dryers, compressor, surge tanks/cylinders, and pressure regulation for service and instrument air.

### 2.3.3.8 Area 800: Dilution/Extraction Gas Sampling System

Area 800 is the gas analysis system for measuring the flue gas components, particularly NO<sub>x</sub> and O<sub>2</sub> at various points throughout the SCR test facility. A dilution/extraction system was chosen to provide continuously measured flue gas composition data. The concept for the gas analysis system was to use six analyzer banks, plus continuous in-situ O<sub>2</sub> measurement at most sample locations. The six analyzer banks consisted of the following:

#### Analyzer Bank #1 (main test facility inlet)

CO (0-500 ppm)  
CO<sub>2</sub> (0-20 %)  
SO<sub>2</sub> (0-2500 ppm)  
NO<sub>x</sub> (0-1000 ppm)

#### Analyzer Bank #2 (small low-dust reactor inlet)

NO<sub>x</sub> (0-1000 ppm)

#### Analyzer Bank #3 (intermediate (movable) NO<sub>x</sub> probe)

NO<sub>x</sub> (0-250 ppm)

#### Analyzer Bank #4 (outlet for reactors A,B, and C)

NO<sub>x</sub> (0-100 ppm)

#### Analyzer Bank #5 (outlet for reactors D, E, and F)

NO<sub>x</sub> (0-100 ppm)

#### Analyzer Bank #6 (outlet for reactors G, H, and J)

NO<sub>x</sub> (0-100 ppm)

#### 2.3.3.8.1 O<sub>2</sub> Analysis

In-situ analyzers were utilized for all O<sub>2</sub> sample requirements. This method used a heated zirconium oxide sensor mounted in the flue gas stream. It required no external pumps or other mechanical hardware to acquire a sample. The calibration method was remote/auto. The operator had the option of initiating the calibration of each sample point. The calibration was completed using two calibration gases, one near the lower end of the measured span and one near

the upper end of the measured span. The calibration procedure was set up using a minimum amount of down time and a minimum amount of calibration gas. The output of each analyzer was 4-20 ma continuous, with no requirement for time sharing.

#### 2.3.3.8.2 CO, CO<sub>2</sub>, SO<sub>2</sub>, and NO<sub>x</sub> Analysis

The dilution/extraction system used dry air as the dilution medium, practically eliminating the problems associated with the transport and measurement of these gases as compared to other available methods. The sample was filtered and cooled when it reached the analyzers.

The automated sampling system consisted of electrically actuated solenoid gas sampling valves that operated in sequence set by the main system's control logic. The concept of controlling the NH<sub>3</sub>/NO<sub>x</sub> ratio was that all the reactors could be continuously controlled, using the NO<sub>x</sub> readings from analyzer bank 1.

In the automatic mode, the gas sampling valves opened as programmed for each desired sample sequence. Since this was a dilution extractive system, the sample line was always pressurized. Therefore, continuous venting between samples was the only requirement to have a sample ready for the subsequent cycle. Since dilution was with dry air and the actual sample quantity was very small, this eliminated the need for NH<sub>3</sub> or SO<sub>3</sub> traps in all systems with the exception of the intermediate NO<sub>x</sub> probe which required an NH<sub>3</sub> trap.

Analyzer bank 3 was used to continuously monitor a single sample point between the catalyst layers for a single reactor. There was no sequential sampling between the catalyst layer for the test facility, due to the higher ammonia concentrations and increased potential for pluggage of the sample line from ammonium bisulfate formation. Manual connection of the sampling line to analyzer bank 3 was required to change sampling points between the reactors or catalyst layers. In practice, this intermediate probe performed very poorly due to reactions of NH<sub>3</sub> and NO<sub>x</sub> occurring on the metallic surfaces of the probe. All efforts to remedy this failed and the

intermediate measurement using the dilutional extraction system was subsequently abandoned. A portable NO<sub>x</sub> instrument was used to replace this lost measurement.

Calibration means were provided to calibrate each probe using the required calibration gases. This was a remote/auto system, which allowed an operator to initiate the sequence, if desired. A means was provided for blowing back the probe, which could also be initiated by the operator.

### 2.3.3.8.3 Gas Analyzers

#### NO<sub>x</sub> Analyzers

The NO<sub>x</sub> analyzers were of the chemiluminescent type, which senses radiation emitted when electrically excited NO<sub>2</sub> molecules are produced by reaction of NO with ozone. About 7 percent of the NO molecules are converted to excited NO<sub>2</sub> molecules. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier tube, and the output is linearly proportional to the initial NO concentration. Air from the ozonator is drawn from ambient supply, through an air dryer, and is mixed with the sample gas within the instrument's reaction chamber to generate the activated NO<sub>2</sub> molecule, which then decays emitting visible light.

The following specifications applied:

|                    |  |
|--------------------|--|
| Accuracy           | ± 1% of full scale   |
| Zero drift         | ± 1% of full scale in 24 hrs.  |
| Span drift         | ±1% of full scale in 24 hrs.   |
| Repeatability      | ± 1% of full scale   |
| Power requirements | 115 VAC/60 Hz/1000 watts   |
| Range              | 1000/dilution ratio (AB-1, AB-2)<br>250/dilution ratio (AB-3)<br>100/dilution ratio (AB-4) |
| Output             | 4-20 ma  |
| Sensitivity        | 0.5 ppm or better  |

#### O<sub>2</sub> Analyzers

The O<sub>2</sub> analyzers was of the zirconium oxide in-situ type. Each analyzer had a 4-20 ma linear output which was fed to the SCR control system.

The following specifications applied:

|                                  |                          |
|----------------------------------|--------------------------|
| Maximum probe insertion diameter | 2.5"                     |
| Probe insertion length           | 3' or 1 meter            |
| Probe mounting                   | 4"/150#/4 bolt SS flange |
| Flue gas temperature             | 750 °F                   |
| Probe filter                     | ceramic                  |
| Probe material                   | 316 SS                   |
| Power requirement                | 115 VAC/60 Hz/300 VA     |
| Accuracy                         | ± 2% of reading          |
| Measurement range                | 0-21%                    |

#### CO<sub>2</sub> Analyzer

The CO<sub>2</sub> analyzer was of the single beam, non-dispersive infrared-type. The following specifications applied:

|                          |                      |
|--------------------------|----------------------|
| Accuracy                 | ±1% of full scale    |
| Noise                    | ± 1% of full scale   |
| Zero drift<br>scale/week | ± 2% of full         |
| Span drift<br>scale/week | ± 2% of full         |
| Response time to 90%     | 10 seconds           |
| Range                    | 0-20%/dilution ratio |
| Output                   | 4-20 ma              |
| Power requirements       | 115 VAC/60 Hz/250 W  |

#### CO Analyzer

The CO analyzer was of a single beam, non-dispersive, infrared-type, using a microflow detector to provide a reliable measurement of CO that was stable and interference free. It had a high degree of sensitivity and selectivity. The following specifications applied:

|                      |                           |
|----------------------|---------------------------|
| Noise                | Less than .5% full scale  |
| Zero drift           | ± 1% of full scale/day    |
| Span drift           | ± 1% of full scale/day    |
| Repeatability        | ± 1% of full scale        |
| Response time to 90% | 10 seconds                |
| Range                | 0-500 ppm /dilution ratio |
| Output               | 4-20 ma                   |
| Power requirements   | 115 VAC/60 Hz/250 W       |

### SO<sub>2</sub> Analyzer

The SO<sub>2</sub> analyzer used the ultraviolet spectrophotometric process to measure the SO<sub>2</sub> concentration, by comparing absorption between a measured wavelength passing through a gas sample and a reference wavelength. The output was linearly proportional to the concentration of the sample. The following specifications applied:

|                    |                           |
|--------------------|---------------------------|
| Noise              | Less than .5% full scale  |
| Accuracy           | ± 1% of full scale        |
| Zero drift         | ± 1% of full scale/day    |
| Span drift         | ± 1% of full scale/day    |
| Linearity          | 2% of full scale          |
| Range              | 0-2500 PPM/dilution ratio |
| Output             | 4-20 ma                   |
| Power requirements | 115 VAC/60 Hz/200 W       |

### Non-Routine Gas Analysis

Manual gas sampling for non-routine analysis of NH<sub>3</sub>, SO<sub>3</sub>, HCl, N<sub>2</sub>O and other gaseous component and particulates was conducted periodically, using the sample ports at various points along the reactor train. These analyses are discussed in detail in Section 5.0 of this report.

#### **2.3.3.9 Area 900: Control Room**

Area 900 was the control room for the SCR test facility. The control room contained the DCS control consoles. Two operator consoles were used, each consisting of two high resolution color CRTs and one keyboard. One engineer work station was also provided consisting of one color CRT and one keyboard, which could be used as an operator console when not engaged in its primary role.

A personal computer, with color monitor and keyboard, was used for data gathering and modem transmission. Two dot matrix printers were provided with the operator consoles for logs, reports, and CRT screen copies.

Behind the control room was the electronics room, which contained the DCS cabinets. These cabinets had top entry for all field wiring and bottom entry for all cross cabinet wiring. The cabinets contained all terminations, input/output cards, and microprocessors.

### **2.3.3.10 Area 1000: Utility Systems**

#### **2.3.3.10.1 Electric Service**

The electric service distribution system scope changed significantly from the original proposal. The original design was rather simple, and was based on using station service from Gulf Power Company (Gulf) through an existing 4160-volt switchgear as the main source feed and tie point for the entire SCR electrical station service. This source fed two transformers, with each transformer feeding a 600-volt motor control center (MCC). Each MCC had a distribution capability of five frames.

The scope for electrical station service loading increased substantially as facility design was finalized. The primary reasons for the scope changes were the growth of electrical demands for the test facility over original design, limitation of Plant Crist station service reserves (less than the required SCR test facility load), and the rearrangement of the Crist 115-KV bus. The scope changes follow.

1. The 600-volt system was replaced with a 480-volt, low voltage distribution system, which was state of the art, and stock or off the shelf equipment.
2. An entire 115-KV system was added. This system consisted of cable bus (4160-volt, 3000-amp), transformer (12/16/20 MVA), oil circuit breaker, 115-KV bus work at the tie in point, 4160V protective relaying, 115-KV disconnects, 7.5-KV disconnects, and 115-KV relaying.

3. A medium voltage 4160-volt distribution system was required consisting of 4 feeds, with 4 transformers and 4 MCCs, instead of the single 4160-volt tie in breaker described in the original design. Each of four 4160-volt switchgear breakers fed a 4160-volt/480-volt transformer, which in turn fed four 480-volt MCCs. One of the 480-volt MCCs fed three 225-KVA, 480V-208V/120V transformers, for 120/208V low voltage distribution.
4. Seven variable speed motors and controllers were added to the original design. In addition, the greater power loads increased the requirements for power and control cables, conduits, and cable trays.

The power consumed by the SCR test facility was metered, and Gulf was reimbursed for this power usage. A watt-hour meter was used at the 4.16-KV station service switchgear, grouping and metering the SCR facility's power consumption.

Proper isolation of the silicon control rectifiers, used with the duct heaters and adjustable speed drive systems, was incorporated into the station service design of the SCR project.

#### **2.3.3.10.2 Potable Water**

A 2-inch potable water line was installed to provide drinking and sanitary water to the project's control room. This line tied into the existing potable water line located along the turbine room crane rail.

#### **2.3.3.10.3 Service Water**

A service water pump with a capacity of 2200 gpm was installed in the basement of the Unit 4 turbine room. The water source for the pump was the Unit 4 and 5 circulating water tunnel. The water was strained prior to entering the pump and was then conveyed through an 8-inch diameter line to the test facility consumption points in the Unit 5 precipitator area.

#### **2.3.3.10.4 Steam**

A steam supply piping system was installed from the Unit 5 boiler to provide high temperature steam to the reactor sootblower systems. This system was designed according to established codes and consisted of isolation valves, steam control and pressure regulating valves, piping, hangers, and accessories.

#### **2.3.3.10.5 Fire Protection System**

The plant's existing fire protection system was extended to incorporate the addition of project equipment and improvements. The system was designed to meet the Southern electric system insurance requirements for personnel safety, property protection, and any additional U.S. Department of Energy requirements.

#### **2.3.3.10.6 Heating, Ventilation and Air Conditioning System**

Heating and air conditioning systems were installed in the project control room and gas analyzer building for equipment protection and operator comfort.

### **2.3.4 Initial Site Characterization**

#### **2.3.4.1 Particulate Concentrations**

Particle mass concentrations using EPA Method 17 were obtained as a function of position in the duct at three sampling locations: the inlet of the Unit 5 ESP, the outlet of the Unit 5 ESP, and the air heater inlet of Unit 6. A 12 point sample matrix was used at the Unit 5 ESP inlet, and a nine point sample matrix was used at the Unit 5 ESP outlet. For the Unit 6 air heater inlet, an eight point sample matrix was employed which was limited to the two existing ports. A 47 mm Gelman filter was used instead of the usual thimble filter for the inlet measurements. This change

in procedure was adopted to facilitate weighing of the relatively small mass increments which result from the single-point sampling measurements.

#### **2.3.4.2 Particle Size Distributions**

In-situ cascade impactors were used to obtain the average size distribution of suspended fly ash particles at each of the three sampling locations. The sampling matrix for the impactor measurements generally included more points and covered the duct more completely than did the mass measurements, but no effort was made to determine the variations in particle size distribution as a function of position in the duct.

Pre-conditioned glass fiber substrates were employed to minimize artifacts resulting from flue gas-substrate chemical reactions. Modified Brink impactors were used for the inlet sampling, and University of Washington (UW) Mark III impactors were used for the outlet sampling. The Brink impactors are relatively low-flow rate sampling devices which are suitable for sampling inlet locations. The sampling rate (about 0.03-0.04 acfm) allowed an average size distribution to be obtained over approximately a 10-minute sampling period with a multi-point traverse. In contrast, the UW instruments are relatively high flow rate devices (about 0.40 acfm) suitable for sampling the often very low mass concentrations which are encountered at control device outlets.

Both types of impactors sample at a constant flow rate during a given sampling period, under conditions that are isokinetic with respect to the average velocity over the sampling plane. This procedure is necessary because changing the flow rate through an impactor changes the cut-point of the stages; thus, constant-rate sampling is necessary to preserve the size-resolution capability of the impactor.

### **2.3.4.3 Chemical Species Concentrations**

Concentrations of NO, NO<sub>x</sub> and O<sub>2</sub> were obtained as a function of position at the three sampling locations. A Thermo-Electron Model 10 Chemiluminescence Analyzer was used for the NO and NO<sub>x</sub>, and a Teledyne Portable Oxygen Monitor was employed for the O<sub>2</sub> traverses.

### **2.3.4.4 Schedule**

The previously described measurements were performed at Plant Crist during the time period July 28 through August 7, 1990. Appendix B, Table 1 shows actual test conditions, locations, and sampling dates.

### **2.3.4.5 Results**

Tabular presentations of traverse data are contained in Appendix B, Table 1 through 15. Table 16 provides the duct static pressure for the dates, locations, and load conditions which encompass the test program.

Point-to-point and port-to-port variations in mass concentration, gas velocity, temperature, and key gas components were of particular interest to the pre-design test effort. Examination of the data in Tables 2 and 3 indicated relatively uniform gas velocities and temperatures across the Unit 5 ESP inlet sampling plane, with coefficients of variation of 1% or less (based on the Fahrenheit scale) for the temperatures, and of 8% or less for the gas velocities.

The mass loadings exhibited a somewhat greater point-to-point variation with coefficients of variation ranging from 8% to 16%. However, the mass loadings were still considered to be relatively uniform. Relatively uniform NO and NO<sub>x</sub> profiles are also indicated by the data in Tables 4 and 5.

In contrast to the relatively uniform profiles found for the Unit 5 ESP inlet, large mass concentration and velocity profile differences were found at the Unit 6 ESP sampling locations, as indicated by the data in Tables 6 and 7. These profile variations would have complicated the task of obtaining a representative slipstream sample. Table 8 indicates that significant O<sub>2</sub> increases and NO<sub>x</sub> decreases are apparent as the traverse proceeds from point 1 to point 4, but this pattern is not apparent in the low-load data contained in Table 9.

Since a flue gas stream with a low-dust concentration was required for a portion of the demonstration project, the test program included sampling at the outlet of the Unit 5 hot-side ESP. Mass loadings obtained at this location under high load conditions are presented in Table 10. These mass concentrations are consistently low, and the average (0.0034 gr/acf at 4.65% O<sub>2</sub> and 613 °F) would correspond to a particulate emission rate of only 0.0095 pounds per million BTU. The mass train results were confirmed by the impactors, which averaged a total mass loading of only 0.0024 gr/acf. In view of the low mass concentrations, the point-to-point variations and the differences between mass train and impactor data are not considered to be excessive.

Oxygen, NO<sub>x</sub>, and NO profiles for the Unit 5 outlet location are presented in Tables 11, 12, and 13. The relatively small differences between NO and NO<sub>x</sub> values appear anomalous, and may indicate a problem with the measuring system. Temperature and gas velocity distribution profiles for this location are presented in Tables 14 and 15.

Table 16 contains duct static pressures obtained at the various sampling locations during the test program. The largest negative pressure readings were obtained at the Unit 5 outlet sampling location under high load conditions.

Since the particle size distribution of the fly ash was a significant factor in catalyst performance during the demonstration project, it is appropriate to compare the Unit 5 and Unit 6 size distribution data to similar data obtained at other plants burning a bituminous coal. The following tabulation compares data obtained under the current project at high load with a typical plant from

the EPRI data base (J.L. DuBard, R.S. Dahlin. Precipitator Performance Estimation Procedure. Electric Power Research Institute. EPRI CS-5040. February 1987.)

Table 2.3-14 Fly-Ash Particle Size Comparison

| Size Band<br>(microns) | EPRI-SRI DATA |           | SCS-SRI DATA |             |
|------------------------|---------------|-----------|--------------|-------------|
|                        | Mean          | 50% Conf. | Unit 5 Mean  | Unit 6 Mean |
| <1                     | 1.28          | 1.02-1.54 | 1.2          | 1.3         |
| <2                     | 4.32          | 3.52-5.12 | 3.5          | 5.2         |
| <5                     | 17.6          | 13.9-21.3 | 15.5         | 21.0        |
| <10                    | 35.4          | 27.0-43.8 | 30.0         | 38.6        |

This comparison indicated that the Crist size distribution data were generally typical of those that have been measured at other utility power boilers firing pulverized bituminous coal.

In conclusion, the data indicate that the inlet location tested at Plant Crist Unit 5 was suitable for providing a representative fly ash sample for the SCR project. In contrast to this location, the Unit 6 was characterized by unstable flow conditions and large particle concentration and gas velocity variations with position. The Unit 5 outlet profiles were relatively uniform, but the particle concentration was quite low and was unrepresentative of the outlet from many hot-side ESP's. As a result, the original concept of being able to take slip streams of gas from either Units 5 or 6 for the SCR facility was cancelled and only a slip stream from Unit 5 was used.

### **3.0 TEST PROGRAM**

#### **3.1 SRI Test Plan**

The proposed SRI test plan is contained in Appendix C. This test plan contains a description of sampling and analytical methods, a technical testing plan, and other sections related to the management and organization of the testing. This test plan can be organized into several main sections which are described below.

##### **3.1.1 Start-up and Commissioning Tests**

The start-up and commissioning of the test facility was of extreme importance to the overall success of the project. Tests were designed to insure that each reactor had a representative slip stream from the host unit. These tests were designed to show that parameters such as ash loading, flue gas flow, flue gas constituents, etc., were comparable between the reactors and were representative of the host unit flue gas parameters. These tests were divided into three main tasks as follows in Table 3.1-1. The start-up and commissioning of the SCR Test facility were scheduled for a 15 week period. Tasks 1, 2, and 3 were performed during the commissioning exercises.

Table 3.1-1 Start-up and Commissioning Tests

|   |
|---|
| <b>Task 1: Commissioning Without Catalyst and Ammonia</b>   |
| Calibrate Flow Control Venturis   |
| Verify Gas Sampling System  |
| High Load Tests   |
| Measure Mass Concentration & Collect Ash Samples  |
| Collect Trace Metal Samples   |
| Measure Concentrations of O <sub>2</sub> , NO, N <sub>2</sub> O, HCl, NH <sub>3</sub> , SO <sub>3</sub> |
| Measure SO <sub>2</sub> & SO <sub>3</sub> Concentrations at Reactor Heaters                             |
| Analyze Ash Samples and Trace Metals Samples  |
| Low Load Tests  |
| Measure Mass Concentration & Collect Ash Samples  |
| Collect Trace Metal Samples   |
| Measure Concentrations of O <sub>2</sub> , NO, N <sub>2</sub> O, HCl, NH <sub>3</sub> , SO <sub>3</sub> |
| Measure SO <sub>2</sub> & SO <sub>3</sub> Concentrations at Reactor Heaters                             |
| Analyze Ash Samples and Trace Metals Samples  |
| Complete Verification of Gas Sampling System  |
| Complete Any Tests From Weeks 1, 2, 3   |
| <b>Task 2: Commissioning Without Catalyst &amp; With Ammonia</b>  |
| Monitor Ammonia Oxidation   |
| Verify Ammonia Flow Control and Ammonia Mass Balance  |
| Determine Gas Sampling System Equilibrium Times   |
| <b>Task 3A: Commissioning With Catalyst &amp; Without Ammonia</b>                                       |
| Measure SO <sub>2</sub> /SO <sub>3</sub> Conversion Rates   |
| <b>Task 3B: Commissioning With Catalyst and Ammonia</b>   |
| Measure Velocity, NO <sub>x</sub> , and NH <sub>3</sub> at Reactor Outlets                              |
| Collect Ash Samples at Reactor Outlets  |
| Preliminary Parametric Test Sequence  |

### **3.1.1.1 TASK 1 - Commissioning Without Catalyst and Without Ammonia Injection**

The objectives of Task 1 were to measure the performance of the flue gas extraction system, to define the base-line physical and chemical properties of the flue gas at various points in the test facility ducting, and to confirm the accuracy of the flue gas continuous monitoring system. The three full-time on-site SRI personnel were augmented by an SRI field testing crew for Task 1 testing. The temporary crew was primarily engaged in particulate sampling and analysis while the resident crew was engaged in gaseous sampling and analysis. This task required 23 weeks to complete. The details of this work are provided below.

#### Calibrations and Verifications

- A. The flow control venturis for each of the nine reactors were calibrated by measuring gas velocity (pitot traverses), temperature, and static pressure at three flow rates; minimum, design, and maximum, 3000, 5000, and 7500 scfm for the large reactors and 240, 400, and 600 scfm for the small reactors. This work was carried out by the field testing crew. Because it was necessary to repeat several calibrations due to operational problems, three weeks were needed to complete this work. In addition to the initial calibrations, all flow rates were rechecked after one month. Since several calibrations had drifted, a schedule of monthly calibrations was adopted.
- B. The SRI on-site crew assisted in the verification of the gas sampling system. This included characterization of flue gas composition ( $O_2$ , CO,  $CO_2$ ,  $NO_x$ ,  $N_2O$ ,  $SO_2$ ) at selected gas sampling points. The following methods were used:

$O_2$  - Teledyne Oxygen Analyzer

CO - Fyrite analyzer

$CO_2$  - Fyrite analyzer

$NO_x$  - Portable ThermoElectron Chemiluminescence Monitor

$SO_2$  -  $H_2O_2$  bubbler, Ion Chromatography

$N_2O$  - Gas Chromatography

### High Boiler Load

A. While the Unit 5 boiler was at stable high-load operation, particulate mass concentration and particle size distribution were measured at eleven locations in the test facility and Unit 5 ducts. These locations were:

- 1) Unit 5 Hot-Side ESP Inlet Duct (source of high-dust stream)
- 2) Unit 5 Hot-Side ESP Outlet Duct (source of low-dust stream)
- 3) Each of the Nine Reactor Inlets

The high load mass concentration at each sampling point was determined for two, consecutively-run, EPA Method 17 mass trains.

- B. The particle size distribution of the combined mass train catches for each pair of mass train runs was determined in SRI's Birmingham laboratory using a Shimadzu particle sizing device. Quality assurance for this laboratory work was provided by a pair of consecutive cascade impactors and a pair of consecutive six-stage series cyclones run at the Unit 5 hot-side ESP inlet duct (the source of the high-dust stream) to verify the Shimadzu particle size distributions.
- C. The combined mass train catches for the pair of Method 17 runs at the Unit 5 hot-side ESP inlet duct (the source of the high-side stream) were subjected to an ash mineral analysis.
- D. The high-load base-line trace metals profile of the test facility was documented using modified Method 29 (EPA) metals trains. The metals trains were run at the high-mass extraction scoop (Unit 5 hot-side ESP outlet duct), at the inlet to one of the large reactors, and at the inlet to the low-dust small reactor. The high-load trace metals profile required four sampling runs and the analysis of four samples.
- E. The fly ash samples collected with the six-stage series cyclone sampling train at the Unit 5 ESP inlet duct were subjected to a size-specific mineral and trace metals analysis (ICAP).
- F. High-load base-line concentrations of HCl, NH<sub>3</sub>, SO<sub>2</sub>/SO<sub>3</sub>, NO, N<sub>2</sub>O, and O<sub>2</sub> were measured in the two main ducts at the extraction points: the unit 5 hot-side ESP inlet and outlet ducts. Three samples were collected at each location for each species. O<sub>2</sub> was measured using a portable Teledyne O<sub>2</sub> analyzer. NO was measured using a portable NO<sub>x</sub> analyzer and grab samples of flue gas were analyzed by gas chromatography. The determinations of HCl, NH<sub>3</sub>, and SO<sub>2</sub>/SO<sub>3</sub> required manual sampling methods and subsequent laboratory analysis of individual samples.

- G. Concentrations of SO<sub>2</sub> and SO<sub>3</sub> were measured simultaneously in one of the large reactors before and after the reactor heater and at the reactor outlet. Identical SO<sub>2</sub>/SO<sub>3</sub> measurements were made for one of the small reactors. Two samples were collected at each sampling site (twelve in all). Additional testing on other reactors was performed to confirm the results of the initial tests.
- H. Laboratory analysis of particulate samples and trace metals samples was conducted at the SRI Birmingham laboratory.

#### Low Boiler Load

- A. While the Unit 5 boiler was at stable low-load operation, particulate mass concentration and particle size distribution were measured at twelve locations in the test facility and Unit 5 ducts. These locations were:
- 1) Unit 5 Hot-Side ESP Inlet Duct (source of high-dust stream)
  - 2) Unit 5 Hot-side ESP Outlet Duct (source of low-dust stream)
  - 3) The Economizer Bypass Duct
  - 4) Each of the Nine Reactor Inlets

The low-load mass concentration at each sampling point was determined for two, consecutively-run, EPA Method 17 mass trains.

- B. The particle size distribution of the combined mass train catches for each pair of Method 17 runs was determined in SRI's Birmingham laboratory using a Shimadzu particle sizing device. Quality assurance for this laboratory work was provided by a pair of consecutive cascade impactors and a pair of consecutive six-stage series cyclones run at the Unit 5 hot-side ESP inlet duct (the source of the high-dust stream) to verify the Shimadzu particle size distributions.
- C. The combined mass train catches for the pair of Method 17 runs at the Unit 5 hot-side ESP inlet duct (the source of the high-dust stream) were subjected to an ash mineral analysis.
- D. The low-load base-line trace metals profile of the test facility was documented using modified Method 29 (EPA) metals trains. The metals trains were run at the high-mass extraction scoop (Unit 5 hot-side ESP inlet duct), at the low-mass extraction scoop (Unit 5 hot-side ESP outlet duct), at the economizer bypass duct, at the inlet to one of the large reactors, and at the inlet to the low dust small reactor.

- E. The fly ash samples collected with the six-stage series cyclone sampling train at the Unit 5 ESP inlet duct were subjected to a size-specific mineral and trace metals analysis (ICAP).
- F. Low-load base-line concentrations of HCl, NH<sub>3</sub>, SO<sub>2</sub>/SO<sub>3</sub>, NO, N<sub>2</sub>O, and O<sub>2</sub> were measured at two locations: after the point at which the economizer bypass mixes with the flue gas from the hot-side ESP inlet and at the hot-side ESP outlet duct. Three measurements of each species were made at each location. O<sub>2</sub> was measured using a portable Teledyne O<sub>2</sub> analyzer. NO was measured using a portable NO<sub>x</sub> analyzer and N<sub>2</sub>O was measured by extracting a grab sample of flue gas which was analyzed by gas chromatography. The determinations of HCl, NH<sub>3</sub>, and SO<sub>2</sub>/SO<sub>3</sub> required manual sampling methods and subsequent laboratory analysis of individual samples.
- G. Concentrations of SO<sub>2</sub> and SO<sub>3</sub> were measured simultaneously in one of the large reactors before and after the reactor heater and at the reactor outlet. Identical SO<sub>2</sub>/SO<sub>3</sub> measurements were made for one of the small reactors. Two samples were collected at each sampling site. Additional testing on other reactors was performed to confirm the results of these tests.
- H. Laboratory analysis of particulate samples and trace metals samples began at the SRI Birmingham laboratory. These analyses were completed prior to the beginning of Task 3 (commissioning with catalyst).

#### **3.1.1.2 TASK 2 - Commissioning Without Catalyst and With Ammonia Injection**

The objective of task 2 was to verify ammonia flow control, establish the ammonia mass balance, and to measure ammonia oxidation across the reactors prior to loading catalyst into the reactors. Seven personnel were needed to complete this task. The mass flow rate of ammonia into each of the nine reactors was determined, the ammonia mass balance for the system was verified, and the distribution of ammonia across each reactor inlet cross section was measured. Ammonia oxidation at four combinations of flue gas flow rate and temperature was measured on one large reactor and on one small reactor. Task 2 testing and analysis required approximately six weeks to complete. The details of this work are provided below.

## NH<sub>3</sub> Distribution and Mass Balance

A. Ammonia oxidation was profiled at an approximate NH<sub>3</sub>/NO<sub>x</sub> injection ratio of 1.0 (held at constant injection rate) for two typical reactor streams; one through a large reactor and one through a small reactor. The profile was constructed from samples at these conditions:

- 1) High Temperature (750 °F), Low Flow Rate (3000 or 240 scfm)
- 2) High Temperature (750 °F), High Flow Rate (7500 or 600 scfm)
- 3) Low Temperature (620 °F), Low Flow Rate (3000 or 240 scfm)
- 4) Low Temperature (620 °F), High Flow Rate (7500 or 600 scfm)

This testing required simultaneous sampling for NH<sub>3</sub> at the inlet and the outlet of each of the two reactors at each of the above combinations of temperature and flow rate.

B. Verification of ammonia flow control and confirmation of ammonia mass balance were monitored by measuring ammonia in the gas phase and on particulate at the inlet and outlet of each of the nine reactors. Measurements were conducted at nine points at the inlet and outlet cross sections of each of the large reactors at an NH<sub>3</sub>/NO<sub>x</sub> ratio of 1.0. Due to constraints imposed by the physical size of the small reactors, only four points were measured.

### 3.1.1.3 TASK 3 - Commissioning with Catalyst, without Ammonia Injection and with Ammonia Injection

Under Task 3, SRI measured the conversion rate of SO<sub>2</sub> to SO<sub>3</sub> across each reactor with catalysts installed with ammonia injection, collected isokinetic ash samples at the outlet of each reactor under two operating conditions (with catalyst and ammonia), measured the velocity distribution, NO<sub>x</sub> concentration and NH<sub>3</sub> distribution across each reactor outlet cross section at a single operating condition (with catalyst and ammonia), and performed a preliminary (first) parametric test sequence (with catalyst and ammonia). Each of these measurements is described in more detail below. Task 3 required 23 weeks to complete.

#### **3.1.1.3.1 TASK 3A Commissioning With Catalyst and Without Ammonia Injection**

The planned objective of Task 3A was to characterize the  $\text{SO}_2/\text{SO}_3$  conversion across each of the nine reactors with catalyst, but without ammonia injection. However, to expedite completion of Task 3 and to provide data more relevant to full-scale SCR operation, these tests were combined with Task 3B and were performed with ammonia injection. To fully characterize conversion over the range of temperatures and flow rates anticipated during parametric testing,  $\text{SO}_2$  and  $\text{SO}_3$  concentrations were measured at the inlet and outlet of each reactor at nine conditions; three flow rates (design, minimum, and maximum), and three temperatures (620 °F, 700 °F, and 750 °F). The characterization of  $\text{SO}_2/\text{SO}_3$  conversion for each reactor (each with a different catalyst) required simultaneous inlet/outlet  $\text{SO}_2/\text{SO}_3$  runs at each of the nine combinations of temperature and flow rate. Triplicate runs were made to provide statistical validity. This subtask required five weeks for completion.

#### **3.1.1.3.2 TASK 3B Commissioning With Catalyst and With Ammonia Injection: [Preliminary Parametric Test Sequence]**

The commissioning activities under Task 3B were centered around a preliminary parametric test sequence that was performed after the catalysts were installed in the reactors and with ammonia injection. The matrix of flue gas temperatures, flow rates, and  $\text{NH}_3/\text{NO}_x$  ratios for this testing is shown in Table 3.1-2.

Table 3.1-2 SCR Reactor Preliminary Parametric Test Sequence

| Test Parameters |        |         |       |                                     |  | Special Measurements   |                        |
|-----------------|--------|---------|-------|-------------------------------------|--|------------------------|------------------------|
| Day             | Test # | Temp. F | Rank* | Flow rate SV, fraction of base case | NH <sub>3</sub> /NO <sub>x</sub> Ratio | NH <sub>3</sub> Outlet | SO <sub>3</sub> Outlet |
| 1               | 3      | 700     | A     | 1.5                                 | 0.8                                    | X                      |                        |
| 1               | 4**    | 700     | A     | 1                                   | 0.8                                    | X                      | X                      |
| 1               | 5      | 700     | A     | 1                                   | 0.9                                    | X                      |                        |
| 1               | 6      | 700     | A     | 1.5                                 | 0.9                                    | X                      |                        |
| 1               | 7      | 700     | A     | 1.5                                 | 1                                      | X                      |                        |
| 1               | 8      | 700     | A     | 1                                   | 1                                      | X                      |                        |
| 2               | 12     | 750     | A     | 1.5                                 | 0.8                                    | X                      | X                      |
| 2               | 13     | 750     | A     | 1                                   | 0.8                                    | X                      |                        |
| 2               | 15     | 750     | A     | 1                                   | 0.9                                    | X                      |                        |
| 2               | 17     | 750     | A     | 0.6                                 | 1                                      | X                      | X                      |
| 2               | 18     | 750     | A     | 1.5                                 | 1                                      | X                      | X                      |
| 3               | 22     | 620     | A     | 0.6                                 | 0.8                                    | X                      | X                      |
| 3               | 23     | 620     | A     | 1.5                                 | 0.8                                    | X                      | X                      |
| 3               | 24     | 620     | A     | 1                                   | 0.9                                    | X                      |                        |
| 3               | 25     | 620     | A     | 1                                   | 1                                      | X                      |                        |
| 3               | 26     | 620     | A     | 0.6                                 | 1                                      | X                      | X                      |

\* Rank: A, first tier of tests, considered most important.

\*\* This test included tests at the reactor outlet for HCl and particulate concentration.

### 3.1.2 Parametric Tests

Five sequences of parametric tests were performed on each of the catalysts during the project life. The SRI test plan describes the proposed first (preliminary) test sequence and was shown in Section 3.1.1.3.2. In practice, this proposed test sequence was modified slightly as more was learned about the test facility operational limitations and about manual testing limitations. Section 5.3 contains both graphical and tabular representations of the tests that were performed during all five of the parametric test sequences. In general, the parametric tests were designed to examine ammonia slip, deNO<sub>x</sub> efficiency (intermediate ammonia), SO<sub>2</sub> oxidation, N<sub>2</sub>O formation, NO<sub>x</sub> and ammonia distributions,

fly ash composition and loading, velocity distributions, and particulate distribution at varying conditions. The general parametric condition ranges and long-term base-line conditions follow in Table 3.1-2 .

Table 3.1-2 General Base-line and Parametric Conditions

| Parameter                                    | Minimum | Base-line | Maximum |
|--|---------|-----------|---------|
| Temperature, (°F)                            | 620     | 700       | 750     |
| NH <sub>3</sub> /NO <sub>x</sub> molar ratio | 0.6     | 0.8       | 1.0     |
| Space velocity, (% of design flow)           | 60      | 100       | 150     |
| Flow rate, (scfm)                            |         |           |         |
| -large reactor                               | 3000    | 5000      | 7500    |
| -small reactor                               | 240     | 400       | 600     |

### 3.1.2.1 Ammonia Measurement

The measurement of ammonia (both intermediate and slip) and SO<sub>2</sub> oxidation are of primary importance in evaluating the performance of SCR catalysts. Ammonia slip is an excellent indicator of overall reactor performance (assuming deNO<sub>x</sub> rate is held constant). Ammonia slip measurements indicate the “health” of the entire reactor system including catalyst activity, ammonia and NO<sub>x</sub> distribution, velocity distribution, etc. Slip measurements were used throughout the test program as an indicator of reactor performance. Intermediate ammonia measurements were also used as a measure of reactor performance. In particular, intermediate ammonia measurements are more apt to indicate the performance of a particular catalyst than the reactor as a whole. Decline in catalyst activity is likely to be noted using intermediate ammonia measurements prior to it being noted using slip measurements. The response of a particular catalyst to changes in parametric operating conditions is an important aspect of the testing, allowing predictions to be made as to catalyst performance for varying conditions in full-scale installations.

### **3.1.2.2 SO<sub>2</sub> Oxidation Measurements**

Another important reactivity characteristic of SCR catalysts, in addition to NO<sub>x</sub> reduction activity, is their propensity to oxidize sulfur dioxide. This is an important aspect of SCR catalyst, since increased SO<sub>3</sub> can exacerbate problems with equipment downstream of the SCR due to increased formation of acidic deposits. SO<sub>2</sub> oxidation is normally considered to be a first order reaction. Thus, in the absence of mass transfer limitations, SO<sub>2</sub> oxidation should have a nearly linear relationship to reactor flow rate and an exponential relationship to temperature. SO<sub>2</sub> oxidation is normally considered to be constant with exposure time, based on catalyst supplier historical experience.

The SO<sub>2</sub> oxidation potential of the catalyst is normally determined by examining the SO<sub>3</sub> concentration at the inlet and outlet of the reactor to evaluate the amount of SO<sub>2</sub> that is oxidized to SO<sub>3</sub>. SO<sub>3</sub> oxidation is normally quoted as percent of inlet SO<sub>2</sub> oxidized to SO<sub>3</sub>. In practice, the SO<sub>2</sub> oxidation rates for most catalysts under most conditions is less than 1%. Thus, the SO<sub>2</sub> concentration, inlet to outlet, remains relatively constant.

### **3.1.2.3 N<sub>2</sub>O Formation**

The possible formation of N<sub>2</sub>O across SCR reactors was a concern with early SCR experience in the U.S. Subsequent investigations of the problem revealed that this was a sampling/analysis anomaly rather than the true formation of N<sub>2</sub>O across SCR catalysts. Measurements at the test facility have included evaluation of N<sub>2</sub>O concentrations to further confirm this finding. Relatively few N<sub>2</sub>O measurements were performed during the project. The majority of these were performed at base-line conditions.

### **3.1.2.4 Ammonia to NO<sub>x</sub> Distribution**

A balanced NH<sub>3</sub>/NO<sub>x</sub> distribution within an SCR reactor is critical to its efficient operation. Maldistribution of either component can create areas within the reactor where

the local  $\text{NH}_3/\text{NO}_x$  ratio is very high or low. This leads to an increase in overall ammonia slip from the reactor and a reduction in  $\text{deNO}_x$  efficiency. Reactor design criteria are set to minimize this problem. In the pilot facility, design criteria are primarily set to maintain a smooth distribution of both ammonia and  $\text{NO}_x$  resulting in an even  $\text{NH}_3/\text{NO}_x$  ratio across the reactor. In full scale installations, the ammonia injection grid is tuneable, thus allowing ammonia to be injected in a profile which matches the  $\text{NO}_x$  profile, thereby creating a smooth  $\text{NH}_3/\text{NO}_x$  ratio distribution across the reactor. Tests were performed during the project to evaluate both the  $\text{NO}_x$  distribution and the ammonia distribution within the SCR reactors.

#### **3.1.2.5 Fly Ash Composition and Loading**

The evaluation of potential catalyst poisons in U.S. coals is an important goal of this project. One method of tracking this is to evaluate fly ash composition. These tests were performed several times during the project life to track the relative concentrations of trace and primary constituents of the fly ash. Because some species tend to show "enrichment" with particle size variations, samples for fly ash composition tests are normally acquired isokinetically. In addition to fly ash composition, fly ash loading is an important measurement because it indicates the quantity of ash present in the flue gas stream. Loading is important in determining catalyst erosion rates and was particularly important in this project in determining comparability between reactors.

#### **3.1.2.6 Velocity and Particulate Distributions**

The flue gas velocity distribution within an SCR unit is important for several reasons. First, severe maldistributions in velocity make tuning of ammonia injection difficult, because the flue gas velocity maldistributions have the same effect as  $\text{NO}_x$  maldistributions. Further exacerbating the problem is the fact that velocity maldistributions are often strong functions of reactor flow rate. Thus, unit load changes would require constant adjustment to the ammonia tuning grid when velocity

maldistributions are present. Another concern with velocity maldistributions is the possible erosion impact on the SCR catalyst. Localized high velocities can cause premature catalyst erosion in some areas of the catalyst, thereby reducing the overall life of the catalyst installation. Velocity distribution measurements were conducted during the majority of the parametric sequences. These tests proved to be extremely valuable in determining the physical condition of the catalyst in terms of erosion and fouling.

Particulate distributions are also an important parameter in SCR units primarily for the potential erosion problems that can occur with particulate maldistributions. Localized high particulate concentrations can accelerate erosion in particulate areas, similar to localized high velocities. This increased localized erosion can reduce the overall life of the catalyst installation. Several particulate distribution measurements were made throughout the life of the project to insure that each catalyst was being operated under appropriate conditions.

### **3.1.3 Long Term Tests**

When not undergoing parametric tests, each reactor was returned to its base-line operating condition for long-term performance evaluation. These long-term tests were designed to track parameters such as pressure drop, catalyst erosion, and catalyst deactivation over the life of the project. Problems associated with these parameters tend to be chronic and may require several years of operation before they become evident. Pressure drop across the reactors was measured on a continuous basis and is presented in Section 5.2.3. Catalyst erosion was primarily evaluated by periodic visual inspections and by analyses of samples acquired quarterly and tested by the respective catalyst suppliers. Long-term catalyst deactivation was also measured in the laboratory by the catalyst suppliers. A more detailed discussion of the catalyst supplier's testing is presented in Section 3.3 and results of these tests are presented in Section 5.6.

### 3.2 Air Heater Evaluation

An evaluation of air preheaters operating in conjunction with SCR technology was made, using the three large reactors at the test facility. The three air heater designs (two-layer and three-layer Ljungstrom<sup>®</sup>, and heat pipe) were evaluated, using manual tests conducted during the parametric test sequences, long-term tests, and evaluations made by the air preheater supplier (ABB) utilizing laboratory analyses of sample deposits, baskets, washwater, and by visual inspections. Appendix C, which is the proposed SRI test plan, describes many of the manual tests that were performed on the air preheaters during the parametric test sequences by SRI.

Table 3.2-1 offers a synopsis of the originally proposed tests that were to be performed and Section 5.5 presents the actual tests that were performed and their results. In practice, tests varied from those originally proposed, due to scheduling requirements and refinements in testing requirements as the project progressed.

The original design of the test facility included bypass heat exchangers which were designed to cool the flue gas in substitute of the air preheaters. These bypass heat exchangers were to be placed in service whenever parametric tests were being run on their respective reactors. Thus, the air preheaters would only be operated at base-line condition. Cooling of the flue gas was necessary to protect the large reactor fans which were located just downstream of the air preheaters and bypass heat exchangers. Shortly after start-up, however, severe fouling prevented the continued operation of these heat exchangers. Thus, the test program was conducted with each air preheater in service at all times that the respective reactors were in service. Consequently, the air preheaters were exposed to all parametric operating conditions performed on their respective reactors.

Table 3.2-1 Original Proposed Air Heater Test Schedule

| Measured Parameter     | Measurement Location | Number of Measurements per Air Heater | Measurement Frequency |
|------------------------|----------------------|---------------------------------------|-----------------------|
| NH <sub>3</sub> (ppm)  | AH Inlet             | 1                                     | Quarterly             |
| NH <sub>3</sub> (ppm)  | AH Inlet             | 1                                     | Quarterly             |
| SO <sub>3</sub> (ppm)  | Reactor Inlet        | 1                                     | Quarterly             |
| SO <sub>3</sub> (ppm)  | AH Inlet             | 1                                     | Quarterly             |
| SO <sub>3</sub> (ppm)  | AH Outlet            | 1                                     | Quarterly             |
| HCl (ppm)              | AH Inlet             | 1                                     | Monthly               |
| Ash Concentration      | Manifold             | *                                     | Semi-Annual           |
| Ash Composition        | Manifold             | *                                     | Monthly               |
| Ash Particle           | Manifold             | *                                     | Semi-Annual           |
| Ash Concentration      | AH Inlet             | 1                                     | Semi-Annual           |
| Ash Composition        | AH Inlet             | 1                                     | Monthly               |
| Ash Particle Size      | AH Inlet             | 1                                     | Semi-Annual           |
| Ash Concentration      | AH Outlet            | 1                                     | Quarterly             |
| Ash Composition        | AH Outlet            | 1                                     | Quarterly             |
| Flue Gas Flow rate     | AH Inlet             | 1                                     | Monthly               |
| AH Basket Analysis     |                      |                                       |                       |
| Corrosion Rate         | Air Heater           | 1                                     | Quarterly             |
| Weight Loss            | Air Heater           | 1                                     | Quarterly             |
| Metallographic Exam    | Air Heater           | 1                                     | Quarterly             |
| Deposit Composition    | Air Heater           | 1                                     | Quarterly             |
| Morphology             | Air Heater           | 1                                     | Quarterly             |
| AH Wash Water Analysis |                      |                                       |                       |
| Total Suspended Solids | Air Heater           | 1                                     | Quarterly             |
| Total Dissolved Solids | Air Heater           | 1                                     | Quarterly             |
| pH, Chlorides          | Air Heater           | 1                                     | Quarterly             |
| Trace Metals           | Air Heater           | 1                                     | Quarterly             |

\*These tests in ducting prior to split to the three large SCR reactors.

### 3.3 Catalyst Supplier Laboratory Tests

A series of tests were devised to be performed by the catalyst suppliers on catalyst samples removed from the reactors on a quarterly basis. These tests were performed by the catalyst suppliers at their respective internal testing laboratories and reported directly to SCS. A sample laboratory testing protocol is contained in Appendix D. Conditions and test methods varied slightly with individual catalyst supplier. The laboratory tests

were designed to track deNO<sub>x</sub> activity and SO<sub>2</sub> oxidation activity as a function of time. Also included in the test protocol were physical and chemical characteristics of the catalysts. The following table offers an overview of some of the tests performed. The table is divided into three levels of priority depending on the expected technical value of the test performed. Many tests are proprietary, and cannot be reported. Non-proprietary information is presented in Section 5.6.

Table 3.2-2 Tests Performed by Catalyst Suppliers

| First Priority           | Second Priority                      | Third Priority                  |
|--------------------------|--------------------------------------|---------------------------------|
| Specific Surface Area    | Acidity of Active Sites by Titration | Erosion Resistance              |
| Pore Volume Distribution | Chemisorption of NH <sub>3</sub>     | Oxidation State of Active Sites |
| Crystal Structure        | Crystallite Site                     | Migration of Active Metal       |
| Density                  |                                      |                                 |
| Mechanical Strength      |                                      |                                 |

### 3.4 Coal Testing

One of the primary purposes of this project was to evaluate the performance of SCR technology on U.S. coals. To insure that an adequate database of coal composition was generated, daily "as burned" coal samples were acquired from the host boiler. Monthly composites were then used to carefully track both primary and trace coal constituents. Where possible, instrumental neutron activation analysis (INAA) was used to augment other measurement techniques. A data synopsis is presented in Section 5.7 and a detailed data presentation is given in Appendix E.

#### 3.4.1 Coal Supply

The coal supply during the SCR Demonstration project at Plant Crist Unit 5 consisted of eastern bituminous coals with sulfur contents greater than or equal to 2.5%. When the coal monitoring began (March 1993), Peabody coal having 2.9% sulfur content was being burned. In September 1993, however, a coal miners' strike and buy-out of the Peabody contract caused a change in coal supply. During September and October, Kerr-McGee

and Taft coals were purchased. The Kerr-McGee coal was a blend of Illinois #5 and #6 mines while the Taft coal was from Walker and Jefferson counties in Alabama. For November and December, coal from the Illinois basin in Western Kentucky was purchased from Jader to be burned. All of these coals had a sulfur content of approximately 2.5%.

In January 1994, a new contract was set up to purchase high sulfur coal (2.7% sulfur) for Unit 5 from Old Ben Franklin and Kerr-McGee coal companies. The Old Ben coal from the Illinois #6 mine and Kerr-McGee from the Herrin #6 mine continued to be the source of coal throughout the remainder of this project.

### **3.4.2 Samples**

In order to monitor the quality of coal being burned throughout the project, daily, monthly, and quarterly samples were taken. A brief description of each sample type is included here.

Grab samples were collected hourly from the four scales at Unit 5 by the plant personnel. These samples were then combined and split into three equivalent "daily composite" splits. At the end of the month, four "monthly as burned" composites were formed by combining one set of the daily samples and riffing down to four equivalent 1000-gram samples. One bag was stored on-site while the other three were sent to Southern Company Services in Birmingham. From there, one bag was sent to the Alabama Power General Services Laboratory, the second was used to make a quarterly composite, and the third was stored at a SCS storage facility in Birmingham along with the second set of the daily "as burned" samples. The final set of daily samples was kept at the plant for 60 days for back-up. Quarterly composites were prepared from monthly composites to be analyzed by the University of Missouri - Columbia Research Reactor Center.

### **3.4.3 Analytical Methods**

Certain volatile trace elements found in coal are known to be potential catalyst poisons. These poisons react with the catalyst and deactivate the NO<sub>x</sub> reaction site. Because of this potential reaction, trace element concentrations must be monitored when evaluating catalysts for the removal of nitrogen oxides from the flue gas.

Each monthly composite sent to the Alabama Power General Services Laboratory was analyzed for approximately twenty trace elements. All analyses were performed according to standard methods for coal from ASTM. In addition to trace elements, the APC lab also performed the following analyses on monthly composites: short prox (moisture, ash, Btu, and sulfur), volatiles/fixed carbon, carbon, hydrogen, nitrogen, oxygen, chlorine, and fluorine.

Trace element concentrations of quarterly composites were determined by the University of Missouri - Columbia Research Reactor Center using Instrumental Neutron Activation Analysis. This method utilizes neutrons to make trace elements radioactive and quantifiable. INAA provides 36 trace element analyses (18 additional elements to APC). Several of these such as rubidium, strontium, molybdenum, antimony, and cesium are considered potential catalyst poisons. However, INAA does not include cadmium and lead and has poor sensitivity for nickel and strontium.

### **3.5 Waste Stream Impacts**

A concern associated with the implementation of SCR technology is the effect that it may have on plant waste streams. This is thought to be primarily due to the adsorption of slip ammonia on fly ash. A special study was conducted to examine the effects of ammonia concentration on the rate of ammonia volatilization, ammonia extraction, and metals extraction from fly ash. The results of this study are presented in Section 5.8.

### 3.6 Miscellaneous Other Tests

Several additional tests were performed during the course of the project. These included toxicity characteristics leaching procedure (TCLP) analysis of fly ash, fly ash resistivity measurements, and gas/solid phase ammonia partitioning. These miscellaneous tests were designed to insure the applicability of SCR to U.S. boilers. TCLP analyses were performed to insure that SCR did not adversely affect the leachability of toxic metals and that metals eroded from the catalyst did not present a toxicity concern. Ash resistivity measurements were performed to insure that SCR did not negatively impact fly ash resistivity, thereby reducing the efficiency of downstream electrostatic precipitators. The partitioning of gas/solid phase ammonia was also measured. These tests were performed to supplement the current data based mainly on foreign coals. Partitioning data are important because they allow one to make a prediction of the total slip ammonia, using solid phase ammonia measurements which are in general much easier to acquire. The results of these miscellaneous tests are reported in Sections 5.9.1 through 5.9.3.

In addition to the above tests, a special high-velocity catalyst configuration was tested late in the program on reactor H. For this test, reactor H was modified to increase the linear velocity through the reactor. This was done by halving the flow area and by increasing the base-line flow rate of gas through the reactor. These tests were performed to investigate the physical characteristics of the application only. No chemical constituents were measured and no ammonia was injected for the duration of the special testing. The results of this testing are discussed in Section 5.9.4.

The ability to determine slip ammonia concentrations on a continuous basis was deemed extremely valuable to the ultimate success of SCR technology. As a result, tests were performed to evaluate commercially available ammonia monitors for their efficacy in measuring ammonia slip on a continuous basis. A brief discussion of the results of these tests is contained in Section 5.9.5.

### **3.7 Data Acquisition/Analyses (Standard Methods/QA/QC)**

Many of the data acquisition/analysis methods for SCR testing are relatively immature. One of the benefits of this project was the ability to gain experience within the U.S. in appropriate analytical and testing methods for parameters of concern to SCR technology. Where available, standard testing methods were used. Appropriate scientific QA/QC procedures were used throughout this test program. Appendix F contains a report prepared by SRI, listing standard methods and QA/QC procedures used in the test program.

## **4.0 OPERATIONS/HISTORICAL HIGHLIGHTS**

The following discussions offer an operational history of the test facility. The discussions are divided into four main categories: 1) Design/Construction, 2) Start-up/Commissioning, 3) Long Term Operations, and 4) Availability. Where appropriate the categories are divided on a quarterly basis. A chronological listing which offers a synopsis of major events follows each discussion.

### **4.1 Design/Construction**

#### **4.1.1 Fourth Quarter 1991**

The detailed design engineering phase was in progress during this period. Evaluation of supplier bids and technical responses on the specifications for the flue gas and air electric heaters was completed and the contract awarded. Specifications were developed, inquiries issued for bids, bid evaluations completed, and contracts awarded on the following items: service/cooling water pump, gas analyzer system, and the oxygen analyzer system. Specifications were completed and released for bids on the plant air compressor, bulk ammonia system, dampers/actuators, reactor sootblowers, and structural steel/grating. Bids were received and evaluations were underway at the end of December for the plant air compressor, bulk ammonia system, dampers/actuators, and reactor sootblowers.

Design work continued and specifications were being prepared for the concrete/pilings, reactor vessels, control room, ductwork and reactor transition ductwork, fly ash handling, and personnel and catalyst hoist. Design work also continued on the instrumentation and controls, regarding locating instrument connections associated with the reactors, piping and ductwork, rack drawing, functional logic drawings, and erection specifications. Vendor drawings were approved for fabrication of all air heaters, the fly ash cyclones, and flue gas and air fans.

In view of required ductwork routing changes and reactor design revisions, additional work was requested of the flow modeling subcontractor. The areas in which review was requested included the following:

- 1) Effects of revised ductwork routing on the large reactor takeoff, with respect to obtaining representative gas sample and sufficient pipe diameters downstream of last elbow outlet;
- 2) Review of venturi relocation to vertical run of ductwork and influences of other piping arrangements;
- 3) Comment on options for mixing economizer bypass gas and gas from main extraction scoop and comment on distance between this mixing point and the first takeoff to the small reactors;
- 4) Comment on small reactor takeoff design and effects on representative gas sample; and
- 5) Comment on small reactor inlet design geometry, including resistance piping (ammonia injection grid) and vane requirements.

DynaGen responded to each of these comments and SCS facility design was modified to incorporate the recommendations.

The catalyst suppliers commented on the proposed common laboratory test methods and conditions for SCR catalyst evaluation. These test methods had been compiled by SCS based on earlier communications with the catalyst suppliers, for use by all the catalyst suppliers in measuring results of this project. SCS reviewed comments and issued a revised proposed common laboratory testing protocol for catalyst supplier review and approval (see Appendix D). In the revision, SCS clarified details on the minimum laboratory tests expected and differences in sampling frequency between catalysts loaded in the small versus large reactors. Some of the catalyst suppliers also provided comments on the reactor design and catalyst module design with respect to loading/unloading of the catalysts in the reactor and reactor support of the catalyst modules. SCS also corresponded with Haldor Topsoe and Hitachi Zosen supplying catalyst to small reactors

for details on catalyst coupon holders, to assist SCS in final design details for their reactors.

Vendor bid responses to the Request for Proposal for the testing services subcontractor were received. The evaluation was completed using the following major criteria: technical approach and understanding; cost and corporate resources; personnel qualifications; organization and management plan; corporate experience and past performance; and acceptance of contractor terms and conditions. Southern Research Institute was selected.

#### **4.1.2 First Quarter 1992**

The detailed design engineering phase continued during this period. Evaluations of vendor bids and technical responses on the specifications for the reactor sootblowers, ammonia storage system, plant air compressor, and dampers/actuators were completed by SCS Engineering and the contracts awarded. Bids on the structural steel/grating were received and evaluated by SCS Engineering and a contract awarded. Personnel hoist specifications were developed and released for bids on March 18.

Design work and specification preparation continued for the reactor vessels and reactor transition ductwork. Development of specifications for painting, insulation, and asbestos removal was also begun.

Additional work was requested of the flow modeling subcontractor. The requested work and summary results follow.

- 1) Using graphical techniques, recommend an improved injection mixing geometry for the design of the economizer bypass sparger into the main extraction gas stream. A wall jet injection design was recommended over a sparger design and a two jet injection geometry was selected.

- 2) Review and make suggestions on the small reactor takeoff and elbow design. The review showed our design to be appropriate although there were minor comments which were incorporated.
- 3) Design small reactor inlet and develop ammonia injection pipe size specifications and nozzle location, including nozzle sizing for both small and large reactors. The recommended small reactor inlet design was similar to that modeled for the large reactor. Ammonia injection pipe sizing of 0.625 inch outer diameter was recommended. Nozzle location for the small reactors had four pipes with four holes each for a total of sixteen. (The previous information showed 25 nozzles for the large reactor.) Nozzle sizing recommendations ranged from 0.326 - 0.360 inches for the large reactors and 0.115 - 0.124 inches of pressure loss and velocities of 65 to 75 feet per second.
- 4) Brief review of revised layout drawings.
- 5) Crate and store large reactor inlet model of selected test facility geometry. The model was placed in storage.

The above requested work was finished and the work with the flow modeling contractor was completed except for duration of model storage.

Some, but not all, catalyst suppliers provided additional information in response to the last request from SCS regarding the revised proposed common laboratory testing protocol. SCS began reviewing these latest comments and issued another revised proposed common laboratory testing protocol during the second quarter 1992 for final catalyst supplier review and approval.

Negotiations of a contract and final scope of work began through a series of meetings and correspondence during this quarter with the previously selected bidder for the testing and analytical services (Southern Research Institute). Test port locations and sizing details were also developed at this time.

One of the major milestones of the project occurred when facility construction began with the start of work on the concrete/piling subcontract. Specifications were developed, inquiries issued for bids, bid evaluations completed, and a contract awarded on the

concrete/piling erection package, the first construction package awarded. The contract award was made in late March, about two months behind the expected date of late January. The concrete/piling subcontractor mobilized and construction of the SCR demonstration facility began on March 23, 1992.

Specifications were prepared for the structural steel erection package by SCS Engineering, reviewed by Gulf Power Company, and revised. The structural steel erection specifications were released by Gulf Power for bids.

SCS Engineering also prepared specifications for review by Gulf Power on the following construction packages: control building, mechanical (final), electrical (preliminary), and I&C (preliminary). Review comments on the control building specifications were incorporated and the modified specifications were submitted to Gulf Power to allow issuing for bids. Gulf Power's comments on the mechanical erection specifications were received and SCS Engineering began incorporating them into the final bid package specifications. Gulf Power reviewed and supplied comments on the preliminary specification packages on electrical and I&C. SCS Engineering completed the revisions and submitted the revised specifications for Gulf Power's final review.

#### **4.1.3 Second Quarter 1992**

The detailed design engineering phase continued during this period with over 80 percent of the total project completed. The personnel/catalyst hoist erection package was issued for bids, bids were received and the evaluation of bids was completed. A purchase order issued on June 18, 1992. Major equipment delivered to the site included the air heaters, fly ash cyclones, flue gas/air fans, bypass heat exchangers, 4KV switchgear, venturis, 480V motor control center, flue gas/air electric heaters, dampers/actuators, and portions of the air compressor system.

Design work and specification preparation was completed for the reactor vessels and reactor transition ductwork and the specifications were released for bids. The bid responses were received and a contract was awarded.

Ductwork and fan system analyses during this period indicated certain fans had insufficient static pressure capability. As a resolution to this problem, modifications to the small reactor fans and hot air fan were made, and certain ductwork was increased in size to improve the system pressure drop. Modifications to the large reactor fans were not deemed to be cost effective.

In reviewing supplier drawings of the reactor sootblowers, for which a contract was awarded during the previous quarter, it was discovered that there were interferences with the retractable sootblower system and the structural steel support of the demonstration facility. In resolving this issue, the sootblowers' length was shortened and the sootblowers were relocated perpendicularly to the original orientation (i.e., the sootblower traversed the width of the reactor instead of the length).

The data acquisition and distributed control system hardware and software were delivered to SCS. Configuration of the control system was begun.

Construction continued during this quarter with the concrete/piling work being essentially completed. All of the pilings were driven, major foundations poured, and 98 percent of all foundations were finished.

Steel fabrication began and the first of four sequences was completed. This first sequence represented about 50 percent of the total steel to be manufactured. Fabrication of the second sequence was underway.

Vendor bids were received, evaluated, and the contract awarded on the structural steel erection package. This subcontractor mobilized and began structural steel erection in June.

Specifications were issued for bid on the control room and gas analysis systems buildings. A prebid meeting was held on April 9 and bids were received on April 29, 1992. The bids were evaluated and alternative bids were subsequently requested for the heating and air conditioning portion of the bid. The alternative bids were evaluated and a contract was awarded on June 4, 1992.

With the specifications on the passenger elevator within the control room building having been released for bid during the previous quarter, a prebid meeting was held on April 20, 1992. Bids were received on April 30, the bid evaluation was completed and a contract awarded on June 5, 1992.

The combined mechanical and insulation construction package specifications were issued for bids. A prebid meeting was held on May 5, 1992, and vendor bids were received on May 27, 1992. The evaluation of bids was completed and a contract awarded on June 30, 1992. The award included having 12 inches of insulation on the SCR reactors and reactor inlet ducting. Originally, the planned insulation thickness was only 6 inches. However, the insulation thickness was increased based on recommendations from catalyst suppliers, with their previous test facility experiences, and from EPRI. EPRI's SCR test facility had 6 inch thick insulation. EPRI agreed with the plans to have more insulation.

The specification packages for electrical and I&C erection were combined into one construction package and issued for bids. A prebid meeting was held on May 18 and bids were received on June 9, 1992. The evaluation was essentially completed and contract award was in progress at the end of this period.

Preparation of painting specifications was begun during this period. Asbestos removal specifications were finalized and were added in the individual construction packages as warranted.

#### 4.1.4 Third Quarter 1992

A dedication ceremony was held on July 1, 1992 at the test facility site. The detailed design engineering phase continued during this period with over 90 percent of the total engineering on the project completed. Major equipment delivered to the site during this period included the ammonia storage tank, service water pump, and reactors. Some instruction books for the major equipment already delivered were received and provided to construction and operations personnel.

Based on the previously awarded contract, drawings for the fabrication of the SCR reactors and transition ductwork pieces were received and reviewed. Fabrication of the reactors and transition pieces was begun and a preliminary progress inspection was made. As fabrication neared completion, a final progress inspection was held. All the reactors and transition pieces were shipped to the site. The erection of the small reactors upon the support steel structure was begun.

All mechanical drawings were updated to reflect modifications in design and vendor recommendations. Piping expansion joint bids were issued, bids received and evaluated, and an award made. These were procured and delivered to the site.

Vendor drawings were received and reviewed for the personnel and catalyst hoist. The design of the ductwork expansion joints was completed and an inquiry issued. After review of vendor bid submittals, an award for supply of the ductwork expansion joints was made to Senior Flexonics.

Initial design was completed for instrumentation platforms at elevation 202', economizer bypass support steel at elevation 156'8", walkway and duct support at elevation 141', and additional pipe and support brackets. Additional platforms to provide access to instrumentation were requested based on review by the testing services subcontractor. Design of these platforms was begun.

The structural steel painting package was issued to Gulf Power for release to request bids. Vendor bids were evaluated by SCS Engineering and Gulf Power and a contract award was in progress at the end of this period. The vendor drawings for the control room elevator were reviewed and approved.

Within the electrical engineering scope, the high voltage system design and procurement of materials were completed. The low voltage system design and procurement of materials were 99% complete. With the exception of a few minor revisions, all electrical drawings were transmitted to the field.

Instrumentation and Controls personnel completed configuration of the Bailey Control System, and check-out and testing was underway. Development of the graphic screens was begun and almost finished. Manual/auto switches were developed and placed on screen for operator controls. Updating of domestic loop diagrams was initiated. Preparation of the control system for simulation and testing of logic, and for operator training during October, was begun. Work was also started in programming to trend and archive data.

Manufacturing of the gas analysis system continued. A visit was made to inspect the first system produced and the reported inspection results on quality were favorable. A final witness test by SCS was scheduled for October, prior to shipment of the system to the site.

Construction of the Plant Crist SCR demonstration facility continued during this quarter, with the remaining steel fabrication being completed. Sequence two was completed in July, sequence three was finished in August, and sequence four was completed in September. The structural steel erection also concluded in September. The large crane for steel erection was subsequently moved, providing access to the control room contractor.

The construction of the control room building and gas analysis room was started. The structural steel for each was erected and the concrete slabs were poured. Erection of roof and siding materials was begun.

The mechanical and insulation contractor mobilized and began work. The large fly ash cyclones, bypass heat exchangers, air preheaters, and large reactor fans were set in place. The service water piping, from the pump to the peripheral of the project, and service water filter were installed. The host unit fly ash piping was relocated. The cutting of ductwork, piping, structural steel, and cable tray penetrations in asbestos siding were completed. Fire protection piping work at the 4160V switchgear was completed. Installation of some ductwork commenced. About half of the ductwork runs from the cyclones to the fans and the return ductwork from the fans to the Unit 5 ductwork was erected. Work on insulating some of the installed equipment was begun. The ammonia storage tank was also set in place.

The construction package contract for electrical and I&C erection was awarded. The electrical contractor mobilized and began work. Fabrication of cable trays and construction of switchgear foundations was started and completed. Erection of the cable trays and setting of the switchgear was begun. Gulf Power substation personnel began their check-out of the 115-KV transformer.

The operators for the demonstration facility were selected from Gulf Power Plant Crist operating personnel. They were scheduled to begin work on the project in October 1992. They were provided with an SCR information manual and other training materials were gathered and edited for operator use. Training on the data acquisition/distributed control system was scheduled for mid-October. Print and video safety media on ammonia storage and handling were collected on-site for review. The process of securing operating and maintenance manuals on most major equipment was begun.

Negotiations of terms and conditions for the testing/analytical services were completed and a contract was signed. Development of the data reduction methodology was begun through formulating plans for retrieval and storage of data within the Bailey control system, transfer of data into a DOS data base format, extraction of data, down-loading, and configuration of special calculations (ammonia slip, NO<sub>x</sub> reduction efficiency, etc.).

#### **4.1.5 Fourth Quarter 1992**

The detailed design engineering phase was essentially completed during this quarter with the exception of assistance during equipment check out and start-up. Major equipment delivered to the site during this period included the gas analysis system, personnel and catalyst hoist, and control system. Instruction books for some of the major equipment already delivered were received and provided to construction and operations personnel.

The ductwork expansion joints, designed and ordered by SCS Engineering during the previous quarter, were procured and delivered to the site. Design of additional platforms to provide access to instrumentation (requested based on review by the testing services subcontractor) was completed and the award was made for installation of these additional platforms.

The contract for the structural steel painting was issued after completion of bid evaluations by SCS Engineering and Gulf Power. Within the electrical engineering scope, both the high and low voltage system designs and procurement of materials were completed.

Instrumentation and Controls personnel completed configuration check out and testing of the Bailey Control System to the extent possible in the engineering labs at Birmingham during October. Updating of domestic loop diagrams was completed and the control system was prepared for operator training during October. The control system was delivered to the site during November and installation continued through December. The system was energized in December and check out on site was begun. Work continued on

revisions to the control system configuration, development of the graphic screens, and programming to trend and archive data.

Manufacturing of the gas analysis system was completed. A final witness test visit was made by SCS during October prior to shipment of the system to the site. The gas analysis system was delivered to the site during November. Installation commenced immediately and continued through December.

Construction of the Plant Crist SCR demonstration facility continued during this quarter. The control room and gas analysis room buildings were erected with completion of the roof and siding, flooring, ceiling, walls, lighting, and HVAC ductwork. Remaining work included HVAC unit installation and some painting.

The mechanical and insulation contractor installed both the small and large reactor vessels and completed erection of the service water pump and piping system. With installation of the small reactor fans and air return fan, erection of all major gas/air fans were completed. Work was begun and essentially completed in installation of all the test facility ductwork; i.e., ducts between the main takeoff scoop and the reactor inlets, the return ducts from the fans to the re-injection point on the plant's duct, the bypass ductwork, and the combustion air ductwork. Remaining work included installation of some expansion joints and some minor work on the ducts. Insulation of the equipment continued; insulation of the ductwork was begun; and a majority of the ductwork insulating was finished. The reactor sootblowers were erected and work was completed on the service air system. Work was begun and substantial progress made in the installation of the ammonia and dilution air supply systems and the purge air system. Equipment was lubricated and coupled to the motors.

The electrical and I&C erection continued during this period. The switchgear was set and cable trays were installed. The 4160V cable was installed to the control room building. Gulf Power personnel completed their check-out of the 115KV transformer. The 115KV

transformer and switchgear were successfully energized in November. During December, the 4160V/480V transformers and the motor control centers were energized. A significant amount, but not all, of the electric cable was installed. Installation of instrumentation was begun. Pressure taps and thermocouples were installed on the reactors during November. Installation of other temperature, pressure, and flow measuring devices continued through December.

Erection of the personnel/catalyst hoist was started and almost completed. The installation of some additional platform steel was begun. The starting and check-out of some equipment was initiated, e.g., service water system, instrument air system, and air heater drives. The necessary tie-ins (gas, air, steam, etc.) for the demonstration facility were made with the plant in late December.

The operator training on the data acquisition/distributed control system was conducted during October at the SCS Engineering labs. Operator training for equipment/process familiarization continued through December and was essentially concluded. Operators assisted in preparing procedures for check-out, start-up, and emergencies. At the end of December, operators were supporting equipment check-out.

Southern Research Institute (SRI), the testing subcontractor, submitted a Quality Assurance Program Plan for obtaining reliable monitoring data and method verification. Copies of the sampling and analytical methodology, plus the testing plans were sent to the project participants for review. Comments were received from the catalyst suppliers, and where appropriate, incorporated into the test plan. This QA/QC Plan is shown in Appendix F.

SRI personnel who conducted the testing and analytical services for the two years of operation began their on-site work. The trailer which housed the majority of the analytical equipment and working space was delivered, set up, and utility connections were made. Preparation and set-up of equipment and testing and analytical procedures was begun.

Development of the data reduction methodology continued. This included work on plans for retrieval and storage of data within the Bailey Control System, transfer of data into a DOS data base format, extraction of data from the gas analysis system, and use of the data in modeling results. Customized software was purchased for modifying data format and enhancing data archiving capabilities.

#### **4.1.6 Design/Construction Synopsis**

The following is a chronological synopsis of major events occurring during the Design/Construction phase of the project:

##### **October 1991**

- Contract awarded for flue gas heaters
- DOE/SCS visit to Japanese catalyst suppliers
- Specifications for ammonia storage and injection system completed

##### **November 1991**

- Revised common laboratory testing protocol issued
- Testing and analytical services bids received

##### **December 1991**

- Bid awarded for service cooling water pumps
- Award of testing and analytical services bid
- Request for response from interested catalyst supplier participants to replace withdrawn supplier (Norton)

### **January 1992**

- Contracts awarded for ammonia storage, reactor sootblowers, control/isolation dampers, and air compressor
- Contract awarded for gas sampling/analysis system
- Flow modeling started on small reactor inlets and ammonia injection grid
- Project review meeting held at Gulf Power
- Technical briefing to DOE and congressional staff at Plant Smith
- Technical briefing to DOE at Pittsburgh

### **February 1992**

- Steel/grating fabrication bid awarded
- Project review meeting held at Plant Crist
- Replacement catalyst supplier selected (Cormetech)

### **March 1992**

- Construction began with concrete/piling work (March 23)
- Final report from flow modeling subcontractor provided
- Project review meeting held with Gulf Power

### **April 1992**

- Personnel/Catalyst hoist erection package was issued for bids
- Control system hardware checked out
- Status report issued to catalyst suppliers
- Design/Construction status meeting held

### **May 1992**

- Electrical/I & C specification package was released for bid
- Configuring of the control strategy begun
- Design/Construction status meeting held

**June 1992**

- Personnel/catalyst hoist erection package awarded
- Contract awarded for control room and gas analysis building
- Structural steel erection contractor mobilization
- Revised laboratory testing protocol was released to catalyst suppliers
- Design/construction status meeting held

**July 1992**

- Structural steel erection commenced
- Contract for mechanical/insulation erection package awarded
- Contract awarded for ductwork transition pieces
- Electrical/I & C systems contract awarded
- Design/Construction status meeting held

**August 1992**

- Signed contract with Southern Research Institute for testing
- Dedication ceremonies held at Plant Crist
- Mechanical /insulation contractor mobilized
- Fly ash cyclones and bypass heat exchangers set
- Service water piping and fan installation begun
- Electrical contractor began work
- Design/construction status meeting held at site

### **September 1992**

- Continuation application submitted to DOE
- Construction of control room begun
- Contract awarded for facility painting
- Design/construction status meeting held
- Paper presented at the First Annual Clean Coal Technology Conference in Cleveland (September 24)

### **October 1992**

- Ontario Hydro joins as co-funder
- Operator training begun
- Final witness test of the gas analysis system
- Cormetech agreement signed as catalyst supplier replacement
- Design/construction meeting held
- Paper presented at the Pittsburgh Coal Conference (October 15)
- Paper presented at the International Joint Power Generation Conference in Atlanta (October 20)
- Two U.S. catalyst suppliers visited

### **November 1992**

- Began installation of sootblowers
- Switchgear and transformers energized
- Installation of instrumentation begun
- Erection of hoist begun
- Large reactor vessels installed
- Project review meeting with participants held
- Laboratory Testing Protocol established

## **December 1992**

- Detailed design engineering completed
- Completion of majority of control room and gas analysis building construction
- Initial equipment check-out started
- Bailey control system energized
- Operator training concluded
- Procedures for check-out, start-up, and emergencies developed
- Engineering/construction status meeting held at Plant Crist

## **4.2 Start-up/Commissioning**

### **4.2.1 First Quarter 1993**

The start-up and shakedown period was commenced during the first quarter 1993 as was commissioning testing. Equipment check-out was conducted for all the areas of the facility. By January 10, all the flue gas fans, hot air fan for the air preheaters, and rotary air heaters were started and checked to allow the SCR facility to begin taking flue gas from Unit 5. Later, the fans were further tested under load and temperature under supervision of the manufacturer. The large reactor fans and hot air fan ran very well, but the small reactor fan began experiencing substantial bearing damage after only 12 hours of operation. Replacement bearings were used temporarily for about a month while the fans were run at half-speed and had daily oil changes at the bearings. Eventually another bearing design was installed which solved the problem. Other problems experienced with the fans included motor base-plate vibration on the small fans, and freezing of all fan inlet vanes.

The "dummy layers" (flow straightening grids) were loaded into the top level of each reactor in preparation for beginning the commissioning tests. All catalysts to be evaluated were delivered to the site. The air preheaters were started and checked out and appeared to be very effective throughout this period.

The flue gas/air electric heaters required significant efforts to bring on line as a result of being grounded because of moisture saturation prior to installation, thus not having enough resistance to ground to prevent a short circuit or a ground fault. After consulting the heater vendor, the moisture was "baked out" of the elements by heating with flue gas until satisfactory resistance was obtained. As soon as the electric heaters dried out sufficiently, they were placed in service. Concerns about fly ash deposits produced plans to install sootblowing ports near these heaters.

The sootblowing system was functionally checked out and required some rewiring and changes to the control system configuration. Different design steam traps were ordered for installation at a later date. This was done to correct a potential problem with condensate buildup in the supply piping that would potentially introduce liquid water into the reactor which could damage the catalyst.

Although there were some minor problems, the ash handling system operated satisfactorily. Some changes which were planned to improve the system's operation included adding hopper vibrators and hopper insulation. These were installed during the second quarter 1993.

The bypass heat exchangers were tested. After only a few hours of operation, these exchangers experienced significant plugging. Alternative corrective measures were considered. Also, there was a problem maintaining sufficient service water pressure for cleaning and a means to improve this situation was examined.

Check-out of the Bailey control system continued. Extensive modifications were made to the control system configuration as a result of changes in equipment specifications and from experience gained during equipment start-up and operation. Several transmitters, damper positioners and solenoids were repaired or replaced during the start-up period. Work continued to insure that all field instrumentation was in proper working order.

Installation of the gas analysis system was completed and start-up was begun. The control software was extensively modified and work continued on automatic calibration of the system. Some analyzers and probes had to be removed and repaired. A list of items to be completed before final acceptance of this system was furnished to the manufacturer, Lear Siegler Measurement Controls, Inc.

Check-out of the ammonia injection system, one of the last areas to be completed by construction, was begun. It was discovered that the header system and piping near the reactor inlet, just outside the duct, was plugged with flue gas deposition products. This resulted from flue gas components condensing in this piping during the operation of the facility on flue gas while the ammonia/air system was incomplete and therefore, unable to act as a purge on this system piping. During an April 1993 outage, the nozzles and injection header were cleaned and some portions of the feed piping were completely replaced.

Commissioning tests officially commenced at the beginning of March, although some preliminary testing began earlier in February. All flow control venturis were calibrated. Concentrations of  $\text{NO}_x$ ,  $\text{SO}_x$ , and other gas species were measured at both the high- and low-dust extraction points at both high and low boiler loads. Particulate mass concentration measurements were made for both high and low boiler loads at the test facility slipstream extraction points from the main duct. Particle size analysis was underway at the end of this period. All trace metals train sampling was completed, which included sampling at both extraction scoops, economizer bypass, and one large and one small reactor. Analysis was underway at the end of this period.

Mass concentration measurements were made at the reactor inlets. The results indicated that mass concentration data for reactors A, B, and C (large reactors) closely matched the values previously measured in the plant duct at the hot-side ESP inlet (2.95 and 3.33 gr/dscf). The mass concentration at reactor J (low-dust reactor) was comparable to the

values measured at the hot-side ESP outlet. However, results measured at the inlet ducts for the high-dust, small reactors (D, E, F, G, and H) were much greater than those for the large reactors. Initial mass concentrations for the small reactors ranged from 5.16 to 11.67 gr/dscf. Subsequent tests to confirm the above results were run on reactors A and F. The results from these tests confirmed the higher particulate loading to the small reactors, although the magnitude of the difference was less in these tests. Additional flow and mass concentration stratifications were investigated at the inlet transition with a nine position sampling matrix. The test results did not show a large stratification in mass concentration that was seen in the small reactor inlet data. However, since the velocity in the transition regions leading to the small reactors was about half that leading to the large reactors (based on the area of the small reactor take-off scoop), it was felt that the transition was acting like a large particle concentrator.

DynaGen, Inc., the flow modeling subcontractor, was contacted about the above maldistribution problem and recommendations were made by DynaGen. During the outage in April 1993, the following modifications were planned: reduce the slot size of the small reactor take-offs; install a flow straightening grid just prior to the split between the small and large reactors; and install a mixing device just prior to the flow straightening grid.

#### 4.2.2 Second Quarter 1993

The start-up and shakedown of equipment continued during the second quarter of 1993 as did commissioning testing without catalysts. The SCR demonstration facility was taken off line the first weekend in April as a result of a boiler outage. While off line for over two weeks, necessary construction modifications were made to the SCR facility. These modifications included installation of a damper on the gas-side ductwork returning flue gas from the facility to the host plant duct. The inlet vanes on all fans were modified to resolve a freezing problem with the vanes. Manual sootblowing capability with air was added at the electric heaters and the bypass gas heat exchangers because of concerns with fly ash deposits. The most significant modification included changes to the main inlet scoop-ductwork and small reactor take-off. To resolve a maldistribution problem of particulate between the small and large reactors, the slot size of the small reactor take-off was reduced, and a mixing device and flow straightening grid were installed just prior to the split between the small and large reactors. Additional construction modifications included installation of more platforms and walkways for access to equipment and instrumentation and for testing purposes. Some instrumentation was also relocated or replaced. Contracts for instrumentation and controls maintenance were awarded upon completion of bid evaluations. The process for acquiring mechanical maintenance was established. Some configurational changes with the Bailey control system were made and checked out and acceptance of the gas analysis system continued.

Near the end of the second quarter, the ammonia flow controllers were repaired and cleaned by service representatives and the controllers tested against calibrated standards. Sootblowing appeared to be effective on the hot-side of the air preheaters since essentially no fouling was observed when inspected in June 1993. After installing sootblowing capability at the electric heaters in April 1993, sootblowing seemed to be controlling the ash fouling problem at the electric heaters.

The commissioning tests without catalysts were completed by the middle of June 1993. The loading of the catalysts into the reactors began on June 14 and was finished June 22, 1993. The catalyst supplier, assigned reactor, and the catalyst supplier representatives on site for their catalyst loading were as follows in Table 4.2-1.

Table 4.2-1 Catalyst Suppliers and Reactor Designation

| Catalyst supplier | Reactor designation | Representatives on site for catalyst loading              |
|-------------------|---------------------|---|
| W.R. Grace        | A(large)/D(small)   | Mohit Uberoi  |
| Nippon Shokubai   | B(large)            | Montonobu Kobayashi,<br>Noboru Sugishima, Taka<br>Yatagai |
| Siemens           | C(large)            | Ralf Sigling  |
| Cormetech         | E(small)            | Chris DiFrancesco, Johnny<br>Yamaguchi                    |
| Haldor Topsoe     | F(small)            | John Holst  |
| Hitachi Zosen     | G(small)            | -   |
| Engelhard         | H(small)/J(small)   | Ed Balko, Howard Furbeck                                  |

Some of the major issues experienced during start-up are highlighted below.

- Sulfate Deposition

There were problems with plugging in ductwork/piping areas without continuous flow because of the high sulfur concentrations in the fuel and the flue gas. While the ammonia injection system was being completed, the installed injectors presented one such low flow area that sulfates diffused into and precipitated out, plugging almost every injection system. The nozzles and injection header were cleaned and some portions of the feed piping had to be replaced. The air fan for ammonia dilution was subsequently placed in service and was used to supply a continuous air flow to act as a purge to prevent recurrence of the plugging. The horizontal sections of the large reactor bypass lines accumulated a large amount of sulfate that blocked operation of several dampers. These dampers were exercised on a weekly basis to prevent the blockage from binding the dampers again.

- Bypass Heat Exchangers

The bypass heat exchangers, which were included for use during the parametric testing on the large reactors to minimize effects of high ammonia slip upon the long term evaluation of the air preheaters, were easily plugged by ash and sulfate deposits. Cleaning with the previously installed manual sootblowing ports was not a satisfactory solution nor was water washing. Work to develop another means to cool the flue gas while bypassing the air preheaters remained underway at the end of the second quarter 1993.

- Ash Accumulation

During start-up, especially during low flows, ash build-ups were found in several areas of the ductwork including the main scoop area, the electric flue gas heaters, and the bypass heat exchangers. Extra access ports for sootblowing were added to clean these areas.

#### **4.2.3 Start-up/Commissioning Synopsis**

The following listing is a chronological synopsis of major events occurring during the start-up/commissioning phase of the project.

##### **January 1993**

- Conditional approval of EMP
- Flue gas first passed through system
- Start of staffing of facility on a 24-hour basis
- Fan tests on flue gas started
- Dummy beds installed
- Technology briefing and facility tour provided to congressional staff (January 14)

### **February 1993**

- Completed construction of test facility
- Facility ash system operated
- Painting of structure completed
- Initial host unit flue gas testing begun
- Begin of start-up/shakedown

### **March 1993**

- Wrap-up at lagging/insulation completed
- Commissioning tests without catalysts commenced

### **April 1993**

- Host unit outage
- Modification to fan inlet vanes
- Sootblowing capability added to electric heaters
- Modifications made to main inlet scoop
- Contract for I & C maintenance awarded
- Check-out of NH<sub>3</sub> systems

### **May 1993**

- Steam condensate drains or sootblower system installed
- Plugging of the bypass heat exchangers

### **June 1993**

- Commissioning tests without catalysts completed
- Ammonia flow distribution tests conducted
- Catalysts installed

## 4.3 Long Term Operations

### 4.3.1 Third Quarter 1993

July 1, 1993, is considered the beginning of the long term operation phase of the project with catalysts. Immediately after catalyst loading, all reactors were operated with ammonia briefly to obtain fly ash samples for the Toxicity Characteristics Leaching Procedure (TCLP) analysis. The TCLP results indicated no detectable amounts or change in constituents between base-line ash samples and ash samples from the SCR process outlet. These TCLP results are discussed in Section 5.9.

During July - September, 1993, reactors A - C were the primary reactors operated with ammonia. The first set of parametric tests were completed for these reactors. The parametric tests for reactors D - F had just begun at the completion of the quarter.

There was a brief outage over the July 4th holiday to allow final tie-in of fire protection piping. In August, one bypass heat exchanger developed a water leak that led to the plugging of the reactor cyclone. The cyclone was cleaned without taking the reactor off-line, but further cleaning was reserved until the next outage in September. Also, a large reactor fan caused a brief outage when ash build-up caused an imbalance that vibrated the bearing pedestal bolts loose. After ash removal, bearing inspection, and acceptable balance testing, the fan was returned to service. There were two outages in September. The first outage was scheduled over the Labor Day holiday to inspect and clean the cyclone hoppers which were plugged, inspect the air preheaters, and clean two of the large reactor fans. These efforts restored flow rates above the maximum rates needed during parametric testing. The second outage was unscheduled and resulted from a bearing failure on the host boiler's forced draft fan.

As may be normally expected, there were several issues encountered during the quarter's operation, some of which are not associated with the SCR process per se. The major experiences are highlighted below.

- Dilution/Extraction Gas Sampling/Monitoring System

The SCR test facility used a Lear Siegler Dilution/extraction sampling system for measurement of NO<sub>x</sub>, SO<sub>2</sub>, CO<sub>2</sub>, and CO in the flue gas. This sampling method used dry air as a dilution medium, with typical air/sample dilution ratios ranging from 30 to 250, to minimize the problems associated with the transport and measurement of these gases as compared to other available methods. There were several issues with this system, including accuracy of NO<sub>x</sub> outlet data with ammonia injection, coordinating the shared analyzers, and communicating with the test facility's data collection system.

Problems were experienced with NO<sub>x</sub> measurements in the presence of ammonia, apparently with catalytic reactions proceeding in the sampling system, thus reducing NO<sub>x</sub> before the sample reached the analyzers. A series of traps and filters were installed in sample lines to capture the ash, water vapor, and acid condensate in order to improve the accuracy of the analyzer system. Work was also underway to investigate a probe with different material of construction.

For the nine reactors, there were three NO<sub>x</sub> analyzers for the reactor outlet measurements. Each of these analyzers operated on a time-shared basis serving three specific reactors. These systems used a complex system of pumps and valves to direct the sample that was continuously extracted to the analyzer. Problems occurred with erroneous data being transmitted for the two points which were supposedly holding their previous values while the third reactor sampling point was active.

The gas analyzer system had a dedicated programmable controller that collected the data from all the analyzers and then sent this to the test facility's control and data collection

system. Because these were different systems, the communication protocol had to be evaluated during start-up. Although many of the communication problems were solved during the start-up of the test facility, there were still some communication failures occurring. All these problems with the gas sampling/analysis systems were addressed or were in the process of being addressed at the end of this quarter.

- Ammonia Injection Flow Control

Precision mass flow control valves supplied by Sierra Instrumentation were installed to control the ammonia vapor flow rates for injection into the reactors. These controllers were affected by liquid in the flow stream, pressure variations, debris in the line, and the orientation of the controller itself. These controllers were calibrated on nitrogen and scaled to read ammonia flow. Although initial results indicated accurate flow control, subsequent measurements indicated that actual ammonia flow was 10 to 25 percent higher than the controllers were indicating. Actions taken to correct this situation included installation of coalescent filters on the ammonia supply lines to each control valve, reorientation of the controllers, replacing the ammonia header pressure regulator, cleaning each controller, and recalibrating and verifying with other instruments.

- Low-Dust Reactor Fouling

After only a few hours of operation during its first start-up after catalyst loading, the low-dust reactor experienced severe fouling of the first catalyst layer. While the large reactor bypass lines were originally designed to flush any ash accumulations associated with the main extraction scoop, the low-dust reactor ductwork was not provided with any bypass capability. Also, the isolation damper for that line was approximately 100' downstream of the scoop allowing a dead leg for sulfate formation when the reactor was off-line. So during start-up an unusually large amount of solid material may have been introduced to the low-dust reactor. The first layer catalyst element was returned to the catalyst supplier for examination and a study undertaken to evaluate solutions to prevent recurrence of this

problem. The resulting design changes on the low-dust reactor included the following: the reactor isolation and purge dampers were relocated to minimize the dead leg; and the reactor heater capacity was increased and the heater moved to just downstream of the isolation damper so the piping could be slowly warmed while drawing flue gas. These changes were made during the fourth quarter of 1993.

- Reactor and Air Preheater Sootblowing

The large reactors used steam-supplied sootblowers for both the catalyst baskets as well as the air preheaters. Much work went into eliminating the condensate from the sootblowing steam-supply piping, including an extra steam isolation valve on each sootblower, using a process steam condensate trap on each reactor's steam-supply header, and adding warm-up vents to insure that the piping was hot enough to prevent condensation. Follow up inspections revealed that the sootblowers were effective throughout this period in dislodging any ash build-up on both the reactor baskets and the air preheater baskets. The schedules and procedures for sootblowing of the reactors and air preheaters are shown below:

Table 4.3-1 Sootblowing Schedule and Procedures

|                    |   |
|--------------------|---|
| <b>Schedules:</b>  |   |
|                    | Large Reactors - every 8 hours                          |
|                    | Small Reactors - every 8 or 12 hours                    |
|                    | Air Preheaters - every 4 hours                          |
| <b>Procedures:</b> |   |
|                    | Warm-up lines by venting the top of verticals           |
|                    | Condensate drains under each vertical and air preheater |
|                    | Monitoring pressure drops-before/after                  |

- Reactor Fans

Due to the small flow, high head requirements of the test facility, the reactor fans were custom designed. Because of the head requirement, the fan wheels were narrow, large diameter with relatively high inertial moments that made bearing selection difficult. On the small reactor fans, the bearings were replaced twice before changing the design to ball bearings.

Because of high speed requirements, the small reactor fans used fan belts to increase the speed. The belt tension adjustment system moved the motor, placing the motor on a thin sheet metal base that vibrated at harmonics to the motor speed. The motor base-plate was stiffened to prevent this vibration.

Because of the possibility of ammonia slip in the flue gas, materials used in fan construction had to be compatible with ammonia. The original vane support bushings were pressed carbon and very brittle, in fact several were broken in shipment and more broken during installation. The first replacements fabricated were brass, but these were rejected due to the ammonia attack of copper alloys. The next offering was stainless steel, which galled soon after installation. The last solution was a silicon alloyed cast iron, which performed well. The vane bearings were also extended off of the fan housing and new seals were also installed.

#### **4.3.2 Fourth Quarter 1993**

The preliminary parametric test sequences for the three large reactors (A - C) were completed during the previous quarter. During this fourth quarter of 1993, the large reactors were operated in long-term base-line operating conditions, i.e. at an  $\text{NH}_3/\text{NO}_x$  ratio near 0.83 for 80%  $\text{NO}_x$  removal. The parametric tests for reactors D - F were completed after an operational shakedown period consisting of recalibration of the venturis and ammonia mass flow controllers on each of the reactors, as well as a check-

out of the gas analysis equipment. Although parametric testing was initiated, testing was interrupted and not completed on reactors G - J. The reasons for this incomplete testing are discussed later in this section.

The test facility experienced several outages during October. Two outages were a result of the Unit 5 boiler being forced off-line, thus causing a test facility outage. The test facility operators used these times to clean fans and inspect the cyclones for plugging. A scheduled test facility outage occurred over a Saturday to replace the service water bypass valve with an upgraded version. Also, failure of one of the control system's analog input cards forced the small reactors to be taken off-line part of a day while manual overrides kept the large reactors on-line until the card was replaced.

There was a planned outage during the first week of November, during which the first catalyst samples were retrieved from the three large reactors and sent to the catalyst suppliers for laboratory testing. Upon inspection, the top catalyst bed on reactor C was found to be damaged by the sootblower rake twisting in the reactor and physically striking the catalyst modules. At the end of December, during the next outage for catalyst sampling, the catalyst in reactor C which had been damaged by physical contact with the sootblower was replaced. Although this catalyst had been physically damaged, there had been no previous indication operationally or by NO<sub>x</sub> removal or pressure drop that this damage had occurred. Thus, although damaged, the catalyst was still yielding excellent NO<sub>x</sub> reduction performance. Since the catalyst module for each layer in reactor C consisted of two levels of catalyst baskets, the new replacement catalyst baskets were loaded into the bottom of the first bed. The original catalyst in the lower half of the first catalyst bed, which had not been damaged, was moved to the top half of the first bed. The reactor sootblowers were inspected and repaired as needed, with most having their rake covers trimmed for clearance and all fitted with an external anti-rotation device to prevent a similar occurrence as previously experienced on reactor C.

During the early November catalyst sampling on the three large reactors, the dummy bed on reactor A was discovered to be heavily eroded, and plans were made to replace the dummy bed. This dummy bed replacement was made in late December. The dummy bed in reactor D was also replaced since it was the same material as that originally in reactor A. Otherwise, the dummy beds and catalyst baskets had little apparent damage or erosion and were relatively clean regarding fouling from ash. Also in November, the test facility experienced a few outage days due to Unit 5 tube failures and loss of power from the switchyard due to a transformer failure on Unit 6.

During an outage over the Thanksgiving holiday, the plate catalyst in reactor G was inspected due to a large increase in pressure drop noticed prior to the outage. About half the catalyst elements were found to be damaged, collapsed upon themselves. Based upon inspection, the vertically downward sootblowing with air was thought to be the cause of the damage. All but two of the nine reactor catalysts were sampled directly from the actual catalyst beds. In reactors F and G, the catalyst was a monolithic plate structure which prohibited samples from being pulled directly from the catalyst bed. In these two reactors, catalyst coupons were mounted above each catalyst bed for catalyst sampling purposes. It appeared that the air sootblowing procedures destroyed the coupons, and, in reactor G, the coupons subsequently fell down and may have contributed to damage at the main catalyst layers. The catalyst supplier provided replacement catalyst elements for installation in the first quarter of 1994. Per the supplier's advice, this reactor was operated subsequently without sootblowing. Operation of this reactor ceased until the catalyst was replaced early in 1994.

During the holidays at the end of December 1993, there was a planned outage for catalyst sampling and facility modifications. Reactors A - F were inspected and catalyst samples were removed and sent to the suppliers for laboratory analysis. The only catalyst sampling coupons present for the December sampling in reactor F were those at the reactor exit, and there were no coupons for reactor G. As noted above, the catalyst sample coupons

for reactors F and G were destroyed due to air sootblowing procedures. Replacement coupons were supplied and were installed as soon as received.

Also during the December planned outage, valves and test ports, not insulated originally, were insulated to reduce heat losses. Additional insulation projects were planned to assist operations in maintaining desired temperatures. The control system was also reconfigured for calibration corrections on the venturis and ammonia flow controllers (see the later discussions on gas sampling and ammonia-to-NO<sub>x</sub> ratios).

As with the previous quarter, Southern Research Institute (SRI) continued this quarter to maintain a staff of six people, supplementing their regular staff of three people with two additional testing crew and an additional analytical chemist. This doubling of staff was required to complete the preliminary parametric testing on all reactors before the end of December 1993.

Laboratory analysis was begun by the catalyst suppliers on the catalyst samples taken after one quarter of operation on the three large reactors. Initial results indicated little or no loss in overall kinetic activity and little change in other critical properties. Upon completion of the initial parametric testing in early December, base-line ammonia slip measurements were repeated. These tests were completed during December and the results indicated all catalysts were performing well with less than 2 ppm slip under base-line conditions, and in many cases the measured slip was below the nominal 1 ppm detection limit.

Several other major experiences encountered during operation are highlighted below.

- Dilution/Extraction Gas Sampling/Monitoring System

The SCR test facility used a dilution/extraction sampling system from Lear Siegler Measurement Controls Corporation (LSMCC, now Monitor Labs). The system consisted

of thirteen dilution/extraction probes for the measurement of NO<sub>x</sub>, SO<sub>2</sub>, CO<sub>2</sub>, and CO. There were 26 Yokagawa in-situ probes for the measurement of oxygen. Using dry air as a dilution medium, normal dilution ratios ranged from 30:1 to 250:1. NO<sub>x</sub> analysis was performed using an LSMCC model ML8840 chemiluminescence NO<sub>x</sub> analyzer with a detection limit of 2 ppb resulting in a flue gas detection limit of approximately 0.25 ppm. CO was measured using a LSMCC model ML8830 infrared CO analyzer with a detection limit of 0.1 ppm resulting in a flue gas detection limit of approximately 3 ppm. CO<sub>2</sub> was measured using a Siemens Ultimat 5E non-dispersive infrared CO<sub>2</sub> analyzer. SO<sub>2</sub> was measured using LSMCC model ML8850 fluorescence SO<sub>2</sub> analyzer with a detection limit of 1 ppb resulting in a flue gas detection limit of 0.1 ppm. Oxygen was measured using in-situ zirconium oxide cell technology.

The issues reported for the previous quarter continued to be addressed during this quarter. In addition to these issues, significant dilution effects due to air in-leakage into the reactor were also creating apparent data anomalies. The NO<sub>x</sub> concentration inputs for automatic ammonia injection were taken from the inlet ductwork to the test facility, rather than from the ammonia injection point. Therefore, air in-leakage after the sample point decreased the NO<sub>x</sub> concentration at the ammonia injection point. This skewed the calculation for ammonia injection rate and resulted in a higher than expected ammonia-to-NO<sub>x</sub> ratio. The ammonia injection rate could easily be corrected by material balance to compensate for oxygen in-leakage. This, however, linked a large number of continuous measurements to the calculation, resulting in frequent errors when one of the measurement points was not operating correctly. To avoid similar problems in future facilities, NO<sub>x</sub> readings should be taken close to the ammonia injection point, rather than upstream of potential in-leakage sources.

Problems previously experienced with NO<sub>x</sub> measurements in the presence of ammonia, apparently with catalytic reactions occurring in the sampling system, thus reducing NO<sub>x</sub> before the sample reached the analyzers, continued. There were a series of traps and filters previously installed in the sample line to capture the ash, water vapor, and acid

condensate, in order to improve the accuracy of the analyzer system. The original dilution probe, made of Inconel, for measuring NO<sub>x</sub> at intermediate levels in the reactors appeared to produce up to 30% NO<sub>x</sub> reduction in the presence of ammonia, thus giving low NO<sub>x</sub> readings at the analyzer. In December 1993, after modifying the probe with 316 SS, the probe was re-tested with and without ceramic probe tips. The results were still the same, with or without the ceramic probe tips, i.e., about 30% NO<sub>x</sub> reduction across the probe. Work continued to resolve this issue with plans formulated to evaluate a glass-lined tip early in 1994.

The above issues were the reasons there were rather limited long-term gas analysis data during this period.

- Ammonia Injection Flow Control

As discussed in previous quarters, actions were taken to improve ammonia flow control. However, the results for the controllers on the large reactors were still unacceptable. One of the original ammonia flow controllers was replaced with another vendor's controller (Brooks) for a trial period of two months. The evaluation was concluded in December and based on the better performance of the Brooks equipment, the decision was made to replace the original ammonia flow controllers for the large reactors.

- Low-dust Reactor Fouling

As discussed in the previous quarter, the low-dust reactor, reactor J, experienced severe plugging of the first catalyst layer after only a few hours of operation during its first start-up after catalyst loading. Modifications were made to this reactor to correct this problem. However, prior to restarting reactor J, Engelhard cited commercial reasons for withdrawing from the project. Thus, operation of both reactors H and J were ceased temporarily because of this decision. Solicitation, evaluation, and selection of catalyst replacements were performed during the next quarter.

- Bypass Heat Exchangers

The bypass heat exchangers, which were included for use during the parametric testing on the large reactors to minimize effects of high ammonia slip upon the long-term evaluation of the air preheaters, were easily plugged by ash and sulfate deposits during start-up. Cleaning with either air or water was not a satisfactory solution. Other means to cool the flue gas while bypassing the air preheaters were evaluated during this period without satisfactory results (based on expected performance or costs). The decision was made to continue to allow flue gas to pass through the air preheaters during parametric testing, thus never requiring these bypass heat exchangers. The parametric tests were for brief periods of time and the higher  $\text{NH}_3/\text{NO}_x$  ratios ( $>0.80$ ) were only a portion of these tests. Therefore, the total time that excursions were at relatively high ammonia slip levels was minimal, resulting in a minimal effect on the long-term evaluation of the air preheaters.

#### 4.3.3 First Quarter 1994

During the first quarter of 1994, all the reactors were operated in long-term base-line operating conditions, i.e. at an effective  $\text{NH}_3/\text{NO}_x$  ratio near 0.81 for 80%  $\text{NO}_x$  removal. In addition to the long-term base-line operating conditions, the second sequence of parametric tests was completed for reactors A - G by May 1994. There were no parametric tests performed on reactor J since there was no catalyst in the reactor until late April, 1994.

The test facility resumed operation on January 3, 1994, after a catalyst sampling and maintenance outage over the holidays at the end of December 1993. After resuming operation of the test facility, complete calibrations of the venturis and ammonia flow controllers were performed. By the end of January most of the ammonia work on the second parametric sequence had been completed on reactors A - C. Except for a brief three hour boiler outage on Crist Unit 5, the SCR test facility remained on-line until shut-down over February 14 to reload catalyst in reactor G. During the last quarter of 1993,

catalyst in reactor G was severely damaged, apparently from air sootblowing procedures destroying the sample-coupons located above the catalyst beds and the catalyst beds themselves. The catalyst supplier, Hitachi Zosen, provided replacement catalyst elements and, based upon their recommendation, sootblowing was discontinued for reactor G. The catalyst coupons which had been destroyed in reactors F and G were also replaced during this outage.

Southern Research Institute (SRI) had previously maintained a staff of six people, supplementing their regular staff of three people with two additional testing crew and an additional analytical chemist. This doubling of staff was required to complete the preliminary parametric testing on all reactors before the end of December 1993. Beginning in January 1994, SRI's staff was reduced to four (one supervisor, two test crew, and one analytical chemist) for handling the remaining parametric test sequences. Supplemental staff was used as circumstances dictated.

There were several unscheduled boiler outages on Crist Unit 5 due to preheater leaks which caused delays in the testing schedule during March. Some of this lost time was made up by the end of the month due to test crew efforts. The test facility was shut-down at the end of March for a catalyst sampling outage. Catalyst sampling was performed on all the previously operating reactors (reactors A - G) and no problems were noted during the sampling. Although scheduled to take two days, the actual sampling was accomplished in one working day and the test facility was returned to service a day early. All samples were shipped to their respective catalyst supplier for laboratory analysis.

Several other major experiences encountered during operation are highlighted below.

- Dilution/Extraction Gas Sampling/Monitoring System

Significant problems were experienced with NO<sub>x</sub> measurements at intermediate levels in the reactors (between catalyst layers) in the presence of ammonia. Apparently catalytic

reactions were occurring in the sampling system, thus reducing NO<sub>x</sub> before the sample reached the analyzers. Work continued to resolve this issue with plans formulated to evaluate a glass-lined tip. In January 1994 the development of a glass-lined tip was completed. On February 1 and 2, 1994, the revised dilution probe was tested. The results were still not acceptable. The best results seen in all the testing were still at least a 10 percent reduction in NO<sub>x</sub> readings, but as much as 60 to 80% reduction had been noted. At the end of this quarter, negotiations were underway regarding final equipment disposition/payment for resolution of the failure of this equipment to meet the specifications under which this system was procured.

- Ammonia Injection Flow Control

By the end of February 1994, all the large reactor ammonia flow controllers were replaced with the Brooks' model, which had been determined in previous trials to be superior to the originally installed controller. These new controllers improved repeatability and experienced fewer malfunctions than those originally purchased. The original controllers for the small reactors did not experience the level of problems as those on the large reactors and no plans were made to replace the ammonia flow controllers for the small reactors.

- Reactor and Air Preheater Sootblowing

As discussed previously, based upon damage to the catalyst in reactor G from sootblowing practices and subsequent catalyst supplier recommendation, sootblowing was discontinued for reactor G. This practice produced no significant effects on reactor pressure drop. Also at a supplier's request, sootblowing frequency was reduced from three to two times per day for reactor D beginning in February 1994 to decrease the rate of erosion noted. After one month, an increase above former values in the reactor pressure drop during operation at the higher flue gas flow rates was observed. The sootblowing schedule for reactor D was re-evaluated at the end of March. Initial studies indicated that the

previously noted erosion may have resulted from a manufacturing problem, and while further review was begun, the normal sootblowing schedule was resumed after March 1994.

#### 4.3.4 Second Quarter 1994

Upon resuming operation after the catalyst sampling at the end of March 1994, the SCR test facility remained on-line the entire month of April and through May 11, when the facility was shut-down for a scheduled boiler outage. Prior to the outage, the replacement catalyst for reactor J, the low-dust train, was loaded; and operation of reactor J began on April 21 and continued until the outage (see catalyst replacement evaluation results later in this section). The second parametric testing sequence and the air heater testing were completed prior to the outage. Testing across the inlet and outlet of each air preheater included the following: particulate and velocity traverses, ammonia partitioning between solid/gas phase,  $\text{SO}_3$ , and HCl measurements.

The May outage was used to meet facility maintenance needs. The electric heater from reactor H train was relocated to the original heater location at the reactor J inlet to compensate for the extra heat loss in the over 100 foot length of ductwork between the ESP outlet and reactor inlet. (The original reactor J electric heater was relocated to the ESP outlet.) Extreme wear was found on the first row of elements of the electric heater on A train. The eroded heater elements were left in the bundle as shields, and spare elements were wired in place. The reactor fans, air booster fan, and ductwork on the suction side of the fans were washed. Maintenance was performed on the service water pump and air compressor. The ammonia storage, handling, and injection system was inspected and minor repairs were made. Two  $\text{NO}_x$  analyzers, several analyzer pumps, and two operator work stations on the gas analyzer system were repaired. The oxygen analysis system had also been giving some erroneous readings, primarily attributed to routine aging of the zirconium cells. The most important oxygen measurements were corrected and work was planned to replace other aged cells.

Also during this outage, one replacement section of APH baskets was supplied by ABB with different materials of construction. These were loaded into the two rotary air heaters and the removed baskets were weighed. There was a notable amount of deposition in the cold end basket of air heater A. During the inspection, the A air preheater cold end sootblower was found to have two plugged nozzles that contributed to the fouling. Both the rotary air heaters were water washed with a high pressure system.

The SCR facility resumed operations on Friday, June 2, 1994. Because of a host boiler outage to resolve air preheater problems, the facility was taken off line on Friday, June 17. The SCR facility was started up again on Monday, June 20. After returning to service and after receiving the high pressure water wash during the May outage, the two rotary air heaters experienced reduced pressure drops at design flows: gas-side pressure drops were reduced by 3 inches of H<sub>2</sub>O for A air heater (from about 9 inches) and by 2 inches of H<sub>2</sub>O for B air heater (from 5.5 inches).

During June 1994 the flue gas venturis and ammonia flow controllers were recalibrated and velocity distributions were performed across all reactors. Particulate distribution and resistivity sampling, and SO<sub>2</sub>/SO<sub>3</sub> balances were completed across the air heaters. Ammonia balances were underway at the end of June 1994.

A special discussion of the replacement/operation of the low-dust catalyst follows:

- Catalyst Replacement on Low-Dust Reactor

Near the end of 1993, Engelhard cited "commercial and strategic considerations" for withdrawing from the project. Thus, operation of two small reactors, reactors H and J were ceased in the fourth quarter of 1993 because of this decision. In considering the alternatives for replacement of the Engelhard catalysts, it was decided to approach the catalyst suppliers already participating in this project for offerings to immediately replace

the low-dust catalyst in reactor J. It was also decided not to seek a replacement for the high-dust catalyst in reactor H. The reasoning for these decisions was as follows:

Since there may be considerably less market for low-dust SCR catalyst, the catalyst by Engelhard was the only low-dust catalyst in the project. However, replacement would maintain the broader applications of the project results. There continued to be interest by all co-funders on the low-dust alternative SCR configuration.

The test plan was reduced from the originally conceived scope because the actual testing manpower and testing time requirements were greater than anticipated. Originally, it was thought that eight parametric test sequences could be performed on each catalyst during the two-year operating duration of this demonstration, with well over 30 different test conditions in each test sequence. In actual practice, the first parametric test sequence, which had a lower number of total tests conducted (at nine different test conditions), required six months to be completed for all operating reactors. With this number of reactors and tests, a total of only three sets of parametric tests could be performed for each catalyst during the demonstration. Replacing only one of the two Engelhard catalysts allowed extra flexibility in the testing for the remaining catalysts. Modification of the test plan to reduce the number of tests conducted in each test sequence from the original plans and replacement of only one of the two catalysts would allow the completion of a total of five parametric test sequences to be performed during the project on the remaining eight catalysts.

The decision to contact only participating project catalysts suppliers was a timing decision. Selection of a supplier already on the project significantly reduced the time required to obtain a replacement catalyst and actually begin testing. If a catalyst supplier outside the project were selected, the time required to secure a new contract (with flowdown provisions and confidentiality agreements) would probably have reduced the length of testing opportunity by three to six months.

In summary, the decision to replace only the low-dust catalyst was based on the higher priority for the low-dust catalyst versus the high-dust catalyst, and the greater value of performing additional tests with the seven existing high-dust catalysts than a reduced testing scope with eight high-dust catalysts.

Solicitation, evaluation, and selection of catalysts replacements were initiated in January 1994. A low-dust catalyst offering from Cormetech was selected as the replacement in March. The catalyst was loaded into reactor J and operation began on April 21, 1994. There were only a few weeks of operation prior to the outage in May. There were no parametric tests performed on this catalyst during this period. The first parametric tests on this catalyst were completed during the next period.

- Low-Dust Reactor Operation

Several changes were made during the fourth quarter of 1993 on the low-dust reactor, reactor J, to prevent recurrence of the severe plugging of the first catalyst layer experienced after only a few hours of operation during its first start-up after catalyst loading. One of the resulting design changes previously described and implemented was increasing the reactor heater capacity and moving the heater to just downstream of the isolation damper to raise the minimum gas temperature throughout the entire length of ductwork between the scoop and reactor inlet.

Prior to the May 1994 outage, the replacement low-dust catalyst from Cormetech was received and loaded into the reactor in April 1994. During the brief operational period prior to the mid May 1994 outage, reaching and maintaining desired upper ranges of flue gas temperature were still difficult. Based on the decision mentioned above to not replace the catalysts in reactor H, the electric heater from reactor H train was relocated during the May outage to the original heater location at the reactor J inlet to compensate for the extra heat loss in the over 100 foot length of ductwork between the ESP outlet and

reactor inlet. During the June operations, improved temperature control was achieved as a result of the two heaters located on this train.

Upon resuming operation of the low-dust reactor (reactor J) after the May outage, pressure drop rapidly increased, caused by deposits breaking loose from the ductwork and depositing on the wire-mesh screens covering the catalysts. The catalyst baskets were removed and vacuumed cleaned, and the reactor was operated without catalyst until deposits were cleared from the system. The catalyst was reloaded and new screens were installed which matched the pitch of the new catalyst which had been loaded just prior to the May outage. The pressure drop returned to normal after these measures were taken. Screen fouling, however, continued to be a source of high pressure drop on the low-dust reactor throughout the remainder of the project. Upset conditions creating high particulate loading as well as periods when the reactor was idled contributed to periodic fouling of the reactor screens.

#### 4.3.5 Third Quarter 1994

During the third quarter of 1994, all the reactors were operated at long-term operating conditions, i.e. at an effective  $\text{NH}_3/\text{NO}_x$  ratio near 0.81 for 80%  $\text{NO}_x$  removal. In addition to the long-term operating conditions, the third sequence of parametric tests was completed for reactors A - J by September 27, 1994.

A short outage was conducted over the July 4th holiday weekend to remove catalyst samples. All catalysts were sampled with the exception of Cormetech, Inc. and Nippon Shokubai America, Inc. The sampling of these catalysts was deferred until August when replacement coupons were available. All catalyst samples were sent to their respective suppliers for analysis. The sampling coupons from one catalyst supplier were nearly completely destroyed, leaving only enough catalyst material for a single sampling. Options were evaluated for replacement of the coupons. Erosion did appear very evident for the Grace Synox catalyst, however, catalyst sampling was performed successfully. The other

catalyst samples/coupons appeared in good condition. While most catalysts appeared to be relatively free of fouling problems, there was some fouling noted on one catalyst. Catalysts were again sampled in reactors A, C, D, F, and G on September 6 and 7 and all samples were returned for analysis to their manufacturer. Reactors B, E, and J were sampled during October to complete the round of sampling. Reactor D (Grace Synox) was inspected by the catalyst supplier during October, and the decision was made to replace the existing catalyst because of physical deterioration. The first catalyst bed was replaced with new catalyst prepared by improved production methods. Some of the original catalyst bed coupons were relocated to this new catalyst bed, allowing the project to continue collecting aging information on the original catalysts. Long-term aging data was also collected on the newer catalyst since all coupons replaced during the previous samplings on the original first bed were of the improved catalyst type.

Weather during the month of July created several operational problems including electronic and electrical failures due to a strong lightening storm (from tropical storm Alberto). These failures included a Bailey control processor, one of the large reactor heater controls, and the air compressor controls. In addition, some small reactor heater elements failed. Repairs and replacements were made on all these items. Furthermore, continuous heavy rains created operational problems from very wet coal for the host boiler. These problems resulted in many rapid load swings, delaying some parametric testing which required steady conditions.

During the month of July the "A" air preheater experienced failure of a sootblowing control valve diaphragm in the pneumatic controller, resulting in loss of effectiveness of the sootblowing system. Within two weeks of operation, the pressure drop rapidly increased to 13" w.c. Because of the increased pressure drop and a cyclic pressure swing that developed in this air heater, a high pressure wash was performed in August to further reduce the pressure drop and eliminate the pressure swing. While the high-pressure wash improved the pressure drop of the air heater, the pressure drop did not fully return to previous levels. The gas-side pressure drops across the air heater at base-line flow (5000

SCFM) averaged about 7" w.c., 3.5" w.c., and under 3" w.c., for "A", "B", and "C" trains, respectively, between sootblowings. An inspection of the rotary air preheaters showed that the clutches on the rotary air preheater variable speed motors had deteriorated due to the much greater-than-normal usage at this facility. Replacement clutches were ordered and were installed in December.

During September some minor repairs were also made. On the "A" air preheater, the lower sootblower nozzles, which were plugged, were cleaned; a thermocouple on the air preheater upper bearing was replaced; and the screen on the sootblowing steam pressure regulator was cleaned. The reactor fans were washed. Ash build-up on the inlet vanes, fan suction housing, and fan wheels had impacted flow capacity. Capacity was restored after the washing. Oxygen probes and NO<sub>x</sub> analyzers and probes were repaired.

#### **4.3.6 Fourth Quarter 1994**

Operations during the final quarter of 1994 progressed smoothly without any major unplanned events. The third parametric sequence was completed October 17, 1994. Testing on the fourth parametric sequence began shortly after. Additional manpower was used to supplement the normal testing staff. This allowed acceleration of the testing to insure early completion of the parametric sequence (in preparation for an extended host boiler outage in the early Spring of 1995). During October the bottom sootblower on reactor B experienced a part failure and was inoperable until the replacement part arrived in November. Problems had been experienced with the flue gas heaters for reactor J, preventing the operation of this reactor at high-temperature test conditions. More power elements were added to the reactor J heaters to increase flue gas temperatures during November. Damaged stand-off tubes were also replaced at this time. December operation progressed very smoothly. Routine maintenance (such as fan washes and sootblower repairs) was performed during the month.

#### 4.3.7 First Quarter 1995

Operation of the test facility progressed relatively smoothly during the first quarter 1995. Total operating time during the period was reduced significantly due to a major host unit outage.

The test facility was returned to service during the first week of January after a brief maintenance and catalyst sampling outage. Maintenance performed during the outage included replacement of the service water pump packing, replacement of the "B" air preheater clutch and cleaning of the cyclone hoppers. Air preheater washes were also performed at this time. Significant improvements in air preheater pressure drop were realized from this washing, resulting in a fan speed reduction of 20% at base-line operation. All catalysts were sampled just before start-up with the exception of reactor "A" which was sampled in March. The facility operation progressed smoothly throughout the month of January with the exception of the failure of the service water pump and some ash fouling problems with the "C" cyclone hopper. The service water pump was damaged due to debris fouling the pump intake. Estimates for repair exceeded \$20,000 and the decision was made to operate the test facility on a temporary cooling water connection to Plant Crist for the remainder of test facility operations. The fourth parametric test was completed during the month.

The test facility was shut-down on February 1, 1995, as a result of a major maintenance outage scheduled for the host unit. The test facility outage continued until May 22, 1995, when test facility operation was resumed. Tests to evaluate ammonia partitioning between the gas and solid phase were conducted just before the outage. Also, ash samples were collected to perform laboratory tests on fly ash concerning ammonia adsorption/desorption characteristics. During the month of February, air preheater fouling was investigated by disassembling both of the rotary air preheaters and by inspecting the hot-gas portion of the heat pipe. The air heaters were washed at this time and wash water samples sent to ABB Air Preheater.

The reassembly of the pilot facility air preheaters was completed in March. Other maintenance items included repair and cleaning of the gas sampling and analysis system, including maintenance of sample lines, pumps, valves, and other system components. Preparation of specifications for dismantling bids was begun.

#### 4.3.8 Second Quarter 1995

The major host boiler outage was in progress at the start of this period. General maintenance and reporting items continued to be addressed. Results of the fourth parametric test sequence (completed in February) were sent to project participants in April. No significant differences were noted in the data, compared to previous parametric sequences. General maintenance on the test facility continued and preparations were begun to modify reactor "H" for proposed high-velocity tests using a Cormetech catalyst. Other notable items during the month included the return of the intermediate NO<sub>x</sub> measurement system to Monitor Labs for refund (this system proved unacceptable for the application). Also, a paper was prepared for presentation at the EPRI/EPA 1995 Joint Symposium on Stationary Combustion NO<sub>x</sub> Control in Kansas City, Missouri.

Host boiler operation resumed over the weekend of May 20, 1995, and the SCR facility resumed operation on May 22, 1995. The first several days of operation were spent calibrating instrumentation, etc., and with general facility check-out. Previous to the facility start-up, modifications to the "H" reactor were completed and installation of the high-velocity test catalyst was made. Testing on the fifth parametric test sequence was begun after facility check-out. A short host unit outage to adjust turbine blade balance forced the test facility off line on May 28, 1995. Operations resumed on May 31, 1995. Failure of the reactor "C" fan motor on May 23, 1995, prevented operation of this reactor for approximately two weeks while repairs to the motor were made. High velocity tests on reactor "H" were begun late in the month, marking the end of nearly two years of shut-down for this reactor.

Parametric testing continued throughout the month of June. Particulate and trace-metal testing was also begun by an SRI off-site test crew. This crew was used to supplement the normal test staff to aid in the completion of the fifth parametric testing requirements by mid-July. A paper was also submitted for presentation at the Annual DOE Clean Coal Technology Conference in September, 1995.

The final parametric test sequence was completed on Thursday, July 13, 1995. Shut-down of the test facility began by mid-day and was completed by the end of the day, July 14, 1995. Thus, the operating and testing phase of the project was concluded.

#### **4.3.9 Operational Phase Synopsis**

The following listing is a chronological synopsis of major events occurring during the operational phase of the project.

##### **July 1993**

- Beginning of operation phase of project (July 1, 1993)
- Operation of reactors with catalyst loaded began
- Plugging of low-dust reactor occurred

##### **August 1993**

- Leak developed in by-pass heat exchanger
- Brief outage from fly-ash build-up on large reactor fan

### **September 1993**

- Completion of validation/base-line tests
- First bank of small reactors started
- Project review meeting held with all participants
- Paper presented at the Second Annual Clean Coal Technology Conference, September 7-9 in Atlanta, Georgia
- Outage conducted to inspect APH's

### **October 1993**

- Preliminary parametric test sequence on large reactors completed
- Preliminary parametric test sequence on reactors D, E, F started
- Several unscheduled host unit outages occurred

### **November 1993**

- Parametric testing begun on reactors G and H
- First catalyst samples retrieved from large reactors
- Damage noted to reactor C top catalyst bed
- Modifications to reactor J completed
- Host unit outage due to boiler tube failure

### **December 1993**

- Completion of preliminary parametric tests
- Damage noted to reactor G catalyst
- Project review meeting held with all participants
- Planned outage for catalyst sampling
- Withdrawal of Engelhard - (Reactors H and J)

### **January 1994**

- Reconfiguration of control system to include calibration/dilution corrections
- Evaluation of alternate ammonia flow controllers

### **February 1994**

- Sootblowing for reactor G terminated
- Sootblowing frequency on reactor D decreased
- Large reactor ammonia flow controllers replaced
- Catalyst suppliers approached for low-dust offerings

### **March 1994**

- Several unscheduled outages due to host boiler reheater leaks
- Cormetech selected as supplier of low-dust catalyst replacement
- Catalyst sampling outage

### **April 1994**

- Second parametric test completed
- Low-dust catalyst replacement shipped, loaded into reactor J, and operations resumed

### **May 1994**

- Air preheater testing completed
- Boiler outage to replace tubes
- Relocation of reactor H heater to reactor J
- Inspection of air preheaters
- Data presented at EPRI NO<sub>x</sub> control workshop
- Data presented at DOE's Second Annual Historically Black Colleges Symposium

### **June 1994**

- Unscheduled host boiler outage for air preheater repairs
- Start of third parametric test sequence (June 24, 1994)
- Recalibration of venturis and ammonia flow controllers
- Measurement of particulate distribution, ash resistivity, and SO<sub>2</sub>/SO<sub>3</sub> balance performed across air preheaters

### **July 1994**

- Catalyst sampling of reactors A, C, D, F, G, J
- Electrical failures and repairs from tropical storm Alberto
- Sootblower failure on A Air Preheater
- Facility tour and project discussion with a Chinese Delegation for Clean Combustion Technologies

### **August 1994**

- Pressure wash of A air preheater
- Sootblowers on A air preheater repaired
- Catalyst sampling of reactors B and E
- Status report and tour provided to plant managers of the Southern Company

### **September 1994**

- Catalyst sampling of reactors A, C, D, F, G
- Reconfiguration of the control system to include O<sub>2</sub> corrections
- Status report and tour provided to representatives from Eglin Air Force Base
- Presentation of paper at DOE's Third Annual Clean Coal Technology Conference

### **October 1994**

- Completion of third parametric test sequence
- Start fourth parametric test sequence (accelerated)
- Failure of bottom sootblower on reactor B
- Tube failure of host boiler requiring a three day forced outage
- Problems noted with rotary air preheater clutches
- Catalyst sampling from reactors B, E, and J
- First bed catalyst replacement on reactor D

### **November 1994**

- Reactor B sootblower repaired
- Power elements added to reactor J heater
- Replacement of remaining catalyst beds on reactor D

### **December 1994**

- Completion of majority of fourth parametric sequence
- Rotary air preheater clutches repaired
- Reactor J heaters repaired

### **January 1995**

- Completion of fourth parametric test sequence
- Restart of test facility after maintenance and catalyst sampling outage
- Sampling of all catalysts except A
- Service water pump failure

### **February 1995**

- Shut-down of test facility in preparation for extended host unit outage
- Special sampling of gas and solid phase ammonia for adsorption/desorption
- Inspection of air preheaters to investigate fouling

### **March 1995**

- Reassembling of air preheaters completed
- Completion of various maintenance items
- Start of preparation of specifications for dismantling bid
- Catalyst sampling from reactor A

### **April 1995**

- Results of fourth parametric test sequence sent to project participants
- Modifications made to reactor-H for high-velocity catalyst test
- Return of intermediate NO<sub>x</sub> measurement system to manufacturer

### **May 1995**

- Completion of host unit outage
- Restart of final abbreviated parametric test sequence
- Beginning of high velocity tests on reactor H
- Failure and repair of reactor C fan motor
- Presentation of paper for the EPRI/EPA Joint Symposium on NO<sub>x</sub> Control

### **June 1995**

- Final particulate and trace metal testing started
- Paper submitted to DOE for presentation at the Clean Coal Technology Conference (September, 1995)

### **July 1995**

- Completion of the final parametric test sequence
- Completion of operation phase of the project and final shut-down of the test facility (July 14)

#### 4.4 Availability

The availability of both the host unit and the test facility was generally very good throughout the life of the project. Unscheduled outages for the host boiler were relatively infrequent especially considering the boiler age. This high availability helped to maximize the quantity of tests performed and the time that catalysts were exposed to flue gas over the two-year calendar life of operations. Operating data indicates that the host boiler was approximately 90% operational (sustained operation at greater than 43 MW) over the test program operational period (excluding the major spring outage of 1995). Of the 90% availability of the host boiler, the test facility had approximately 96% availability.

## 5.0 PERFORMANCE EVALUATION

The data presented in this section are, of course, subject to error as are any data obtained in an experimental program. A study of this type, by nature, presents several concerns pertaining to data accuracy, namely; 1) accuracy of analytical methods, 2) accuracy of testing/sampling methods, and 3) accuracy of test facility operating conditions and measurement of those conditions. Consequently, firm conclusions should not be drawn without considering individual data points in the context of the overall test program. Significant differences in operating conditions may be present, making determination of trends difficult. In addition, large measurement variability may exist. The reader is cautioned to take these factors into consideration when evaluating data, and to consult the appendices containing detailed data presentations concerning exact operating conditions and measurement repeatability. Also, Appendix F contains information related to detection limits and analytical accuracies which are valuable in assessing data significance.

## 5.1 Commissioning Tests

### 5.1.1 Task 1

As discussed in section 3.1.1, the commissioning tests for the facility were divided into three main categories or tasks. The results of the Task 1 commissioning tests are shown in Appendix G. This appendix is divided into several sections as follows. All of the tests in this task were performed without catalyst and without ammonia injection.

|           |   |  |
|-----------|---|--|
| Section 1 | - | Introduction                             |
| Section 2 | - | Venturi Calibration                      |
| Section 3 | - | Particulate (Fly Ash) Mass Concentration |
| Section 4 | - | Particle Size Distribution               |
| Section 5 | - | Flue Gas Chemistry                       |
| Section 6 | - | Fly Ash and Coal Chemistry               |
| Section 7 | - | Trace Metals Analysis                    |

#### 5.1.1.1 Venturi Calibration

Results of each reactor venturi calibration test are shown in Appendix G, pages 2-1 and 2-2. Table 2-1, page 2-2 of the appendix shows the required correction factor for each venturi. This correction factor represents the required multiplier to correct the values of the vendor provided venturi equations (based on pressure drop). The benchmark for these tests were S-type and standard pitots. In most cases the correction was less than 10%. These calibrations were made routinely throughout the test program and subsequent measurements are not reported in detail.

### 5.1.1.2 Particulate Measurements

Results of particulate measurements are reported in pages 3-1 through 3-9 of Appendix G. Task 1 testing began by measuring the particulate mass concentrations of the fly ash in the Unit 5 hot-side ESP inlet and outlet ducting at both high (84 MW) and low (43 MW) load conditions. Two samples were collected at each condition. Table 3-1 in the appendix summarizes the test data. Mass concentrations at the ESP inlet averaged 3.19 and 2.71 gr/dscf @ 3% O<sub>2</sub> for high and low load, respectively. Mass concentrations at the ESP outlet averaged 0.0041 and 0.0007 gr/dscf @ 3% O<sub>2</sub> for high and low load, respectively. The measured flow rates at the ESP inlet and outlet are different because tests were only sampling a portion of the total flow into and out of the Unit 5 hot-side ESP (there are several ESP inlet and outlet ducts). Also, it should be noted that the moisture levels in the flue gas are different at high and low load. These differences are taken into account when measuring and calculating the concentration of nitrogen oxides and other gas phase constituents in the flue gas.

In order to verify that the mass concentration into each of the eight high-dust reactors was similar in magnitude to that measured in the main hot-side ESP inlet duct, mass concentrations were measured at the reactor inlet test ports located immediately upstream of each reactor's flow measuring venturi. Initial measurements indicated a large disparity among the eight reactors as shown in Table 3-2 of Appendix G. Values ranged from a high of 11.9 gr/dscf @ 3% O<sub>2</sub> (reactor G) to a low of 2.8 gr/dscf @ 3% O<sub>2</sub> (reactor A).

Also shown in this table are the data for reactor J, the low-dust small reactor. The data for reactor J were well behaved and of the expected magnitude for high-load conditions. The fact that the measured inlet loadings on reactor J (0.0034 and 0.0037 lb/MBtu) were about half of that measured at the ESP outlet (0.0073 lb/MBtu) can be explained by the fact that the ESP outlet test was performed with a detailed traverse of the entire outlet duct cross section, while the reactor J take-off duct samples were from only a fraction of the total duct cross-sectional area. (Reactor J inlet mass concentrations were not

measured at low load because of the extremely low values expected and the very long sampling times that would have been required to collect sufficient mass for accurate weighing.)

As a result of the large differences between the mass concentration values in the eight high-dust reactors, additional mass concentration tests were performed just upstream of the inlet transition to the eight reactors. Figure 3-2 of Appendix G shows the locations of the nine test positions in the transition piece. The test results are presented in Table 3-3. These data, together with the discovery that the original design of the inlet transition did not provide for proper isokinetic flow transition between the transition piece and the ducting to the five high-dust small reactors, provided sufficient evidence that modification to the design of the inlet transition was required. DynaGen, Inc. was asked to make recommendations as to appropriate modifications. These recommendations were discussed in Section 4.2.1 of this report. These modifications included a static in-line mixer and modifications to the small reactor takeoffs to correct isokinetic problems.

After modifications to the inlet transition were complete, a repeat series of tests was performed. Because of the difficulty of collecting proper samples at the inlet to the five high-dust small reactors, a decision was made to repeat all of the mass concentration measurements in the eight high-dust reactors at a position downstream of the third catalyst layer (the reactor outlet test location). To validate this method, tests were conducted on the three large reactors, both at the inlet and outlet of the reactor. These tests confirmed the validity of this sampling protocol. Tests were performed at both high and low load conditions. Two measurements were performed at each reactor outlet. At the large reactors a nine-point matrix was traversed (three equally-spaced positions in each of three ports). On the small reactors a single port provided for a three point traverse. The test results are shown in Table 3-4 of Appendix G. The mass concentrations were much more uniform after the modification to the inlet transition. In general, the mass concentrations at low load were slightly less variable compared to high load. For all reactors [excluding the low-dust reactor J, and reactor D (due to measurement problems)] the average high

load mass concentration was  $4.01 \pm 0.31$  gr/dscf @ 3% O<sub>2</sub>, with a relative standard deviation of 10.6%. At low load conditions the average mass concentration for all eight reactors was  $3.52 \pm 0.22$  gr/dscf @ 3% O<sub>2</sub>, with a relative standard deviation of 6.3%.

The mass concentration was measured in the economizer bypass duct at low load conditions. The test data are presented in Table 3-5 of Appendix G. The average mass concentration, 3.60 gr/dscf @ 3% O<sub>2</sub>, was about 33% higher than the value measured in the main Unit 5 hot-side ESP inlet duct under similar load conditions, 2.71 gr/dscf @ 3% O<sub>2</sub> (see Table 3-1, Appendix G).

Part of the Task 1 program was to demonstrate that fly ash characteristics (mass concentration and particle size distribution) at the inlet of each of the high-dust reactors were similar under both high-load and low-load conditions. The results of these tests are shown in Appendix G, pages 4-1 through 4-16. The tests also included a comparison of reactor inlet distributions to the host unit (Unit 5) distribution. The instrument used to determine particle size distribution of the fly ash was a Shimadzu Model SA-CP4 Centrifugal Particle Size Analyzer. It is able to size the particles into approximately 25 size intervals between 0.056 and 56.2 micrometers physical diameter (or Stokes diameter, assumed spherical shape and true (actual) particle density). In addition to the fly ash tests for the eight high-dust reactors, particle size tests were also conducted on ash samples collected at the Unit 5 hot-side ESP inlet duct at high and low load conditions.

To supplement the laboratory determination of particle size and to demonstrate the accuracy of the laboratory technique to measure a particle size distribution on a redispersed ash sample (Shimadzu), cascade impactors and series cyclones were used at the Unit 5 hot-side ESP inlet duct to measure the fly ash particle size distribution in situ. Two tests were conducted at high load and two at low load for each instrument. The cascade impactors (University of Washington Mark III (seven stage) Source Test Cascade Impactor) fractionate the fly ash into eight size ranges with stage cut points of 8.0, 5.2, 2.7, 1.4, 0.7, 0.3, and 0.16 micrometers physical diameter. The series cyclones (SRI/EPA

Five-Stage Series Cyclone) fractionate the fly ash into six size ranges with stage cut points of 5.3, 3.3, 1.8, 1.19 and 0.44 micrometers physical diameter.

The particle size distributions of the fly ash at the Unit 5 ESP inlet duct at high and low load are presented in Figures 4-1 and 4-2 of Appendix G, respectively. Figures 4-1a and 4-2a present the data as a differential particle size distribution (percent of total mass in each size range) on a linear scale. Figures 4-1b and 4-2b present the same data with a logarithmic scale. The data in Figures 4-1c and 4-2c are presented on a cumulative percent basis (cumulative percent less than the indicated size). The mass median diameter at high load was measured to be 13 microns with the Shimadzu, 9.5 microns with the cascade impactor, and approximately 6 microns with the series cyclone. At low load the mass median diameter was 9.4 microns with the Shimadzu, 12.6 microns with the cascade impactor, and 8 microns with the series cyclone. The difference in these mass median diameters is likely caused by the more detailed nature of the Shimadzu distribution (25 size fractions) compared to the particle size distributions fitted to the cascade impactor (8 size fractions) and series cyclone (6 size fractions) data. The graphs show best fit spline curves for the impactor and cyclone data.

The individual particle size distributions for the fly ash collected downstream of the third catalyst layer on each of the high-dust reactors (the reactor outlet test location) are shown in Figure 4-3 (high load) and Figure 4-4 (low load) of Appendix G. Figures 4-3a and 4-4a present the data as differential particle size distributions (percent of total mass in the indicated size range) on a linear scale, Figures 4-3b and 4-4b present the same data on a probability scale, Figures 4-3c and 4-4c present the same data on a logarithmic scale, and Figures 4-3d and 4-4d present the cumulative percent particle size distributions. A comparison of the high and low load data show that the low load data are much more tightly grouped. Since the reactors were operating at the same conditions during each set of tests (high and low load) and the fly ash sampling techniques were identical, the more tightly grouped low load data may be caused by more favorable isokinetic flow patterns either at the inlet scoop in the main Unit 5 hot-side ESP inlet duct or in the inlet transition

piece where the flow splits to the eight high-dust reactors. Particle size distributions were not measured for reactor J because the low mass concentration precluded collection of adequate fly ash samples on each stage for accurate weighing.

The particle size distributions measured at the main duct at high and low load conditions (shown in Figures 4-1 and 4-2 of Appendix G, respectively) are compared to the average of the eight high-dust reactor outlet particle size distributions in Figures 4-5 (high load) and 4-6 (low load). The data are shown as differential particle size distributions (percent of total mass in the indicated size range) on three scales, linear (Figures 4-5a and 4-6a), probability (Figures 4-5b and 4-6b), and logarithmic (Figures 4-5c and 4-6c). On each graph a pair of lines without data points are shown. They represent the range of one standard deviation about the average of the eight individual reactor size distributions. For both high and low load conditions the main inlet size distribution agreed very well with the average for the eight high-dust reactors.

#### 5.1.1.3 Flue Gas Chemistry

Results of flue gas chemistry measurements are shown in Appendix G, pages 5-1 through 5-6. The base-line concentrations of the chemical constituents of the flue gas in the Unit 5 hot-side ESP inlet and outlet ducts were measured at both high and low load conditions. The concentrations of the following gases were measured:  $\text{NH}_3$ ,  $\text{HCl}$ ,  $\text{SO}_2$ , and  $\text{SO}_3$ . Because of instrument problems, SRI was not able to measure the concentrations of oxygen and  $\text{NO}_x$  during this test period. In addition, the concentrations of  $\text{SO}_2$  and  $\text{SO}_3$  were measured upstream and downstream of the in-duct heaters on one large and one small reactor to determine whether there was measurable conversion of  $\text{SO}_2$  to  $\text{SO}_3$  across the heaters.

Table 5-1 of the Appendix G summarizes the measured gas-phase pollutant concentrations at the Unit 5 hot-side ESP inlet and outlet ducts for both high and low load conditions.

The concentrations of the gases are presented on a parts per million basis adjusted to a 3% oxygen concentration. The standard deviation of each value is presented.

The data in Table 5-1 of Appendix G show that the concentrations of SO<sub>2</sub> and HCl decrease between high and low load at both the ESP inlet and outlet, while the concentration of SO<sub>3</sub> increased. For all three species there is a somewhat smaller concentration at the ESP outlet compared to the ESP inlet. In all cases the concentration of NH<sub>3</sub> in the flue gas was below the detection limit. (The absence of detectable NH<sub>3</sub> was expected, since NH<sub>3</sub> is not typically found in flue gas unless it is injected from an outside source. The injection of NH<sub>3</sub> to react with NO<sub>x</sub> had not started when these analyses were made).

Test data were acquired to document any SO<sub>2</sub> to SO<sub>3</sub> conversion across the flue gas heaters installed upstream of each reactor. Tests were conducted on a large reactor (B) and a small reactor (D). Three simultaneous SO<sub>2</sub> and SO<sub>3</sub> measurements were performed downstream of the inlet transition (upstream of the reactor heaters), downstream of each reactor heater at the port used for venturi flow calibration, and at the reactor outlet downstream of the third catalyst layer. Tests were conducted at both high and low load. Two tests were performed at each condition. As can be seen in Table 5-2, the increase in SO<sub>3</sub> concentration across the in-duct heaters ranged from 21% to 51% depending on the reactor and load condition. Somewhat unexpected was the apparent reduction in SO<sub>3</sub> concentration across each reactor. This could possibly be explained by localized cool spots within each reactor.

#### 5.1.1.4 Fly Ash and Coal Chemistry, Fly Ash Resistivity

Appendix G, pages 6-1 through 6-7 show results of fly ash and coal chemistry tests as well as fly ash resistivity tests. A more detailed presentation of coal chemistry data is presented in Section 5.7 of this report which details coal analyses for the life of project operations.

Mineral analyses were performed on fly ash samples collected at the Unit 5 hot-side ESP inlet at high and low load conditions. Mineral analyses were also performed on ashed coal samples collected from Unit 5 corresponding to the days on which the fly ash samples were collected. The data are presented on a weight percent basis in Table 6-1 of Appendix G. The analysis shows very similar weight percents for the various chemical constituents for both high and low load conditions. These data match very well with the values for the ash generated from the ignited coal samples.

Seven Plant Crist Unit 5 coal samples were sent by SRI to the University of Missouri-Columbia Research Reactor Facility for Neutron Activation Analysis to determine the concentrations of major (5) and trace (31) elements. These samples included five monthly composite samples prepared by Southern Company Services, Inc. (four from 1992 and one from 1993) and two daily samples obtained near the time when the Task 1 tests were being conducted (CRST-10 from February 10, 1993 and CRST-20 from March 6, 1993). The test results are presented in Table 6-2 of Appendix G. Also included in this table are the results from NIST SRM-1632a Standard Bituminous Coal samples tested for quality control purposes. The last line of the table presents average reference values for each element as found in the literature. Average values and standard deviations are presented for each set of samples. There is good agreement between the average concentrations of the 36 elements between the five monthly composite samples and the two daily samples. Also, there is very good agreement between the quality control test values for the standard coal and the reference values.

Using a series cyclone sampling system, size segregated samples of fly ash were collected at the Unit 5 hot-side ESP inlet at high and low load conditions. The main purpose of this test was to determine the concentration of trace metals in each particle size range. As an additional step it was requested that the concentrations of lithium, sodium, and potassium be measured by Flame Atomic Emission Spectroscopy and that the concentrations of magnesium, calcium, iron, and aluminum be measured using Inductively Coupled Argon Plasma (ICAP) emission spectroscopy. These test data are presented in Table 6-3 of Appendix G (the trace metal data are discussed in Section 5.1.1.5 of this report). At the top of each column the cut size of the cyclone stage is presented. An analysis of the data in the table indicates that while there is an enrichment of element concentration as particle size decreases for lithium, sodium, and magnesium. This trend does not exist for potassium, calcium, iron, and aluminum.

Fly ash resistivity was measured in the laboratory on a fly ash sample collected at the Unit 5 hot-side ESP at high load conditions. The technique for measuring resistivity was based on the IEEE 548 (1984) test method, commonly referred to as a descending temperature method. The atmosphere in the laboratory oven holding the sample was controlled to a moisture content of 7.6%, comparable to that occurring in the actual Unit 5 flue gas. Figure 6-1 of Appendix G presents the relationship between resistivity (ohm-cm) and inverse temperature (1000/K). This is a relatively high resistivity ash ( $3.9 \times 10^{11}$  ohm-cm @ 293 °F) and demonstrates the requirement for flue gas conditioning in cold-side ESPs treating ashes of this type, as well as the reason hot-side ESPs were selected for Crist Unit 5.

#### **5.1.1.5 Trace Metal Analysis**

Appendix G, pages 7-1 through 7-13 show details of trace metal analyses performed during Task 1 commissioning tests. Trace metal concentrations were measured at the Unit 5 hot-side ESP inlet (high and low load), at the reactor A inlet (high and low load), at the Unit 5 hot-side ESP outlet (high load only), and at the economizer bypass duct (low load

only). For collecting trace metals, the U.S. EPA has sanctioned the use of a Method 5 filtration device and back-up impingers - two filled with nitric acid and hydrogen peroxide and two filled with potassium permanganate and sulfuric acid. This test method is commonly referred to as Method 29 - Determination of Metals Emissions from Stationary Sources. This is a proposed method and has not been formally promulgated. Method 29 was used to collect samples at the locations described above. The combination of a particulate filter and the back-up impingers provides a convenient way to collect the trace elements both in the solid and gaseous phases that are of paramount concern. The trace elements that occur as components of the fly ash (solids) are collected on the filter, except for the fractions of certain metals (such as arsenic and selenium) that may occur partly in the vapor state. These partly volatile metals are collected in the  $\text{HNO}_3/\text{H}_2\text{O}_2$  impingers. Mercury is usually completely in the vapor state at temperatures above 300 °F and is collected both in the  $\text{HNO}_3/\text{H}_2\text{O}_2$  and  $\text{KMnO}_4/\text{H}_2\text{SO}_4$  impingers.

Analysis was performed separately on the fly ash (front end) and impinger (back end) samples. The ash was dissolved as completely as possible in concentrated mineral acids and the screening analysis was performed by Inductively Coupled Argon Plasma Emission Spectroscopy (ICAP). ICAP required auxiliary determination of arsenic and selenium by atomic absorption with the elements converted to hydrides for improved sensitivity. Cold vapor atomic absorption was used for mercury determination.

The concentrations of the following elements were determined with Method 29: antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), cesium (Cs), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), rubidium (Rb), selenium (Se), strontium (Sr), tin (Sn), vanadium (V), and zinc (Zn). Analysis of the Method 29 samples was conducted at SRI laboratories in Birmingham.

Finally, trace element concentrations were determined for size segregated fly ash samples collected at the Unit 5 hot-side ESP inlet at high and low load. The samples were

collected using a five-stage series cyclone sampling system. These ash samples were analyzed by ICAP in SRI's Birmingham laboratory.

Additional tests for mercury were performed with iodated carbon mercury vapor traps. Tests were conducted at the Unit 5 hot-side ESP inlet (high and low load), reactor A inlet (high and low load), the Unit 5 hot-side ESP outlet (high and low load), and the economizer bypass duct (low load only). These traps were analyzed by Brooks Rand, Ltd. of Seattle, Washington.

#### **5.1.1.6 Trace Elements Determined By Method 29 and Series Cyclones**

The concentrations of metal species determined by the Method 29 Multiple Metals Train are presented in Tables 7-1, 7-2, and 7-3 of Appendix G. Table 7-1 gives the metal concentrations as weight fractions ( $\mu\text{g/g}$ ) of the total solids collected in the probe and on the filter (front half). Table 7-2 presents cumulative data for the metal concentrations in the front half and in the impingers (back half), also as weight fractions ( $\mu\text{g/g}$ ) of the total solids. Table 7-2 reflects differences from Table 7-1 due only to the amounts of some elements that were in the vapor state. The third table, Table 7-3, expresses the total of each element (front and back halves) as a concentration in the gas stream ( $\mu\text{g}/\text{Nm}^3$ ); it also includes values for total solids in the gas stream (last line of the table). The right-hand column in each table shows the average and the standard deviation of all of the tests, except the one at the ESP outlet at high load (next to last column, Run 3). To calculate averages when data are reported only as upper limits, the true value is assumed to be half the limit.

Table 7-4 lists the concentrations of elements based on analyses of the back half of each train when detected in the back half. The data in the second column (in  $\mu\text{g/g}$ ) are the differences between the averages (columns 9) in Tables 7-1 and 7-2; they are to be interpreted as vapor concentrations but are expressed as weight fractions of the total particulate matter. The data in the third column express apparent vapor concentrations as

percentages of the total of front and back halves. Thus, on a percentage basis, the most volatile element is mercury; the next most volatile is tin; and the third most volatile is selenium.

It is important to realize that the apparent distributions of the metals between the particulate and vapor states are controlled by the temperature of the filter (250 °F) in the multiple metals sampling train (Method 29). The indicated ratios of vapor to particulate are undoubtedly lower in the train than they are in the gas streams sampled at 700 °F. Unfortunately, there is no sanctioned method for sampling flue gas and preserving the in-duct distributions between particulate and vapor states. Given the uncertainty of error from this source, we would expect that both mercury and selenium were mostly in the vapor state at 700 °F. However, these data indicate that only 50% of the mercury and 10% of the selenium were in the vapor state. Perhaps arsenic, considered a threat to the long-term performance of SCR catalysts, occurred mostly in the vapor state at 700 °F, although in these tests it was found to be insignificant in the vapor state.

As a first approximation, all of the runs except that at the ESP outlet at high load were expected to show the same metal concentrations in either  $\mu\text{g/g}$  or  $\mu\text{g}/\text{Nm}^3$ . All tests except that at the ESP outlet were made at sampling locations that were unaffected by the ESP (ESP inlet, reactor A inlet, and economizer bypass). Conceivably, stratification of the gas and particulate matter could have made compositions different at these three sampling locations. Also, differences could be attributed to the different dates when the tests were performed and the differences in boiler load during each test. Nevertheless, any variations at these locations would have been expected to be relatively subtle.

No significant effect is evident between high and low load at the same sampling location, except possibly for selenium, vanadium, and zinc at the ESP inlet and selenium at the reactor A inlet. Selenium is known for difficult-to-reproduce results; however, it is not clear why there was such a spread in the vanadium and zinc results. The difficulty in obtaining reproducible results in these types of measurements is represented by the data

for selenium and cadmium in Tables 7-1, 7-2, and 7-3 of Appendix G. In each case the standard deviation of the average is larger than the average concentration for each element. This is not a necessarily surprising result. Also, there are insufficient test data to draw any conclusions regarding effects on trace metal concentrations by surface area and temperature losses created by the test facility ductwork.

The ESP outlet data, however, are very different from all of the other data. The test results show much higher values on a  $\mu\text{g/g}$  basis as a general rule. This is expected, since the outlet dust is finer in particle size and contains a higher concentration of any metal that at some time existed as a vapor which underwent condensation or adsorption onto existing particle nuclei. On a  $\mu\text{g}/\text{Nm}^3$  basis, however, Table 7-3 shows much lower values for the ESP outlet since most of any metal not in the vapor state has been collected in the ESP.

Table 7-5 of Appendix G compares data precision for all runs except the test at the ESP outlet on the basis of concentrations as  $\mu\text{g/g}$  and  $\mu\text{g}/\text{Nm}^3$ . The comparison suggests that variability was due more to imprecision in analyses than to imprecision in the determination of total particulate concentration, although there was considerable variation in the latter.

Tables 7-6 and 7-7 of Appendix G present the metal concentrations in the dust fractions obtained from the five-stage series cyclone at high and low load, respectively. The tables show the cut points for each stage and give the percentage of the total mass on each stage. By use of the metal concentrations and the weight percentages on each stage, it is possible to calculate the apparent metal concentration in the total ash sample. The results of these calculations are given in the final column in each table.

The data in Tables 7-6 and 7-7 suggest that increasing concentration of an element in the solid ( $\mu\text{g/g}$ ) as particle size decreases is more the rule than the exception. There were very few elements where this did not occur. It suggests that nearly all of the elements, if not exactly all, were in the vapor state at some time in the time-temperature history of the

flue gas and became enriched more in the small particles than the larger ones, because of the greater ratios of surface area to mass in the smaller particles. This explanation, however, is contrary to the widely held belief that some metals (barium and other elements of low volatility, some of which are subsequently identified in Table 7-9) partition evenly between bottom ash and fly ash. Therefore, some alternative, and as yet undetermined, explanation accounts for some of the apparent trends.

Two of the metals shown in Tables 7-6 and 7-7, mercury and selenium, are volatile. This fact may account for the poor data quality for these metals. The concentrations of some metals appear to increase with decreasing particle size even though the data given are only limits. Limits that increase in magnitude as particle size decreases do not imply that actual concentrations increase; they merely signify that the sample amount decreases with particle size and thus the detection limit increases.

There are some differences between the high-load and low-load data in Tables 7-6 and 7-7 of Appendix G that are difficult to associate with just the difference in load conditions. For example, Sb, As, Pb, and Mn appear at higher concentrations in the high-load samples, and Mo was high at low load. Conceivably, there was a change in coal composition accounting for these differences, but there may have been unknown problems in the analytical laboratory that account for the differences.

Table 7-8 compares specific concentrations in the solids (concentrations on the  $\mu\text{g/g}$  basis) for samples from the Method 29 Multiple Metals Train and samples from the cyclones (high load only). The data for the metals train are from Table 7-1, Columns (2 and 3). The data for the cyclones are from Table 7-6, Column 7. There are outstanding differences for four elements: Sb, As, Se, and Sn. The first three of these are known to be relatively volatile. As and Se follow a logical pattern; they are more concentrated in the solids collected on the filter of the metals train (at 250 °F) than they are in the solids collected in the cyclones (at temperatures exceeding 600 - 700 °F). In other words, they show evidence of having been absorbed at the lower collection temperature. Sb seems not

to have followed this pattern. Sn shows evidence of being relatively volatile. Sn, like As and Se, appears to have been removed from the vapor state in the filtration step.

Table 7-9 of Appendix G lists ratios of ESP outlet concentrations to ESP inlet concentrations (in  $\mu\text{g/g}$ , the single ESP outlet test compared to the average of the other tests). The smaller the ratio the more the element is indicated as a matrix element with low volatility. All of the elements with ratios below 2 are plausible as matrix elements; the element with the highest ratio, Hg, is the one expected to be the most volatile. Some of the other elements seem misplaced; for example, Zn seems to be in the wrong place in the company with Se and Sn. Cd and Mo give evidence of being relatively volatile, although this would not be expected.

#### **5.1.1.7 Mercury Concentrations Determined From Iodated Carbon Traps**

The concentration of mercury in the flue gas at the Plant Crist SCR Test Facility was also measured by sampling flue gas through iodated carbon mercury vapor traps. Tests were performed at both the Plant Crist Unit 5 hot-side ESP inlet and outlet ducts at high and low load conditions. Tests were also performed at the reactor A inlet at high and low load and in the economizer bypass duct at low load conditions. For the purpose of material balance calculations, both Plant Crist Unit 5 and NIST certified coal samples were submitted for determination of mercury concentration. The carbon traps and coal samples were analyzed by Brooks Rand, Ltd. of Seattle, WA. The test results are summarized in Table 7-10 of Appendix G.

The mercury concentration in each trap was measured and reported as nanograms per trap. Based on the volume of flue gas sampled through each trap, SRI calculated the mercury concentration in the flue gas as nanograms per standard dry liter corrected to 3% oxygen. The values generally fell in the range of 9 to 14 nanograms per liter. In two cases (CRST-Hg-2 and CRST-Hg-7) Brooks Rand performed triplicate analyses to provide a level of quality assurance. For CRST-Hg-2 the relative standard deviation (rsd)

was 2% and for CRST-Hg-7 the rsd was 5%. Another quality assurance test was to spike blank samples with a known quantity of mercury. (For each test two iodated carbon traps are run in series. The second trap is analyzed and treated as a blank. The mercury concentration measured in the blank trap is then used to adjust the concentration measured in the first trap. Generally the blank mercury concentration averages approximately 1 nanogram per trap.) Mercury spiking was done on two samples, CRST-Hg-3 and CRST-Hg-7. The recovery was 102% and 91%, respectively.

Two coal samples were submitted for analysis. Brooks Rand, as part of their normal service, also tested NIST certified coal samples. The NIST certified value is 0.13  $\mu\text{g/g}$ . In both cases this value was recovered. The mercury concentration in the Plant Crist coal samples differed significantly between the two dates, 0.11  $\mu\text{g/g}$  for 2/10/93 and 0.081  $\mu\text{g/g}$  for 3/6/93. A triplicate of tests was performed on the 3/6/93 sample. The rsd was 4%. Using the mercury concentration values for the coal, the approximate coal feed rate for Unit 5 at high and low load conditions, and the measured flue gas flow rate at the hot-side ESP inlet (the number was doubled to account for the two inlet ducts), the predicted mercury vapor concentration in the flue gas was calculated. The values, ranging from 9.7 to 14.6 nanograms per dry standard liter @ 3% oxygen, agree well with the range of values measured by the iodated carbon mercury vapor traps (9.2 to 14.1 nanograms per dry standard liter @ 3% oxygen).

## 5.1.2 Task 2

Appendix H contains the results of the Task 2 commissioning tests. These tests were performed without catalyst and with ammonia injection. The appendix is divided into the following sections.

|           |   |   |
|-----------|---|---|
| Section 1 | - | Introduction                            |
| Section 2 | - | Ammonia Distribution                    |
| Section 3 | - | Ammonia Loss in the Absence of Catalyst |
| Section 4 | - | Conclusions                             |

### 5.1.2.1 Ammonia Distribution

Ammonia concentrations were measured in cross section at the inlet of each reactor, at a position just above the first catalyst layer, in order to determine the effectiveness of the ammonia injection nozzles and turning vanes to evenly distribute the ammonia across the inlet to the first catalyst bed, as well as to determine an ammonia mass balance relative to the predicted rate of ammonia injection. Ammonia was injected in a horizontal section of ducting upstream of the dummy catalyst bed of each reactor. In the large reactors an array of twenty-five nozzles was used. In the six small reactors sixteen nozzles were used. Just upstream of the ammonia injection port the duct made a transition from round to square. Immediately downstream of the ammonia injection port the duct made a transition from horizontal to vertical. In this 90° transition piece turning vanes were installed to evenly distribute the flue gas and maintain laminar flow. The dummy catalyst layer, located just below this horizontal to vertical transition, was also used to assist in evening out the flow prior to the first catalyst bed.

Ammonia concentrations were measured at six cross-sectional positions above the first catalyst bed in each of the three large reactors. There were three ports that allowed horizontal entry into the reactor at this location. Tests were conducted in the two outer

ports. The middle port was occupied by the NO<sub>x</sub> dilution probe and could not be used for these tests. For each of the six small reactors, ammonia concentrations were measured at four cross-sectional positions (the middle of the four quadrants of the cross section) at a position just above the first catalyst bed. Although the small reactors had only a single sampling port allowing horizontal entry into the reactor, the test probe and nozzle were turned to the side to allow sampling at the selected points. In addition to these measurements upstream of the first catalyst bed, the on-site SCS process engineer requested that an ammonia distribution also be measured upstream of the dummy layer on reactor F.

The reactors were operated at design conditions. For the large reactors this included a nominal space velocity of 1.0 min<sup>-1</sup> (5000 scfm (wet)), a flue gas temperature of 700 °F, and an ammonia injection rate equivalent to an NH<sub>3</sub>/NO<sub>x</sub> ratio of 0.8. The small reactors were also operated at design conditions: a space velocity of 1.0 min<sup>-1</sup> (400 scfm (wet)), a flue gas temperature of 700 °F, and an ammonia injection rate equivalent to an NH<sub>3</sub>/NO<sub>x</sub> ratio of 0.8. Boiler load on the host unit was not maintained at a set value during these tests. However, based on the flue gas oxygen concentrations measured during each test, most of the tests were conducted when the boiler was at full load conditions (84 MW).

Ammonia concentrations were determined by a manual extraction method pulling the flue gas sample through a series of bubblers filled with dilute sulfuric acid. The solutions were then made alkaline in the laboratory (converting the NH<sub>4</sub><sup>+</sup> ion to free NH<sub>3</sub> in solution). The concentration of ammonia was then determined with an ammonia ion specific electrode, Orion Model 920A. In most cases two individual measurements of ammonia concentration were made at each sampling location. This, however, was not done on reactors B and C, where only a single ammonia concentration measurement was made at each sampling point.

The test data for each reactor, A through J, are presented graphically in Figures 2-2 through 2-10, respectively in Appendix H. Each figure shows a plan view of the cross

section of the reactor (the figure also shows the port location) with the average ammonia concentration values (if applicable) positioned at the point of measurement. At the bottom of each figure is the average ammonia concentration for the six or four measurements plus the standard deviation. The relative standard deviation is also presented. All of the data have been adjusted to represent oxygen concentrations of 3%.

Average ammonia concentrations for the three large reactors (A, B, and C) were 294, 346, and 218 ppm(v) @ 3% O<sub>2</sub>, respectively. Average ammonia concentrations for the six small reactors (D, E, F (dummy layer), F (first catalyst layer), G, H, and J) were 360, 369, 264, 238, 291, 316, and 388 ppm(v) @ 3% O<sub>2</sub>, respectively. For the most part, the variations in ammonia concentration across the reactor cross sections were low to moderate. The relative standard deviations for the three large reactors (A, B, and C) were somewhat higher (19.7%, 14.7%, and 24.7%, respectively) than for the six small reactors (D, E, F (dummy layer), F (first catalyst layer), G, H, and J) (11.7%, 9.8%, 2.7%, 10.5%, 8.9%, 10.4%, and 14.9%, respectively). Subsequent to the completion of these tests and based on the variability of the average ammonia concentrations among the reactors, the ammonia mass flow meter for each reactor underwent an extensive recalibration procedure.

#### **5.1.2.2 Ammonia Loss in the Absence of Catalyst**

The second part of Task 2 testing involved the determination of ammonia loss in the absence of catalyst within the reactor caused by ammonia oxidation by oxygen or nitrogen oxides. Also, the host boiler at the Plant Crist SCR Test Facility burns a high-sulfur coal. As a result, the flue gas contains high concentrations of sulfur dioxide and sulfur trioxide. There was a concern that ammonia concentrations within the SCR reactors could be lowered by the reaction of sulfur trioxide with ammonia. To document whether ammonia loss in the absence of catalyst was taking place, ammonia concentrations were measured

simultaneously upstream of the dummy layer and upstream of the third catalyst layer. Tests were conducted on a single large reactor (B) and a single small reactor (F) at four separate operating conditions.

Three tests were performed at each operating condition evaluated. Test conditions included high temperature and high space velocity, high temperature and low space velocity, low temperature and high space velocity, and low temperature and low space velocity. The high temperature was 750 °F. The low temperature was 620 °F. The high nominal space velocity was  $1.5 \text{ min}^{-1}$  (7,500 scfm, large and 600 scfm, small). The low nominal space velocity was  $0.6 \text{ min}^{-1}$  (3,000 scfm, large and 240 scfm, small). The ammonia injection rate during the tests was maintained at a value corresponding to an  $\text{NH}_3/\text{NO}_x$  ratio of 0.8. During each test the oxygen content of the flue gas was measured. The final ammonia concentrations were corrected to 3%  $\text{O}_2$ . Although boiler load was not intentionally held constant during these tests, a review of the oxygen concentrations in the flue gas during the tests showed that all tests occurred during full load conditions (84 MW).

Ammonia concentrations were determined by a manual extraction method pulling the flue gas sample through a series of bubblers filled with dilute sulfuric acid. (At each test location on the large reactor a nine point (3 x 3) traverse was conducted covering the cross-section of the duct. On the small reactor with its single sampling port, a three point matrix was sampled.) The bubbler solutions were then made alkaline in the laboratory (converting the  $\text{NH}_4^+$  ion to free  $\text{NH}_3$  in solution). The concentration of ammonia was then determined with an ammonia ion specific electrode, Orion Model 920A. Two ammonia determinations were made for each sample. As mentioned above, a triplicate of tests was conducted at each sampling location.

The test results are presented in Table 3-1 of Appendix H. Ammonia concentrations were typically in the range of 180 to 250 ppm(v) @ 3%  $\text{O}_2$ . Within the limits of the measurement technique, no significant ammonia loss in the absence of catalyst was

detected between the dummy layer and the third catalyst layer on either reactor. For the data shown in Table 3-1, relative standard deviations ranged from 2.4 to 17.9%.

### 5.1.2.3 Conclusions

As a part of Task 2 testing, Commissioning without Catalysts and with Ammonia Injection, ammonia distribution measurements were conducted upstream of the first catalyst layer on each of the nine reactors. Also ammonia loss tests in the absence of catalyst were conducted simultaneously upstream of the dummy layer and upstream of the third catalyst layer on one large reactor and one small reactor.

Ammonia distribution measurements indicated low to moderate variability of ammonia concentration at the reactor inlet cross-section. Ammonia distributions were somewhat more uniform for the small reactors compared to the large reactors. Relative standard deviations for the large reactors ranged from 14.7% to 24.7%, while relative standard deviations for the small reactors ranged from 2.7% to 14.9%. A consequence of these tests was a thorough recalibration of the ammonia flow control system for each reactor.

No significant ammonia loss in the absence of catalyst across either the large reactor (B) or small reactor (F) was detected. Actual ammonia concentrations ranged from 180 to 250 ppm(v) @ 3% O<sub>2</sub>.

### 5.1.3 Task 3

The original start-up and commissioning test schedule as shown in section 3.1.1 called for task 3 to be split into two sections, one performed without ammonia injection and one with ammonia injection. Specifically, SO<sub>2</sub>/SO<sub>3</sub> conversion rates were to be measured without ammonia present. The decision was made, however, to perform these initial SO<sub>2</sub> oxidation tests with ammonia present as this would be more applicable to a real case

scenario. Thus, all tests performed as part of Task 3 were performed as part of the preliminary (first) parametric sequence as reported in sections 5.3 and 5.4 (Parametric Test Results).

## 5.2 Long Term Tests

### 5.2.1 Flue Gas Composition

An important parameter in evaluating the performance of the facility SCR catalysts was the measurement of flue gas composition being processed by the catalysts. Several of these important constituents were measured on a continuous basis using facility dilution/extraction and in-situ probes. Quarterly averages of these constituents are presented below in Table 5.2-1. Also included are average highs and lows which are computed by averaging daily highs and daily lows for the quarter.

Table 5.2-1 Test Facility Gas Concentrations  
July - September 1993

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 70      | 86   | 44   |
| Inlet NO <sub>x</sub> (ppm) | 320     | 370  | 280  |
| Inlet O <sub>2</sub> (%)    | 4.0     | 7.0  | 2.6  |
| Inlet CO <sub>2</sub> (%)   | 11.9    | 17.1 | 9.2  |
| Inlet CO (ppm)              | 47      | 330  | 7    |
| Inlet SO <sub>2</sub> (ppm) | 1850    | 2170 | 1560 |

#### October - December 1993

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 62      | 79   | 43   |
| Inlet NO <sub>x</sub> (ppm) | 316     | 367  | 268  |
| Inlet O <sub>2</sub> (%)    | 5.6     | 7.1  | 2.5  |
| Inlet CO <sub>2</sub> (%)   | 14.4    | 16.5 | 11.9 |
| Inlet CO (ppm)              | 24      | 165  | 2    |
| Inlet SO <sub>2</sub> (ppm) | 1490    | 1680 | 1275 |

Table 5.2-1 (Cont'd) Test Facility Gas Concentrations

**January - March 1994**

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 64      | 84   | 40   |
| Inlet NO <sub>x</sub> (ppm) | 322     | 376  | 274  |
| Inlet O <sub>2</sub> (%)    | 4.4     | 7.2  | 2.4  |
| Inlet CO <sub>2</sub> (%)   | 16.2    | 19.0 | 12.7 |
| Inlet CO (ppm)              | 63      | 386  | 17   |
| Inlet SO <sub>2</sub> (ppm) | 1690    | 1935 | 1355 |

**April - June 1994**

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 68      | 85   | 45   |
| Inlet NO <sub>x</sub> (ppm) | 334     | 396  | 281  |
| Inlet O <sub>2</sub> (%)    | 4.3     | 7.7  | 2.1  |
| Inlet CO <sub>2</sub> (%)   | 16.4    | 19.0 | 12.9 |
| Inlet CO (ppm)              | 21      | 182  | 0.7  |
| Inlet SO <sub>2</sub> (ppm) | 1583    | 1821 | 1004 |

**July - September 1994**

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 58      | 82   | 37   |
| Inlet NO <sub>x</sub> (ppm) | 351     | 404  | 285  |
| Inlet O <sub>2</sub> (%)    | 5.3     | 8.2  | 2.3  |
| Inlet CO <sub>2</sub> (%)   | 14.6    | 17.7 | 11.5 |
| Inlet CO (ppm)              | 12.2    | 97.1 | 0.6  |
| Inlet SO <sub>2</sub> (ppm) | 1414    | 1699 | 1074 |

**October - December 1994**

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 58      | 81   | 34   |
| Inlet NO <sub>x</sub> (ppm) | 353     | 423  | 276  |
| Inlet O <sub>2</sub> (%)    | 5.3     | 8.2  | 2.7  |
| Inlet CO <sub>2</sub> (%)   | 14.8    | 17.7 | 11.2 |
| Inlet CO (ppm)              | 19      | 88   | 4.4  |
| Inlet SO <sub>2</sub> (ppm) | 1379    | 1618 | 1079 |

Table 5.2-1 (Cont'd) Test Facility Gas Concentrations

**January - March 1995**

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 57      | 71   | 39   |
| Inlet NO <sub>x</sub> (ppm) | 398     | 477  | 335  |
| Inlet O <sub>2</sub> (%)    | 5.1     | 7.4  | 3.2  |
| Inlet CO <sub>2</sub> (%)   | 15.2    | 17.4 | 11.6 |
| Inlet CO (ppm)              | 7       | 28   | 2    |
| Inlet SO <sub>2</sub> (ppm) | 1697    | 1652 | 1728 |

\*Continuous data not available, based on manual test data during high load only

**April - July 1995**

| Constituent                 | Average | High | Low  |
|-----------------------------|---------|------|------|
| Unit #5 Load (MW)           | 74      | 87   | 48   |
| Inlet NO <sub>x</sub> (ppm) | 334     | 365  | 286  |
| Inlet O <sub>2</sub> (%)    | 4.4     | 6.9  | 3.0  |
| Inlet CO <sub>2</sub> (%)   | 15.4    | 17.1 | 12.7 |
| Inlet CO (ppm)              | 4.2     | 4.3  | 2.7  |
| Inlet SO <sub>2</sub> (ppm) | 948     | 1096 | 731  |

**5.2.2 Test Facility Inlet Gas Temperature**

The SCR facility was equipped with an economizer bypass duct. This allowed for high temperature flue gas extracted upstream of the host unit economizer to be mixed with flue gas extracted downstream of the host economizer. By adjusting the relative flows of these two components of the test facility feed gas, the temperature to the test facility could be adjusted. Under normal operation, the flue gas temperature to the test facility was maintained at 650 °F even with full use of the economizer bypass duct. Also, under some circumstances, while the host unit was operating at very high load, the feed gas to the test facility could exceed 650 °F even with no economizer bypass gas being used. The average flue gas temperature on a quarterly basis to the test facility as well as the average of daily high and low temperatures are shown in Table 5.2-2. As with the previously shown gas concentration data, these data are constructed using daily averages, daily highs, and daily lows, during periods of on-line host boiler operation.

Table 5.2-2 Test Facility Inlet Gas Temperature (°F)

| 1993         |         |      |     |
|--------------|---------|------|-----|
|              | Average | High | Low |
| July - Sept. | 642     | 658  | 617 |
| Oct. - Dec.  | 640     | 675  | 624 |
| 1994         |         |      |     |
| Date         | Average | High | Low |
| Jan. - Mar.  | 633     | 655  | 602 |
| Apr. - Jun.  | 654     | 666  | 634 |
| Jul. - Sept. | 652     | 676  | 624 |
| Oct. - Dec.  | 659     | 683  | 623 |
| 1995         |         |      |     |
|              | Average | High | Low |
| Jan. - Mar.  | 666     | 687  | 627 |
| Apr. - July  | 664     | 686  | 636 |

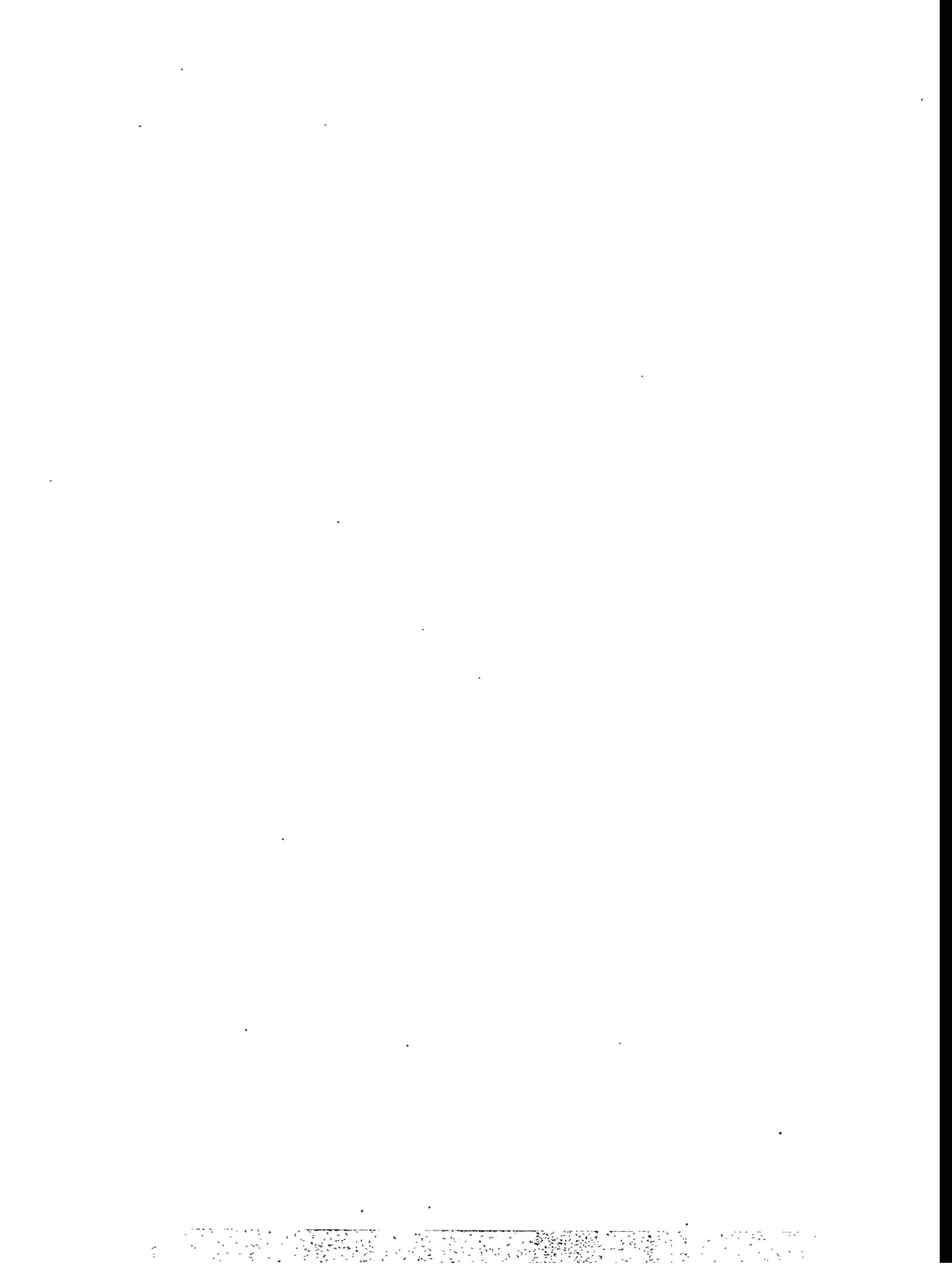
Each reactor was equipped with a flue gas heater which maintained strict control over the temperature of the flue gas entering the reactors. Under normal operating conditions the flue gas was maintained at 700 °F. Under parametric conditions, the flue gas temperature to the reactors was varied approximately from a low of 620 °F to a high of 750 °F. Under these conditions, the economizer bypass duct flow rate could be adjusted to assist the heaters in obtaining the appropriate temperature. Heat loss in the system required some additional flue gas heating over the 50 °F temperature difference noted. Under high temperature parametric conditions, heat loss through the system was more apparent, and flue gas temperatures of 780 °F just downstream of the heater were often required to give 750 °F at the reactor inlet. Lower temperature parametric conditions did not show as extreme a temperature loss between the heaters and the inlet to the reactors. As a result, the heater exit temperature was normally much closer to the reactor inlet gas temperature during low temperature parametric tests and normal operating conditions.

### 5.2.3 Reactor Pressure Drops

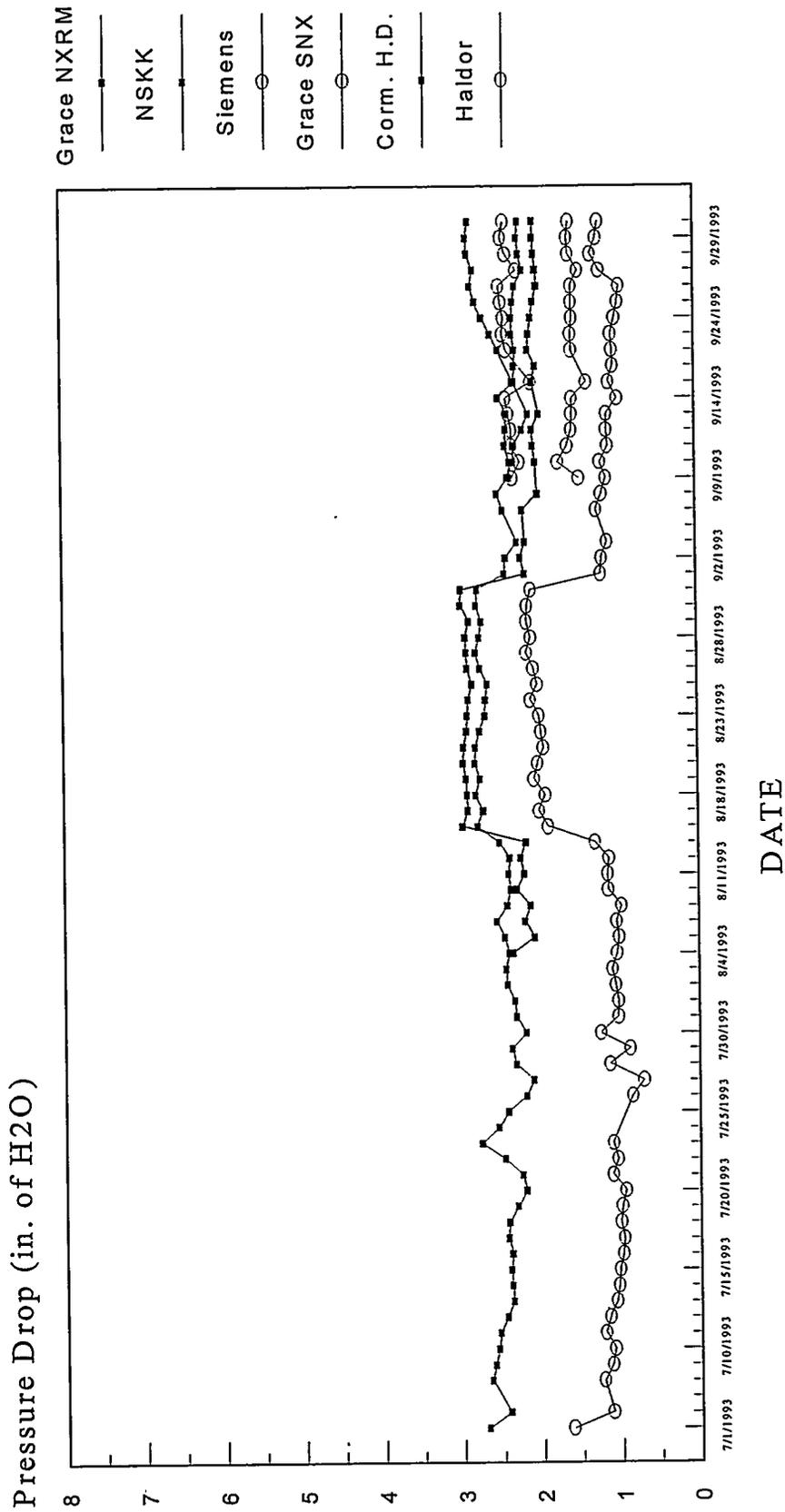
Reactor pressure drops were measured continuously using the facility's distributed control system/data acquisition system. This information is presented in Figure 5.2-1 through 5.2-

8. The data shown represent pressure drops in inches of water column across the entire reactor including the dummy bed and all catalyst beds present. To produce a meaningful plot, the data have been limited to periods of operation at or near base-line conditions (i.e., at temperatures and flow rates within 2% of base-line conditions). Periods where no data are shown indicate that either the reactor or entire test facility was not in operation.

The majority of the catalysts exhibited stable pressure drop with respect to time indicating appropriate sootblowing actions were being made. However, the low-dust reactor (Cormetech, reactor J) exhibited relatively erratic pressure drop swings due to fouling problems on this reactor (see Section 4.3.4, "Low-Dust Reactor Operation").

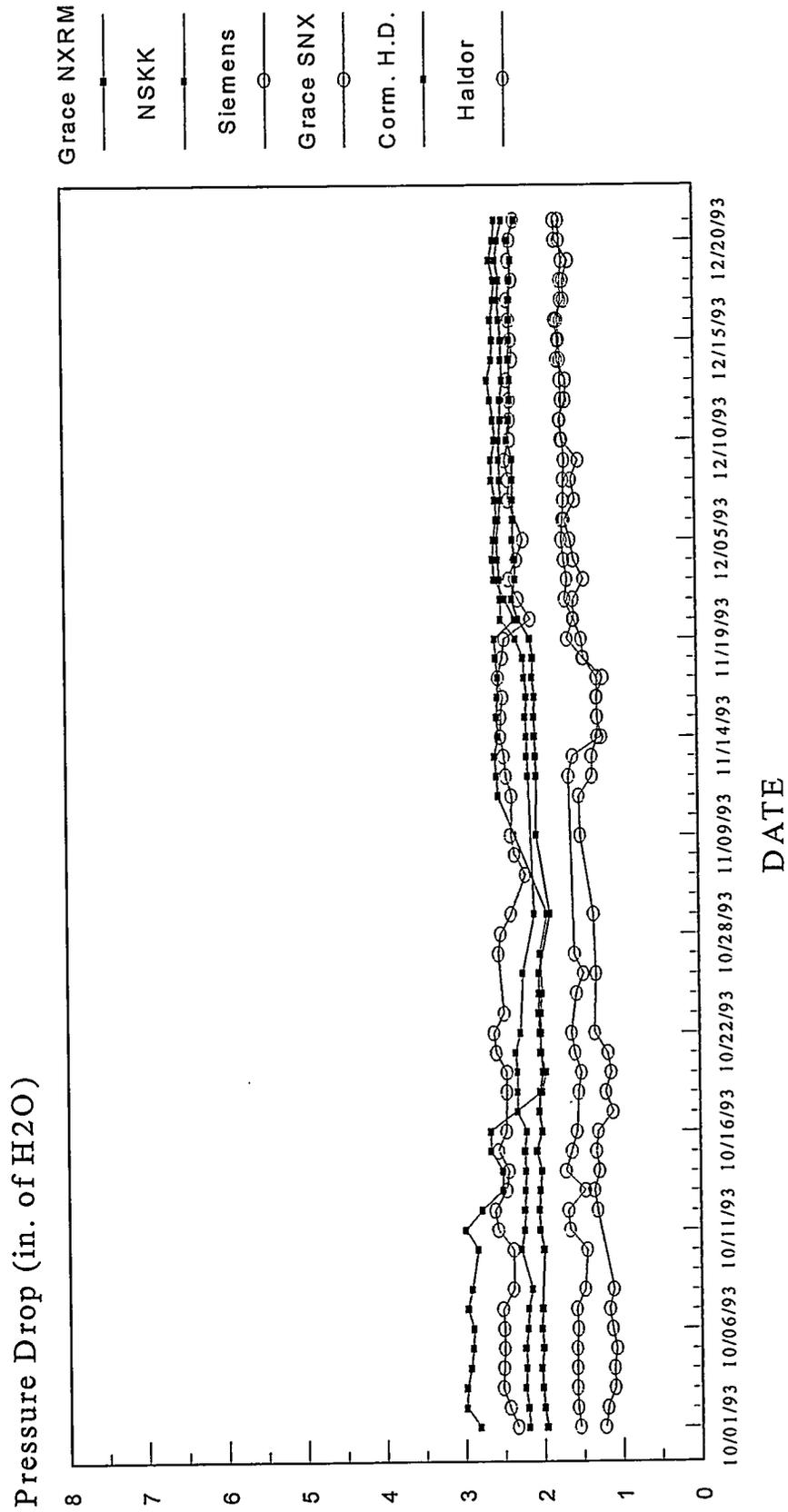


**Figure 5.2-1 Pressure Drop vs. Time**  
**3rd Quarter 1993**



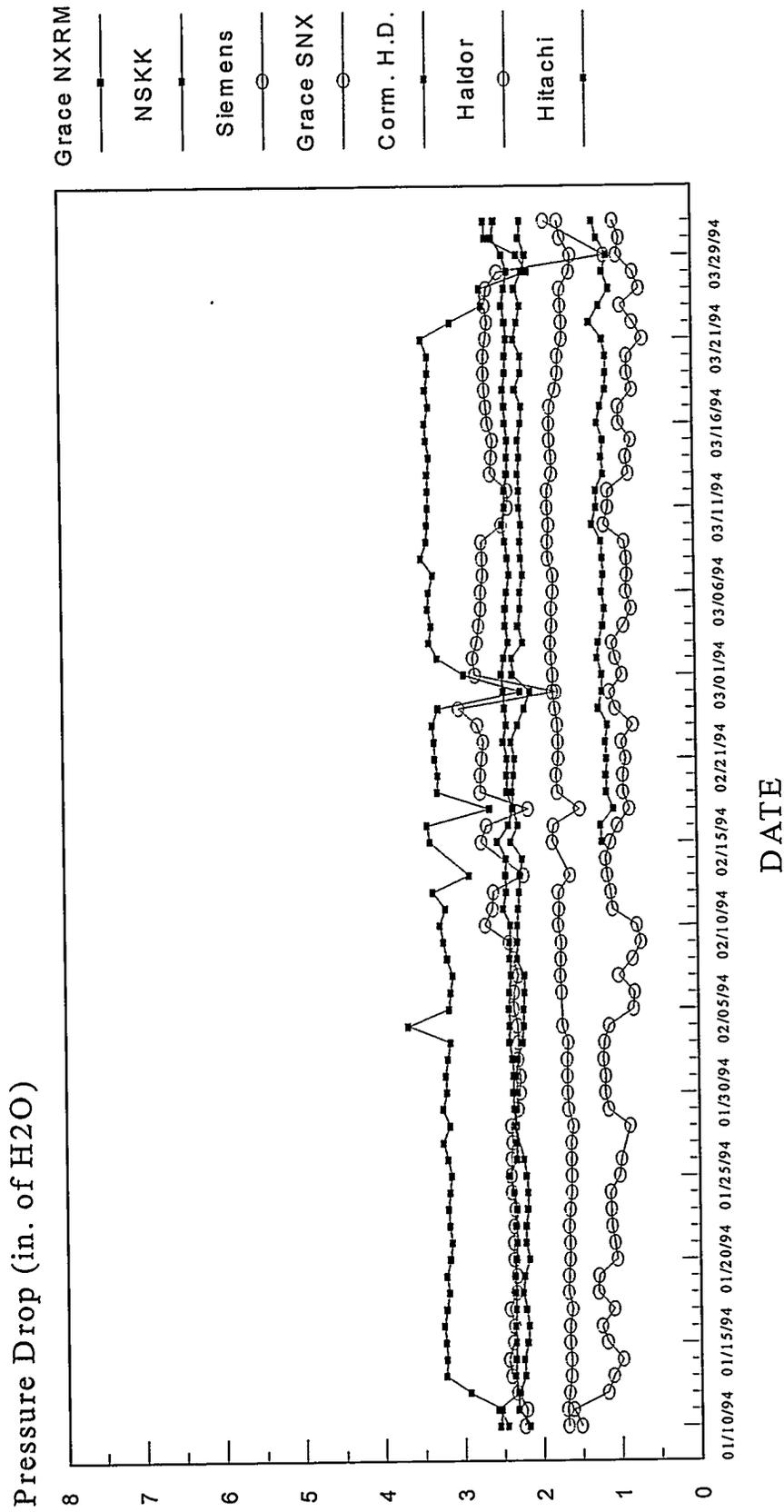


**Figure 5.2-2 Pressure Drop vs. Time**  
 4rth Quarter 1993



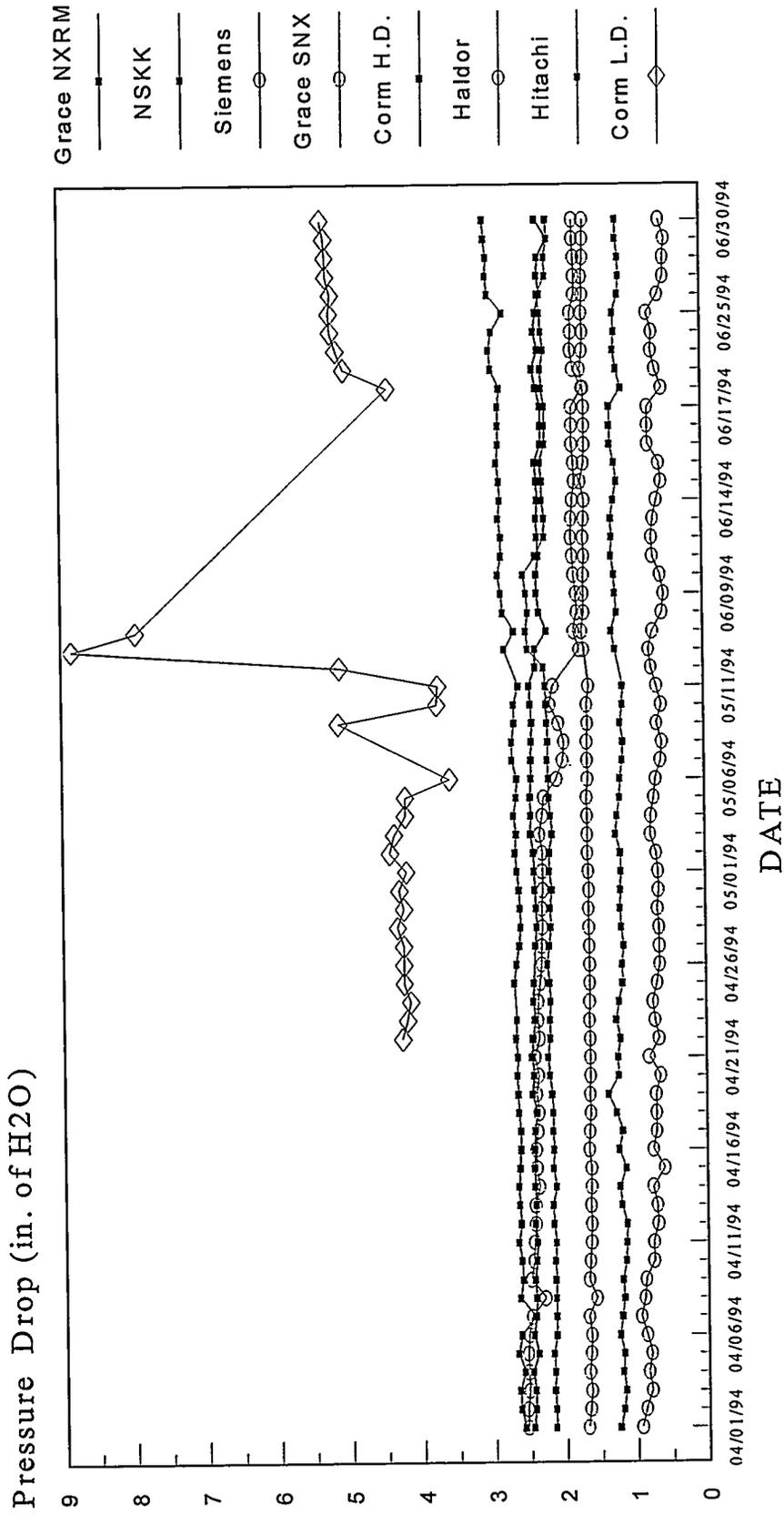


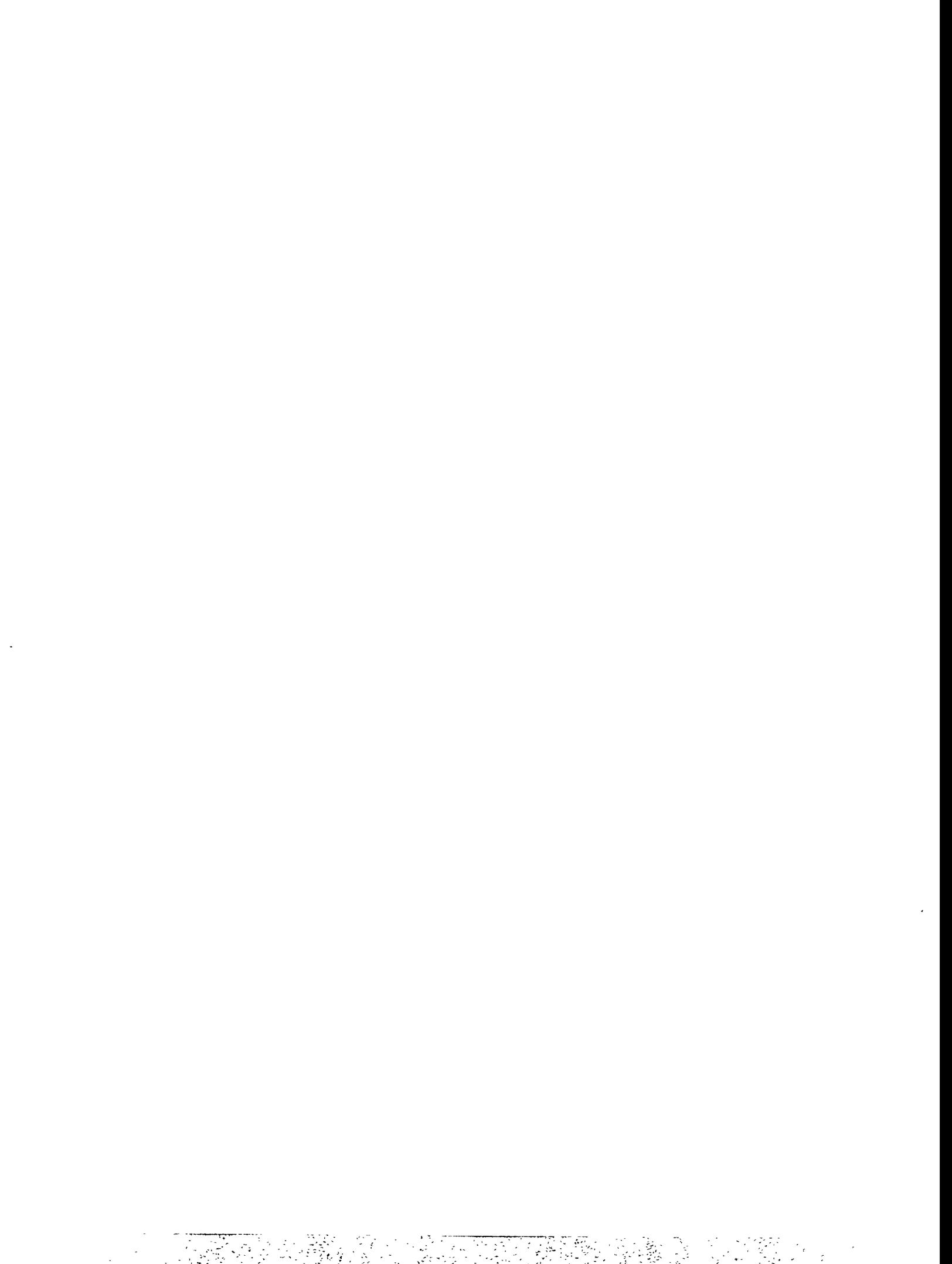
**Figure 5.2-3 Pressure Drop vs. Time**  
**1st Quarter 1994**





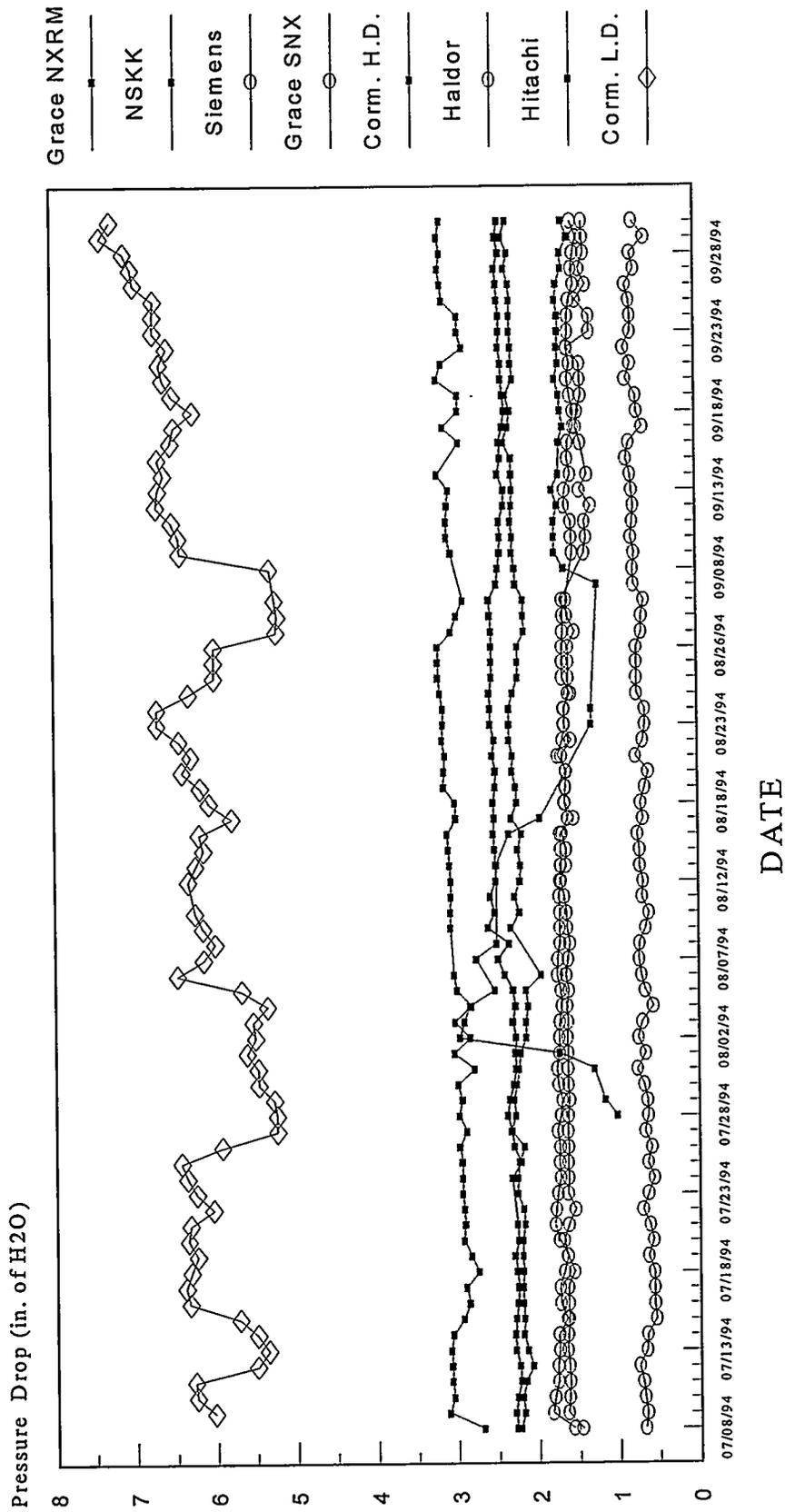
**Figure 5.2-4 Pressure Drop vs. Time**  
 2nd Quarter 1994





# Figure 5.2-5 Pressure Drop vs. Time

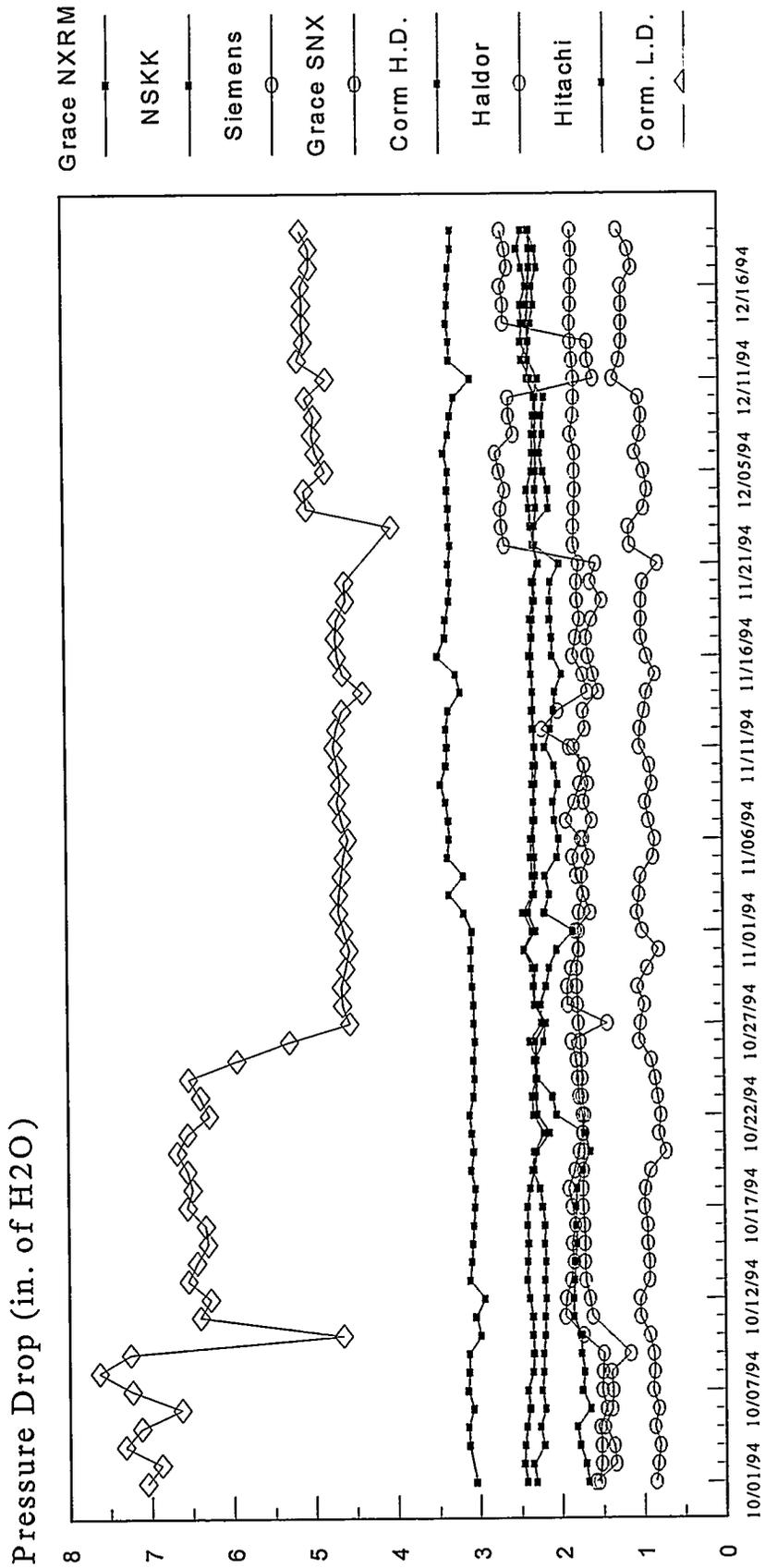
## 3rd Quarter 1994



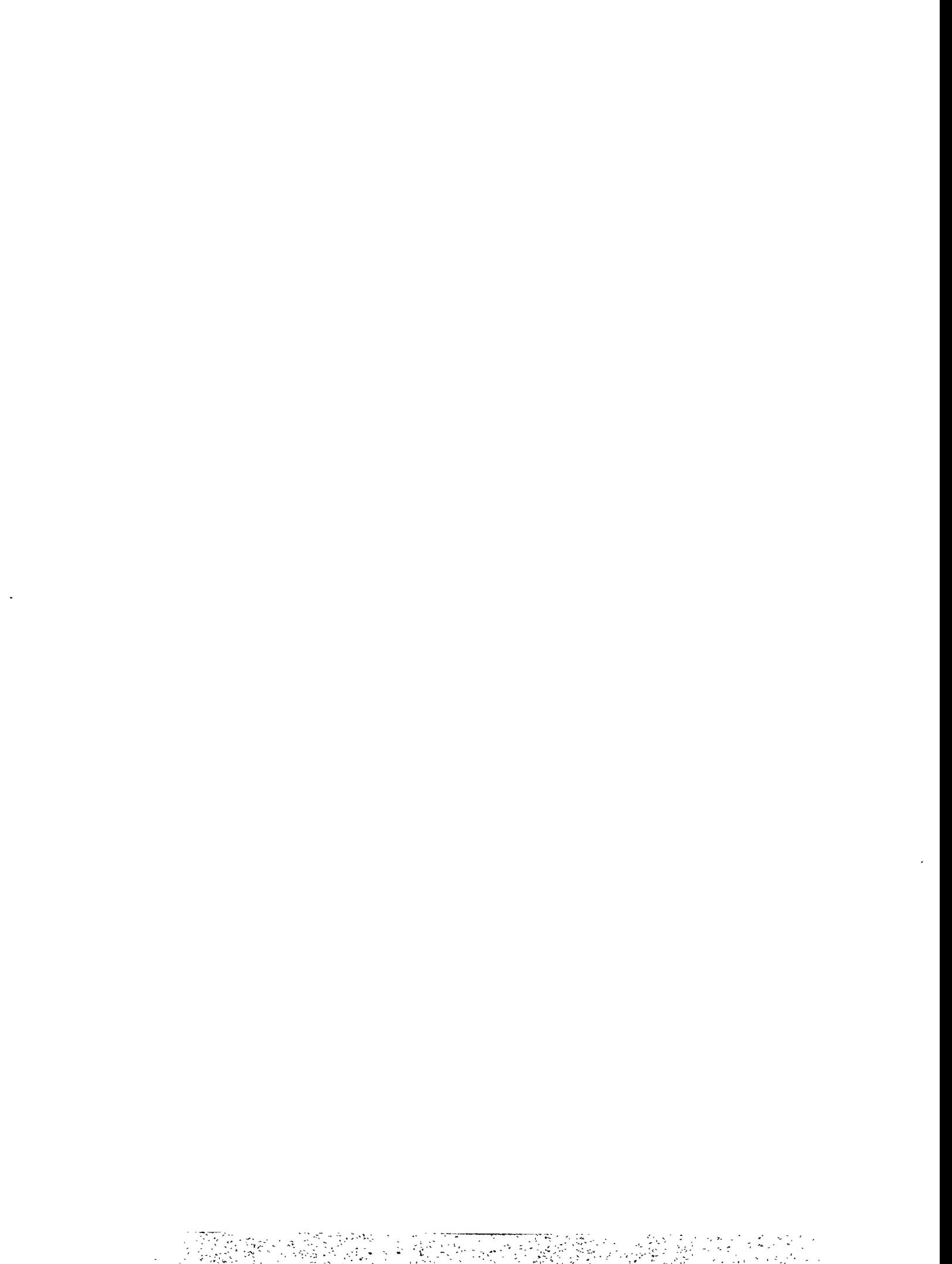


# Figure 5.2-6 Pressure Drop vs. Time

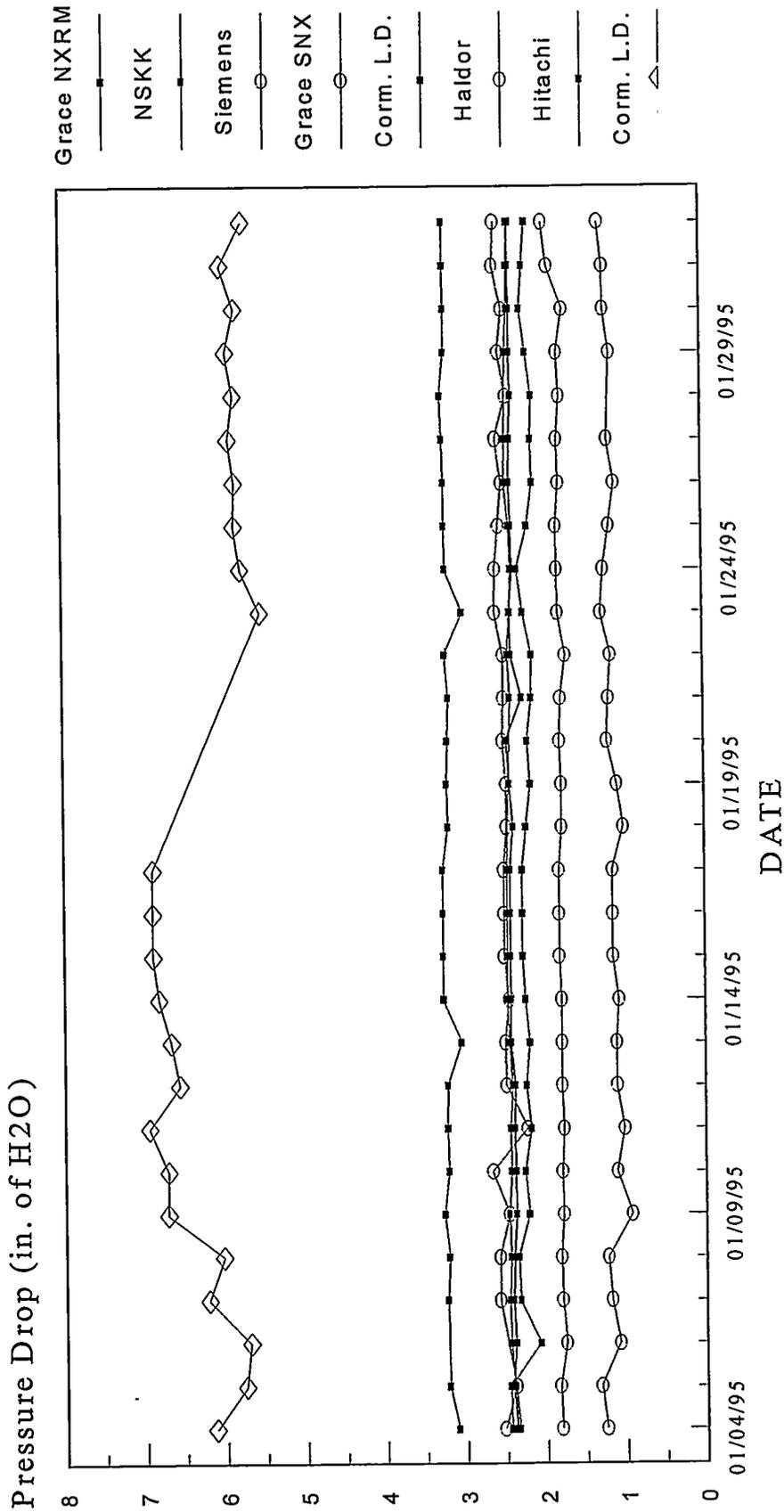
## 4th Quarter 1994



DATE

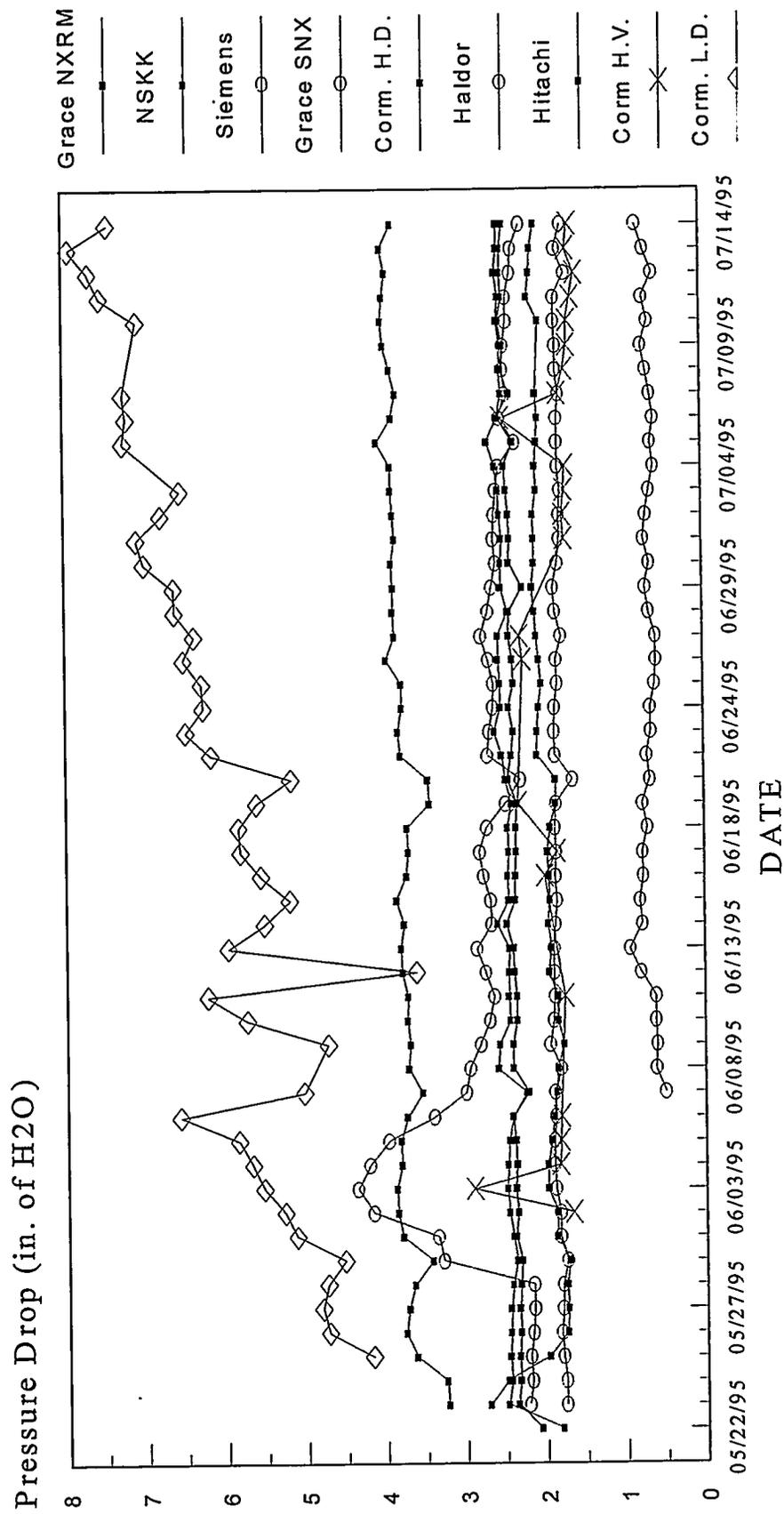


**Figure 5.2-7 Pressure Drop vs. Time**  
**1st Quarter 1995**





**Figure 5.2-8 Pressure Drop vs. Time**  
**3rd Quarter 1995**





### 5.2.4 Long-term NO<sub>x</sub> Reduction

The following tables show long-term NO<sub>x</sub> reduction for each reactor on a quarterly basis. The NO<sub>x</sub> data reflect information obtained on a continuous basis by the gas analysis system and are averages of the data taken at 15 minute intervals. Other data (flow rate, NH<sub>3</sub>/NO<sub>x</sub> ratio) are based on the average of data taken at five minute intervals. NO<sub>x</sub> reduction is calculated as:  $[100\% * (\text{NO}_x \text{ inlet} - \text{NO}_x \text{ outlet}) / \text{NO}_x \text{ inlet}]$  with oxygen variation corrections applied. Continuous data prior to the fourth quarter 1993 are not available. Data of this type are valuable in demonstrating the ability of a catalyst to meet deNO<sub>x</sub> specifications. However, deNO<sub>x</sub> data from a facility such as this are not accurate enough to show catalyst deactivation or to attempt to compare activity between catalysts due to measurement inaccuracy and the strong dependency on other variables.

Table 5.2-3 Reactor A - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD     | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|-----------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| OCT. - DEC. '93 | 4991             | 373                          | 0.77                                   | 35                            | 88                      |
| JAN. - MAR.'94  | 5000             | 348                          | 0.76                                   | 71                            | 76                      |
| APRIL - JUNE'94 | 4992             | 347                          | 0.78                                   | 66                            | 78                      |
| JUL. - SEPT.'94 | 4974             | 376                          | 0.78                                   | 82                            | 77                      |
| OCT. - DEC.'94  | 4945             | 379                          | 0.79                                   | 49                            | 86                      |
| JAN. - MAR.'95  | 4974             | 404                          | 0.79                                   | 48                            | 88                      |
| APRIL - JULY'95 | 5540             | 340                          | 0.76                                   | 61                            | 80                      |

Table 5.2-4 Reactor B - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD     | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|-----------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| OCT. - DEC. '93 | 4969             | 364                          | 0.77                                   | 33                            | 90                      |
| JAN. - MAR.'94  | 5070             | 344                          | 0.77                                   | 71                            | 76                      |
| APRIL - JUNE'94 | 4963             | 359                          | 0.77                                   | 64                            | 81                      |
| JUL. - SEPT.'94 | 5050             | 370                          | 78                                     | 63                            | 81                      |
| OCT. - DEC.'94  | 4987             | 377                          | 0.79                                   | 48                            | 85                      |
| JAN. - MAR.'95  | 4954             | 399                          | 0.79                                   | 32                            | 89                      |
| APRIL - JULY'95 | 5128             | 338                          | 0.80                                   | 51                            | 83                      |

Table 5.2-5 Reactor C - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD      | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|------------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| OCT. - DEC. '93  | 4945             | 359                          | 0.77                                   | 65                            | 80                      |
| JAN. - MAR. '94  | 5101             | 348                          | 0.77                                   | 75                            | 75                      |
| APRIL - JUNE '94 | 5000             | 354                          | 0.78                                   | 59                            | 81                      |
| JUL. - SEPT. '94 | 5090             | 368                          | 0.78                                   | 46                            | 86                      |
| OCT. - DEC. '94  | 4946             | 388                          | 0.79                                   | 50                            | 85                      |
| JAN. - MAR. '95  | 4967             | 410                          | 0.79                                   | 32                            | 89                      |
| APRIL - JULY '95 | 5233             | 345                          | 0.71                                   | 42                            | 85                      |

Table 5.2-6 Reactor D - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD      | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|------------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| OCT. - DEC. '93  | 392              | 340                          | 0.79                                   | 45                            | 84                      |
| JAN. - MAR. '94  | 399              | 345                          | 0.77                                   | 68                            | 73                      |
| APRIL - JUNE '94 | 404              | 345                          | 0.78                                   | 78                            | 77                      |
| JUL. - SEPT. '94 | 401              | 360                          | 0.80                                   | 22                            | 92                      |
| OCT. - DEC. '94  | 400              | 383                          | 0.79                                   | 34                            | 89                      |
| JAN. - MAR. '95  | 404              | 423                          | 0.80                                   | 38                            | 89                      |
| APRIL - JULY '95 | 359              | 336                          | 0.79                                   | 64                            | 78                      |

Table 5.2-7 Reactor E - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD      | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|------------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| OCT. - DEC. '93  | 393              | 358                          | 0.77                                   | 38                            | 86                      |
| JAN. - MAR. '94  | 391              | 343                          | 0.75                                   | 76                            | 73                      |
| APRIL - JUNE '94 | 402              | 331                          | 0.78                                   | 52                            | 82                      |
| JUL. - SEPT. '94 | 406              | 359                          | 0.80                                   | 42                            | 86                      |
| OCT. - DEC. '94  | 400              | 386                          | 0.79                                   | 41                            | 88                      |
| JAN. - MAR. '95  | 400              | 413                          | 0.79                                   | 77                            | 80                      |
| APRIL - JULY '95 | 431              | 338                          | 0.66                                   | 109                           | 62                      |

Table 5.2-8 Reactor F - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD      | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|------------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| OCT. - DEC. '93  | 378              | 353                          | 0.78                                   | 45                            | 85                      |
| JAN. - MAR. '94  | 398              | 346                          | 0.76                                   | 81                            | 71                      |
| APRIL - JUNE '94 | 402              | 354                          | 0.76                                   | 56                            | 78                      |
| JUL. - SEPT. '94 | 401              | 366                          | 0.76                                   | 35                            | 88                      |
| OCT. - DEC. '94  | 401              | 382                          | 0.79                                   | 46                            | 86                      |
| JAN. - MAR. '95  | 400              | 404                          | 0.78                                   | 43                            | 88                      |
| APRIL - JULY '95 | 391              | 334                          | 0.66                                   | 69                            | 75                      |

Table 5.2-9 Reactor G - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD      | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|------------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| APRIL - JUNE '94 | 399              | 345                          | 0.80                                   | 51                            | 80                      |
| JUL. - SEPT. '94 | 401              | 359                          | 0.79                                   | 47                            | 84                      |
| OCT. - DEC. '94  | 402              | 391                          | 0.79                                   | 44                            | 85                      |
| JAN. - MAR. '95  | 400              | 420                          | 0.79                                   | 66                            | 81                      |
| APRIL - JULY '95 | 462              | 323                          | 0.58                                   | 111                           | 46                      |

Table 5.2-10 Reactor J - Long Term NO<sub>x</sub> Reduction

| TIME PERIOD      | FLOW RATE (SCFM) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> ratio | OUTLET NO <sub>x</sub> (ppmv) | NO <sub>x</sub> RED (%) |
|------------------|------------------|------------------------------|--|-------------------------------|-------------------------|
| JUL. - SEPT. '94 | 398              | 386                          | 0.76                                   | 106                           | 71                      |
| OCT. - DEC. '94  | 404              | 398                          | 0.76                                   | 69                            | 79                      |
| JAN. - MAR. '95  | 399              | 422                          | 0.75                                   | 26                            | 88                      |
| APRIL - JULY '95 | 395              | 333                          | 0.61                                   | 87                            | 60                      |

### 5.3 Parametric Tests - Sequential

The following sections (5.3.1 through 5.3.5) contain the results of the five parametric test sequences that were performed on the test facility reactors during the life of the project. The format of each section is similar with basic results shown in the text using figures and tables. Appendices I through M contain the detailed parametric data from which the figures and tables were generated. Section 5.4 shows these parametric data on a summary basis, attempting to consolidate the data, and show exposure time dependency where appropriate.

A large number of plots are shown indicating the effects of various parameters on NO<sub>x</sub> reduction, ammonia slip, SO<sub>2</sub> oxidation, etc. Although somewhat cumbersome, these plots allow the reader to determine catalyst responses of interest. Unfortunately, mathematical models describing the SCR system are extremely complicated and global correlations were not developed, although some attempt was made. The reader is cautioned against direct comparisons of one catalyst's performance to another since significant variations in testing conditions were often present.

#### 5.3.1 First Parametric Sequence (Preliminary)

The parametric test results characterizing the performance for reactors A - F for the first parametric sequence are discussed in the following sections. The parametric tests conducted were composed of nine reactor operating conditions defined by variations in the flue gas flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio. The test conditions for the first parametric sequence are presented graphically in Figure 5.3.1-1 and are shown in tabular form in Table 5.3.1-1. The particular measurements that were made (intermediate ammonia, slip ammonia, SO<sub>2</sub>/SO<sub>3</sub>, HCl, and velocity and mass concentration profiles) are also shown at the various test conditions. Although identical test conditions are indicated, the measurements were not taken simultaneously (e.g., ammonia and SO<sub>2</sub> data for the

same conditions were not collected during the exact same test run, but rather under similar process conditions at different times.)

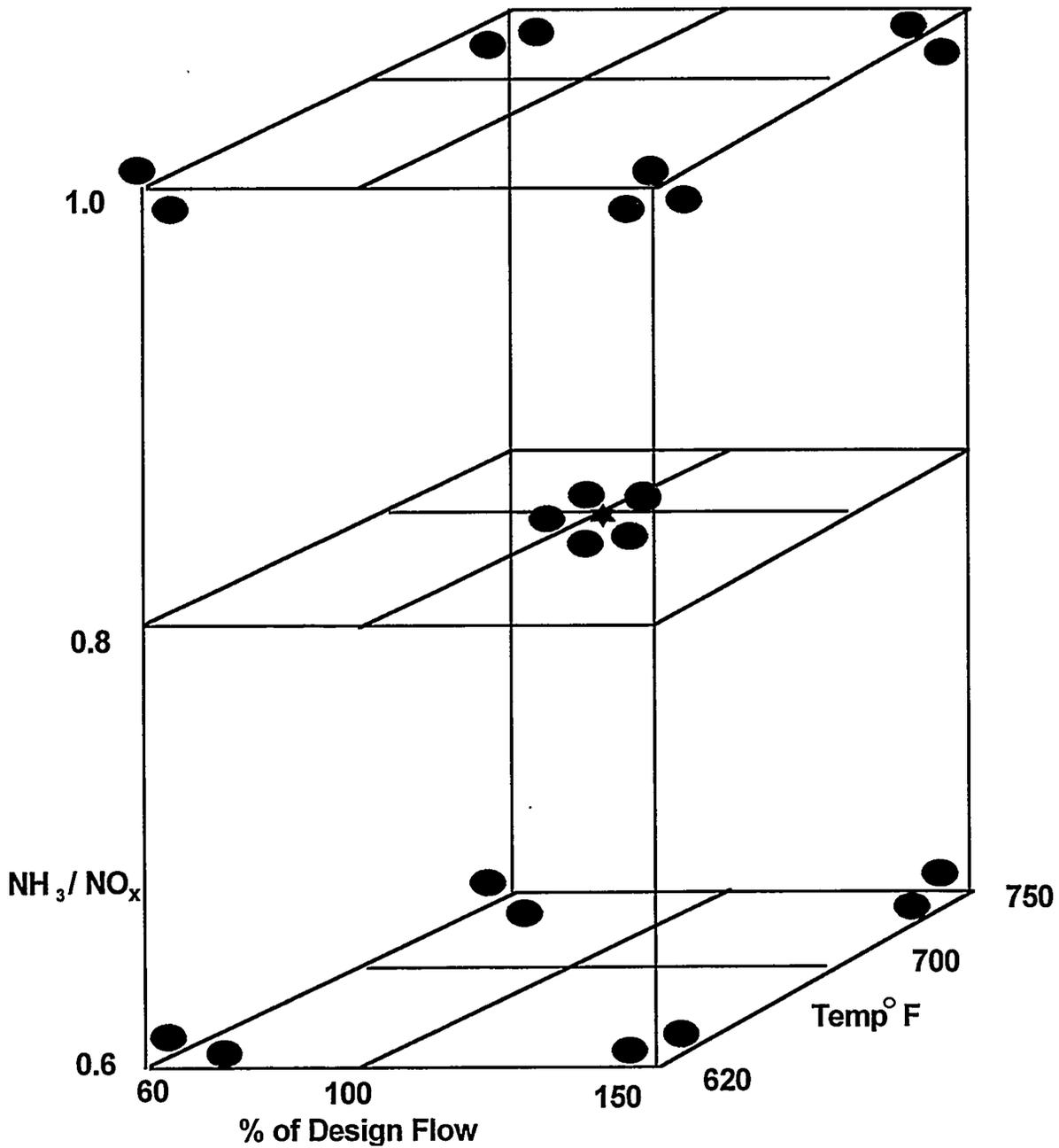
Tables 5.3.1-2 through 7 show the first parametric test data on intermediate ammonia, slip ammonia, and sulfur dioxide oxidation for reactors A - F, respectively. Appendix I contains the detailed data spreadsheets for this parametric sequence. As can be seen in these tables, the actual measured ammonia-to-NO<sub>x</sub> ratios are greater than the intended test condition values. This is primarily the result of some miscalibrations in both flow rate and ammonia injection rate. This higher ratio, however, has one beneficial effect of creating ammonia slip values that were well within the ammonia sampling method detection range. Slips within the detection limits allow for more accurate comparisons between operating conditions and also allow for more accurate reactor modeling to be performed. In some cases a negative SO<sub>2</sub> oxidation rate is quoted. In these cases, it is likely that cold spots within the reactor contributed to SO<sub>3</sub> condensation creating an apparent loss in SO<sub>3</sub>. In some cases, SO<sub>2</sub>/SO<sub>3</sub> adsorption equilibrium may not have been reached creating inconsistencies in the SO<sub>3</sub> data. The inlet SO<sub>3</sub> is "predicted" or correlated using data from previous tests which determined inlet SO<sub>3</sub> as a function of boiler load. This is also a source of error in the SO<sub>2</sub> oxidation calculation. Subsequent parametric series used measured rather than predicted values of SO<sub>3</sub>.

Table 5.3.1-1 Parametric Test Conditions (1st Test Sequence)

| Flue gas flow rate<br>Large / Small reactor<br>(KSCFM) | Flue gas<br>temperature<br>(°F) | NH <sub>3</sub> /NO <sub>x</sub><br>Ratio | Measurements   |
|--|---------------------------------|---|--|
| 3.0 / 0.24   | 620                             | 0.6                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |
| 3.0 / 0.24   | 620                             | 1.0                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub> (A, B, C only)   |
| 7.5 / 0.60   | 620                             | 0.6                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub> (A, B, C only)   |
| 7.5 / 0.60   | 620                             | 1.0                                       | intermediate & slip NH <sub>3</sub> ,<br>SO <sub>2</sub> /SO <sub>3</sub> (A, B, C only)   |
| 5.0 / 0.40   | 700                             | 0.8                                       | * intermediate & slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub> , HCl<br>(D, E, F only), mass and flue gas velocity<br>profile (D, E, F only) |
| 3.0 / 0.24   | 750                             | 0.6                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |
| 3.0 / 0.24   | 750                             | 1.0                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |
| 7.5 / 0.60   | 750                             | 0.6                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |
| 7.5 / 0.60   | 750                             | 1.0                                       | intermediate NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |

\*Design conditions

**Fig 5.3.1-1 First (Abbreviated) SCR Parametric Test Plan**



- Intermediate NH3
- SO2/SO3 (A, B, C, only)
- HCl (D, E, F only)
- ★ Design Point - Long Term
- Mass and Flue Gas Velocity Profile (D, E, F)
- Slip NH3

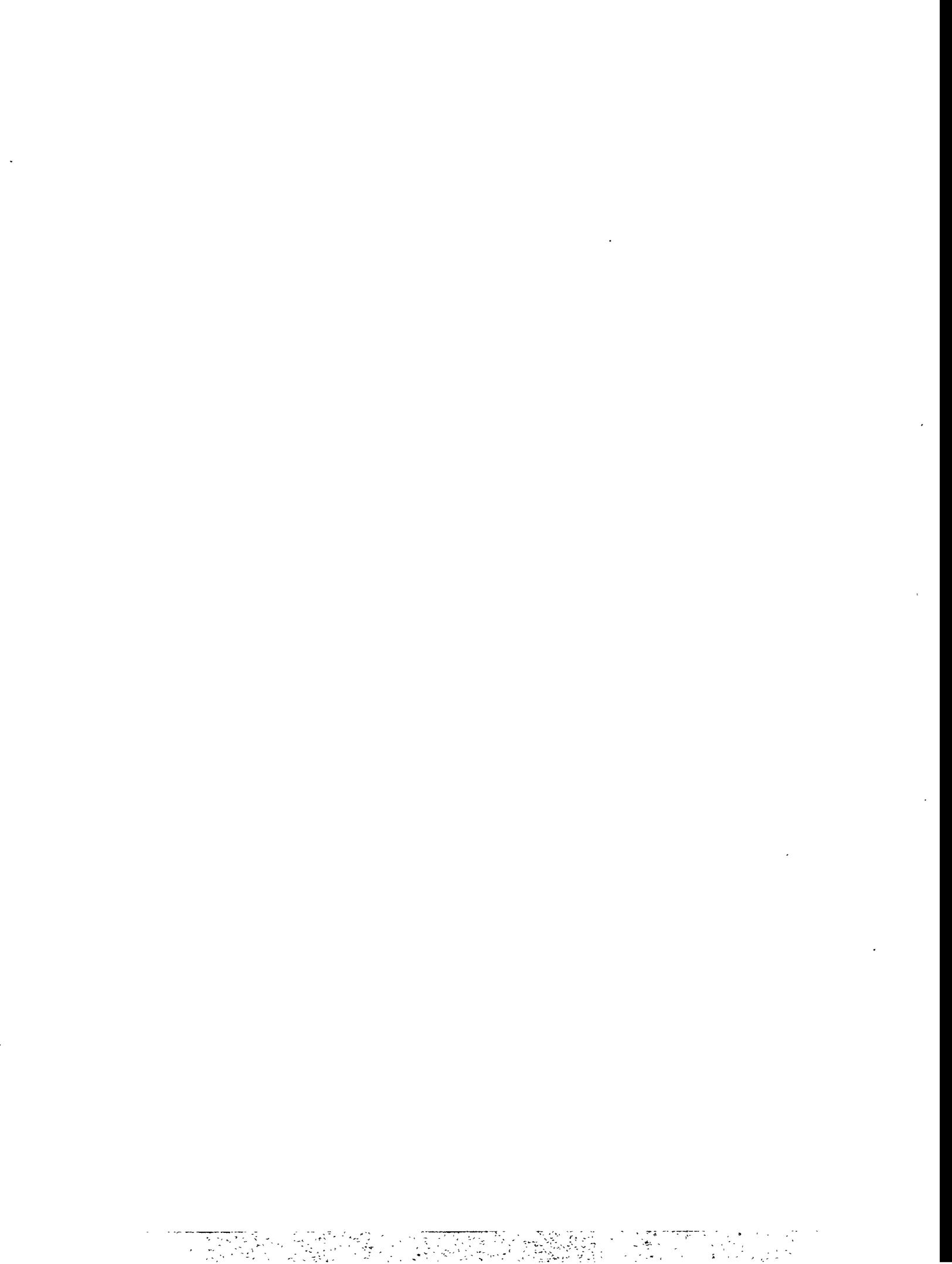


Table 5.3.1-2 Reactor A Data (1st Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 2588             | 620        | 2.914                    | 287                          | 0.694                                  | 5.3                         | 67.6                               |
| 2641             | 620        | 2.731                    | 293                          | 1.112                                  | 39.3                        | 97.8                               |
| 6637             | 620        | 4.989                    | 356                          | 0.638                                  | 20.6                        | 58.0                               |
| 5910             | 620        | 5.414                    | 368                          | 1.201                                  | 86.3                        | 83.4                               |
| 4211             | 700        | 5.765                    | 326                          | 0.966                                  | 14.1                        | 92.3                               |
| 2667             | 750        | 1.916                    | 274                          | 0.680                                  | 3.6                         | 66.7                               |
| 2619             | 750        | 1.842                    | 374                          | 0.810                                  | 11.9                        | 77.8                               |
| 6299             | 750        | 5.503                    | 320                          | 0.742                                  | 13.3                        | 70.0                               |
| 5799             | 750        | 3.191                    | 287                          | 1.206                                  | 31.9                        | 109.5                              |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 6560             | 620        | 4.630                    | 334                          | 1.202                                  | 23.5                        |
| 4491             | 700        | 2.239                    | 292                          | 0.919                                  | 5.7                         |
| 4884             | 700        | 5.868                    | 342                          | 0.918                                  | 1.2                         |

Sulfur Dioxide Oxidation Parametric Test Data

| Flow Rate (SCFM) | Rxr Inlet Temp. (°F) | Outlet O <sub>2</sub> (%) | Inlet SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>3</sub> Formed (ppmv) | Predicted/ SO <sub>3</sub> in (ppmv) | Measured SO <sub>3</sub> out (ppmv) | Oxid. Rate (%) |
|------------------|----------------------|---------------------------|------------------------------|--|-------------------------------|--------------------------------------|-------------------------------------|----------------|
| 2683             | 620                  | 3.265                     | 2002                         | 0.700                                  | -9                            | 13.9                                 | 4.7                                 | 0.46           |
| 2698             | 620                  | 4.633                     | 1658                         | 1.164                                  | -6                            | 13.9                                 | 7.6                                 | -0.39          |
| 6581             | 620                  | 3.117                     | 1944                         | 0.714                                  | -1                            | 8.4                                  | 7.8                                 | -0.03          |
| 6560             | 620                  | 2.884                     | 1947                         | 1.194                                  | -5                            | 8.0                                  | 3.1                                 | -0.25          |
| 4398             | 700                  | 1.986                     | 2216                         | 0.917                                  | 5                             | 9.3                                  | 14.1                                | 0.22           |
| 2716             | 750                  | 3.055                     | 2080                         | 0.674                                  | 43                            | 10.5                                 | 53.3                                | 2.13           |
| 2713             | 750                  | 3.023                     | 2682                         | 1.111                                  | 30                            | 10.1                                 | 39.8                                | 1.48           |
| 5952             | 750                  | 2.603                     | 2066                         | 0.581                                  | 19                            | 9.3                                  | 29.1                                | 0.91           |
| 6454             | 750                  | 6.462                     | 1278                         | 1.089                                  | -12                           | 22.2                                 | 10.7                                | -0.93          |

Table 5.3.1-3 Reactor B (1st Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 2562             | 620        | 2.157                    | 290                          | 0.718                                  | 7.7                         | 69.2                               |
| 2428             | 620        | 5.024                    | 353                          | 1.174                                  | 46.5                        | 104.2                              |
| 6310             | 620        | 2.752                    | 292                          | 0.713                                  | 34.1                        | 59.6                               |
| 6161             | 620        | 2.541                    | 291                          | 1.228                                  | 120.6                       | 81.4                               |
| 4211             | 700        | 4.902                    | 357                          | 0.896                                  | 30.4                        | 81.1                               |
| 2522             | 750        | 2.052                    | 283                          | 0.734                                  | 4.1                         | 71.9                               |
| 2509             | 750        | 2.080                    | 284                          | 1.198                                  | 13.4                        | 115.1                              |
| 6211             | 750        | 1.699                    | 276                          | 0.724                                  | 24.9                        | 63.4                               |
| 6084             | 750        | 2.264                    | 281                          | 1.210                                  | 49.7                        | 103.3                              |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 6229             | 620        | 2.770                    | 298                          | 1.226                                  | 33.4                        |
| 4208             | 700        | 3.106                    | 316                          | 0.985                                  | 0.9                         |
| 5129             | 700        | 5.853                    | 362                          | 1.002                                  | 1.2                         |

Sulfur Dioxide Oxidation Parametric Test Data

| Flow Rate (SCFM) | Rxr Inlet TEMP. (°F) | Outlet O <sub>2</sub> (%) | Inlet SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>3</sub> Formed (ppmv) | Predicted/ SO <sub>3</sub> in (ppmv) | Measured SO <sub>3</sub> out (ppmv) | Oxid. Rate (%) |
|------------------|----------------------|---------------------------|------------------------------|--|-------------------------------|--------------------------------------|-------------------------------------|----------------|
| 4191             | 700                  | 1.850                     | 2198                         | 0.930                                  | -9                            | 10.1                                 | 1.5                                 | -0.39          |
| 2504             | 620                  | 4.162                     | 1728                         | 0.713                                  | -12                           | 17.6                                 | 5.2                                 | -0.73          |
| 2514             | 620                  | 3.572                     | 1951                         | 1.235                                  | -5                            | 8.9                                  | 4.0                                 | -0.25          |
| 6274             | 620                  | 2.654                     | 2007                         | 0.729                                  | -2                            | 8.4                                  | 5.9                                 | -0.13          |
| 6282             | 620                  | 2.342                     | 2006                         | 1.187                                  | -6                            | 8.0                                  | 2.2                                 | -0.29          |
| 2514             | 750                  | 3.717                     | 1886                         | 0.720                                  | 6                             | 16.8                                 | 23.1                                | 0.34           |
| 2511             | 750                  | 4.293                     | 1741                         | 1.221                                  | 1                             | 14.3                                 | 14.8                                | 0.03           |
| 6135             | 750                  | 3.522                     | 1814                         | 0.743                                  | 7                             | 13.5                                 | 20.7                                | 0.40           |
| 6167             | 750                  | 2.951                     | 1970                         | 1.254                                  | 0                             | 8.9                                  | 9.2                                 | 0.01           |

Table 5.3.1-4 Reactor C (1st Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 2526             | 620        | 1.853                    | 275                          | 0.671                                  | 8.7                         | 64.0                               |
| 2504             | 620        | 2.697                    | 286                          | 1.199                                  | 55.1                        | 100.6                              |
| 6323             | 620        | 1.931                    | 275                          | 0.725                                  | 25.6                        | 63.2                               |
| 4195             | 620        | 2.250                    | 280                          | 1.207                                  | 85.5                        | 90.2                               |
| 2549             | 700        | 5.169                    | 351                          | 0.909                                  | 26.9                        | 83.2                               |
| 2443             | 750        | 2.320                    | 286                          | 0.728                                  | 6.9                         | 70.4                               |
| 6206             | 750        | 5.713                    | 330                          | 1.252                                  | 37.4                        | 113.9                              |
| 6228             | 750        | 2.518                    | 284                          | 0.736                                  | 18.8                        | 67.0                               |
| 6084             | 750        | 2.868                    | 287                          | 1.223                                  | 53.1                        | 103.8                              |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 6295             | 620        | 1.836                    | 269                          | 1.213                                  | 70.6                        |
| 4221             | 700        | 1.988                    | 301                          | 0.960                                  | 5.6                         |
| 5451             | 700        | 6.108                    | 358                          | 0.688                                  | 2.0                         |

Sulfur Dioxide Oxidation Parametric Test Data

| Flow Rate (SCFM) | Rxr Inlet Temp. (°F) | Outlet O <sub>2</sub> (%) | Inlet SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>3</sub> Formed (ppmv) | Predicted/ SO <sub>3</sub> in (ppmv) | Measured SO <sub>3</sub> out (ppmv) | Oxid. Rate (%) |
|------------------|----------------------|---------------------------|------------------------------|--|-------------------------------|--------------------------------------|-------------------------------------|----------------|
| 2530             | 620                  | 4.851                     | 1629                         | 0.708                                  | -7                            | 23.5                                 | 16.7                                | -0.42          |
| 2528             | 620                  | 3.259                     | 1921                         | 1.213                                  | -3                            | 9.7                                  | 6.6                                 | -0.16          |
| 6198             | 620                  | 3.032                     | 1032                         | 0.704                                  | -22                           | 25.5                                 | 2.7                                 | -2.34          |
| 6326             | 620                  | 3.364                     | 1945                         | 1.197                                  | -9                            | 15.5                                 | 6.6                                 | -0.46          |
| 4313             | 700                  | 6.313                     | 1415                         | 1.169                                  | 17                            | 9.7                                  | 26.2                                | 1.19           |
| 2527             | 750                  | 4.321                     | 1706                         | 0.723                                  | 17                            | 16.4                                 | 66.0                                | 2.97           |
| 2522             | 750                  | 3.134                     | 1985                         | 1.221                                  | 50                            | 8.9                                  | 56.3                                | 2.43           |
| 6326             | 750                  | 2.533                     | 2019                         | 0.720                                  | 47                            | 8.0                                  | 39.7                                | 1.58           |
| 6326             | 750                  | 4.468                     | 1655                         | 1.128                                  | 13                            | 14.3                                 | 27.5                                | 0.81           |

Table 5.3.1-5 Reactor D (1st Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 224              | 620        | 6.083                    | 306                          | 0.713                                  | 7.9                         | 68.7                               |
| 230              | 620        | 5.794                    | 322                          | 1.190                                  | 29.1                        | 110.0                              |
| 532              | 620        | 5.151                    | 272                          | 0.696                                  | 28.2                        | 59.2                               |
| 559              | 620        | 6.204                    | 303                          | 0.969                                  | 101.5                       | 63.4                               |
| 351              | 700        | 6.335                    | 315                          | 0.994                                  | 22.4                        | 92.2                               |
| 228              | 750        | 6.067                    | 309                          | 0.714                                  | 5.6                         | 69.6                               |
| 226              | 750        | 2.990                    | 241                          | 1.207                                  | 12.5                        | 115.6                              |
| 556              | 750        | 3.419                    | 258                          | 0.702                                  | 25.0                        | 60.5                               |
| 560              | 750        | 3.638                    | 237                          | 1.202                                  | 67.7                        | 91.8                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 560              | 620        | 2.710                    | 311                          | 1.197                                  | 75.2                        |
| 372              | 700        | 2.320                    | 330                          | 0.951                                  | 2.4                         |
| 412              | 700        | 4.472                    | 340                          | 0.857                                  | 1.4                         |

Sulfur Dioxide Oxidation Parametric Test Data

| Flow Rate (SCFM) | Operating Temp. (°F) | Outlet O <sub>2</sub> (%) | Inlet SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>3</sub> Formed (ppmv) | Predicted/ SO <sub>3</sub> in (ppmv) | Measured SO <sub>3</sub> out (ppmv) | Oxid. Rate (%) |
|------------------|----------------------|---------------------------|------------------------------|--|-------------------------------|--------------------------------------|-------------------------------------|----------------|
| 298              | 620                  | 8.089                     | 1896                         | 0.715                                  | -2                            | 6.9                                  | 5.0                                 | -0.13          |
| 418              | 700                  | 6.194                     | 1723                         | 0.951                                  | 12.3                          | 7.5                                  | 19.8                                | 0.80           |
| 287              | 750                  | 7.689                     | 1847                         | 0.721                                  | 17                            | 6.3                                  | 23.4                                | 1.19           |
| 289              | 750                  | 7.960                     | 2025                         | 1.207                                  | 26                            | 6.6                                  | 32.7                                | 1.66           |
| 555              | 750                  | 4.371                     | 1680                         | 0.721                                  | 14                            | 7.5                                  | 21.5                                | 0.84           |
| 568              | 750                  | 5.009                     | 1631                         | 1.187                                  | 6                             | 8.4                                  | 14.1                                | 0.36           |

Table 5.3.1-6 Reactor E (1st Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM), | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|-------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 223               | 620        | 3.655                    | 279                          | 0.695                                  | 2.6                         | 68.6                               |
| 222               | 620        | 5.563                    | 265                          | 1.117                                  | 3.6                         | 110.4                              |
| 565               | 620        | 5.320                    | 286                          | 0.666                                  | 14.2                        | 61.7                               |
| 558               | 620        | 3.026                    | 274                          | 1.156                                  | 90.6                        | 82.6                               |
| 366               | 700        | 4.314                    | 280                          | 0.940                                  | 11.8                        | 89.8                               |
| 226               | 750        | 3.504                    | 250                          | 0.713                                  | 1.3                         | 70.8                               |
| 227               | 750        | 3.718                    | 237                          | 1.199                                  | 4.4                         | 118.1                              |
| 544               | 750        | 5.969                    | 292                          | 0.665                                  | 10.8                        | 62.8                               |
| 559               | 750        | 2.934                    | 242                          | 1.202                                  | 41.1                        | 103.2                              |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 560              | 620        | 3.699                    | 232                          | 1.131                                  | 59.8                        |
| 373              | 700        | 3.929                    | 334                          | 0.938                                  | BDL                         |
| 327              | 700        | 5.761                    | 341                          | 0.991                                  | 0.1                         |

Sulfur Dioxide Oxidation Parametric Test Data

| Flow Rate (SCFM) | Operating Temp. (°F) | Outlet O <sub>2</sub> (%) | Inlet SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>3</sub> Formed (ppmv) | Predicted/ SO <sub>3</sub> in (ppmv) | Measured SO <sub>3</sub> out (ppmv) | Oxid. Rate (%) |
|------------------|----------------------|---------------------------|------------------------------|--|-------------------------------|--------------------------------------|-------------------------------------|----------------|
| 267              | 620                  | 6.683                     | 1884                         | 0.722                                  | 0                             | 6.9                                  | 6.3                                 | -0.04          |
| 403              | 700                  | 5.608                     | 1730                         | 0.950                                  | 6.8                           | 7.5                                  | 14.3                                | 0.43           |
| 257              | 750                  | 6.312                     | 2043                         | 0.728                                  | 29                            | 6.6                                  | 35.1                                | 1.60           |
| 254              | 750                  | 6.324                     | 2027                         | 1.220                                  | 8                             | 6.6                                  | 14.5                                | 0.45           |
| 592              | 750                  | 4.930                     | 1768                         | 0.689                                  | 6                             | 7.5                                  | 13.7                                | 0.38           |
| 578              | 750                  | 5.559                     | 1660                         | 1.171                                  | 0                             | 8.4                                  | 8.9                                 | 0              |

Table 5.3.1-7 Reactor F (1st Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 213              | 620        | 3.512                    | 300                          | 0.700                                  | 5.2                         | 68.3                               |
| 223              | 620        | 3.265                    | 315                          | 1.098                                  | 21.6                        | 102.9                              |
| 557              | 620        | 4.913                    | 290                          | 0.656                                  | 33.7                        | 54.0                               |
| 554              | 620        | 2.166                    | 310                          | 1.015                                  | 98.8                        | 69.6                               |
| 368              | 700        | 3.248                    | 290                          | 0.887                                  | 30.9                        | 78.1                               |
| 224              | 750        | 6.218                    | 325                          | 0.663                                  | 4.4                         | 64.9                               |
| 226              | 750        | 3.732                    | 271                          | 1.144                                  | 11.7                        | 110.1                              |
| 554              | 750        | 6.123                    | 199                          | 0.980                                  | 28.1                        | 83.9                               |
| 555              | 750        | 1.867                    | 289                          | 1.068                                  | 75.9                        | 80.6                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 559              | 620        | 2.714                    | 311                          | 1.091                                  | 31.8                        |
| 368              | 700        | 2.323                    | 331                          | 0.896                                  | 76.8                        |
| 377              | 700        | 4.471                    | 336                          | 0.872                                  | 0.7                         |

Sulfur Dioxide Oxidation Parametric Test Data

| Flow Rate (SCFM) | Operating Temp. (°F) | Outlet O <sub>2</sub> (%) | Inlet SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>3</sub> Formed (ppmv) | Predicted/ SO <sub>3</sub> in (ppmv) | Measured SO <sub>3</sub> out (ppmv) | Oxid. Rate (%) |
|------------------|----------------------|---------------------------|------------------------------|--|-------------------------------|--------------------------------------|-------------------------------------|----------------|
| 201              | 620                  | 3.696                     | 2013                         | 0.791                                  | -4                            | 6.9                                  | 3.2                                 | -0.19          |
| 393              | 700                  | 3.602                     | 1908                         | 0.862                                  | 0.4                           | 7.5                                  | 7.9                                 | 0.02           |
| 237              | 750                  | 3.833                     | 2202                         | 0.674                                  | 4                             | 6.6                                  | 10.9                                | 0.21           |
| 237              | 750                  | 3.887                     | 2177                         | 1.124                                  | 3                             | 6.6                                  | 9.1                                 | 0.12           |
| 538              | 750                  | 2.930                     | 1868                         | 0.656                                  | 2                             | 7.2                                  | 9.1                                 | 0.10           |
| 538              | 750                  | 3.687                     | 1757                         | 1.094                                  | -2                            | 8.4                                  | 6.7                                 | -0.10          |

### Intermediate NO<sub>x</sub> Reduction

The majority of the ammonia measurements during the preliminary parametric tests focused on concentrations downstream of the first catalyst bed. These measurements were made as part of a series of statistically designed tests which varied flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio. Each of these parameters was varied using a high and low value. Thus, eight permutations were created which correspond to the eight test conditions for this portion of the parametric tests. The results of this series of tests conducted for reactors A - F are shown as plots of NO<sub>x</sub> removal across the first catalyst bed versus ammonia-to-NO<sub>x</sub> ratio in Figures 5.3.1-2 through 7, respectively. Test procedures called for the measurement of ammonia, which is used in the kinetic analyses. The NO<sub>x</sub> removals reported with the intermediate ammonia measurements were computed from the measured ammonia concentrations using a material balance which assumed a 1:1 stoichiometry for the reaction of ammonia and NO<sub>x</sub>. Thus, the moles of ammonia consumed equaled the moles of NO<sub>x</sub> reduced, from which NO<sub>x</sub> reduction was computed, after oxygen corrections were made.

### SO<sub>2</sub> Oxidation

The plots for SO<sub>2</sub> oxidation versus flow rate for the combination of all catalyst beds in the reactors are shown in Figures 5.3.1-8 through 13 for reactors A - F, respectively. The flow rate effect data are based on high temperature data, with two lines shown, one for high ammonia-to-NO<sub>x</sub> ratio, and one for low ammonia-to-NO<sub>x</sub> ratio. In general, decreasing SO<sub>2</sub> oxidation is noted with flow rate. This finding is expected since the reaction rate is predicted to be inversely proportional to flow rate, according to published rate data and information provided by catalyst suppliers. These plots also show a definite ammonia-to-NO<sub>x</sub> ratio effect on the sulfur dioxide oxidation characteristics of the catalysts. However, this effect is not thought to be a true catalytic effect, but actually a precipitation effect. Earlier studies with no catalyst present showed that sulfur trioxide was lost through the reactors, most likely in cold spots such as test ports, etc. The

presence of ammonia may have affected this precipitation phenomenon. Most likely this occurred by changing the precipitation characteristics of the sulfur trioxide through the formation of by-products such as ammonium bisulfate in the cold spots of the reactors. In addition, some error may be due to non-attainment of  $\text{SO}_3$  equilibrium prior to the measurements being made.

$\text{SO}_2$  oxidation versus temperature for the combination of all catalyst beds in the reactors is shown in Figures 5.3.1-14 through 19 for reactors A - F, respectively. The plots show a linear increase in  $\text{SO}_2$  oxidation with increasing temperature. Published information describing the effects of temperature on  $\text{SO}_2$  oxidation and information obtained from the catalyst suppliers indicates that increases in  $\text{SO}_2$  oxidation are expected to be more exponential with respect to temperature. The general trend of increasing  $\text{SO}_2$  oxidation is expected, however, and the plots provide a good basis for determining the potential for  $\text{SO}_3$  formation across the SCR reactors at various operating temperatures.

The  $\text{SO}_2$  oxidation data are corrected to reactor outlet oxygen concentrations. The value for sulfur trioxide produced in the reactors is based on the measured reactor outlet sulfur trioxide concentration and estimated reactor inlet sulfur trioxide values. The reactor inlet sulfur trioxide values are estimated using past measurements of inlet sulfur trioxide based on host boiler load. In many cases, especially those involving low temperature conditions, there was no net increase in sulfur trioxide concentration across the reactors. In fact, some operating conditions showed an apparent loss in sulfur trioxide across the reactors. It is believed that the apparent loss was caused by phenomena such as acid condensation and the formation of ammonium bisulfate on cold spots at the reactor surfaces. (Tables showing  $\text{SO}_2$  oxidation rates quote reactor flow rates as calculated for the reactor exits, since  $\text{SO}_3$  was measured at this point.) For consistency with other figures, the plots of  $\text{SO}_2$  oxidation versus flow rate are based on reactor inlet flow rates. In practice, differences between inlet and outlet flow rates are slight and do not greatly affect the overall analysis.

### Additional Base-Line Measurements

Mass concentrations (three-point) and flue gas velocity profiles (three-point) were conducted at an 84-MW boiler load near design operating conditions (700 °F, 100% flow rate, and NH<sub>3</sub>/NO<sub>x</sub> ratio of 0.8) for reactors D, E, and F. The mass concentration profile data is given in Figures 5.3.1-20 through 22 for reactors D - F, respectively, in four different units of concentration and as mass emission rates. The flue gas velocity profiles are presented in Figures 5.3.1-23 through 25 for reactors D - F, respectively. The results of the mass concentrations and flue gas velocity profiles are given in Table 5.3.1-8 .

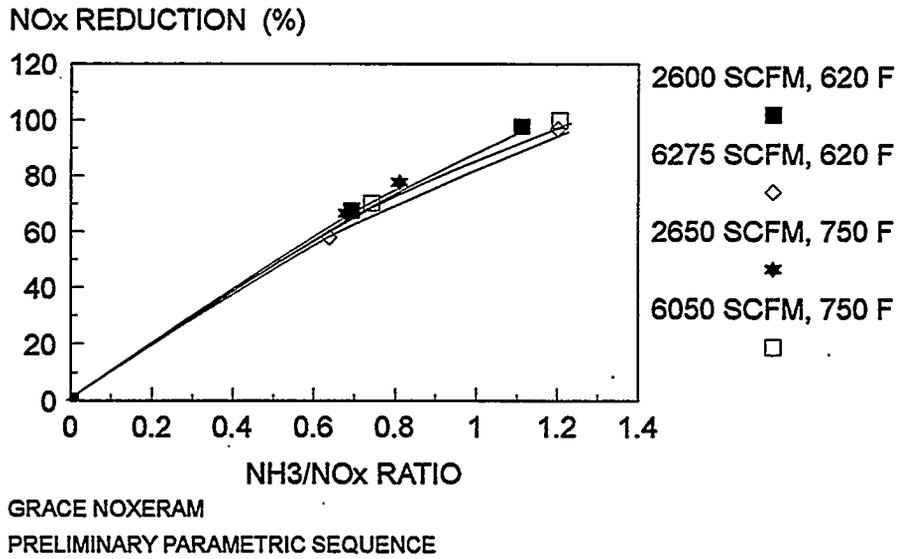
HCl concentrations were also measured at the design operating conditions for reactors D, E, and F at the reactor exits. The resulting HCl concentrations (at 3% O<sub>2</sub>, wet) are shown in Table 5.3.1-8.

Table 5.3.1-8 Additional Base-line Measurements

| Reactor<br>(Catalyst)      | Mass<br>concentration<br>(gr/dscf) | Velocity<br>Profile<br>(ft/sec) | HCl<br>concentration<br>(ppmv) |
|----------------------------|------------------------------------|---------------------------------|--------------------------------|
|                            | rxr outlet                         | rxr outlet                      | rxr outlet                     |
| Reactor D<br>(Grace Synox) | 2.89 ± 8%                          | 11.6 ± 0.4                      | 124 ± 8.7                      |
| Reactor E<br>(Corm. HD)    | 3.39 ± 18%                         | 12.0 ± 2.3                      | 194 ± 8.1                      |
| Reactor F<br>(Haldor)      | 4.01 ± 13.5%                       | 13.1 ± 0.87                     | 186 ± 6.6                      |

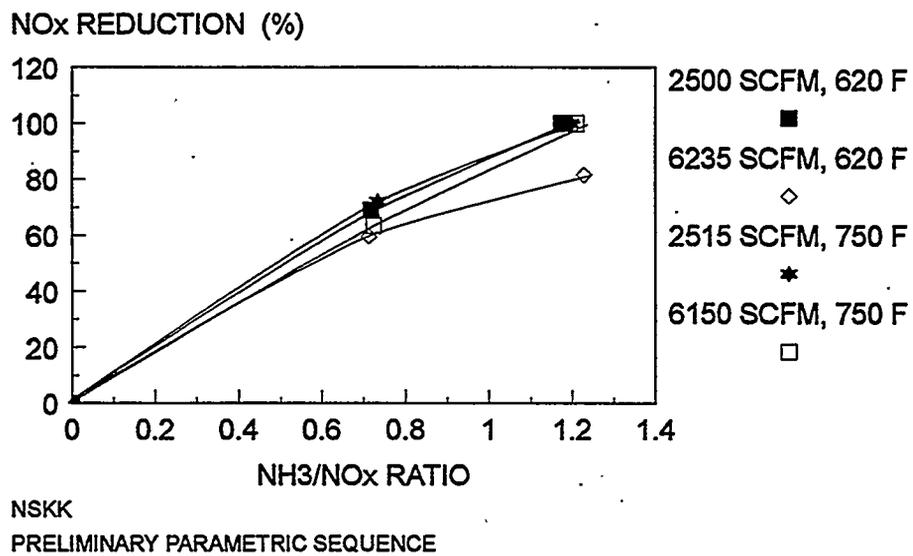
**Figure 5.3.1-2**

**FIRST BED NO<sub>x</sub> RED. vs. NH<sub>3</sub>/NO<sub>x</sub> RATIO**



**Figure 5.3.1-3**

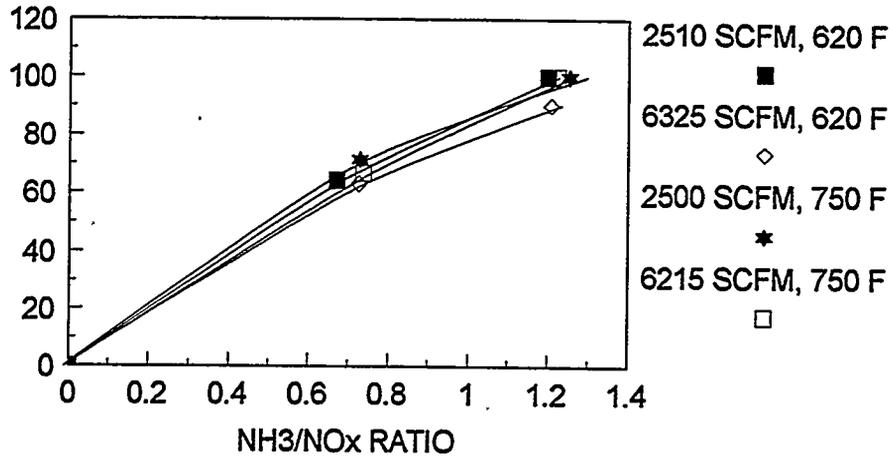
**FIRST BED NO<sub>x</sub> RED. vs. NH<sub>3</sub>/NO<sub>x</sub> RATIO**



**Figure 5.3.1-4**

**FIRST BED NO<sub>x</sub> RED. vs. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

NO<sub>x</sub> REDUCTION (%)



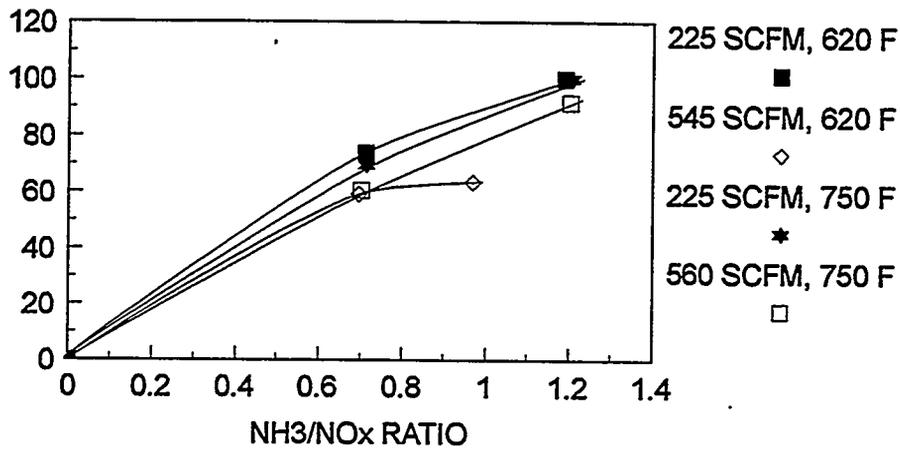
SIEMENS

PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-5**

**FIRST BED NO<sub>x</sub> RED. vs. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

NO<sub>x</sub> REDUCTION (%)



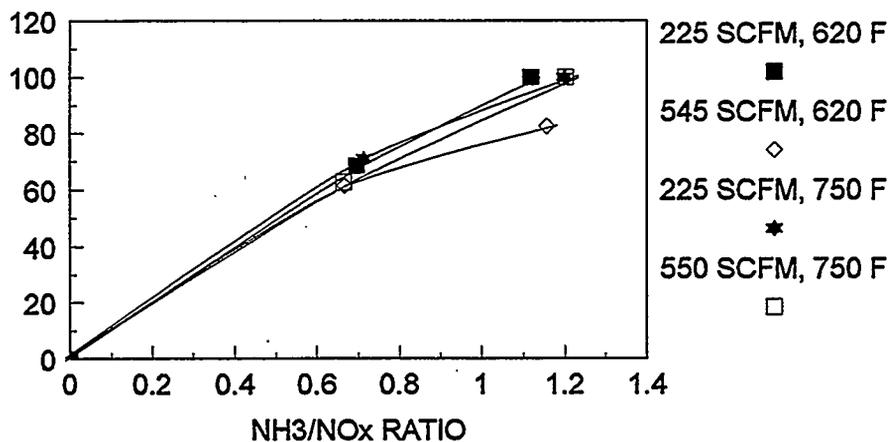
GRACE SYNOX

PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-6**

**FIRST BED NO<sub>x</sub> RED. vs. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

NO<sub>x</sub> REDUCTION (%)

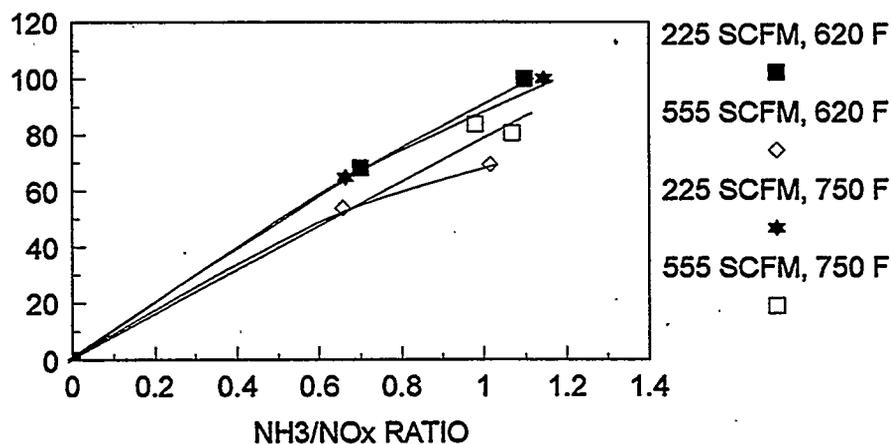


CORMETECH HIGH-DUST  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-7**

**FIRST BED NO<sub>x</sub> RED. vs. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

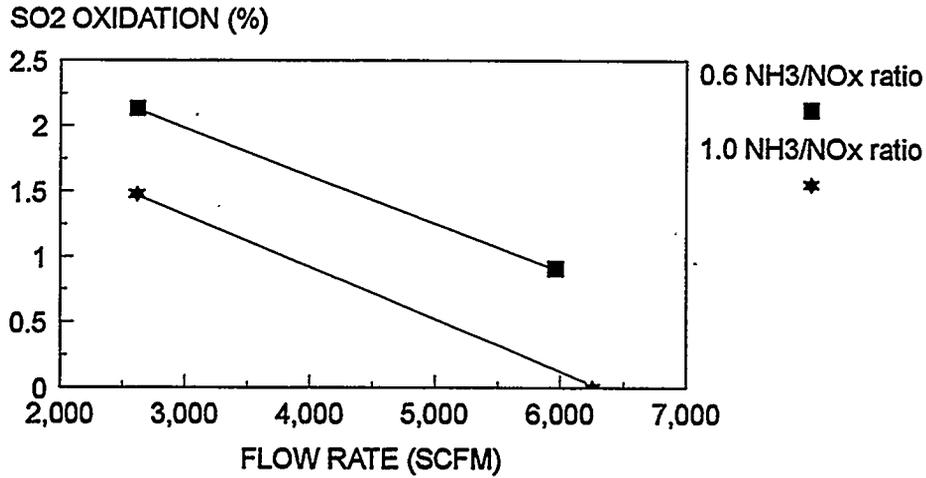
NO<sub>x</sub> REDUCTION (%)



HALDOR TOPSOE  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-8**

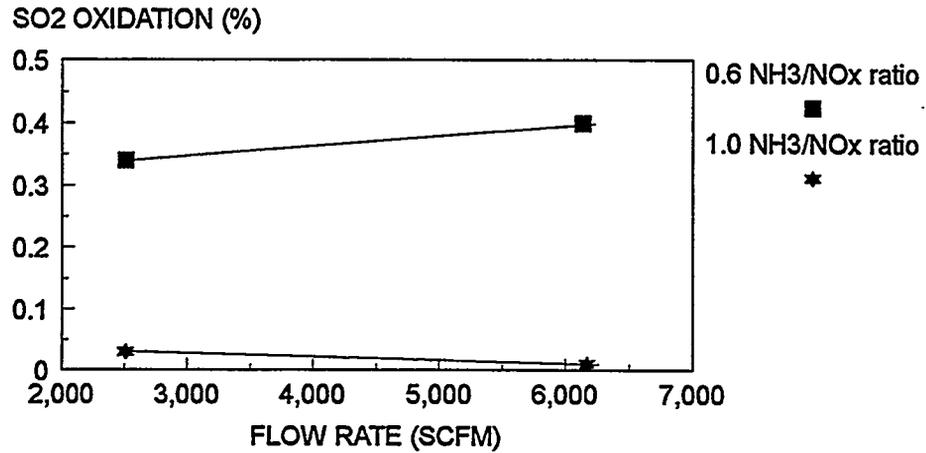
**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



GRACE NOXERAM: 750 F  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-9**

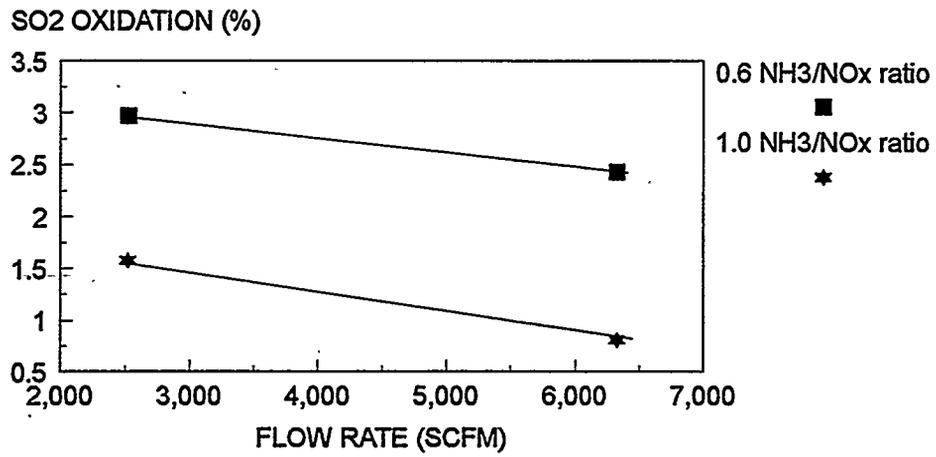
**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



NSKK: 750 F  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-10**

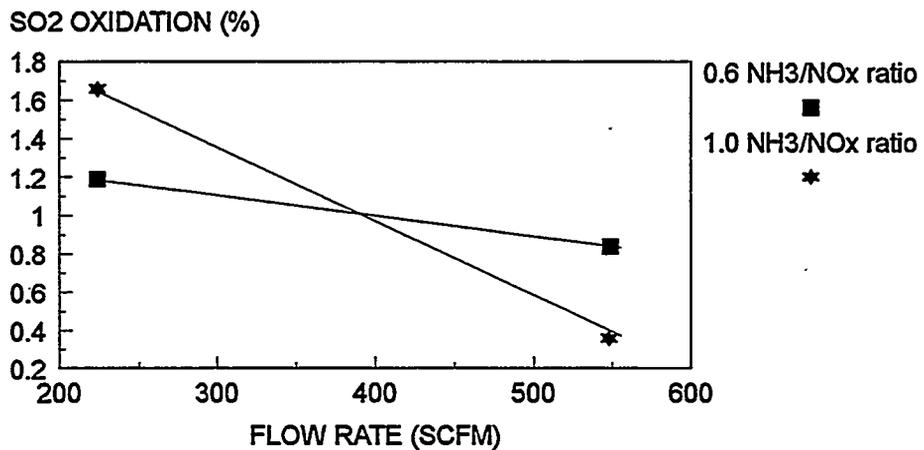
**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



SIEMENS: 750 F  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-11**

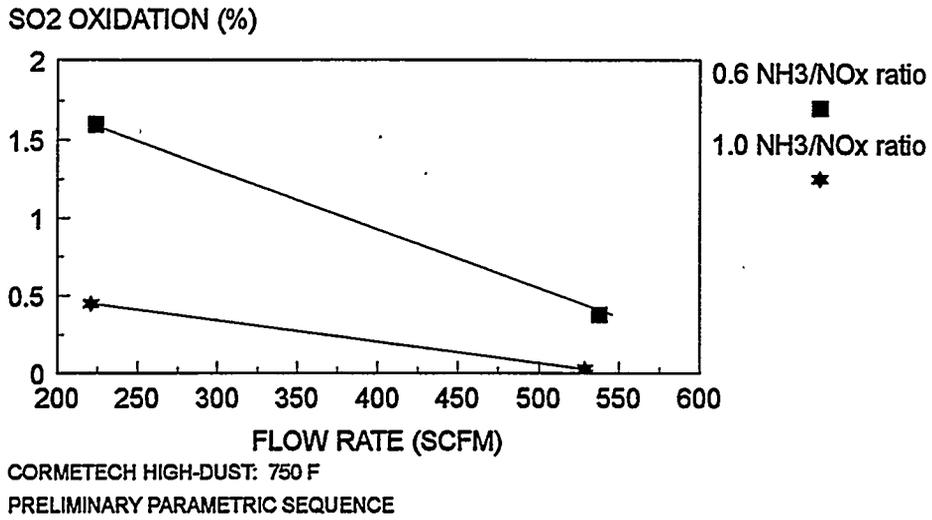
**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



GRACE SYNOX: 750 F  
PRELIMINARY PARAMETRIC SEQUENCE

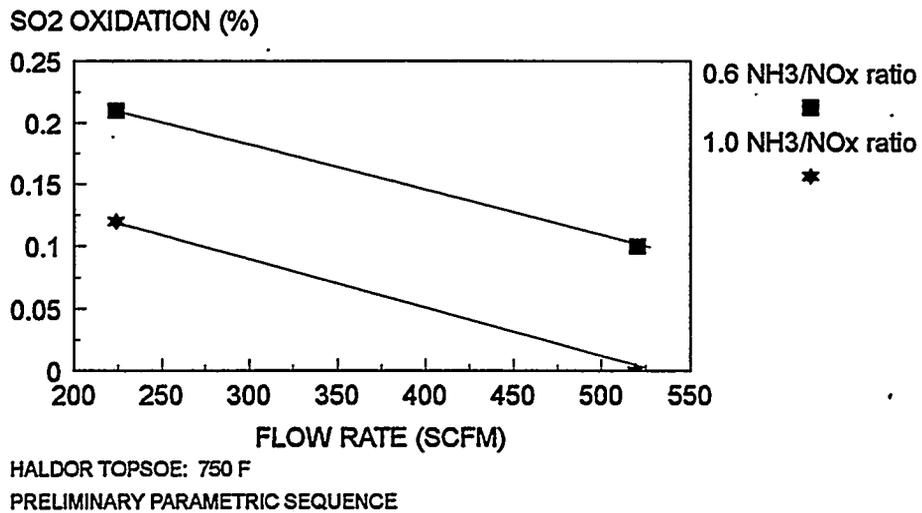
**Figure 5.3.1-12**

**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



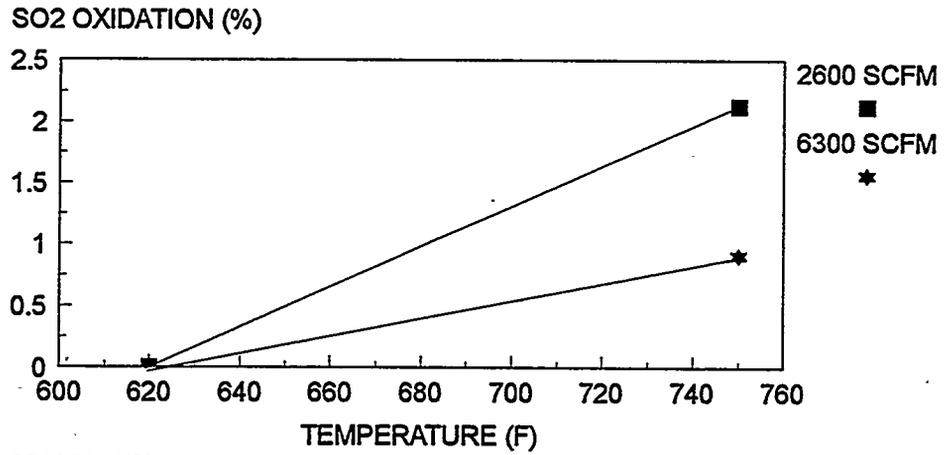
**Figure 5.3.1-13**

**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



**Figure 5.3.1-14**

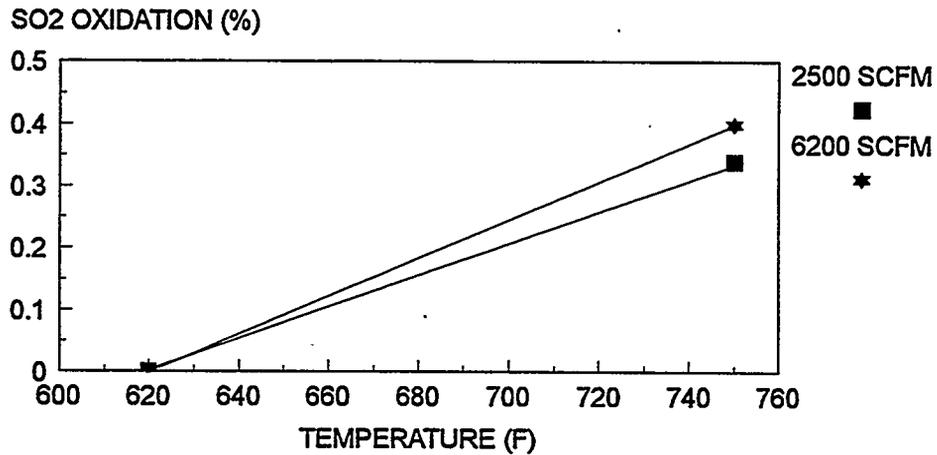
**SO2 OXIDATION VS. TEMPERATURE**



GRACE NOXERAM: 0.6 NH3/NOx RATIO  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-15**

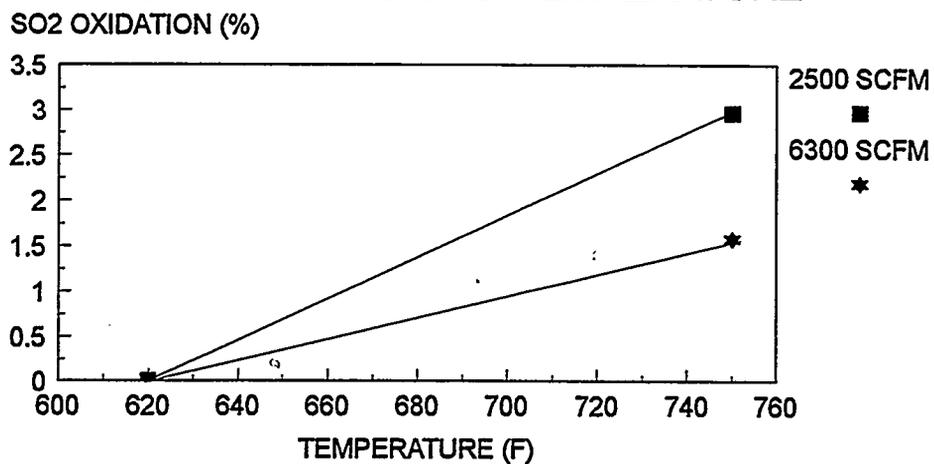
**SO2 OXIDATION VS. TEMPERATURE**



NSKK: 0.6 NH3/NOx RATIO  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-16**

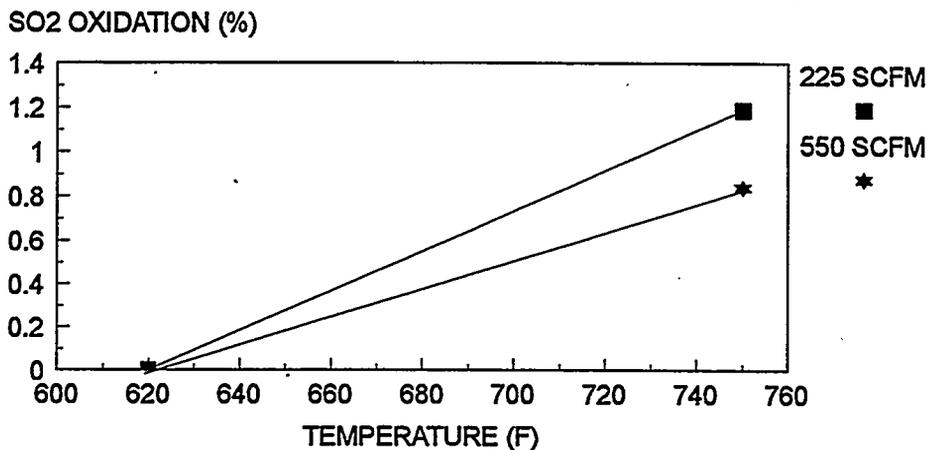
**SO2 OXIDATION VS. TEMPERATURE**



SIEMENS: 0.6 NH3/NOx RATIO  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-17**

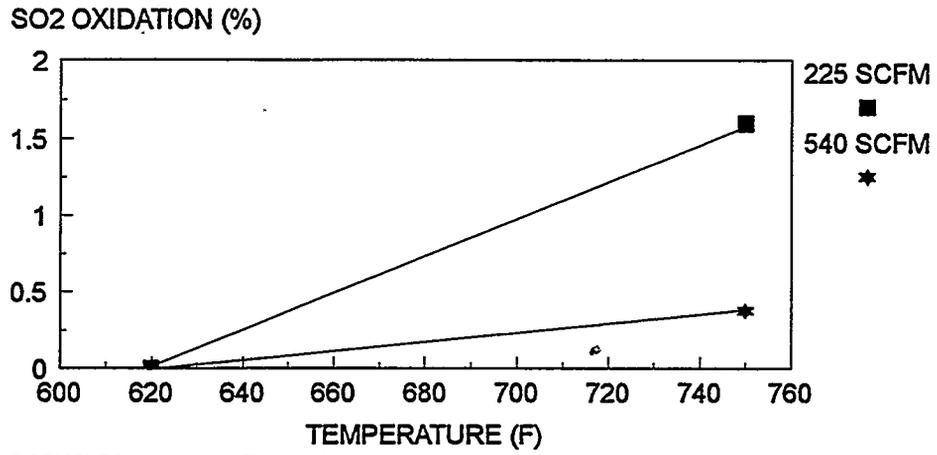
**SO2 OXIDATION VS. TEMPERATURE**



GRACE SYNOX: 0.6 NH3/NOx RATIO  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-18**

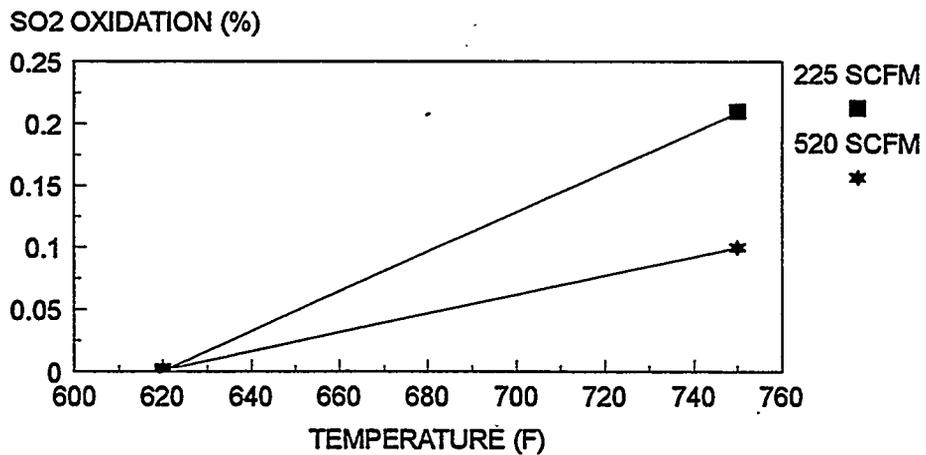
**SO2 OXIDATION VS. TEMPERATURE**



CORMETECH HIGH-DUST: 0.6 NH3/NOx RATIO  
PRELIMINARY PARAMETRIC SEQUENCE

**Figure 5.3.1-19**

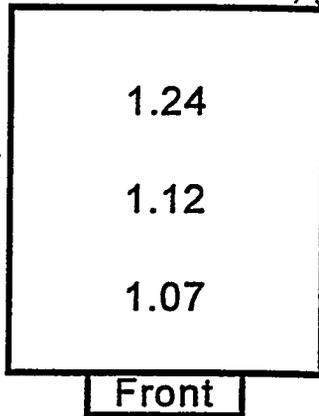
**SO2 OXIDATION VS. TEMPERATURE**



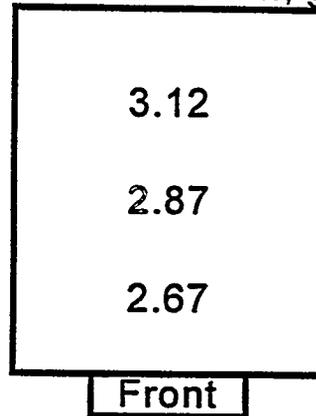
HALDOR TOPSOE: 0.6 NH3/NOx RATIO  
PRELIMINARY PARAMETRIC SEQUENCE

Figure 5.3.1-20  
Mass concentration and mass emission rate profiles at the Reactor D outlet.

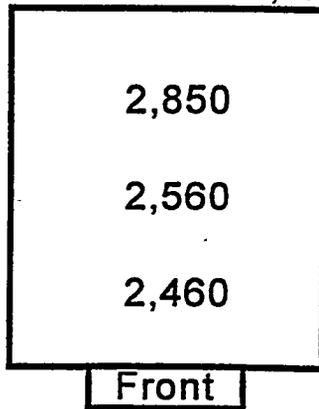
Mass Concentration, gr/acf



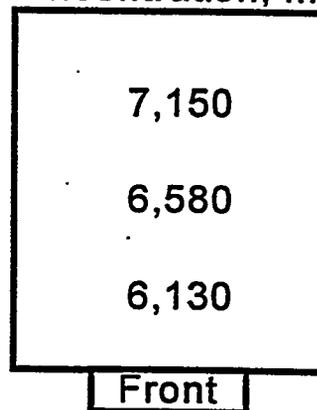
Mass Concentration, gr/dscf



Mass Concentration, mg/acm



Mass Concentration, mg/dscm



Mass Emission Rate, lb/MBtu

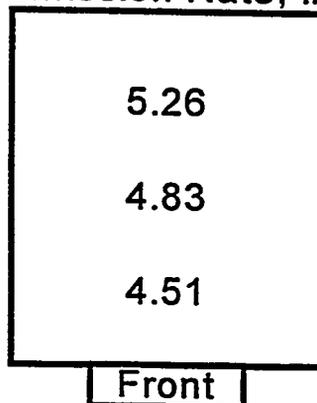
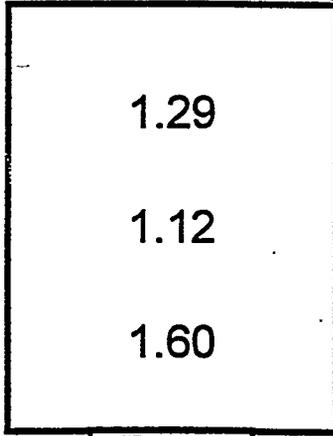


Figure 5.3.1-21

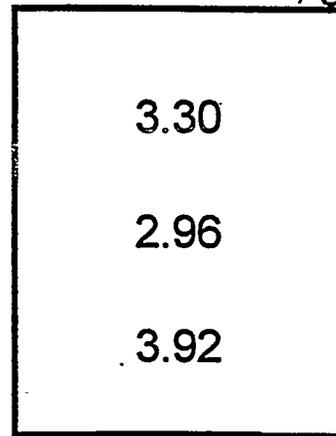
Mass concentration and mass emission rate profiles at the Reactor E outlet.

Mass Concentration, gr/acf



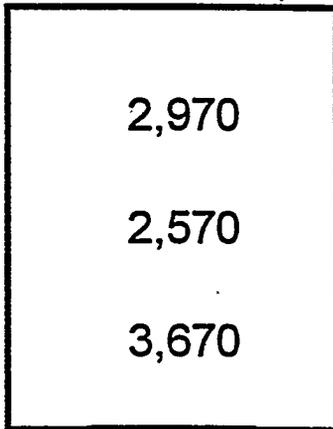
Front

Mass Concentration, gr/dscf



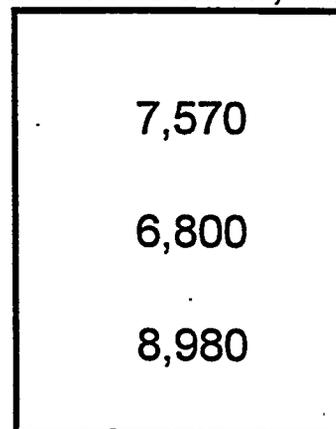
Front

Mass Concentration, mg/acm



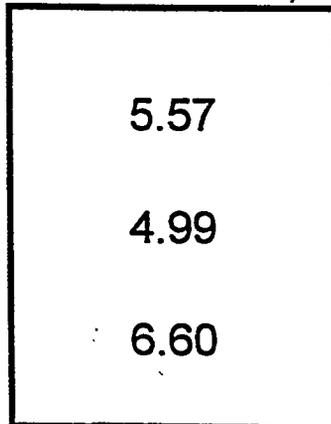
Front

Mass Concentration, mg/dscm



Front

Mass Emission Rate, lb/MBtu

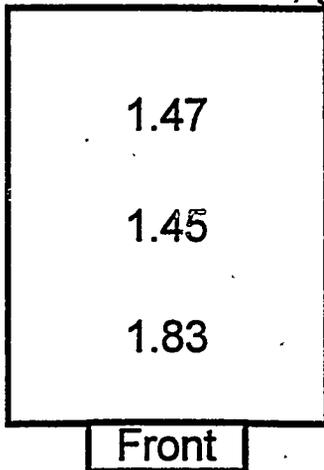


Front

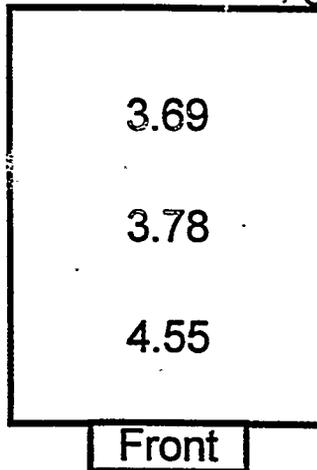
Figure 5.3.1-22

Mass concentration and mass emission rate profiles at the Reactor F outlet.

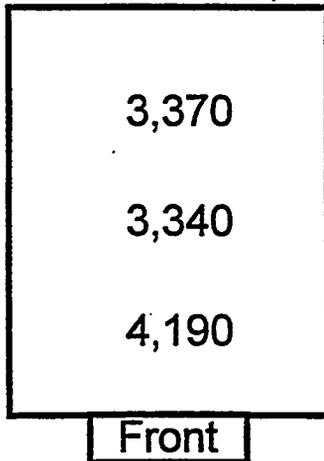
Mass Concentration, gr/acf



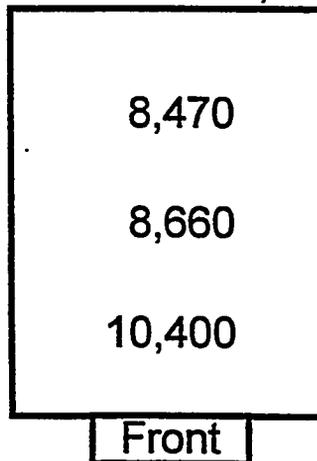
Mass Concentration, gr/dscf



Mass Concentration, mg/acm



Mass Concentration, mg/dscm



Mass Emission Rate, lb/MBtu

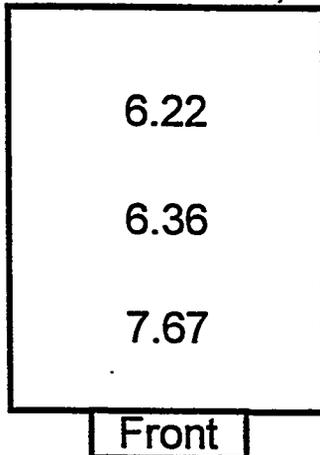


Figure 5.3.1-23  
Flue gas velocity profile at the Reactor D outlet.

## Flue Gas Velocity, ft/s

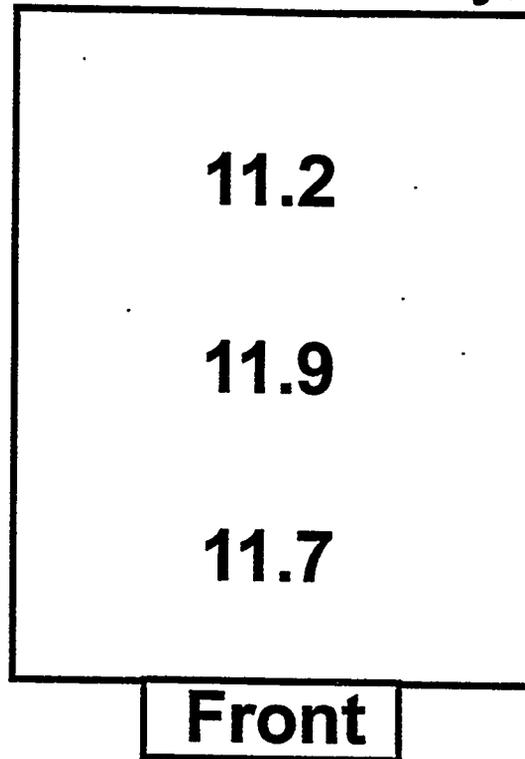


Figure 5.3.1-24  
Flue gas velocity profile at the Reactor E outlet.

Flue Gas Velocity, ft/s

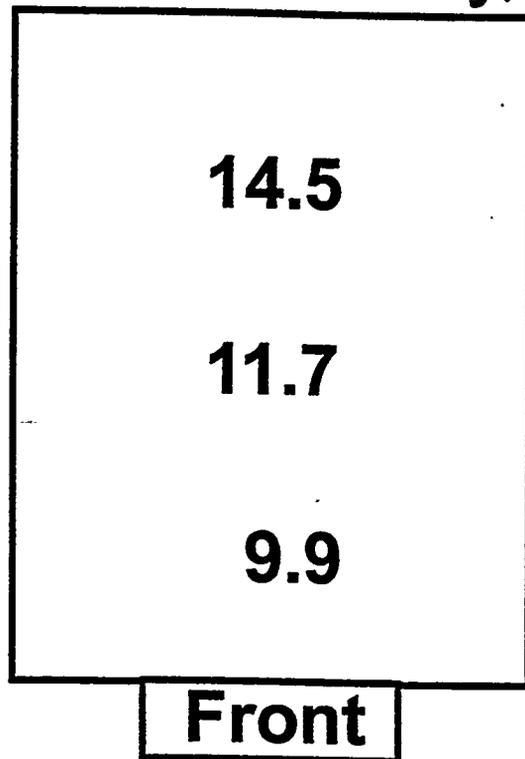
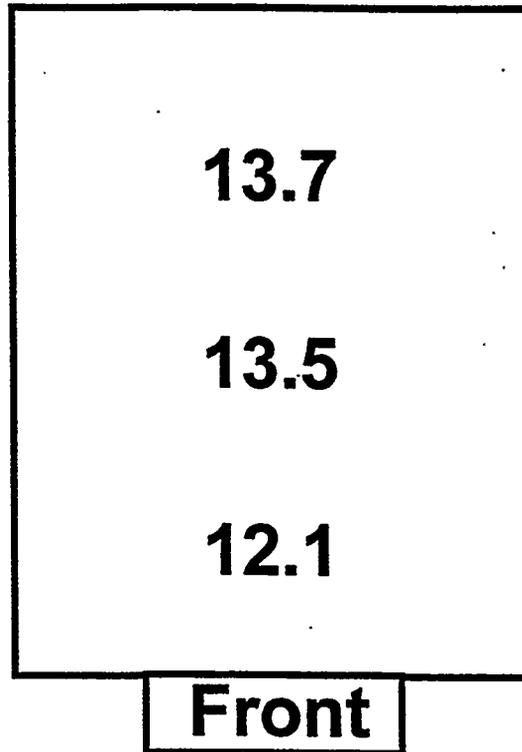


Figure 5.3.1-25  
Flue gas velocity profile at the Reactor F outlet.

## Flue Gas Velocity, ft/s



### 5.3.2 Second Parametric Sequence

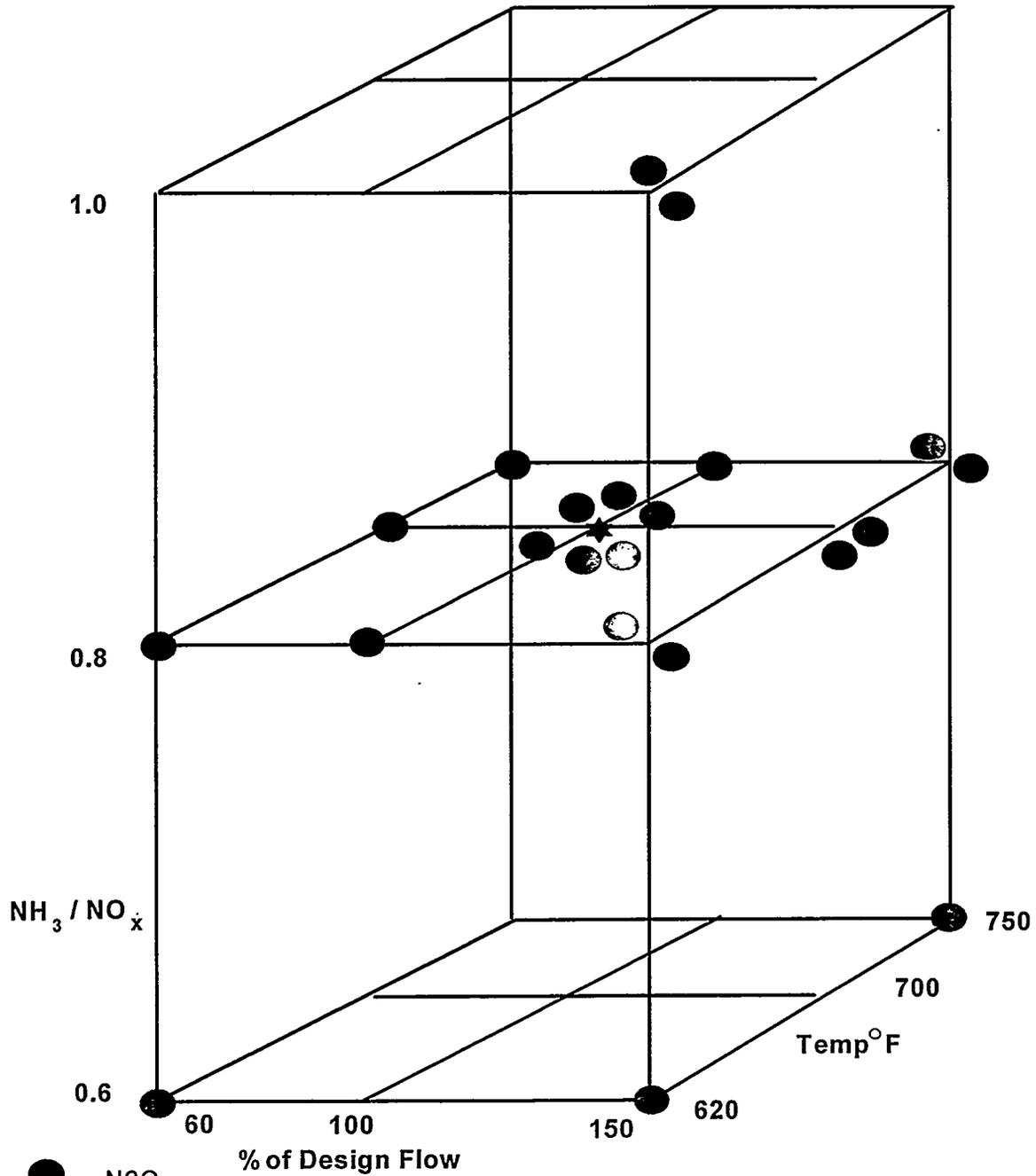
The parametric test results characterizing the performance for reactors A - G for the second parametric sequence are discussed in the following section. The parametric tests were composed of 13 reactor operating conditions defined by variations in the flue gas flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio. The test conditions for the second parametric sequence are shown graphically in Figure 5.3.2-1 and in tabular format in Table 5.3.2-1. The particular measurements that were made (intermediate ammonia, slip ammonia, SO<sub>2</sub>, SO<sub>3</sub>, HCl, N<sub>2</sub>O, and velocity and mass concentration profiles) are also shown at the various test conditions. Although identical test conditions are indicated, the measurements were not taken simultaneously (e.g., ammonia and SO<sub>2</sub> data for the same conditions were not collected during the exact same test run, but rather under similar process conditions at different times). Parametric test data were not taken on reactor J because replacement of the catalyst (withdrawn by Engelhard) occurred late in the test period. Tables 5.3.2-2 through 8 show the second parametric test data on intermediate ammonia, slip ammonia, and sulfur dioxide oxidation. Appendix J contains the detailed data spreadsheets for the parametric sequence.

Table 5.3.2-1 Parametric Test Conditions (2nd Test Sequence)

| Flue gas flow rate<br>Large / Small reactor<br>(KSCFM) | Flue gas<br>temperature<br>(°F) | NH <sub>3</sub> /NO <sub>x</sub><br>Ratio | Measurements   |
|--|---------------------------------|---|--|
| 3.0 / 0.24   | 620                             | 0.6                                       | intermediate NH <sub>3</sub>   |
| 3.0 / 0.24   | 620                             | 0.8                                       | SO <sub>2</sub> /SO <sub>3</sub>   |
| 5.0 / 0.40   | 620                             | 0.8                                       | slip NH <sub>3</sub>   |
| 7.5 / 0.60   | 620                             | 0.6                                       | intermediate NH <sub>3</sub>   |
| 7.5 / 0.60   | 620                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 7.5 / 0.60   | 620                             | 1.0                                       | intermediate & slip NH <sub>3</sub>  |
| 3.0 / 0.24   | 700                             | 0.8                                       | SO <sub>2</sub> /SO <sub>3</sub>   |
| 5.0 / 0.40   | 700                             | 0.8                                       | * intermediate & slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub> , N <sub>2</sub> O,<br>HCl, velocity & mass concentration profile |
| 7.5 / 0.60   | 700                             | 0.8                                       | slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |
| 3.0 / 0.24   | 750                             | 0.8                                       | SO <sub>2</sub> /SO <sub>3</sub>   |
| 5.0 / 0.40   | 750                             | 0.8                                       | SO <sub>2</sub> /SO <sub>3</sub>   |
| 7.5 / 0.60   | 750                             | 0.6                                       | intermediate NH <sub>3</sub>   |
| 7.5 / 0.60   | 750                             | 0.8                                       | slip NH <sub>3</sub> & SO <sub>2</sub> /SO <sub>3</sub> **   |

\*Design conditions. \*\*An extra intermediate NH<sub>3</sub> test was able to be run on a few reactors.

**Fig 5.3.2-1 Second SCR Parametric Test Plan**



- N2O
- Intermediate NH3
- SO2/SO3
- HCl
- ★ Design Point - Long Term
- Slip NH3
- Velocity & Mass Concentration

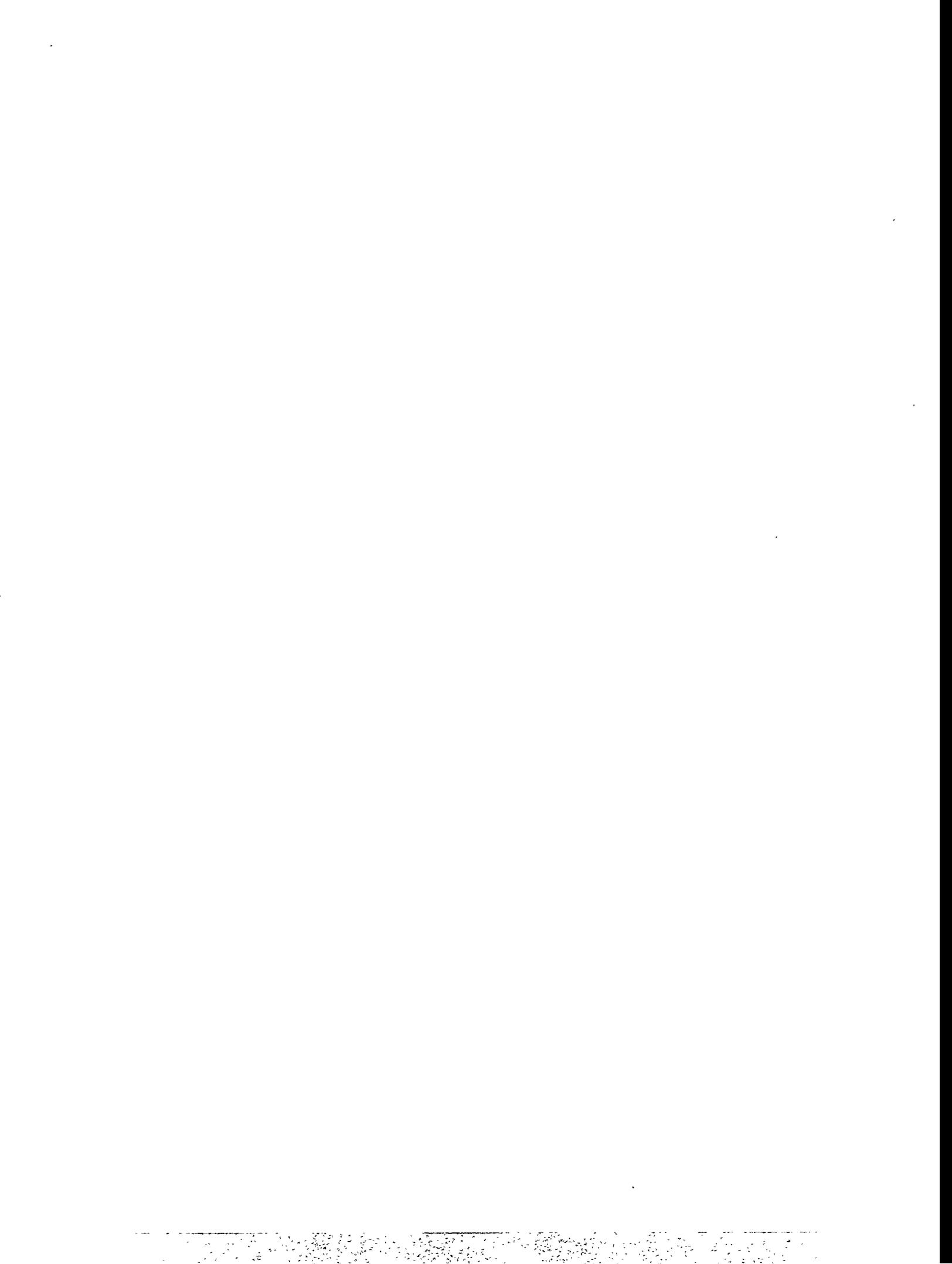


Table 5.3.2-2 Reactor A (2nd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 2999             | 622        | 2.451                    | 280                          | 0.561                                  | 17.4                        | 49.8                               |
| 7161             | 625        | 2.240                    | 252                          | 0.561                                  | 30.0                        | 44.2                               |
| 7179             | 625        | 2.808                    | 269                          | 0.773                                  | 41.2                        | 62.0                               |
| 6998             | 626        | 3.633                    | 311                          | 0.978                                  | 45.7                        | 83.1                               |
| 4999             | 705        | 3.234                    | 295                          | 0.765                                  | 31.7                        | 65.8                               |
| 6234             | 751        | 4.826                    | 351                          | 0.568                                  | 28.1                        | 48.8                               |
| 6351             | 747        | 5.313                    | 253                          | 0.847                                  | 28.7                        | 73.4                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 7000             | 625        | 6.328                    | 312                          | 0.800                                  | 3.8                         |
| 6986             | 625        | 6.328                    | 333                          | 0.895                                  | 6.6                         |
| 7092             | 625        | 4.638                    | 287                          | 1.059                                  | 21.7                        |
| 4997             | 704        | 5.531                    | 294                          | 0.803                                  | 2.0                         |
| 6297             | 704        | 6.316                    | 316                          | 0.799                                  | 3.0                         |
| 5991             | 756        | 6.154                    | 321                          | 0.852                                  | 2.1                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 3005             | 624        | 3.261                     | 1817                         | 0.739                                  | 9.3                      | 8.4                 | -0.9                          | -0.05          |
| 3002             | 705        | 3.611                     | 1727                         | 0.739                                  | 9.7                      | 22.5                | 12.8                          | 0.77           |
| 5001             | 710        | 2.666                     | 1890                         | 0.771                                  | 8.0                      | 9.9                 | -17.9                         | 0.10           |
| 6654             | 704        | 3.135                     | 1787                         | 0.781                                  | 8.0                      | 10.0                | 2                             | 0.11           |
| 2999             | 754        | 3.984                     | 1691                         | 0.740                                  | 9.3                      | 23.8                | 14.5                          | 0.89           |
| 4997             | 756        | 3.770                     | 1685                         | 0.777                                  | 9.3                      | 27.6                | 18.3                          | 1.11           |
| 6166             | 757        | 3.221                     | 1725                         | 0.765                                  | 9.3                      | 15.4                | 6.1                           | 0.36           |

Table 5.3.2-3 Reactor B (2nd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 2996             | 626        | 4.965                    | 354                          | 0.564                                  | 5.5                         | 54.8                               |
| 6690             | 632        | 3.323                    | 280                          | 0.560                                  | 54.4                        | 36.5                               |
| 7232             | 623        | 5.912                    | 353                          | 0.786                                  | 54.2                        | 63.2                               |
| 7271             | 623        | 1.914                    | 258                          | 0.828                                  | 86.5                        | 49.2                               |
| 4999             | 706        | 2.531                    | 272                          | 0.763                                  | 19.4                        | 69.2                               |
| 6808             | 755        | 4.736                    | 289                          | 0.573                                  | 22.8                        | 49.4                               |
| 6630             | 757        | 4.699                    | 269                          | 0.792                                  | 26.1                        | 69.5                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 7000             | 625        | 6.154                    | 319                          | 0.880                                  | 0.2                         |
| 7003             | 628        | 6.154                    | 335                          | 0.889                                  | 1.6                         |
| 6948             | 623        | 5.809                    | 335                          | 1.015                                  | 5.0                         |
| 4992             | 706        | 5.066                    | 300                          | 0.781                                  | 0.4                         |
| 6599             | 707        | 6.341                    | 317                          | 0.798                                  | 0.6                         |
| 6503             | 755        | 5.895                    | 328                          | 0.839                                  | 0.6                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 3006             | 624        | 2.397                     | 1926                         | 0.743                                  | 9.3                      | 3.9                 | -5.4                          | -0.28          |
| 2999             | 710        | 2.013                     | 2116                         | 0.761                                  | 8.9                      | 21.8                | 12.9                          | 0.62           |
| 4999             | 706        | 2.435                     | 1902                         | 0.752                                  | 9.3                      | 7.2                 | -2.1                          | -0.11          |
| 6427             | 704        | 2.949                     | 1696                         | 0.769                                  | 10.1                     | 4.7                 | -5.4                          | -0.32          |
| 5000             | 750        | 2.365                     | 1914                         | 0.770                                  | 9.3                      | 18.8                | 9.5                           | 0.50           |
| 4955             | 753        | 2.365                     | 1815                         | 0.760                                  | 9.7                      | 12.4                | 2.7                           | 0.15           |
| 6604             | 752        | 3.128                     | 1679                         | 0.752                                  | 9.7                      | 14.2                | 4.5                           | 0.27           |

Table 5.3.2-4 Reactor C (2nd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 2990             | 625        | 3.468                    | 291                          | 0.564                                  | 1.5                         | 55.9                               |
| 7447             | 629        | 3.584                    | 300                          | 0.768                                  | 19.5                        | 70.3                               |
| 7487             | 625        | 5.167                    | 364                          | 0.811                                  | 23.7                        | 74.6                               |
| 7428             | 623        | 4.975                    | 272                          | 1.018                                  | 47.2                        | 84.5                               |
| 5003             | 703        | 5.059                    | 350                          | 0.982                                  | 12.4                        | 94.6                               |
| 7001             | 745        | 3.227                    | 277                          | 0.562                                  | 12.8                        | 51.6                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 5007             | 623        | 4.344                    | 293                          | 0.832                                  | 2.2                         |
| 7441             | 622        | 5.911                    | 331                          | 0.801                                  | 4.8                         |
| 7477             | 624        | 4.609                    | 266                          | 1.017                                  | 10.6                        |
| 4995             | 704        | 4.170                    | 342                          | 0.783                                  | 1.1                         |
| 7408             | 707        | 4.814                    | 365                          | 0.782                                  | 2.3                         |
| 7202             | 743        | 6.191                    | 301                          | 0.832                                  | 3.0                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 2999             | 621        | 3.060                     | 1891                         | 0.770                                  | 8.0                      | 7.5                 | -0.5                          | -0.03          |
| 3020             | 709        | 3.408                     | 1804                         | 0.775                                  | 8.0                      | 17.4                | 9.4                           | 0.54           |
| 5002             | 706        | 3.671                     | 1693                         | 0.754                                  | 9.7                      | 19.8                | 10.1                          | 0.62           |
| 7497             | 704        | 3.423                     | 1790                         | 0.752                                  | 9.3                      | 10.1                | 0.8                           | 0.04           |
| 3002             | 756        | 4.210                     | 1670                         | 0.781                                  | 9.3                      | 50.5                | 41.2                          | 2.55           |
| 5000             | 755        | 3.877                     | 1689                         | 0.775                                  | 9.3                      | 39.7                | 30.4                          | 1.85           |
| 7299             | 749        | 3.579                     | 1891                         | 0.743                                  | 9.7                      | 26.9                | 17.2                          | 0.95           |

Table 5.3.2-5 Reactor D (2nd Parametric Sequence)

Intermediate-Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 239              | 625        | 5.425                    | 267                          | 0.771                                  | 20.0                        | 69.6                               |
| 601              | 624        | 4.319                    | 294                          | 0.706                                  | 59.1                        | 50.5                               |
| 600              | 624        | 4.475                    | 277                          | 0.915                                  | 88.7                        | 59.5                               |
| 602              | 624        | 4.440                    | 282                          | 1.149                                  | 147.2                       | 62.7                               |
| 403              | 705        | 4.473                    | 289                          | 0.989                                  | 54.8                        | 79.9                               |
| 598              | 753        | 4.094                    | 294                          | 0.711                                  | 44.2                        | 56.1                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 382              | 623        | 7.505                    | 324                          | 1.050                                  | 0.9                         |
| 597              | 627        | 5.416                    | 304                          | 0.930                                  | 25.6                        |
| 602              | 627        | 4.589                    | 263                          | 1.192                                  | 50.0                        |
| 399              | 705        | 4.284                    | 231                          | 1.028                                  | 3.0                         |
| 588              | 705        | 3.851                    | 232                          | 0.941                                  | 8.5                         |
| 599              | 705        | 5.165                    | 321                          | 0.903                                  | 11.2                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 240              | 625        | 6.414                     | 1896                         | 1.045                                  | 9.3                      | 2.1                 | -7.2                          | -0.44          |
| 240              | 709        | 6.176                     | 1742                         | 1.010                                  | 10.1                     | 17.3                | 7.2                           | 0.46           |
| 400              | 705        | 5.901                     | 1629                         | 0.996                                  | 9.7                      | 18.5                | 8.8                           | 0.58           |
| 600              | 704        | 5.090                     | 1746                         | 0.912                                  | 9.7                      | 8.1                 | -1.6                          | -0.09          |
| 240              | 756        | 6.688                     | 1604                         | 1.060                                  | 10.1                     | 21.0                | 10.9                          | 0.74           |
| 400              | 753        | 5.079                     | 1831                         | 1.033                                  | 9.3                      | 21.0                | 11.7                          | 0.65           |
| 600              | 746        | 4.706                     | 1825                         | 0.926                                  | 8.9                      | 21.6                | 12.7                          | 0.73           |

Table 5.3.2-6 Reactor E (2nd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 238              | 627        | 3.025                    | 280                          | 0.569                                  | 7.1                         | 54.3                               |
| 600              | 623        | 2.332                    | 321                          | 0.528                                  | 40.1                        | 40.3                               |
| 599              | 627        | 5.278                    | 372                          | 0.729                                  | 47.3                        | 60.1                               |
| 600              | 625        | 4.723                    | 372                          | 0.926                                  | 111.0                       | 62.8                               |
| 400              | 703        | 6.832                    | 362                          | 0.733                                  | 18.8                        | 68.1                               |
| 600              | 741        | 4.333                    | 349                          | 0.545                                  | 23.6                        | 47.8                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 400              | 625        | 3.446                    | 328                          | 0.751                                  | 0.8                         |
| 599              | 626        | 3.384                    | 305                          | 0.776                                  | 1.2                         |
| 597              | 627        | 2.750                    | 313                          | 0.943                                  | 5.9                         |
| 401              | 706        | 3.698                    | 327                          | 0.750                                  | 1.0                         |
| 600              | 704        | 2.598                    | 288                          | 0.727                                  | 0.5                         |
| 595              | 756        | 3.078                    | 325                          | 0.738                                  | 1.0                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET SO <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|----------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 240              | 625        | 3.493                      | 1876                         | 0.751                                  | 9.3                      | 11.0                | 1.7                           | 0.10           |
| 244              | 700        | 4.171                      | 1695                         | 0.740                                  | 10.5                     | 15.5                | 5                             | 0.31           |
| 400              | 708        | 3.631                      | 1717                         | 0.731                                  | 10.1                     | 21.1                | 11                            | 0.66           |
| 583              | 708        | 2.785                      | 1935                         | 0.729                                  | 9.7                      | 19.4                | 9.7                           | 0.53           |
| 240              | 755        | 3.943                      | 1810                         | 0.740                                  | 10.1                     | 28.6                | 18.5                          | 1.08           |
| 389              | 755        | 3.435                      | 1887                         | 0.724                                  | 9.7                      | 29.3                | 19.6                          | 1.08           |
| 601              | 756        | 3.374                      | 1836                         | 0.718                                  | 9.7                      | 30.5                | 20.8                          | 1.17           |

Table 5.3.2-7 Reactor F (2nd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> REDUCTION (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------------|
| 245              | 622        | 2.880                    | 310                          | 0.544                                  | 13.0                        | 50.2                               |
| 594              | 626        | 2.266                    | 293                          | 0.539                                  | 38.1                        | 40.9                               |
| 599              | 625        | 5.348                    | 373                          | 0.729                                  | 71.9                        | 53.6                               |
| 599              | 625        | 4.514                    | 372                          | 0.930                                  | 96.9                        | 66.9                               |
| 400              | 706        | 2.682                    | 312                          | 0.747                                  | 39.0                        | 62.2                               |
| 594              | 755        | 6.724                    | 368                          | 0.525                                  | 37.1                        | 42.4                               |
| 600              | 754        | 2.704                    | 318                          | 0.741                                  | 51.8                        | 57.7                               |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 397              | 624        | 5.835                    | 380                          | 0.708                                  | 0.8                         |
| 600              | 626        | 3.991                    | 339                          | 0.722                                  | 3.6                         |
| 597              | 625        | 2.212                    | 281                          | 0.929                                  | 19.5                        |
| 400              | 708        | 3.455                    | 359                          | 0.699                                  | 0.5                         |
| 601              | 705        | 1.837                    | 286                          | 0.714                                  | 2.6                         |
| 594              | 706        | 2.730                    | 337                          | 0.730                                  | 3.1                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 240              | 623        | 3.828                     | 1840                         | 0.726                                  | 10.1                     | 7.5                 | -2.6                          | -0.15          |
| 240              | 708        | 3.640                     | 1910                         | 0.717                                  | 9.7                      | 17.9                | 8.2                           | 0.46           |
| 400              | 706        | 3.531                     | 1723                         | 0.729                                  | 10.1                     | 13.4                | 3.3                           | 0.20           |
| 605              | 704        | 3.408                     | 1722                         | 0.726                                  | 10.1                     | 12.6                | 2.5                           | 0.15           |
| 246              | 755        | 2.928                     | 1848                         | 0.721                                  | 8.9                      | 7.9                 | -1                            | -0.05          |
| 400              | 757        | 2.619                     | 1848                         | 0.606                                  | 8.9                      | 10.0                | 1.1                           | 0.06           |
| 597              | 756        | 2.941                     | 1804                         | 0.725                                  | 8.9                      | 10.9                | 2                             | 0.12           |

Table 5.3.2-8 Reactor G (2nd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 242              | 626        | 3.638                    | 361                          | 0.514                                  | 5.5                         | 49.9                          |
| 600              | 625        | 2.728                    | 374                          | 0.511                                  | 19.6                        | 45.9                          |
| 600              | 626        | 2.724                    | 362                          | 0.708                                  | 38.1                        | 60.2                          |
| 402              | 676        | 1.928                    | 324                          | 1.083                                  | 72.2                        | 86.1                          |
| 401              | 705        | 2.023                    | 344                          | 0.695                                  | 15.2                        | 65.1                          |
| 601              | 757        | 2.322                    | 355                          | 0.506                                  | 19.9                        | 45.0                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 400              | 625        | 1.404                    | 272                          | 0.711                                  | 0.8                         |
| 591              | 626        | 1.385                    | 265                          | 0.700                                  | 1.1                         |
| 600              | 264        | 2.079                    | 369                          | 0.895                                  | 16.2                        |
| 400              | 704        | 2.438                    | 331                          | 0.684                                  | 0.8                         |
| 589              | 707        | 1.423                    | 304                          | 0.719                                  | 2.2                         |
| 593              | 755        | 2.488                    | 354                          | 0.704                                  | 2.2                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 241              | 624        | 3.439                     | 1899                         | 0.721                                  | 9.3                      | 6.9                 | -2.4                          | -0.13          |
| 240              | 707        | 3.314                     | 1890                         | 0.721                                  | 9.3                      | 21.0                | 11.7                          | 0.66           |
| 400              | 704        | 3.196                     | 1851                         | 0.711                                  | 10.1                     | 20.8                | 10.7                          | 0.59           |
| 590              | 707        | 2.706                     | 1885                         | 0.715                                  | 9.3                      | 19.1                | 9.8                           | 0.53           |
| 241              | 753        | 3.452                     | 1693                         | 0.725                                  | 9.7                      | 31.3                | 21.6                          | 1.33           |
| 400              | 758        | 2.954                     | 1804                         | 0.714                                  | 9.7                      | 22.6                | 12.9                          | 0.74           |
| 600              | 750        | 2.889                     | 1773                         | 0.720                                  | 9.7                      | 21.2                | 11.5                          | 0.67           |

### Intermediate NO<sub>x</sub> Reduction

The intermediate ammonia measurements were made after the first catalyst bed and at conditions thought to give the best kinetic information. The NO<sub>x</sub> removals reported with the intermediate ammonia measurements were computed from the measured ammonia concentrations using a material balance which assumed a 1:1 stoichiometry for the reaction of ammonia and NO<sub>x</sub>. Thus, the moles of ammonia consumed equaled the moles of NO<sub>x</sub> reduced, from which NO<sub>x</sub> reduction was computed, after oxygen corrections were made.

### Ammonia Slip

The ammonia slip data given in Tables 5.3.2-2 through 8 is presented below in three sets of plots: ammonia slip versus each of flow rate, ammonia-to-NO<sub>x</sub> ratio, and temperature. Figures 5.3.2-2 through 8 show ammonia slip versus flow rate for reactors A - G, respectively. All plots are shown for roughly 80% NO<sub>x</sub> reduction except for reactor D which is shown for 95% NO<sub>x</sub> reduction. Data has been extrapolated to zero for the 60% of design flow point. As expected, the trends show increasing ammonia slip with increasing reactor flow rate. In general, the ammonia slip is relatively minor indicating the ability of the catalyst design to withstand significant increases in flow while maintaining ammonia slip limits. For reactor D, the Grace Synox catalyst reactor, a fairly significant increase in ammonia slip is noted with flow rate. However, the ammonia slip is not likely to be nearly as significant at lower NO<sub>x</sub> removal rates. Since a portion of the overall reaction rate is due to mass transfer limitations, improvements in bulk mass transfer coefficients were likely mitigating the effect of increased flow on slip ammonia increases. Overall, these plots demonstrate the ability of an SCR system to follow load variations dictated by the host boiler while maintaining design specifications.

Figures 5.3.2-9 through 15 show ammonia slip versus ammonia-to-NO<sub>x</sub> ratio at low temperature and high flow rate (worst case scenario) for reactors A - G, respectively. The plots show sharp increases in ammonia slip as the ammonia-to-NO<sub>x</sub> ratio approaches 1.0. This finding is in keeping with published data of this type. At ammonia-to-NO<sub>x</sub> ratios near 1.0, non-idealities in the reactor systems forced the catalysts to slip ammonia since areas were present in the reactors where NO<sub>x</sub> was the limiting reagent. Again, these plots are for the worst case scenario and ammonia slip values are likely to be lower for higher temperature or lower flow rate.

Ammonia slip versus temperature is plotted in Figures 5.3.2-16 through 22 for high flow rate and roughly 80% NO<sub>x</sub> reduction for reactors A - G, respectively. Some improvement (decrease) in ammonia slip is noted between 620 and 700 °F, likely due to improvements in the kinetic reaction rate with increasing temperature. In general, only slight improvements are noted with increasing temperatures above 700 °F. In Figures 5.3.2-18 through 21 (reactors C - F) a slight increase is shown between the 700 and 750 °F points, however, this was likely due to measurement variability and is not considered significant. In these cases, the plots should not be construed as demonstrating increases in ammonia slip with increasing temperature above 700 °F. It is expected that the 700 and 750 °F values are roughly equivalent which may be due in part to mass transfer limitations that become controlling at these higher temperatures. Overall, these plots demonstrate that in terms of ammonia slip, significant improvements are not realized with temperatures above 700 °F. Losses in boiler efficiency would probably outweigh any improvements that may be obtained in ammonia slip by designing an SCR reactor to operate at temperatures near 750 °F.

### SO<sub>2</sub> Oxidation

The plots for SO<sub>2</sub> oxidation versus flow rate at high temperature for the combination of all catalyst beds in the reactors are shown in Figures 5.3.2-23 through 29 for reactors A - G, respectively. In Figures 5.3.2-23, 24, 25, 29 (reactors A, B, C, G), decreasing SO<sub>2</sub>

oxidation is noted with increasing flow rate. This finding is expected since the reaction rate is predicted to be inversely proportional to flow rate, according to published rate data and information provided by catalyst suppliers. In contrast, Figures 5.3.2-26, 27, and 28 (reactors D, E, F) show relatively flat profiles indicating that either chemical or physical characteristics of the catalysts and reactors were masking the expected linear effect or that measurements problems were occurring.

SO<sub>2</sub> oxidation versus temperature at low flow rate for the combination of all catalyst beds in the reactors is shown in Figures 5.3.2-30 through 36 for reactors A - G, respectively. In general, the trend of the plots shows an increase in SO<sub>2</sub> oxidation with increasing temperature. Published information describing the effects of temperature on SO<sub>2</sub> oxidation and information obtained from the catalyst suppliers indicates that increases in SO<sub>2</sub> oxidation are expected to be exponential with respect to temperature. The exact shape of the plots is somewhat unclear since fairly large measurement variability existed in the test facility and other phenomena such as SO<sub>3</sub> deposition occurred in the test facility reactors. The general trend of increasing SO<sub>2</sub> oxidation is expected, however, and the plots provide a good basis for determining the potential for SO<sub>3</sub> formation across the SCR reactors at various operating temperatures. In the case of Figure 5.3.2-35 (reactor F), the extremely low oxidation rate of the catalyst further exacerbated the problem of measurement precision. In fact, only one data point on this plot shows any detectable amount of SO<sub>2</sub> oxidation, with this value being very close to the detection limit. This particular plot is valuable in the context of showing that the Haldor Topsoe catalyst has very low SO<sub>2</sub> oxidation potential.

The SO<sub>2</sub> oxidation data are corrected to reactor outlet oxygen concentrations. The value for sulfur trioxide produced in the reactors is based on the measured reactor outlet sulfur trioxide concentration and estimated reactor inlet sulfur trioxide values. The reactor inlet sulfur trioxide values were estimated using past measurements of inlet sulfur trioxide based on host boiler load. In many cases, especially those involving low temperature conditions, there was no net increase in sulfur trioxide across the reactors. In fact, some

operating conditions showed an apparent loss in sulfur trioxide across the reactors. It is believed that the apparent loss was caused by phenomena such as acid condensation and the formation of ammonium bisulfate on cold spots at the reactor surfaces. (Tables showing SO<sub>2</sub> oxidation rates quote reactor flow rates as calculated for the reactor exits, since SO<sub>3</sub> was measured at this point. For consistency with other figures, the plots of SO<sub>2</sub> oxidation versus flow rate are based on reactor inlet flow rates. In practice, differences between inlet and outlet flow rates are slight and do not greatly affect the overall analysis).

#### Additional Base-Line Measurements

Mass concentration (five-point for reactors A, B, C) (two-point for reactors D, E, F) and flue gas velocity profiles (nine-point for reactor A, B, C) (three-point for reactors D, E, F) were conducted near design operating conditions (700 °F, 100% flow rate) at the reactor outlets and reactor inlets, respectively. The mass concentration profile data are given in Figures 5.3.2-37 through 42 for reactors A - F, respectively, in four different units of concentration and as mass emission rates. The flue gas velocity profiles are presented in Figures 5.3.2-43 through 49 for reactors A - G, respectively. The results of the mass concentrations and flue gas velocity profiles are given in Table 5.3.2-9 for all reactors.

HCl concentration (at 3% O<sub>2</sub>, dry) was measured at the design operating conditions at the reactor outlets. The N<sub>2</sub>O concentrations were also measured at the reactor inlets and at the reactor outlets (both measurements are dry at 3% O<sub>2</sub>). The results of these measurements are shown in Table 5.3.2-9.

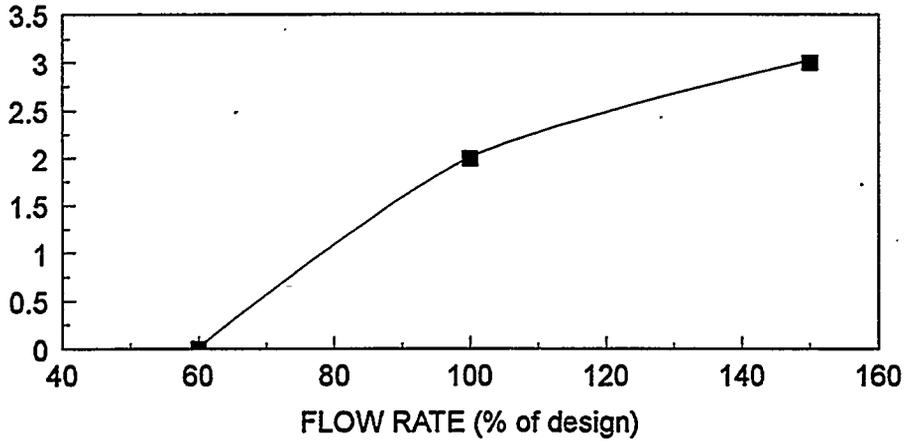
Table 5.3.2-9 Additional Base-line Measurements

| Reactor<br>(Catalyst<br>Supplier) | Mass<br>concentration<br>(gr/dscf) | Velocity<br>Profile<br>(ft/sec) | HCl<br>concentration<br>(ppmv) | N <sub>2</sub> O<br>concentration<br>(ppmv) |            |
|-----------------------------------|------------------------------------|---------------------------------|--------------------------------|---|------------|
|                                   |                                    |                                 |                                | rxr inlet                                   | rxr outlet |
| Reactor A<br>(Grace Nxrm)         | 3.49 ± 0.24                        | 13.3 ± 1.4                      | 241 ± 11                       | 2.4   | 1.2        |
| Reactor B<br>(NSKK)               | 3.22 ± 0.52                        | 12.2 ± 0.5                      | 158 ± 36                       | 2.4   | 1.0        |
| Reactor C<br>(Siemens)            | 3.27 ± 0.29                        | 12.4 ± 1.0                      | 211 ± 14                       | 2.4   | 1.7        |
| Reactor D<br>(Grace Synox)        | 3.72 ± 0.58                        | 13.2 ± 0.1                      | 163 ± 8                        | 1.8   | 1.8        |
| Reactor E<br>(Corm. HD)           | 5.25 ± 0.84                        | 12.5 ± 1.3                      | 196 ± 9                        | 1.8   | 1.8        |
| Reactor F<br>(Haldor)             | 7.87 ± 1.05                        | 9.5 ± 3.6                       | 140 ± 5                        | 2.4   | 1.6        |
| Reactor G<br>(Hitachi)            | N/A                                | 6.9 ± 1.3                       | 157 ± 2                        | 2.4   | 1.6        |

**Figure 5.3.2-2**

**AMMONIA SLIP VS. FLOW RATE**

AMMONIA SLIP (ppm)

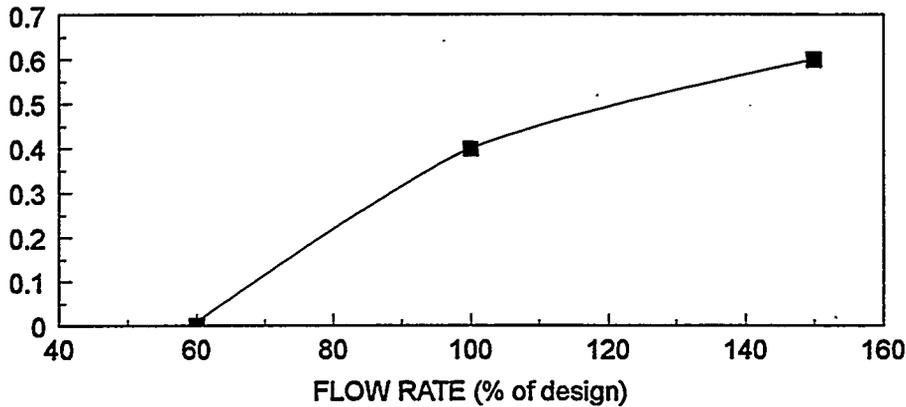


GRACE NOXERAM: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-3**

**AMMONIA SLIP VS. FLOW RATE**

AMMONIA SLIP (ppm)

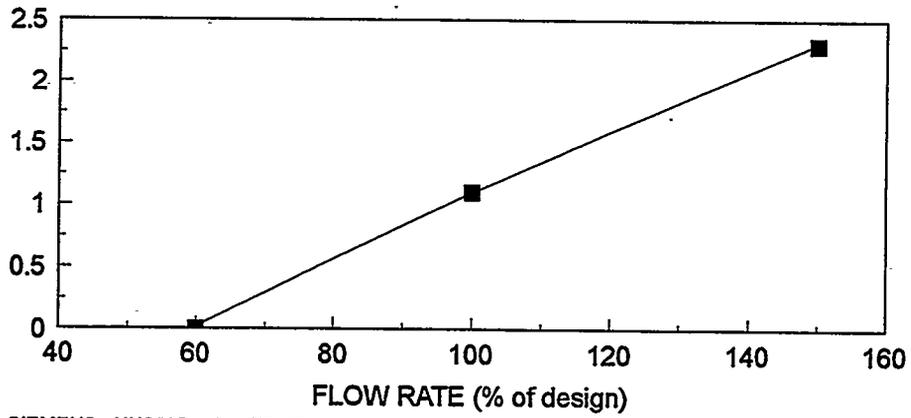


NSK: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-4**

**AMMONIA SLIP VS. FLOW RATE**

AMMONIA SLIP (ppm)

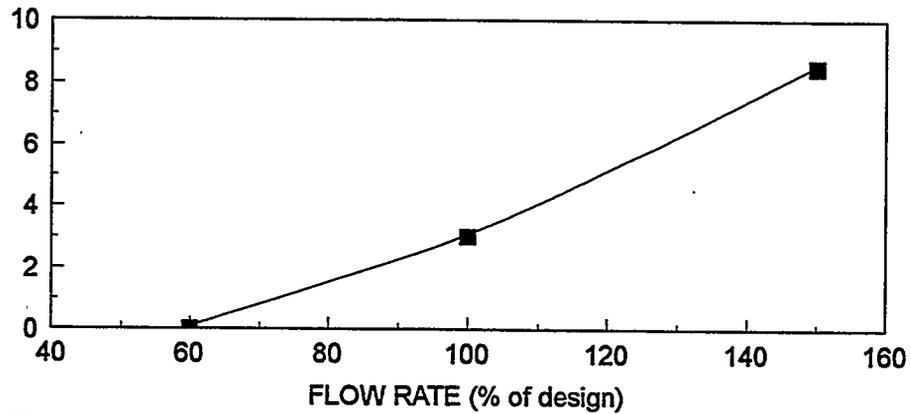


SIEMENS: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-5**

**AMMONIA SLIP VS. FLOW RATE**

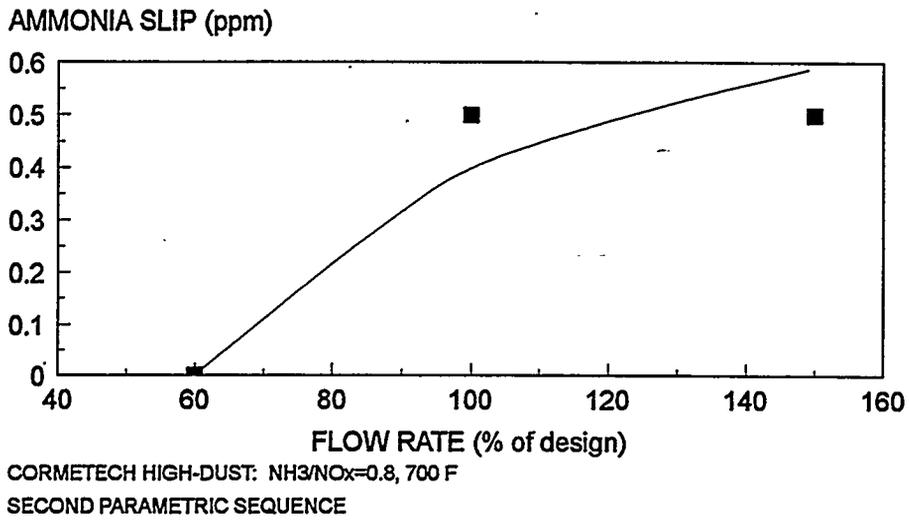
AMMONIA SLIP (ppm)



GRACE SYNOX: NH<sub>3</sub>/NO<sub>x</sub>=0.95, 700 F  
SECOND PARAMETRIC SEQUENCE

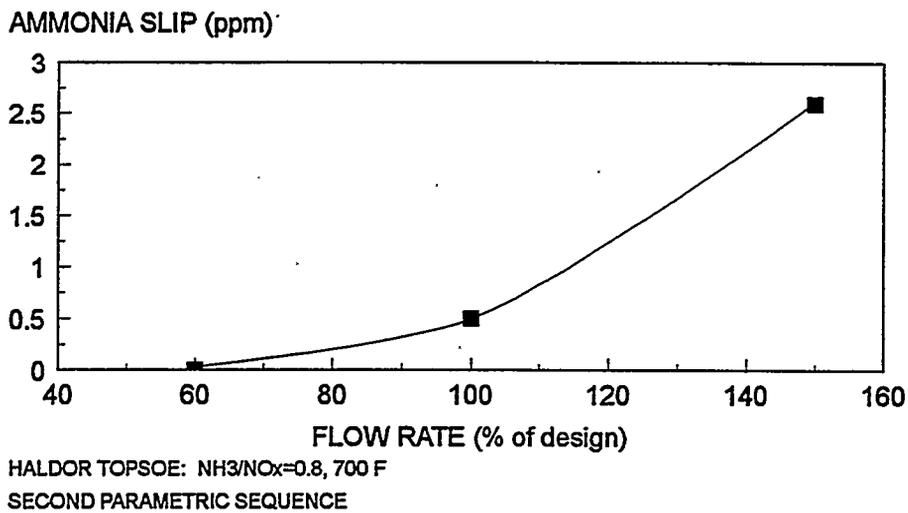
**Figure 5.3.2-6**

**AMMONIA SLIP VS. FLOW RATE**



**Figure 5.3.2-7**

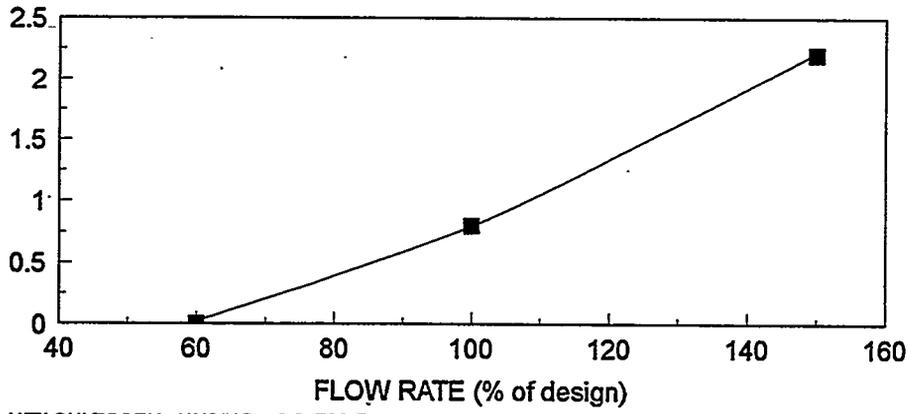
**AMMONIA SLIP VS. FLOW RATE**



**Figure 5.3.2-8**

**AMMONIA SLIP VS. FLOW RATE**

AMMONIA SLIP (ppm)

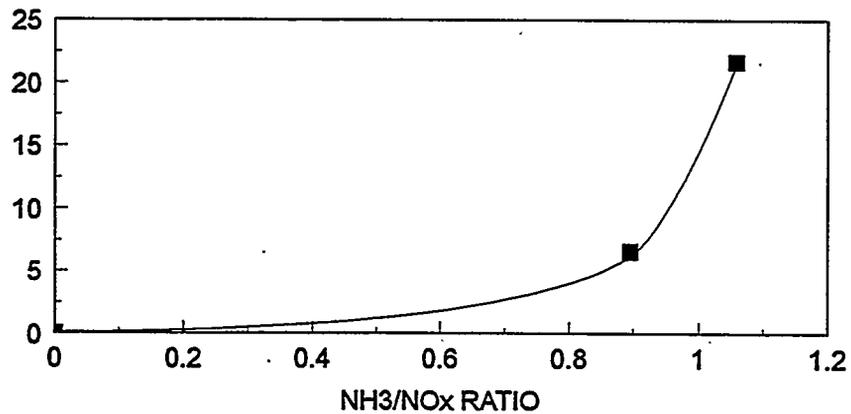


HITACHI ZOSEN: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-9**

**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

AMMONIA SLIP (ppm)

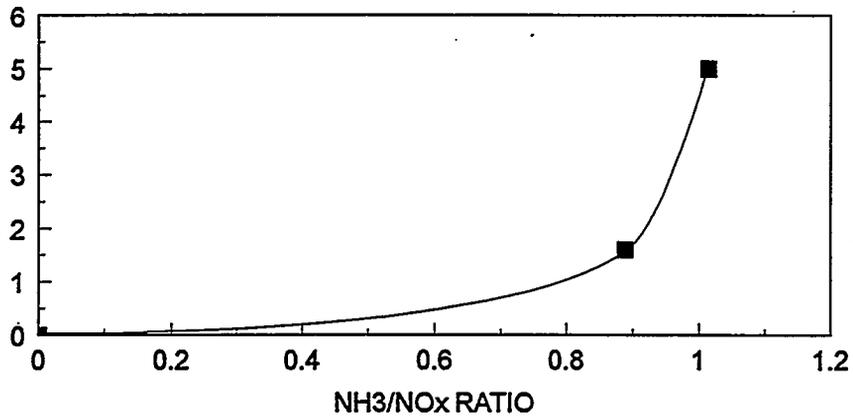


GRACE NOXERAM: 620 F, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-10**

**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

AMMONIA SLIP (ppm)



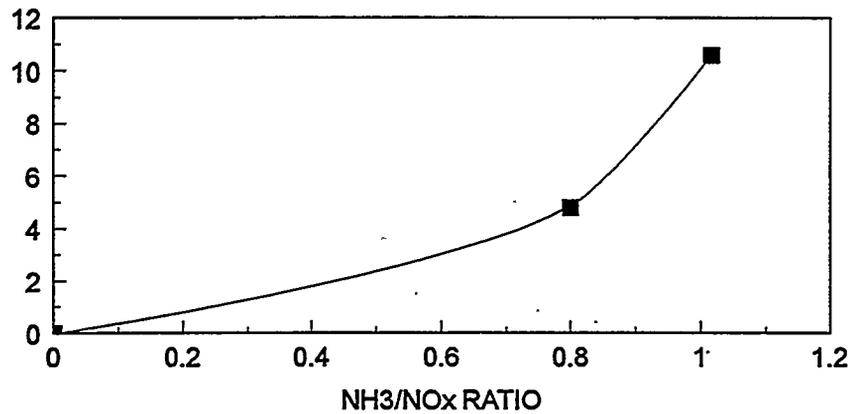
NSKK: 620 F, HIGH FLOW

SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-11**

**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

AMMONIA SLIP (ppm)



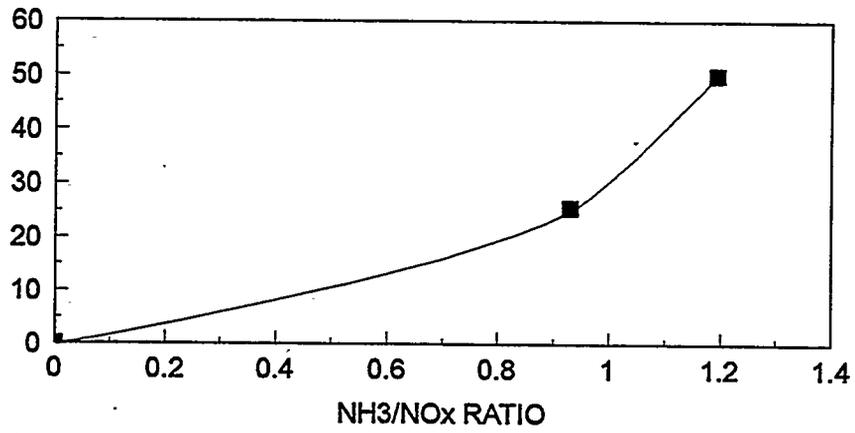
SIEMENS: 620 F, HIGH FLOW

SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-12**

**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

AMMONIA SLIP (ppm)

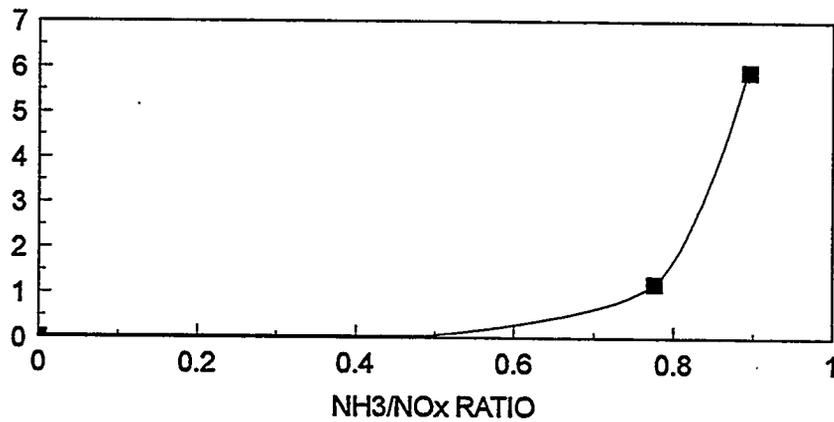


GRACE SYNOX: 620 F, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-13**

**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**

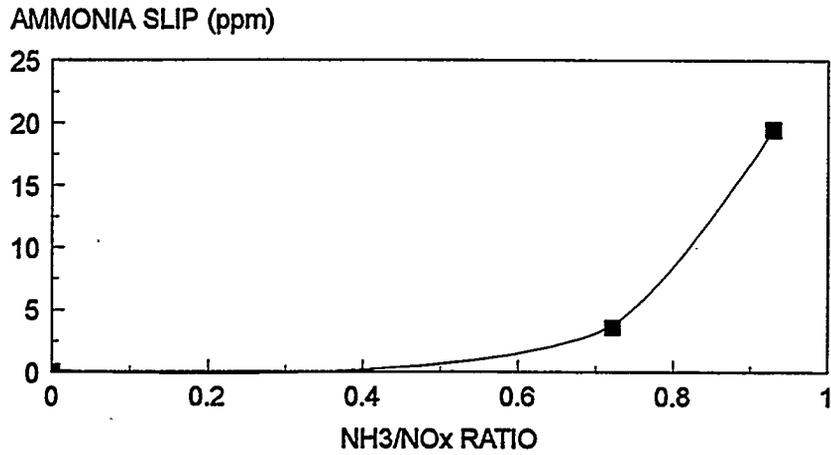
AMMONIA SLIP (ppm)



CORMETECH HIGH-DUST: 620 F, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-14**

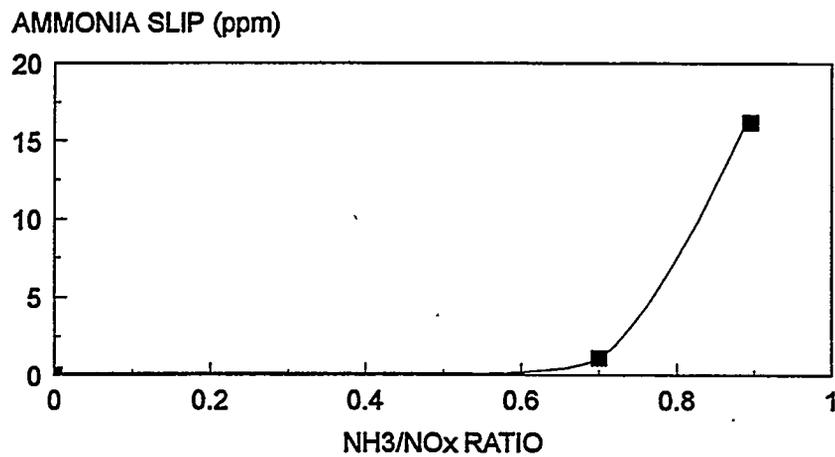
**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**



HALDOR TOPSOE: 620 F, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-15**

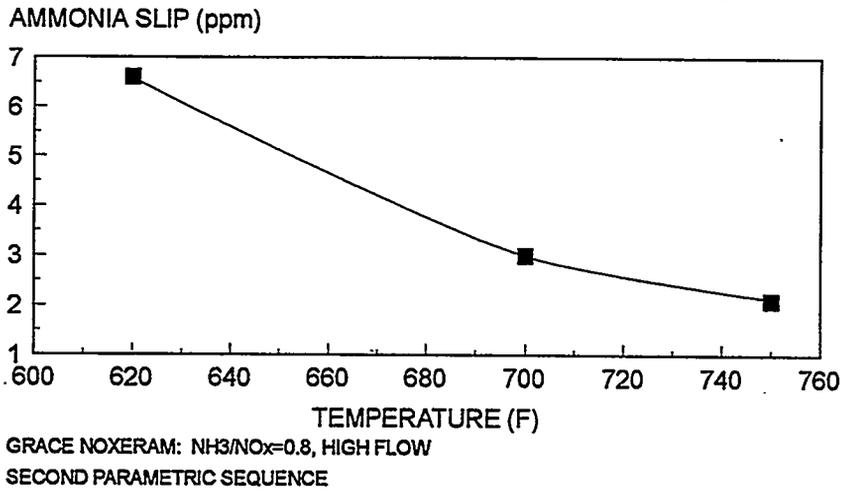
**AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO**



HITACHI ZOSEN: 620 F, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

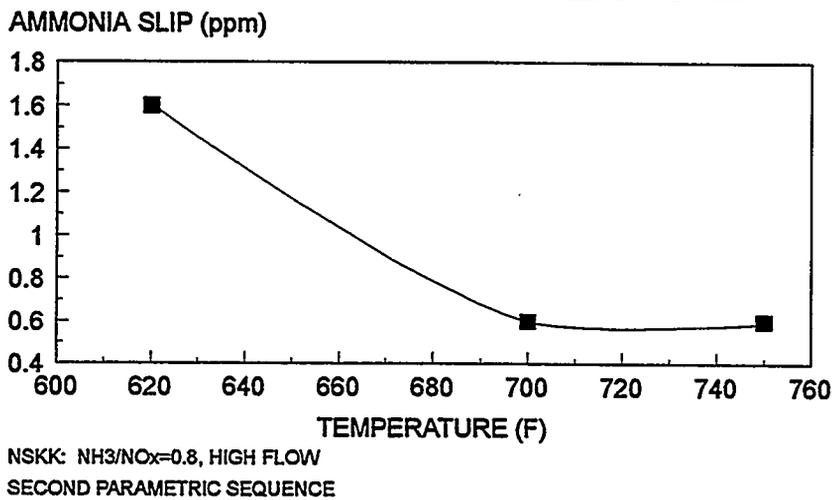
**Figure 5.3.2-16**

**AMMONIA SLIP VS. TEMPERATURE**



**Figure 5.3.2-17**

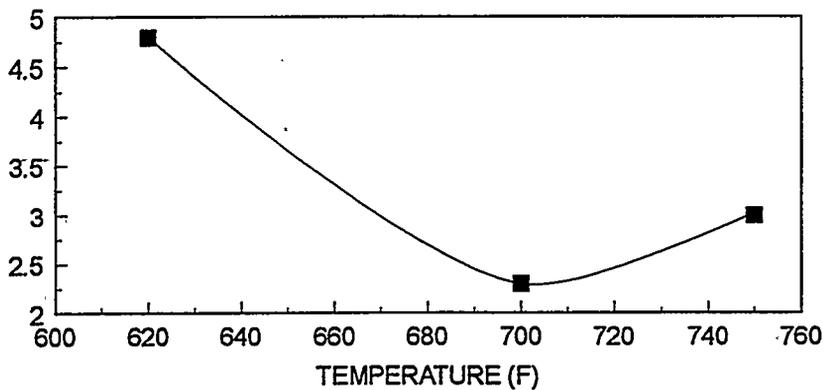
**AMMONIA SLIP VS. TEMPERATURE**



**Figure 5.3.2-18**

**AMMONIA SLIP VS. TEMPERATURE**

AMMONIA SLIP (ppm)

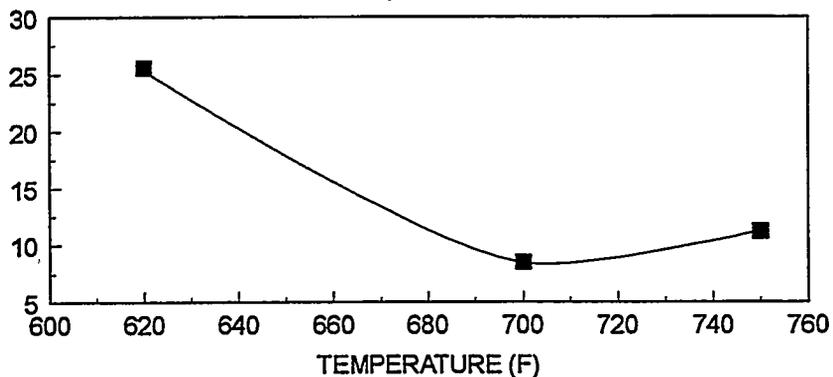


SIEMENS: NH<sub>3</sub>/NO<sub>x</sub>=0.8, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-19**

**AMMONIA SLIP VS. TEMPERATURE**

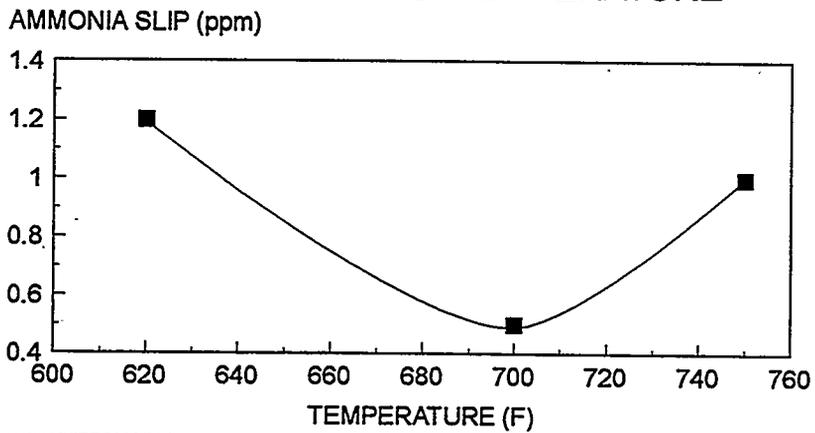
AMMONIA SLIP (ppm)



GRACE SYNOX: NH<sub>3</sub>/NO<sub>x</sub>=0.9, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-20**

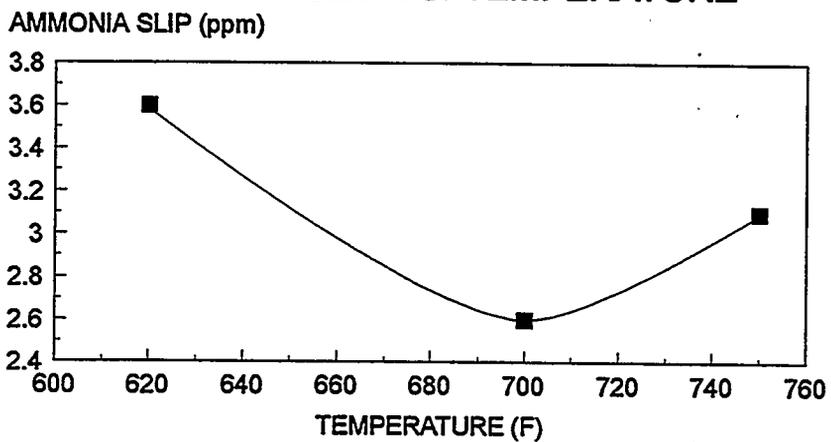
**AMMONIA SLIP VS. TEMPERATURE**



CORMETECH HIGH-DUST: NH<sub>3</sub>/NO<sub>x</sub>=0.8, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-21**

**AMMONIA SLIP VS. TEMPERATURE**

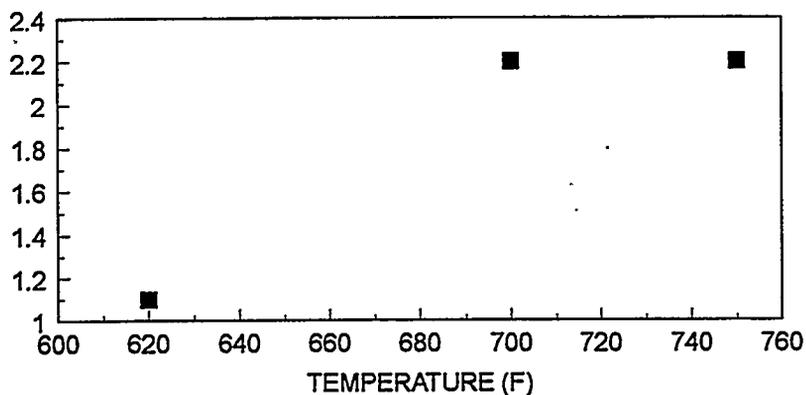


HALDOR TOPSOE: NH<sub>3</sub>/NO<sub>x</sub>=0.8, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-22**

**AMMONIA SLIP VS. TEMPERATURE**

AMMONIA SLIP (ppm)

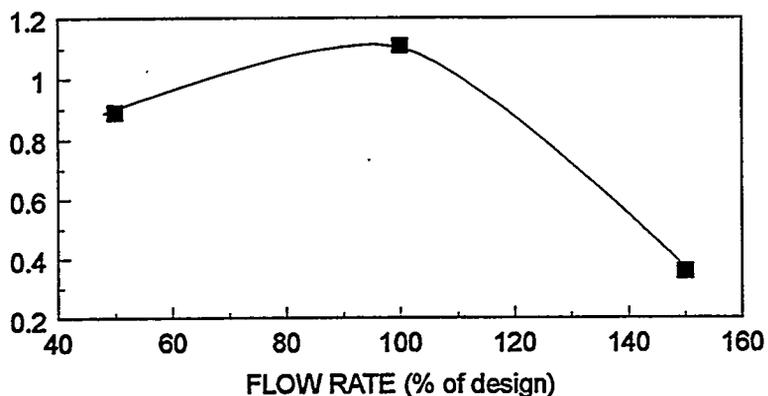


HITACHI ZOSEN: NH<sub>3</sub>/NO<sub>x</sub>=0.8, HIGH FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-23**

**SO<sub>2</sub> OXIDATION VS. FLOW RATE**

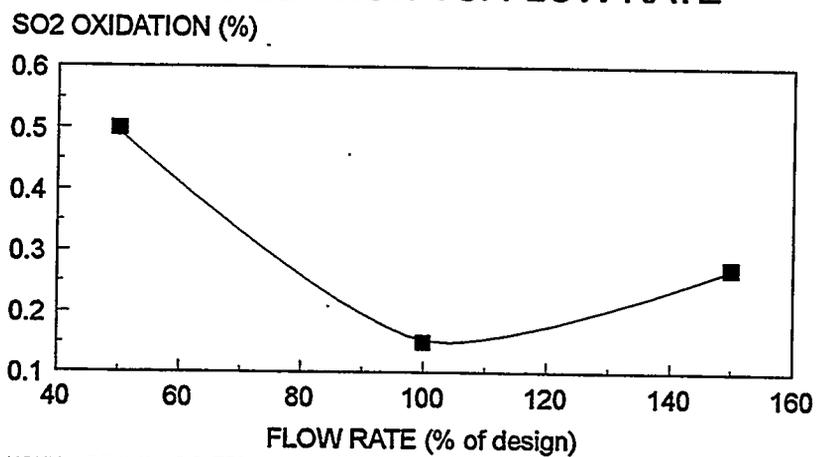
SO<sub>2</sub> OXIDATION (%)



GRACE NOXERAM: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 750 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-24**

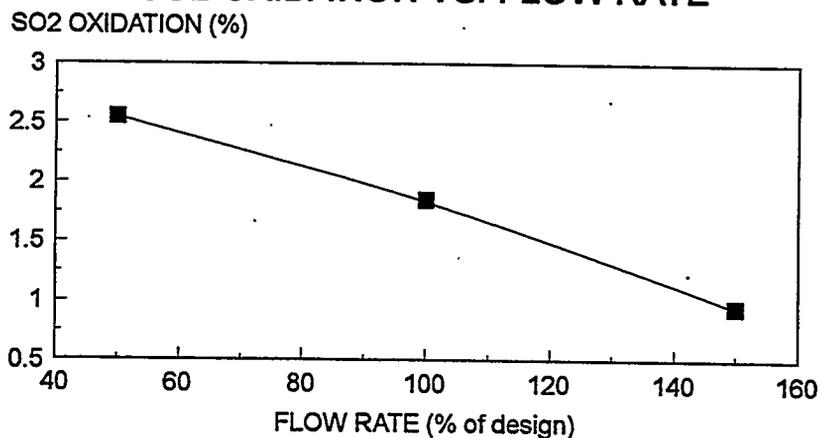
**SO2 OXIDATION VS. FLOW RATE**



NSKK: NH3/NOx=0.8, 750 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-25**

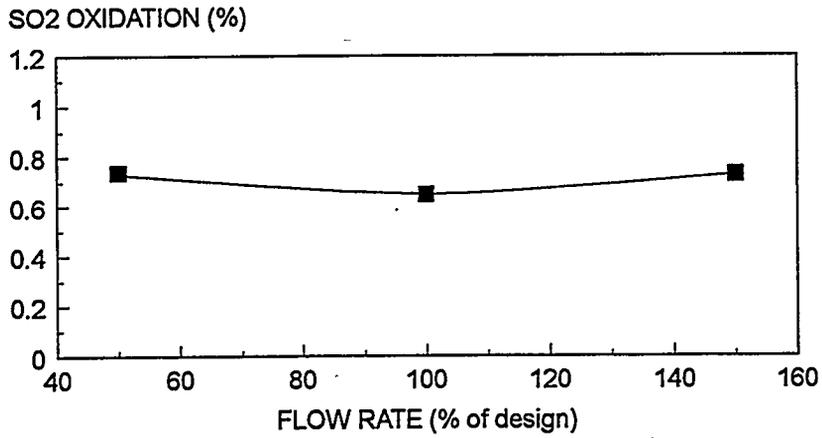
**SO2 OXIDATION VS. FLOW RATE**



SIEMENS: NH3/NOx=0.8, 750 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-26**

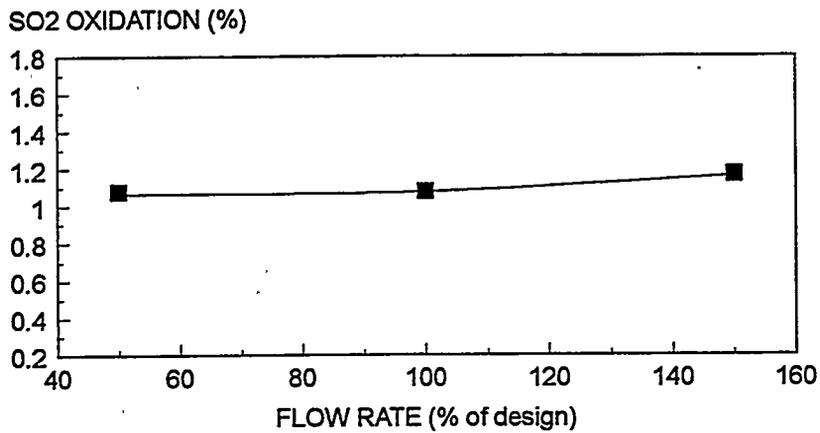
**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



GRACE SYNOX: NH<sub>3</sub>/N NO<sub>x</sub>=0.98, 750 F  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-27**

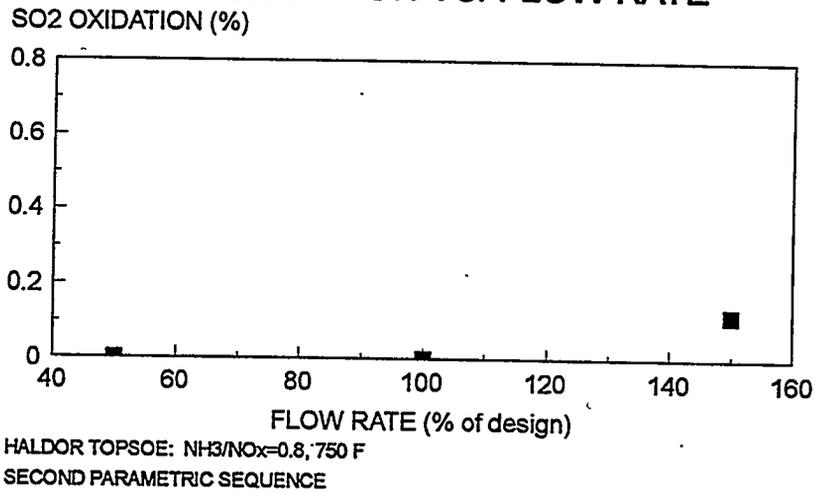
**SO<sub>2</sub> OXIDATION VS. FLOW RATE**



CORMETECH HIGH-DUST: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 750 F  
SECOND PARAMETRIC SEQUENCE

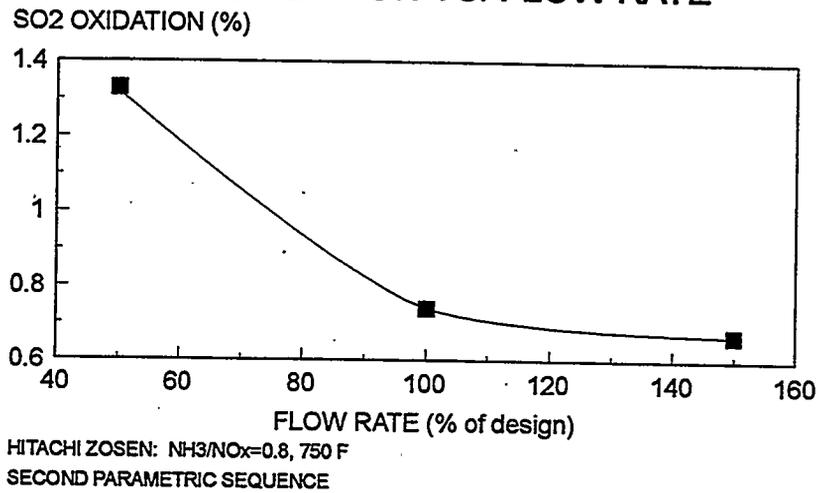
**Figure 5.3.2-28**

**SO2 OXIDATION VS. FLOW RATE**



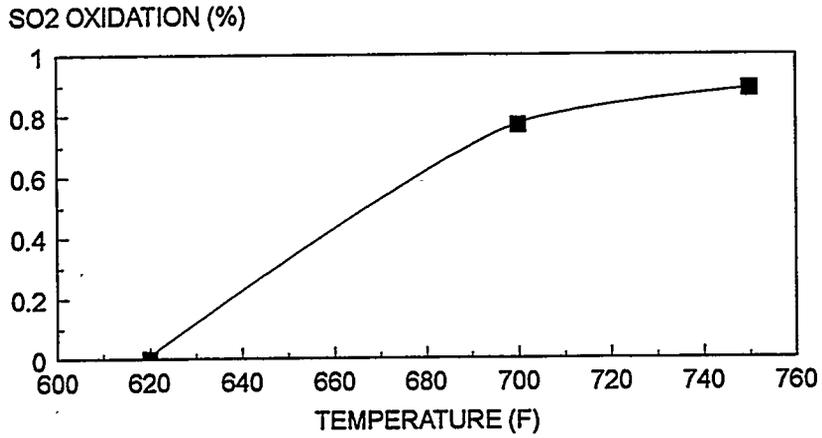
**Figure 5.3.2-29**

**SO2 OXIDATION VS. FLOW RATE**



**Figure 5.3.2-30**

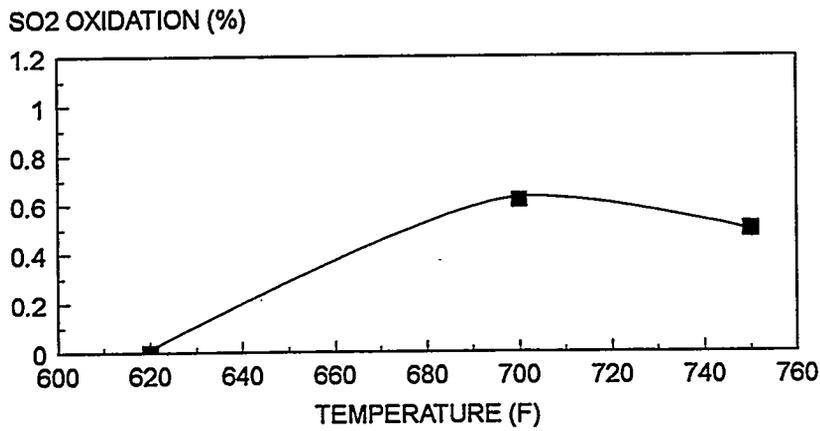
**SO<sub>2</sub> OXIDATION VS. TEMPERATURE**



GRACE NOXERAM: NH<sub>3</sub>/NO<sub>x</sub>=0.8, LOW FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-31**

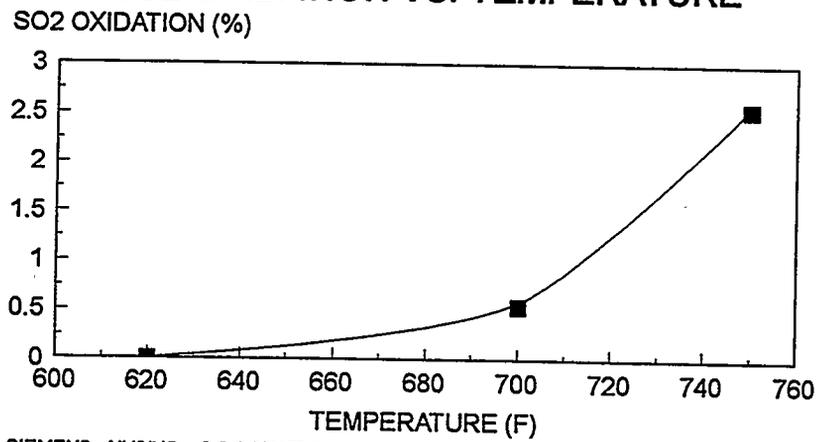
**SO<sub>2</sub> OXIDATION VS. TEMPERATURE**



NSKK: NH<sub>3</sub>/NO<sub>x</sub>=0.8, LOW FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-32**

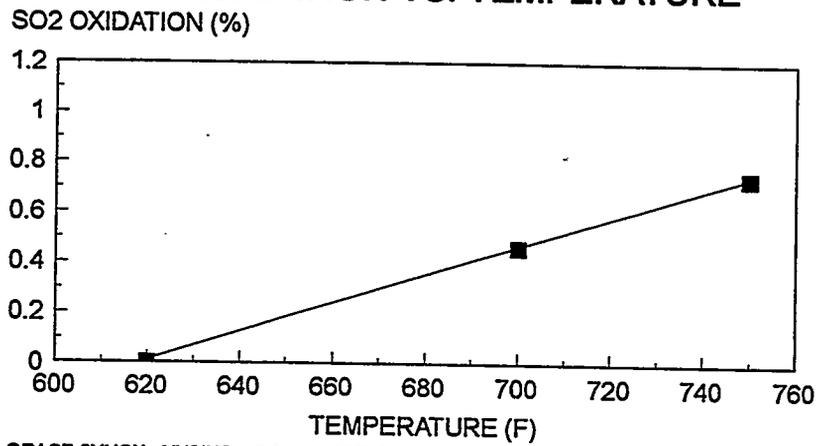
**SO2 OXIDATION VS. TEMPERATURE**



SIEMENS: NH3/NOx=0.8, LOW FLOW  
SECOND PARAMETRIC SEQUENCE

**Figure 5.3.2-33**

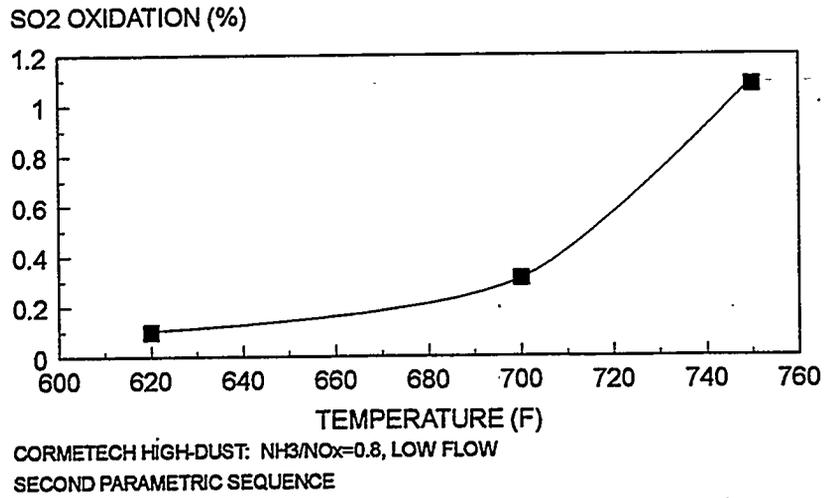
**SO2 OXIDATION VS. TEMPERATURE**



GRACE SYNOX: NH3/NOx=0.98, LOW FLOW  
SECOND PARAMETRIC SEQUENCE

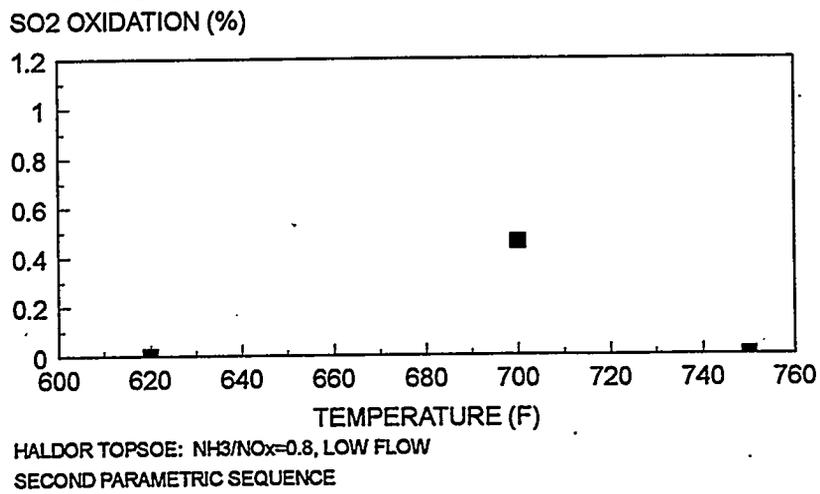
**Figure 5.3.2-34**

**SO<sub>2</sub> OXIDATION VS. TEMPERATURE**



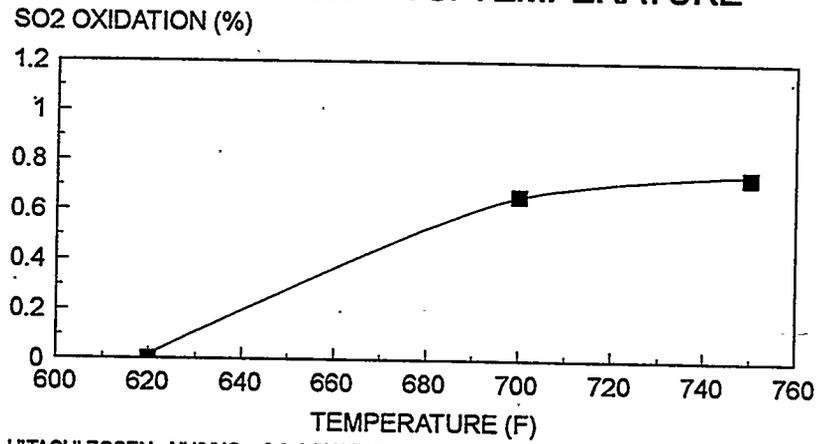
**Figure 5.3.2-35**

**SO<sub>2</sub> OXIDATION VS. TEMPERATURE**



**Figure 5.3.2-36**

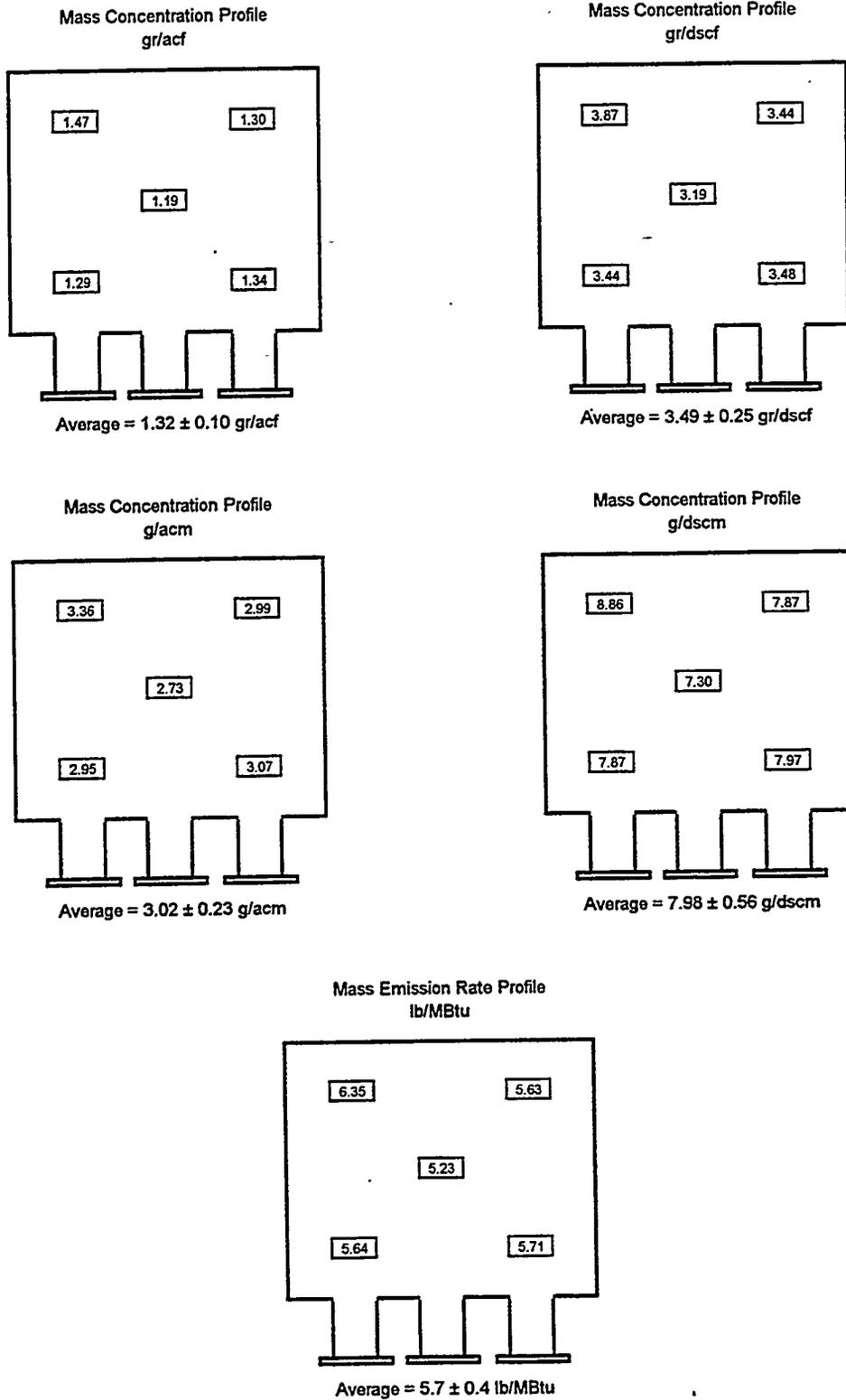
**SO<sub>2</sub> OXIDATION VS. TEMPERATURE**



HITACHI ZOSEN: NH<sub>3</sub>/NO<sub>x</sub>=0.8, LOW FLOW  
SECOND PARAMETRIC SEQUENCE

Figure 5.3.2-37

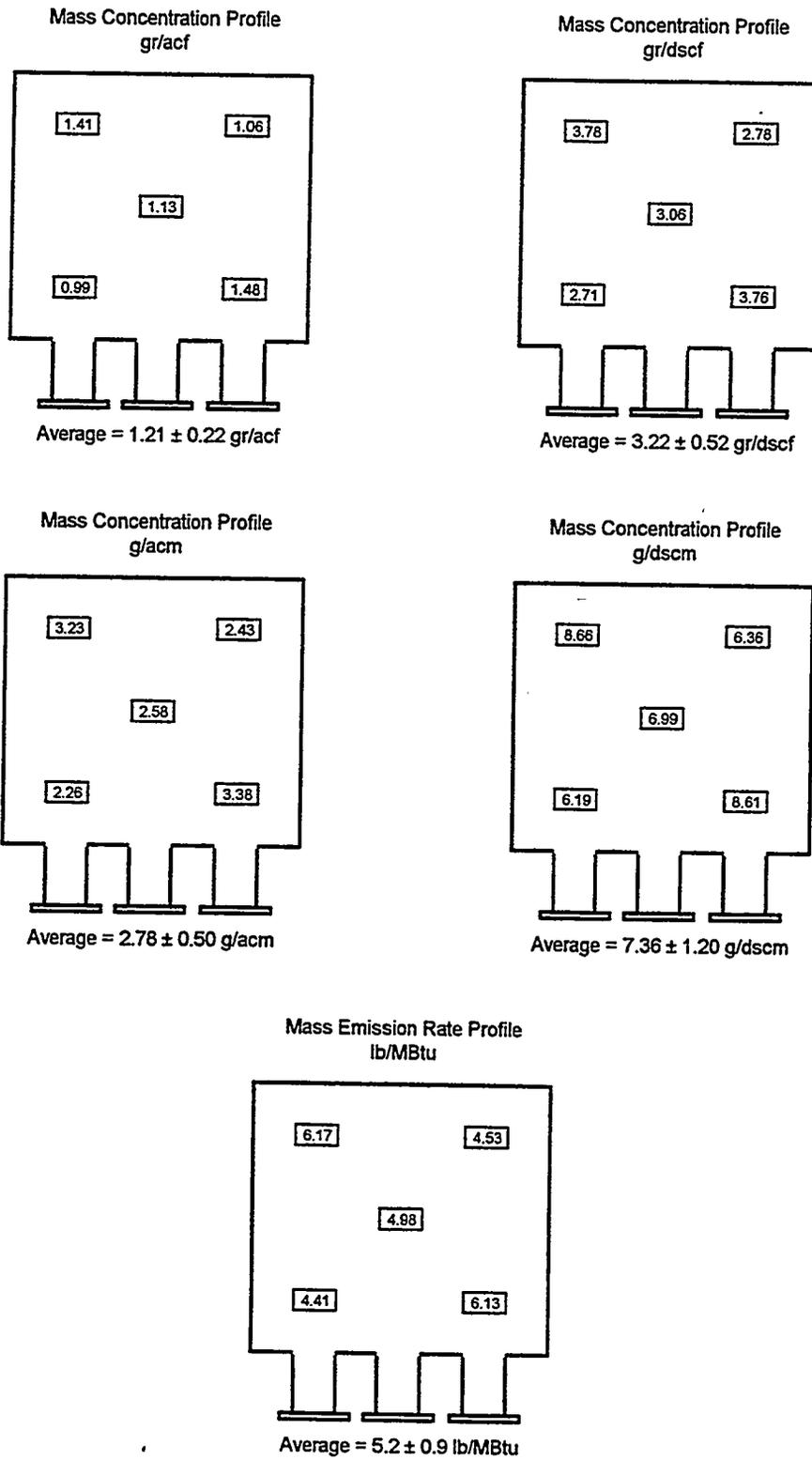
**REACTOR A**  
CATALYST LAYER 4 (REACTOR OUTLET)



Five presentations of the Reactor A outlet mass concentration profile.

Figure 5.3.2-38

**REACTOR B**  
CATALYST LAYER 4 (REACTOR OUTLET)

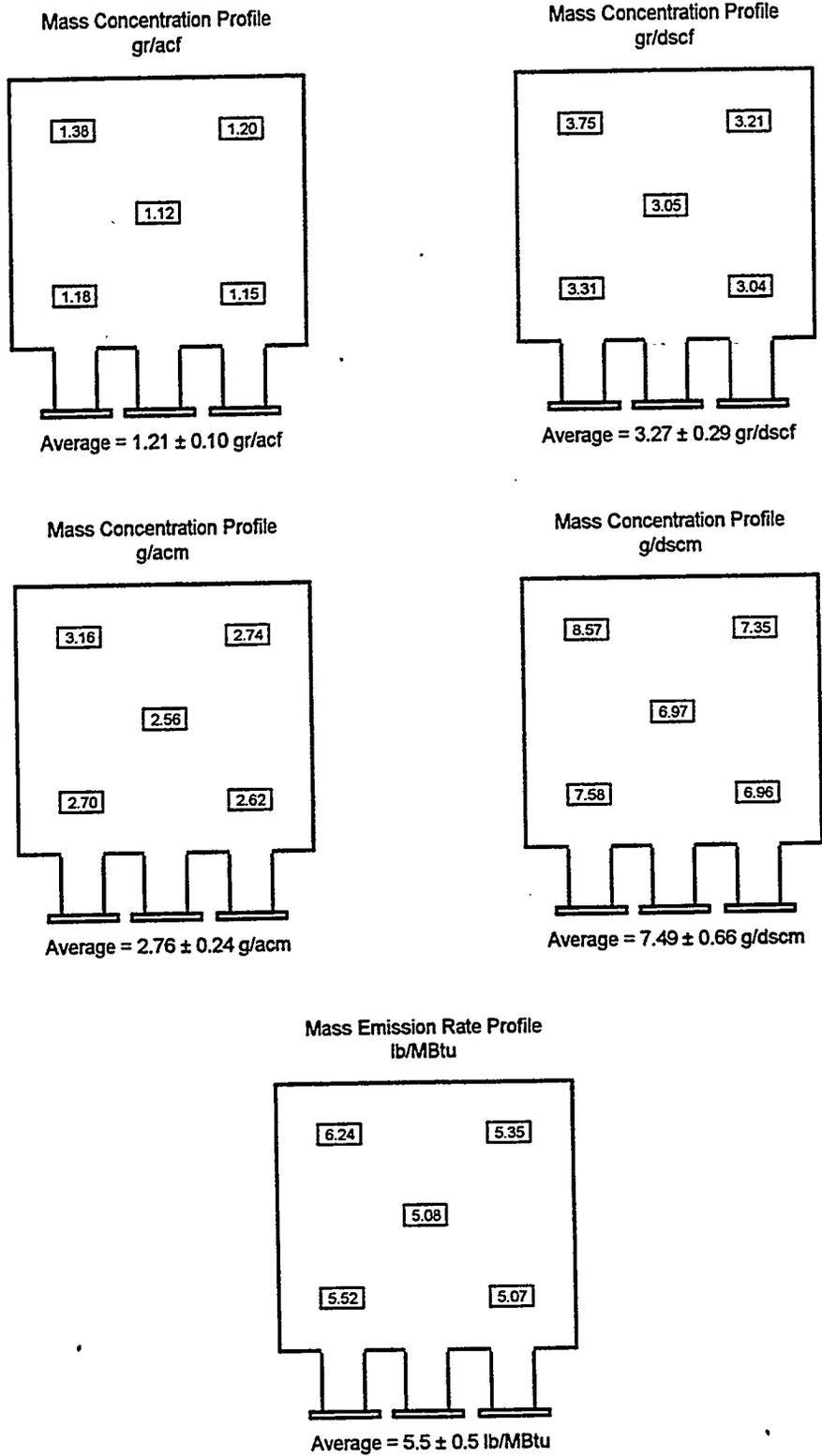


Five presentations of the Reactor B mass concentration profile.

Figure 5.3.2-39

**REACTOR C**

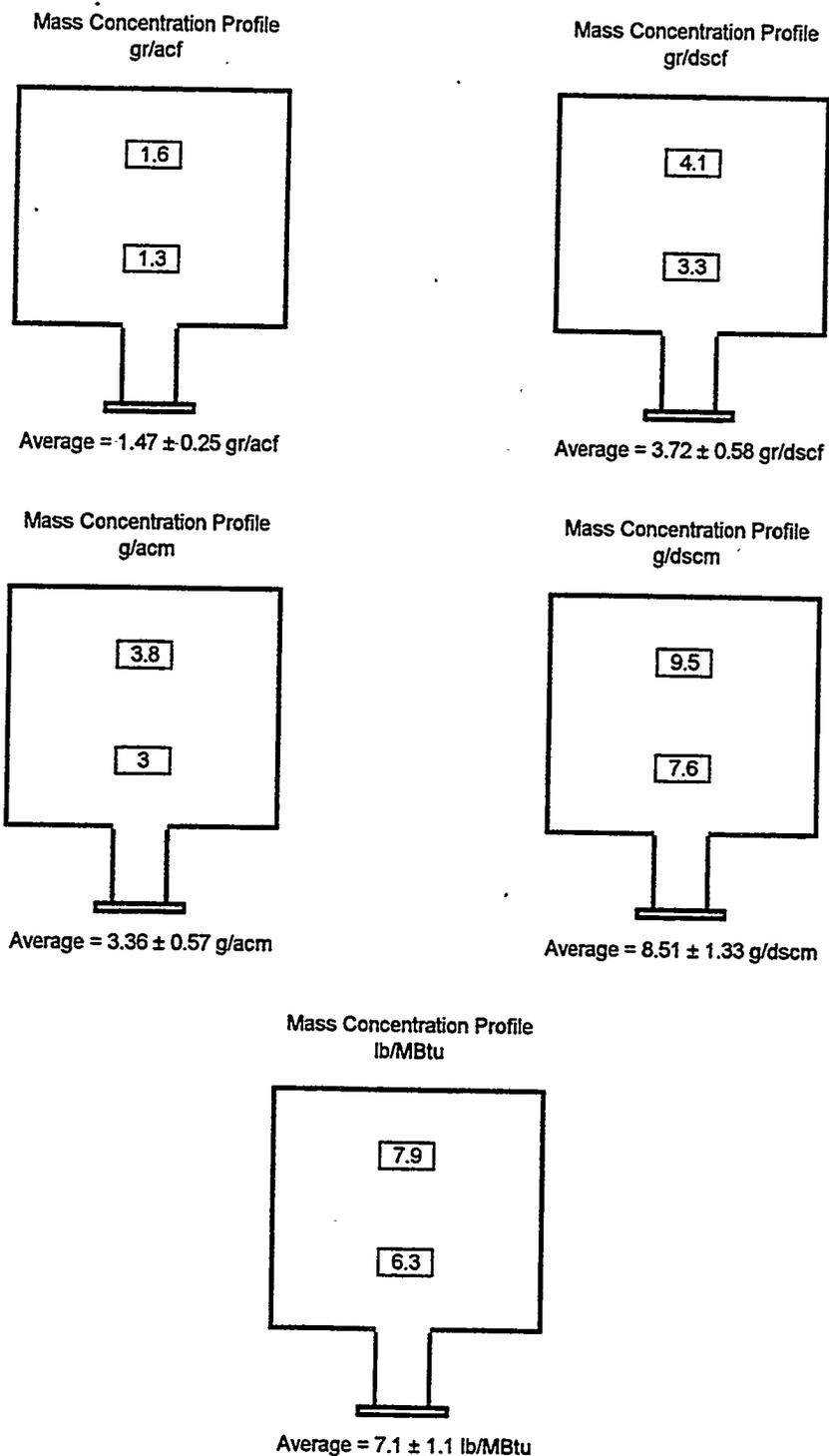
CATALYST LAYER 4 (REACTOR OUTLET)



Five presentations of the Reactor C mass concentration profile.

Figure 5.3.2-40

**REACTOR D**  
CATALYST LAYER 4 (REACTOR OUTLET)

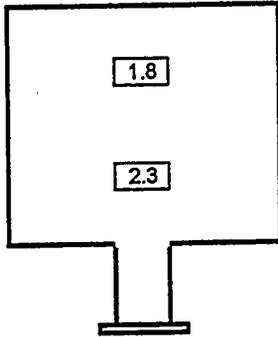


Five presentations of the Reactor D mass concentration profile.

Figure 5.3.2-41

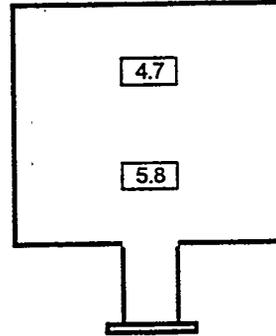
**REACTOR E**  
**CATALYST LAYER 4 (REACTOR OUTLET)**

Mass Concentration Profile  
gr/acf



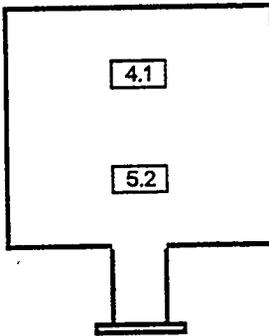
Average =  $2.03 \pm 0.35$  gr/acf

Mass Concentration Profile  
gr/dscf



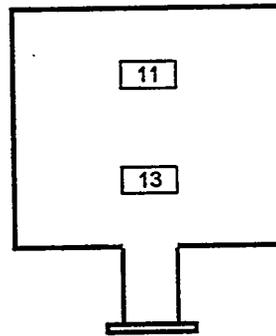
Average =  $5.25 \pm 0.84$  gr/dscf

Mass Concentration Profile  
g/acm



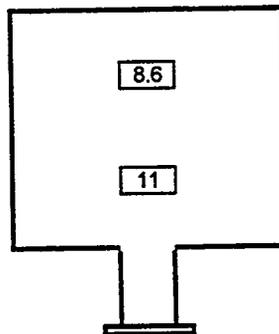
Average =  $4.64 \pm 0.80$  g/acm

Mass Concentration Profile  
g/dscm



Average =  $12.02 \pm 1.93$  g/dscm

Mass Concentration Profile  
lb/MBtu

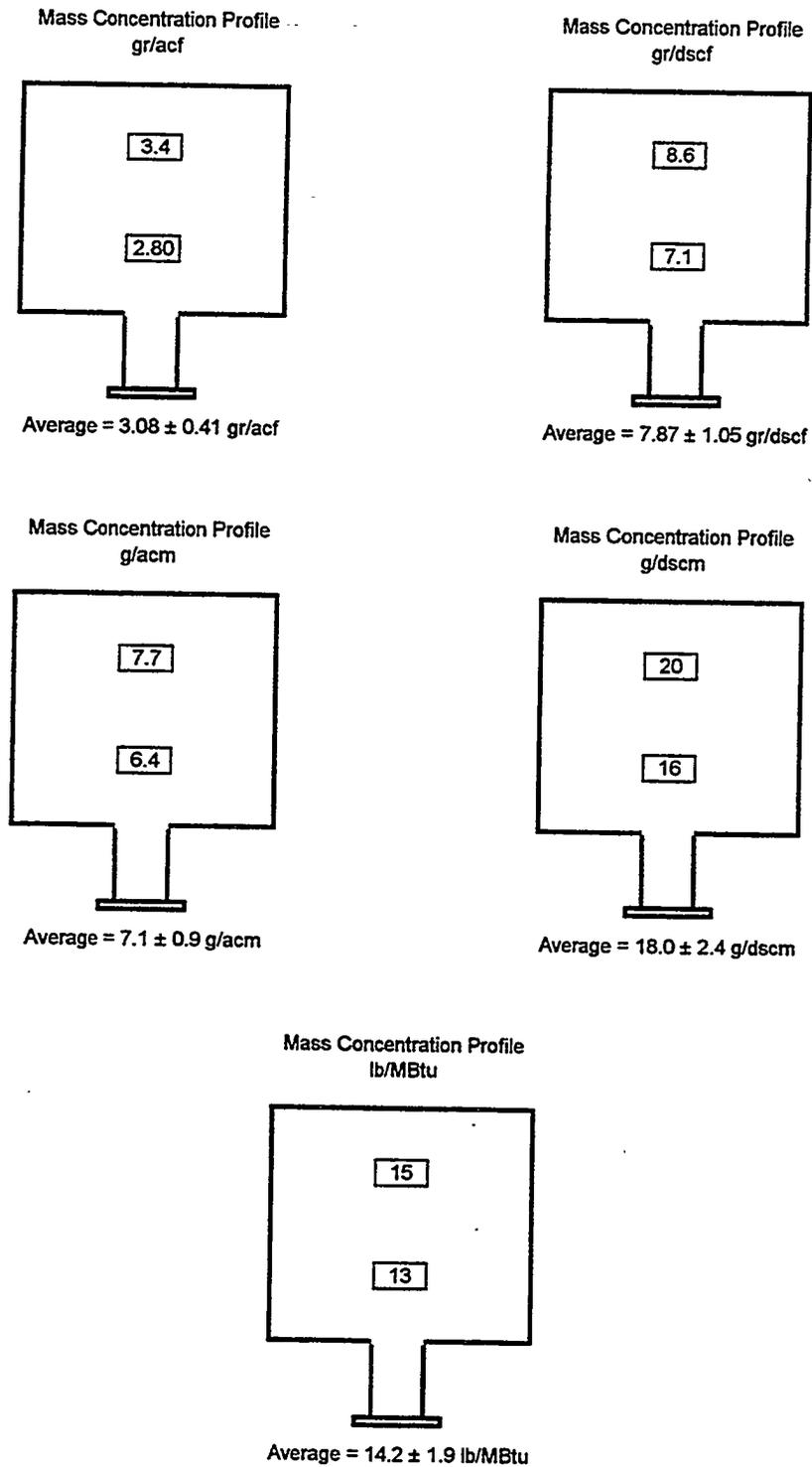


Average =  $9.68 \pm 1.55$  lb/MBtu

Five presentations of the Reactor E mass concentration profile.

Figure 5.3.2-42

**REACTOR F**  
**CATALYST LAYER 4 (REACTOR OUTLET)**

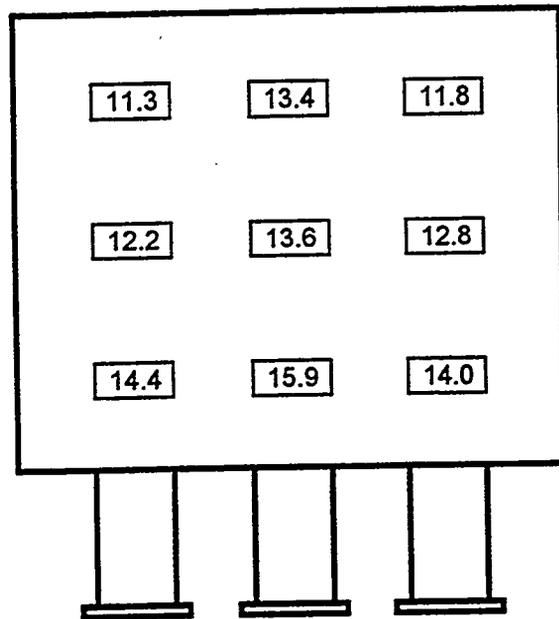


Five presentations of the Reactor F mass concentration profile.

Figure 5.3.2-43

**REACTOR A**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



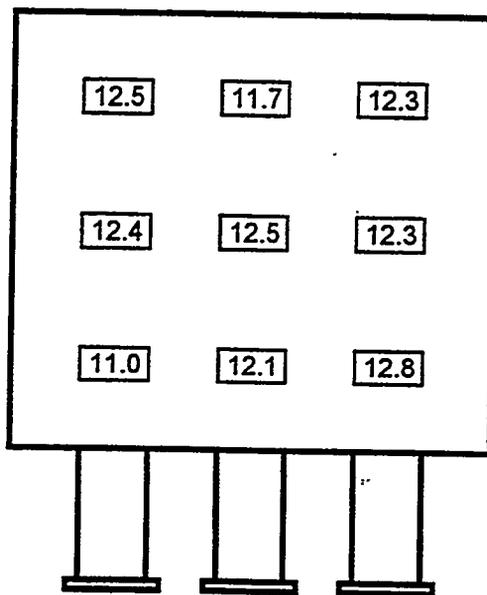
Average =  $13.3 \pm 1.4$  ft/s

Reactor A flue gas velocity profile.

Figure 5.3.2-44

**REACTOR B**  
CATALYST LAYER 1 INLET

Velocity Profile  
ft/s



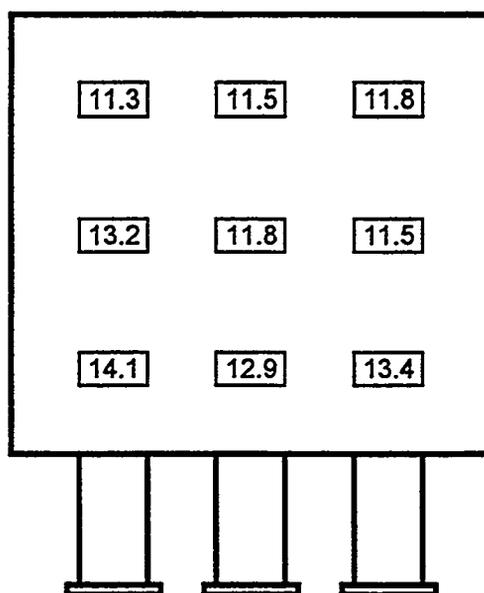
Average =  $12.2 \pm 0.5$  ft/s

Reactor B flue gas velocity profile.

Figure 5.3.2-45

**REACTOR C**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



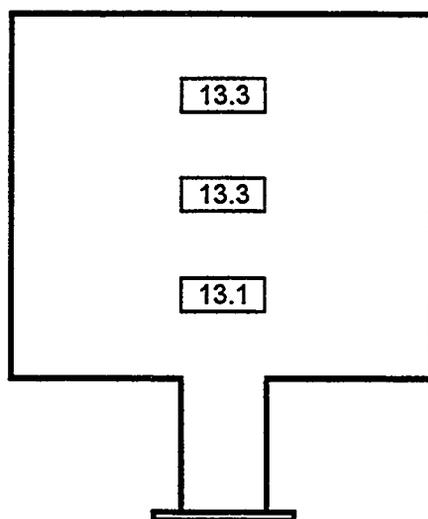
Average =  $12.4 \pm 1.0$  ft/s

Reactor C flue gas velocity profile.

Figure 5.3.2-46

**REACTOR D**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



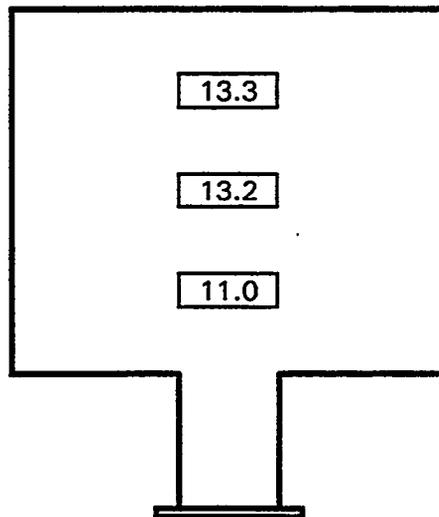
Average =  $13.2 \pm 0.1$  ft/s

Reactor D flue gas velocity profile.

Figure 5.3.2-47

**REACTOR E**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



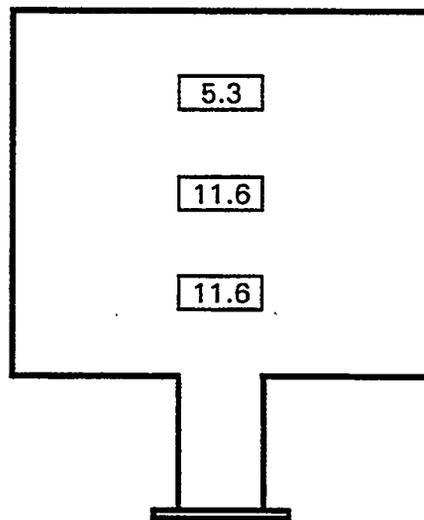
Average =  $12.5 \pm 1.3$  ft/s

Reactor E flue gas velocity profile.

Figure 5.3.2-48

**REACTOR F  
CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



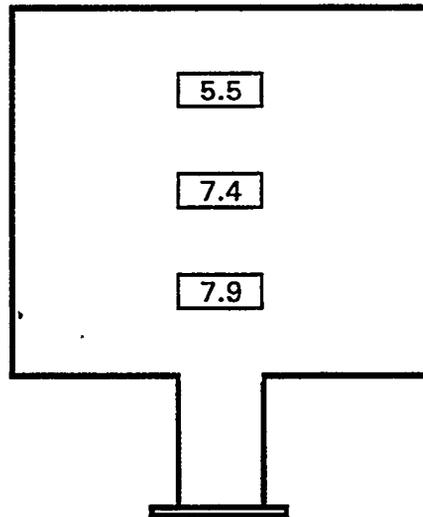
Average =  $9.5 \pm 3.6$  ft/s

Reactor F flue gas velocity profile.

Figure 5.3.2-49

**REACTOR G**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



Average =  $6.9 \pm 1.3$  ft/s

Reactor G flue gas velocity profile.

### 5.3.3 Third Parametric Sequence

The parametric test results characterizing the performance for reactors A - J for the third parametric sequence are discussed in the following sections. The parametric tests were composed of 14 reactor operating conditions defined by variations in the flue gas flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio. The test conditions for the third parametric sequence are presented graphically in Figure 5.3.3-1 and in tabular form in Table 5.3.3-1. The particular measurements that were made (intermediate ammonia, slip ammonia, SO<sub>2</sub>, SO<sub>3</sub>, HCl, N<sub>2</sub>O, and velocity profiles) are also shown at the various test conditions. Although in some cases identical test conditions are indicated, the measurements were not taken simultaneously (e.g., ammonia and SO<sub>2</sub> data for the same conditions were not collected during the exact same test run, but rather under similar process conditions at different times). Tables 5.3.3-2 through 9 show the third parametric test data on intermediate ammonia, slip ammonia, and sulfur dioxide oxidation for reactors A - J, respectively. Appendix K contains the detailed data spreadsheet for this parametric sequence.

Table 5.3.3-1 Parametric Test Conditions (3rd Test Sequence)

| Flue gas flow rate<br>Large / Small reactor<br>(KSCFM) | Flue gas<br>temperature<br>(°F) | NH <sub>3</sub> /NO <sub>x</sub><br>Ratio | Measurements   |
|--|---------------------------------|---|--|
| 3.0/0.24   | 620                             | 0.8                                       | slip NH <sub>3</sub>   |
| 5.0/0.40   | 620                             | 0.6                                       | slip NH <sub>3</sub>   |
| 5.0/0.40   | 620                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0/0.40   | 620                             | 1.0                                       | slip NH <sub>3</sub>   |
| 5.0/0.40   | 700                             | 0.6                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0/0.40   | 700                             | 0.8                                       | *Intermediate & slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub> , N <sub>2</sub> O,<br>HCl (gas phase only), velocity profile. |
| 5.0/0.40   | 700                             | 1.0                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0/0.40   | 750                             | 0.6                                       | slip NH <sub>3</sub>   |
| 5.0/0.40   | 750                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0/0.40   | 750                             | 1.0                                       | slip NH <sub>3</sub>   |
| 7.5/0.60   | 620                             | 1.0                                       | intermediate & slip NH <sub>3</sub>  |
| 7.5/0.60   | 700                             | 0.6                                       | slip NH <sub>3</sub>   |
| 7.5/0.60   | 700                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 7.5/0.60   | 700                             | 1.0                                       | slip NH <sub>3</sub>   |

\*Design conditions.

Fig 5.3.3-1 Third SCR Parametric Test Plan

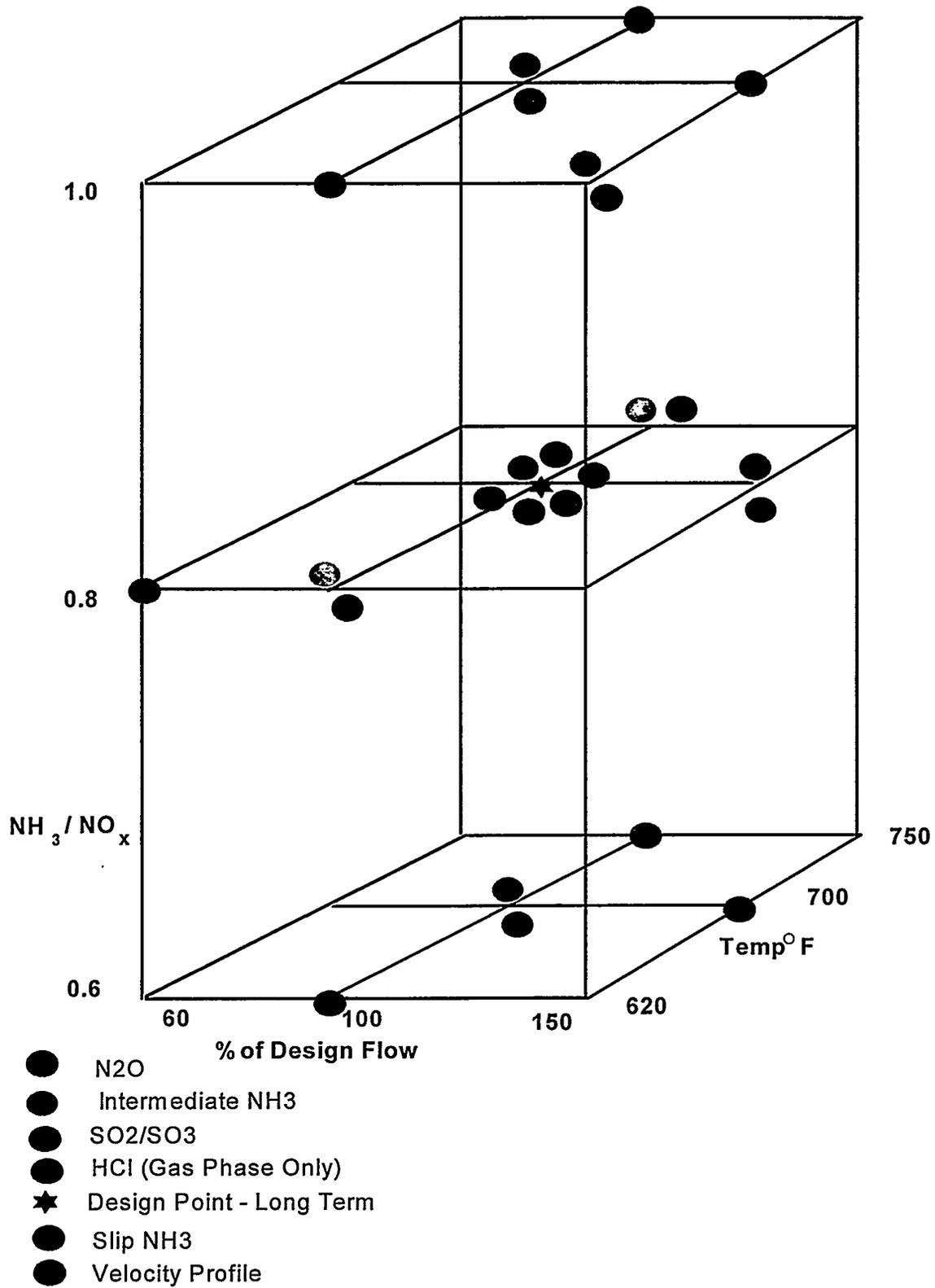




Table 5.3.3-2 Reactor A Data (3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 5000             | 646        | 3.631                    | 348                          | 0.786                                  | 35.3                        | 68.4                          |
| 6496             | 650        | 3.554                    | 341                          | 1.008                                  | 76.1                        | 78.5                          |
| 4997             | 705        | 6.103                    | 335                          | 0.586                                  | 19.7                        | 52.7                          |
| 5002             | 707        | 4.051                    | 367                          | 0.785                                  | 30.6                        | 70.2                          |
| 4998             | 706        | 7.005                    | 338                          | 1.050                                  | 36.8                        | 94.1                          |
| 6169             | 704        | 4.614                    | 299                          | 0.793                                  | 39.0                        | 66.3                          |
| 4984             | 756        | 4.428                    | 329                          | 0.767                                  | 31.7                        | 67.1                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3000             | 630        | 5.133                    | 365                          | 0.800                                  | 1.9                         |
| 5000             | 630        | 5.133                    | 350                          | 0.568                                  | 1.5                         |
| 5000             | 631        | 3.953                    | 353                          | 0.793                                  | 2.0                         |
| 5003             | 623        | 5.532                    | 278                          | 1.014                                  | 3.5                         |
| 6105             | 622        | 5.511                    | 204                          | 1.011                                  | 4.2                         |
| 4996             | 707        | 3.265                    | 314                          | 0.592                                  | 1.4                         |
| 5010             | 708        | 3.879                    | 347                          | 0.790                                  | 2.2                         |
| 5007             | 706        | 6.573                    | 291                          | 0.975                                  | 1.6                         |
| 6087             | 707        | 4.409                    | 337                          | 0.591                                  | 1.8                         |
| 5165             | 703        | 3.090                    | 315                          | 0.943                                  | 2.5                         |
| 6063             | 706        | 3.342                    | 311                          | 1.019                                  | 2.7                         |
| 4991             | 756        | 4.963                    | 399                          | 0.561                                  | 1.7                         |
| 4999             | 756        | 4.255                    | 376                          | 0.784                                  | 1.7                         |
| 5011             | 755        | 5.496                    | 289                          | 0.992                                  | 1.8                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5011             | 705        | 2.509                     | 2020                         | 0.802                                  | 0.2                      | 16.8                | 16.6                          | 0.82           |
| 4996             | 750        | 2.729                     | 1959                         | 0.906                                  | 0.2                      | 30.5                | 30.3                          | 1.55           |

Table 5.3.3-3 Reactor B Data (3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 4998             | 625        | 6.124                    | 335                          | 0.797                                  | 46.4                        | 65.8                          |
| 7429             | 628        | 3.955                    | 374                          | 0.975                                  | 131.4                       | 62.3                          |
| 5002             | 710        | 3.330                    | 348                          | 0.576                                  | 18.1                        | 52.4                          |
| 4999             | 706        | 3.512                    | 350                          | 0.782                                  | 40.7                        | 66.5                          |
| 5006             | 706        | 2.994                    | 461                          | 0.820                                  | 98.4                        | 60.7                          |
| 6780             | 709        | 6.498                    | 370                          | 0.769                                  | 65.7                        | 59.1                          |
| 5002             | 755        | 3.107                    | 360                          | 0.763                                  | 47.9                        | 63.0                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3003             | 624        | 3.058                    | 319                          | 0.8                                    | 1.5                         |
| 5005             | 625        | 2.285                    | 311                          | 0.571                                  | 0.9                         |
| 5011             | 626        | 6.983                    | 303                          | 0.794                                  | BDL                         |
| 4998             | 623        | 6.334                    | 342                          | 0.977                                  | 2.6                         |
| 6498             | 625        | 7.149                    | 352                          | 1.056                                  | 8.7                         |
| 5018             | 704        | 5.558                    | 345                          | 0.572                                  | 0.9                         |
| 4998             | 700        | 5.055                    | 319                          | 0.775                                  | BDL                         |
| 5003             | 704        | 3.328                    | 340                          | 0.987                                  | 3.2                         |
| 6493             | 706        | 5.051                    | 322                          | 0.582                                  | 1                           |
| 6367             | 707        | 2.426                    | 292                          | 0.78                                   | 1.8                         |
| 6499             | 705        | 5.109                    | 334                          | 1.019                                  | 4.3                         |
| 4998             | 757        | 6.061                    | 228                          | 0.916                                  | 0.9                         |
| 5004             | 757        | 5.258                    | 389                          | 0.777                                  | 0.8                         |
| 5006             | 756        | 4.476                    | 375                          | 0.989                                  | 1.7                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5365             | 704        | 3.464                     | 2094                         | 0.802                                  | 0.1                      | 4.4                 | 4.3                           | 0.20           |
| 5396             | 755        | 3.361                     | 2119                         | 1.193                                  | 0.2                      | 6.5                 | 6.3                           | 0.30           |

Table 5.3.3-4 Reactor C Data (3rd Parametric Sequence)

## Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 5014             | 625        | 4.490                    | 367                          | 0.756                                  | 33.1                        | 66.6                          |
| 7493             | 652        | 2.261                    | 321                          | 0.969                                  | 74.6                        | 73.6                          |
| 5005             | 706        | 5.858                    | 365                          | 0.554                                  | 16.7                        | 50.8                          |
| 4999             | 709        | 2.784                    | 357                          | 0.761                                  | 26.9                        | 68.6                          |
| 5005             | 708        | 3.654                    | 366                          | 0.972                                  | 61.6                        | 80.4                          |
| 7007             | 707        | 4.644                    | 378                          | 0.761                                  | 40.3                        | 65.5                          |
| 4992             | 753        | 4.582                    | 376                          | 0.764                                  | 27.5                        | 69.1                          |

## Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3003             | 638        | 3.757                    | 340                          | 0.8                                    | 0.8                         |
| 5010             | 641        | 2.689                    | 325                          | 0.583                                  | 1.3                         |
| 5005             | 630        | 4.665                    | 361                          | 0.751                                  | 2.5                         |
| 4998             | 631        | 3.801                    | 353                          | 0.997                                  | 22.2                        |
| 7404             | 629        | 7.395                    | 384                          | 0.938                                  | 18.4                        |
| 4990             | 706        | 2.831                    | 326                          | 0.571                                  | 1.1                         |
| 4998             | 706        | 6.357                    | 387                          | 0.702                                  | 2.7                         |
| 4995             | 706        | 6.465                    | 313                          | 0.967                                  | 13.8                        |
| 7021             | 708        | 6.058                    | 348                          | 0.561                                  | 3.4                         |
| 7073             | 705        | 5.037                    | 319                          | 0.772                                  | 7                           |
| 7050             | 705        | 5.037                    | 376                          | 1                                      | 15.5                        |
| 4994             | 758        | 2.783                    | 328                          | 0.573                                  | 1.5                         |
| 4997             | 756        | 4.676                    | 332                          | 0.827                                  | 3                           |
| 5005             | 757        | 2.129                    | 318                          | 0.972                                  | 10.9                        |

## Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5392             | 704       | 3.406                     | 2106                         | 0.802                                  | 0.1                      | 13.7                | 13.6                          | 0.64           |
| 5411             | 754       | 3.305                     | 2127                         | 0.801                                  | 0.2                      | 24.3                | 24.1                          | 1.13           |

Table 5.3.3-5 Reactor D Data (3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED.(%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------|
| 394              | 626        | 7.014                    | 274                          | 0.890                                  | 81.6                        | 59.2                         |
| 602              | 624        | 5.523                    | 242                          | 1.106                                  | 133.3                       | 55.5                         |
| 399              | 705        | 5.747                    | 258                          | 0.676                                  | 42.9                        | 51.0                         |
| 401              | 705        | 5.706                    | 248                          | 0.935                                  | 66.4                        | 66.7                         |
| 400              | 707        | 5.606                    | 240                          | 1.176                                  | 103.0                       | 74.7                         |
| 601              | 706        | 8.799                    | 242                          | 1.127                                  | 76.4                        | 81.2                         |
| 402              | 756        | 6.212                    | 273                          | 1.085                                  | 82.8                        | 78.2                         |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 240              | 622        | 8.839                    | 266                          | 0.800                                  | 06.3                        |
| 400              | 625        | 9.419                    | 272                          | 0.716                                  | 02.8                        |
| 400              | 625        | 7.996                    | 272                          | 0.844                                  | 10.0                        |
| 400              | 623        | 7.163                    | 266                          | 1.106                                  | 51.1                        |
| 601              | 625        | 6.147                    | 274                          | 1.052                                  | 55.9                        |
| 400              | 705        | 6.61                     | 238                          | 0.701                                  | 01.9                        |
| 401              | 705        | 8.918                    | 243                          | 0.897                                  | 04.1                        |
| 400              | 705        | 6.626                    | 251                          | 1.226                                  | 28.4                        |
| 583              | 706        | 8.195                    | 293                          | 0.647                                  | 04.8                        |
| 599              | 707        | 3.007                    | 340                          | 0.802                                  | 19.6                        |
| 600              | 706        | 2.955                    | 334                          | 1.001                                  | 52.8                        |
| 400              | 755        | 2.85                     | 269                          | 0.602                                  | 01.7                        |
| 400              | 755        | 2.761                    | 267                          | 0.795                                  | 03.2                        |
| 403              | 755        | 2.965                    | 317                          | 0.992                                  | 13.6                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 415              | 706       | 3.576                     | 1972                         | 0.801                                  | 0.4                      | 7.9                 | 7.5                           | 0.38           |
| 421              | 756       | 3.916                     | 1857                         | 0.792                                  | 0.5                      | 21.8                | 21.3                          | 1.15           |

Table 5.3.3-6 Reactor E Data ( 3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 387              | 624        | 4.947                    | 250                          | 0.874                                  | 156.1                       | 24.9                          |
| 603              | 626        | 5.268                    | 300                          | 1.013                                  | 49.6                        | 84.8                          |
| 401              | 707        | 7.135                    | 314                          | 0.645                                  | 7.6                         | 62.0                          |
| 400              | 704        | 7.673                    | 300                          | 0.924                                  | 12.3                        | 88.3                          |
| 401              | 706        | 5.496                    | 367                          | 0.920                                  | 50.0                        | 78.4                          |
| 600              | 706        | 7.996                    | 331                          | 0.881                                  | 41.8                        | 75.5                          |
| 400              | 757        | 7.147                    | 278                          | 0.990                                  | 11.9                        | 94.7                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 243              | 625        | 10.244                   | 183                          | 0.8                                    | BDL                         |
| 400              | 625        | 7.493                    | 225                          | 0.555                                  | BDL                         |
| 401              | 623        | 7.752                    | 217                          | 0.774                                  | BDL                         |
| 403              | 626        | 8.061                    | 219                          | 1.064                                  | BDL                         |
| 598              | 625        | 3.099                    | 306                          | 1.002                                  | 24.5                        |
| 400              | 705        | 8.367                    | 284                          | 0.6                                    | BDL                         |
| 403              | 705        | 8.367                    | 275                          | 0.904                                  | BDL                         |
| 396              | 704        | 8.251                    | 196                          | 1.242                                  | 1.6                         |
| 602              | 704        | 6.180                    | 281                          | 0.668                                  | BDL                         |
| 602              | 702        | 9.402                    | 293                          | 0.904                                  | 0.7                         |
| 598              | 705        | 8.000                    | 272                          | 1.039                                  | 7.6                         |
| 400              | 755        | 2.447                    | 313                          | 0.604                                  | BDL                         |
| 41               | 755        | 2.620                    | 303                          | 0.799                                  | 0.6                         |
| 400              | 755        | 7.180                    | 251                          | 0.994                                  | BDL                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET SO <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|----------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 436              | 706       | 3.924                      | 2088                         | 0.806                                  | 1.8                      | 8.3                 | 6.5                           | 0.31           |
| 434              | 755       | 3.763                      | 2124                         | 0.806                                  | 0.4                      | 13.2                | 12.8                          | 0.60           |

Table 5.3.3-7 Reactor F Data (3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 402              | 624        | 1.876                    | 300                          | 1.276                                  | 106.8                       | 92.1                          |
| 580              | 627        | 2.468                    | 327                          | 0.926                                  | 180.2                       | 37.6                          |
| 399              | 706        | 1.883                    | 319                          | 0.510                                  | 051.3                       | 35.0                          |
| 401              | 706        | 3.573                    | 316                          | 0.753                                  | 082.6                       | 49.2                          |
| 399              | 712        | 2.586                    | 289                          | 0.927                                  | 113.2                       | 53.5                          |
| 599              | 706        | 1.803                    | 314                          | 0.757                                  | 119.3                       | 37.7                          |
| 400              | 757        | 1.968                    | 308                          | 0.753                                  | 070.0                       | 52.6                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 241              | 623        | 4.321                    | 355                          | 0.800                                  | 01.5                        |
| 400              | 627        | 2.364                    | 313                          | 0.599                                  | 00.8                        |
| 402              | 627        | 2.994                    | 329                          | 0.796                                  | 02.9                        |
| 400              | 624        | 4.507                    | 289                          | 1.070                                  | 66.3                        |
| 600              | 625        | 5.672                    | 349                          | 0.934                                  | 70.4                        |
| 4.02             | 704        | 7.205                    | 359                          | 0.541                                  | 01.5                        |
| 400              | 706        | 2.702                    | 322                          | 0.715                                  | 00.9                        |
| 402              | 706        | 2.886                    | 344                          | 0.998                                  | 16.0                        |
| 596              | 705        | 3.669                    | 282                          | 0.592                                  | 03.4                        |
| 592              | 705        | 2.333                    | 332                          | 0.798                                  | 08.8                        |
| 600              | 705        | 2.264                    | 327                          | 1.003                                  | 53.9                        |
| 400              | 747        | 5.828                    | 339                          | 0.559                                  | 02.2                        |
| 400              | 753        | 4.688                    | 256                          | 0.737                                  | 02.5                        |
| 400              | 755        | 4.115                    | 344                          | 0.915                                  | 15.9                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 414              | 705       | 3.016                     | 2045                         | 0.793                                  | 0.3                      | 1.6                 | 1.3                           | 0.06           |
| 412              | 756       | 2.891                     | 1976                         | 0.808                                  | 0.9                      | 3.1                 | 2.2                           | 0.11           |

Table 5.3.3-8 Reactor G Data (3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 402              | 624        | 6.311                    | 263                          | 0.821                                  | 45.8                        | 64.7                          |
| 596              | 625        | 6.737                    | 192                          | 1.039                                  | 79.2                        | 62.6                          |
| 397              | 707        | 5.581                    | 332                          | 0.613                                  | 18.2                        | 55.8                          |
| 361              | 706        | 5.316                    | 344                          | 0.853                                  | 32.2                        | 76.0                          |
| 394              | 706        | 4.667                    | 302                          | 1.053                                  | 70.5                        | 82.0                          |
| 600              | 703        | 6.357                    | 325                          | 0.810                                  | 61.3                        | 64.1                          |
| 403              | 755        | 5.617                    | 264                          | 0.902                                  | 34.4                        | 77.1                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 241              | 626        | 8.349                    | 283                          | 0.800                                  | BDL                         |
| 404              | 625        | 7.021                    | 294                          | 0.631                                  | BDL                         |
| 400              | 625        | 8.739                    | 309                          | 0.851                                  | 1.4                         |
| 401              | 625        | 3.573                    | 340                          | 1.002                                  | 83.6                        |
| 602              | 628        | 2.251                    | 309                          | 0.964                                  | 41.9                        |
| 397              | 707        | 2.518                    | 349                          | 0.603                                  | 0.7                         |
| 400              | 707        | 2.480                    | 342                          | 0.801                                  | 2.1                         |
| 400              | 704        | 7.496                    | 310                          | 1.072                                  | 39.5                        |
| 603              | 705        | 2.300                    | 277                          | 0.601                                  | 1.2                         |
| 599              | 705        | 2.190                    | 275                          | 0.791                                  | 2.9                         |
| 599              | 705        | 3.723                    | 285                          | 1.031                                  | 36.7                        |
| 400              | 755        | 2.590                    | 331                          | 0.598                                  | 1.2                         |
| 400              | 755        | 2.436                    | 324                          | 0.803                                  | 2.1                         |
| 399              | 741        | 5.725                    | 271                          | 1.142                                  | 25.5                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 402              | 706       | 2.240                     | 2009                         | 0.799                                  | 0.3                      | 2.1                 | 1.8                           | 0.09           |
| 401              | 756       | 2.699                     | 1855                         | 0.815                                  | 0.4                      | 16.0                | 15.6                          | 0.84           |

Table 5.3.3-9 Reactor J Data (3rd Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 403              | 625        | 4.427                    | 290                          | 0.752                                  | 29.6                        | 65.0                          |
| 597              | 628        | 3.917                    | 283                          | 0.972                                  | 67.0                        | 73.5                          |
| 401              | 707        | 3.702                    | 305                          | 0.595                                  | 15.4                        | 54.5                          |
| 404              | 706        | 3.686                    | 309                          | 0.794                                  | 25.6                        | 71.1                          |
| 391              | 706        | 3.745                    | 310                          | 1.018                                  | 39.8                        | 88.9                          |
| 605              | 693        | 3.294                    | 313                          | 0.795                                  | 43.1                        | 65.8                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 240              | 623        | 5.534                    | 307                          | 0.800                                  | 0.9                         |
| 402              | 623        | 5.534                    | 320                          | 0.604                                  | 1.5                         |
| 400              | 623        | 3.775                    | 299                          | 0.766                                  | 2.7                         |
| 400              | 625        | 7.436                    | 331                          | 0.940                                  | 3.5                         |
| 596              | 625        | 6.061                    | 323                          | 0.933                                  | 16.6                        |
| 375              | 707        | 3.835                    | 301                          | 0.580                                  | 0.7                         |
| 401              | 708        | 3.039                    | 308                          | 0.596                                  | 1.2                         |
| 395              | 706        | 3.881                    | 322                          | 1.001                                  | 3.6                         |
| 594              | 695        | 3.488                    | 300                          | 0.540                                  | 1.8                         |
| 601              | 688        | 1.715                    | 294                          | 0.740                                  | 3.9                         |
| 600              | 691        | 1.882                    | 302                          | 0.931                                  | 10.6                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 413              | 705       | 3.381                     | 2078                         | 0.798                                  | 0.6                      | 8.4                 | 7.8                           | 0.37           |

### Intermediate NO<sub>x</sub> Reduction

The intermediate ammonia measurements were made after the first catalyst bed and at conditions thought to give the best kinetic information. The NO<sub>x</sub> removals reported with the intermediate ammonia measurements were computed from the measured ammonia concentrations using a material balance which assumed a 1:1 stoichiometry for the reaction of ammonia and NO<sub>x</sub>. Thus, the moles of ammonia consumed equaled the moles of NO<sub>x</sub> reduced, from which NO<sub>x</sub> reduction was computed, after oxygen corrections were made.

### Ammonia Slip

The ammonia slip data given in Tables 5.3.3-2 - 5.3.3-9 are presented below in three sets of plots: ammonia slip versus each of flow rate, ammonia-to-NO<sub>x</sub> ratio, and temperature. Figures 5.3.3-2 through 8 show ammonia slip versus flow rate at roughly 80% NO<sub>x</sub> reduction for reactors B - J, respectively (This plot was not available for reactor A). As expected, the trends show increasing ammonia slip with increasing reactor flow rate. In general, the ammonia slip is relatively minor indicating the ability of the catalyst designs to withstand significant increases in flow while maintaining ammonia slip limits. For reactor D, the Grace Synox catalyst reactor, a relatively significant increase in ammonia slip is noted with flow rate. Since a portion of the overall reaction rate is due to mass transfer limitations, improvements in bulk mass transfer coefficients were likely mitigating the effect of increasing flow on slip ammonia increases. Overall, these plots demonstrate the ability of an SCR system to follow load variations dictated by the host boiler while maintaining design specifications.

Figures 5.3.3-9 through 16 show ammonia slip versus ammonia-to-NO<sub>x</sub> ratio at low temperature and design flow rate for reactors A - J, respectively. In general, the plots show sharp increases in ammonia slip as the ammonia-to-NO<sub>x</sub> ratio approaches 1.0. This

finding is in keeping with published data of this type. At ammonia-to-NO<sub>x</sub> ratios near 1.0, non-idealities in the reactor systems forced the catalysts to slip ammonia since areas were present in the reactors where NO<sub>x</sub> was the limiting reagent. For Figures 5.3.3-13 and 15 (reactors E and G) the trend of the plots is somewhat unclear since most of the ammonia slip values were below the detection limit. (The detection limit for ammonia slip was roughly 1 ppmv. Values below the detection limit are plotted as zero.)

Ammonia slip versus temperature is plotted in Figures 5.3.3-17 through 23 for design flow rate and roughly 80% NO<sub>x</sub> reduction for reactors A - G, respectively (This plot was not available for reactor J). In the cases of Figures 5.3.3-20 and 22 (reactors D and F) some improvement (decrease) in ammonia slip is noted between 620 and 700 °F, likely due to improvements in the kinetic reaction rate with increasing temperature. Figures 5.3.3-17, 19, and 23 (reactors A, C, and G) show a slight increase in ammonia slip with increasing temperature. However, this unexpected trend is likely due to measurement variability and/or differences in the set point for NO<sub>x</sub> reduction and is not considered significant. For Figures 5.3.3-18 and 21 (reactors B and E) the trend of the plots is somewhat unclear since most of the ammonia slip values were below the detection limit. (The ammonia slip detection limit was roughly 1 ppmv. Any value below the detection limit is plotted as zero.) In general, only slight improvements are noted with increasing temperatures above 700 °F. This may possibly be due to mass transfer limitations that become controlling at these higher temperatures. Overall, these plots demonstrate that in terms of ammonia slip, significant improvements are not realized with temperatures above 700 °F. Losses in boiler efficiency would probably outweigh any improvements that may be obtained in ammonia slip by designing an SCR reactor to operate at temperatures near 750 °F.

### SO<sub>2</sub> Oxidation

SO<sub>2</sub> oxidation versus temperature at design flow rate for the combination of all catalyst beds in the reactors is shown in Figures 5.3.3-24 through 30 for reactors A - G, respectively. (This plot was not available for reactor J). In general, the trend of the plots

shows an increase in SO<sub>2</sub> oxidation with increasing temperature. Published information describing the effects of temperature on SO<sub>2</sub> oxidation and information obtained from the catalyst suppliers indicates that increases in SO<sub>2</sub> oxidation are expected to be exponential with respect to temperature. The exact shape of the plots is somewhat unclear since fairly large measurement variability existed in the test facility and other phenomena such as SO<sub>3</sub> deposition occurred in the test facility reactors. The general trend of increasing SO<sub>2</sub> oxidation is expected, however, and the plots provide a good basis for determining the potential for SO<sub>3</sub> formation across the SCR reactors at various operating temperatures. In the case of Figure 5.3.3-29 (reactor F), the extremely low oxidation rate of the catalyst further exacerbated the problem of measurement precision. This particular plot is valuable in the context of showing that the Haldor Topsoe catalyst has very low SO<sub>2</sub> oxidation potential.

The SO<sub>2</sub> oxidation data are corrected to reactor outlet oxygen concentrations. The value for sulfur trioxide produced in the reactors is based on the measured inlet and outlet sulfur trioxide concentrations. Tables showing SO<sub>2</sub> oxidation rates quote reactor flow rates as calculated for the reactor exits, since SO<sub>3</sub> is measured at this point.)

#### Additional Base-Line Measurements

Flue gas velocity profiles (nine-point for reactors A, B, C) (three-point for reactors D, E, F, G, J) were conducted near design operating conditions (700 °F, 100% flow rate) at the reactor inlets. The velocity profiles are presented in Figures 5.3.3-31 through 38 for reactor A - J, respectively, and the results are given in Table 5.3.3-10 for all reactors.

HCl concentration (at 3% O<sub>2</sub>, dry) was measured at the design operating conditions at the reactor outlets. The N<sub>2</sub>O concentrations were also measured at the reactor inlets and at the reactor outlets (both measurements are dry at 3% O<sub>2</sub>). The results of these measurements are shown in Table 5.3.3-10.

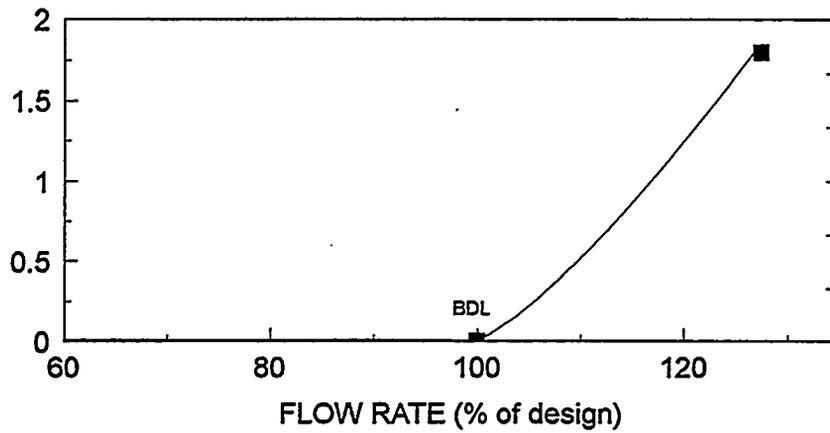
Table 5.3.3-10 Additional Base-line Measurements

| Reactor<br>(Catalyst Supplier) | Velocity<br>Profile<br>(ft/sec) | HCl<br>concentration<br>(ppmv) | N <sub>2</sub> O<br>concentration<br>(ppmv) |            |
|--------------------------------|---------------------------------|--------------------------------|---|------------|
|                                |                                 |                                | rxr inlet                                   | rxr outlet |
| Reactor A<br>(Grace Nxrm)      | 13.2 ± 1.0                      | 233 ± 11                       | 1.2   | 1.3        |
| Reactor B<br>(NSKK)            | 13.5 ± 0.3                      | 238 ± 7                        | 1.2   | 1.3        |
| Reactor C<br>(Siemens)         | 14.1 ± 1.6                      | 233 ± 8                        | 1.2   | 2.0        |
| Reactor D<br>(Grace Synox)     | 14.1 ± 0.3                      | 232 ± 4                        | 1.2   | 2.0        |
| Reactor E<br>(Corm. HD)        | 14.1 ± 0.3                      | 226 ± 4                        | 1.2   | 1.8        |
| Reactor F<br>(Haldor)          | 14.0 ± 1.1                      | 241 ± 13                       | 1.2   | 2.0        |
| Reactor G<br>(Hitachi)         | 18.0 ± 1.5                      | 225 ± 5                        | 1.2   | 2.3        |
| Reactor J<br>(Corm. LD)        | 13.7 ± 1.0                      | 234 ± 5                        | 1.2   | 2.5        |

Figure 5.3.3-2

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



NSKK: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8

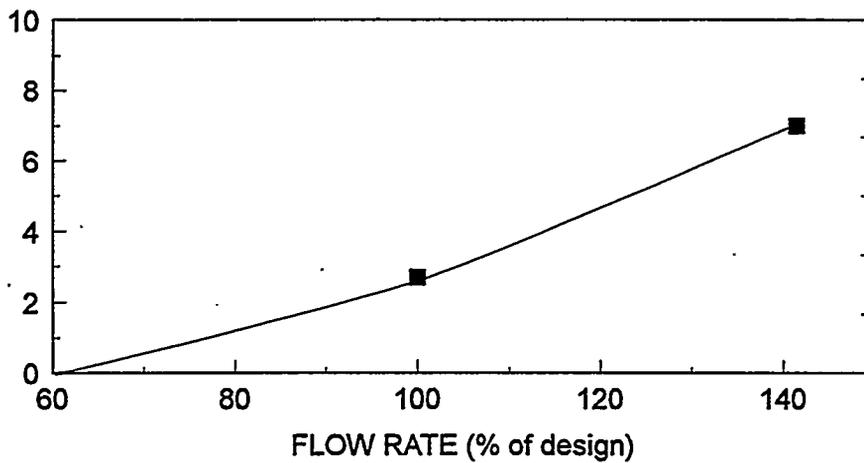
(BDL) Below lower detection limit (<1 ppmv)

THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-3

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)

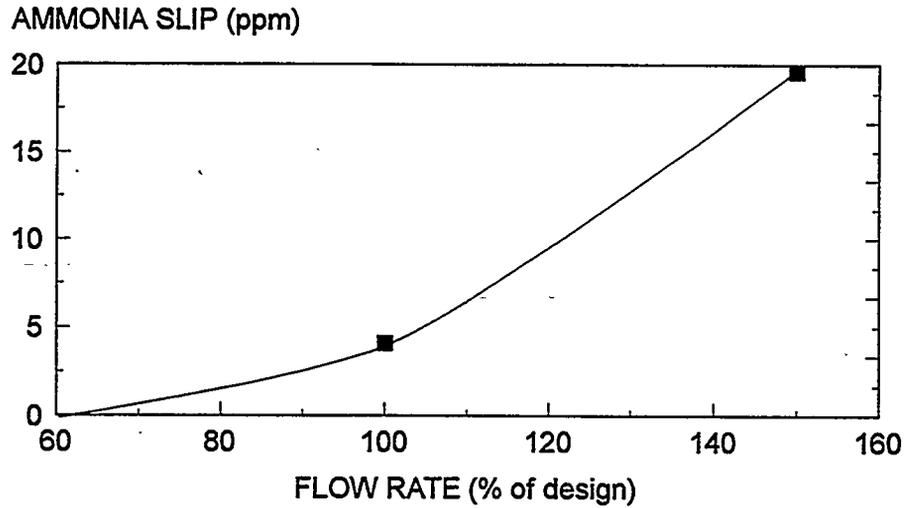


SIEMENS: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8

THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-4

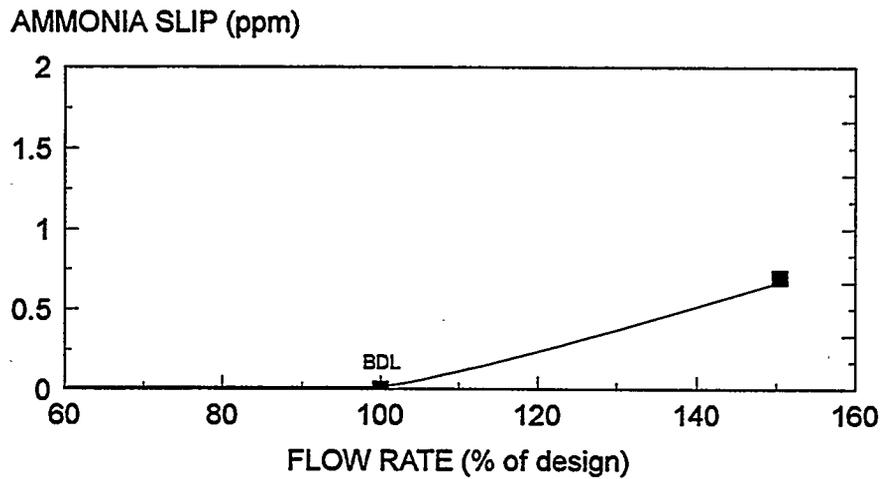
### AMMONIA SLIP VS. FLOW RATE



GRACE SYNOX: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-5

### AMMONIA SLIP VS. FLOW RATE

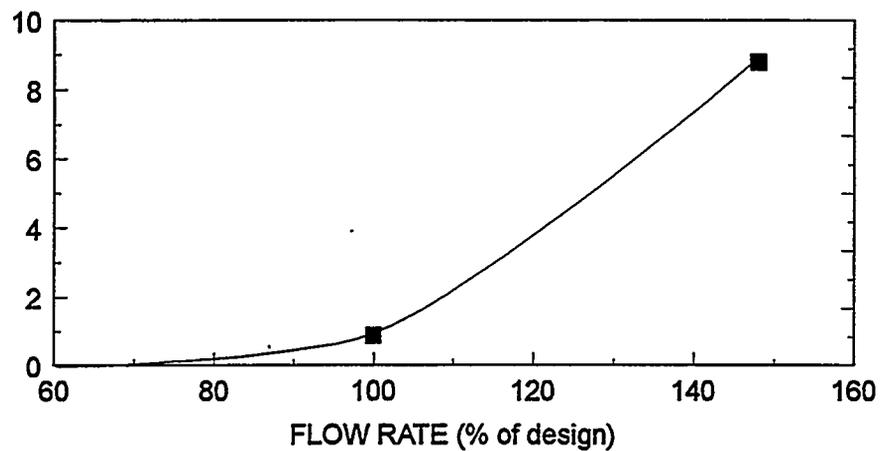


CORM. HD: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
(BDL) Below lower detection limit (<1 ppmv)  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-6

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



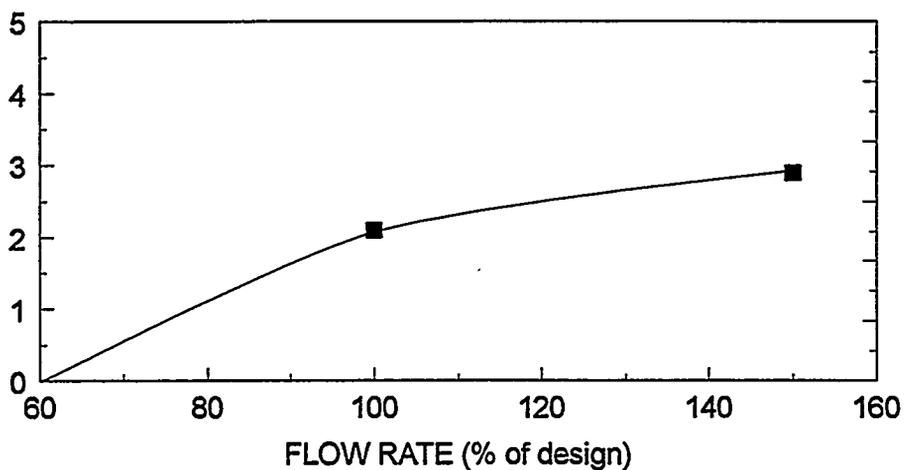
HALDOR: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8

THRID PARAMETRIC SEQUENCE

Figure 5.3.3-7

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



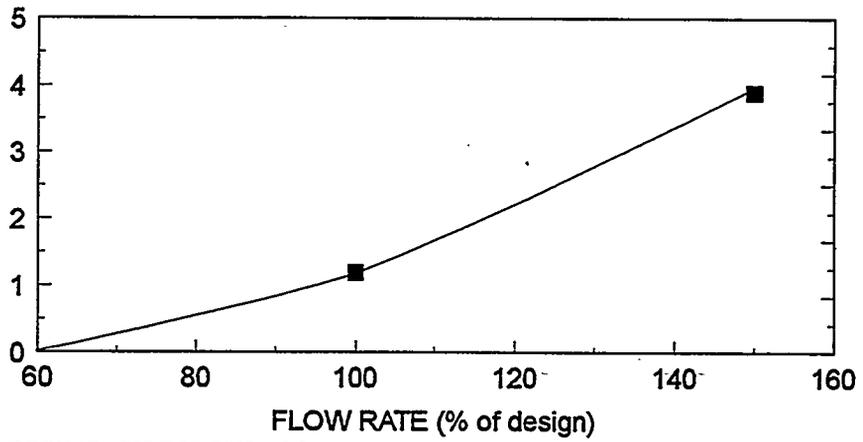
HITACHI: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8

THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-8

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)

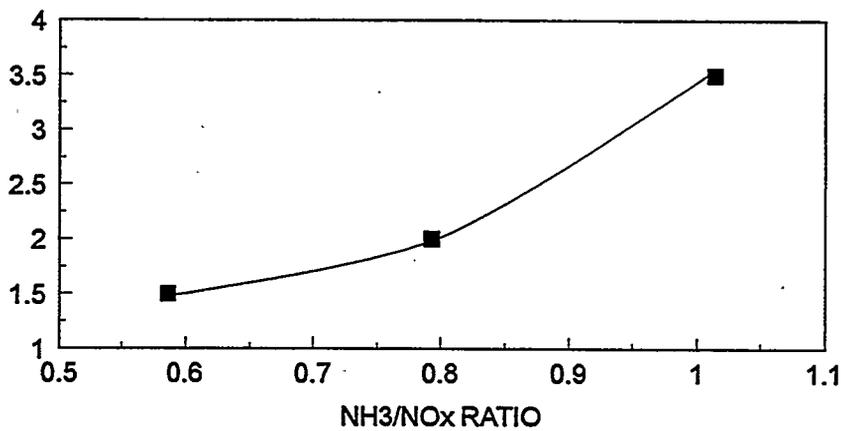


CORM LD: 700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-9

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

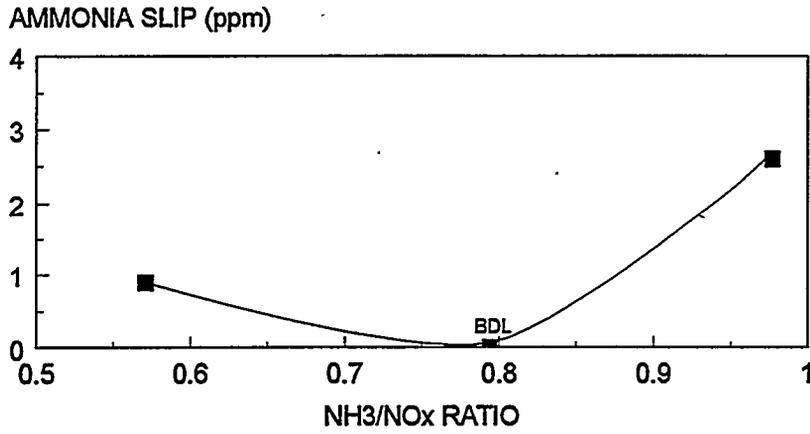
AMMONIA SLIP (ppm)



GRACE NXRM: DESIGN FLOW, 620F  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-10

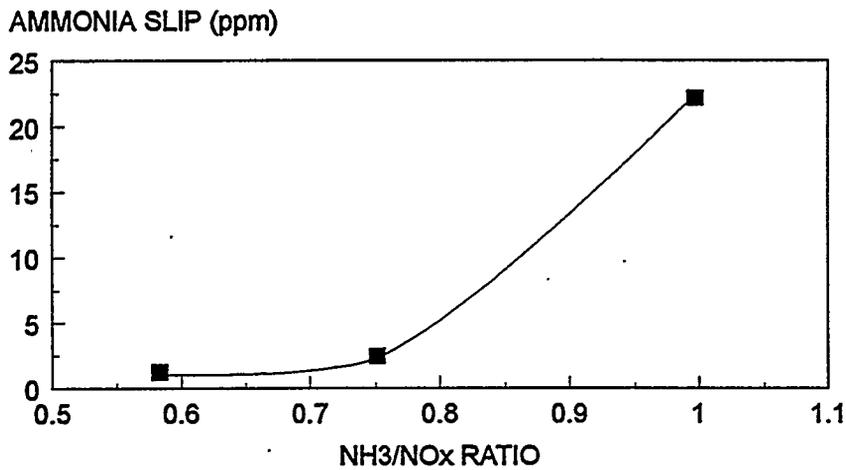
### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO



NSKK: DESIGN FLOW, 620F  
(BDL) Below lower detection limit (< 1 ppmv)  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-11

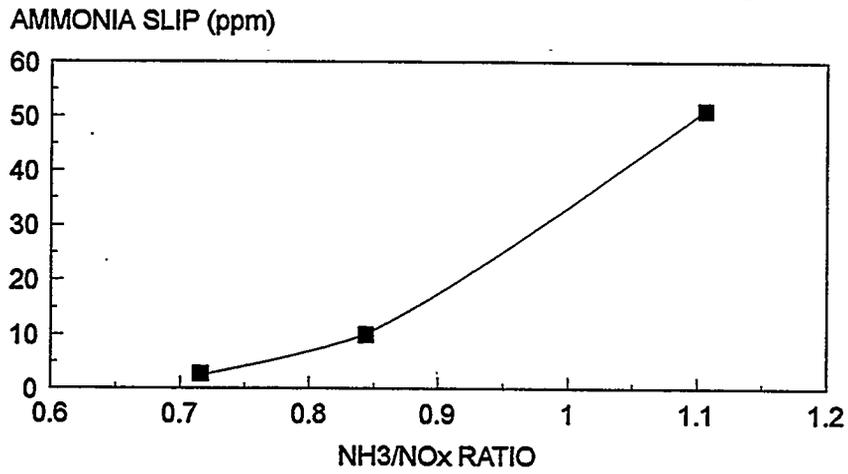
### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO



SIEMENS: DESIGN FLOW, 620F  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-12

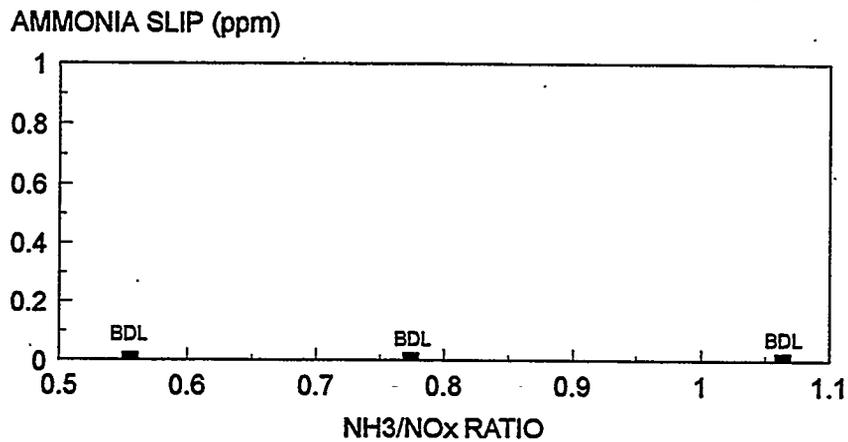
### AMMONIA SLIP VS. NH3/NOx RATIO



GRACE SYNOX: DESIGN FLOW, 620F  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-13

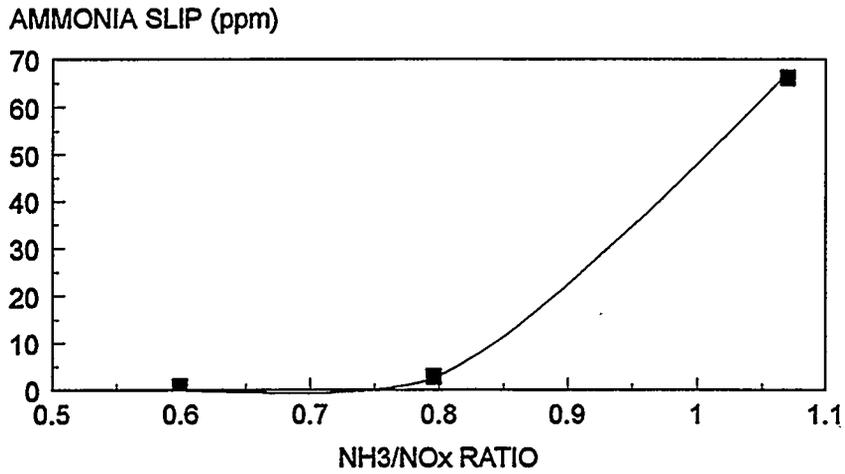
### AMMONIA SLIP VS. NH3/NOx RATIO



CORM HD: DESIGN FLOW, 620F  
(BDL) Below lower detection limit ( <1 ppmv )  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-14

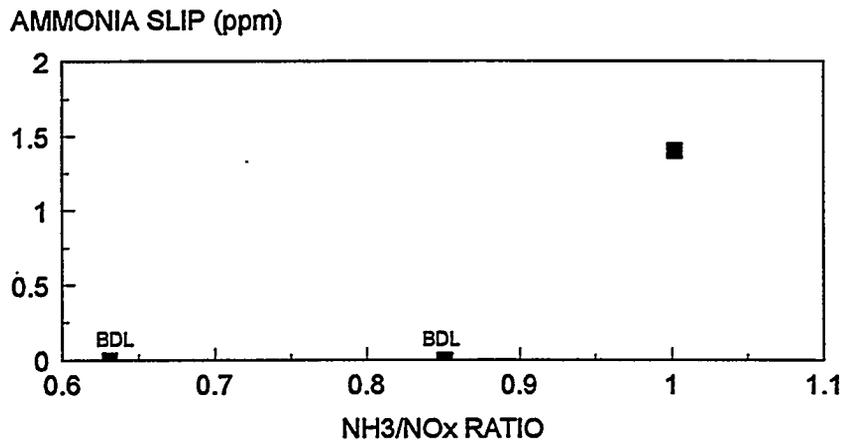
### AMMONIA SLIP VS. NH3/NOx RATIO



HALDOR: DESIGN FLOW, 620F  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-15

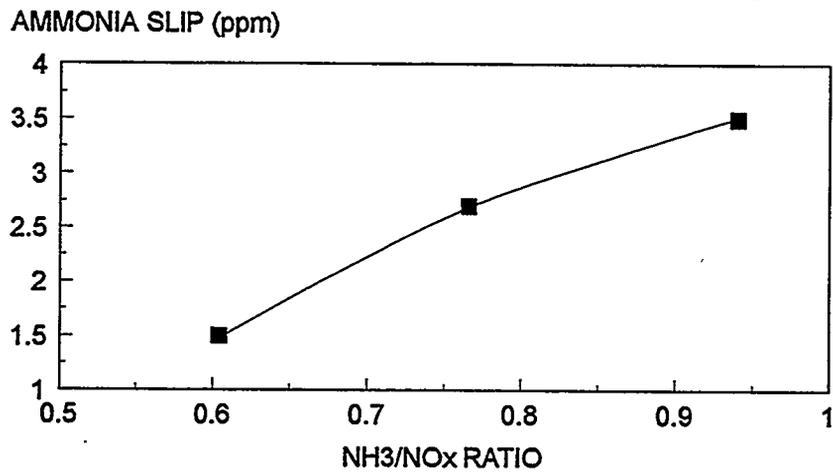
### AMMONIA SLIP VS. NH3/NOx RATIO



HITACHI: DESIGN FLOW, 620F  
(BDL) Below lower detection limit (<1 ppmv)  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-16

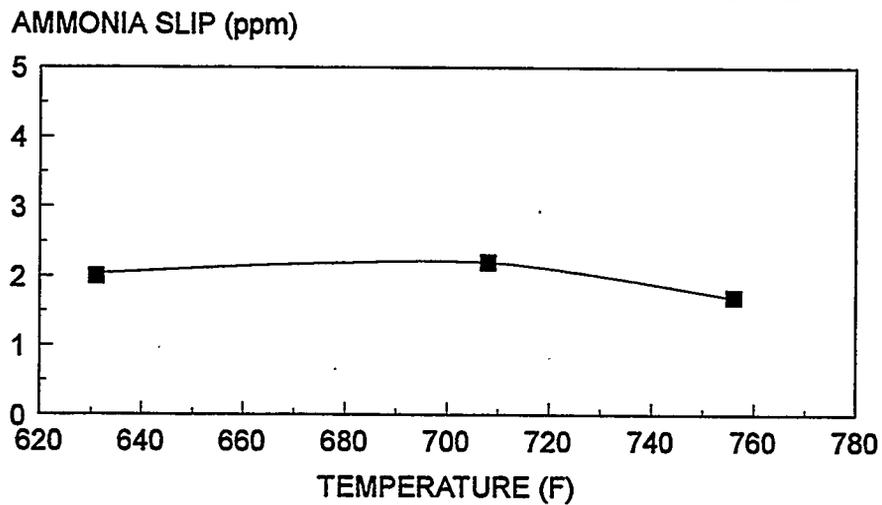
### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO



CORM LD: DESIGN FLOW, 620F  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-17

### AMMONIA SLIP VS. TEMPERATURE

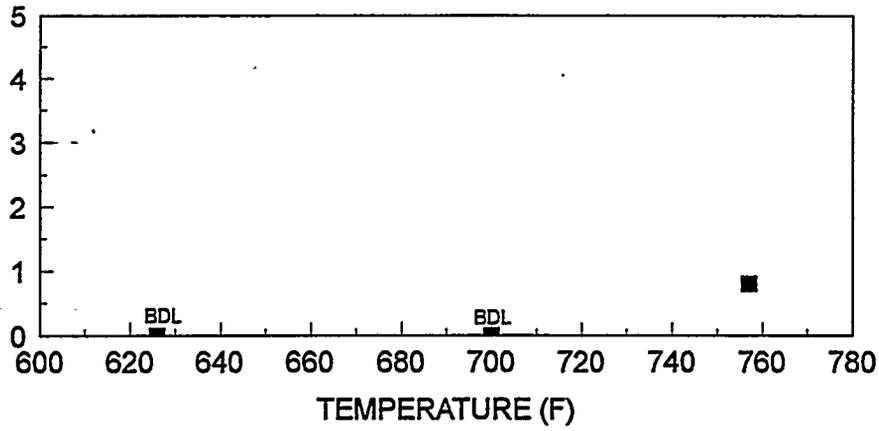


GRACE NXRM: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-18

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



NSKK: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8

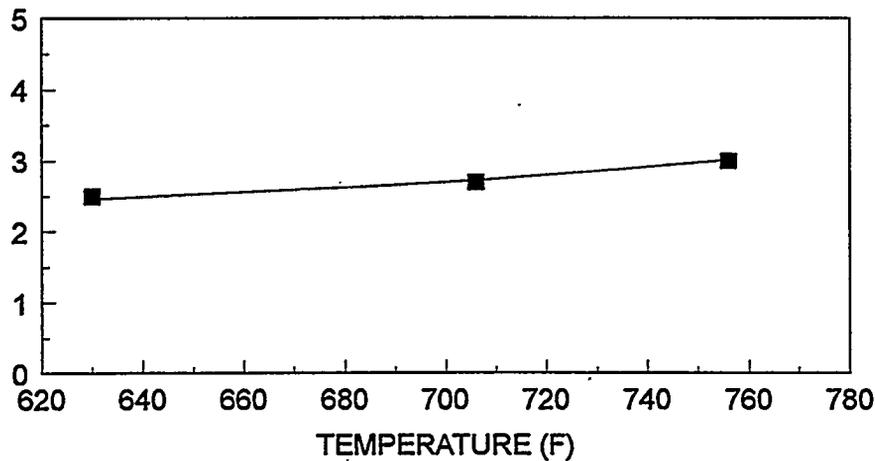
(BDL) Below lower detection limit (<1 ppmv)

THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-19

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



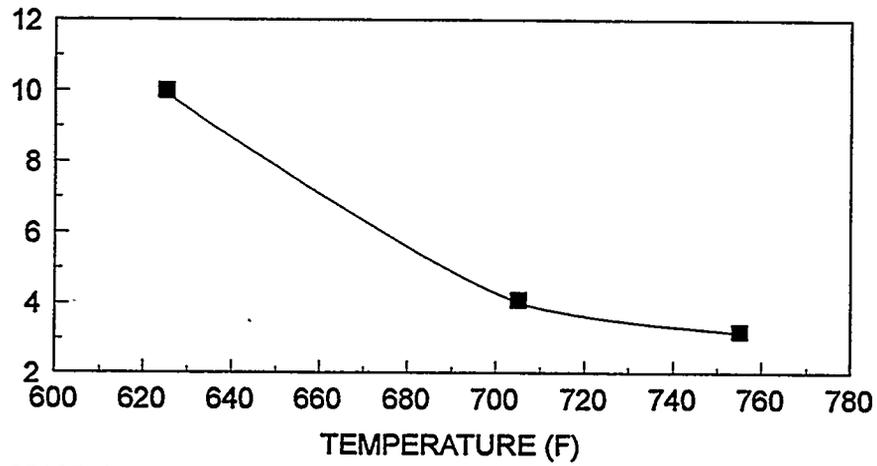
SIEMENS: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8

THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-20

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

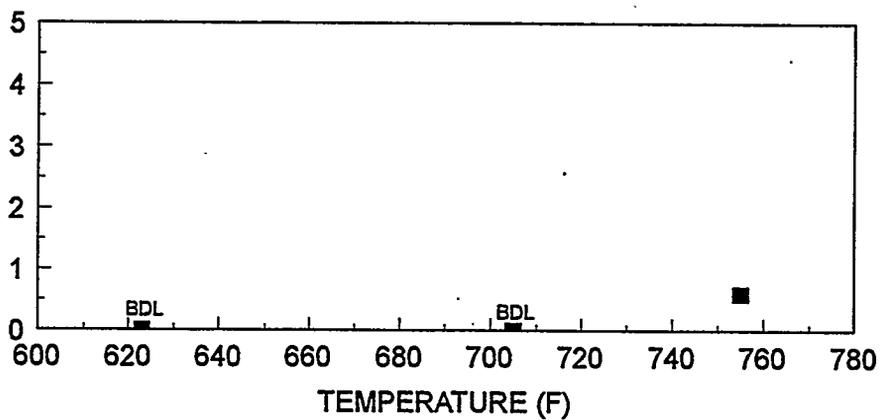


GRACE SYNOX: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-21

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

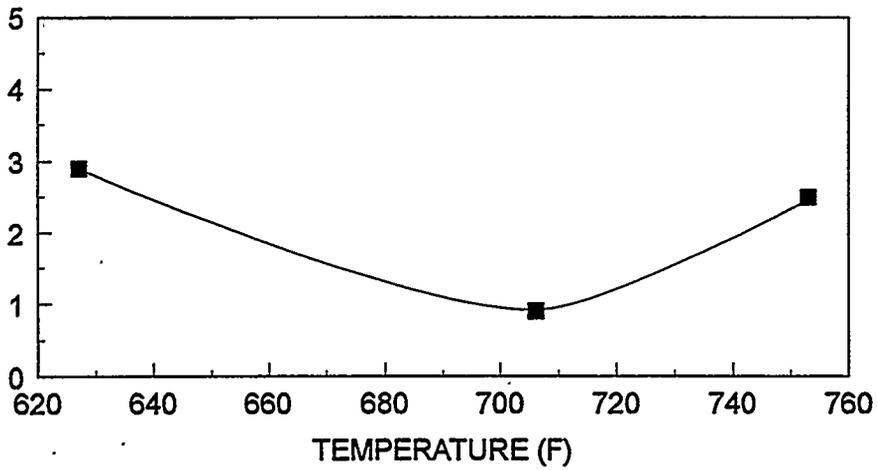


CORM HD: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
(BDL) Below lower detection limit ( <1 ppmv )  
THIRD PARAMETRIC SEQUENCE

FIGURE 5.3.3-22

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

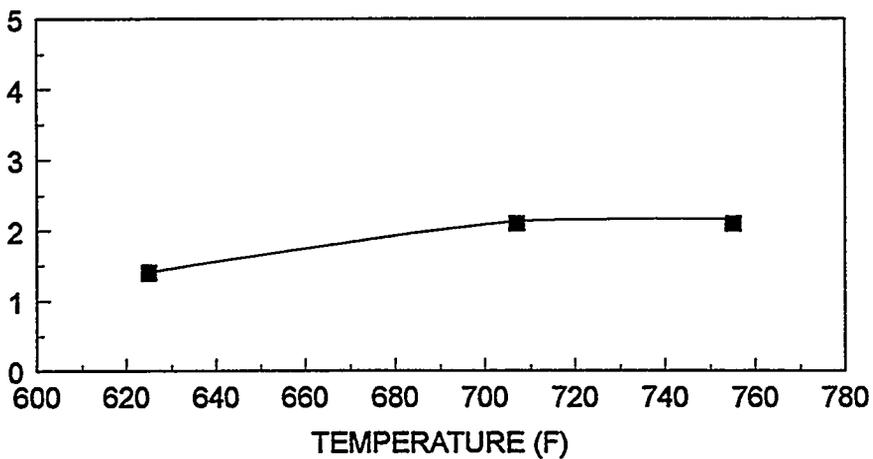


HALDOR: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-23

### AMMONIA SLIP VS. TEMPERATURE

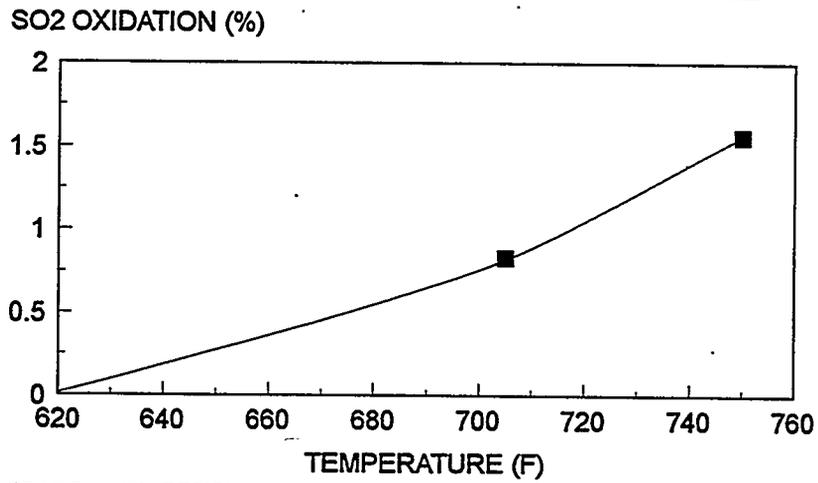
AMMONIA SLIP (ppm)



HITACHI: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-24

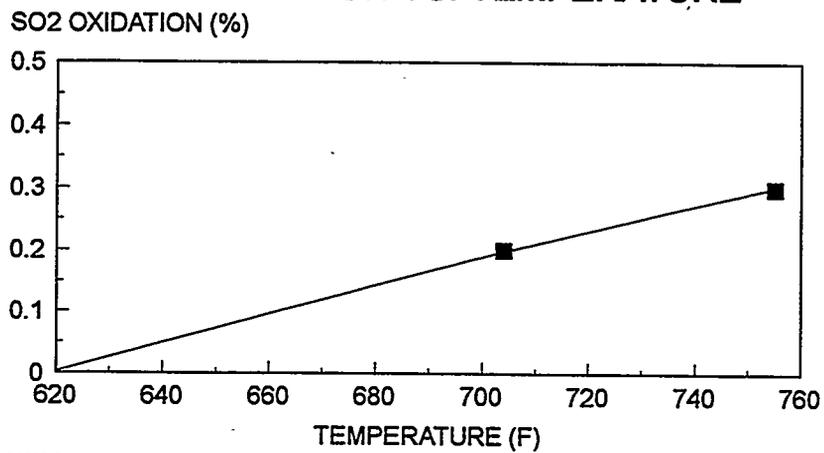
### SO2 OXIDATION VS. TEMPERATURE



GRACE NXRM: DESIGN FLOW, NH3/NOx=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-25

### SO2 OXIDATION VS. TEMPERATURE



NSKK: DESIGN FLOW, NH3/NOx=0.80  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-26

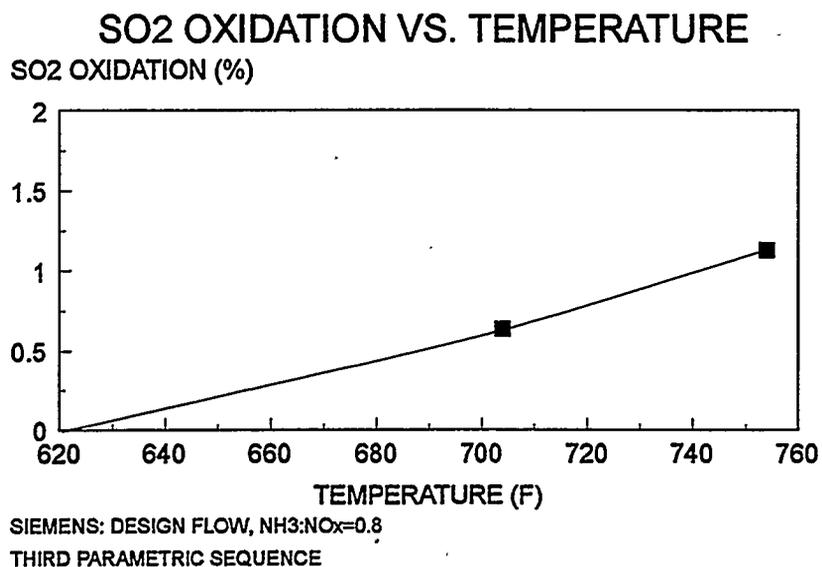


Figure 5.3.3-27

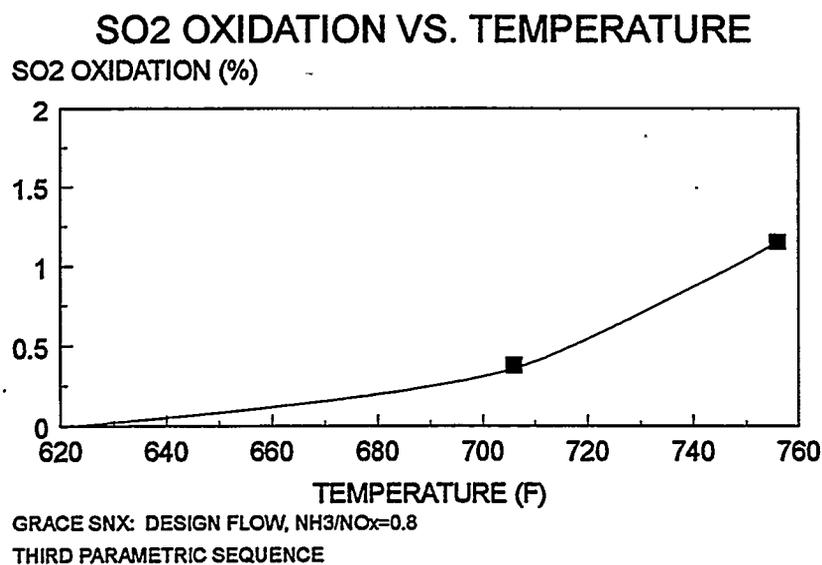
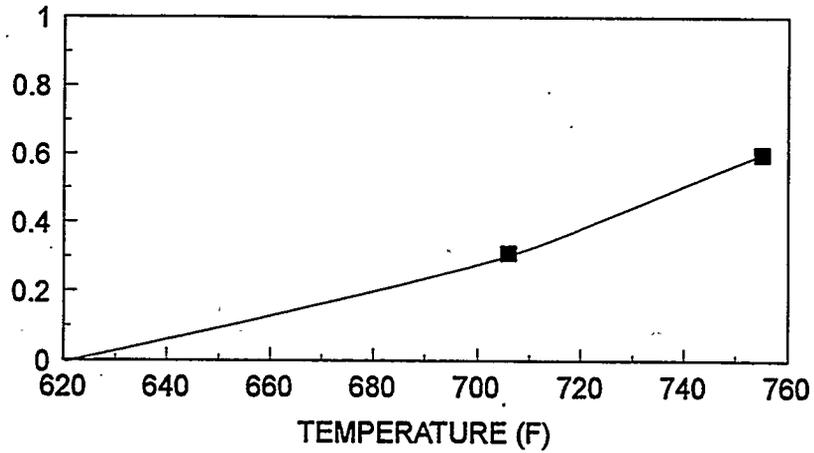


Figure 5.3.3-28

### SO2 OXIDATION VS. TEMPERATURE

SO2 OXIDATION (%)

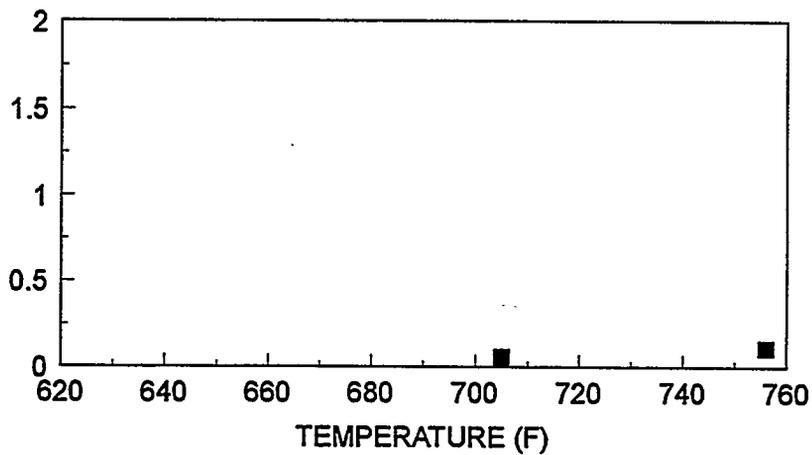


CORM HD: DESIGN FLOW, NH3/NOx=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-29

### SO2 OXIDATION VS. TEMPERATURE

SO2 OXIDATION (%)

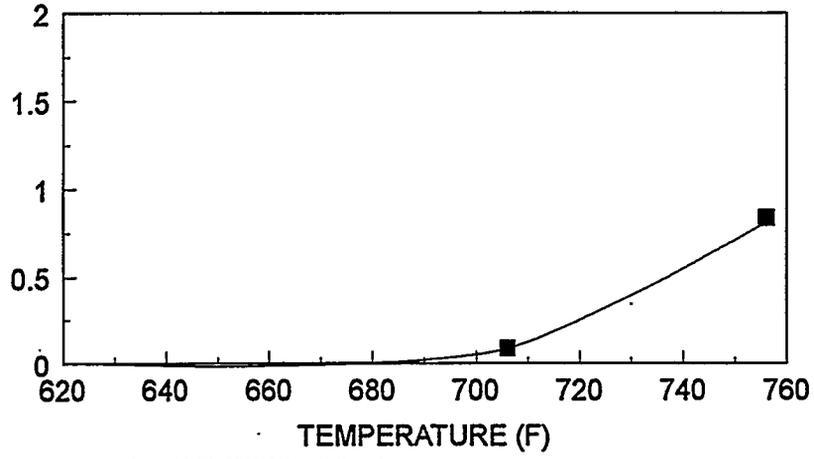


HALDOR: DESIGN FLOW, NH3/NOx=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-30

### SO<sub>2</sub> OXIDATION VS. TEMPERATURE

SO<sub>2</sub> OXIDATION (%)

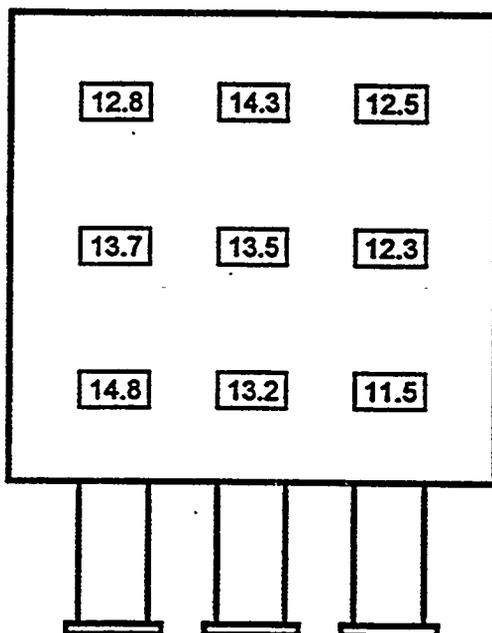


HITACHI: DESIGN FLOW, NH<sub>3</sub>/NO<sub>x</sub>=0.8  
THIRD PARAMETRIC SEQUENCE

Figure 5.3.3-31

**REACTOR A**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



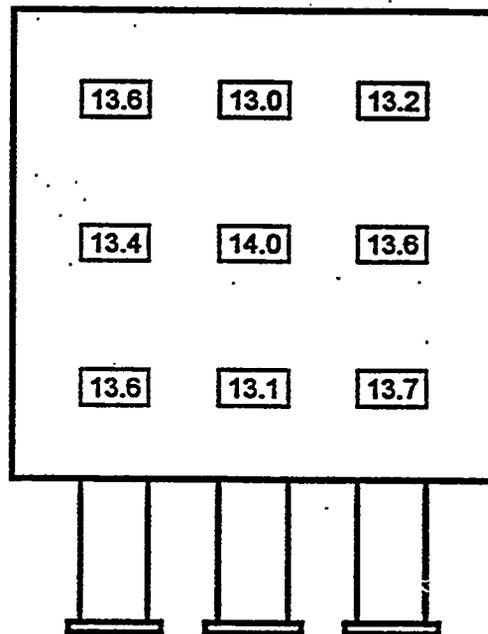
Average =  $13.2 \pm 1.0$  ft/s

Reactor A flue gas velocity profile.

Figure 5.3.3-32

**REACTOR B**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



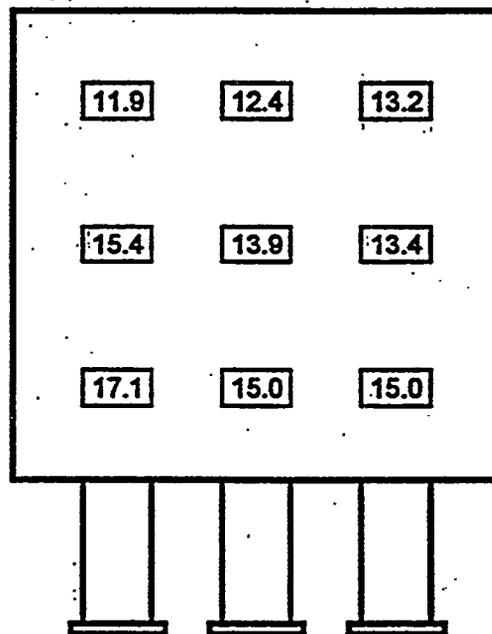
Average =  $13.5 \pm 0.3$  ft/s

Reactor B flue gas velocity profile.

Figure 5.3.3-33

**REACTOR C**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



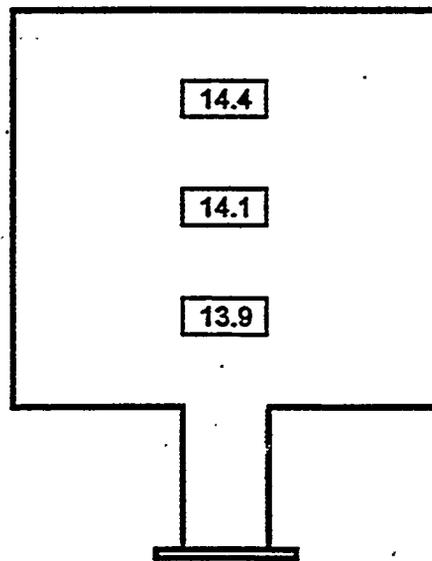
Average =  $14.1 \pm 1.6$  ft/s

Reactor C flue gas velocity profile.

Figure 5.3.3-34

**REACTOR D**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



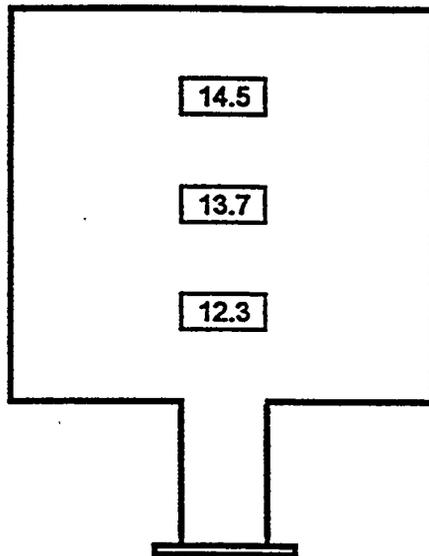
Average =  $14.1 \pm 0.3$  ft/s

Reactor D flue gas velocity profile.

Figure 5.3.3-35

**REACTOR E**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



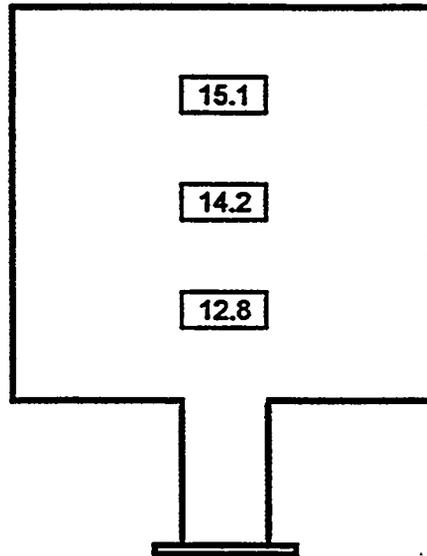
Average =  $13.5 \pm 1.1$  ft/s

Reactor E flue gas velocity profile.

Figure 5.3.3-36

**REACTOR F**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



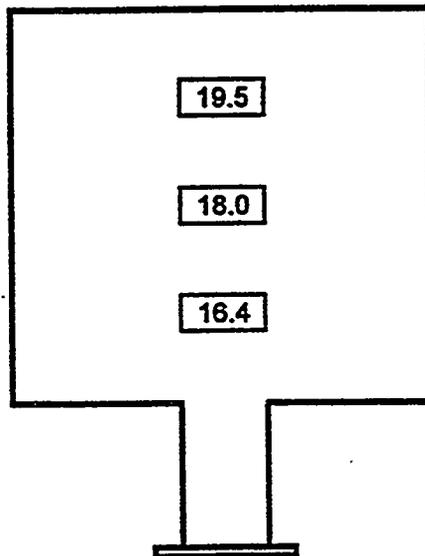
Average =  $14.0 \pm 1.1$  ft/s

Reactor F flue gas velocity profile.

Figure 5.3.3-37

**REACTOR G**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



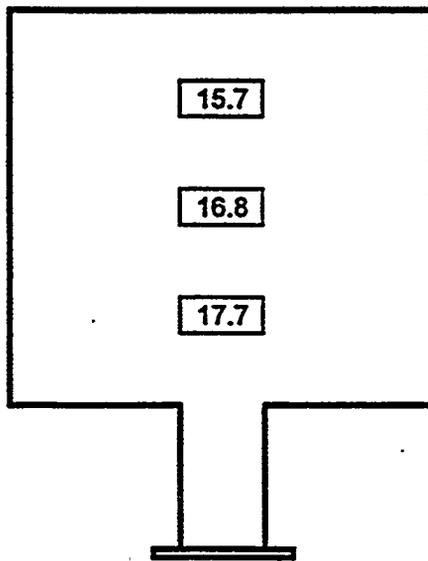
Average =  $18.0 \pm 1.5$  ft/s

Reactor G flue gas velocity profile.

Figure 5.3.3-38

**REACTOR J**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



Average =  $16.7 \pm 1.0$  ft/s

Reactor J flue gas velocity profile.

### 5.3.4 Fourth Parametric Sequence

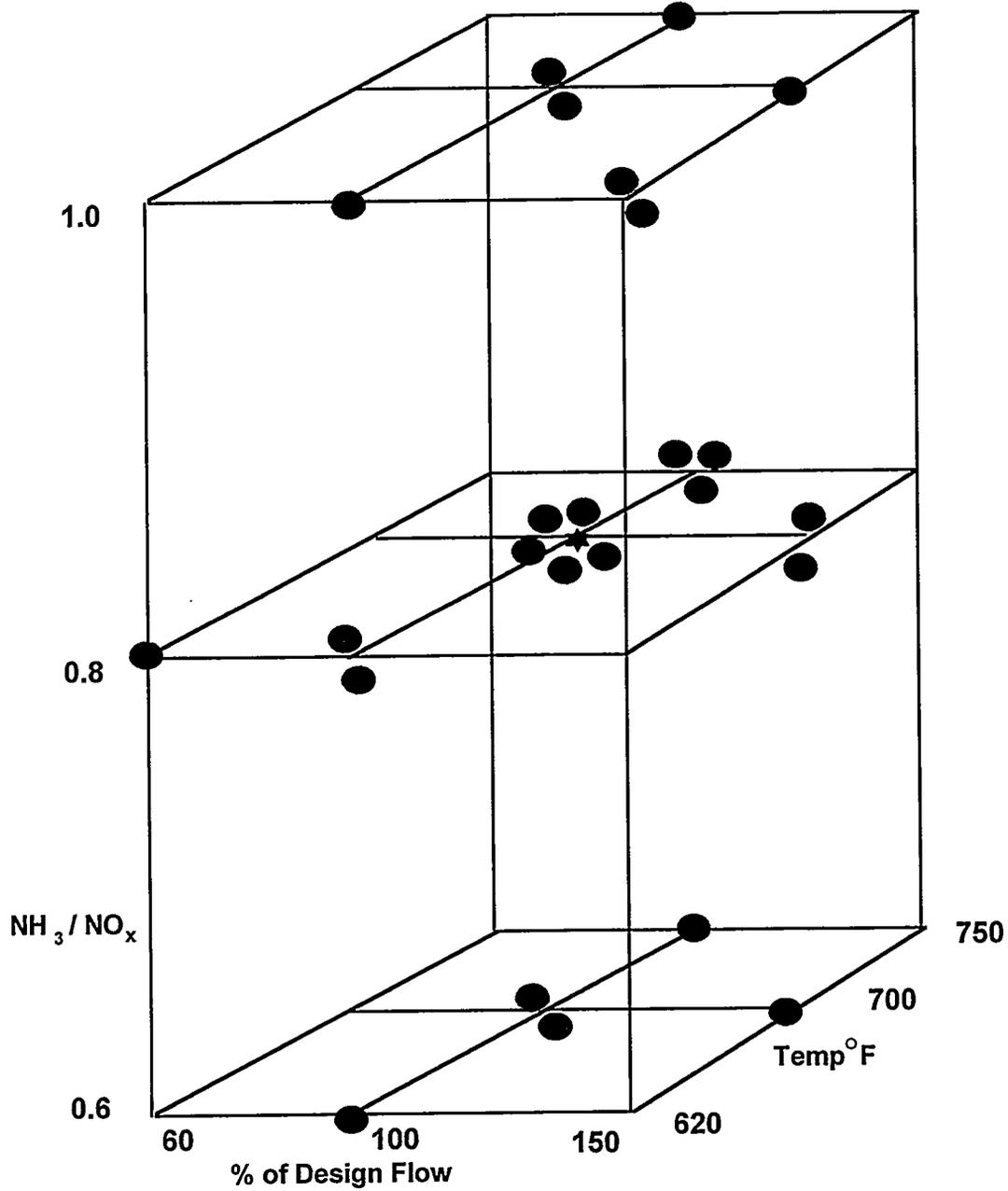
The parametric test results characterizing the performance for reactors A - J for the fourth parametric sequence are discussed in the following sections. The parametric tests were composed of 14 reactor operating conditions defined by variations in the flue gas flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio. The test conditions for the fourth parametric sequence are shown graphically in Figure 5.3.4-1 and in tabular form in Table 5.3.4-1. The particular measurements that were performed (intermediate ammonia, slip ammonia, SO<sub>2</sub>, SO<sub>3</sub>, HCl, and velocity and mass concentration profiles) are shown at the various test conditions. Although in some cases identical test conditions are indicated, the measurements were not taken simultaneously (e.g., ammonia and SO<sub>2</sub> data for the same conditions were not collected during the exact same test run, but rather under similar process conditions at different times). Tables 5.3.4-2 through 9 show the fourth parametric test data on intermediate ammonia, slip ammonia, and sulfur dioxide oxidation for reactors A - J, respectively. The detailed data spreadsheets are contained in Appendix L for this parametric sequence.

Table 5.3.4-1 Parametric Test Conditions (4th Test Sequence)

| Flue gas flow rate<br>Large / Small reactor<br>(KSCFM) | Flue gas<br>temperature<br>(°F) | NH <sub>3</sub> /NO <sub>x</sub><br>Ratio | Measurements  |
|--|---------------------------------|---|---|
| 3.0 / 0.24   | 620                             | 0.8                                       | slip NH <sub>3</sub>  |
| 5.0 / 0.40   | 620                             | 0.6                                       | slip NH <sub>3</sub>  |
| 5.0/0.40   | 620                             | 0.8                                       | intermediate & slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 620                             | 1.0                                       | slip NH <sub>3</sub>  |
| 5.0/0.40   | 700                             | 0.6                                       | intermediate & slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 700                             | 0.8                                       | *Intermediate & slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub><br>HCl, velocity & mass conc. profile |
| 5.0 . 0.40   | 700                             | 1.0                                       | intermediate & slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 750                             | 0.6                                       | slip NH <sub>3</sub>  |
| 5.0 / 0.40   | 750                             | 0.8                                       | intermediate & slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub>  |
| 5.0 / 0.40   | 750                             | 1.0                                       | slip NH <sub>3</sub>  |
| 7.5 / 0.60   | 620                             | 1.0                                       | intermediate & slip NH <sub>3</sub>   |
| 7.5 / 0.60   | 700                             | 0.6                                       | slip NH <sub>3</sub>  |
| 7.5/0.60   | 700                             | 0.8                                       | intermediate & slip NH <sub>3</sub>   |
| 7.5/0.60   | 700                             | 1.0                                       | slip NH <sub>3</sub>  |

\*Design conditions

Fig 5.3.4-1 Fourth SCR Parametric Test Plan



- Intermediate NH3
- SO2/SO3
- HCl
- ★ Design Point - Long Term Testing
- Slip NH3
- Velocity & Mass Concentration Profile



Table 5.3.4-2 Reactor A Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 5006             | 645        | 3.036                    | 272                          | 0.799                                  | 35.1                        | 67.0                          |
| 6590             | 649        | 2.180                    | 272                          | 0.943                                  | 78.2                        | 65.5                          |
| 5000             | 707        | 2.767                    | 258                          | 0.600                                  | 20.6                        | 52.1                          |
| 5001             | 705        | 3.416                    | 295                          | 0.707                                  | 23.1                        | 62.9                          |
| 5007             | 706        | 3.465                    | 258                          | 0.986                                  | 34.4                        | 85.3                          |
| 6100             | 705        | 2.966                    | 347                          | 1.000                                  | 49.5                        | 85.7                          |
| 4994             | 754        | 3.393                    | 283                          | 0.802                                  | 29.1                        | 70.0                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 2995             | 632        | 2.769                    | 275                          | 0.804                                  | 2.0                         |
| 4999             | 647        | 3.583                    | 363                          | 0.600                                  | 2.7                         |
| 5004             | 651        | 3.077                    | 350                          | 0.797                                  | 4.5                         |
| 5009             | 627        | 4.731                    | 369                          | 1.000                                  | 20.7                        |
| 6516             | 652        | 2.946                    | 295                          | 0.999                                  | 6.6                         |
| 5004             | 703        | 3.523                    | 363                          | 0.600                                  | 2.5                         |
| 5004             | 705        | 2.894                    | 259                          | 0.799                                  | 3.0                         |
| 5000             | 703        | 3.443                    | 348                          | 0.602                                  | 2.5                         |
| 6206             | 705        | 3.014                    | 326                          | 0.601                                  | 3.0                         |
| 5998             | 705        | 2.966                    | 254                          | 0.803                                  | 2.8                         |
| 6289             | 704        | 2.475                    | 307                          | 0.934                                  | 1.4                         |
| 4997             | 755        | 3.767                    | 310                          | 0.631                                  | 1.8                         |
| 5001             | 753        | 2.823                    | 300                          | 0.799                                  | 2.8                         |
| 4998             | 756        | 2.761                    | 326                          | 1.003                                  | 7.7                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | PRED. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5109             | 702        | 3.555                     | 1744                         | 0.804                                  | 9.2                      | 16.5                | 7.3                           | 0.49           |
| 6622             | 706        | 3.490                     | 1705                         | 0.798                                  | 4.6                      | 14.0                | 9.4                           | 0.60           |
| 5072             | 758        | 3.433                     | 2028                         | 0.803                                  | 9.7                      | 38.2                | 28.5                          | 1.78           |

Table 5.3.4-3 Reactor B Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 4991             | 632        | 4.478                    | 241                          | 0.843                                  | 33.0                        | 70.6                          |
| 6910             | 652        | 2.96                     | 274                          | 0.997                                  | 78.0                        | 71.2                          |
| 5007             | 706        | 2.704                    | 259                          | 0.601                                  | 20.9                        | 52.0                          |
| 4999             | 704        | 3.111                    | 285                          | 0.799                                  | 24.1                        | 71.5                          |
| 4997             | 706        | 3.764                    | 253                          | 0.999                                  | 31.0                        | 87.6                          |
| 6805             | 706        | 2.731                    | 208                          | 0.804                                  | 43.4                        | 63.6                          |
| 5001             | 755        | 3.359                    | 207                          | 0.708                                  | 19.0                        | 64.3                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3005             | 630        | 2.75                     | 287                          | 0.801                                  | 1                           |
| 4990             | 651        | 2.28                     | 321                          | 0.603                                  | BDL                         |
| 5005             | 650        | 2.976                    | 362                          | 0.796                                  | 1.5                         |
| 4992             | 655        | 2.983                    | 350                          | 1.001                                  | 10.6                        |
| 7331             | 635        | 4.668                    | 375                          | 1.002                                  | 21.6                        |
| 4997             | 704        | 5.397                    | 329                          | 0.599                                  | BDL                         |
| 4983             | 706        | 2.333                    | 299                          | 0.803                                  | 1.1                         |
| 4995             | 705        | 3.214                    | 363                          | 1.001                                  | 10.2                        |
| 6597             | 706        | 3.261                    | 363                          | 0.597                                  | 1.4                         |
| 6794             | 705        | 2.885                    | 259                          | 0.801                                  | 2.1                         |
| 6596             | 706        | 2.857                    | 331                          | 1                                      | 6.2                         |
| 4997             | 757        | 3.157                    | 327                          | 0.582                                  | 1                           |
| 5004             | 756        | 2.677                    | 329                          | 0.799                                  | 1.1                         |
| 4992             | 756        | 2.709                    | 318                          | 1.002                                  | 2.1                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|------------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5329             | 704        | 5.365                     | 2076                         | 0.808                                  | 5.6                      | 3.6                 | -2.0                          | -0.11          |
| 7071             | 705        | 4.706                     | 1515                         | 0.798                                  | 1.8                      | 2.4                 | 0.6                           | 0.04           |
| 5350             | 756        | 4.167                     | 1783                         | 0.800                                  | 8.9                      | 16.2                | 7.3                           | 0.41           |

Table 5.3.4-4 Reactor C Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 4915             | 627        | 4.998                    | 387                          | 0.789                                  | 5.5                         | 77.5                          |
| 6500             | 627        | 4.681                    | 385                          | 1.000                                  | 99.4                        | 74.2                          |
| 5000             | 704        | 4.889                    | 383                          | 0.601                                  | 21.1                        | 54.6                          |
| 5000             | 707        | 4.944                    | 337                          | 0.802                                  | 27.7                        | 72.0                          |
| 4996             | 706        | 4.908                    | 341                          | 0.999                                  | 56.7                        | 83.3                          |
| 6396             | 705        | 2.678                    | 357                          | 0.803                                  | 51.3                        | 65.9                          |
| 5001             | 757        | 4.539                    | 355                          | 0.802                                  | 35.1                        | 70.3                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3004             | 638        | 2.984                    | 369                          | 0.799                                  | 2.5                         |
| 4995             | 652        | 2.733                    | 375                          | 0.6                                    | 2.6                         |
| 5003             | 649        | 3.046                    | 337                          | 0.835                                  | 6.5                         |
| 4998             | 647        | 2.737                    | 326                          | 0.999                                  | 39.4                        |
| 6500             | 627        | 4.681                    | 377                          | 1                                      | 38                          |
| 5008             | 708        | 4.419                    | 376                          | 0.601                                  | 2.8                         |
| 4992             | 708        | 2.365                    | 341                          | 0.8                                    | 5.4                         |
| 4997             | 705        | 2.205                    | 315                          | 1.001                                  | 16.3                        |
| 6479             | 704        | 5.219                    | 339                          | 0.6                                    | 4.1                         |
| 6428             | 704        | 4.681                    | 330                          | 0.802                                  | 7.8                         |
| 6303             | 706        | 3.012                    | 358                          | 1                                      | 20.2                        |
| 4997             | 756        | 2.873                    | 354                          | 0.602                                  | 2.6                         |
| 4998             | 755        | 4.361                    | 318                          | 0.803                                  | 4.1                         |
| 4997             | 757        | 4.542                    | 332                          | 1.006                                  | 14.8                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5293             | 702       | 3.193                     | 2019                         | 0.803                                  | 9.2                      | 12.8                | 3.6                           | 0.18           |
| 6784             | 704       | 5.538                     | 1550                         | 0.802                                  | 5.0                      | 2.1                 | -2.9                          | -0.18          |
| 5354             | 756       | 4.122                     | 1960                         | 0.802                                  | 11.0                     | 35.2                | 24.2                          | 1.23           |

Table 5.3.4-5 Reactor D Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 400              | 623        | 5.088                    | 356                          | 0.802                                  | 148.5                       | 38.5                          |
| 598              | 625        | 5.407                    | 379                          | 1.044                                  | 228.5                       | 44.1                          |
| 399              | 704        | 5.741                    | 376                          | 0.606                                  | 066.5                       | 42.9                          |
| 399              | 705        | 5.712                    | 330                          | 0.802                                  | 094.3                       | 51.6                          |
| 400              | 703        | 5.780                    | 329                          | 1.000                                  | 130.7                       | 60.3                          |
| 600              | 705        | 5.152                    | 342                          | 0.803                                  | 108.6                       | 48.6                          |
| 400              | 756        | 3.848                    | 358                          | 0.805                                  | 089.7                       | 55.5                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 240              | 625        | 4.185                    | 328                          | 0.797                                  | 05.0                        |
| 400              | 625        | 3.526                    | 328                          | 0.603                                  | 07.6                        |
| 400              | 626        | 3.602                    | 338                          | 0.799                                  | 21.7                        |
| 399              | 624        | 4.527                    | 334                          | 1.008                                  | 66.2                        |
| 603              | 625        | 3.633                    | 373                          | 0.994                                  | 83.3                        |
| 400              | 706        | 3.746                    | 324                          | 0.605                                  | 01.9                        |
| 400              | 704        | 6.585                    | 334                          | 0.800                                  | 05.5                        |
| 400              | 703        | 5.780                    | 325                          | 1.000                                  | 23.7                        |
| 402              | 704        | 3.774                    | 322                          | 0.599                                  | 02.8                        |
| 400              | 705        | 3.570                    | 324                          | 0.803                                  | 09.2                        |
| 404              | 703        | 3.644                    | 325                          | 1.004                                  | 35.5                        |
| 400              | 754        | 4.383                    | 334                          | 0.601                                  | 02.5                        |
| 400              | 754        | 4.141                    | 333                          | 0.802                                  | 06.2                        |
| 391              | 754        | 4.102                    | 332                          | 1.019                                  | 25.7                        |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 416              | 704       | 4.830                     | 1554                         | 0.800                                  | 4.2                      | 12.0                | 7.8                           | 0.50           |
| 410              | 705       | 3.984                     | 1600                         | 0.803                                  | 0.7                      | 0.2                 | -0.5                          | -0.03          |
| 413              | 755       | 4.012                     | 1639                         | 0.806                                  | 1.1                      | 10.4                | 9.3                           | 0.57           |

Table 5.3.4-6 Reactor E Data ( 4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 400              | 644        | 2.377                    | 385                          | 0.797                                  | 46.4                        | 67.7                          |
| 600              | 625        | 5.589                    | 383                          | 0.999                                  | 143.8                       | 62.4                          |
| 400              | 706        | 5.059                    | 349                          | 0.599                                  | 14.7                        | 55.7                          |
| 400              | 706        | 4.848                    | 341                          | 0.798                                  | 20.9                        | 73.6                          |
| 401              | 705        | 3.752                    | 325                          | 0.998                                  | 42.3                        | 86.8                          |
| 602              | 706        | 3.549                    | 322                          | 0.805                                  | 52.9                        | 64.1                          |
| 391              | 755        | 2.587                    | 332                          | 0.809                                  | 25.6                        | 73.2                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 250              | 625        | 4.892                    | 388                          | 0.788                                  | BDL                         |
| 399              | 625        | 4.879                    | 334                          | 0.593                                  | BDL                         |
| 400              | 624        | 4.736                    | 316                          | 0.804                                  | BDL                         |
| 400              | 624        | 5.633                    | 380                          | 1.003                                  | 10.6                        |
| 601              | 625        | 5.381                    | 378                          | 1.000                                  | 49.3                        |
| 400              | 706        | 2.936                    | 356                          | 0.600                                  | BDL                         |
| 400              | 706        | 3.272                    | 363                          | 0.807                                  | BDL                         |
| 398              | 706        | 3.055                    | 356                          | 1.004                                  | 1.5                         |
| 599              | 710        | 2.417                    | 346                          | 0.602                                  | 1.0                         |
| 599              | 704        | 3.394                    | 348                          | 0.804                                  | 1.7                         |
| 595              | 705        | 3.359                    | 346                          | 1.005                                  | 5.5                         |
| 401              | 753        | 5.294                    | 339                          | 0.598                                  | BDL                         |
| 400              | 753        | 2.587                    | 334                          | 0.800                                  | BDL                         |
| 400              | 753        | 2.587                    | 356                          | 1.000                                  | BDL                         |
| 400              | 625        | 4.953                    | 360                          | 0.600                                  | BDL                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET SO <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|----------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 408              | 704       | 3.283                      | 1751                         | 0.802                                  | 2.8                      | 9.2                 | 6.4                           | 0.36           |
| 624              | 704       | 4.101                      | 1678                         | 0.804                                  | 0.3                      | 5.7                 | 5.4                           | 0.32           |
| 408              | 749       | 3.377                      | 1720                         | 0.807                                  | 1.2                      | 10.5                | 9.3                           | 0.54           |

Table 5.3.4-7 Reactor F Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 400              | 625        | 3.437                    | 326                          | 0.803                                  | 082.4                       | 55.0                          |
| 599              | 640        | 3.403                    | 331                          | 1.005                                  | 156.1                       | 53.4                          |
| 400              | 707        | 4.696                    | 356                          | 0.598                                  | 058.6                       | 43.4                          |
| 400              | 707        | 4.514                    | 346                          | 0.799                                  | 068.4                       | 60.2                          |
| 402              | 705        | 2.289                    | 337                          | 0.994                                  | 096.2                       | 70.9                          |
| 600              | 704        | 1.974                    | 394                          | 0.788                                  | 136.0                       | 44.2                          |
| 400              | 755        | 3.119                    | 363                          | 0.800                                  | 068.3                       | 61.2                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 240              | 625        | 5.499                    | 383                          | 0.800                                  | BDL                         |
| 402              | 625        | 4.758                    | 380                          | 0.603                                  | 1.1                         |
| 400              | 625        | 4.333                    | 403                          | 0.797                                  | 2.6                         |
| 400              | 624        | 5.044                    | 381                          | 1.002                                  | 9.9                         |
| 595              | 626        | 4.782                    | 321                          | 1.000                                  | 27.1                        |
| 400              | 704        | 3.754                    | 340                          | 0.597                                  | BDL                         |
| 400              | 705        | 3.696                    | 330                          | 0.800                                  | 0.90                        |
| 400              | 706        | 2.635                    | 334                          | 1.003                                  | 11.7                        |
| 600              | 706        | 4.66                     | 312                          | 0.611                                  | 2.5                         |
| 600              | 705        | 4.811                    | 331                          | 0.790                                  | 3.8                         |
| 595              | 707        | 4.976                    | 338                          | 1.013                                  | 20                          |
| 400              | 756        | 2.979                    | 350                          | 0.604                                  | 1.0                         |
| 399              | 755        | 3.119                    | 348                          | 0.808                                  | 0.9                         |
| 399              | 756        | 5.053                    | 339                          | 1.024                                  | 2.3                         |
| 600              | 706        | 2.903                    | 356                          | 0.602                                  | 3.1                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 432              | 706       | 4.236                     | 1784                         | 0.804                                  | 0.7                      | 0.9                 | 0.2                           | 0.01           |
| 631              | 705       | 5.616                     | 1554                         | 0.800                                  | 1.2                      | 0.2                 | -1.0                          | -0.07          |
| 431              | 758       | 3.994                     | 1779                         | 0.804                                  | 0.7                      | 0.7                 | 0.0                           | 0.00           |

Table 5.3.4-8 Reactor G Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 397              | 626        | 3.702                    | 252                          | 0.800                                  | 53.3                        | 58.9                          |
| 601              | 624        | 3.154                    | 252                          | 1.000                                  | 110.9                       | 56.0                          |
| 391              | 705        | 3.384                    | 295                          | 0.546                                  | 31.5                        | 44.0                          |
| 400              | 705        | 3.270                    | 288                          | 0.791                                  | 48.0                        | 62.5                          |
| 406              | 704        | 2.458                    | 339                          | 1.018                                  | 125.3                       | 64.8                          |
| 601              | 703        | 2.908                    | 360                          | 0.796                                  | 107.9                       | 49.6                          |
| 400              | 756        | 2.840                    | 356                          | 0.805                                  | 86.8                        | 56.1                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 219              | 622        | 4.04                     | 276                          | 0.856                                  | BDL                         |
| 404              | 622        | 3.303                    | 279                          | 0.600                                  | BDL                         |
| 403              | 625        | 3.152                    | 308                          | 0.793                                  | 2.9                         |
| 400              | 625        | 3.035                    | 297                          | 1.003                                  | 17.8                        |
| 601              | 624        | 3.079                    | 255                          | 0.991                                  | 11.8                        |
| 400              | 701        | 3.553                    | 304                          | 0.606                                  | 0.8                         |
| 400              | 706        | 6.198                    | 318                          | 0.833                                  | 1.5                         |
| 401              | 706        | 5.683                    | 309                          | 0.971                                  | 8.3                         |
| 600              | 706        | 3.67                     | 350                          | 0.602                                  | 3.2                         |
| 601              | 706        | 3.418                    | 343                          | 0.795                                  | 5.4                         |
| 600              | 705        | 3.38                     | 348                          | 1.002                                  | 14.7                        |
| 400              | 756        | 4.747                    | 316                          | 0.604                                  | 1.2                         |
| 400              | 756        | 4.923                    | 321                          | 0.807                                  | 2.6                         |
| 400              | 755        | 4.033                    | 352                          | 1.000                                  | 7.8                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 467              | 705       | 5.646                     | 1648                         | 0.801                                  | 0.4                      | 3.0                 | 2.6                           | 0.16           |
| 797              | 705       | 7.768                     | 1642                         | 0.800                                  | 2.0                      | 2.9                 | 0.9                           | 0.05           |
| 493              | 757       | 6.722                     | 1799                         | 0.804                                  | 0.5                      | 10.8                | 10.3                          | 0.57           |

Table 5.3.4-9 Reactor J Data (4th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 400              | 624        | 5.470                    | 332                          | 0.802                                  | 16.7                        | 75.2                          |
| 594              | 625        | 5.194                    | 342                          | 1.010                                  | 108.5                       | 69.3                          |
| 400              | 707        | 3.663                    | 330                          | 0.597                                  | 4.3                         | 58.4                          |
| 400              | 707        | 4.022                    | 335                          | 0.805                                  | 9.3                         | 77.7                          |
| 404              | 708        | 3.736                    | 333                          | 1.000                                  | 25.1                        | 92.4                          |
| 600              | 703        | 3.213                    | 319                          | 0.804                                  | 27.7                        | 71.7                          |
| 403              | 756        | 6.328                    | 257                          | 0.810                                  | 37.7                        | 66.3                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 239              | 625        | 3.49                     | 289                          | 0.815                                  | 1.1                         |
| 400              | 625        | 3.306                    | 310                          | 0.603                                  | 0.7                         |
| 402              | 625        | 3.954                    | 332                          | 0.796                                  | 1.6                         |
| 403              | 625        | 4.036                    | 320                          | 0.995                                  | 6.8                         |
| 601              | 624        | 3.25                     | 310                          | 1.004                                  | 18.3                        |
| 399              | 646        | 7.202                    | 330                          | 0.799                                  | 0.5                         |
| 399              | 666        | 6.783                    | 320                          | 0.799                                  | 0.8                         |
| 400              | 705        | 5.236                    | 305                          | 0.852                                  | 1.7                         |
| 601              | 686        | 4.509                    | 299                          | 0.602                                  | 1.3                         |
| 599              | 674        | 3.324                    | 320                          | 0.788                                  | 4.3                         |
| 599              | 676        | 3.267                    | 302                          | 0.994                                  | 22.1                        |
| 401              | 756        | 5.993                    | 224                          | 0.603                                  | 2.2                         |
| 401              | 758        | 6.328                    | 257                          | 0.811                                  | 3.4                         |
| 397              | 754        | 6.272                    | 226                          | 1.001                                  | 8.3                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 498              | 704       | 7.678                     | 1720                         | 0.807                                  | 0.6                      | 2.5                 | 1.9                           | 0.11           |
| 711              | 703       | 7.575                     | 1666                         | 0.783                                  | 1.3                      | 5.2                 | 3.9                           | 0.23           |
| 494              | 756       | 7.751                     | 1769                         | 0.803                                  | 0.8                      | 8.6                 | 7.8                           | 0.44           |

### Intermediate NO<sub>x</sub> Reduction

The intermediate ammonia measurements were made after the first catalyst bed and at conditions thought to give the best kinetic information. The NO<sub>x</sub> removals reported with the intermediate ammonia measurements were computed from the measured ammonia concentrations using a material balance which assumed a 1:1 stoichiometry for the reaction of ammonia and NO<sub>x</sub>. Thus, the moles of ammonia consumed equaled the moles of NO<sub>x</sub> reduced, from which NO<sub>x</sub> reduction was computed, after oxygen corrections were made.

### Ammonia Slip

The ammonia slip data given in Tables 5.3.4-2 through 9 is presented below in three sets of plots: ammonia slip versus each of flow rate, ammonia-to-NO<sub>x</sub> ratio, and temperature. Figures 5.3.4-2 through 9 show ammonia slip versus flow rate at roughly 80% NO<sub>x</sub> reduction for reactors A - J, respectively. As expected, the trends show increasing ammonia slip with increasing reactor flow rate. In general, the ammonia slip is relatively minor indicating the ability of the catalyst designs to withstand significant increases in flow while maintaining ammonia slip limits. For reactor D, the Grace Synox catalyst reactor, a relatively significant increase in ammonia slip is noted with flow rate. Since a portion of the overall reaction rate is due to mass transfer limitations, improvements in bulk mass transfer coefficients were likely mitigating the effect of increased flow on slip ammonia increases. Overall, these plots demonstrate the ability of an SCR system to follow load variations dictated by the host boiler while maintaining design specifications.

Figures 5.3.4-10 through 17 show ammonia slip versus ammonia-to-NO<sub>x</sub> ratio at low temperature and design flow rate for reactors A - J, respectively. These plots show sharp increases in ammonia slip as the ammonia-to-NO<sub>x</sub> ratio approaches 1.0. This finding is in keeping with published data of this type. At ammonia-to-NO<sub>x</sub> ratios near 1.0, non-

idealities in the reactor systems forced the catalysts to slip ammonia since areas were present in the reactors where  $\text{NO}_x$  was the limiting reagent.

Ammonia slip versus temperature is plotted in Figures 5.3.4-18 through 25 for design flow rate and roughly 80%  $\text{NO}_x$  reduction for reactors A - J, respectively. Some improvement (decrease) in ammonia slip is noted between 620 and 700 °F, likely due to improvements in the kinetic reaction rate with increasing temperature. In general, only slight improvements are noted with increasing temperatures above 700 °F. In Figures 5.3.4-24 and 25 (reactors G and J) a slight increase is shown between the 700 and 750 °F points, however, this is likely due to measurement variability and is not considered significant. In these cases, the plots should not be construed as demonstrating increases in ammonia slip with increasing temperature above 700 °F. It is expected that the 700 and 750 °F values are roughly equivalent which may be due in part to mass transfer limitations that become controlling at these higher temperatures. In Figure 22 (reactor E) the trend of the plot is unclear since all values were below the ammonia slip detection limit. (The detection limit for ammonia slip was roughly 1 ppmv; values below the detection limit are plotted as zero.) Overall, these plots demonstrate that in terms of ammonia slip, significant improvements are not realized with temperatures above 700 °F. Losses in boiler efficiency would probably outweigh any improvements that may be obtained in ammonia slip by designing an SCR reactor to operate at temperatures near 750 °F.

### SO<sub>2</sub> Oxidation

The plots for  $\text{SO}_2$  oxidation versus flow rate at high temperature for the combination of all catalyst beds in the reactors are shown in Figures 5.3.4-26 through 32 for reactors A - J, respectively. In Figures 5.3.4-28 and 31 (reactors C and G), decreasing  $\text{SO}_2$  oxidation is noted with increasing flow rate. This finding is expected since the reaction rate is predicted to be inversely proportional to flow rate according to published rate data and information provided by catalyst suppliers. In contrast, Figures 5.3.4-29 and 30 (reactors E and F) show relatively flat profiles with little change in  $\text{SO}_2$  oxidation. Based on

similarities with previous test data the relatively flat profiles indicate that either chemical or physical characteristics of the catalyst and reactors were masking the expected linear effect. Figures 5.3.4-26, 27, and 32 (reactors A, B, and J) show an apparent loss in sulfur trioxide across the reactor. It is believed that this apparent loss is due to large measurement variability that existed in the test facility and factors such as acid condensation on cold spots at the reactor surfaces.

SO<sub>2</sub> oxidation versus temperature at low flow rate for the combination of all catalyst beds in the reactors is shown in Figures 5.3.4-33 through 40 for reactors A - J, respectively. In general, the trend of the plots shows an increase in SO<sub>2</sub> oxidation with increasing temperature. Published information describing the effects of temperature on SO<sub>2</sub> oxidation and information obtained from the catalyst suppliers indicates that increases in SO<sub>2</sub> oxidation are expected to be exponential with respect to temperature. The exact shape of the plots is somewhat unclear since fairly large measurement variability existed in the test facility and other phenomena such as SO<sub>3</sub> deposition occurred in the test facility reactors. The general trend of increasing SO<sub>2</sub> oxidation is expected, however, and the plots provide a good basis for determining the potential for SO<sub>3</sub> formation across the SCR reactors at various operating temperatures. In the case of Figures 5.3.4-38 (reactor F), the extremely low oxidation rate of the catalyst further exacerbated the problem of measurement precision. This particular plot is valuable in the context of showing that the Haldor Topsoe catalyst has very low SO<sub>2</sub> oxidation potential.

The SO<sub>2</sub> oxidation data are corrected to reactor outlet oxygen concentrations. The value for sulfur trioxide produced in the reactors is based on the measured inlet and outlet sulfur trioxide concentrations. In some cases, especially those involving low temperature conditions, there was no net increase in sulfur trioxide across the reactors. In fact, some operating conditions showed an apparent loss in sulfur trioxide across the reactors. It is believed that the apparent loss was caused by phenomena such as acid condensation and the formation of ammonium bisulfate on cold spots at the reactor surfaces. (Tables showing SO<sub>2</sub> oxidation rates quote reactor flow rates as calculated for the reactor exits,

since  $\text{SO}_3$  was measured at this point. For consistency with other figures, the plots of  $\text{SO}_2$  oxidation versus flow rate are based on reactor inlet flow rates. In practice, differences between inlet and outlet flow rates are slight and do not greatly affect the overall analysis.)

#### Additional Base-Line Measurements

Mass concentrations (five-point for reactors A, B, C) (two-point for reactors D, E, F, G) and flue gas velocity profiles (nine-point for reactors A, B, C) (three-point for reactors D, E, F, G, J) were conducted near design operating conditions (700 °F, 100% flow rate) at the reactor outlets and reactor inlets, respectively. The mass concentration profile data are given in Figures 5.3.4-41 through 47 for reactors A - G, respectively, in five different units of concentration and as mass emission rates. The flue gas velocity profiles are presented in Figures 5.3.4-48 through 55 for reactors A - J, respectively. The results of the mass concentrations and flue gas velocity profiles are given in Table 5.3.4-10 for all reactors.

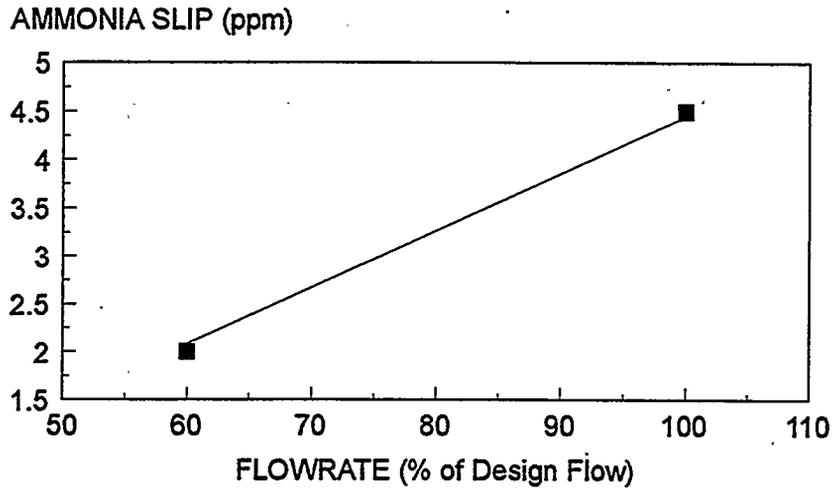
HCl concentration (3%  $\text{O}_2$ , dry) was measured at the design operating conditions at the reactor outlets. The  $\text{N}_2\text{O}$  concentrations were also measured at the reactor inlets and at the reactor outlets (both measurements are dry at 3%  $\text{O}_2$ ). The results of these measurements are shown in Table 5.3.4-10.

Table 5.3.4-10 Additional Base-line Measurements

| Reactor<br>(Catalyst<br>Supplier) | Mass<br>concentration<br>(gr/dscf) | Velocity<br>Profile<br>(ft/sec) | HCl<br>concentration<br>(ppmv) | N <sub>2</sub> O<br>Concentration<br>(ppmv) |
|-----------------------------------|------------------------------------|---------------------------------|--------------------------------|---|
|                                   | rxr outlet                         | rxr inlet                       | rxr outlet                     | rxr inlet/outlet                            |
| Reactor A<br>(Grace Nxrm)         | 3.47 ± 0.33                        | 12.3 ± 1.1                      | 219 ± 13                       | 1.2/1.3                                     |
| Reactor B<br>(NSKK)               | 3.27 ± 0.16                        | 12.6 ± 0.7                      | 222 ± 13                       | 1.2/1.3                                     |
| Reactor C<br>(Siemens)            | 3.42 ± 0.24                        | 12.6 ± 0.7                      | 260 ± 7                        | 1.2/2.0                                     |
| Reactor D<br>(Grace Synox)        | 4.24 ± 0.40                        | 13.9 ± 1.5                      | 223 ± 17                       | 1.2/2.0                                     |
| Reactor E<br>(Corm. HD)           | 4.25 ± 0.25                        | 15.9 ± 1.2                      | 233 ± 5                        | 1.2/1.8                                     |
| Reactor F<br>(Haldor)             | 4.34 ± 0.17                        | 13.3 ± 0.2                      | 250 ± 9                        | 1.2/2.0                                     |
| Reactor G<br>(Hitachi)            | 3.31 ± 0.36                        | 15.9 ± 1.2                      | 256 ± 8                        | 1.2/2.3                                     |
| Reactor J<br>(Corm. LD)           | N/A                                | 14.2 ± 0.4                      | 244 ± 2                        | 1.2/2.5                                     |

Figure 5.3.4-2

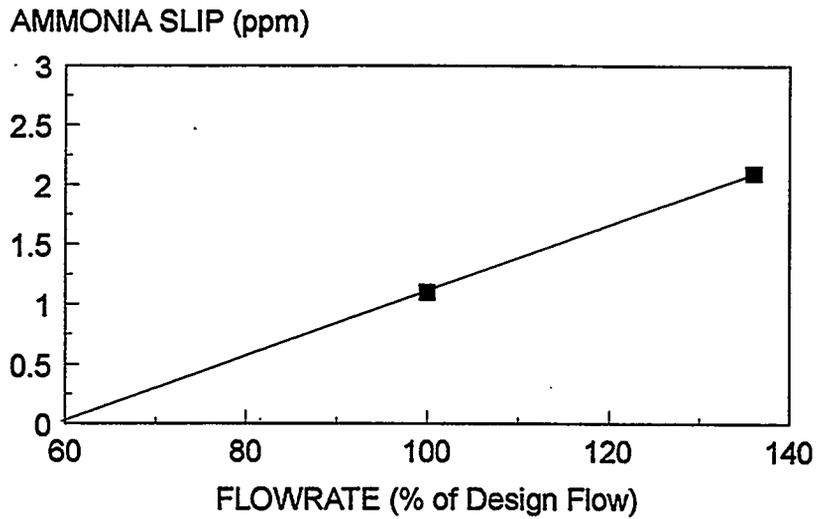
### AMMONIA SLIP VS. FLOW RATE



GRACE NXRM: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 620 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-3

### AMMONIA SLIP VS. FLOW RATE

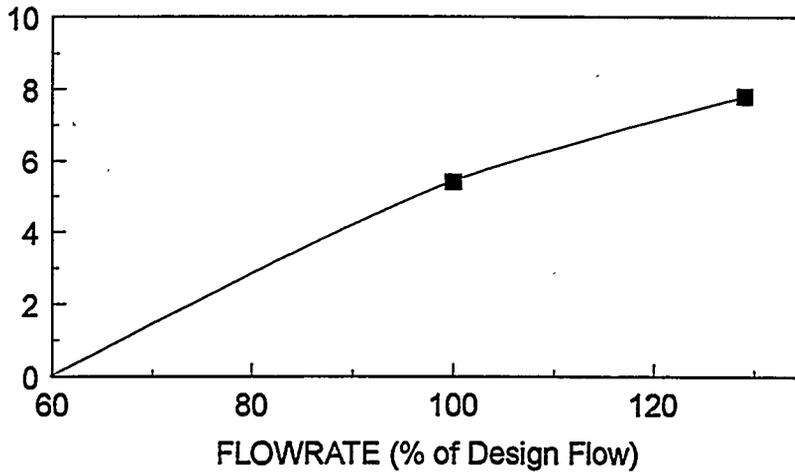


NSKK: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-4

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)

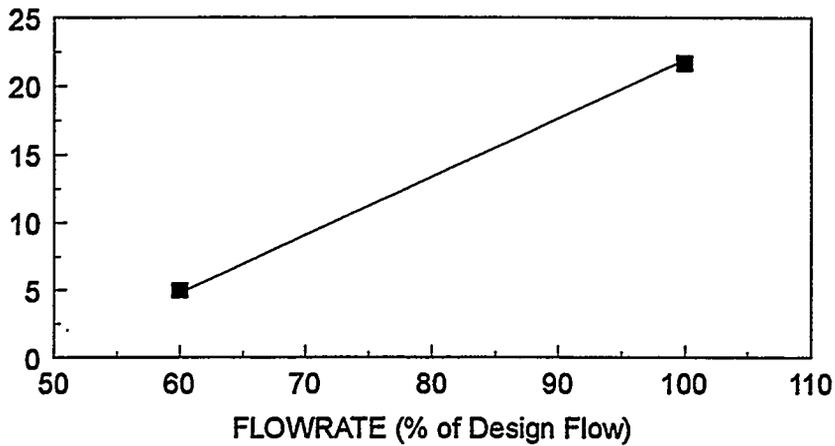


SIEMENS: NH3/NOx=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-5

### AMMONIA SLIP VS. FLOW RATE

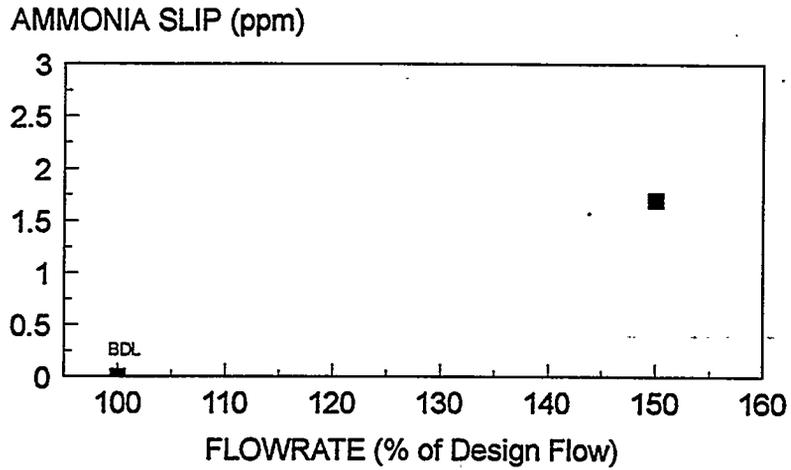
AMMONIA SLIP (ppm)



GRACE SNX: NH3/NOx=0.80, 620 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-6

### AMMONIA SLIP VS. FLOW RATE



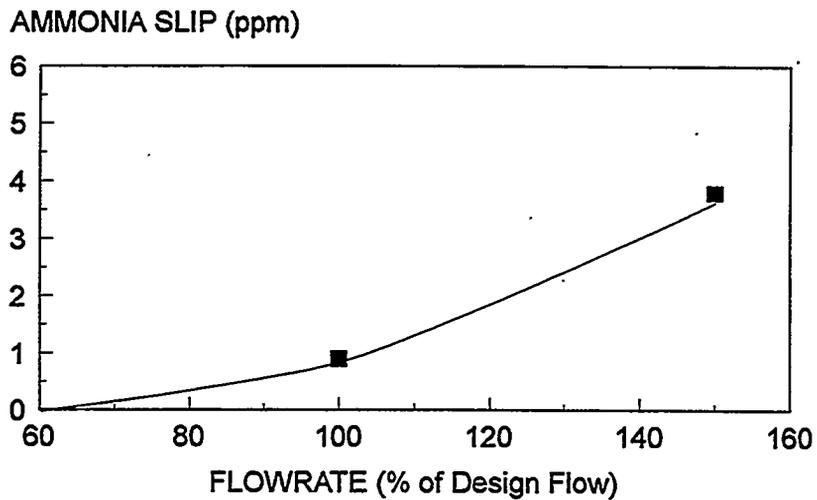
CORM HD: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F

(BDL) Below lower detection limit (<1 ppmv)

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-7

### AMMONIA SLIP VS. FLOW RATE



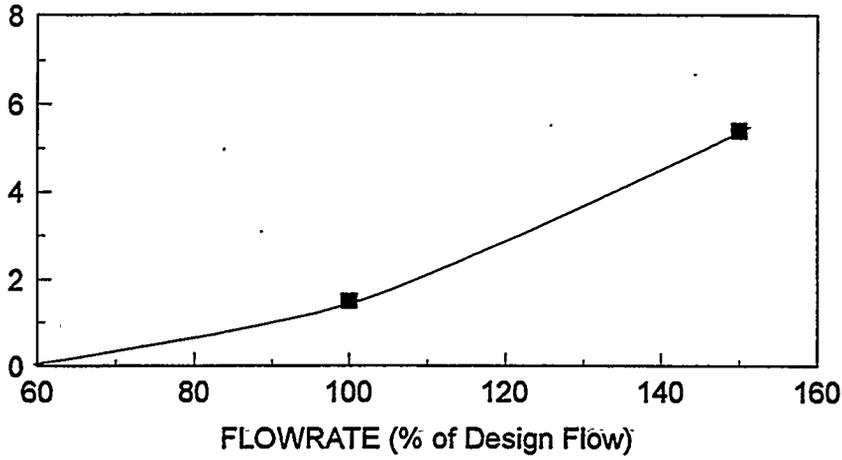
HALDOR: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-8

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



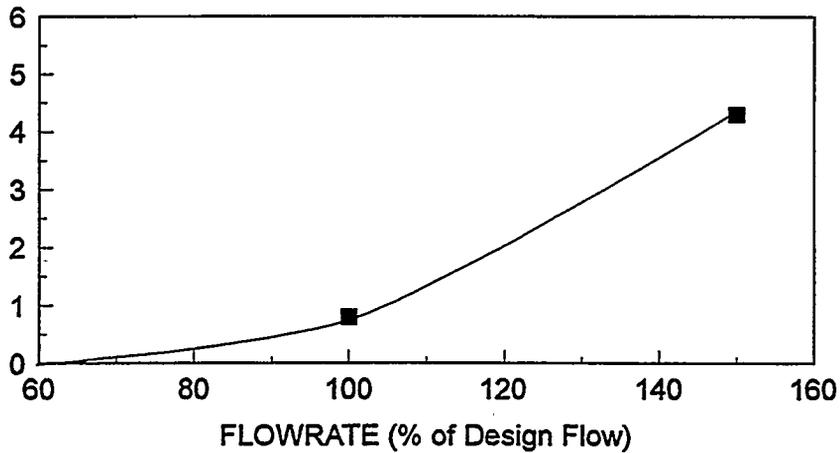
HITACHI: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-9

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



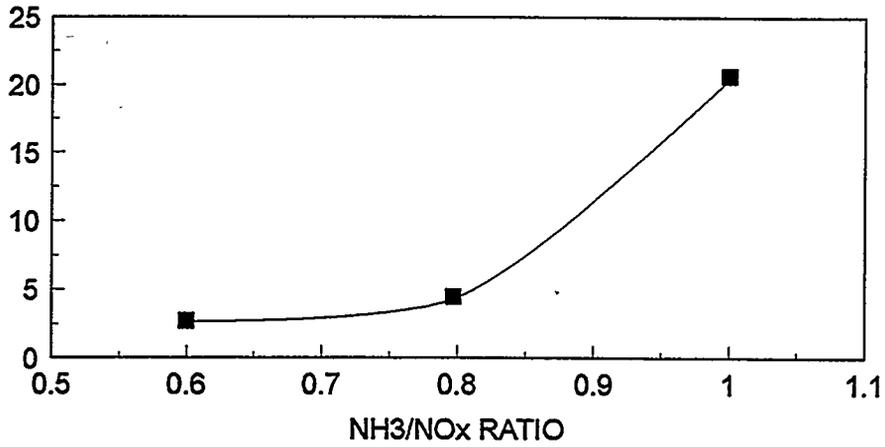
CORM LD: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-10

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

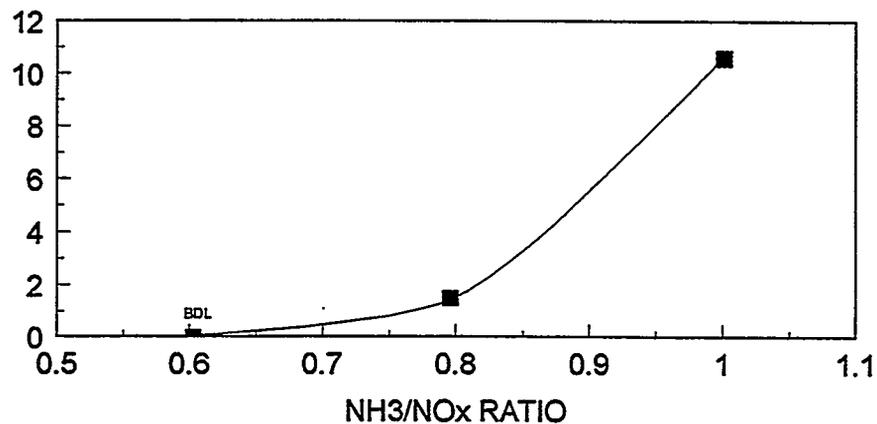


GRACE NXRM: Design Flow, 620 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-11

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

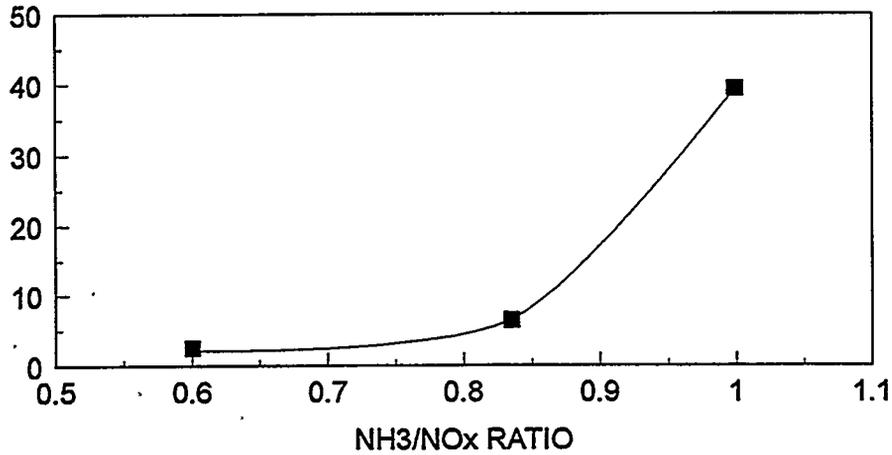


NSKK: Design Flow, 620 F  
(BDL) Below lower detection limit (< 1 ppmv)  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-12

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)



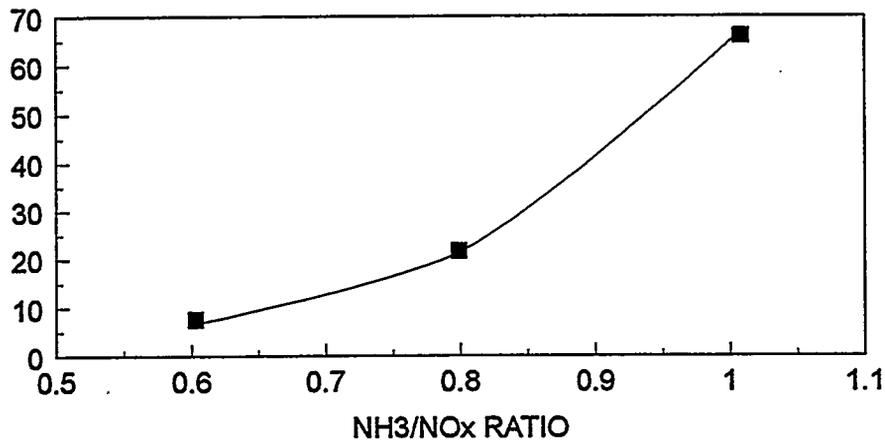
SIEMENS: Design Flow, 620 F

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-13

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

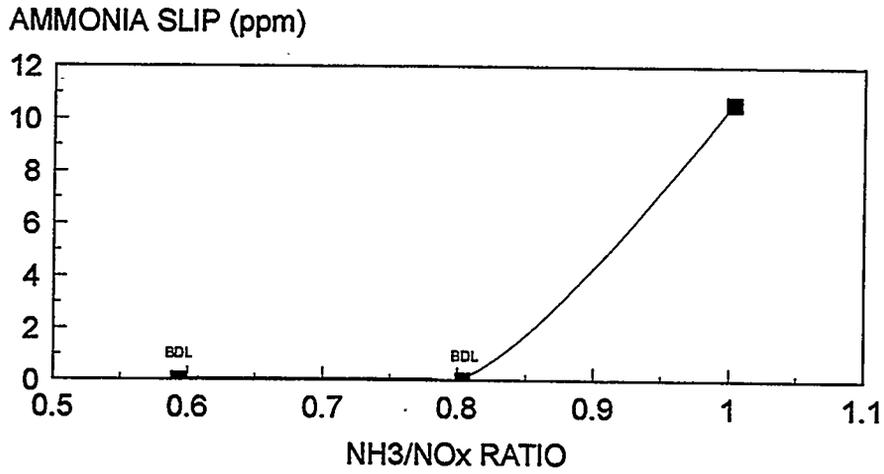


GRACE SNX: Design Flow, 620 F

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-14

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO



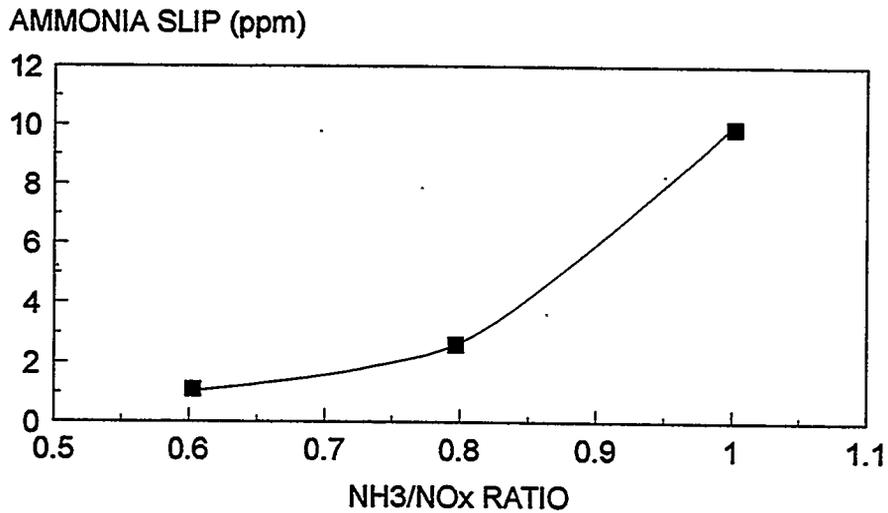
CORM HD: Design Flow, 620 F

(BDL) Below lower detection limit (< 1 ppmv)

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-15

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO



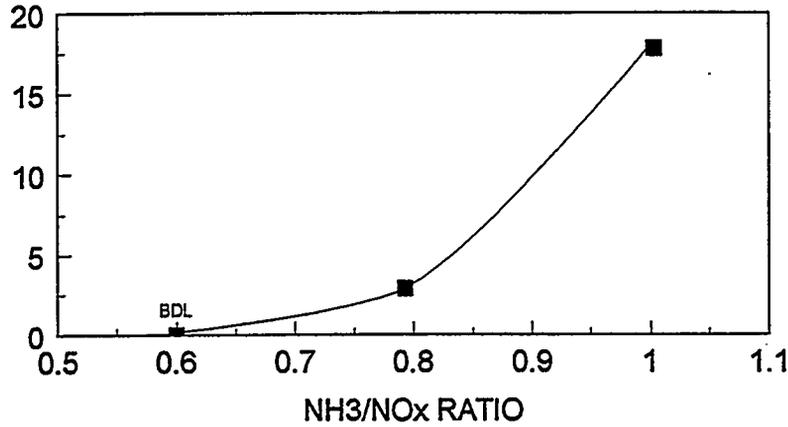
HALDOR: Design Flow, 620 F

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-16

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

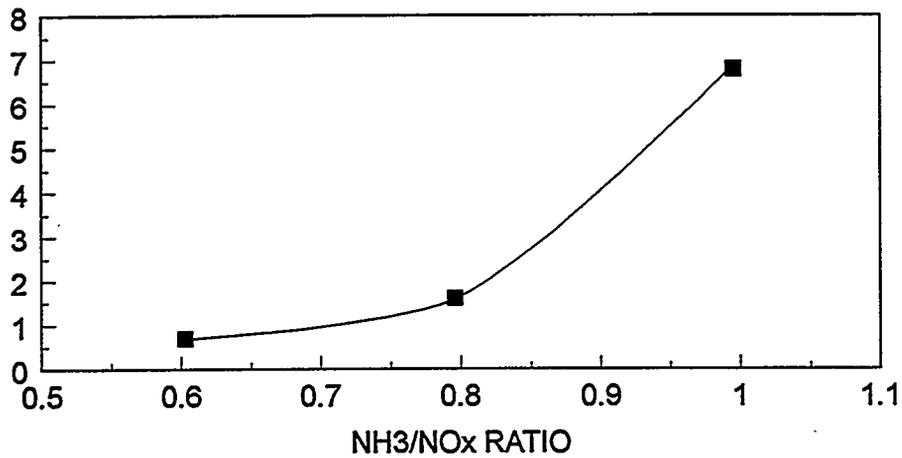


HITACHI: Design Flow, 620 F  
(BDL) Below lower detection limit (<1 ppmv)  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-17

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

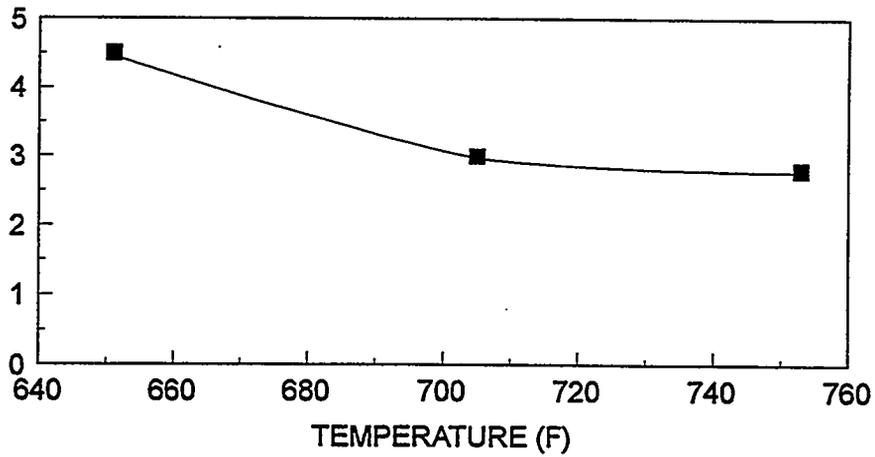


CORM LD: Design Flow, 620 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-18

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

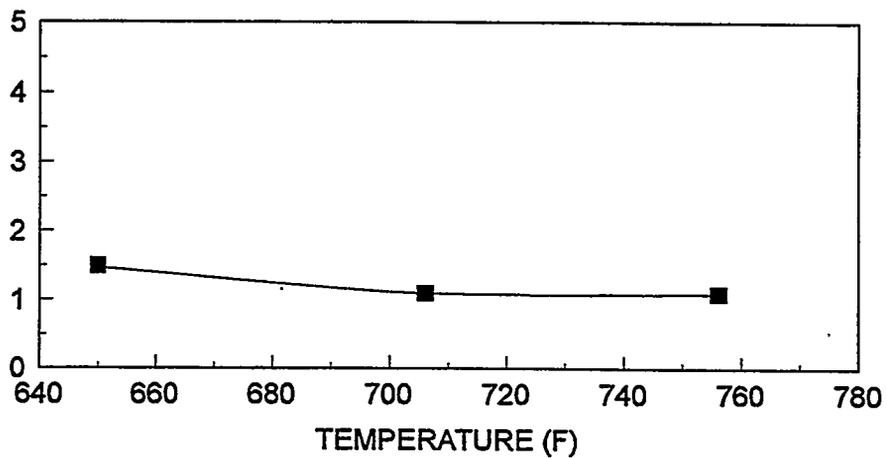


GRACE NXRM: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-19

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

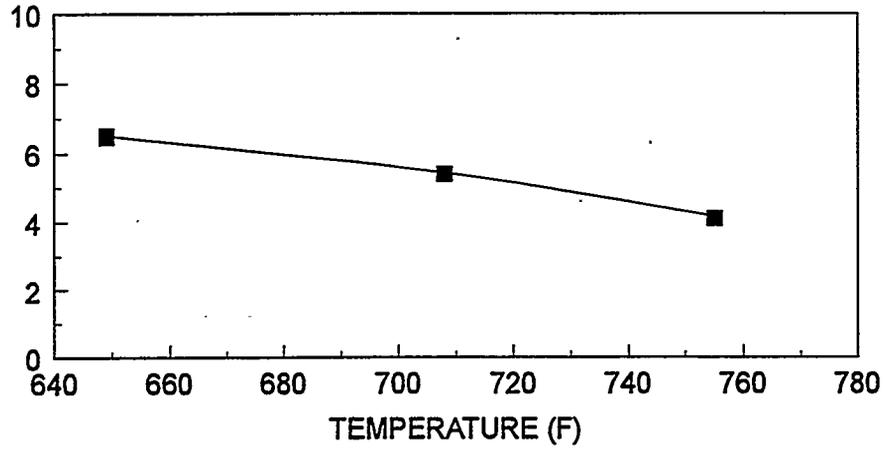


NSKK: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-20

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

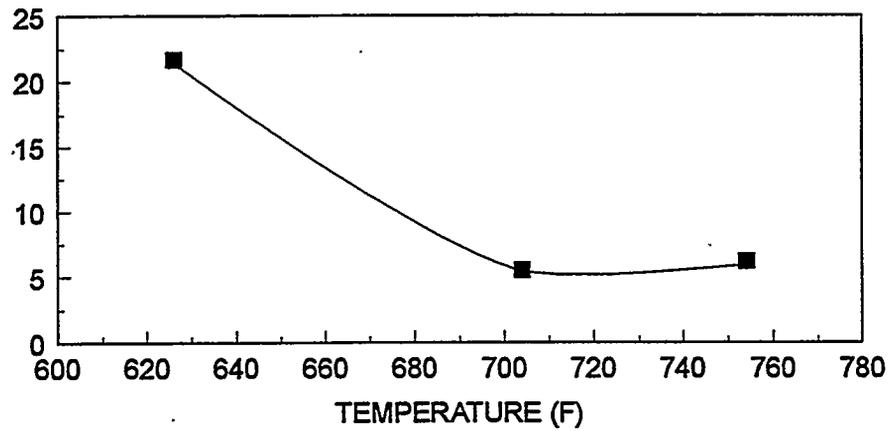


SIEMENS: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-21

### AMMONIA SLIP VS. TEMPERATURE

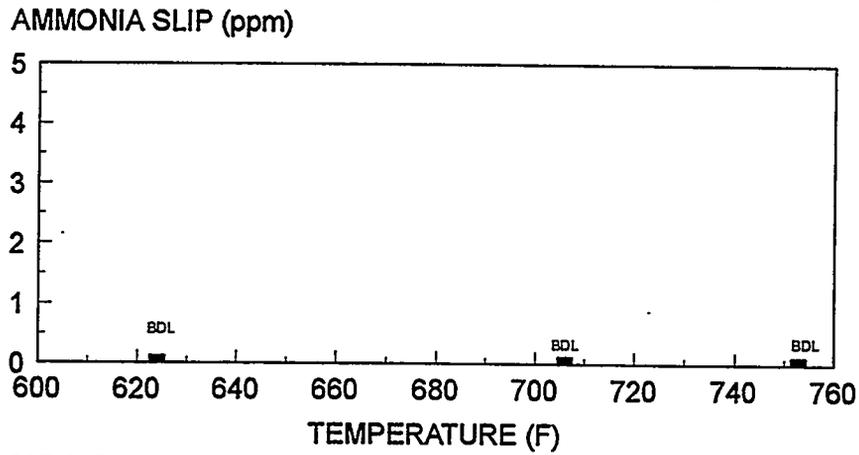
AMMONIA SLIP (ppm)



GRACE SNX: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-22

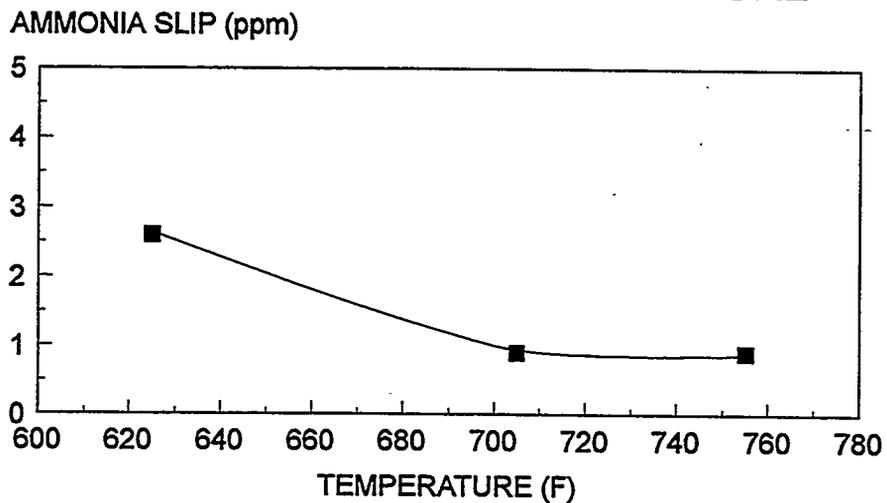
### AMMONIA SLIP VS. TEMPERATURE



CORM HD: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow  
(BDL) Below lower detection limit of 0.7-0.9 ppm  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-23

### AMMONIA SLIP VS. TEMPERATURE

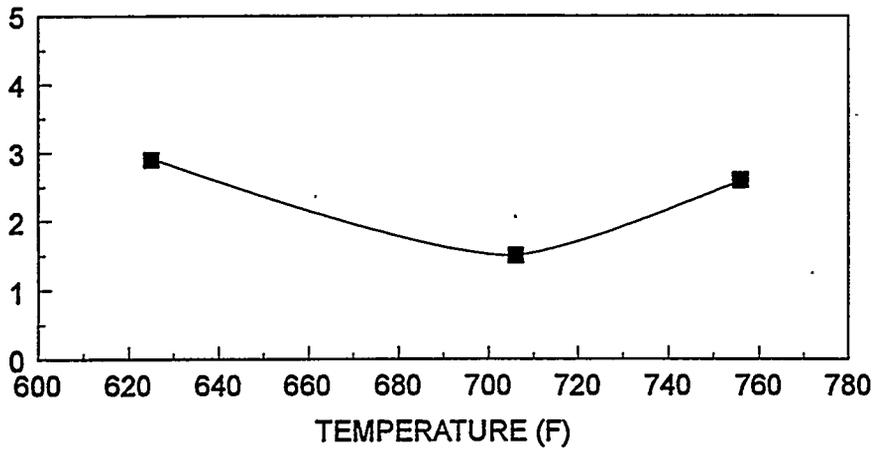


HALDOR: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-24

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



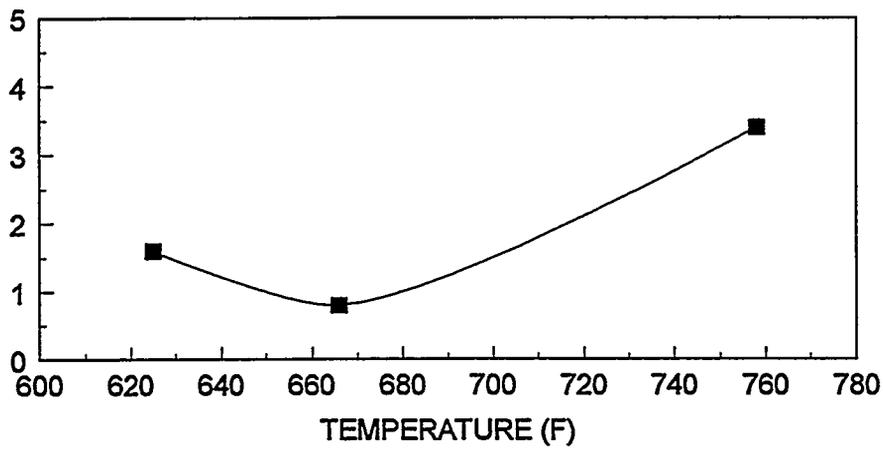
HITACHI: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-25

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

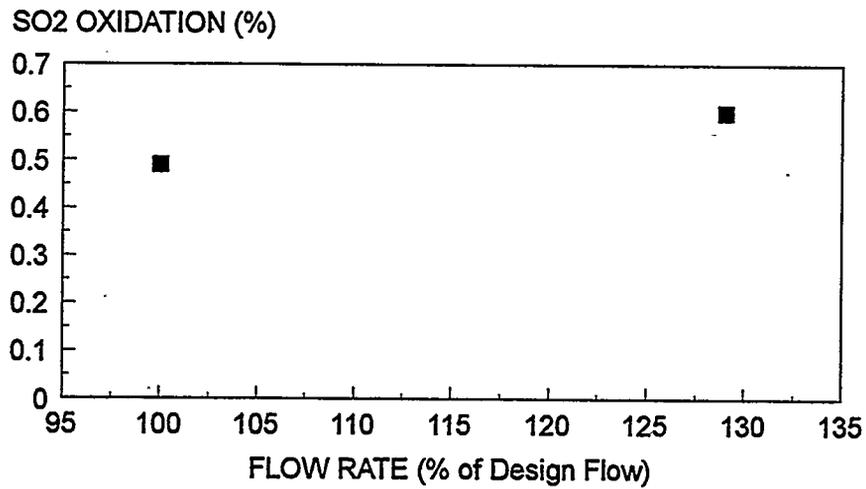


CORM LD: NH<sub>3</sub>/NO<sub>x</sub>=0.80, Design Flow

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-26

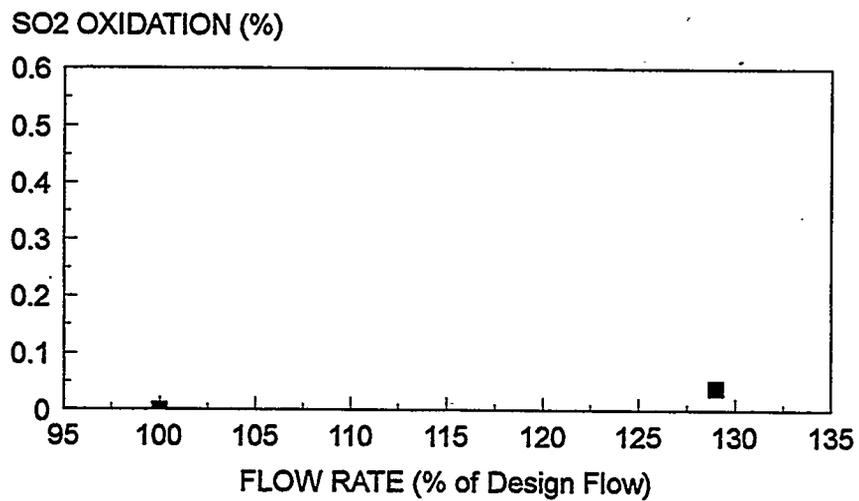
### SO2 OXIDATION VS. FLOWRATE



GRACE NXRM: NH3/NOx=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-27

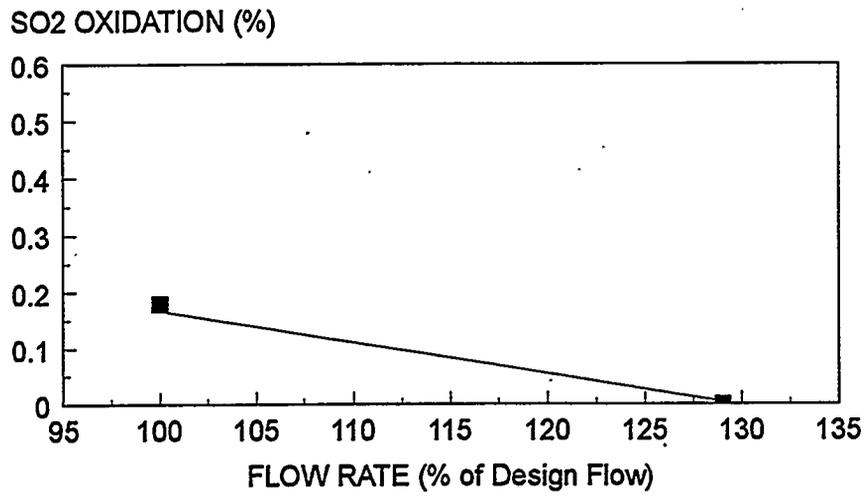
### SO2 OXIDATION VS. FLOWRATE



NSKK: NH3/NOx=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-28

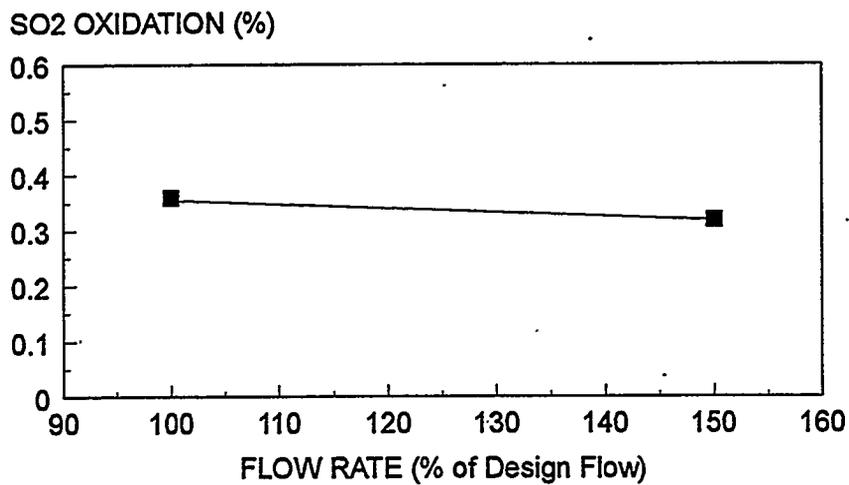
### SO2 OXIDATION VS. FLOWRATE



SIEMENS: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-29

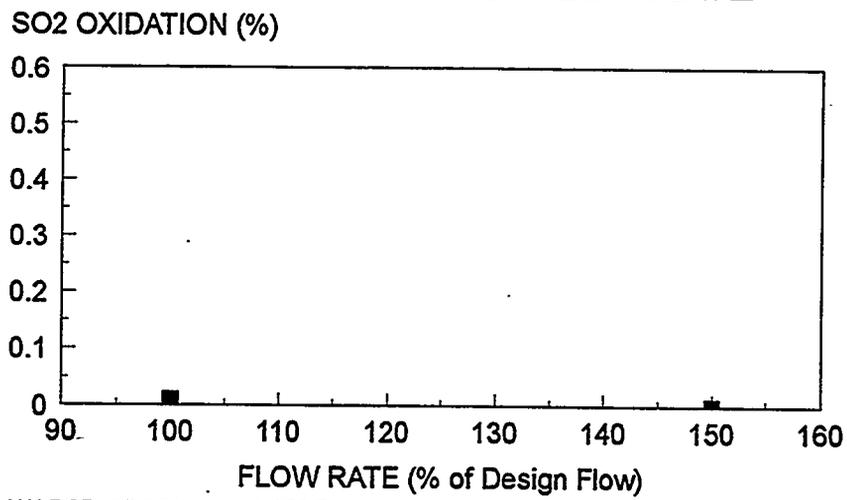
### SO2 OXIDATION VS. FLOWRATE



CORM HD: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-30

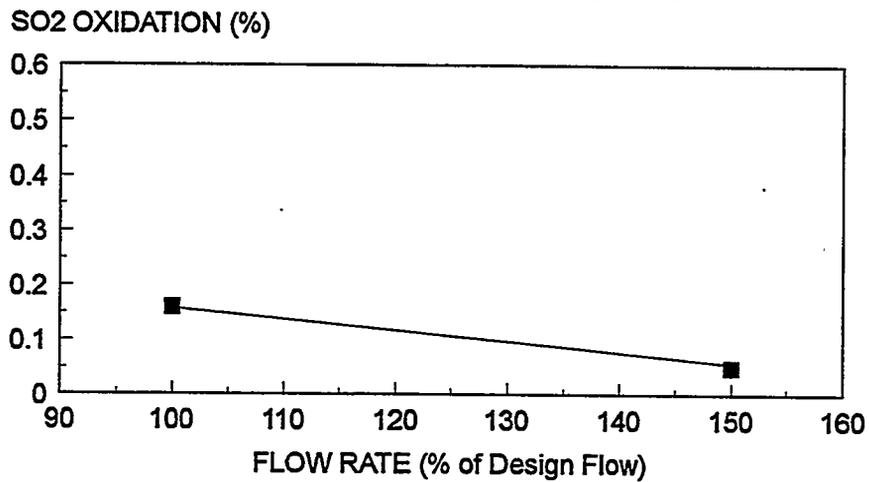
### SO2 OXIDATION VS. FLOWRATE



HALDOR: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-31

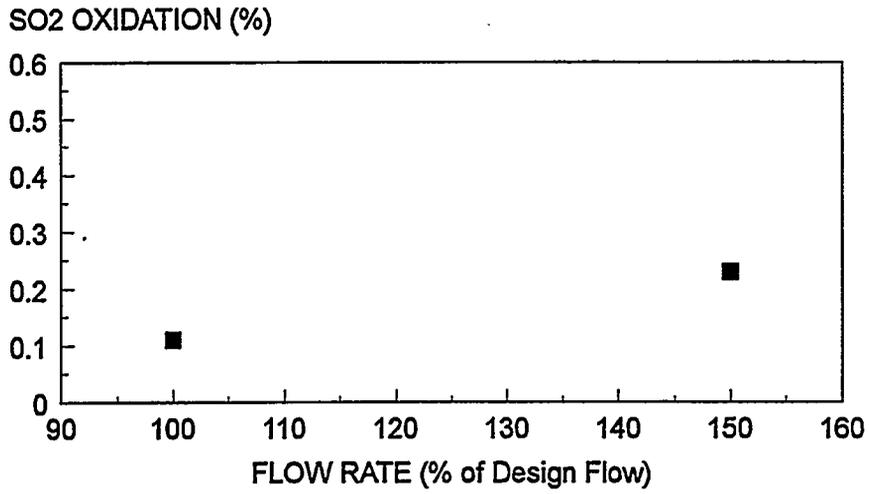
### SO2 OXIDATION VS. FLOWRATE



HITACHI: NH<sub>3</sub>/NO<sub>x</sub>=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-32

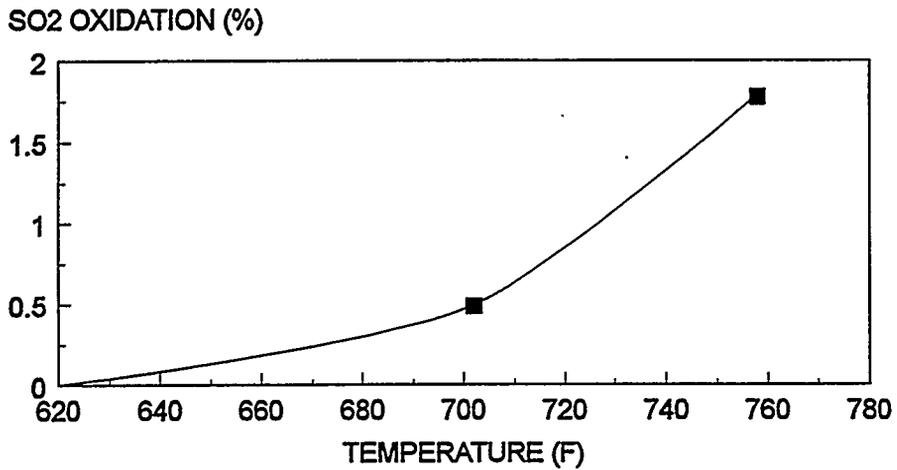
### SO2 OXIDATION VS. FLOWRATE



CORM LD: NH3/NOx=0.80, 700 F  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-33

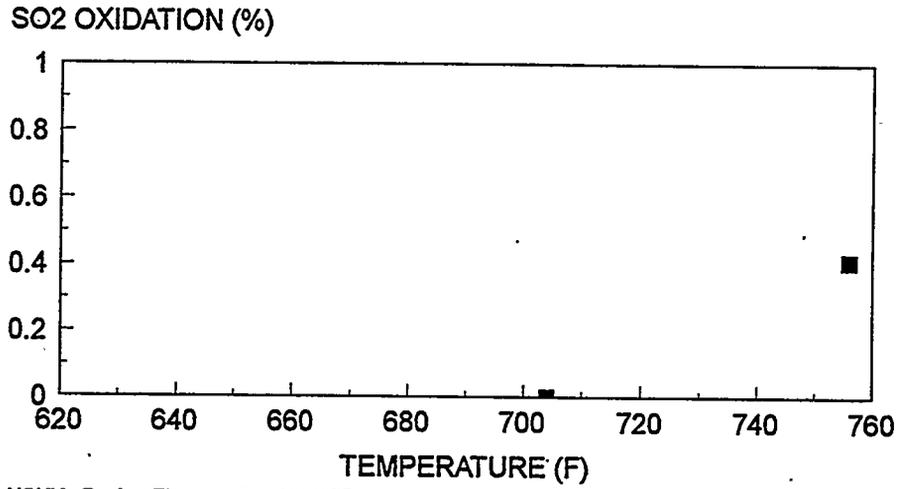
### SO2 OXIDATION VS. TEMPERATURE



GRACE NXRM: Design Flow, NH3/NOx=0.80  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-34

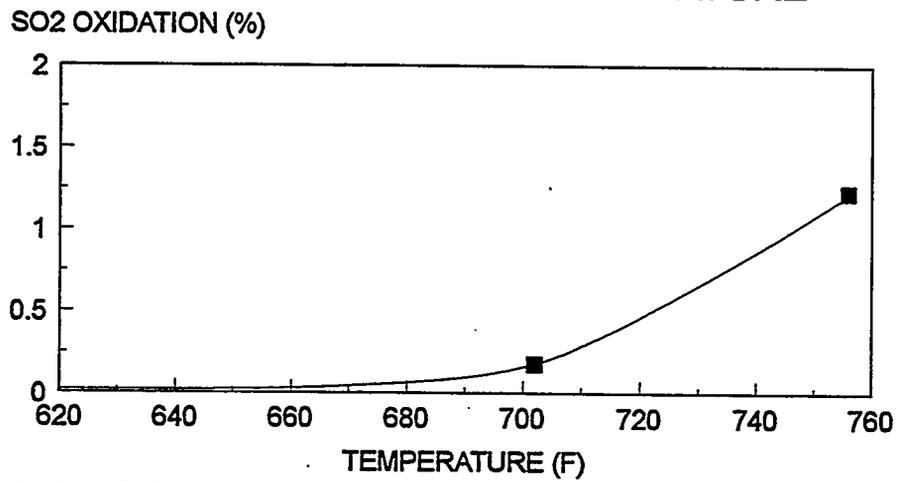
### SO2 OXIDATION VS. TEMPERATURE



NSKK: Design Flow, NH3/NOX=0.80  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-35

### SO2 OXIDATION VS. TEMPERATURE

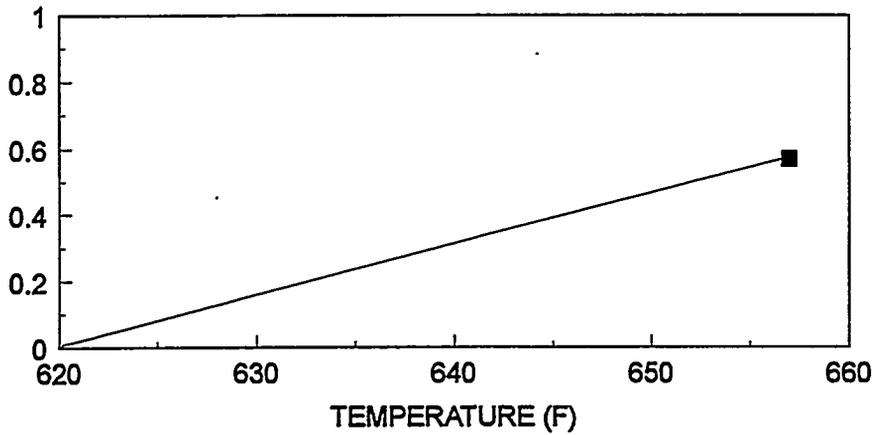


SIEMENS: Design Flow, NH3/NOX=0.80  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-36

### SO2 OXIDATION VS. TEMPERATURE

SO2 OXIDATION (%)

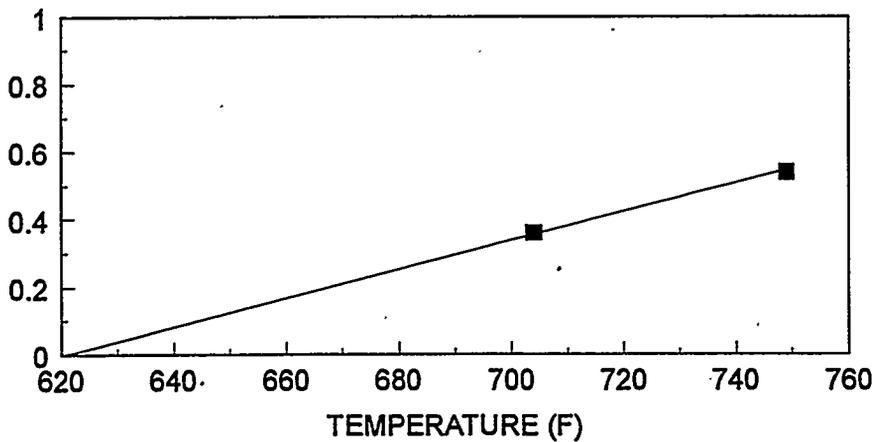


GRACE SNX: Design Flow, NH3/NOX=0.80  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-37

### SO2 OXIDATION VS. TEMPERATURE

SO2 OXIDATION (%)

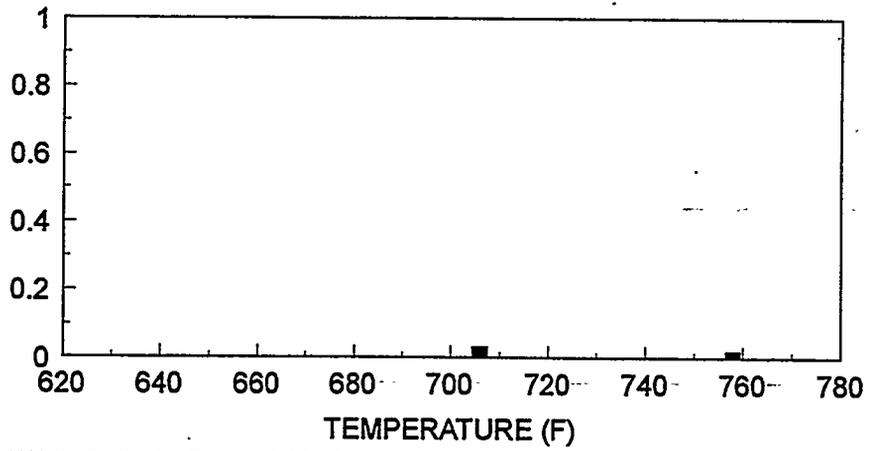


CORM HD: Design Flow, NH3/NOX=0.80  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-38

### SO2 OXIDATION VS. TEMPERATURE

SO2 OXIDATION (%)



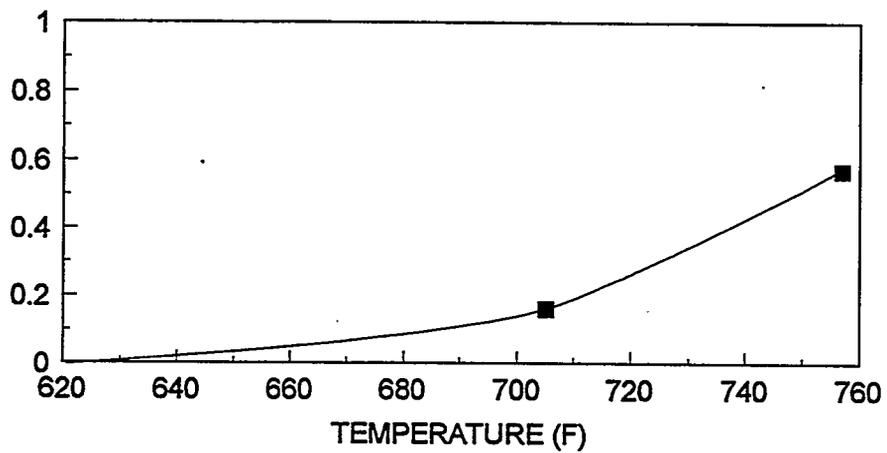
HALDOR: Design Flow, NH3/NOX=0.80

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-39

### SO2 OXIDATION VS. TEMPERATURE

SO2 OXIDATION (%)



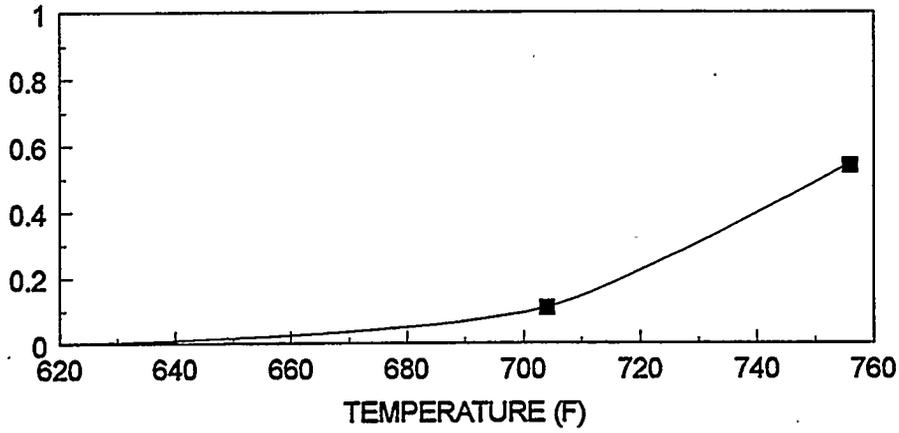
HITACHI: Design Flow, NH3/NOX=0.80

FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-40

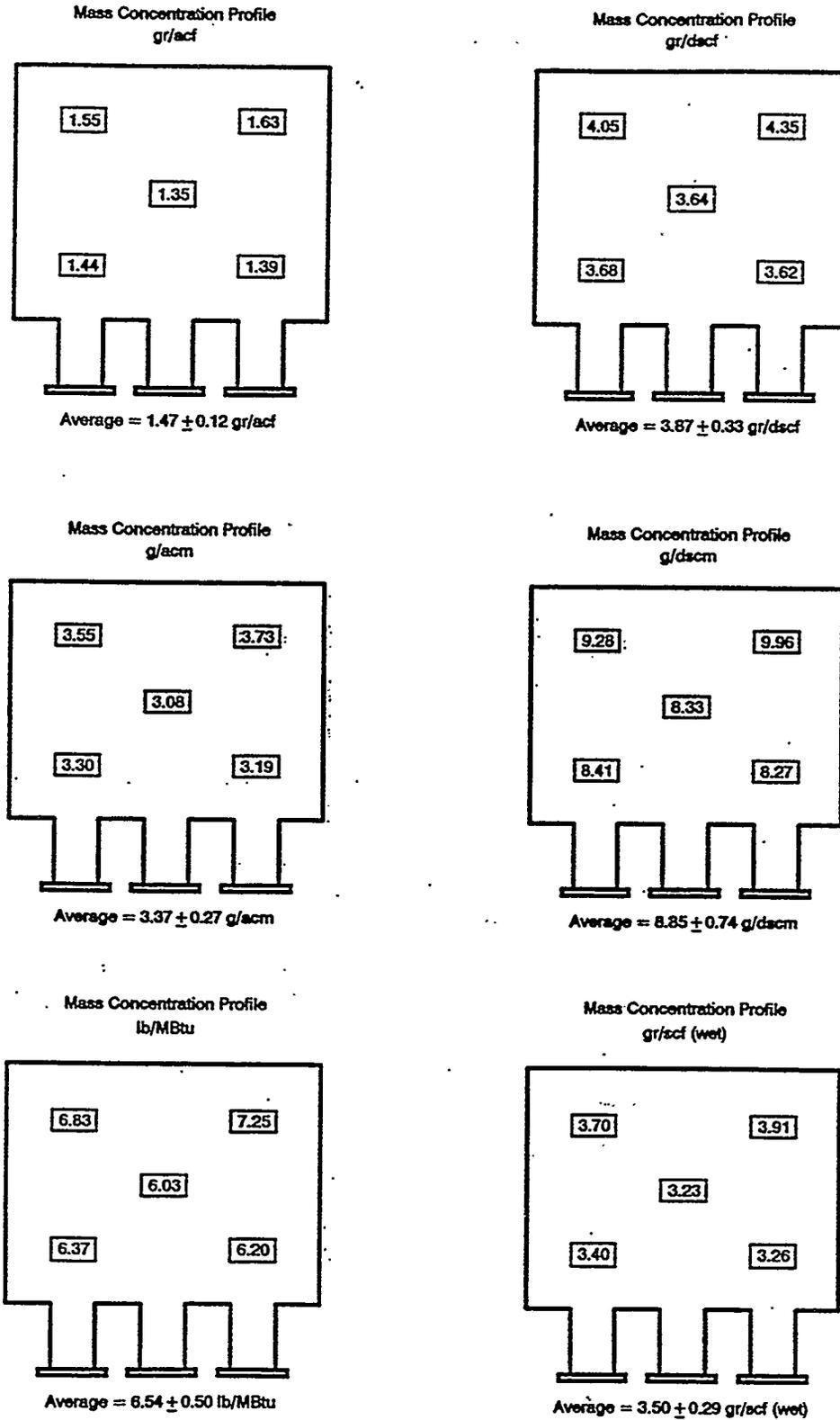
### SO<sub>2</sub> OXIDATION VS. TEMPERATURE

SO<sub>2</sub> OXIDATION (%)



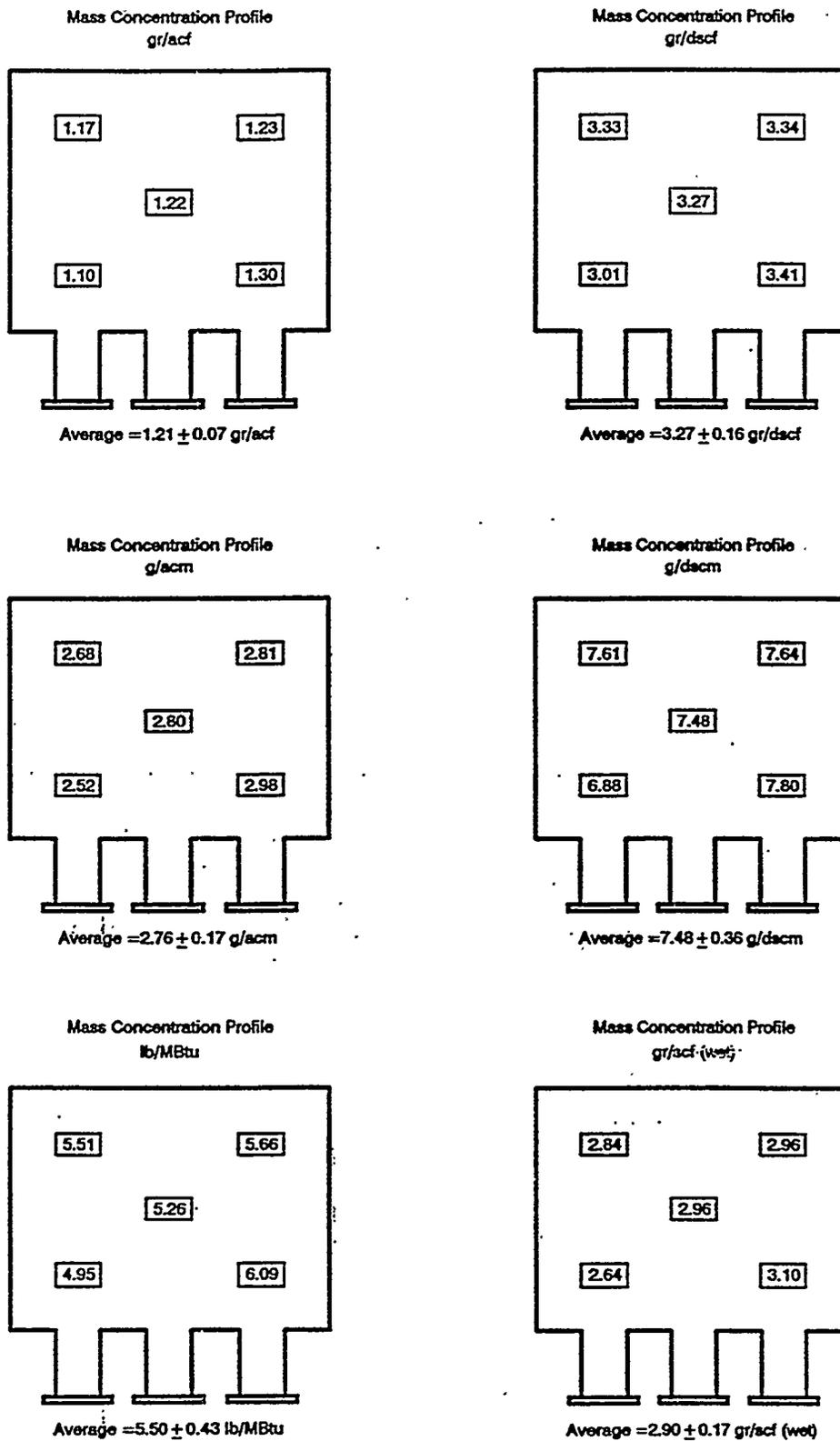
CORM LD: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.80  
FOURTH PARAMETRIC SEQUENCE

Figure 5.3.4-41



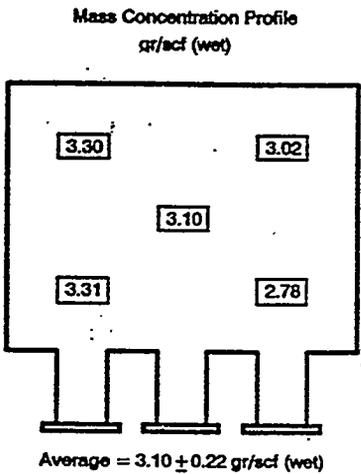
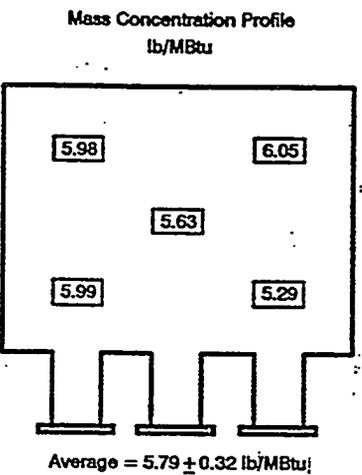
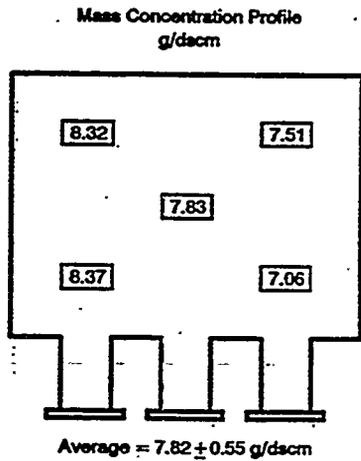
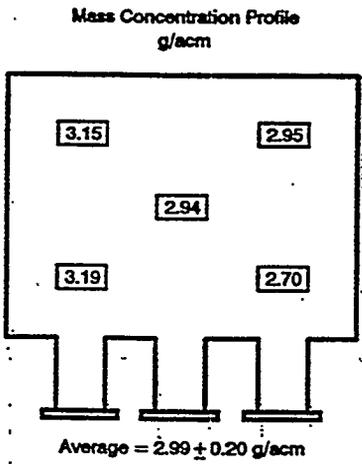
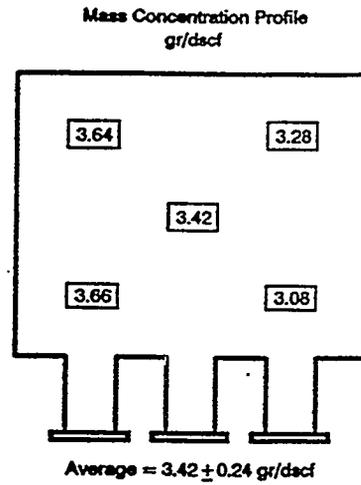
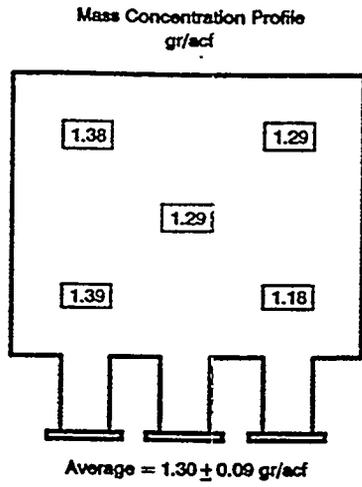
Six presentations of the Reactor A outlet mass concentration/mass emission profile.

Figure 5.3.4-42



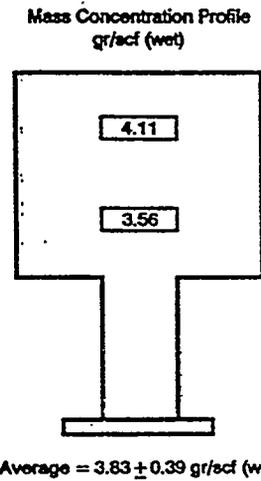
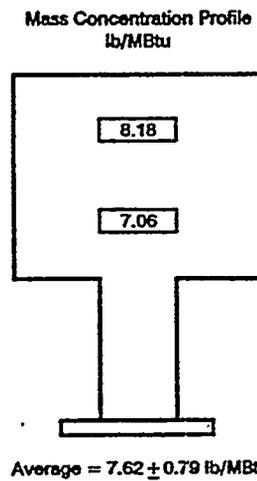
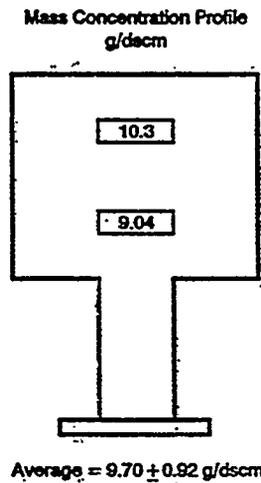
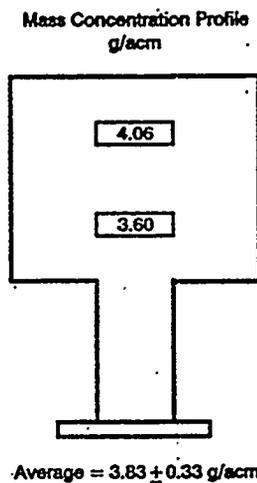
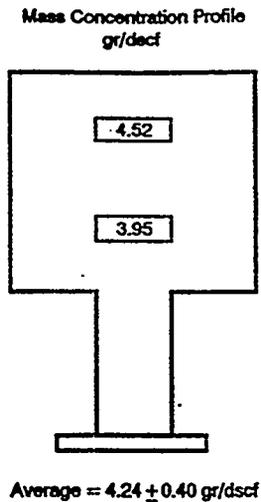
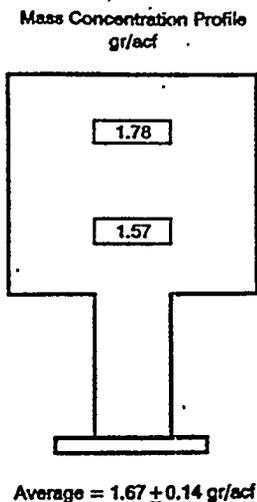
Six presentations of the Reactor B outlet mass concentration/mass emission profile.

Figure 5.3.4-43



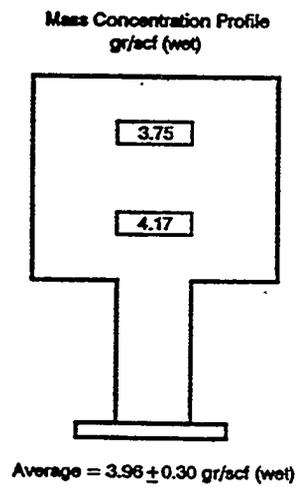
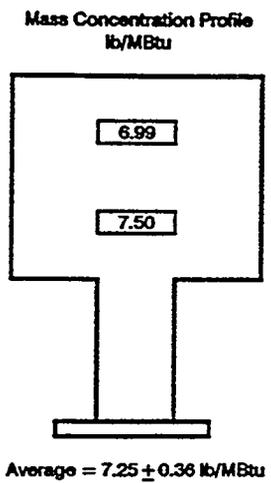
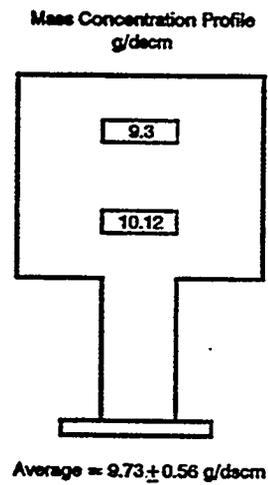
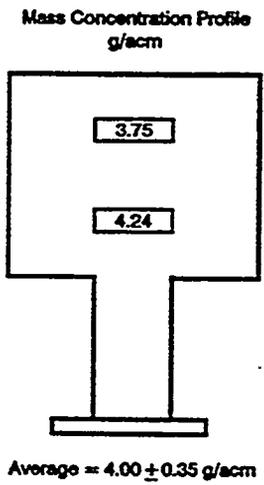
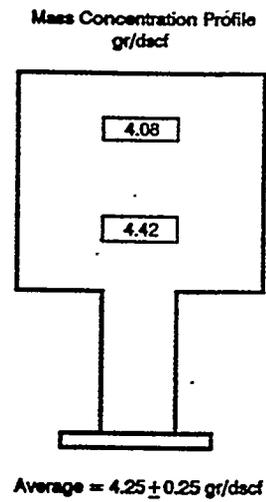
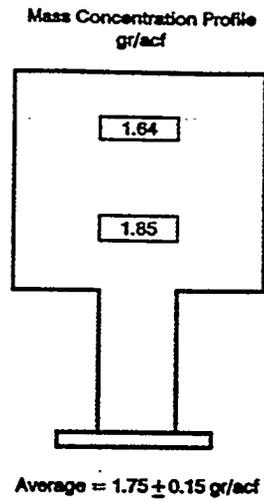
Six presentations of the Reactor C outlet mass concentration/mass emission profile.

Figure 5.3.4-44



Six presentations of the Reactor D outlet mass concentration/mass emission profile.

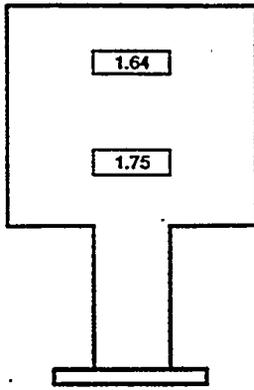
Figure 5.3.4-45



Six presentations of the Reactor E outlet mass concentration/mass emission profile.

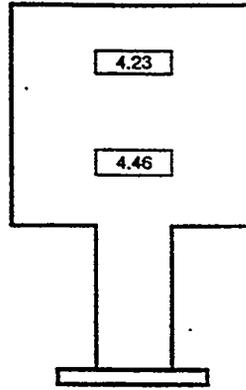
Figure 5.3.4-46

Mass Concentration Profile  
gr/acf



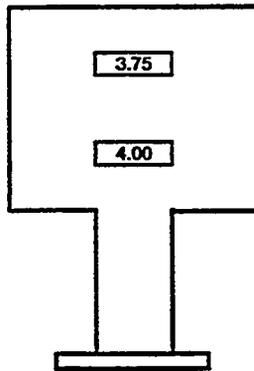
Average =  $1.70 \pm 0.08$  gr/acf

Mass Concentration Profile  
gr/dscf



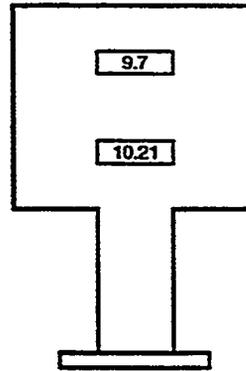
Average =  $4.34 \pm 0.17$  gr/dscf

Mass Concentration Profile  
g/acm



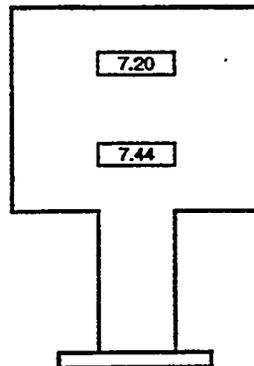
Average =  $3.88 \pm 0.18$  g/acm

Mass Concentration Profile  
g/dscm



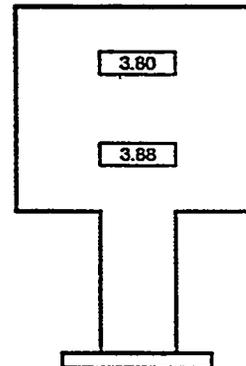
Average =  $9.94 \pm 0.38$  g/dscm

Mass Concentration Profile  
lb/MBtu



Average =  $7.32 \pm 0.17$  lb/MBtu

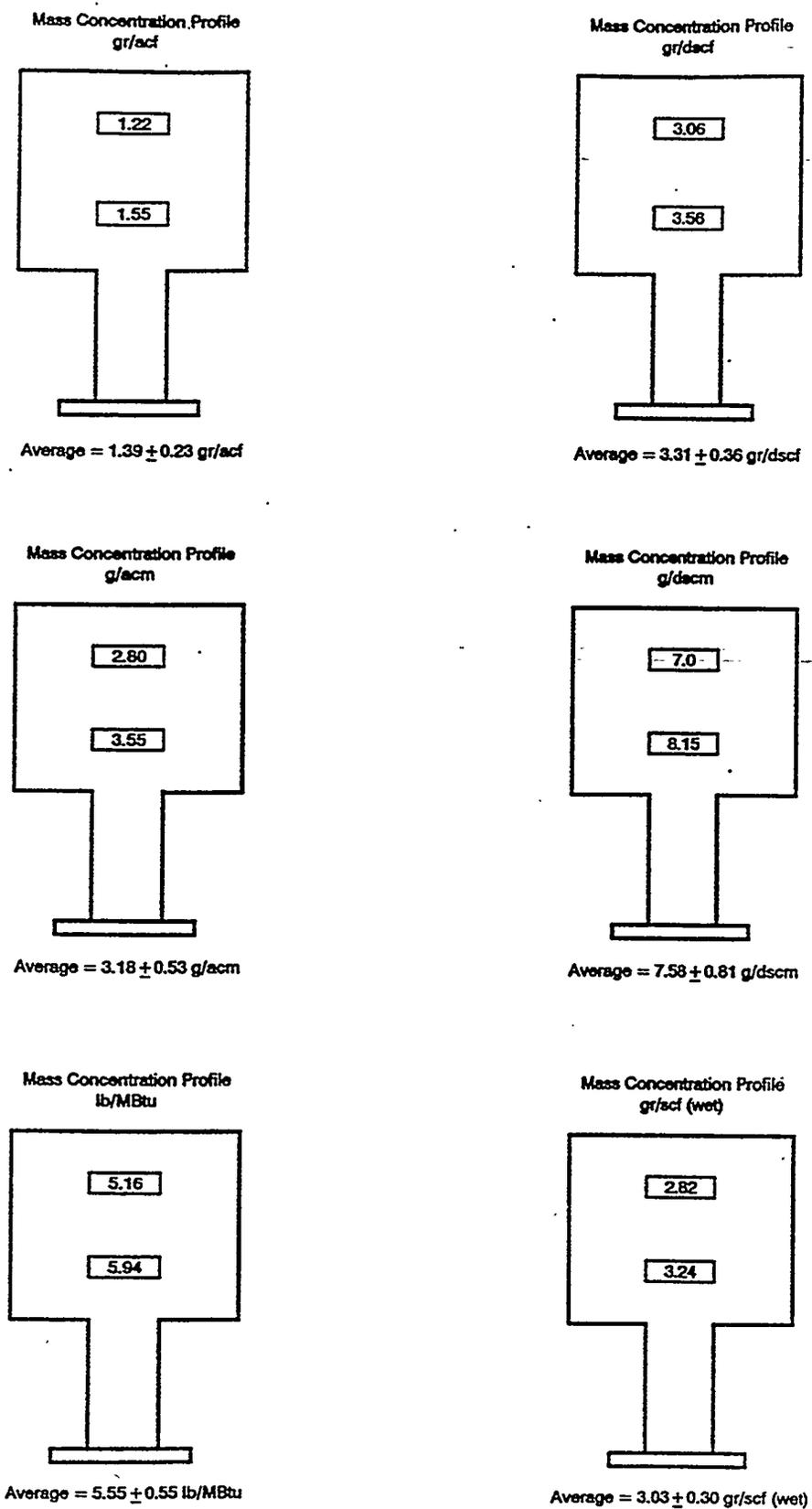
Mass Concentration Profile  
gr/scf (wet)



Average =  $3.84 \pm 0.06$  gr/scf (wet)

Six presentations of the Reactor F outlet mass concentration/mass emission profile.

Figure 5.3.4-47

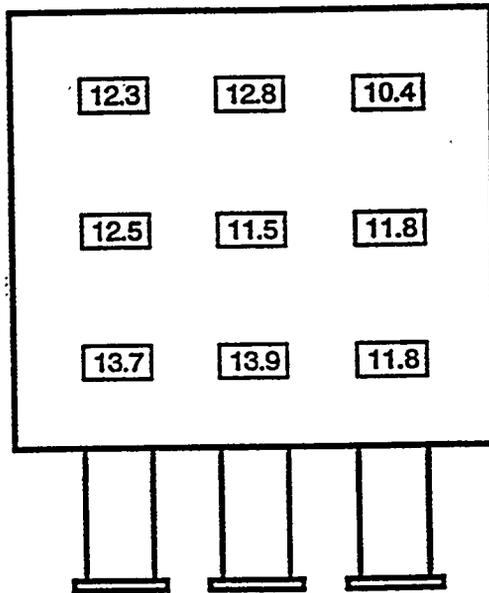


Six presentations of the Reactor G outlet mass concentration/mass emission profile.

Figure 5.3.4-48

**REACTOR A**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



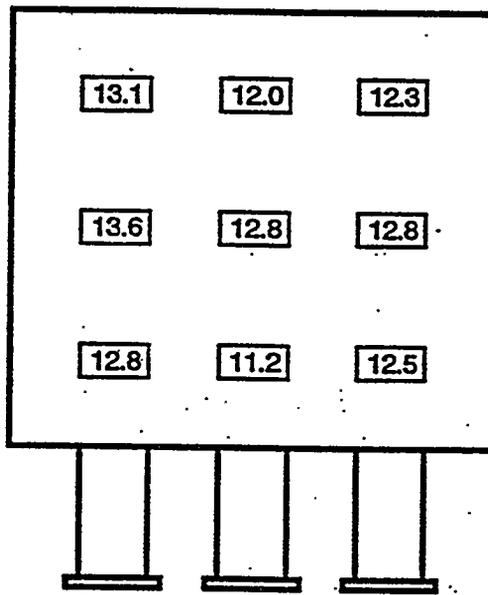
Average =  $123 \pm 1.1$  ft/s

Reactor A flue gas velocity profile.

Figure 5.3.4-49

**REACTOR B**  
CATALYST LAYER 1 INLET

Velocity Profile  
ft/s



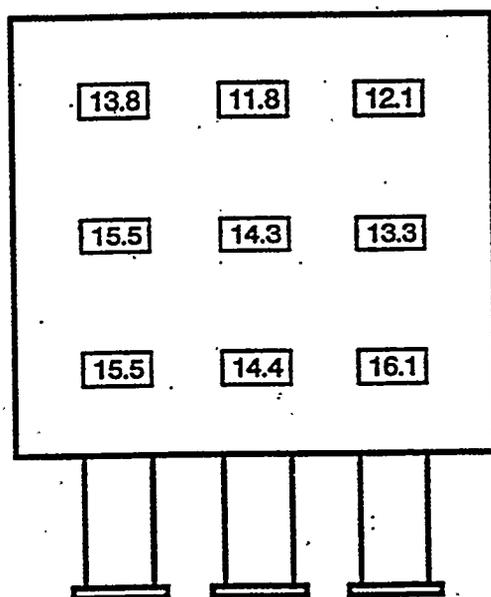
Average =  $12.6 \pm 0.7$  ft/s

Reactor B flue gas velocity profile.

Figure 5.3.4-50

**REACTOR C**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



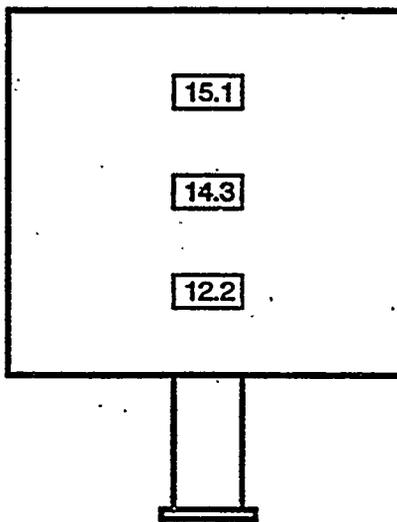
Average =  $14.1 \pm 1.5$  ft/s

Reactor C flue gas velocity profile.

Figure 5.3.4-51

**REACTOR D**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



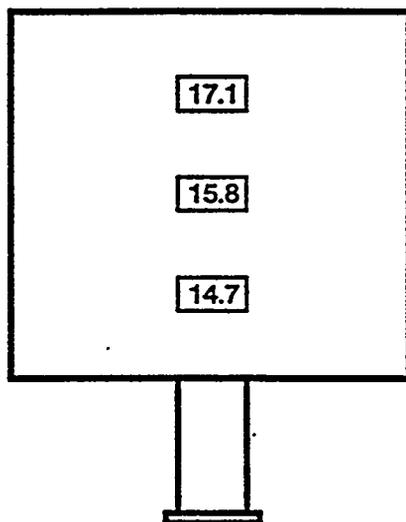
Average =  $13.9 \pm 1.5$  ft/s

Reactor D flue gas velocity profile.

Figure 5.3.4-52

**REACTOR E**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



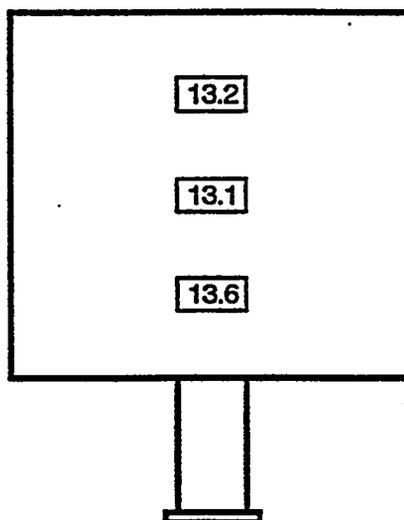
Average =  $15.9 \pm 1.2$  ft/s

Reactor E flue gas velocity profile.

Figure 5.3.4-53

**REACTOR F**  
CATALYST LAYER 1 INLET

Velocity Profile  
ft/s



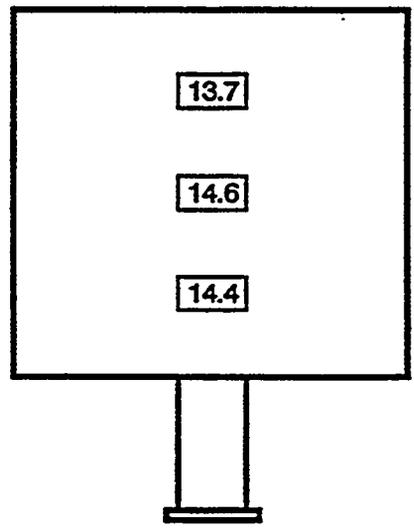
Average =  $13.3 \pm 0.2$  ft/s

Reactor F flue gas velocity profile.

Figure 5.3.4-54

**REACTOR G**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



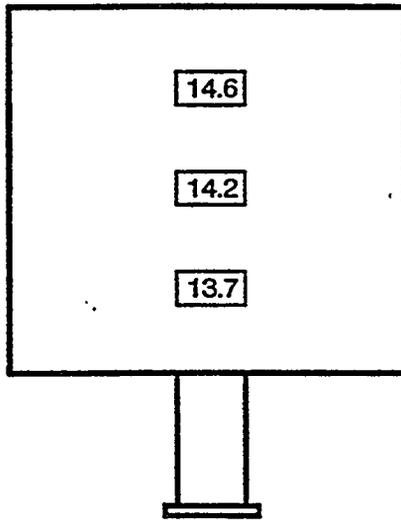
Average =  $14.2 \pm 0.5$  ft/s

Reactor G flue gas velocity profile:

Figure 5.3.4-55

**REACTOR J**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



Average =  $14.2 \pm 0.4$  ft/s

Reactor J flue gas velocity profile.

### 5.3.5 Fifth Parametric Sequence (Abbreviated)

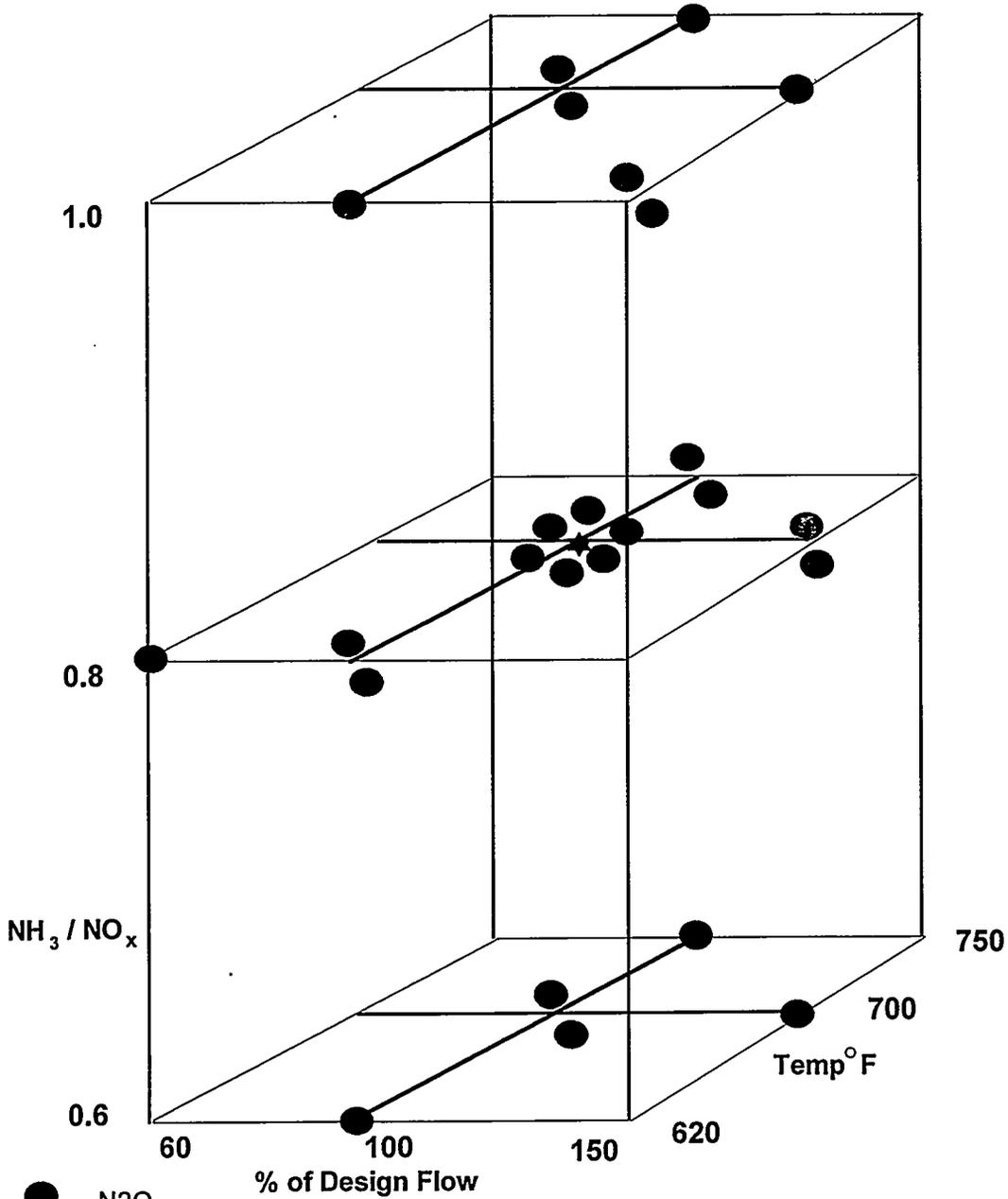
The parametric test results characterizing the performance for reactors A - J for the fifth parametric sequence are discussed in the following sections. This test series was abbreviated due to the short window of operations available for this final test sequence. Tests were chosen based on their value to the overall test program. The parametric tests conducted are composed of 14 reactor operating conditions defined by variations in the flue gas flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio. The test conditions for the fifth parametric sequence are shown graphically in Figure 5.3.5-1 and in tabular format in Table 5.3.5-1. The particular measurements that were performed (intermediate ammonia, slip ammonia, SO<sub>2</sub>, SO<sub>3</sub>, HCl, N<sub>2</sub>O, and velocity profiles) are shown at the various test conditions. Although identical test conditions are indicated, the measurements were not taken simultaneously (e.g., ammonia and SO<sub>2</sub> data for the same conditions were not collected during the exact same test run, but rather under similar process conditions at different times). Tables 5.3.5-2 through 9 show the fifth parametric test data on intermediate ammonia, slip ammonia, and sulfur dioxide oxidation for reactors A - J, respectively. Appendix M contains the detailed data spreadsheets for this parametric sequence. This parametric sequence was abbreviated due to the limited time available for testing prior to the conclusion of the project.

Table 5.3.5-1 Parametric Test Conditions (5th Parametric Sequence - Abbreviated)

| Flue gas flow rate<br>Large / Small reactor<br>(KSCFM) | Flue gas<br>temperature<br>(°F) | NH <sub>3</sub> /NO <sub>x</sub><br>Ratio | Measurements   |
|--|---------------------------------|---|--|
| 3.0 / 0.24   | 620                             | 0.8                                       | slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 620                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 7.5 / 0.60   | 620                             | 1.0                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0 / 0.40   | 750                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 7.5 / 0.60   | 700                             | 0.8                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0 / 0.40   | 700                             | 0.8                                       | *Intermediate & slip NH <sub>3</sub> , SO <sub>2</sub> /SO <sub>3</sub><br>HCl concentration (reactor A only),<br>velocity profile, N <sub>2</sub> O |
| 5.0 / 0.40   | 700                             | 0.6                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0 / 0.40   | 700                             | 1.0                                       | intermediate & slip NH <sub>3</sub>  |
| 5.0 / 0.40   | 620                             | 0.6                                       | slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 620                             | 1.0                                       | slip NH <sub>3</sub>   |
| 7.5 / 0.60   | 700                             | 0.6                                       | slip NH <sub>3</sub>   |
| 7.5 / 0.60   | 700                             | 1.0                                       | slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 750                             | 0.60                                      | slip NH <sub>3</sub>   |
| 5.0 / 0.40   | 750                             | 1.0                                       | slip NH <sub>3</sub>   |

\*Design conditions

**Fig 5.3.5-1 Fifth (Final) SCR Parametric Test Plan**



- N2O
- Intermediate NH3
- SO2/SO3
- HCl (reactor A only)
- ★ Design Point - Long Term Testing
- Slip NH3
- Velocity Profile

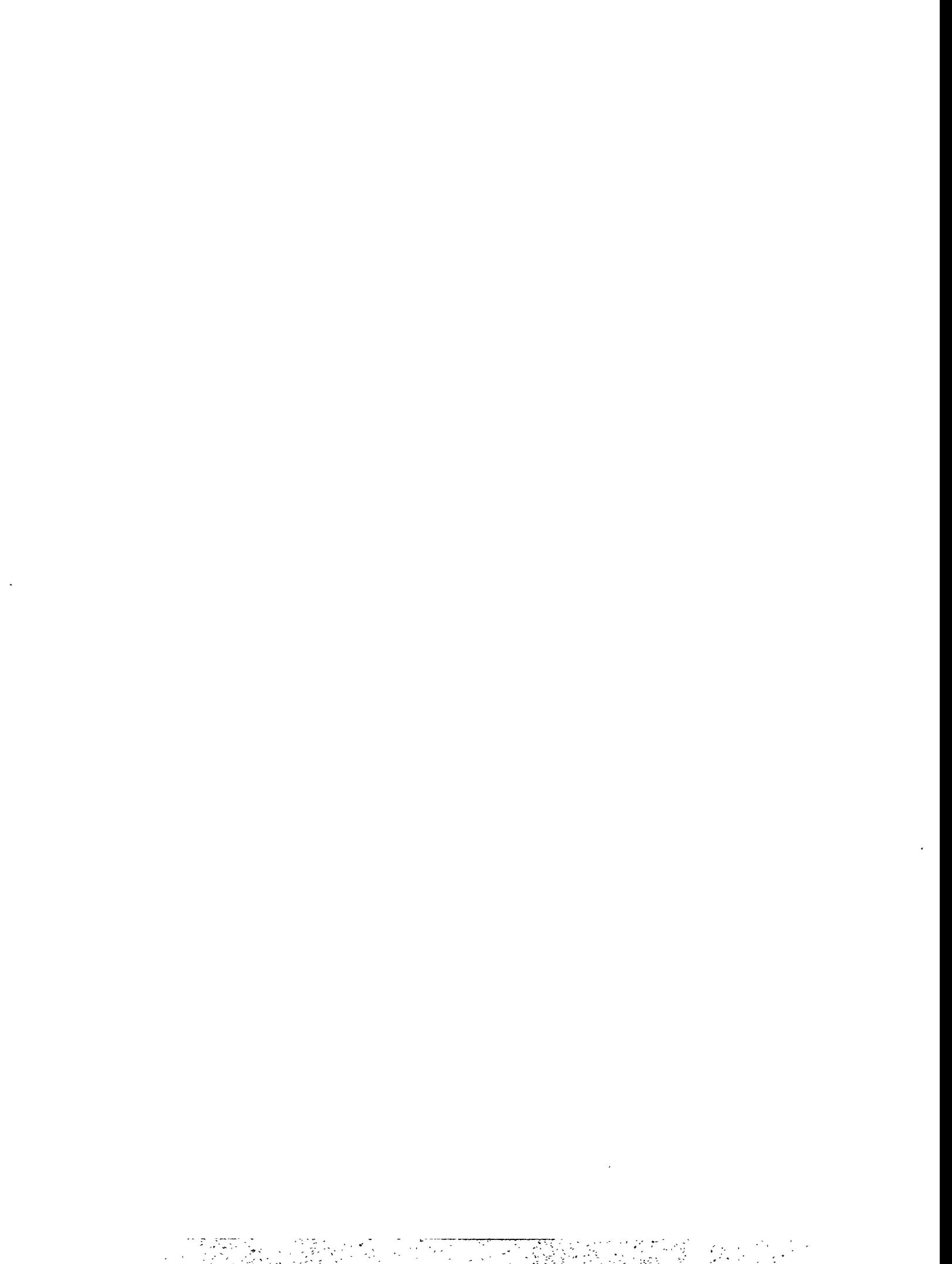


Table 5.3.5-2 Reactor A Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 5671             | 637        | 4.673                    | 286                          | 0.744                                  | 19.6                        | 67.6                          |
| 3394             | 704        | 4.353                    | 293                          | 0.748                                  | 3.6                         | 73.6                          |
| 5705             | 706        | 4.537                    | 290                          | 0.557                                  | 8.5                         | 52.8                          |
| 5462             | 706        | 5.668                    | 275                          | 0.761                                  | 13.0                        | 71.3                          |
| 5654             | 706        | 5.651                    | 338                          | 0.934                                  | 37.0                        | 82.5                          |
| 6875             | 706        | 5.651                    | 323                          | 0.741                                  | 27.5                        | 65.6                          |
| 5580             | 757        | 4.986                    | 297                          | 0.753                                  | 14.6                        | 70.4                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3172             | 623        | 4.932                    | 325                          | 0.774                                  | BDL                         |
| 5282             | 624        | 5.646                    | 328                          | 0.581                                  | BDL                         |
| 5279             | 626        | 5.395                    | 322                          | 0.773                                  | BDL                         |
| 5823             | 637        | 4.8                      | 311                          | 0.919                                  | 1.3                         |
| 6989             | 629        | 5.601                    | 304                          | 0.916                                  | 2.1                         |
| 5250             | 705        | 6.108                    | 302                          | 0.585                                  | BDL                         |
| 5216             | 702        | 6.118                    | 338                          | 0.78                                   | 3.3                         |
| 5803             | 706        | 4.931                    | 317                          | 0.923                                  | BDL                         |
| 6117             | 709        | 4.987                    | 289                          | 0.583                                  | BDL                         |
| 6015             | 703        | 5.939                    | 230                          | 0.58                                   | BDL                         |
| 6193             | 705        | 5.924                    | 310                          | 0.911                                  | 1.2                         |
| 5392             | 757        | 8.803                    | 294                          | 0.575                                  | BDL                         |
| 5409             | 757        | 9.239                    | 293                          | 0.771                                  | BDL                         |
| 5829             | 756        | 4.873                    | 301                          | 0.92                                   | 1.3                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 4781             | 705       | 4.037                     | 1065                         | 0.785                                  | 0.8                      | 6.7                 | 5.9                           | 0.55           |

Table 5.3.5-3 Reactor B Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 5191             | 627        | 4.687                    | 349                          | 0.797                                  | 46.9                        | 66.3                          |
| 3121             | 707        | 4.851                    | 347                          | 0.794                                  | 10.9                        | 76.3                          |
| 5200             | 706        | 3.761                    | 308                          | 0.596                                  | 19.1                        | 53.5                          |
| 5155             | 703        | 4.04                     | 305                          | 0.797                                  | 32.3                        | 69.1                          |
| 5205             | 707        | 3.678                    | 302                          | 0.992                                  | 45.3                        | 84.2                          |
| 6750             | 707        | 3.718                    | 304                          | 0.795                                  | 40.3                        | 66.3                          |
| 5164             | 753        | 6.275                    | 296                          | 0.879                                  | 26.2                        | 79.1                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3046             | 621        | 4.88                     | 310                          | 0.797                                  | BDL                         |
| 5067             | 626        | 3.918                    | 354                          | 0.598                                  | BDL                         |
| 5085             | 625        | 3.896                    | 347                          | 0.795                                  | BDL                         |
| 5241             | 626        | 4.239                    | 331                          | 0.993                                  | 2                           |
| 6501             | 629        | 4.035                    | 336                          | 0.992                                  | 5.1                         |
| 5068             | 705        | 6.158                    | 238                          | 0.593                                  | BDL                         |
| 5074             | 704        | 6.097                    | 337                          | 0.789                                  | BDL                         |
| 5230             | 706        | 4.129                    | 329                          | 0.994                                  | 1.1                         |
| 6148             | 709        | 3.795                    | 328                          | 0.598                                  | BDL                         |
| 6133             | 709        | 5.297                    | 320                          | 0.798                                  | BDL                         |
| 6298             | 707        | 4.448                    | 343                          | 0.991                                  | 2.2                         |
| 5096             | 756        | 4.091                    | 343                          | 0.597                                  | BDL                         |
| 5121             | 757        | 5.723                    | 364                          | 0.793                                  | BDL                         |
| 5228             | 756        | 3.325                    | 318                          | 0.997                                  | 1.4                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5190             | 706       | 5.390                     | 1046                         | 0.798                                  | 0.3                      | 0.5                 | 0.2                           | 0.01           |

Table 5.3.5-4 Reactor C Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 5392             | 632        | 4.582                    | 362                          | 0.690                                  | 41.8                        | 57.5                          |
| 3240             | 703        | 4.578                    | 346                          | 0.692                                  | 16.7                        | 64.3                          |
| 5421             | 708        | 3.518                    | 305                          | 0.515                                  | 17.3                        | 45.8                          |
| 5181             | 708        | 3.727                    | 307                          | 0.749                                  | 31.4                        | 64.7                          |
| 5434             | 707        | 3.573                    | 306                          | 0.857                                  | 56.4                        | 67.3                          |
| 7072             | 706        | 3.522                    | 325                          | 0.683                                  | 52.6                        | 52.1                          |
| 5321             | 756        | 4.081                    | 306                          | 0.712                                  | 34.5                        | 59.9                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 3073             | 624        | 6.15                     | 357                          | 0.763                                  | BDL                         |
| 5083             | 627        | 3.681                    | 382                          | 0.582                                  | 3                           |
| 5075             | 626        | 3.617                    | 380                          | 0.776                                  | 12                          |
| 5677             | 631        | 4.224                    | 321                          | 0.799                                  | 39.7                        |
| 5668             | 623        | 4.24                     | 339                          | 0.798                                  | 40.1                        |
| 5042             | 707        | 3.556                    | 335                          | 0.58                                   | 2.1                         |
| 5048             | 707        | 3.294                    | 334                          | 0.787                                  | 5                           |
| 5698             | 707        | 3.594                    | 330                          | 0.795                                  | 24.1                        |
| 6902             | 707        | 4.223                    | 342                          | 0.591                                  | 5.6                         |
| 6933             | 705        | 4.706                    | 381                          | 0.771                                  | 11.6                        |
| 5604             | 708        | 4.074                    | 342                          | 0.648                                  | 29.9                        |
| 5103             | 756        | 4.675                    | 384                          | 0.577                                  | 2.7                         |
| 5103             | 756        | 4.463                    | 385                          | 0.77                                   | 5.4                         |
| 5662             | 756        | 4.272                    | 312                          | 0.799                                  | 9.3                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 5996             | 705       | 5.240                     | 1027                         | 0.676                                  | 1.1                      | 7.1                 | 6.0                           | 0.59           |

Table 5.3.5-5 Reactor D Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 352              | 625        | 4.714                    | 319                          | 0.788                                  | 93.2                        | 49.6                          |
| 217              | 700        | 5.379                    | 281                          | 0.787                                  | 48.4                        | 61.5                          |
| 352              | 704        | 6.903                    | 327                          | 0.593                                  | 45.3                        | 45.4                          |
| 363              | 704        | 4.287                    | 321                          | 0.789                                  | 63.3                        | 59.2                          |
| 354              | 698        | 4.885                    | 324                          | 0.990                                  | 87.3                        | 72.1                          |
| 469              | 706        | 5.701                    | 319                          | 0.790                                  | 79.4                        | 54.1                          |
| 343              | 756        | 4.623                    | 340                          | 0.790                                  | 74.1                        | 57.2                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 225              | 624        | 4.529                    | 301                          | 0.801                                  | 0.8                         |
| 378              | 625        | 4.751                    | 345                          | 0.597                                  | 1.7                         |
| 374              | 626        | 3.881                    | 327                          | 0.809                                  | 4.8                         |
| 330              | 624        | 4.274                    | 322                          | 0.979                                  | 11.3                        |
| 490              | 625        | 4.699                    | 238                          | 0.989                                  | 29.7                        |
| 382              | 706        | 5.141                    | 231                          | 0.608                                  | 1.4                         |
| 385              | 706        | 6.02                     | 339                          | 0.793                                  | 2.6                         |
| 328              | 703        | 5.06                     | 319                          | 0.989                                  | 3.9                         |
| 506              | 708        | 4.185                    | 338                          | 0.597                                  | 3.9                         |
| 563              | 705        | 4.49                     | 335                          | 0.795                                  | 8.2                         |
| 481              | 705        | 4.673                    | 338                          | 0.988                                  | 16.1                        |
| 367              | 755        | 5.548                    | 364                          | 0.597                                  | 1.3                         |
| 365              | 755        | 5.303                    | 365                          | 0.801                                  | 2.2                         |
| 329              | 757        | 4.565                    | 307                          | 0.979                                  | 3.9                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 402              | 707       | 7.330                     | 840                          | 0.751                                  | 3.0                      | 0.9                 | -2.1                          | -0.25          |

Table 5.3.5-6 Reactor E Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED.(%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|------------------------------|
| 429              | 621        | 4.357                    | 309                          | 0.665                                  | 13.7                        | 62.0                         |
| 259              | 706        | 4.673                    | 311                          | 0.664                                  | 4.6                         | 64.9                         |
| 433              | 706        | 4.570                    | 329                          | 0.490                                  | 10.2                        | 45.9                         |
| 416              | 705        | 3.982                    | 339                          | 0.693                                  | 12.1                        | 65.7                         |
| 439              | 705        | 4.818                    | 349                          | 0.804                                  | 20.7                        | 74.4                         |
| 609              | 704        | 4.404                    | 351                          | 0.643                                  | 30.7                        | 55.6                         |
| 433              | 756        | 5.514                    | 325                          | 0.638                                  | 11.3                        | 60.4                         |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 253              | 624        | 4.619                    | 331                          | 0.714                                  | BDL                         |
| 416              | 625        | 4.2                      | 345                          | 0.555                                  | BDL                         |
| 415              | 625        | 4.11                     | 348                          | 0.725                                  | BDL                         |
| 452              | 627        | 4.357                    | 387                          | 0.615                                  | 0.8                         |
| 672              | 627        | 4.116                    | 335                          | 0.728                                  | 3.1                         |
| 413              | 704        | 5.386                    | 249                          | 0.553                                  | BDL                         |
| 405              | 702        | 5.651                    | 343                          | 0.748                                  | 0.8                         |
| 448              | 706        | 4.286                    | 326                          | 0.735                                  | BDL                         |
| 569              | 705        | 3.461                    | 339                          | 0.549                                  | 0.7                         |
| 563              | 704        | 4.727                    | 334                          | 0.74                                   | 0.8                         |
| 612              | 706        | 4.385                    | 344                          | 0.725                                  | 2.2                         |
| 426              | 756        | 4.493                    | 367                          | 0.457                                  | BDL                         |
| 425              | 756        | 4.384                    | 376                          | 0.608                                  | BDL                         |
| 449              | 756        | 3.402                    | 315                          | 0.74                                   | BDL                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 502              | 706       | 9.422                     | 849                          | 0.760                                  | 3.5                      | 3.2                 | -0.3                          | -0.04          |

Table 5.3.5-7 Reactor F Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 394              | 624        | 6.137                    | 310                          | 0.616                                  | 67.6                        | 39.8                          |
| 243              | 704        | 6.776                    | 276                          | 0.656                                  | 26.0                        | 56.1                          |
| 393              | 705        | 5.219                    | 276                          | 0.456                                  | 29.8                        | 34.9                          |
| 396              | 706        | 3.686                    | 335                          | 0.685                                  | 45.9                        | 54.8                          |
| 398              | 706        | 6.324                    | 316                          | 0.767                                  | 52.4                        | 60.1                          |
| 589              | 706        | 5.755                    | 326                          | 0.618                                  | 79.3                        | 37.5                          |
| 394              | 754        | 5.219                    | 277                          | 0.607                                  | 38.4                        | 46.9                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 240              | 626        | 4.23                     | 375                          | 0.688                                  | BDL                         |
| 397              | 623        | 3.932                    | 343                          | 0.542                                  | 0.8                         |
| 397              | 626        | 3.907                    | 342                          | 0.729                                  | 1.4                         |
| 390              | 628        | 6.57                     | 278                          | 0.721                                  | 1.5                         |
| 586              | 624        | 5.729                    | 305                          | 0.715                                  | 9.7                         |
| 397              | 704        | 3.752                    | 378                          | 0.526                                  | 1.1                         |
| 398              | 706        | 6.13                     | 353                          | 0.738                                  | 1.2                         |
| 391              | 705        | 5.814                    | 279                          | 0.718                                  | 0.9                         |
| 596              | 706        | 3.404                    | 331                          | 0.536                                  | 2.5                         |
| 596              | 706        | 3.926                    | 334                          | 0.71                                   | 4                           |
| 580              | 709        | 5.228                    | 296                          | 0.728                                  | 4.2                         |
| 397              | 754        | 4.053                    | 327                          | 0.549                                  | 1.1                         |
| 397              | 755        | 3.996                    | 341                          | 0.721                                  | 1.3                         |
| 392              | 756        | 5.952                    | 303                          | 1.341                                  | 1.4                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 421              | 706       | 7.702                     | 833                          | 0.752                                  | 3.4                      | 0.8                 | -2.6                          | -0.32          |

Table 5.3.5-8 Reactor G Data (5th Parametric Sequence)

INTERMEDIATE AMMONIA PARAMETRIC TEST DATA

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 470              | 624        | 4.581                    | 322                          | 0.568                                  | 71.6                        | 34.5                          |
| 291              | 707        | 4.496                    | 310                          | 0.551                                  | 23.0                        | 47.7                          |
| 478              | 703        | 6.710                    | 333                          | 0.409                                  | 26.4                        | 32.9                          |
| 464              | 708        | 4.296                    | 298                          | 0.582                                  | 39.3                        | 45.1                          |
| 479              | 696        | 4.442                    | 332                          | 0.682                                  | 59.0                        | 50.4                          |
| 617              | 711        | 5.271                    | 317                          | 0.512                                  | 45.2                        | 36.9                          |
| 492              | 753        | 4.764                    | 343                          | 0.508                                  | 41.4                        | 38.7                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 272              | 624        | 5.21                     | 368                          | 0.622                                  | BDL                         |
| 443              | 624        | 4.256                    | 325                          | 0.489                                  | BDL                         |
| 445              | 625        | 4.168                    | 338                          | 0.65                                   | 0.7                         |
| 518              | 623        | 5.218                    | 324                          | 0.558                                  | 2.1                         |
| 665              | 629        | 5.075                    | 320                          | 0.542                                  | 5.5                         |
| 437              | 704        | 4.165                    | 337                          | 0.501                                  | BDL                         |
| 438              | 705        | 4.158                    | 337                          | 0.661                                  | 0.7                         |
| 531              | 709        | 4.903                    | 325                          | 0.534                                  | 2                           |
| 624              | 706        | 3.967                    | 361                          | 0.451                                  | 2.3                         |
| 649              | 706        | 4.059                    | 372                          | 0.623                                  | 5.1                         |
| 460              | 740        | 6.626                    | 360                          | 0.45                                   | BDL                         |
| 455              | 754        | 6.028                    | 356                          | 0.609                                  | 0.8                         |
| 533              | 756        | 4.849                    | 301                          | 0.539                                  | 2.7                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 523              | 706       | 10.026                    | 794                          | 0.695                                  | 4.2                      | 0.2                 | -4.0                          | -0.51          |

Table 5.3.5-9 Reactor J Data (5th Parametric Sequence)

Intermediate Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | INT. NH <sub>3</sub> (ppmv) | INT. NO <sub>x</sub> RED. (%) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|-------------------------------|
| 411              | 624        | 7.823                    | 220                          | 0.609                                  | 7.0                         | 57.7                          |
| 252              | 706        | 9.672                    | 192                          | 0.588                                  | 2.9                         | 57.3                          |
| 427              | 706        | 7.852                    | 232                          | 0.426                                  | 4.4                         | 40.7                          |
| 417              | 706        | 8.243                    | 225                          | 0.564                                  | 6.0                         | 53.7                          |
| 423              | 704        | 8.096                    | 243                          | 0.638                                  | 10.5                        | 59.4                          |
| 563              | 704        | 7.075                    | 234                          | 0.510                                  | 12.9                        | 45.5                          |
| 417              | 754        | 8.124                    | 223                          | 0.557                                  | 6.5                         | 52.7                          |

Slip Ammonia Parametric Test Data

| FLOW RATE (SCFM) | TEMP. (°F) | INLET O <sub>2</sub> (%) | INLET NO <sub>x</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SLIP NH <sub>3</sub> (ppmv) |
|------------------|------------|--------------------------|------------------------------|--|-----------------------------|
| 236              | 624        | 9.982                    | 211                          | 0.648                                  | 0.5                         |
| 403              | 625        | 8.285                    | 229                          | 0.471                                  | 0.6                         |
| 403              | 624        | 8.309                    | 234                          | 0.619                                  | 0.8                         |
| 447              | 622        | 7.649                    | 255                          | 0.382                                  | 1.5                         |
| 561              | 625        | 6.623                    | 233                          | 0.534                                  | 3.7                         |
| 404              | 706        | 7.671                    | 223                          | 0.47                                   | BDL                         |
| 403              | 707        | 7.677                    | 225                          | 0.63                                   | 0.5                         |
| 453              | 707        | 6.929                    | 238                          | 0.538                                  | 1.8                         |
| 552              | 705        | 7.673                    | 231                          | 0.467                                  | 0.7                         |
| 537              | 753        | 7.667                    | 224                          | 0.615                                  | 0.9                         |
| 552              | 706        | 5.925                    | 235                          | 0.538                                  | 2.8                         |
| 407              | 756        | 7.667                    | 208                          | 0.458                                  | BDL                         |
| 405              | 753        | 7.665                    | 211                          | 0.603                                  | 0.6                         |
| 452              | 756        | 6.378                    | 308                          | 0.4                                    | 1.9                         |

Sulfur Dioxide Oxidation Parametric Test Data

| FLOW RATE (SCFM) | TEMP (°F) | OUTLET O <sub>2</sub> (%) | INLET SO <sub>2</sub> (ppmv) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | MEAS. SO <sub>3</sub> IN | SO <sub>3</sub> OUT | SO <sub>3</sub> formed (ppmv) | OXID. RATE (%) |
|------------------|-----------|---------------------------|------------------------------|--|--------------------------|---------------------|-------------------------------|----------------|
| 517              | 708       | 9.920                     | 904                          | 0.477                                  | 4.7                      | 6.3                 | 1.6                           | 0.18           |

### Intermediate NO<sub>x</sub> Reduction

The intermediate ammonia measurements were made after the first catalyst bed and at conditions thought to give the best kinetic information. The NO<sub>x</sub> removals reported with the intermediate ammonia measurements were computed from the measured ammonia concentrations using a material balance which assumed a 1:1 stoichiometry for the reaction of ammonia and NO<sub>x</sub>. Thus, the moles of ammonia consumed equaled the moles of NO<sub>x</sub> reduced, from which NO<sub>x</sub> reduction was computed, after oxygen corrections were made.

### Ammonia Slip

The ammonia slip data given in Tables 5.3.5-2 through 9 are presented below in three sets of plots: ammonia slip versus each of flow rate, ammonia-to-NO<sub>x</sub> ratio, and temperature. Due to drifts in calibrations in the ammonia and flue gas flow controllers, some actual test conditions differ from the values given in Table 5.3.5-1. Also, since the degree of drift varied from reactor to reactor the plots at the end of this section should not be used as a direct comparison of catalysts' performance.

Figures 5.3.5-2 through 9 show ammonia slip versus flow rate for reactors A - J, respectively. Refer to individual plots for reactor test conditions. As expected, the trends show increasing ammonia slip with increasing reactor flow rate. In general, the ammonia slip is relatively minor indicating the ability of the catalyst designs to withstand significant increases in flow while maintaining ammonia slip limits. For reactor D, the Grace Synox catalyst reactor, a relatively significant increase in ammonia slip is noted with flow rate. However, the set point for NO<sub>x</sub> reduction was near 100%, and the ammonia slip is not likely to be nearly as significant at lower NO<sub>x</sub> removal rates. Overall, as in previous sequences, these plots demonstrate the ability of an SCR system to follow load variations dictated by the host boiler while maintaining design specifications.

Figures 5.3.5-10 through 17 show ammonia slip versus ammonia-to-NO<sub>x</sub> ratio for reactors A - J, respectively. Refer to individual plots for reactor test conditions. These plots show slight increases in ammonia slip as the ammonia-to-NO<sub>x</sub> ratio increases from 0.5 to 0.8. This finding is in keeping with published data of this type. At ammonia-to-NO<sub>x</sub> ratios near 1.0, non-idealities in the reactor systems forced the catalysts to slip higher concentrations of ammonia since areas were presented in the reactors where NO<sub>x</sub> was the limiting reagent.

Ammonia slip versus temperature is plotted in Figures 5.3.5-18 through 25 for reactors A - J, respectively. Refer to individual plots for reactor test conditions. Some improvements (decrease) in ammonia slip is noted between 620 and 700 °F, likely due to improvements in the kinetic reaction rate with increasing temperature. In general, only slight improvements are noted with increasing temperatures above 700 °F. In the cases of Figures 5.3.5-19 and 23 (reactors B and F), a slight increase is shown between the 700 and 750 °F points, however, this is likely due to measurement variability and is not considered significant. In these cases, the plots should not be construed as demonstrating increases in ammonia slip with increasing temperature above 700 °F. It is expected that the 700 and 750 °F values are roughly equivalent which may be due in part to mass transfer limitations that become controlling at these higher temperatures. In Figures 5.3.18 and 22 (reactors A and E) the trend of the plots is unclear since all values were at or below the ammonia slip detection limit. (The detection limit for ammonia slip was roughly 1 ppmv; values below the detection limit are plotted as zero.) Overall, these plots demonstrate that in terms of ammonia slip, significant improvements are not realized with temperatures above 700 °F. Losses in boiler efficiency would probably outweigh any improvements that may be obtained in ammonia slip by designing an SCR reactor to operate at temperatures near 750 °F.

## SO<sub>2</sub> Oxidation

Table 5.3.5-10 shows a summary of SO<sub>2</sub> oxidation data for reactors A - J. In some cases there was an apparent loss in sulfur trioxide across the reactors. It is believed that the apparent loss was caused by phenomena such as acid condensation and the formation of ammonium bisulfate on cold spots at the reactor surfaces. The SO<sub>2</sub> oxidation data is corrected to reactor outlet oxygen concentrations. The value for sulfur trioxide produced in the reactors is based on measured inlet and outlet sulfur trioxide concentration values (tables showing SO<sub>2</sub> oxidation rates quote reactor flow rates as calculated for the reactor exits, since outlet SO<sub>3</sub> was measured at this point).

Table 5.3.5-10 SO<sub>2</sub> Oxidation

| Reactor (Catalyst)                   | Flue Gas Temperature (°F) | Flue Gas Flow Rate (SCFM) | NH <sub>3</sub> /NO <sub>x</sub> Ratio | SO <sub>2</sub> Oxidation (%) |
|--------------------------------------|---------------------------|---------------------------|--|-------------------------------|
| Reactor A (Grace N <sub>x</sub> rm.) | 705                       | 4781                      | 0.785                                  | 0.55                          |
| Reactor B (NSKK)                     | 706                       | 5190                      | 0.798                                  | 0.01                          |
| Reactor C (Siemens)                  | 705                       | 5996                      | 0.676                                  | 0.59                          |
| Reactor D (Grace Synox)              | 707                       | 402                       | 0.751                                  | -0.25                         |
| Reactor E (Corm. HD)                 | 706                       | 502                       | 0.760                                  | -0.04                         |
| Reactor F (Haldor)                   | 706                       | 421                       | 0.752                                  | -0.32                         |
| Reactor G (Hitachi)                  | 706                       | 523                       | 0.695                                  | -0.51                         |
| Reactor J (Corm. LD)                 | 708                       | 517                       | 0.477                                  | 0.18                          |

### Additional Base-Line Measurements

Flue gas velocity profiles (nine-point for reactors A, B, C) (three-point for reactors D, E, F, G, J) were conducted near design operating conditions (700 °F, 100% flow rate) at the

reactor inlets and reactor outlets. The velocity profiles are presented in Figures 5.3.5-26 through 33 (reactor outlets) for reactors A - J, respectively. The results are given in Table 5.3.5-11 for all reactors.

For reactor A only, HCl concentrations (at 3% O<sub>2</sub>, dry) were measured at the design operating conditions before the point of ammonia injection, at the reactor inlet, and at the reactor outlet. N<sub>2</sub>O concentrations were measured for all reactors at the reactor inlets and at the reactor outlets (both measurements are dry at 3% O<sub>2</sub>). The results of these measurements are shown in Table 5.3.5-11.

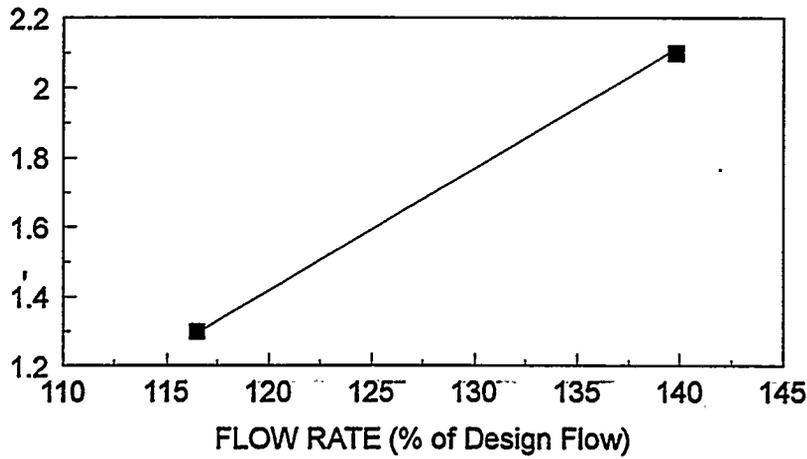
Table 5.3.5-11 Additional Base-line Measurements

| Reactor<br>(Catalyst)      | Velocity Profile<br>(ft/sec) |               | HCl concentration<br>(ppmv)    |              |               | N <sub>2</sub> O concentration<br>(ppmv) |               |
|----------------------------|------------------------------|---------------|--------------------------------|--------------|---------------|--|---------------|
|                            | rxr<br>inlet                 | rxr<br>outlet | before<br>ammonia<br>injection | rxr<br>inlet | rxr<br>outlet | rxr<br>inlet                             | rxr<br>outlet |
| Reactor A<br>(Grace Nxrm)  | 14.1 ± 1.6                   | 11.7 ± 2.1    | 184 ± 6                        | 132 ± 8      | 86 ± 16       | 2.0                                      | 1.6           |
| Reactor B<br>(NSKK)        | 13.2 ± 1.8                   | 13.0 ± 1.6    | N/A                            | N/A          | N/A           | 2.0                                      | 1.6           |
| Reactor C<br>(Siemens)     | 14.8 ± 1.4                   | 13.3 ± 0.9    | N/A                            | N/A          | N/A           | 2.0                                      | 1.6           |
| Reactor D<br>(Grace Synox) | 14.3 ± 1.3                   | 13.8 ± 1.6    | N/A                            | N/A          | N/A           | 2.0                                      | 2.1           |
| Reactor E<br>(Corm. LD)    | 16.1 ± 1.2                   | 13.0 ± 3.7    | N/A                            | N/A          | N/A           | 2.0                                      | 1.8           |
| Reactor F<br>(Haldor)      | 13.3 ± 0.4                   | 18.7 ± 2.2    | N/A                            | N/A          | N/A           | 2.0                                      | 2.2           |
| Reactor G<br>(Hitachi)     | 14.0 ± 2.7                   | 18.4 ± 1.3    | N/A                            | N/A          | N/A           | 2.0                                      | 1.6           |
| Reactor J<br>(Corm. LD)    | 17.7 ± 0.5                   | 19.4 ± 1.5    | N/A                            | N/A          | N/A           | 2.0                                      | 2.9           |

Figure 5.3.5-2

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



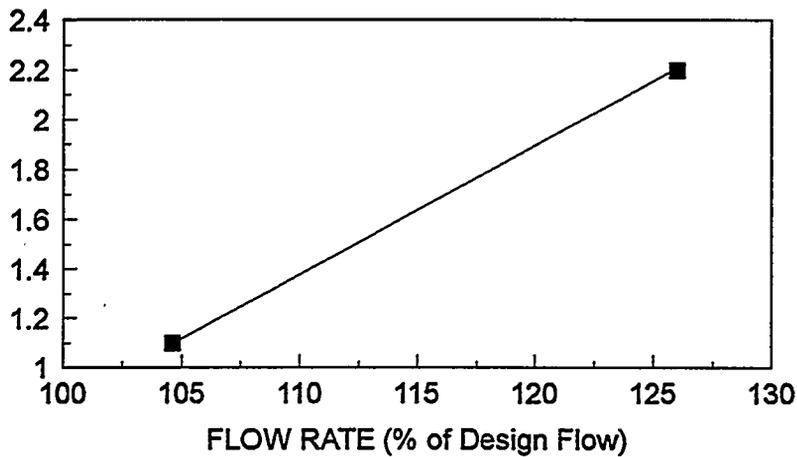
GRACE NXRM:  $\text{NH}_3/\text{NO}_x=0.90$ , 630 F

FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-3

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



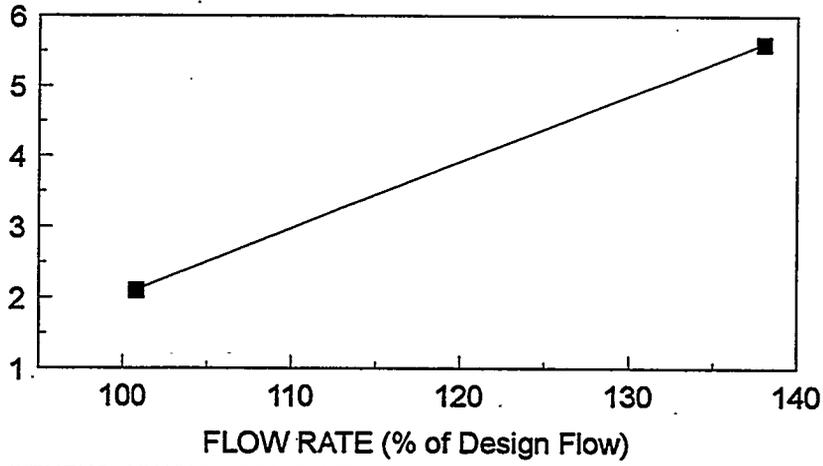
NSKK:  $\text{NH}_3/\text{NO}_x=1.00$ , 700 F

FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-4

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)

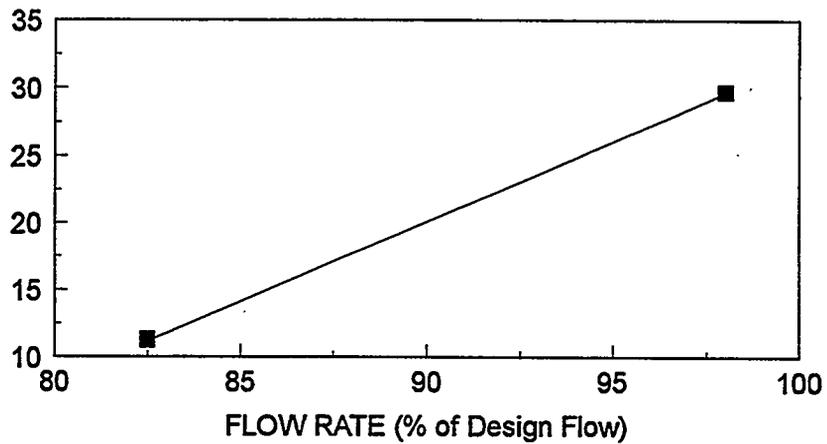


SIEMENS: NH<sub>3</sub>/NO<sub>x</sub>=0.60, 700 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-5

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)

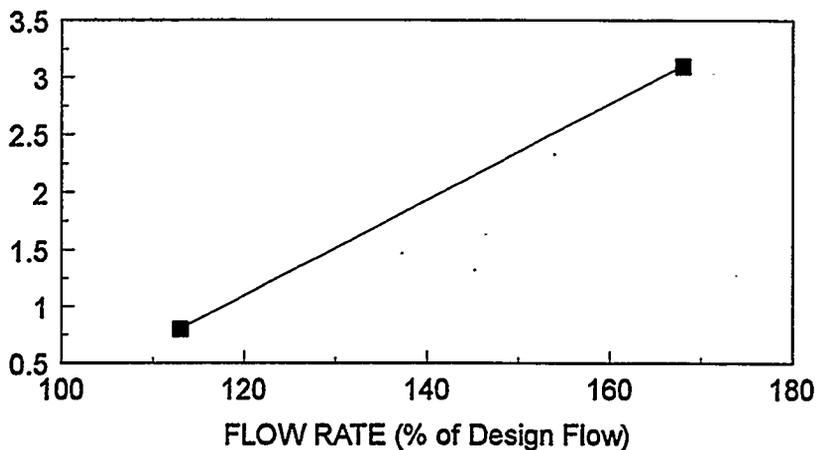


GRACE SNX: NH<sub>3</sub>/NO<sub>x</sub>=1.00, 620 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-6

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)

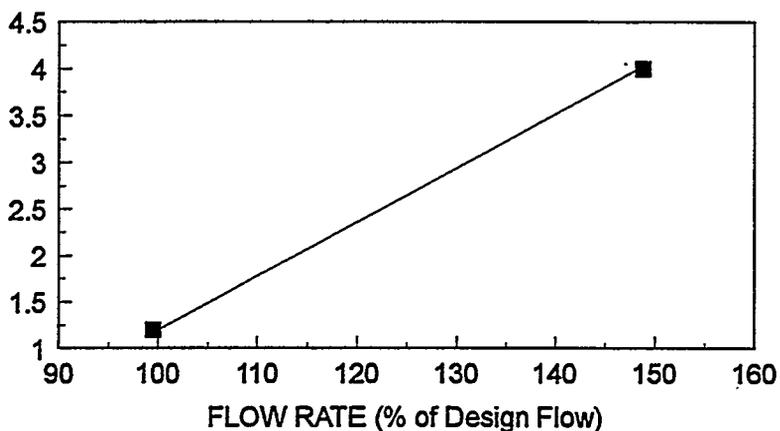


CORM HD: NH<sub>3</sub>/NO<sub>x</sub>=0.65, 625 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-7

### AMMONIA SLIP VS. FLOW RATE

AMMONIA SLIP (ppm)



HALDOR: NH<sub>3</sub>/NO<sub>x</sub>=0.70, 700 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-8

### AMMONIA SLIP VS. FLOW RATE

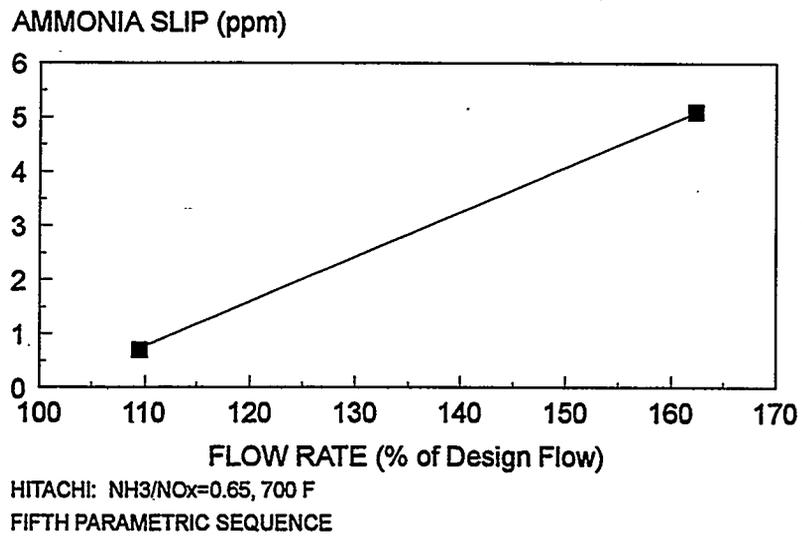


Figure 5.3.5-9

### AMMONIA SLIP VS. FLOW RATE

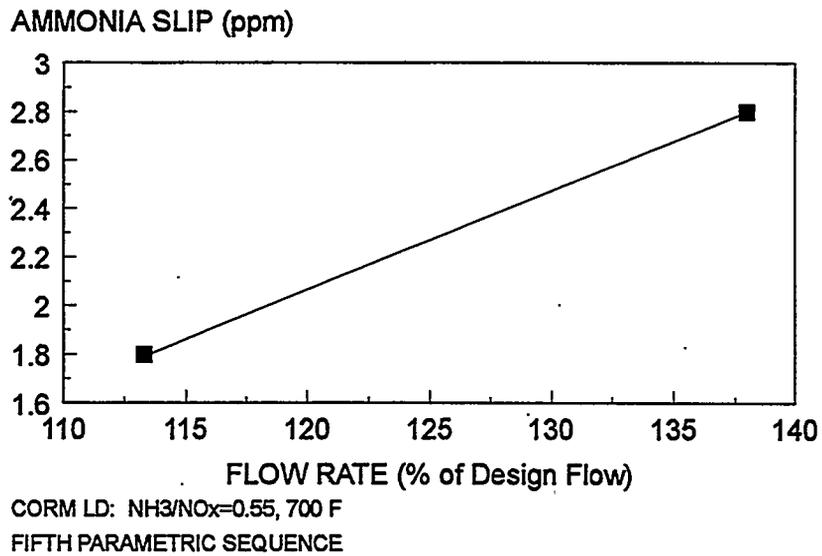
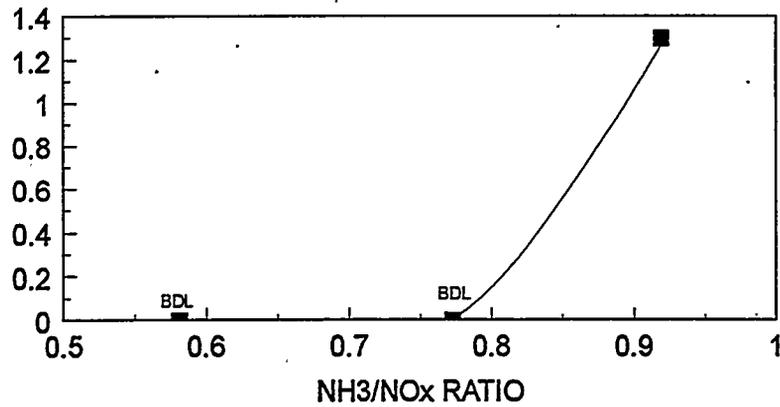


Figure 5.3.5-10

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)



GRACE NXRM: Design Flow, 620 F

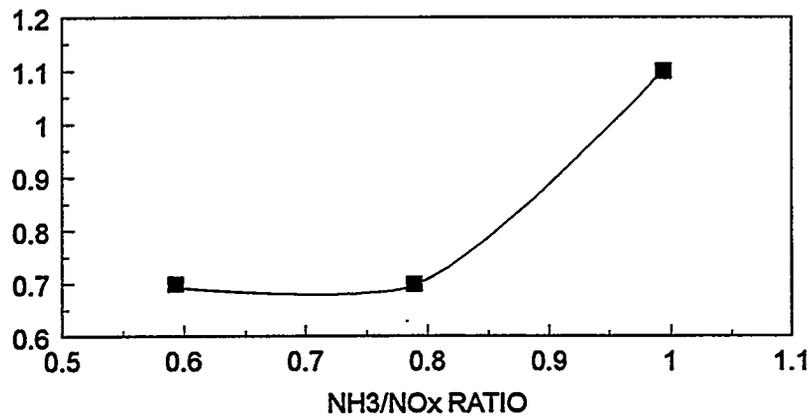
(BDL) Below lower detection limit (<1 ppmv)

FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-11

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

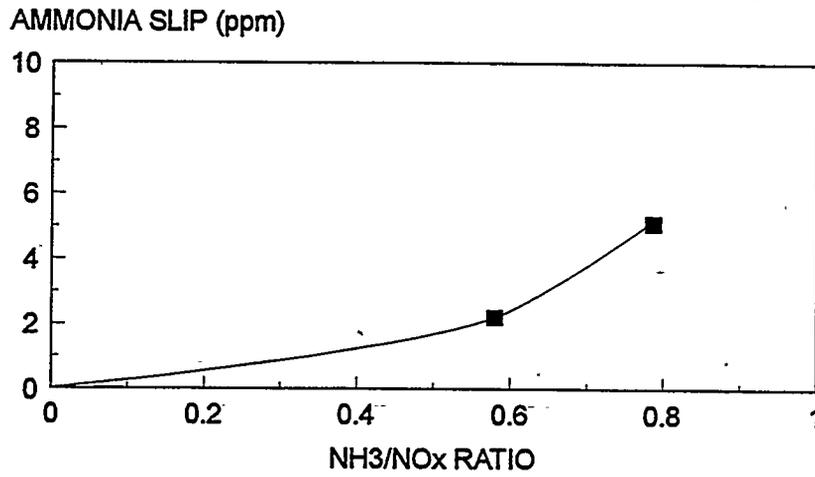


NSKK: Design Flow, 700 F

FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-12

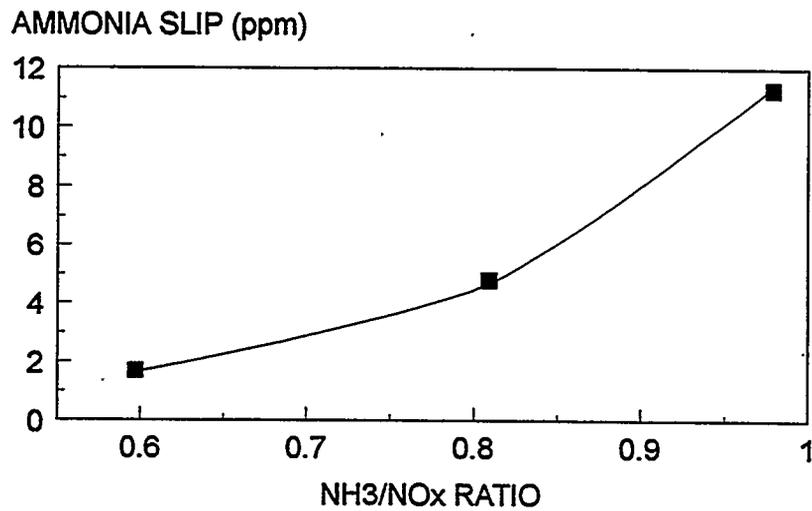
### AMMONIA SLIP VS. NH3/NOx RATIO



SIEMENS: Design Flow, 700 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-13

### AMMONIA SLIP VS. NH3/NOx RATIO

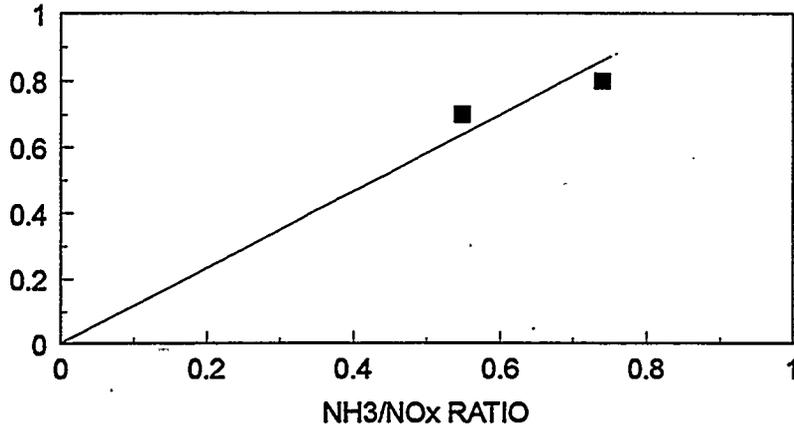


GRACE SNX: Design Flow, 620 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-14

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

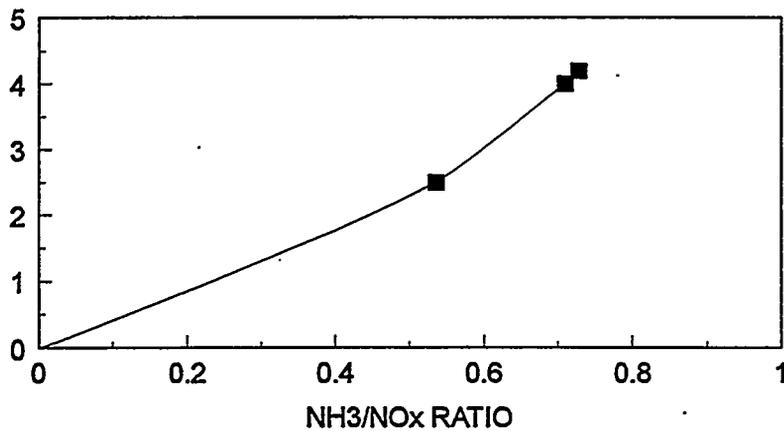


CORM HD: High Flow, 700 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-15

### AMMONIA SLIP VS. NH<sub>3</sub>/NO<sub>x</sub> RATIO

AMMONIA SLIP (ppm)

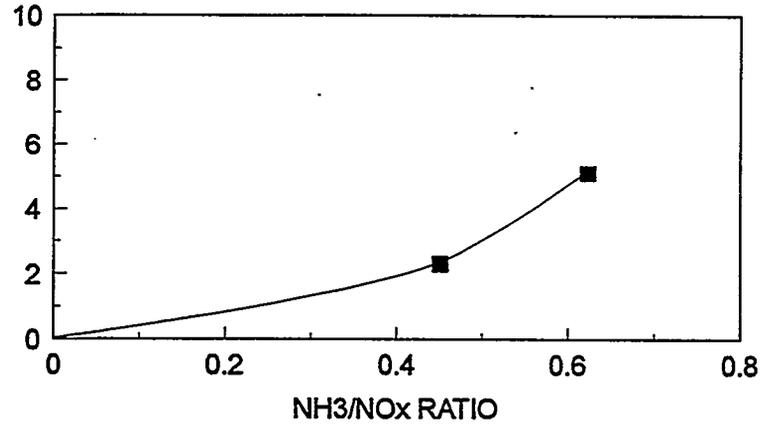


HALDOR: High Flow, 700 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-16

### AMMONIA SLIP VS. NH3/NOx RATIO

AMMONIA SLIP (ppm)

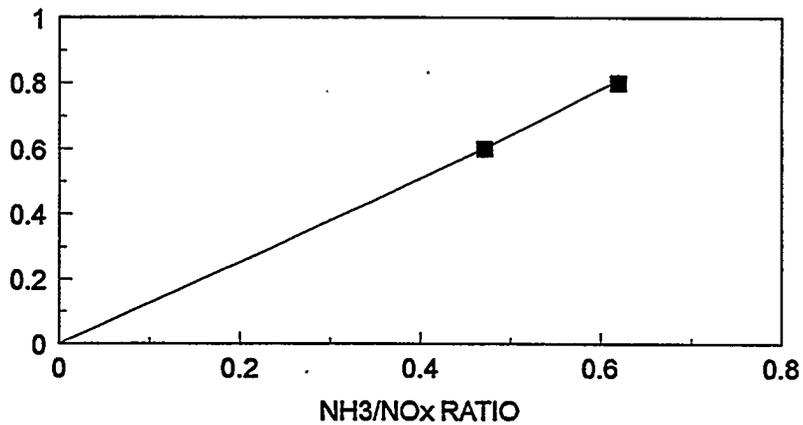


HITACHI: High Flow, 700 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-17

### AMMONIA SLIP VS. NH3/NOx RATIO

AMMONIA SLIP (ppm)

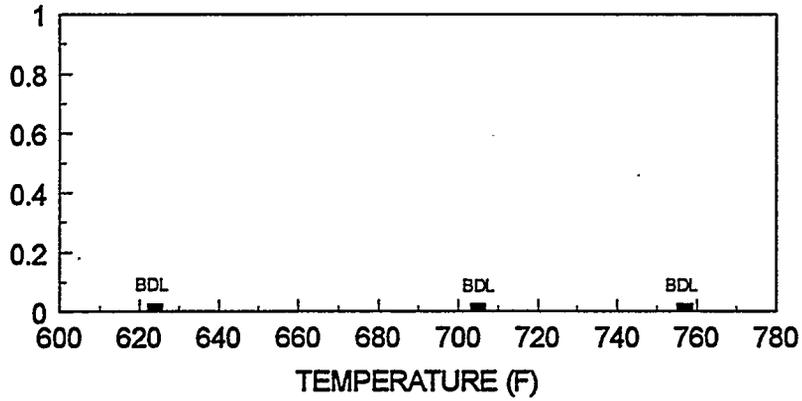


CORM LD: Design Flow, 620 F  
FIFTH PARAMETRIC SEQUENCE

Figure 5.3.5-18

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



GRACE NXRM: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.60

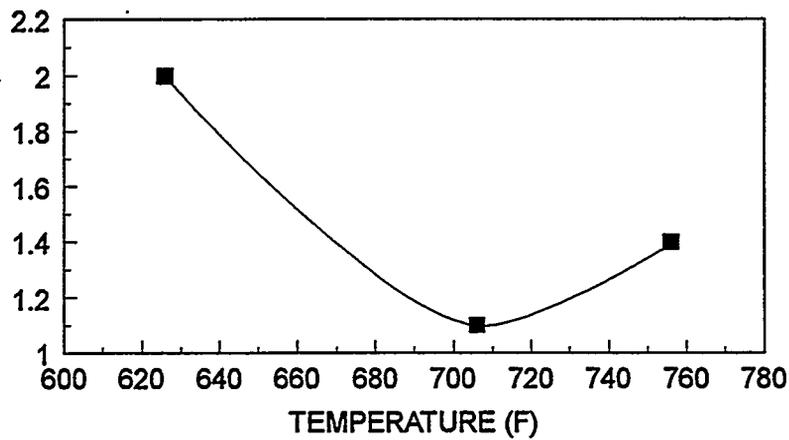
(BDL) Below lower detection limit (<1 ppmv)

Fifth Parametric Sequence

Figure 5.3.5-19

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

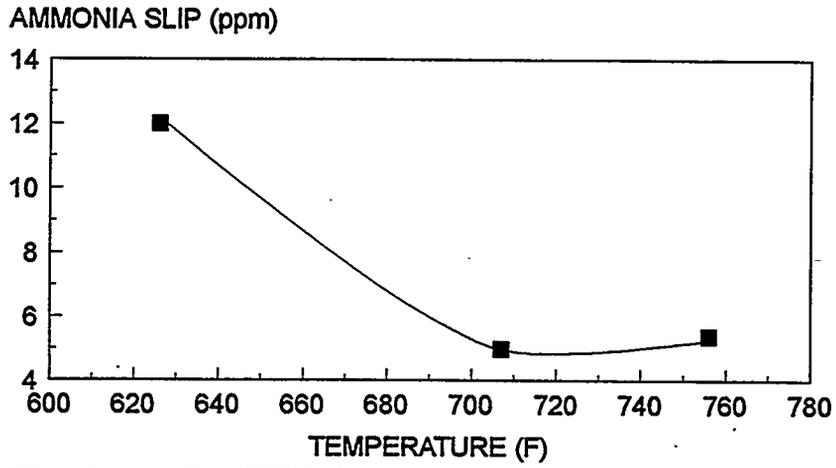


NSKK: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=1.00

Fifth Parametric Sequence

Figure 5.3.5-20

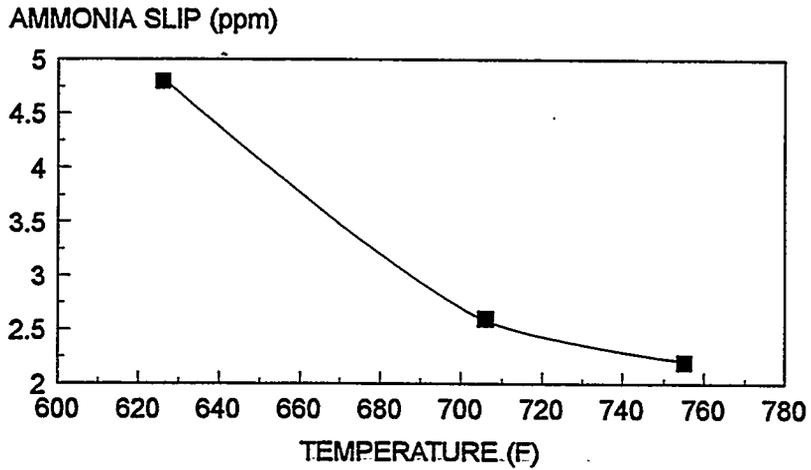
### AMMONIA SLIP VS. TEMPERATURE



SIEMENS: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.80  
Fifth Parametric Sequence

Figure 5.3.5-21

### AMMONIA SLIP VS. TEMPERATURE

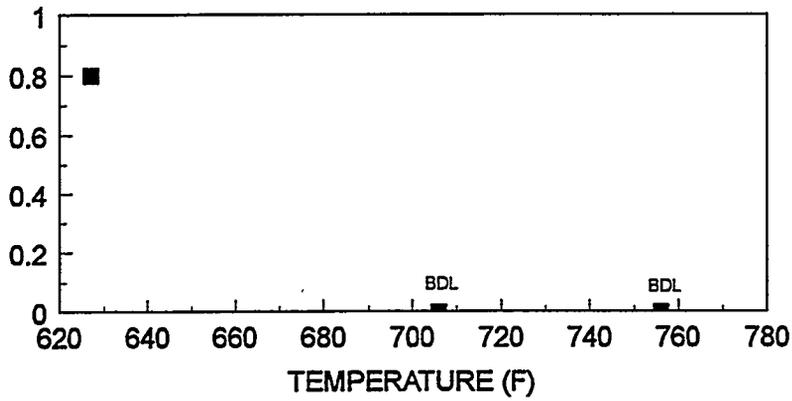


GRACE SNX: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.80  
Fifth Parametric Sequence

Figure 5.3.5-22

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



CORM HD: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.70

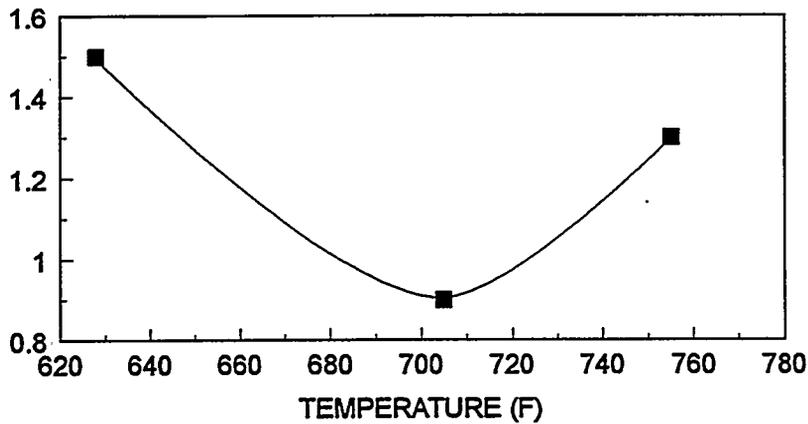
(BDL) Below lower detection limit (<1 ppmv)

Fifth Parametric Sequence

Figure 5.3.5-23

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



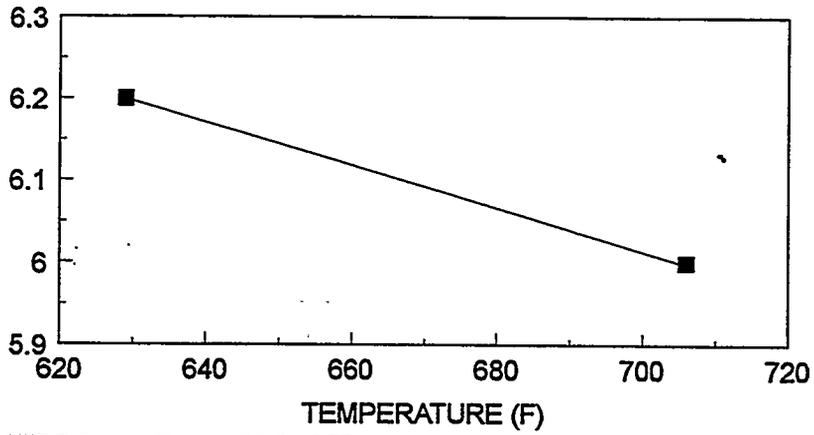
HALDOR: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.70

Fifth Parametric Sequence

Figure 5.3.5-24

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)



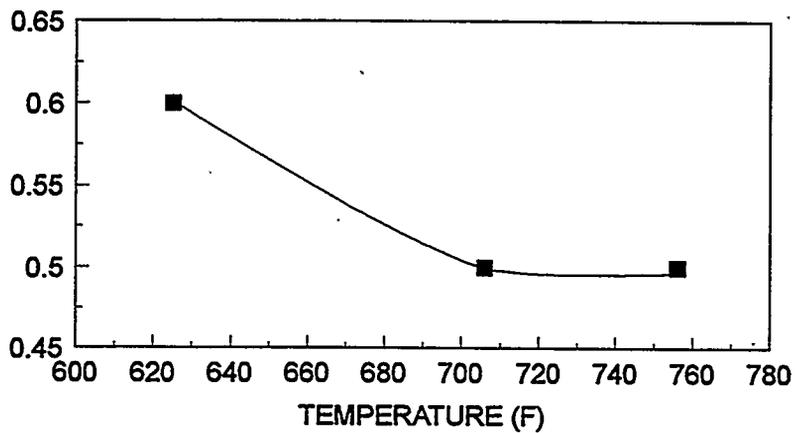
HITACHI: High Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.55

Fifth Parametric Sequence

Figure 5.3.5-25

### AMMONIA SLIP VS. TEMPERATURE

AMMONIA SLIP (ppm)

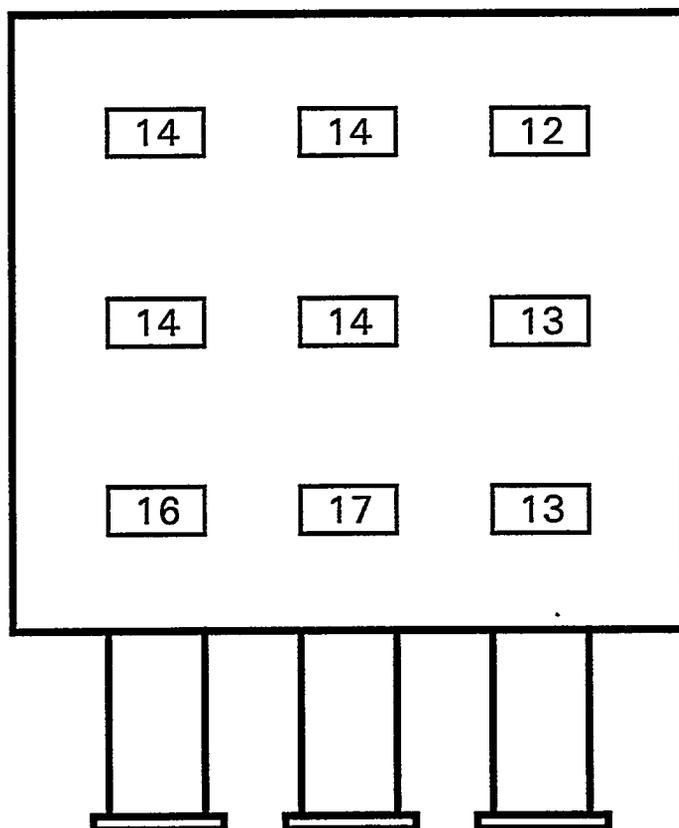


CORM LD: Design Flow, NH<sub>3</sub>/NO<sub>x</sub>=0.50

Fifth Parametric Sequence

**REACTOR A**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s

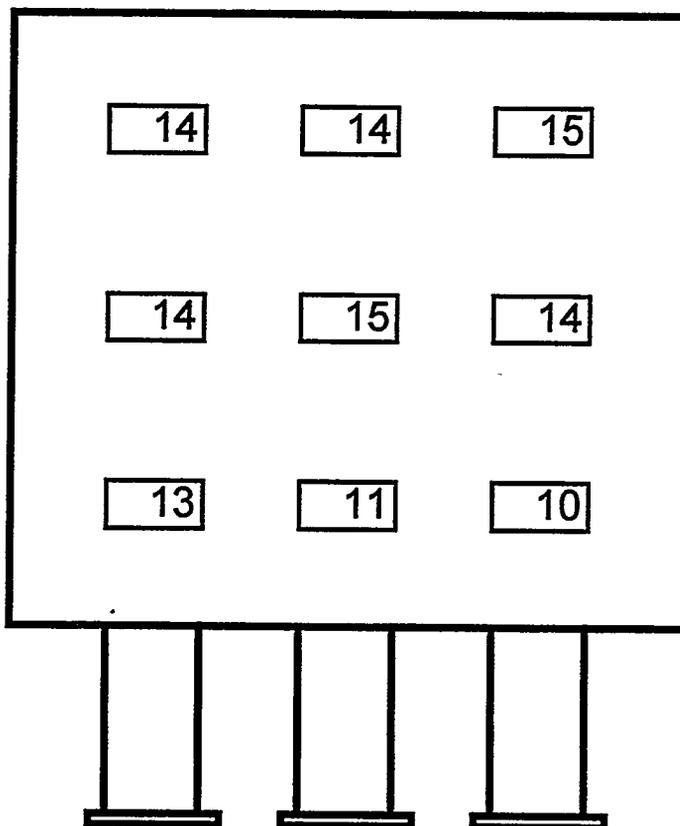


Average = 14 ft/s  
 $\sigma = 2$  ft/s

Figure 5.3.5-26  
Fifth Parametric Sequence

**REACTOR B**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s

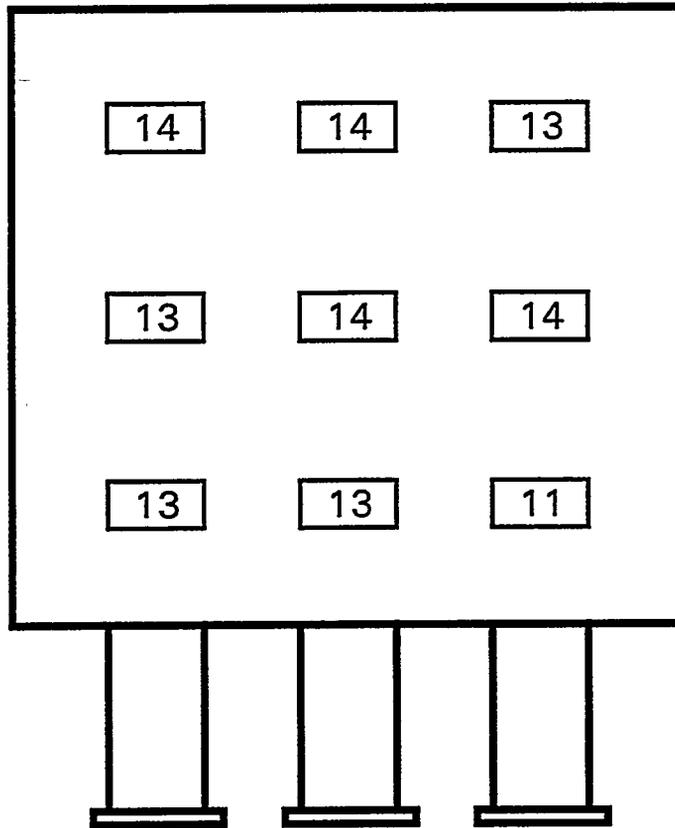


Average = 13 ft/s  
 $\sigma$  = 2 ft/s

Figure 5.3.5-27  
Fifth Parametric Sequence

**REACTOR C**  
**CATALYST LAYER 14INLET**

Velocity Profile  
ft/s

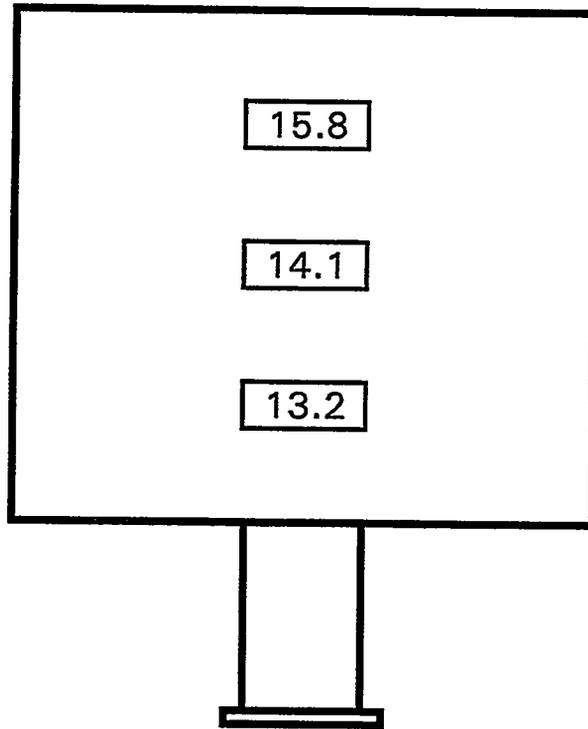


Average = 13 ft/s  
 $\sigma = 1$  ft/s

Figure 5.3.5-28  
Fifth Parametric Sequence

**REACTOR D**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s

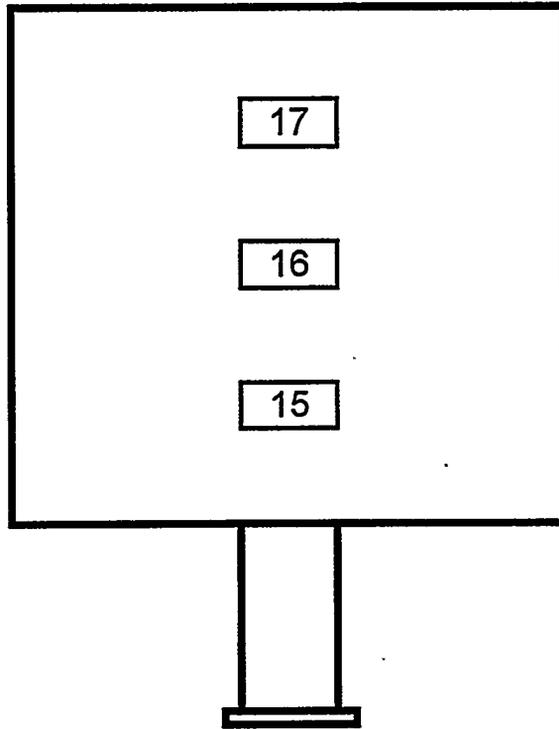


Average = 14 ft/s  
 $\sigma = 1$  ft/s

Figure 5.3.5-29  
Fifth Parametric Sequence

**REACTOR E**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s

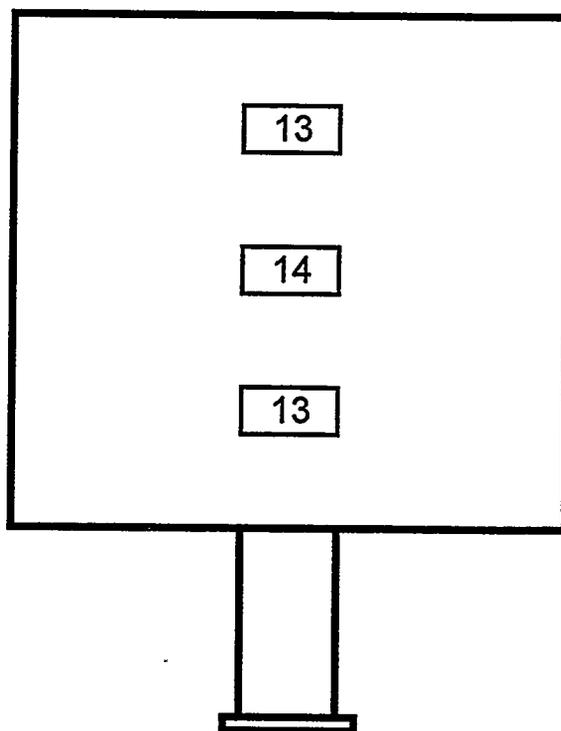


Average = 16 ft/s  
 $\sigma = 1$  ft/s

Figure 5.3.5-30  
Fifth Parametric Sequence

**REACTOR F**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s

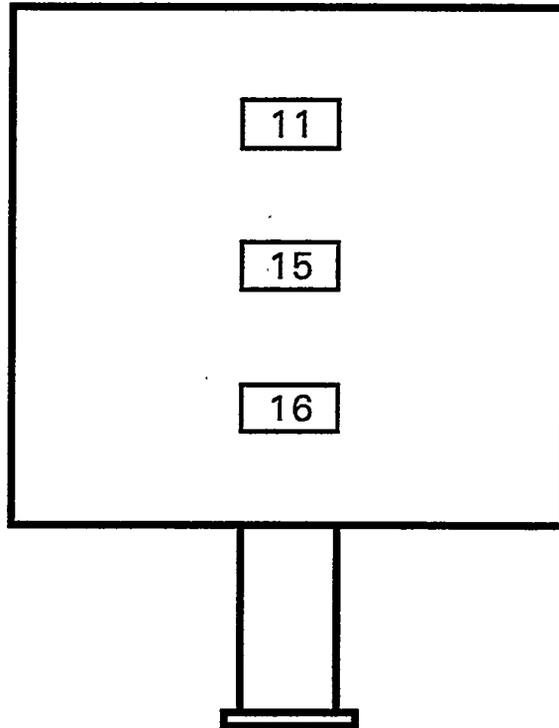


Average = 13 ft/s  
 $\sigma = 0.4$  ft/s

Figure 5.3.5-31  
Fifth Parametric Sequence

**REACTOR G**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s

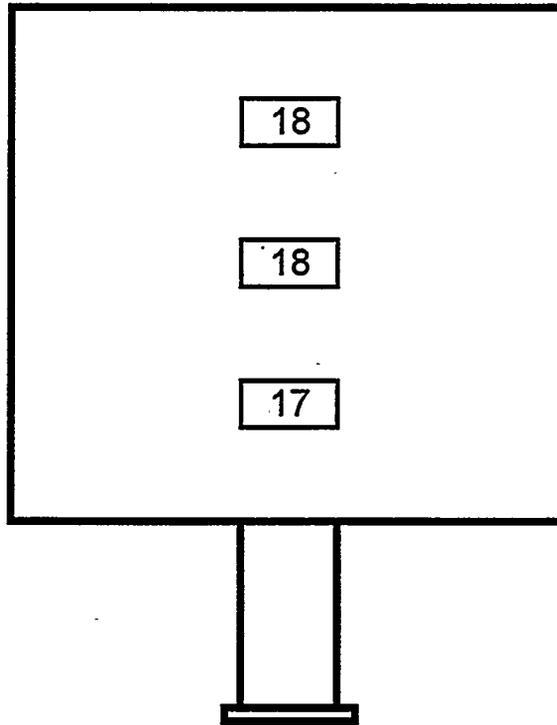


Average = 14 ft/s  
 $\sigma = 3$  ft/s

Figure 5.3.5-32  
Fifth Parametric Sequence

**REACTOR J**  
**CATALYST LAYER 1 INLET**

Velocity Profile  
ft/s



Average = 18 ft/s  
 $\sigma = 0.5$  ft/s

Figure 5.3.5-33  
Fifth Parametric Sequence

## 5.4 Parametric Tests - Summary

This section is a summary of the sequential parametric tests described previously in sections 5.3.1 through 5.3.5. The data from all parametric sequences are combined to show the overall performance of each catalyst for intermediate NO<sub>x</sub> reduction, ammonia slip, and sulfur dioxide oxidation. Also, catalyst specific and overall SCR system performance as a function of exposure time is discussed.

The catalyst suppliers were given a great deal of latitude in selecting the type and amount of catalyst that each provided for the test facility. For this reason, various parameters such as pressure drop, total surface area, and space velocity differ significantly between the catalysts installed in the test facility. Comparisons of catalyst performance should not be made directly from the following data. Rather, the information should be used to evaluate each particular catalyst's performance in terms of changes in operating conditions and the catalysts' performance as a function of exposure time. The data are most valuable in an assessment of a particular catalyst's ability to meet project specifications and its ability to maintain performance over the project life.

### Intermediate NO<sub>x</sub> Reduction

The intermediate NO<sub>x</sub> values reported in the five sequential parametric sequences were computed from intermediate ammonia concentrations using a material balance which assumed a 1:1 stoichiometry for the reaction of ammonia and NO<sub>x</sub>. Thus, the moles of ammonia consumed equaled the moles of NO<sub>x</sub> reduced, from which NO<sub>x</sub> reduction was computed, after oxygen corrections were made. Intermediate ammonia was measured after the first catalyst bed and corrected to reactor inlet oxygen concentrations. The parametric tests were composed of several operating conditions defined by variations in the flue gas flow rate, temperature, and ammonia-to-NO<sub>x</sub> ratio.

Figures 5.4-1 through 8 show base-line intermediate  $\text{NO}_x$  reduction versus exposure time for reactors A-J, respectively. Even though the graphs show base-line parametric values, slight differences in the actual ammonia-to- $\text{NO}_x$  ratios tend to mask the de $\text{NO}_x$  tendencies of the catalysts. This is especially evident in values reported for the first and fifth parametric sequences where calibration errors caused the actual ammonia-to- $\text{NO}_x$  ratios to vary significantly. For points where the ammonia-to- $\text{NO}_x$  ratios are similar, however, the intermediate  $\text{NO}_x$  reduction values are fairly consistent and show little change with respect to exposure time. Figure 5.4-9 shows intermediate  $\text{NO}_x$  reduction versus exposure time at base-line conditions for the combination of all reactors. To give a more accurate view of  $\text{NO}_x$  reduction performance, the data in this graph is edited to show only values where the actual ammonia-to- $\text{NO}_x$  ratios were at or near the design value of 0.8. As expected, there is a decrease in  $\text{NO}_x$  reduction with time, due to factors such as catalyst deactivation and plugging. The decrease, however, is slight, showing only a 3%-4% drop in  $\text{NO}_x$  reduction over the life of the project. This plot confirms the ability of an SCR system to maintain  $\text{NO}_x$  reduction performance over an extended period of operation.

Intermediate  $\text{NO}_x$  reduction for each catalyst/reactor system as an average of parametric test values is shown graphically in Figures 5.4-10 through 13 and in tabular form in Table 5.4-1. The figures show the average intermediate  $\text{NO}_x$  reduction over the project life at the denoted conditions. Also included in the figures, are the high and low values of intermediate  $\text{NO}_x$  reduction showing measurement variability. This measurement variability should not be construed as the variation of intermediate  $\text{NO}_x$  reduction with catalyst exposure time. To avoid misuse of the data, tests which had operating conditions that varied significantly from the denoted (desired) operating condition are not presented in Table 5.4-1 (denoted by N/A). These data have been omitted to prevent inapplicable comparisons of  $\text{NO}_x$  reduction between the various parametric sequences. The reported data show changes in intermediate  $\text{NO}_x$  reduction with respect to changes in flue gas flow rate, temperature, and ammonia-to- $\text{NO}_x$  ratio. Figure 5.4-10 shows average intermediate  $\text{NO}_x$  reduction for all catalyst/reactor systems at base-line conditions. The intermediate

NO<sub>x</sub> reduction varies among reactors and depends partly on the total number of catalyst beds used to achieve the overall 80% NO<sub>x</sub> reduction design criteria. Figure 5.4-11 shows average intermediate NO<sub>x</sub> reduction at NH<sub>3</sub>/NO<sub>x</sub> = 0.8, design flow rate, and low temperature. Due to decreases in the kinetic reaction rate with decreasing temperature, some loss in NO<sub>x</sub> reduction is expected at low temperature conditions. Overall, however, this loss was slight, showing little change from base-line intermediate NO<sub>x</sub> reduction values. Average intermediate NO<sub>x</sub> reduction is shown in Figure 5.4-12 at NH<sub>3</sub>/NO<sub>x</sub> = 0.8, design temperature and high flow rate. The expected trend is decreasing NO<sub>x</sub> reduction with increasing flow rate. Again, however, there is little change from base-line deNO<sub>x</sub> values. Since a portion of the overall reaction rate is due to mass transfer limitations, improvements in bulk mass transfer coefficients were likely mitigating the effects of increased flow on NO<sub>x</sub> reduction values. Figure 5.4-13 shows intermediate NO<sub>x</sub> reduction at NH<sub>3</sub>/NO<sub>x</sub> = 0.6, design temperature, and design flow rate. There was a significant decrease in NO<sub>x</sub> reduction from base-line values for all catalyst/reactor systems. Ammonia-to-NO<sub>x</sub> ratio was the most significant parametric factor in intermediate NO<sub>x</sub> reduction and changes in the ammonia-to-NO<sub>x</sub> ratio often masked changes in other parameters. Although an attempt has been made to show intermediate NO<sub>x</sub> reduction data for comparable operating conditions, this measurements is extremely sensitive to the NH<sub>3</sub>/NO<sub>x</sub> ratio. The reader is cautioned to take this into consideration when evaluating the data and to consult Appendices I through M to determine exact operating condition and measurement accuracy of specific data points.

Table 5.4-1 Average Intermediate NO<sub>x</sub> Reduction

|                       | Condition | P'metric 1<br>NO <sub>x</sub> Red.<br>(%) | P'metric 2<br>NO <sub>x</sub> Red.<br>(%) | P'metric 3<br>NO <sub>x</sub> Red.<br>(%) | P'metric 4<br>NO <sub>x</sub> Red.<br>(%) | P'metric 5<br>NO <sub>x</sub> Red.<br>(%) | Average<br>NO <sub>x</sub><br>Red.<br>(%) |
|-----------------------|-----------|---|---|---|---|---|---|
| Reactor A<br>Noxeram  | 22        | N/A                                       | 65.8                                      | 70.2                                      | 62.9                                      | 71.3                                      | 67.6                                      |
|                       | 7         | N/A                                       | N/A                                       | 68.4                                      | 67.0                                      | 67.6                                      | 67.7                                      |
|                       | 27        | N/A                                       | N/A                                       | 66.3                                      | N/A                                       | 65.6                                      | 65.9                                      |
|                       | 21        | N/A                                       | N/A                                       | 52.7                                      | 52.1                                      | 52.8                                      | 52.5                                      |
| Reactor B<br>NSKK     | 22        | N/A                                       | 69.2                                      | 66.5                                      | 71.5                                      | 69.1                                      | 69.1                                      |
|                       | 7         | N/A                                       | N/A                                       | 65.8                                      | 70.6                                      | 66.3                                      | 67.6                                      |
|                       | 27        | N/A                                       | N/A                                       | 59.1                                      | 63.4                                      | 66.3                                      | 63.0                                      |
|                       | 21        | N/A                                       | N/A                                       | 52.4                                      | 52.0                                      | 53.5                                      | 52.6                                      |
| Reactor C<br>Siemens  | 22        | N/A                                       | N/A                                       | 68.6                                      | 72.0                                      | 64.7                                      | 68.4                                      |
|                       | 7         | N/A                                       | N/A                                       | 66.6                                      | 77.5                                      | N/A                                       | 72.0                                      |
|                       | 27        | N/A                                       | N/A                                       | 65.5                                      | 65.9                                      | N/A                                       | 65.7                                      |
|                       | 21        | N/A                                       | N/A                                       | 50.8                                      | 54.6                                      | N/A                                       | 52.7                                      |
| Reactor D<br>Synox    | 22        | N/A                                       | N/A                                       | N/A                                       | 51.6                                      | 59.2                                      | 55.4                                      |
|                       | 7         | N/A                                       | N/A                                       | N/A                                       | 38.5                                      | 49.6                                      | 44.1                                      |
|                       | 27        | N/A                                       | N/A                                       | N/A                                       | 48.6                                      | 54.1                                      | 51.4                                      |
|                       | 21        | N/A                                       | N/A                                       | N/A                                       | 42.9                                      | 45.4                                      | 44.2                                      |
| Reactor E<br>Corm. HD | 22        | N/A                                       | 68.1                                      | N/A                                       | 73.6                                      | N/A                                       | 70.9                                      |
|                       | 7         | N/A                                       | N/A                                       | N/A                                       | 67.7                                      | N/A                                       | 67.7                                      |
|                       | 27        | N/A                                       | N/A                                       | N/A                                       | 64.1                                      | N/A                                       | 64.1                                      |
|                       | 21        | N/A                                       | N/A                                       | 62.0                                      | 55.7                                      | N/A                                       | 58.9                                      |
| Reactor F<br>Haldor   | 22        | N/A                                       | 62.2                                      | 49.2                                      | 60.2                                      | N/A                                       | 57.2                                      |
|                       | 7         | N/A                                       | N/A                                       | N/A                                       | 55.0                                      | N/A                                       | 55.0                                      |
|                       | 27        | N/A                                       | N/A                                       | 37.7                                      | 44.2                                      | N/A                                       | 41.0                                      |
|                       | 21        | N/A                                       | N/A                                       | N/A                                       | 43.4                                      | N/A                                       | 43.4                                      |
| Reactor G<br>Hitachi  | 22        | N/A                                       | N/A                                       | 76.0                                      | 62.5                                      | N/A                                       | 69.2                                      |
|                       | 7         | N/A                                       | N/A                                       | 64.7                                      | 58.9                                      | N/A                                       | 61.8                                      |
|                       | 27        | N/A                                       | N/A                                       | 62.1                                      | 49.6                                      | N/A                                       | 55.9                                      |
|                       | 21        | N/A                                       | N/A                                       | 55.8                                      | 43.9                                      | N/A                                       | 49.9                                      |
| Reactor J<br>Corm. LD | 22        | N/A                                       | N/A                                       | 71.1                                      | 77.7                                      | N/A                                       | 74.4                                      |
|                       | 7         | N/A                                       | N/A                                       | 65.0                                      | 75.2                                      | N/A                                       | 70.1                                      |
|                       | 27        | N/A                                       | N/A                                       | 65.8                                      | 71.7                                      | N/A                                       | 68.8                                      |
|                       | 21        | N/A                                       | N/A                                       | 54.5                                      | 58.4                                      | N/A                                       | 56.4                                      |

\*Condition 22 (base-line): NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 700 °F, Design flow

\*Condition 7: NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 620 °F, Design flow

\*Condition 27: NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 700 °F, High flow

\*Condition 21: NH<sub>3</sub>/NO<sub>x</sub> = 0.6, 700 °F, Design flow

## Ammonia Slip

Figures 5.4-14 through 21 show base-line ammonia slip versus exposure time for reactors A-J, respectively. Even though the graphs show base-line parametric values, slight differences in the actual ammonia-to-NO<sub>x</sub> ratios tend to mask time dependent trends in ammonia slip. This is especially evident in values reported for the first and fifth parametric sequences where calibration errors caused the actual ammonia-to-NO<sub>x</sub> ratios to vary significantly. For points where the ammonia-to-NO<sub>x</sub> ratios are similar, there is generally a trend of increasing ammonia slip with exposure time. Even at points where the actual ammonia-to-NO<sub>x</sub> ratios were high, however, all of the catalysts remained near or below the design base-line ammonia slip limit of 5 ppm(v) for the entire project life. Figure 5.4-22 shows ammonia slip versus exposure time at base-line conditions for the combination of all reactors. To give a more accurate view of ammonia slip performance, the data in this graph are edited to include only values where the actual ammonia-to-NO<sub>x</sub> ratios were at or near the design value of 0.8. As expected there is an increase in ammonia slip with time due to factors such as catalyst deactivation and plugging. The increase in slip ammonia for the combination of all reactors was only about 2.5 ppm(v) for the life of the project, however, and stayed well below the 5 ppm(v) design limit. This plot confirms the ability of an SCR system to maintain ammonia slip limits over an extended period of operation.

Ammonia slip for each catalyst/reactor system as an average of parametric test values is shown graphically in Figures 5.4-23 through 26 and in tabular form in Table 5.4-2. Also included in the figures, are the high and low values of ammonia slip showing measurement variability. This measurement variability should not be construed as the variation of ammonia slip with catalyst exposure time. To avoid misuse of the data, tests which had operating conditions that varied significantly from the denoted (desired) operating condition are not presented in Table 5.4-1 (denoted by N/A). These data have been omitted to prevent inapplicable comparisons of ammonia slip between the various parametric sequences. The reported data show changes in the catalysts' ammonia slip

performance with respect to changes in flue gas flow rate, temperature, and ammonia-to- $\text{NO}_x$  ratio. Figure 5.4-23 shows average ammonia slip for all catalyst/reactor systems at base-line conditions. The average parametric values stayed well below the design ammonia slip limit of 5 ppm(v) for all catalyst/reactor systems. Figure 5.4-24 shows average ammonia slip at  $\text{NH}_3/\text{NO}_x = 0.8$ , design flow rate, and low temperature. There is some overall increase from base-line conditions. This is expected since the kinetic reaction rate decreases with decreasing temperature. The increase in ammonia slip was slight, however, and in most cases stayed near or below the base-line design limit. As temperatures increased above 700 °F, mass transfer effects became controlling and little change was generally noticed in ammonia slip values. Losses in boiler efficiencies would probably outweigh any improvements that may be obtained by designing an SCR reactor to operate at temperatures near 750 °F. Ammonia slip is shown in Figure 5.4-25 at  $\text{NH}_3/\text{NO}_x = 0.8$ , design temperature, and high flow rate. Again, there were only slight increases in ammonia slip from base-line conditions. Since a portion of the overall reaction rate is due to mass transfer limitations, improvements in bulk mass transfer coefficients were likely mitigating the effects of increased flow on slip ammonia increases. Figure 5.4-26 shows ammonia slip at  $\text{NH}_3/\text{NO}_x = 1.0$ , design temperature, and design flow rate. There was a significant increase in ammonia slip from base-line conditions for almost all catalyst/reactor systems. At ammonia-to- $\text{NO}_x$  ratios near 1.0, non-idealities in the reactor systems forced the catalysts to slip ammonia since areas were present in the reactors where  $\text{NO}_x$  was limiting reagent. Ammonia-to- $\text{NO}_x$  ratio was the most significant factor in ammonia slip performance, and changes in the ammonia-to- $\text{NO}_x$  ratio often masked changes in other parameters.

Table 5.4-2 Average Ammonia Slip

|                       | Condition | P'metric 1                  | P'metric 2                  | P'metric 3                  | P'metric 4                  | P'metric 5                  | Average                     |
|-----------------------|-----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                       |           | NH <sub>3</sub> Slip ppm(v) |
| Reactor A<br>Noxeram  | 22        | N/A                         | 2.0                         | 2.2                         | 3.0                         | 3.3                         | 2.6                         |
|                       | 7         | N/A                         | 3.8                         | 2.0                         | 4.5                         | 0.6                         | 2.7                         |
|                       | 27        | N/A                         | 3.0                         | N/A                         | 2.8                         | N/A                         | 2.9                         |
|                       | 24        | N/A                         | N/A                         | 1.6                         | N/A                         | 0.7                         | 1.2                         |
| Reactor B<br>NSKK     | 22        | N/A                         | 0.4                         | BDL                         | 1.1                         | 0.7                         | 0.55                        |
|                       | 7         | N/A                         | N/A                         | BDL                         | 1.5                         | 0.7                         | 0.7                         |
|                       | 27        | N/A                         | 0.6                         | 1.8                         | 2.1                         | 0.7                         | 1.3                         |
|                       | 24        | N/A                         | N/A                         | 3.2                         | 10.2                        | 1.1                         | 4.8                         |
| Reactor C<br>Siemens  | 22        | N/A                         | 1.1                         | 2.7                         | 5.4                         | 5.0                         | 3.6                         |
|                       | 7         | N/A                         | 2.2                         | 2.5                         | 6.5                         | 12.0                        | 5.8                         |
|                       | 27        | N/A                         | 2.3                         | 7.0                         | 7.8                         | 11.6                        | 7.2                         |
|                       | 24        | N/A                         | N/A                         | 13.8                        | 16.3                        | N/A                         | 15.1                        |
| Reactor D<br>Synox    | 22        | N/A                         | N/A                         | 3.6                         | 5.5                         | 2.6                         | 3.9                         |
|                       | 7         | N/A                         | N/A                         | 10.0                        | 21.7                        | 4.8                         | 12.2                        |
|                       | 27        | N/A                         | N/A                         | 19.6                        | 9.2                         | 8.2                         | 12.3                        |
|                       | 24        | N/A                         | N/A                         | N/A                         | 23.7                        | 3.9                         | 13.8                        |
| Reactor E<br>Corm. HD | 22        | N/A                         | 1.0                         | BDL                         | 0.7                         | 0.8                         | 0.6                         |
|                       | 7         | N/A                         | 0.8                         | BDL                         | 0.7                         | 0.7                         | 0.6                         |
|                       | 27        | N/A                         | 0.5                         | N/A                         | 1.7                         | 0.8                         | 1.0                         |
|                       | 24        | N/A                         | N/A                         | N/A                         | 1.5                         | N/A                         | 1.5                         |
| Reactor F<br>Haldor   | 22        | N/A                         | N/A                         | N/A                         | 0.9                         | 1.2                         | 1.1                         |
|                       | 7         | N/A                         | 0.8                         | 2.9                         | 2.6                         | 1.4                         | 1.9                         |
|                       | 27        | N/A                         | 2.6                         | 8.8                         | 3.8                         | 4.0                         | 4.8                         |
|                       | 24        | N/A                         | N/A                         | 16.0                        | 11.7                        | N/A                         | 13.9                        |
| Reactor G<br>Hitachi  | 22        | N/A                         | N/A                         | 2.1                         | 1.5                         | N/A                         | 1.8                         |
|                       | 7         | N/A                         | 0.8                         | 1.4                         | 2.9                         | N/A                         | 1.7                         |
|                       | 27        | N/A                         | 2.2                         | 2.9                         | 5.4                         | N/A                         | 3.5                         |
|                       | 24        | N/A                         | N/A                         | 39.5                        | 8.3                         | N/A                         | 23.9                        |
| Reactor J<br>Corm. LD | 22        | N/A                         | N/A                         | N/A                         | 0.8                         | N/A                         | 0.8                         |
|                       | 7         | N/A                         | N/A                         | 2.7                         | 1.6                         | N/A                         | 2.2                         |
|                       | 27        | N/A                         | N/A                         | 3.9                         | 4.3                         | N/A                         | 4.1                         |
|                       | 24        | N/A                         | N/A                         | 3.6                         | N/A                         | N/A                         | 3.6                         |

\*Condition 22 (base-line): NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 700 °F, Design flow

\*Condition 7: NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 620 °F, Design flow

\*Condition 27: NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 700 °F, High flow

\*Condition 24: NH<sub>3</sub>/NO<sub>x</sub> = 1.0, 700 °F, Design flow

### SO<sub>2</sub> Oxidation

The SO<sub>2</sub> data are corrected to reactor outlet oxygen concentrations. For the first and second parametric tests, the values for sulfur trioxide produced in the reactors were based on measured reactor outlet sulfur trioxide concentrations and estimated reactor inlet sulfur

trioxide values. The reactor inlet sulfur trioxide values were estimated, using past measurements of inlet sulfur trioxide based on host boiler load. The third, fourth, and fifth parametric tests consisted of measured inlet and outlet sulfur trioxide concentrations. In many cases, especially those involving low temperature conditions, there was no net increase in sulfur trioxide concentrations across the reactors. In fact, some operating conditions showed an apparent loss in sulfur trioxide across the reactors. It is believed that the apparent loss was caused by phenomena such as acid condensation and the formation of ammonium bisulfate on cold spots at the reactor surfaces.

Figures 5.4-27 through 34 show average SO<sub>2</sub> oxidation versus exposure time for reactors A-J, respectively. These figures show no apparent trend in SO<sub>2</sub> oxidation with exposure time for any of the catalyst/reactor systems. This is expected, however, since SO<sub>2</sub> oxidation is affected less by catalyst deactivation than are NO<sub>x</sub> reduction and ammonia slip. Figure 5.4-35 shows SO<sub>2</sub> oxidation versus exposure time at base-line conditions for the combination of all reactors. The data points are widely scattered, but there is a slight trend toward decreasing SO<sub>2</sub> oxidation with exposure time. This is likely due to some limited catalyst deactivation, fouling, and increasing ammonia slip with exposure time. Ammonia slip does not have a true catalytic effect on the formation of sulfur trioxide, but it does have a precipitation effect. Early studies with no catalyst present showed that SO<sub>3</sub> was lost through the reactors, most likely in cold spots such as test ports, etc. The presence of ammonia may have affected the precipitation phenomenon. Most likely this occurred by changing the precipitation characteristics of the sulfur trioxide through the formation of by-products such as ammonium bisulfate in the cold spots of the reactors.

SO<sub>2</sub> oxidation for each catalyst/reactor system as an average of parametric test values is shown graphically in Figures 5.4-36 and 37 and in tabular form in Table 5.4-3. Also included in the figures, are the high and low values of SO<sub>2</sub> oxidation showing measurement variability. This measurement variability should not be construed as the variation of SO<sub>2</sub> oxidation with catalyst exposure time. These data show the catalysts' SO<sub>2</sub> oxidation performance with respect to changes in operating temperature. Figure 5.4-

36 shows average SO<sub>2</sub> oxidation for all catalyst/reactors systems at base-line conditions. The SO<sub>2</sub> oxidation values varied significantly for most reactors, but the average values for all reactors were well within the base-line design limit of 0.75%. Figure 5.4-37 shows average SO<sub>2</sub> oxidation design flow rate and high temperature. There is a definite increase in SO<sub>2</sub> oxidation from base-line conditions. This is expected since published information describing the effects of temperature on SO<sub>2</sub> oxidation and information obtained from the catalyst suppliers indicates that increases in SO<sub>2</sub> oxidation are expected to be exponential with respect to temperature.

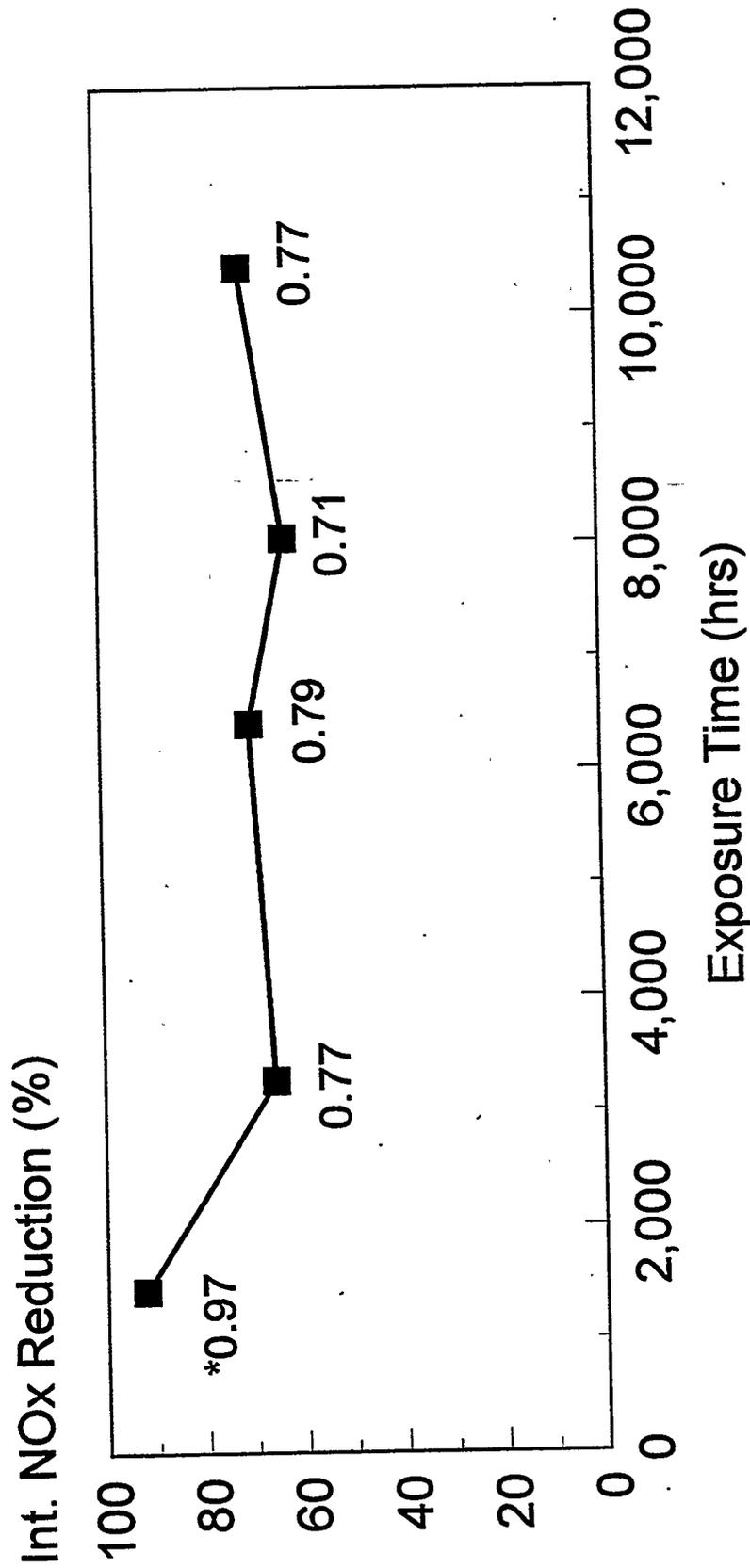
Table 5.4-3 Average SO<sub>2</sub> Oxidation

|             | Condition* | P'metric 1<br>SO <sub>2</sub> Oxid.<br>(%) | P'metric 2<br>SO <sub>2</sub> Oxid.<br>(%) | P'metric 3<br>SO <sub>2</sub> Oxid.<br>(%) | P'metric 4<br>SO <sub>2</sub> Oxid.<br>(%) | P'metric 5<br>SO <sub>2</sub> Oxid.<br>(%) | Average<br>SO <sub>2</sub> Oxid.<br>(%) |
|-------------|------------|--|--|--|--|--|---|
| Reactor A   | 22         | 0.22                                       | 0.10                                       | 0.83                                       | 0.49                                       | 0.50                                       | 0.43                                    |
| Noxeram     | 37         | N/A  | 1.11                                       | 1.56                                       | 1.78                                       | N/A  | 1.48                                    |
| Reactor B   | 22         | -0.39                                      | -0.11                                      | 0.20                                       | -0.11                                      | 0.02                                       | 0.04                                    |
| NSKK        | 37         | N/A  | 0.15                                       | 0.30                                       | 0.41                                       | N/A  | 0.29                                    |
| Reactor C   | 22         | 1.19                                       | 0.62                                       | 0.64                                       | 0.18                                       | 0.65                                       | 0.66                                    |
| Siemens     | 37         | N/A  | 1.85                                       | 1.13                                       | 1.23                                       | N/A  | 1.40                                    |
| Reactor D   | 22         | 0.80                                       | 0.58                                       | 0.38                                       | 0.50                                       | -0.25                                      | 0.45                                    |
| Synox       | 37         | N/A  | 0.65                                       | 1.15                                       | 0.57                                       | N/A  | 0.79                                    |
| Reactor E   | 22         | 0.43                                       | 0.66                                       | 0.31                                       | 0.36                                       | 0.04                                       | 0.36                                    |
| Corm. HD    | 37         | N/A  | 1.08                                       | 0.60                                       | 0.54                                       | N/A  | 0.74                                    |
| Reactor F   | 22         | 0.02                                       | 0.20                                       | 0.06                                       | 0.01                                       | -0.31                                      | 0.06                                    |
| Haldor      | 37         | N/A  | 0.06                                       | 0.11                                       | 0.00                                       | N/A  | 0.06                                    |
| Reactor G   | 22         | N/A  | 0.59                                       | 0.09                                       | 0.16                                       | -0.50                                      | 0.21                                    |
| Hitachi     | 37         | N/A  | 0.74                                       | 0.84                                       | 0.57                                       | N/A  | 0.72                                    |
| Reactor J** | 22         | N/A  | N/A  | 0.36                                       | 0.11                                       | 0.36                                       | 0.28                                    |
| Corm. LD    |            |  |  |  |  |  |   |

\*Condition 22 (base-line): NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 700 °F, Design flow; Condition 37: NH<sub>3</sub>/NO<sub>x</sub> = 0.8, 750 °F

\*\* No data available for Condition 37

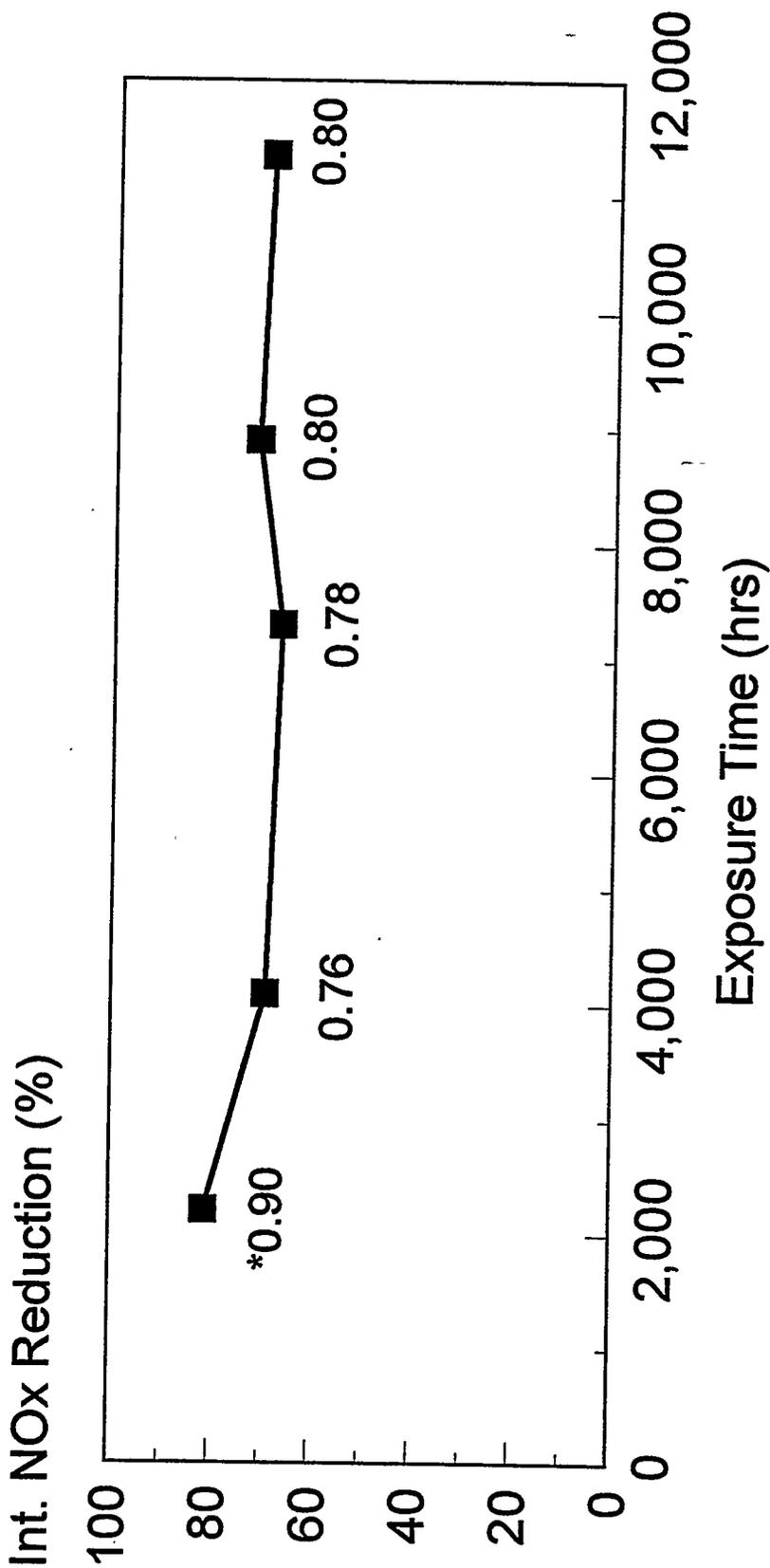
**Figure 5.4-1**  
**INTERMEDIATE NOx REDUCTION**



Grace Noxeram:  $\text{NH}_3/\text{NO}_x=0.8, 700\text{F}, 5000 \text{ SCFM}$

\* Values equal actual ammonia-to-NOx ratios that correspond to given NOx reduction points

# Figure 5.4-2 INTERMEDIATE NOx REDUCTION

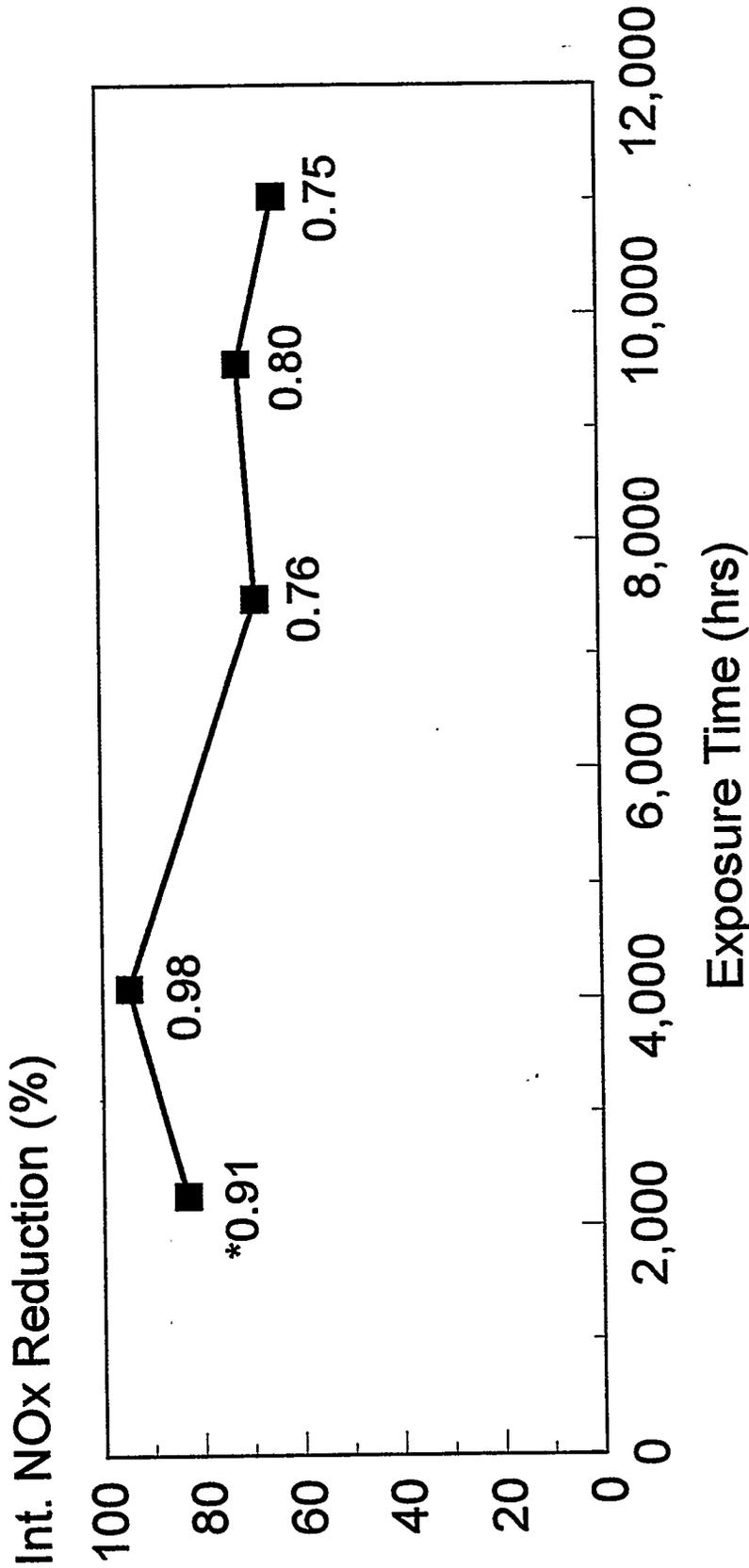


NSKK: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 5000 SCFM

\* Values equal actual ammonia-to-NO<sub>x</sub> ratios that correspond to given NO<sub>x</sub> reduction points

# Figure 5.4-3

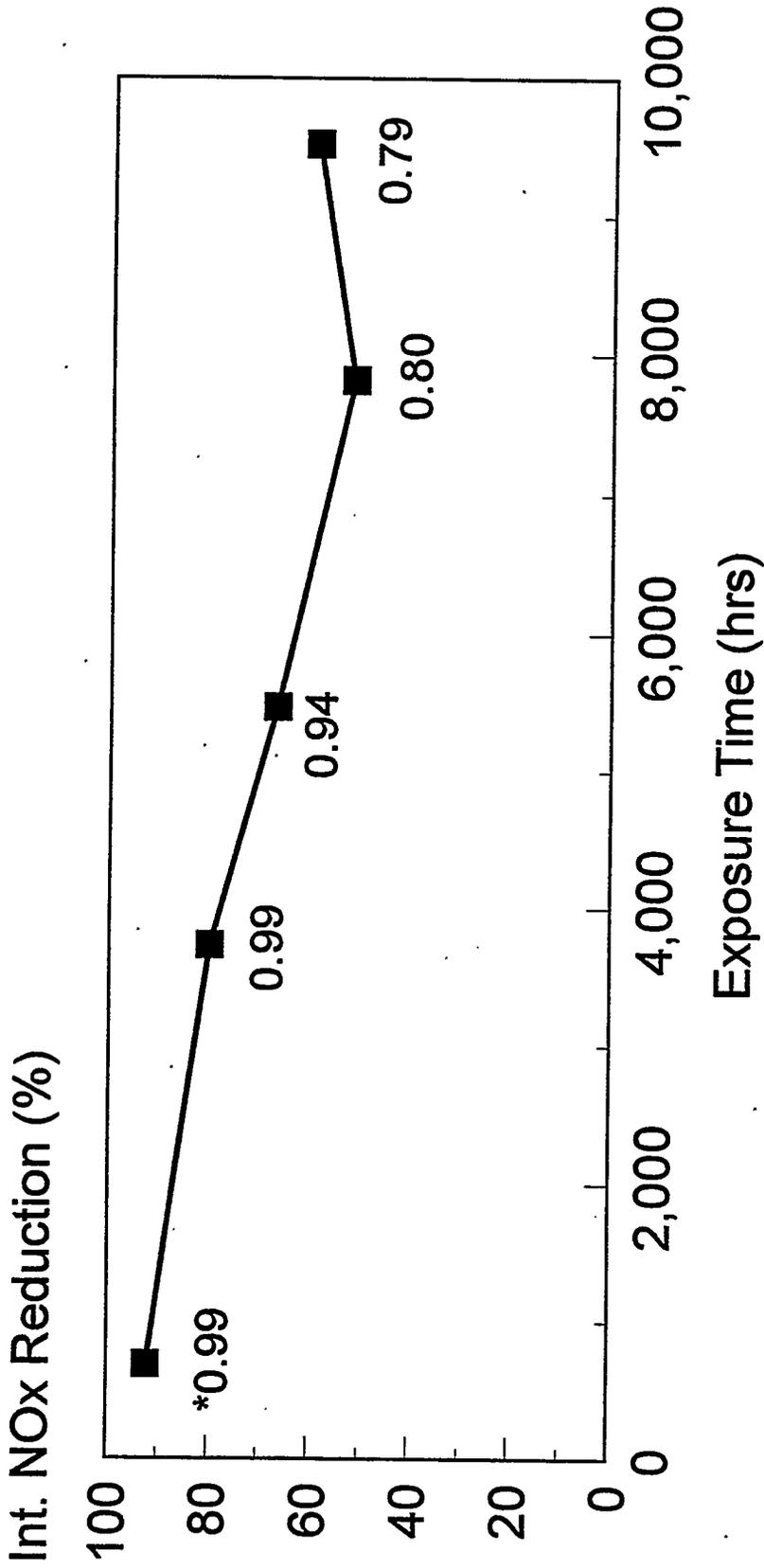
## INTERMEDIATE NOx REDUCTION



Siemens: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 5000 SCFM

\* Values equal actual ammonia-to-NO<sub>x</sub> ratios that correspond to given NO<sub>x</sub> reduction points

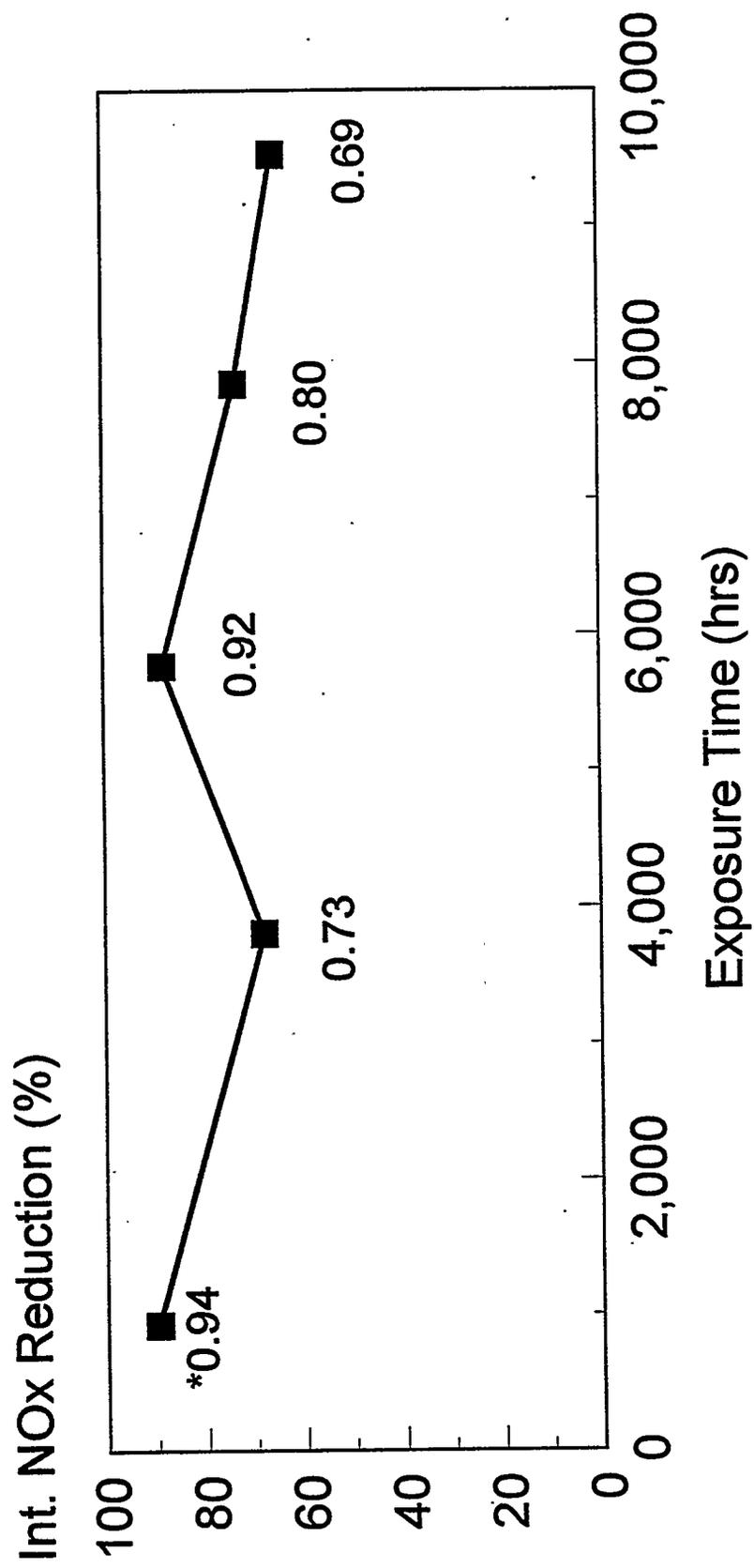
# Figure 5.4-4 INTERMEDIATE NOx REDUCTION



Grace Synox: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 400 SCFM

\* Values equal actual ammonia-to-NO<sub>x</sub> ratios that correspond to given NO<sub>x</sub> reduction points

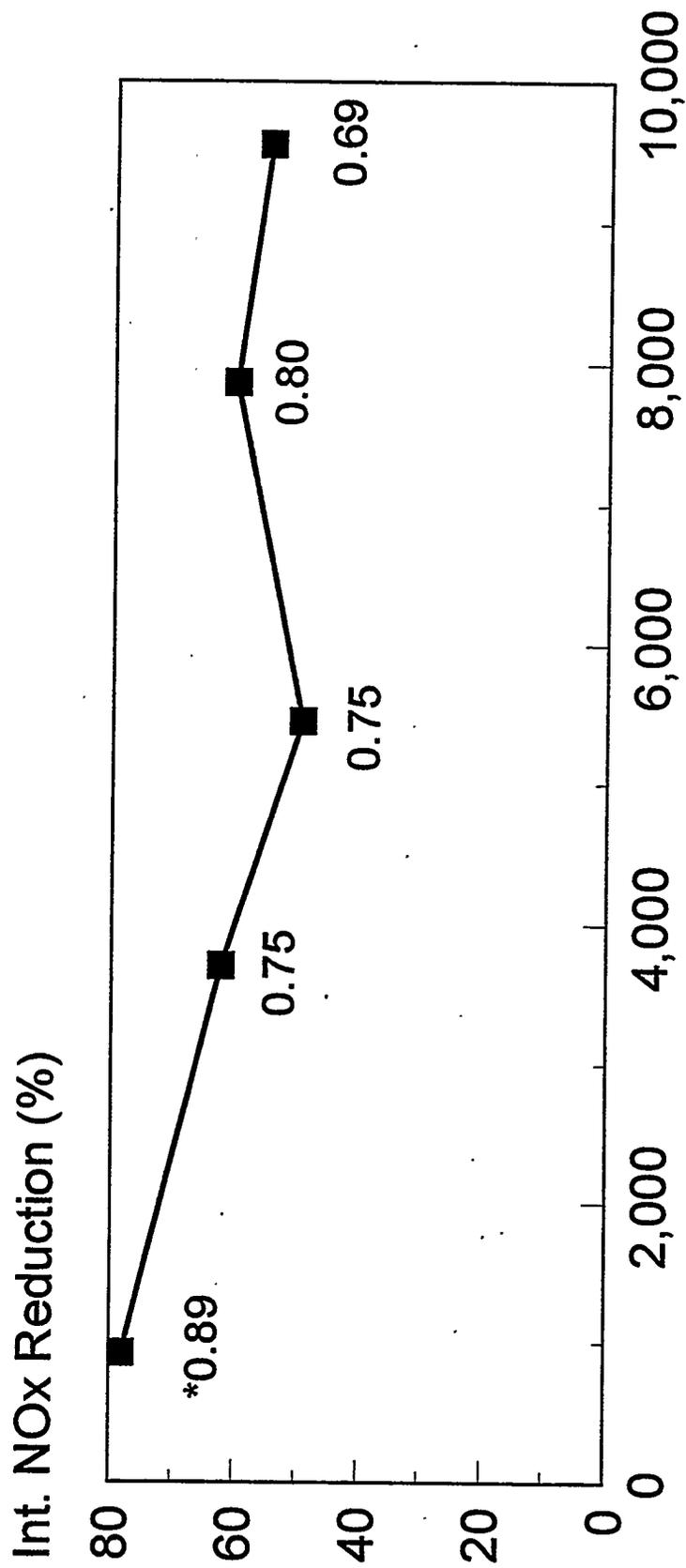
**Figure 5.4-5**  
**INTERMEDIATE NOx REDUCTION**



Cormetech High-Dust: NH3/Nox=0.8, 700F, 400 SCFM

\* Values equal actual ammonia-to-NOx ratios that correspond to given NOx reduction points

# Figure 5.4-6 INTERMEDIATE NOx REDUCTION



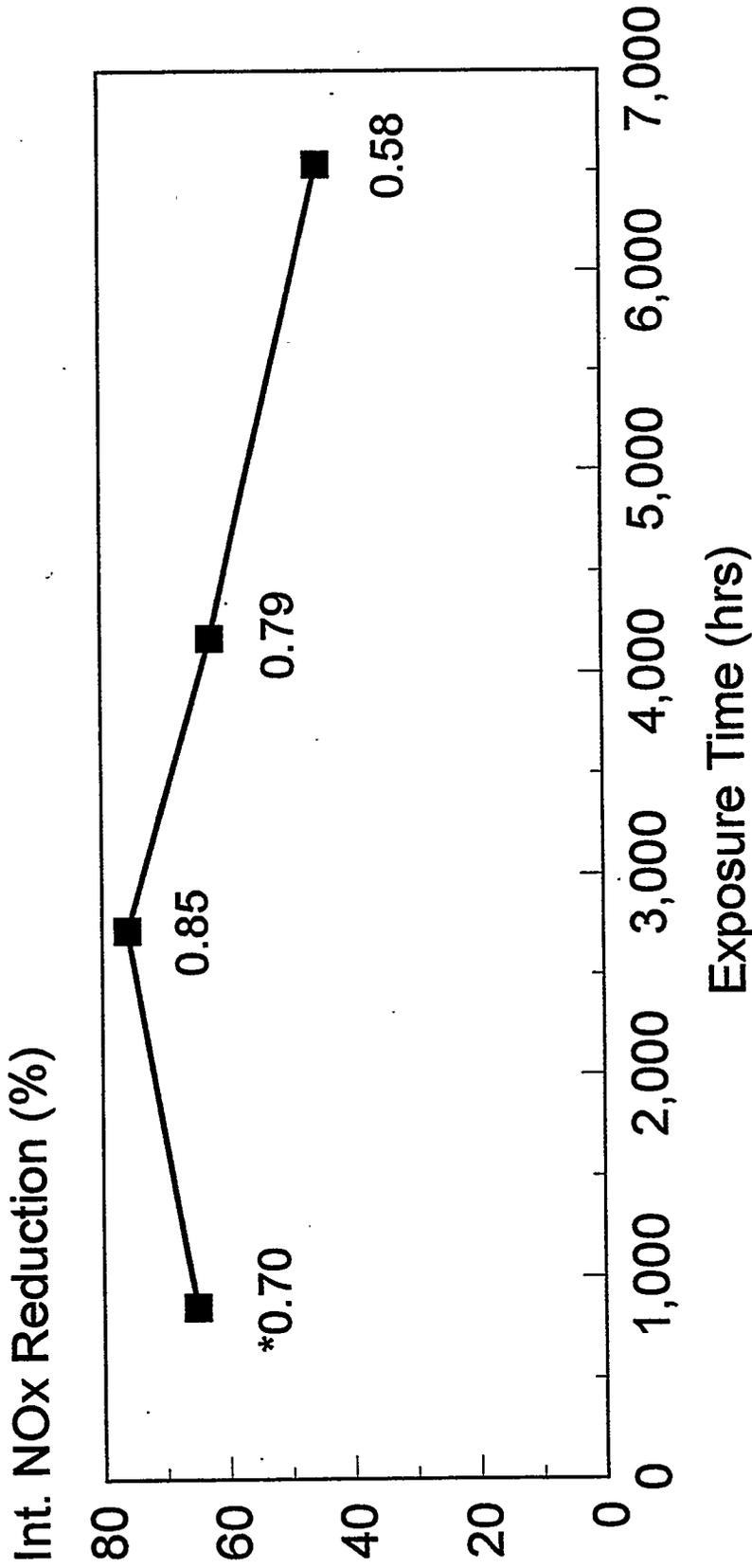
Exposure Time (hrs)

Haldrup Topsoe: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 400 SCFM

\* Values equal actual ammonia-to-NO<sub>x</sub> ratios that correspond to given NO<sub>x</sub> reduction points

# Figure 5.4-7

## INTERMEDIATE NOx REDUCTION

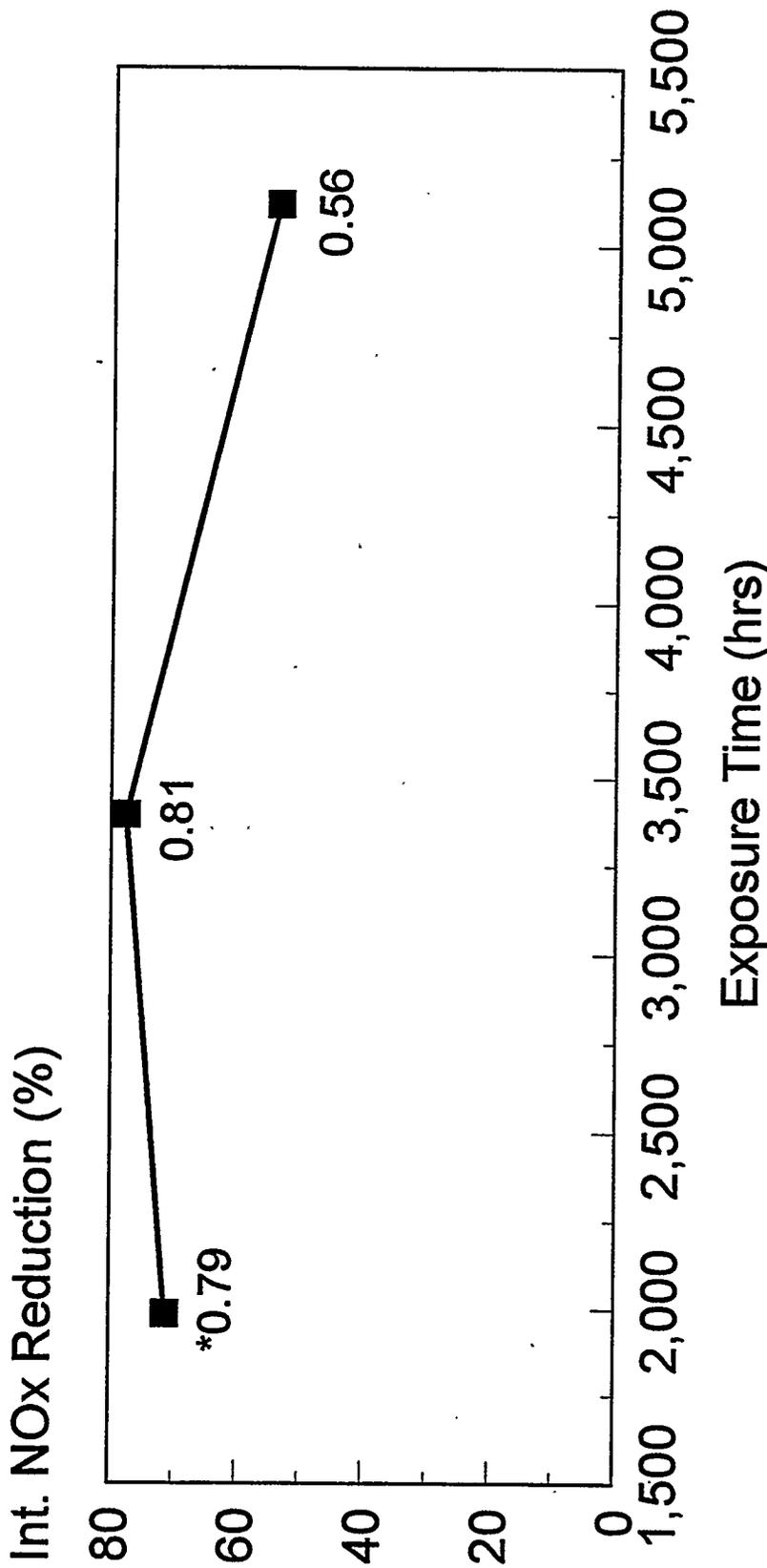


Hitachi Zosen:  $\text{NH}_3/\text{NO}_x=0.8, 700\text{F}, 400 \text{ SCFM}$

\* Values equal actual ammonia-to-NOx ratios that correspond to given NOx reduction points

**Figure 5.4-8**

**INTERMEDIATE NOx REDUCTION**



Cornmetech Low-Dust:  $NH_3/NO_x=0.8, 700F, 400\ SCFM$

\* Values equal actual ammonia-to-NOx ratios that correspond to given NOx reduction points

# FIGURE 5.4-9

## INTERMEDIATE NOx REDUCTION VERSUS EXPOSURE TIME AT BASE-LINE CONDITIONS

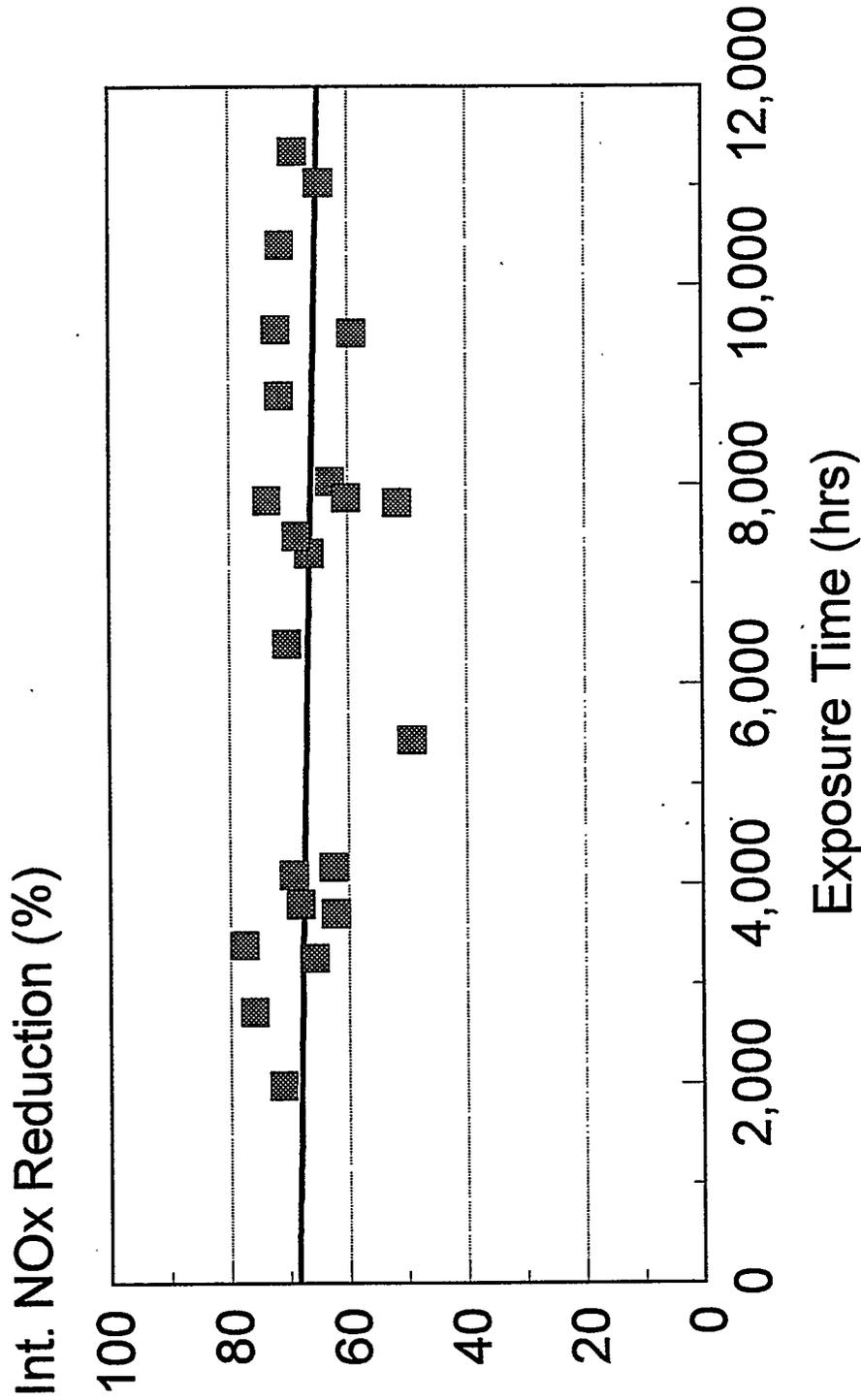


Figure 5.4-10

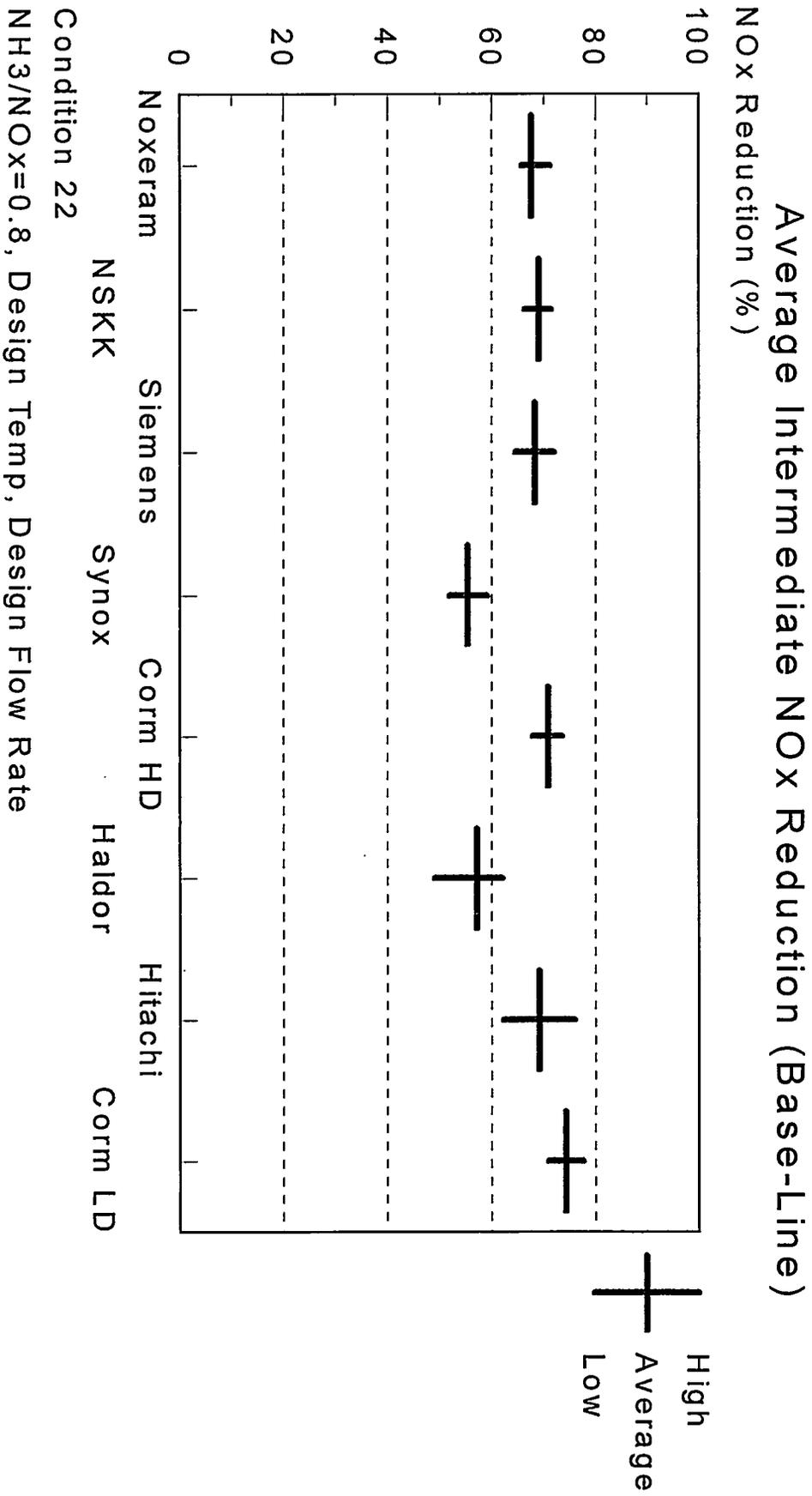
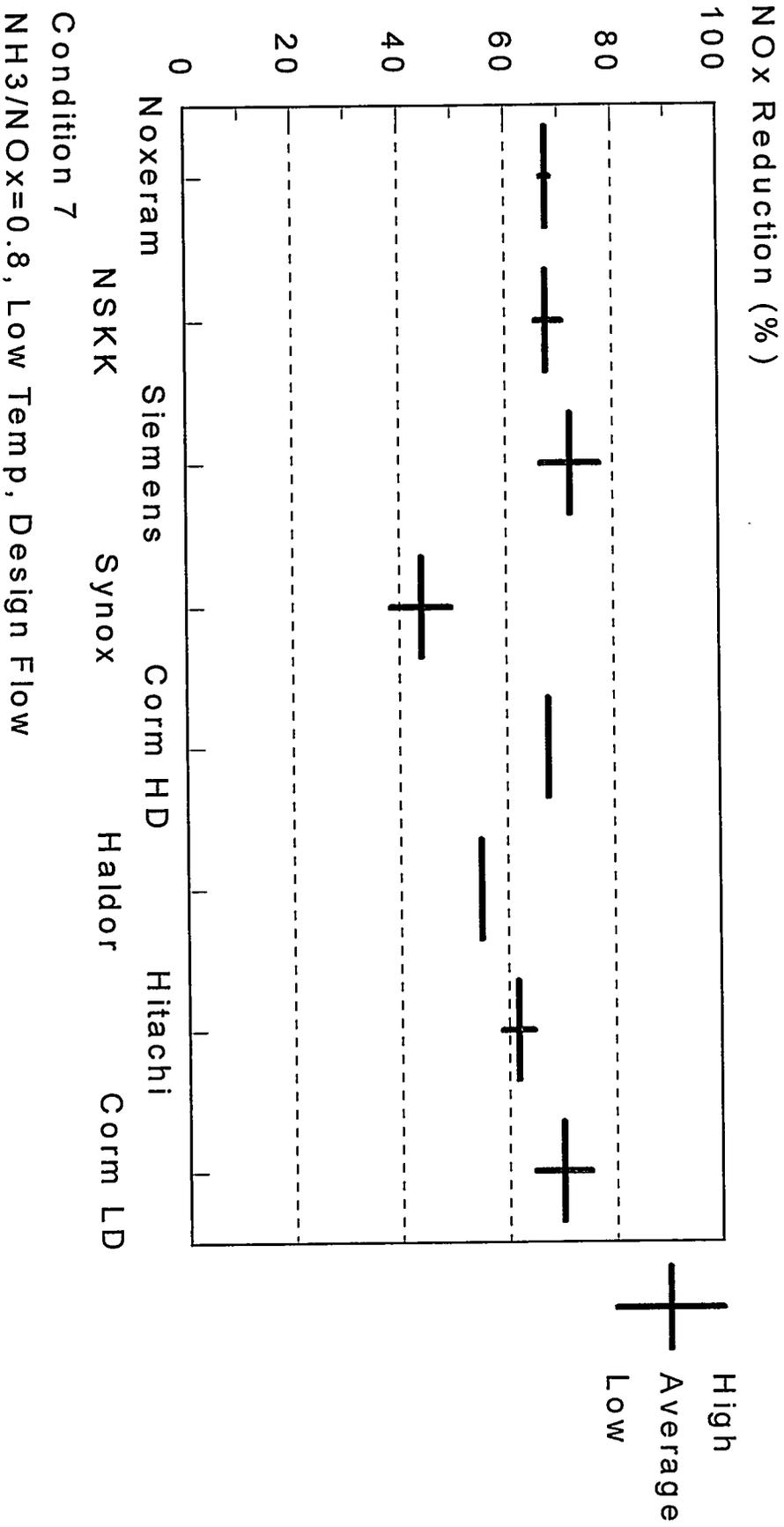
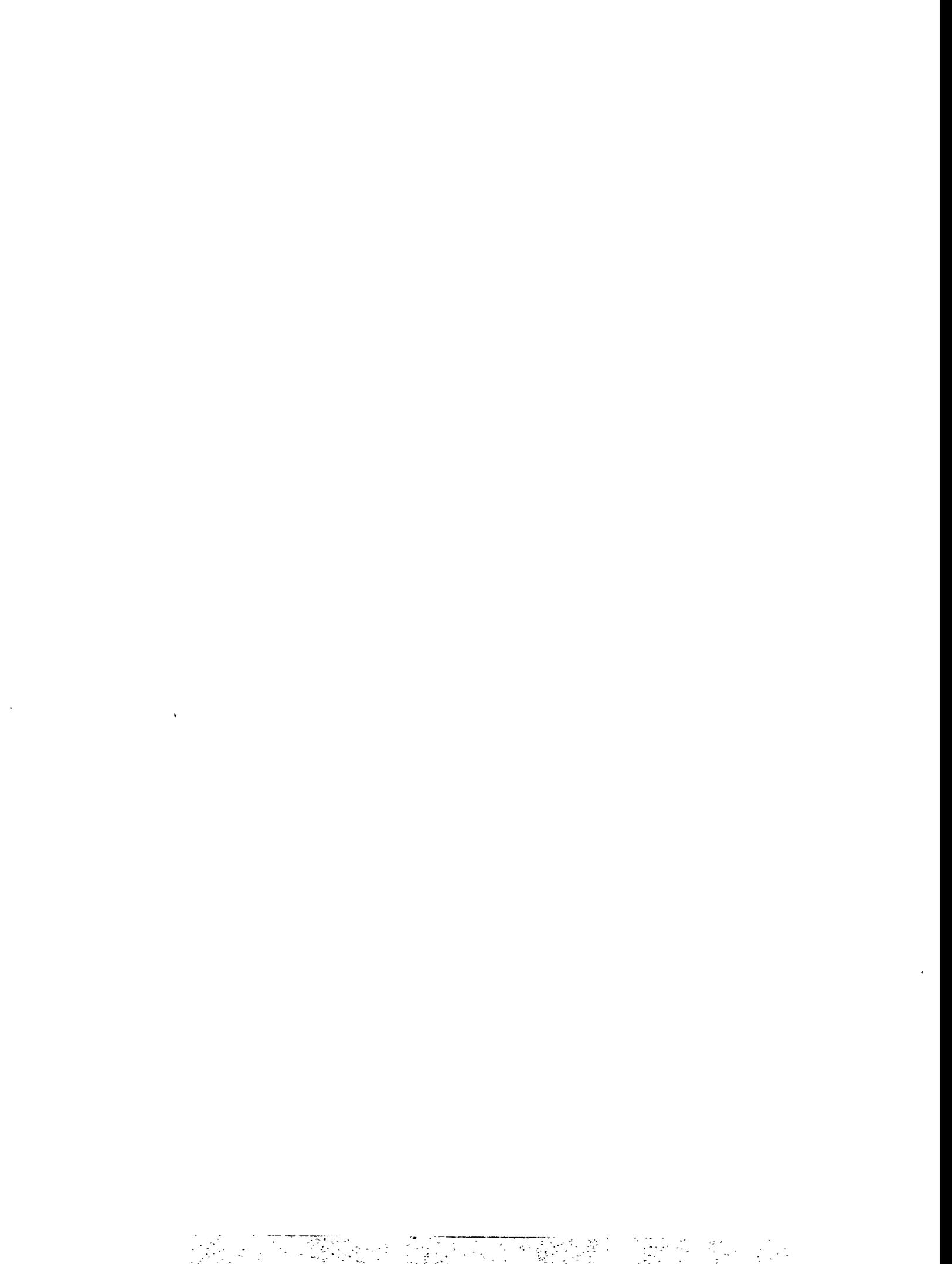




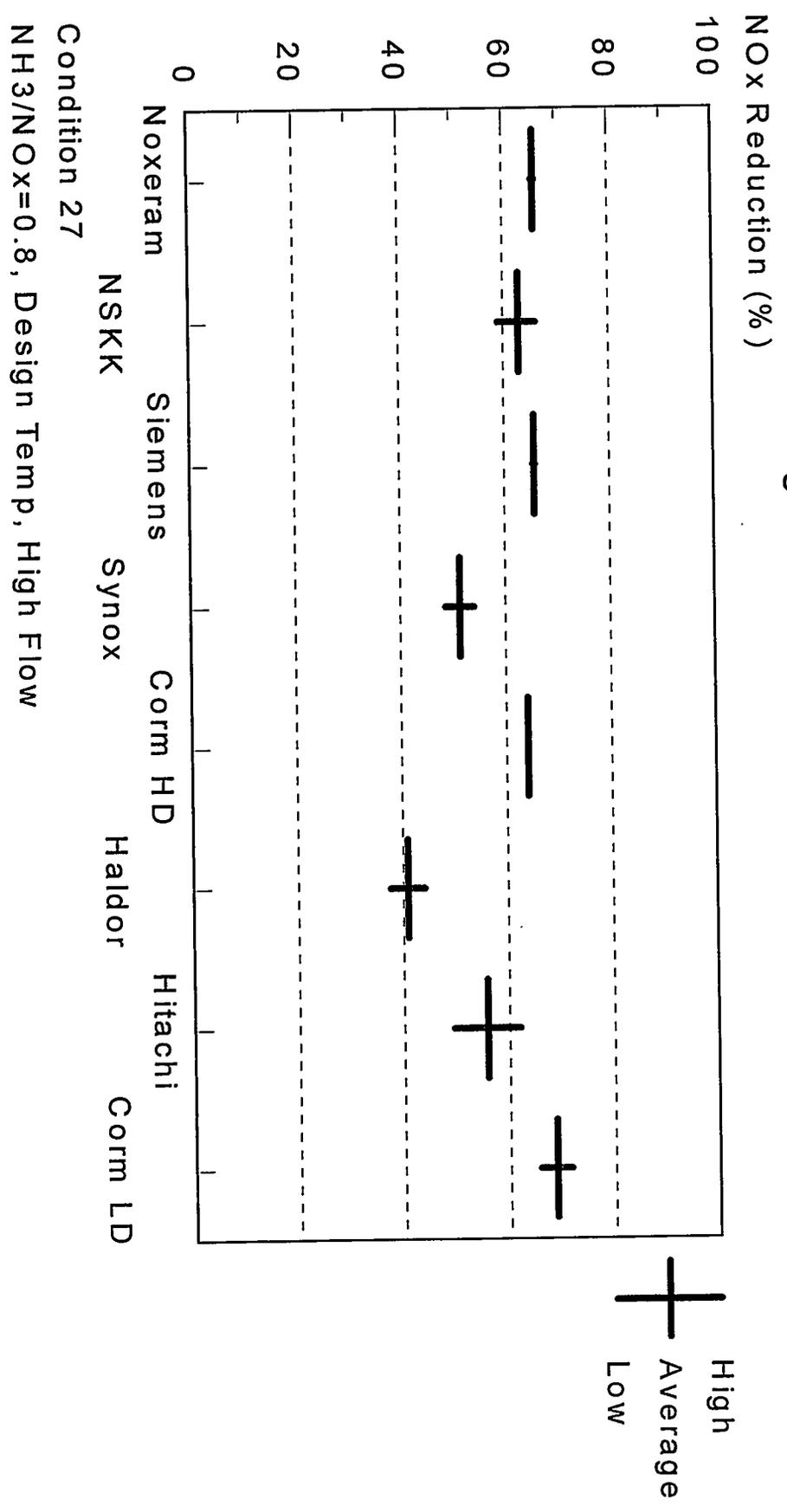
Figure 5.4-11

Average Intermediate NOx Reduction





**Figure 5.4-12**  
Average Intermediate NOx Reduction



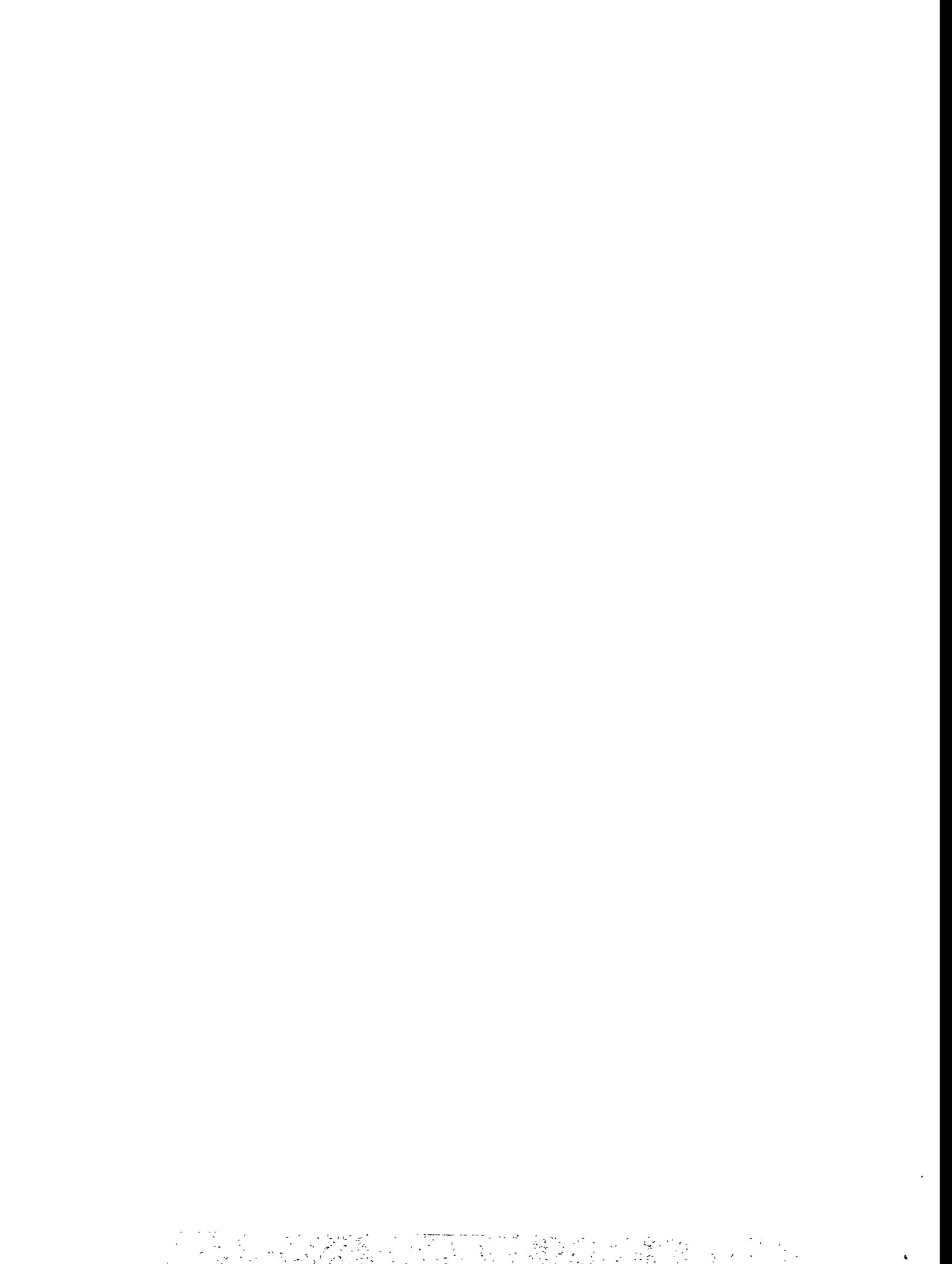
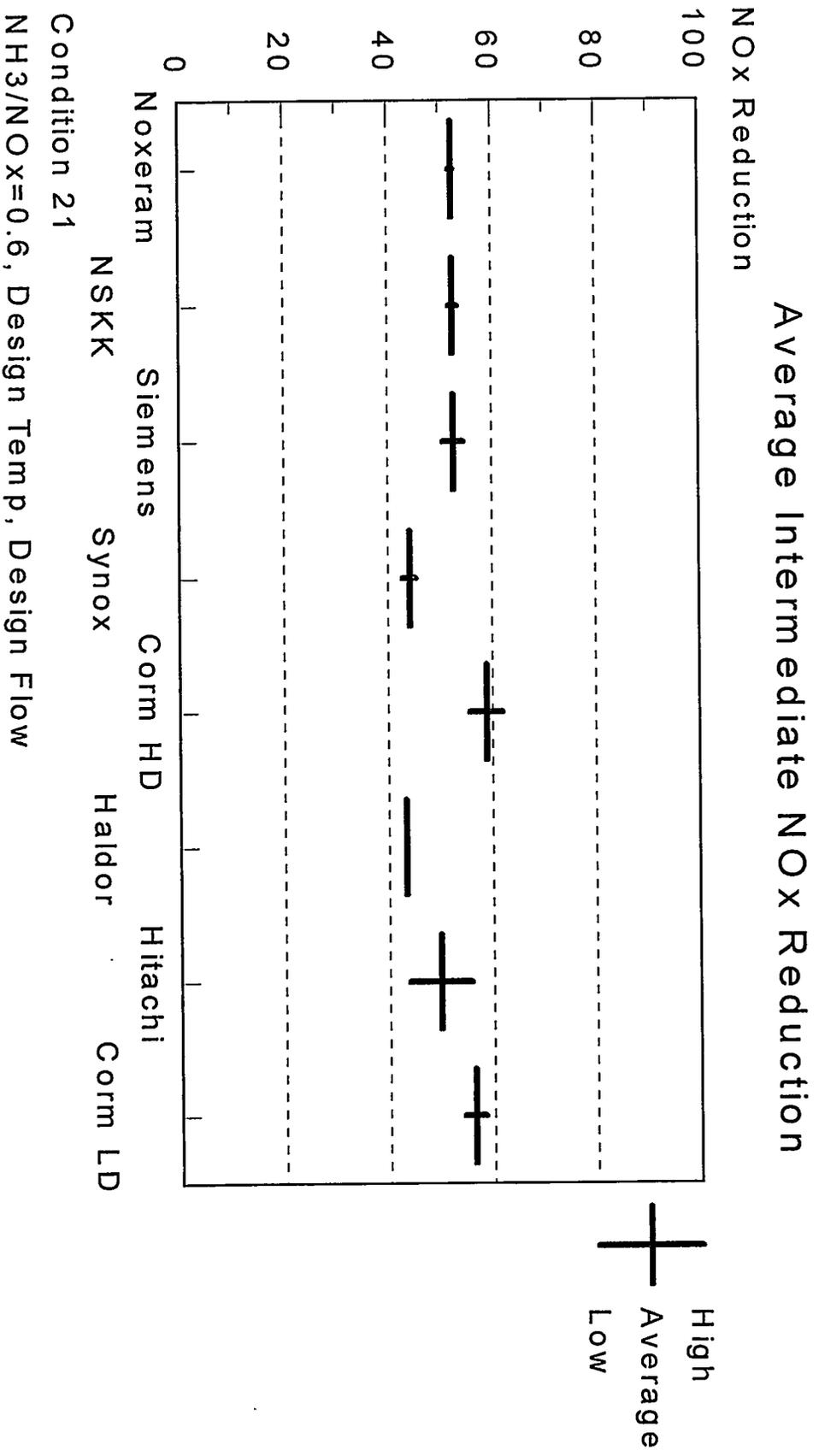
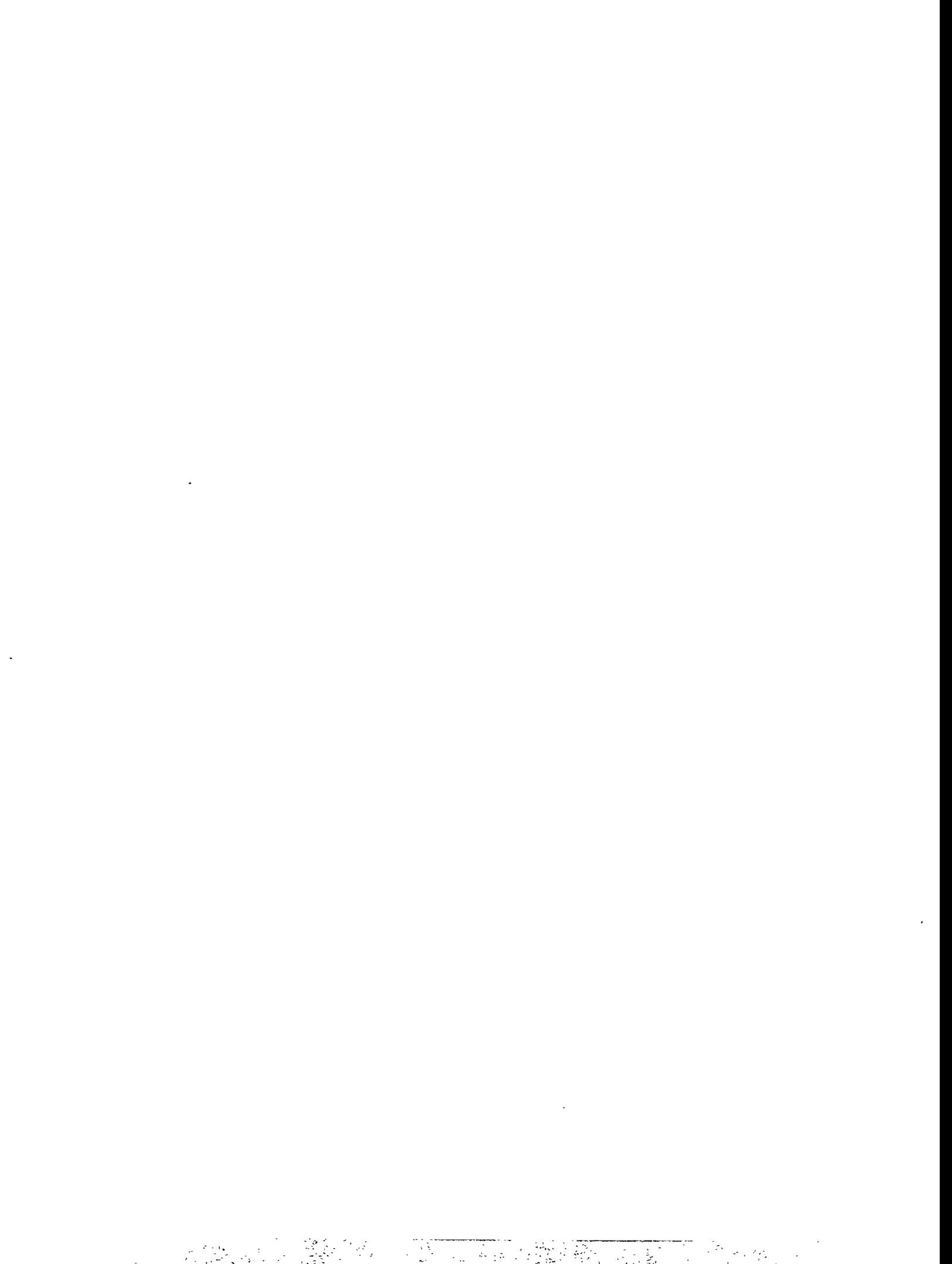


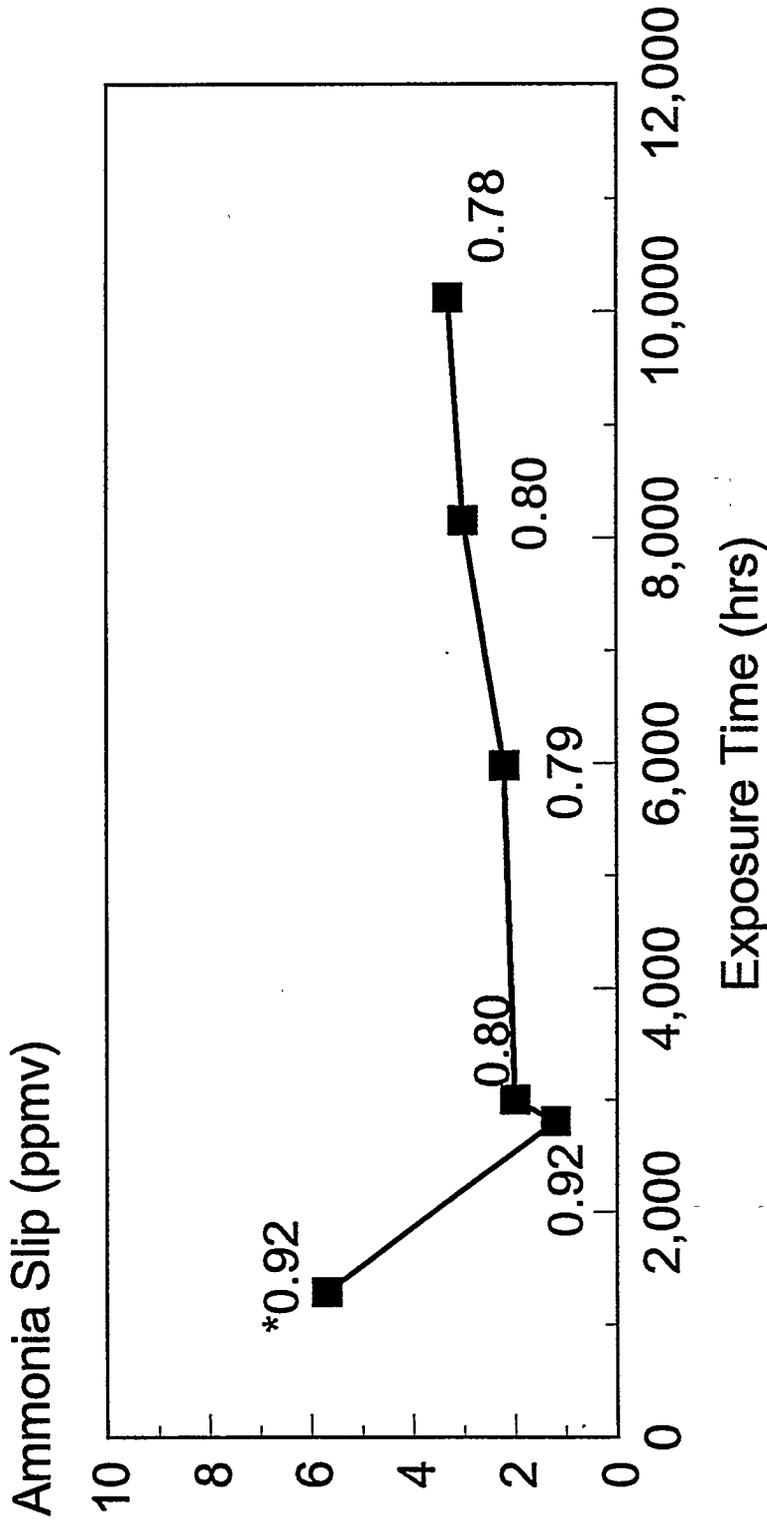
Figure 5.4-13





# Figure 5.4-14

## AMMONIA SLIP VS. TIME

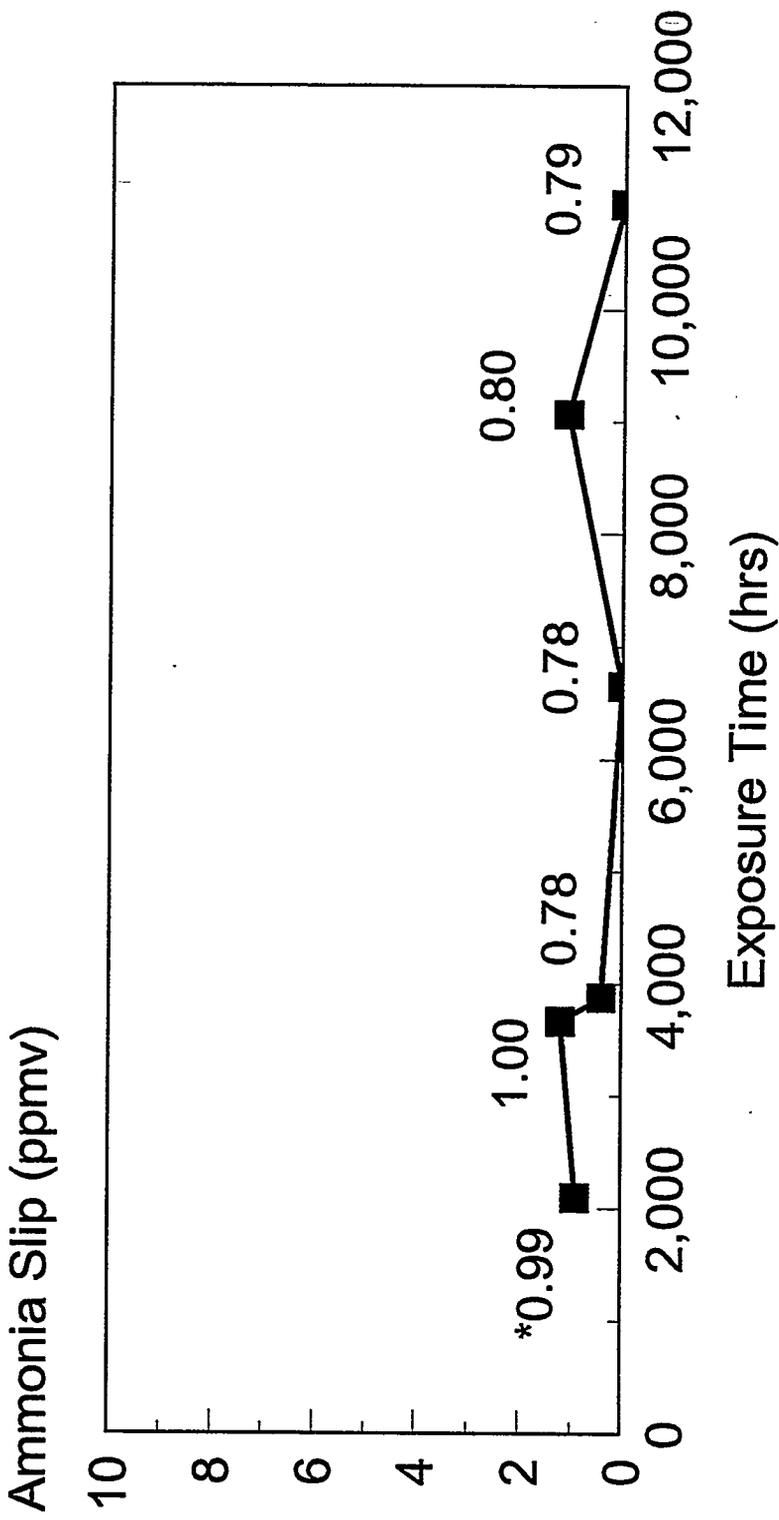


Grace Noxeram: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 5000 SCFM

\*Values equal actual ammonia-to-NO<sub>x</sub> ratios that correspond to given ammonia slip point

# Figure 5.4-15

## AMMONIA SLIP VS. TIME

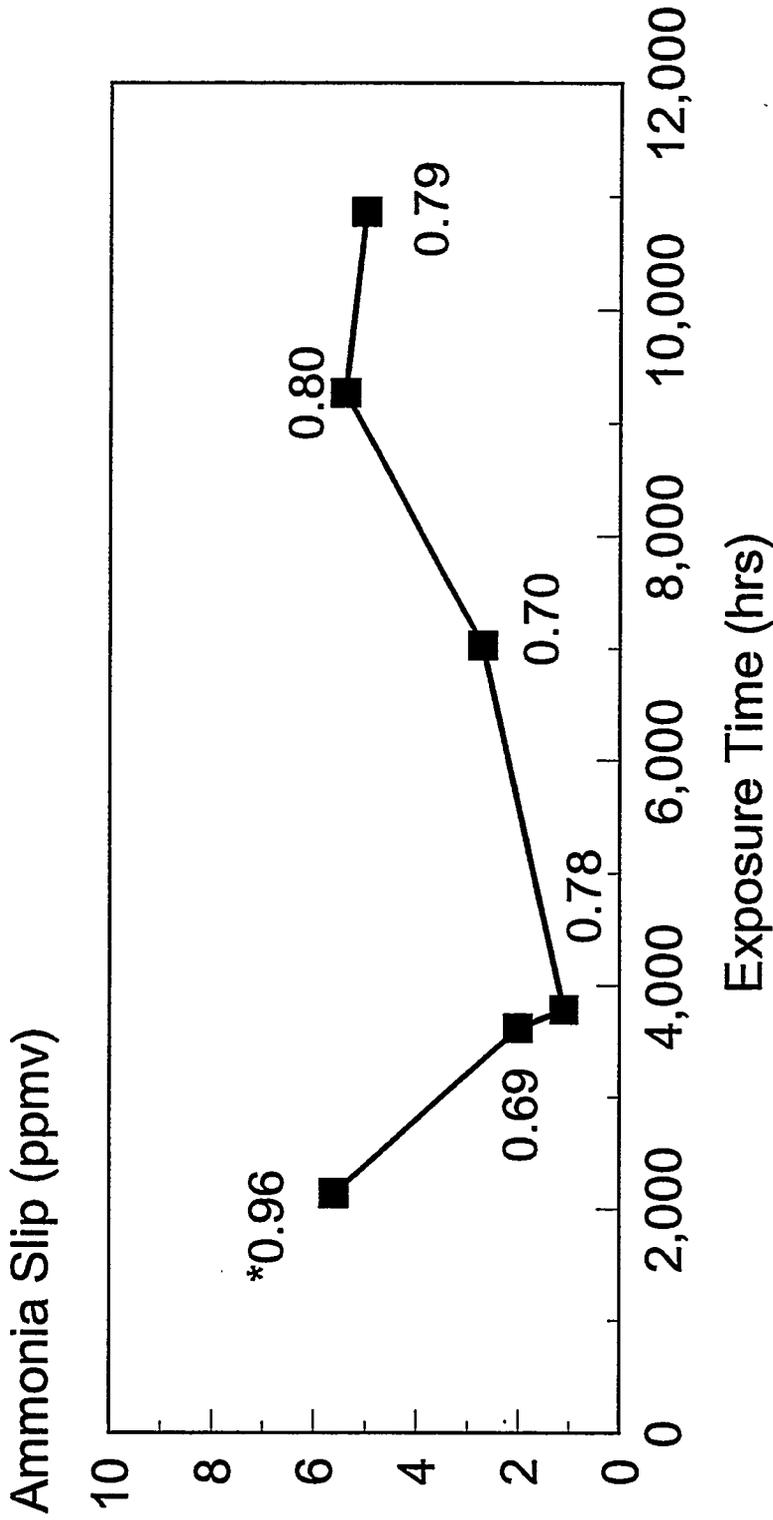


NSKK: NH3/NOx=0.8, 700F, 5000 SCFM

\*Values equal actual ammonia-to-NOx ratios that correspond to given ammonia slip point

# Figure 5.4-16

## AMMONIA SLIP VS. TIME

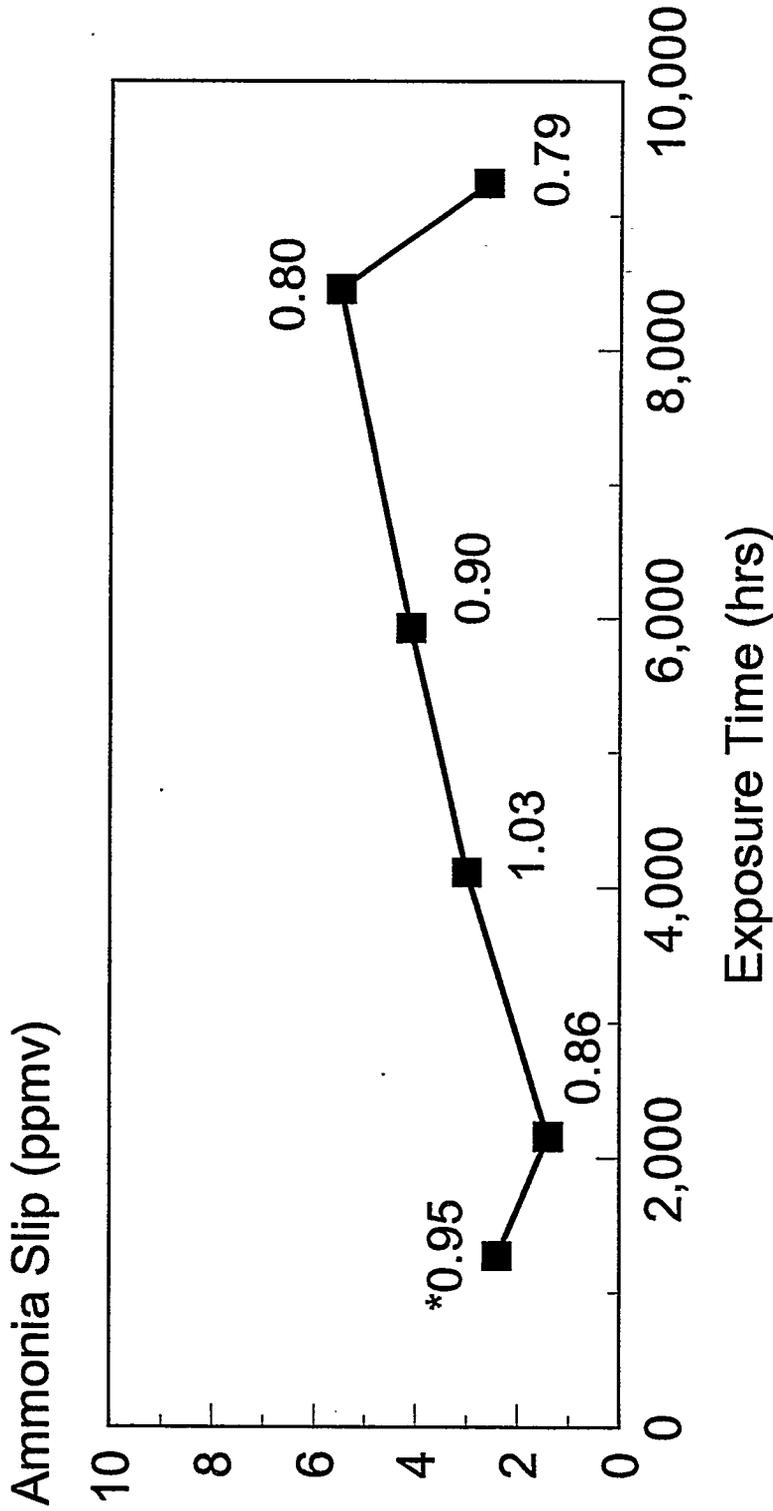


Siemens: NH3/NOx=0.8, 700F, 5000 SCFM

\*Values equal actual ammonia-to-NOx ratios that correspond to given ammonia slip point

Figure 5.4-17

# AMMONIA SLIP VS. TIME

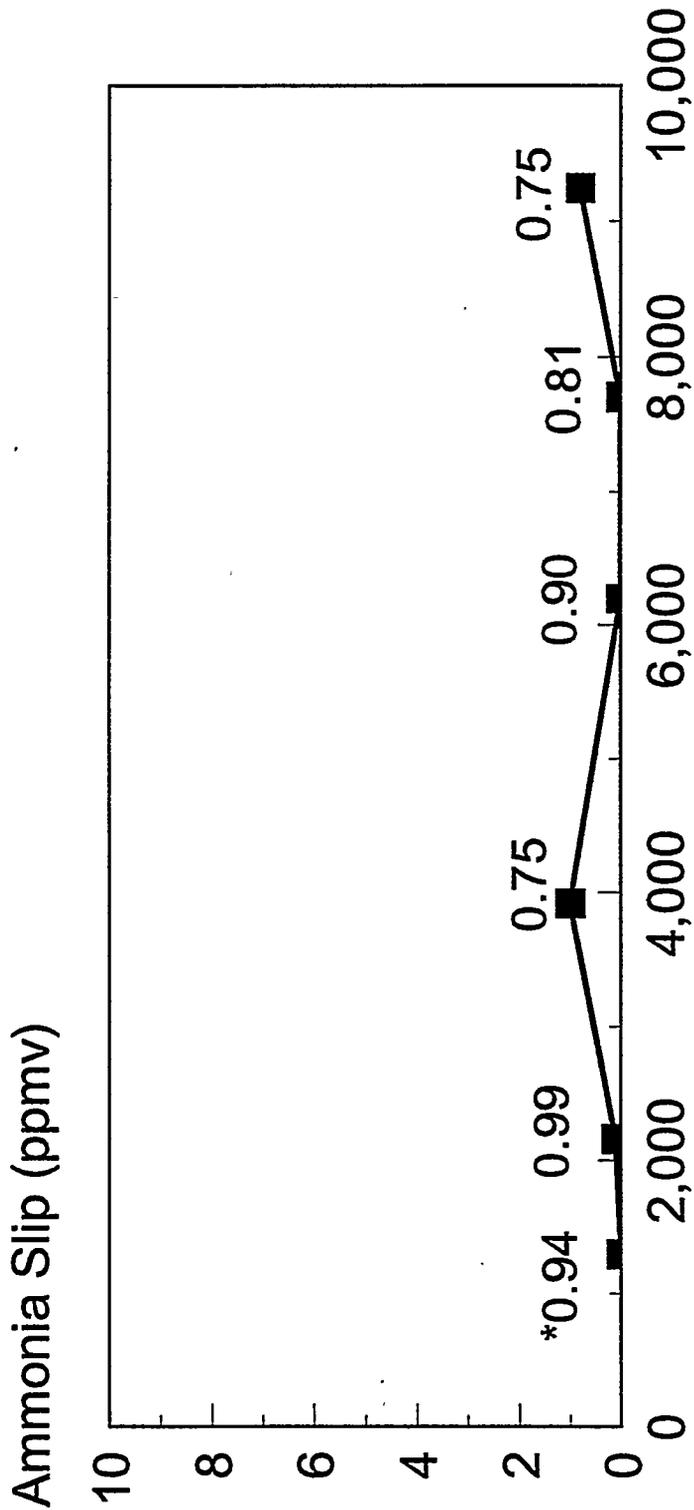


Grace Synox NH3/NOx=0.8, 700F, 400 SCFM

\*Values equal actual ammonia-to-NOx ratios that correspond to given ammonia slip point

# Figure 5.4-18

## AMMONIA SLIP VS. TIME

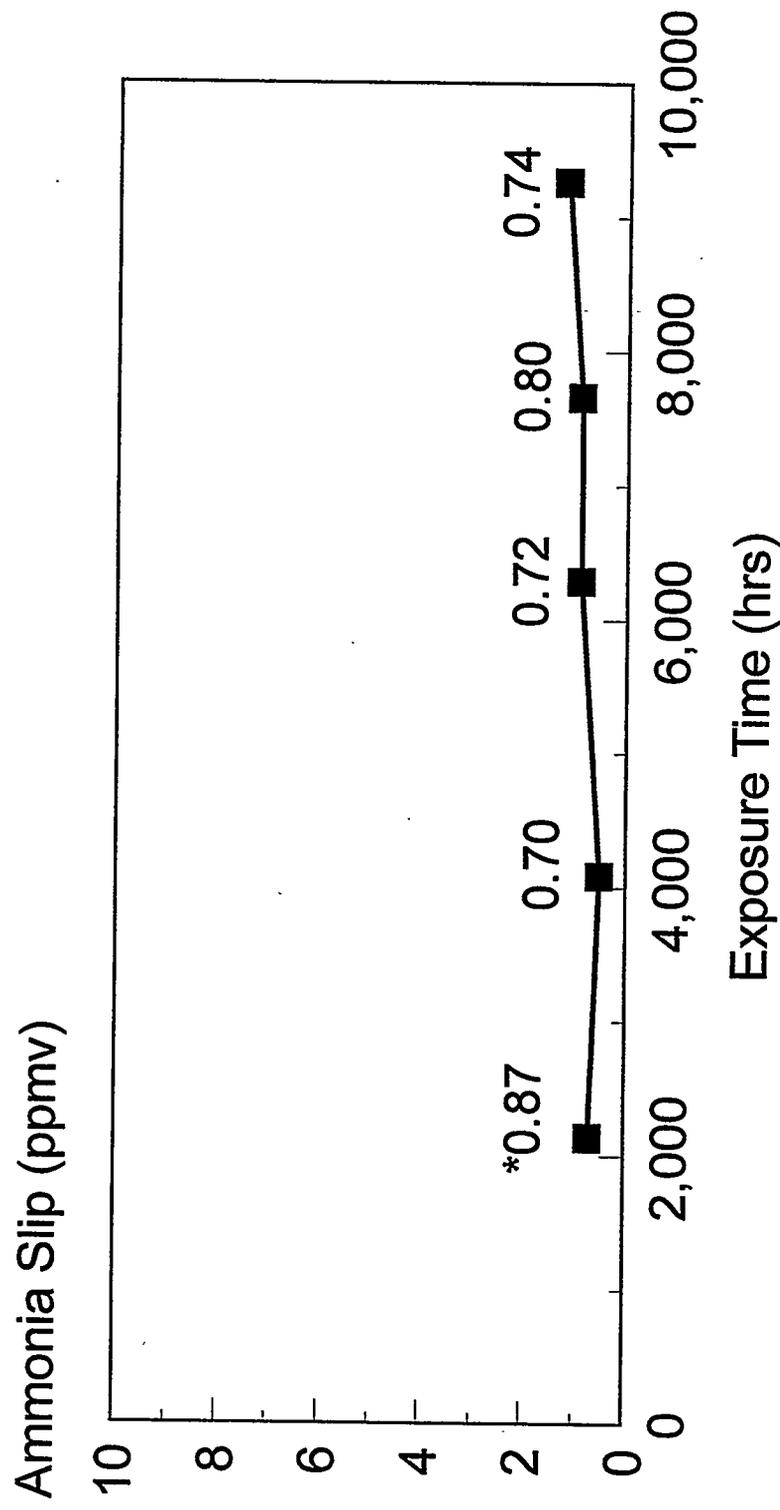


Exposure Time (hrs)

Cormetech High-Dust: NH3/NOx=0.8, 700F, 400 SCFM

\*Values equal actual ammonia-to-NOx ratios that correspond to given ammonia slip point

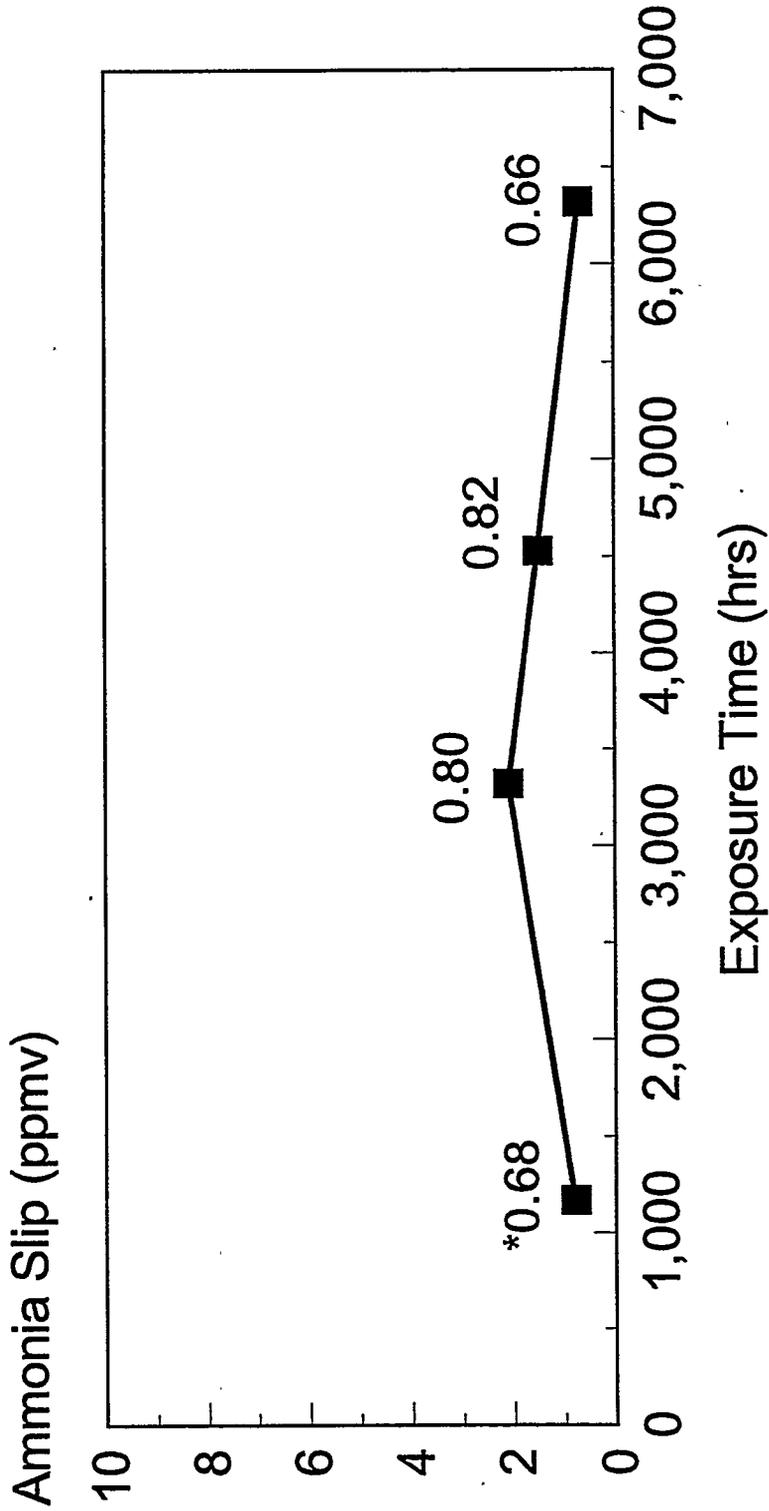
**Figure 5.4-19**  
**AMMONIA SLIP VS. TIME**



Haldor Topsoe: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 400 SCFM

\*Values equal actual ammonia-to-NO<sub>x</sub> ratios that correspond to given ammonia slip point

# Figure 5.4-20 AMMONIA SLIP VS. TIME

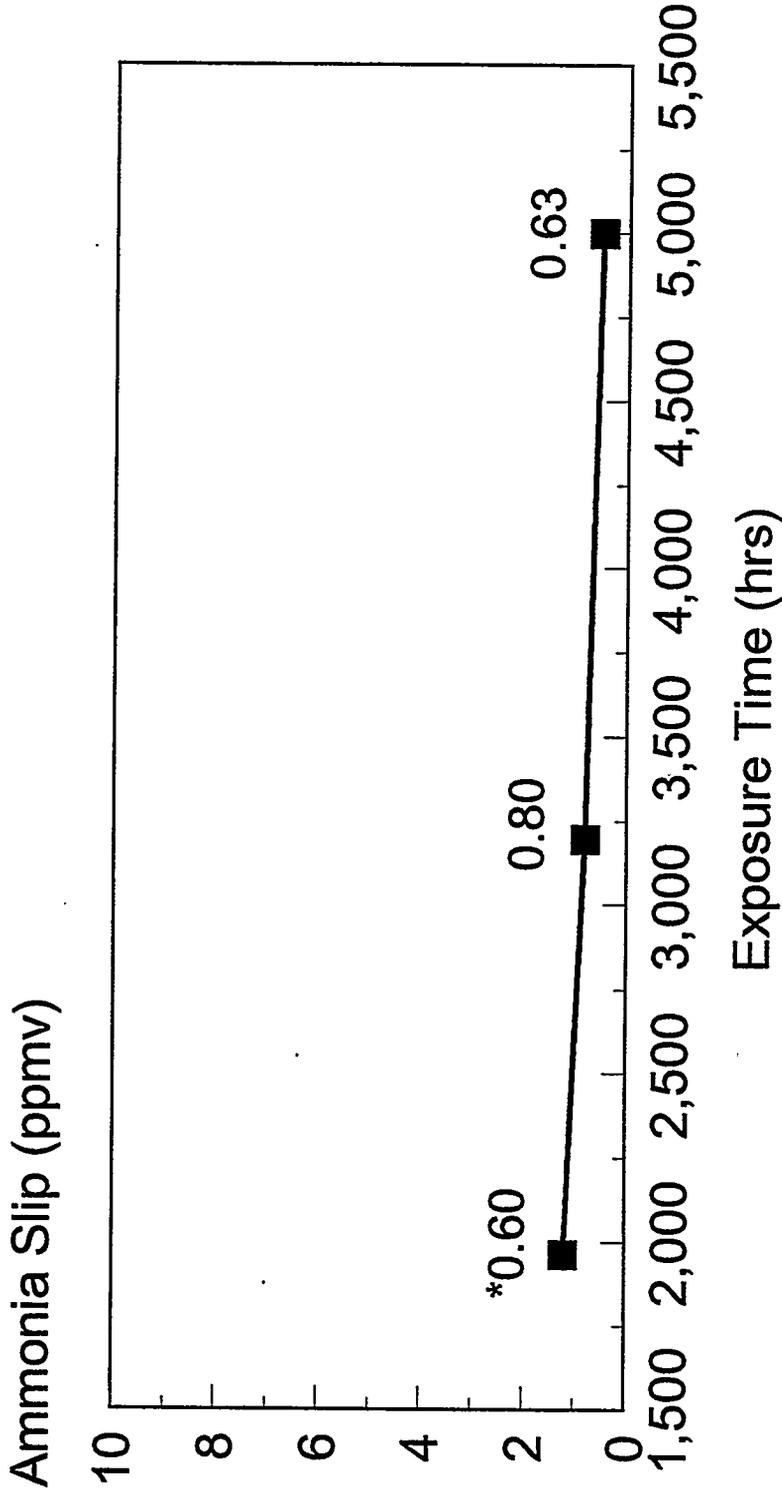


Hitachi Zosen:  $\text{NH}_3/\text{NO}_x=0.8$ , 700F, 400 SCFM

\*Values equal actual ammonia-to- $\text{NO}_x$  ratios that correspond to given ammonia slip point

# Figure 5.4-21

## AMMONIA SLIP VS. TIME



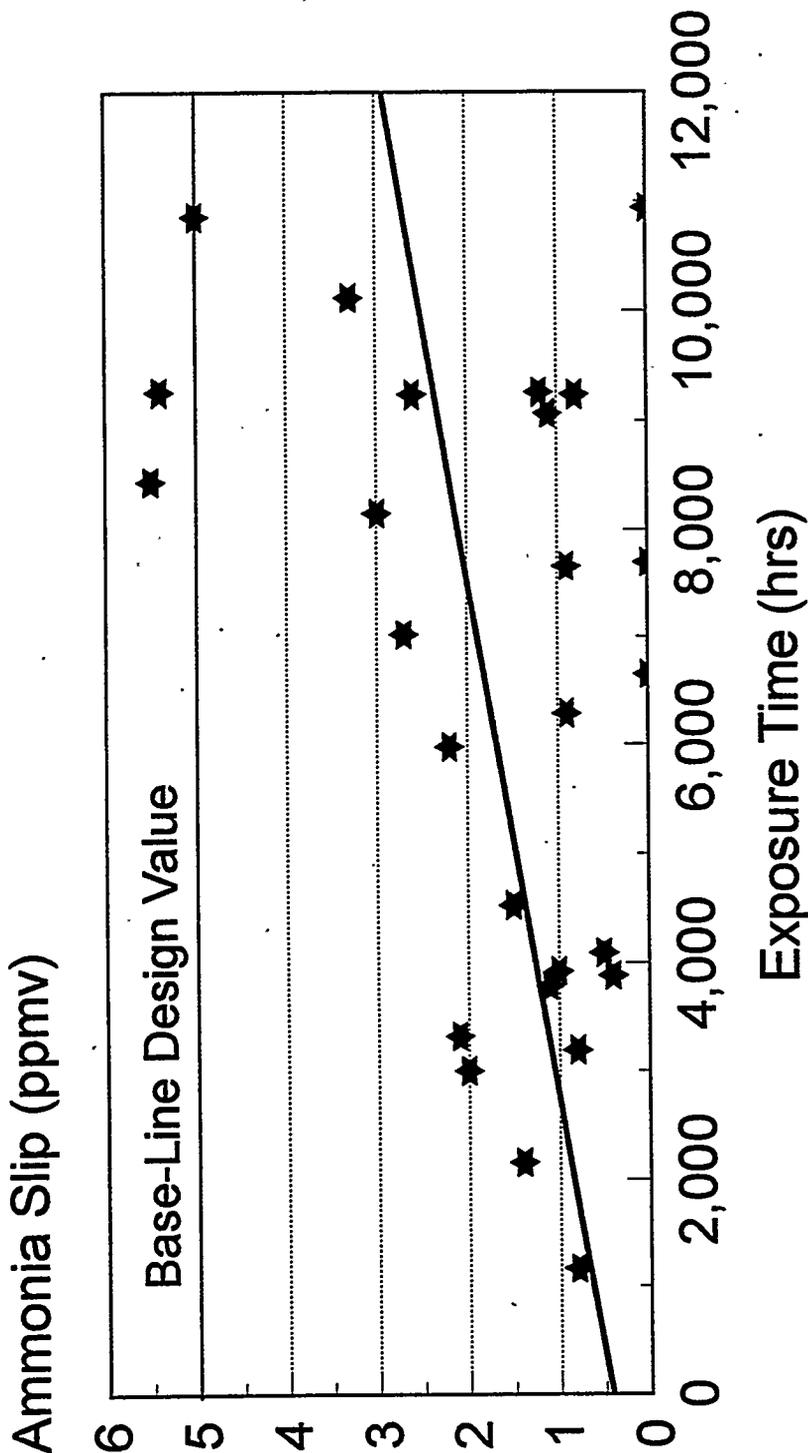
Cormetech Low-Dust: NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 400 SCFM

\*Values equal actual ammonia-to-NO<sub>x</sub> ratios

that correspond to given ammonia slip point

# Figure 5.4-22

## AMMONIA SLIP VERSUS EXPOSURE TIME AT BASE-LINE CONDITIONS

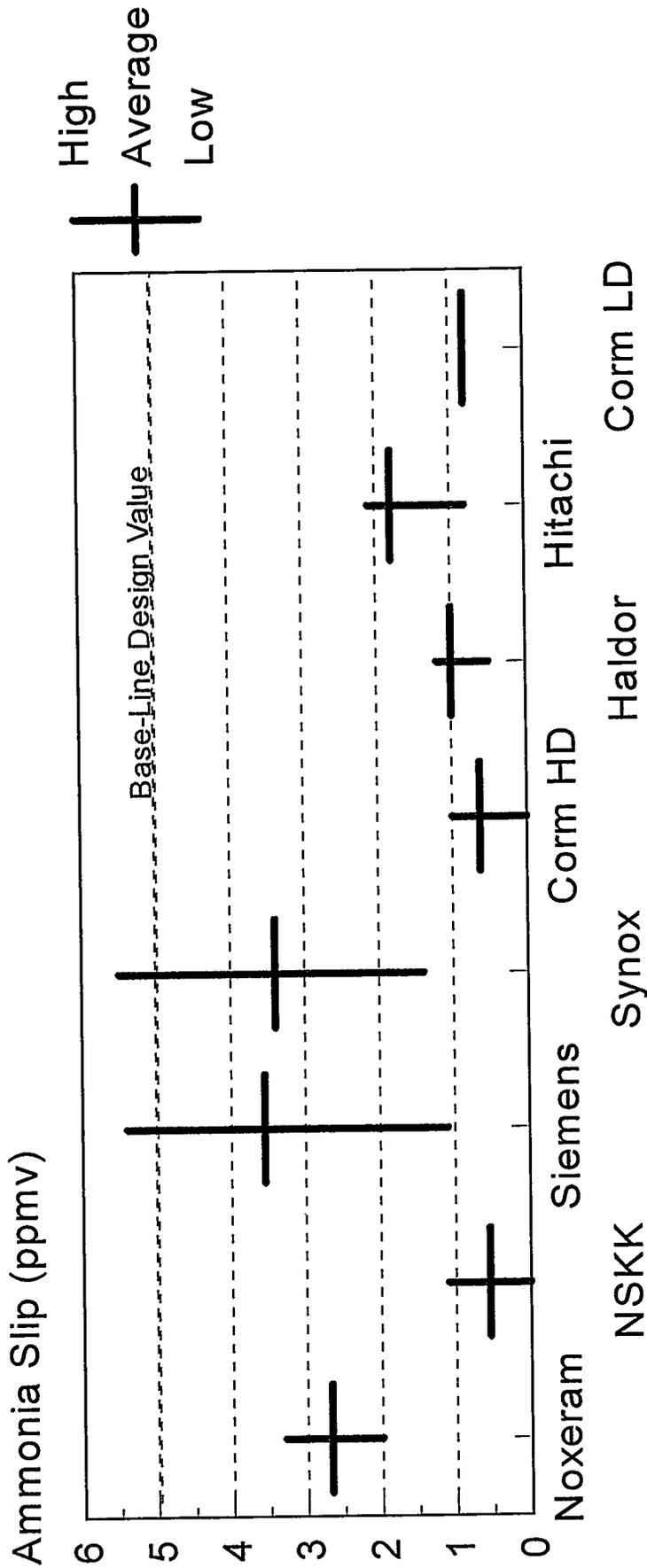


Values are for the Combination of All Reactors  
NH3/NOx=0.8, 700F, 100% Design Flow



**Figure 5.4-23**

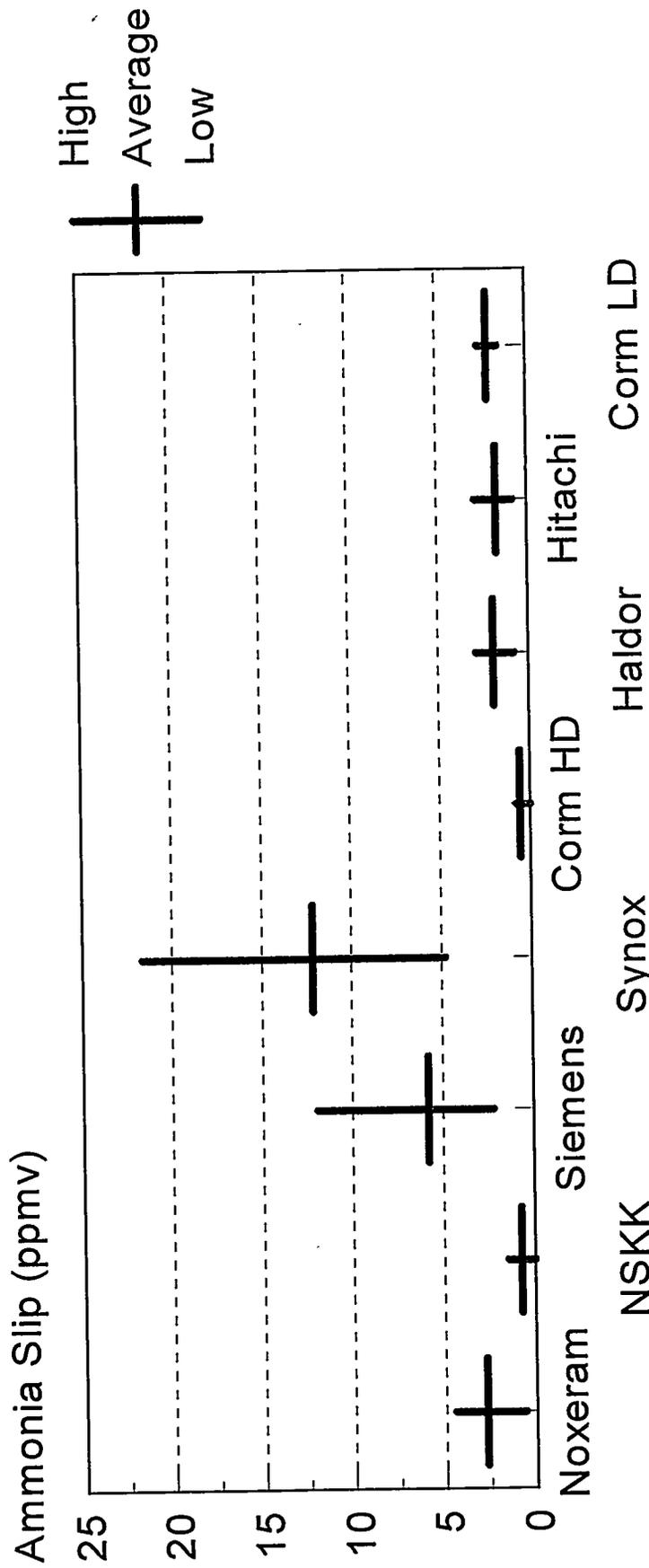
**Average Base-Line Ammonia Slip**



Condition 22  
 NH3/NOx=0.8, Design Temp, Design Flow



# Figure 5.4-24 Average Ammonia Slip

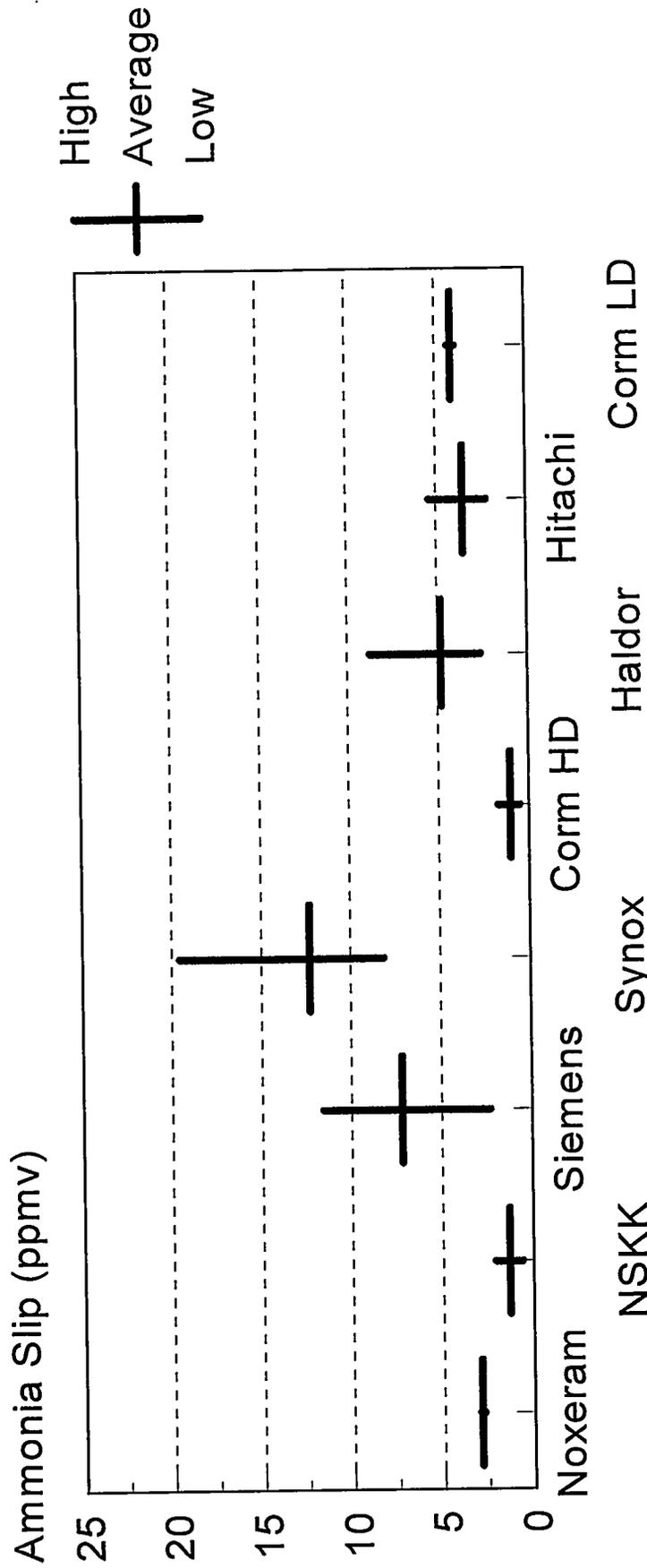


Condition 7  
 NH3/NOx=0.8, Low Temp, Design Flow



# Figure 5.4-25

## Average Ammonia Slip

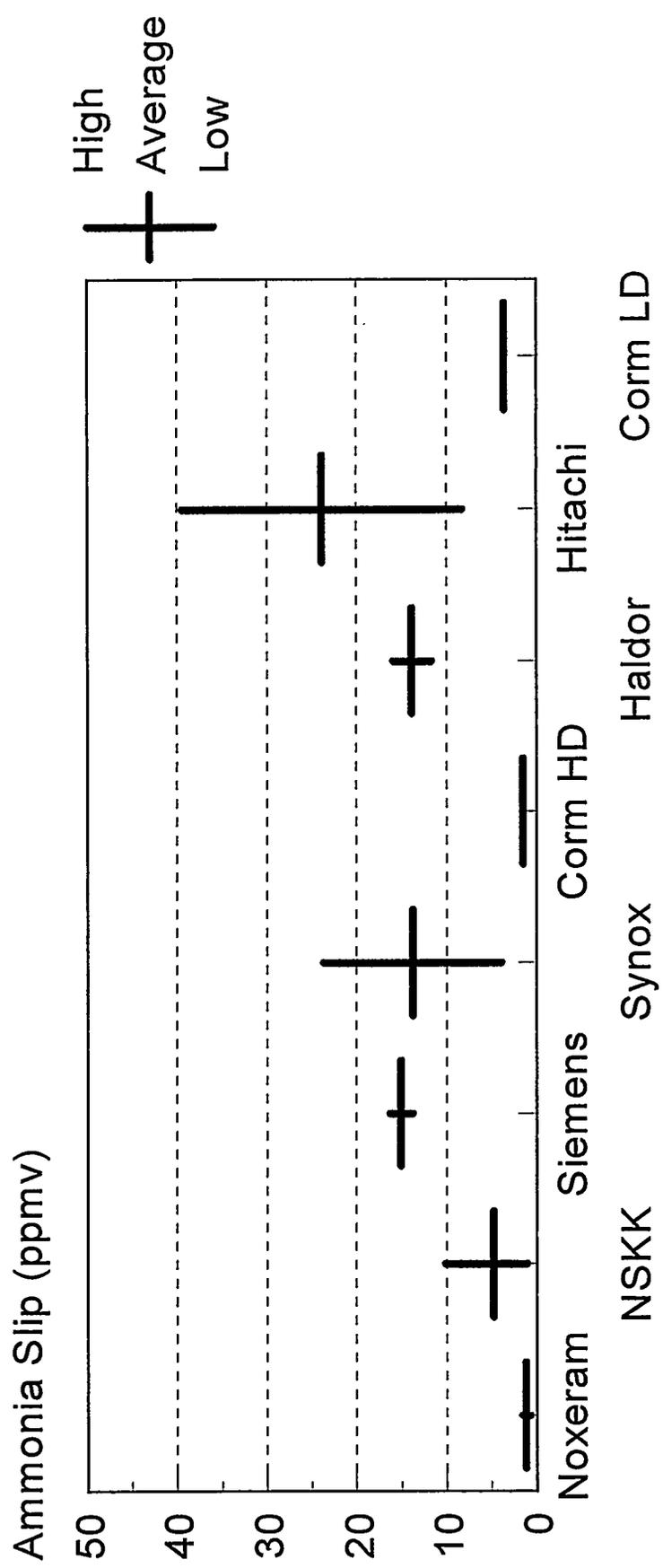


Condition 27  
 NH<sub>3</sub>/NO<sub>x</sub>=0.8, Design Temp, High Flow

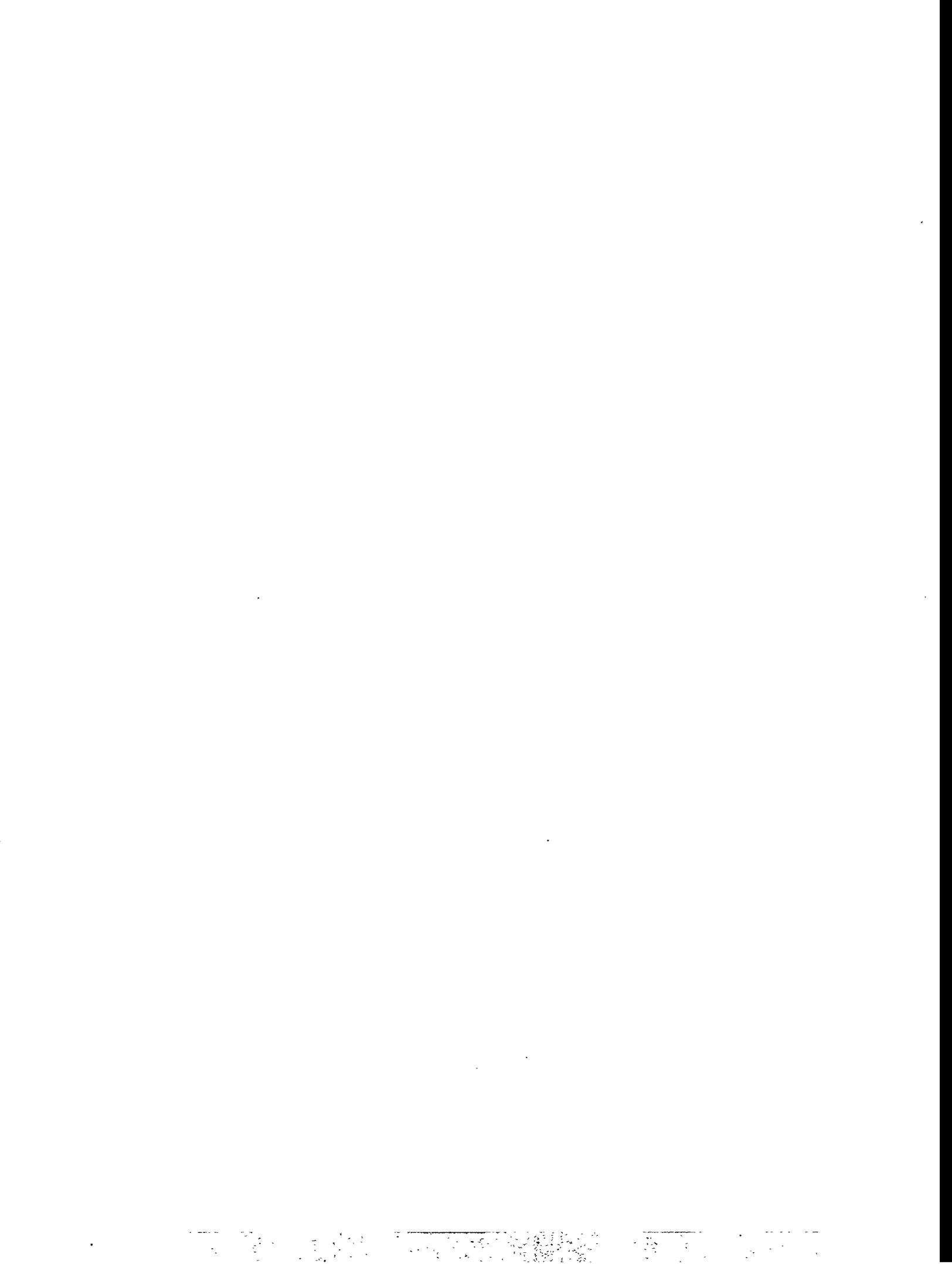


# Figure 5.4-26

## Average Ammonia Slip

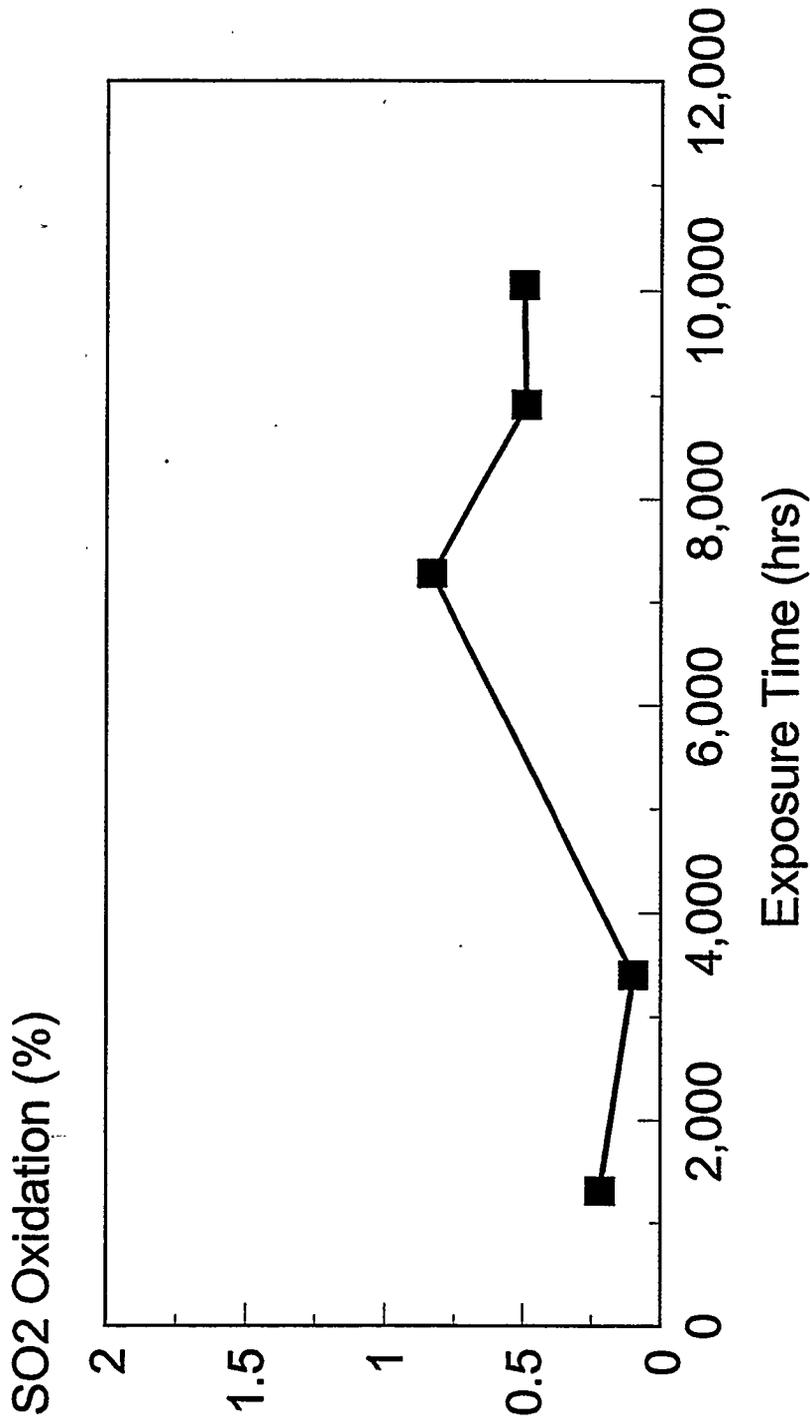


Condition 24  
 NH3/NOx=1.0, Design Temp, Design Flow Rate



# Figure 5.4-27

## SO2 Oxidation VS. Exposure Time

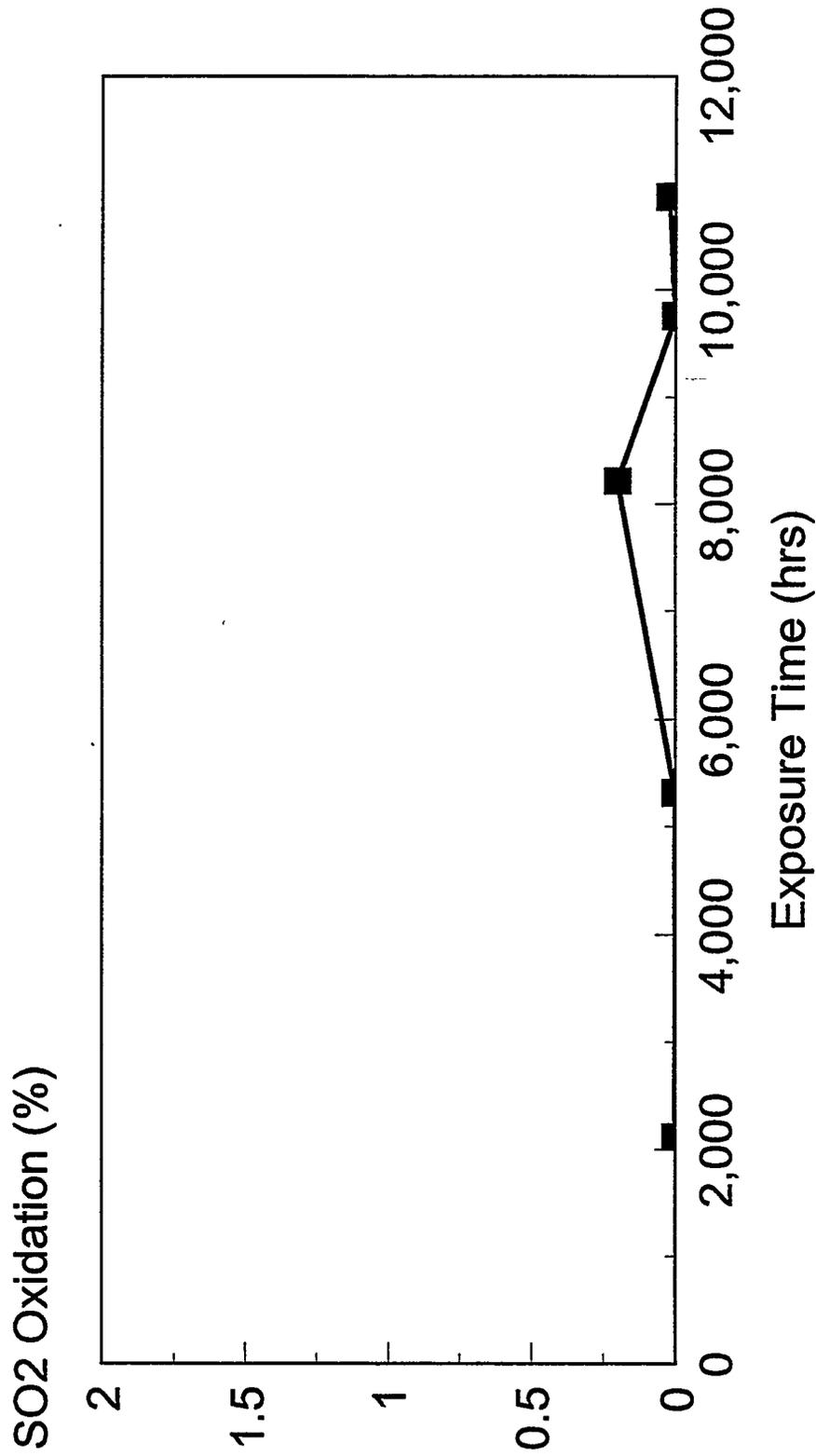


Grace Noxeram:

NH3/NOx=0.8, Design Temp, Design Flow

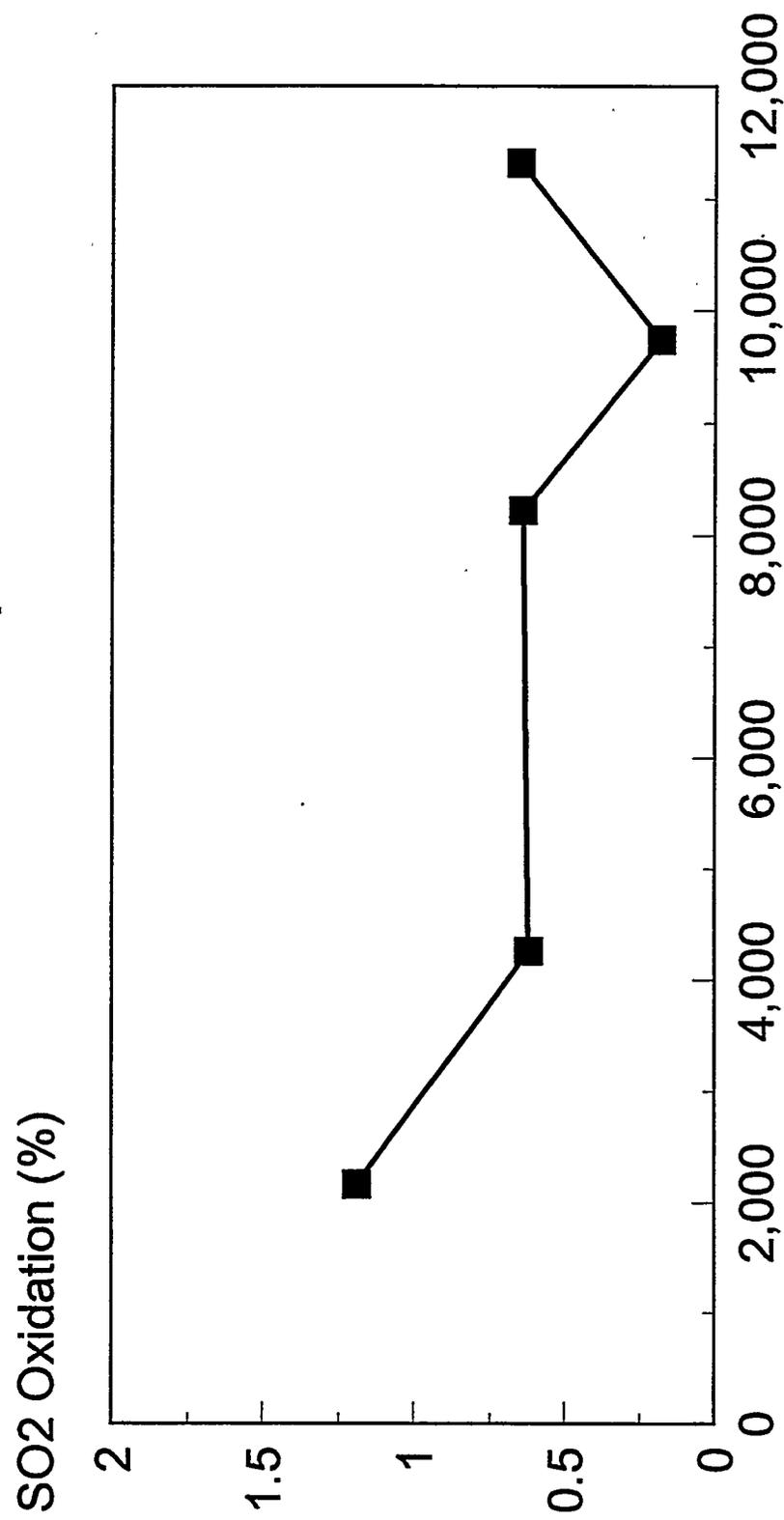
# Figure 5.4-28

## SO2 Oxidation VS. Exposure Time



# Figure 5.4-29

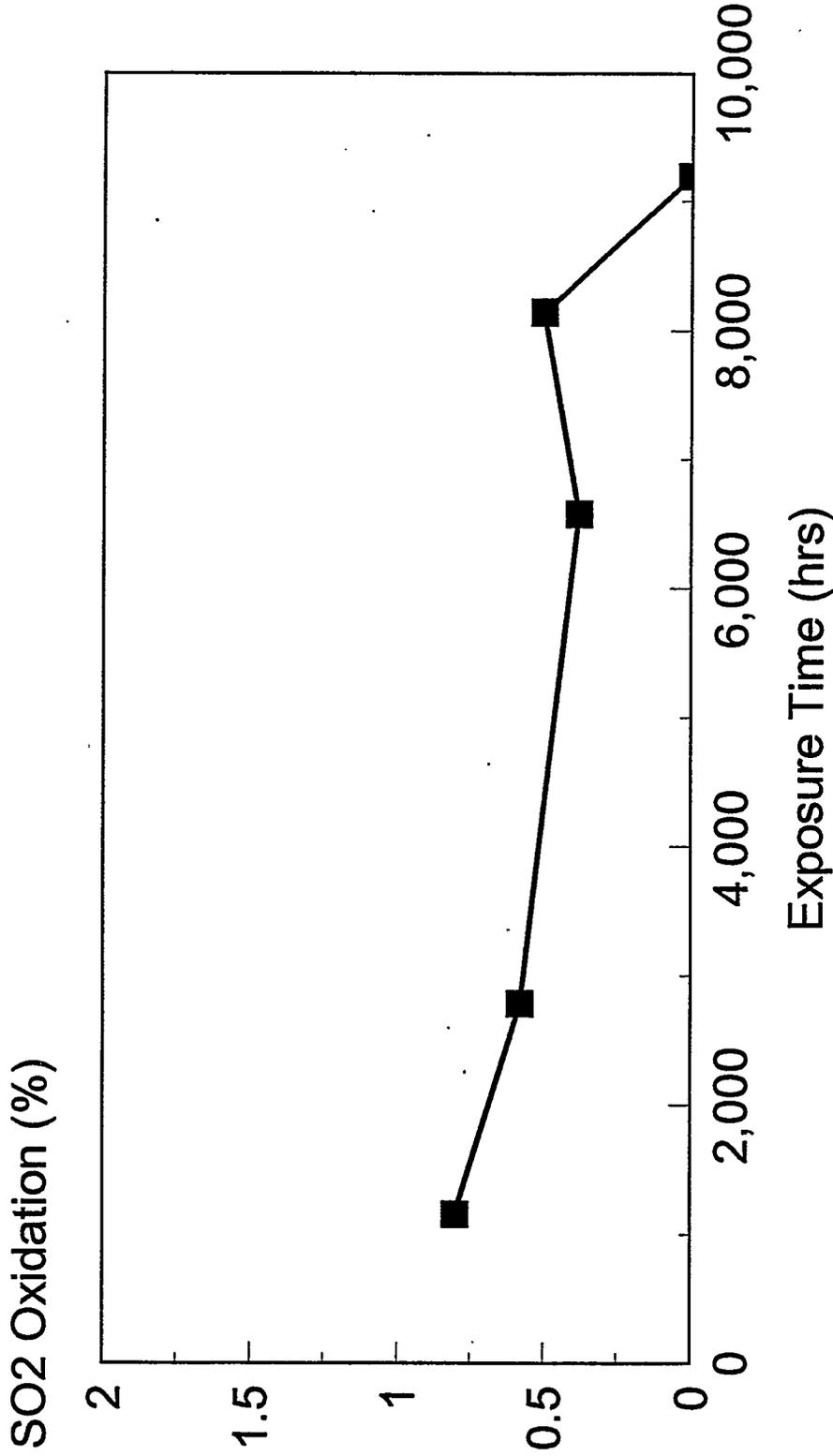
## SO2 Oxidation VS. Exposure Time



Siemens: NH3/NOx=0.8, 700F, 5000 SCFM

# Figure 5.4-30

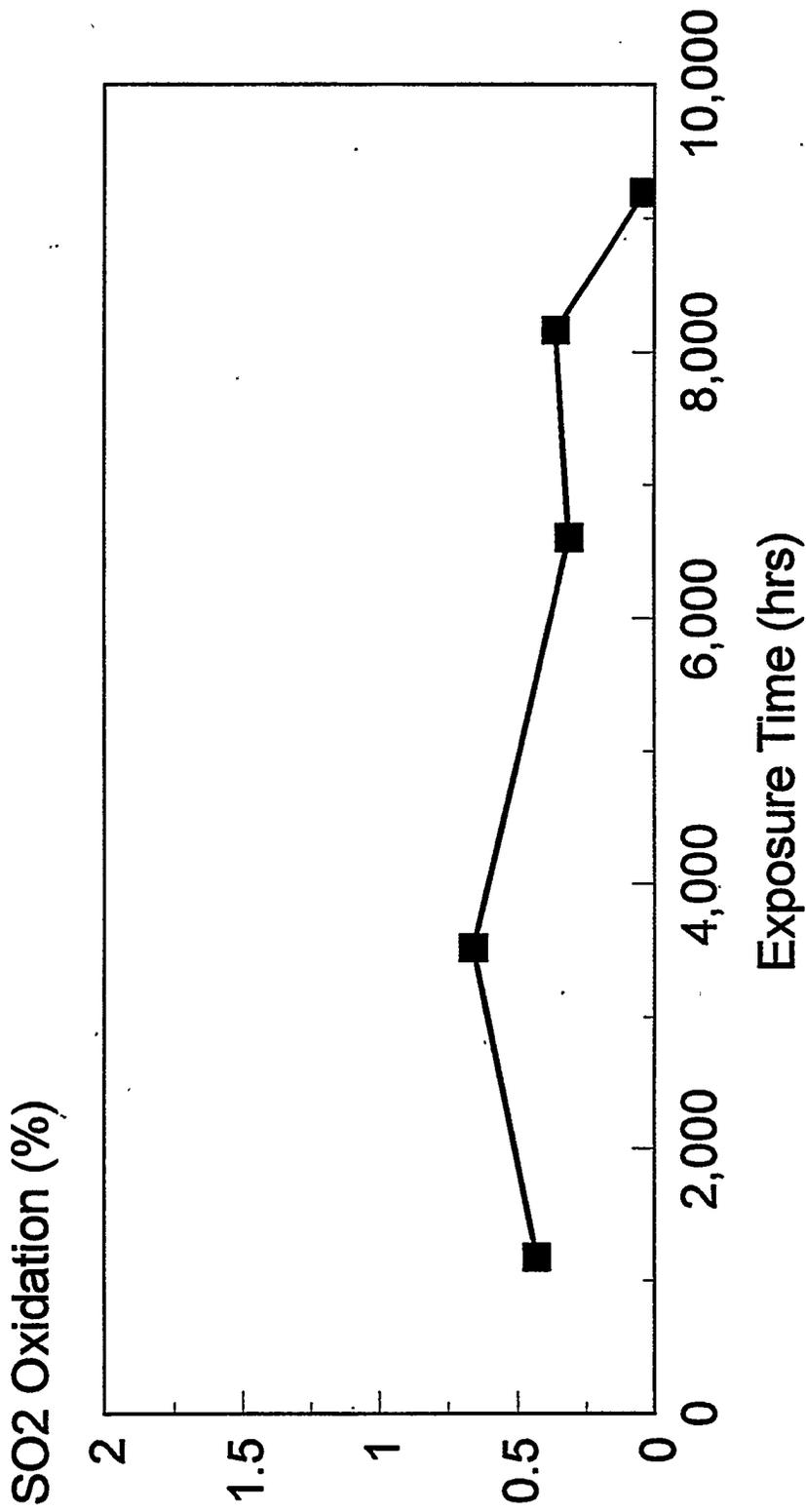
## SO2 Oxidation VS. Exposure Time



Grace Synox: NH3/NOx=0.8, 700F, 400 SCFM

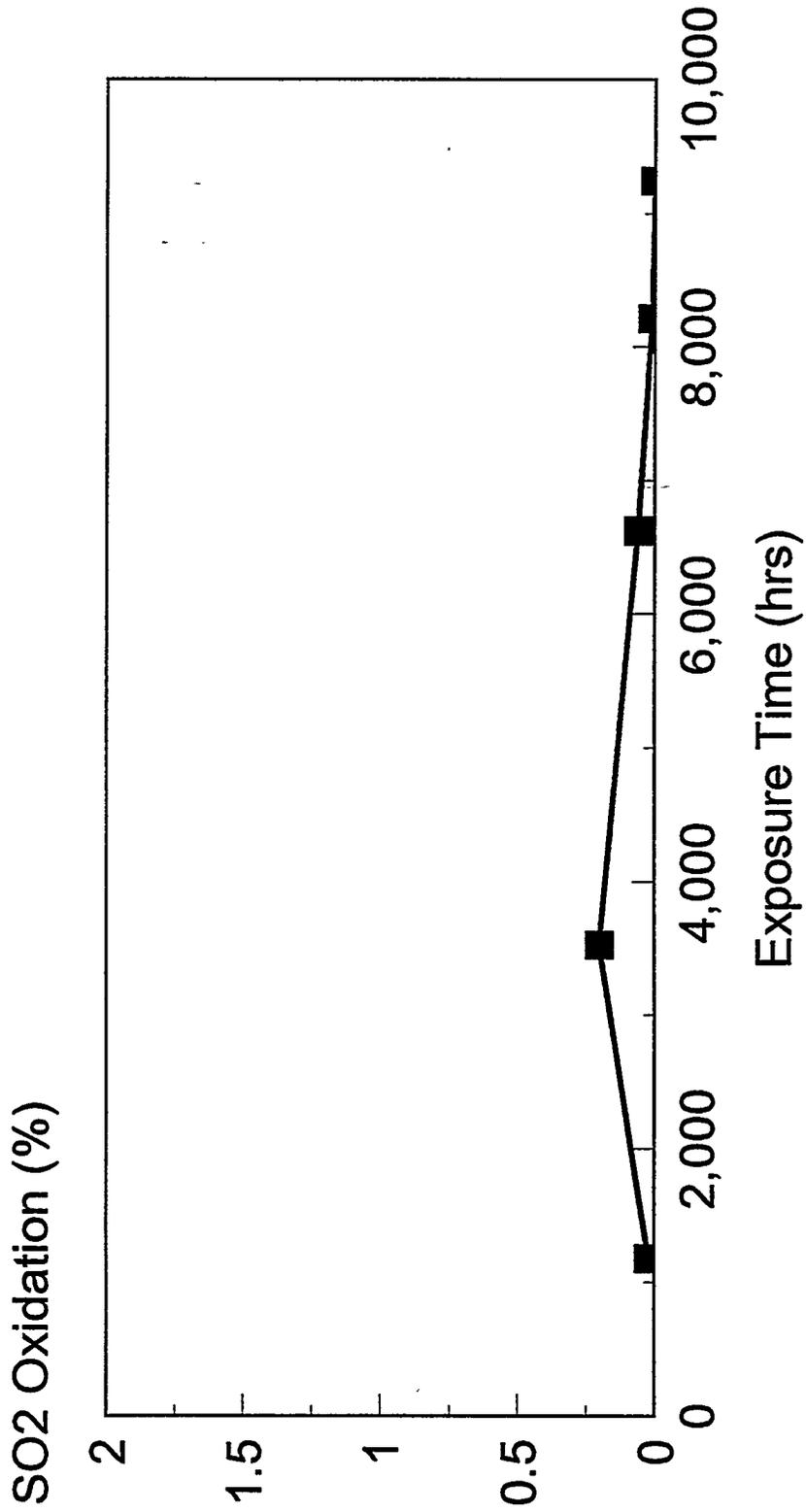
**Figure 5.4-31**

**SO<sub>2</sub> Oxidation VS. Exposure Time**



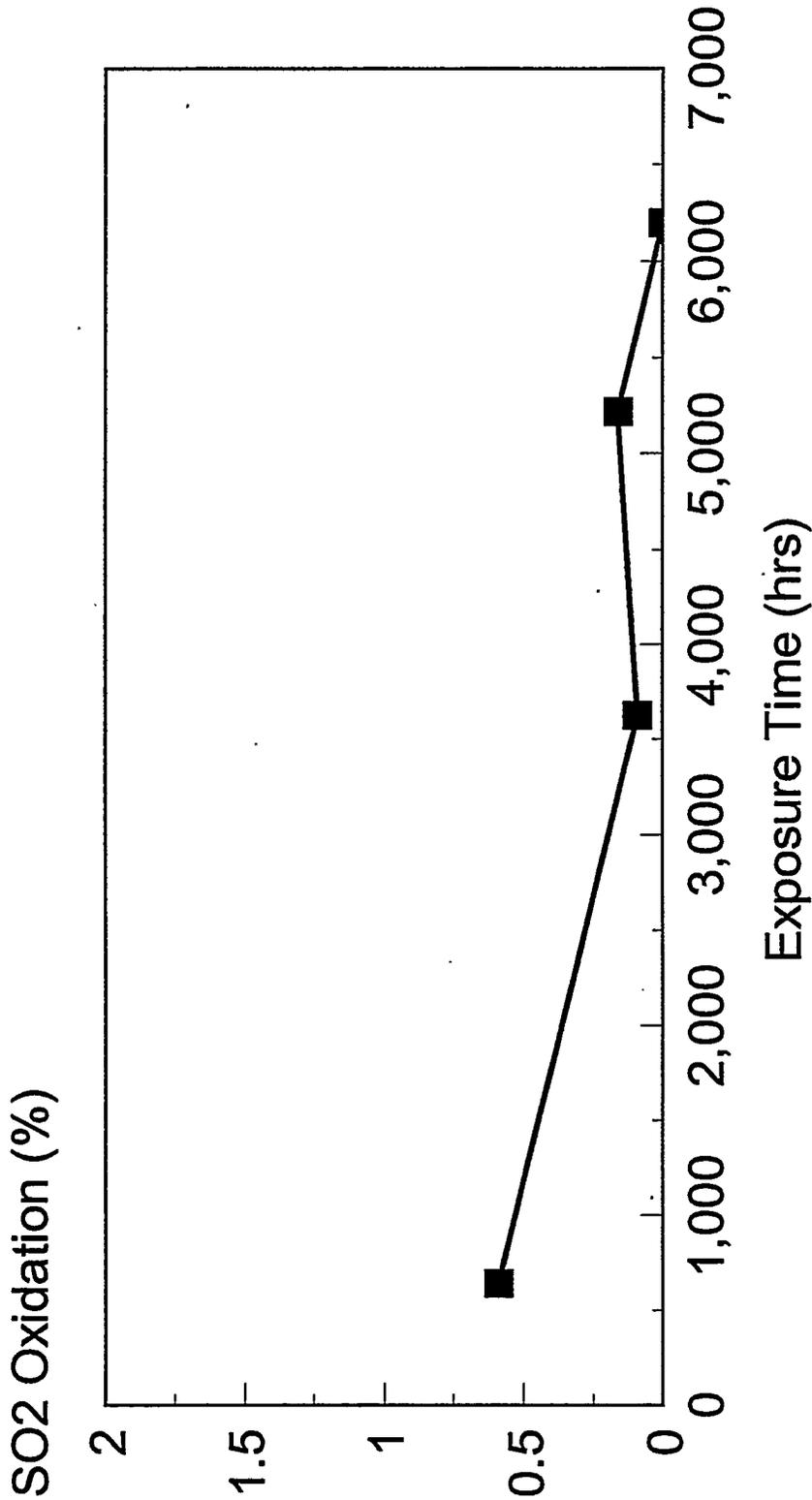
Cormetech High-Dust  
NH<sub>3</sub>/NO<sub>x</sub>=0.8, 700F, 400 SCFM

**Figure 5.4-32**  
**SO2 Oxidation VS. Exposure Time**



Haldor Topsoe  
NH3/NOx=0.8, 700F, 400 SCFM

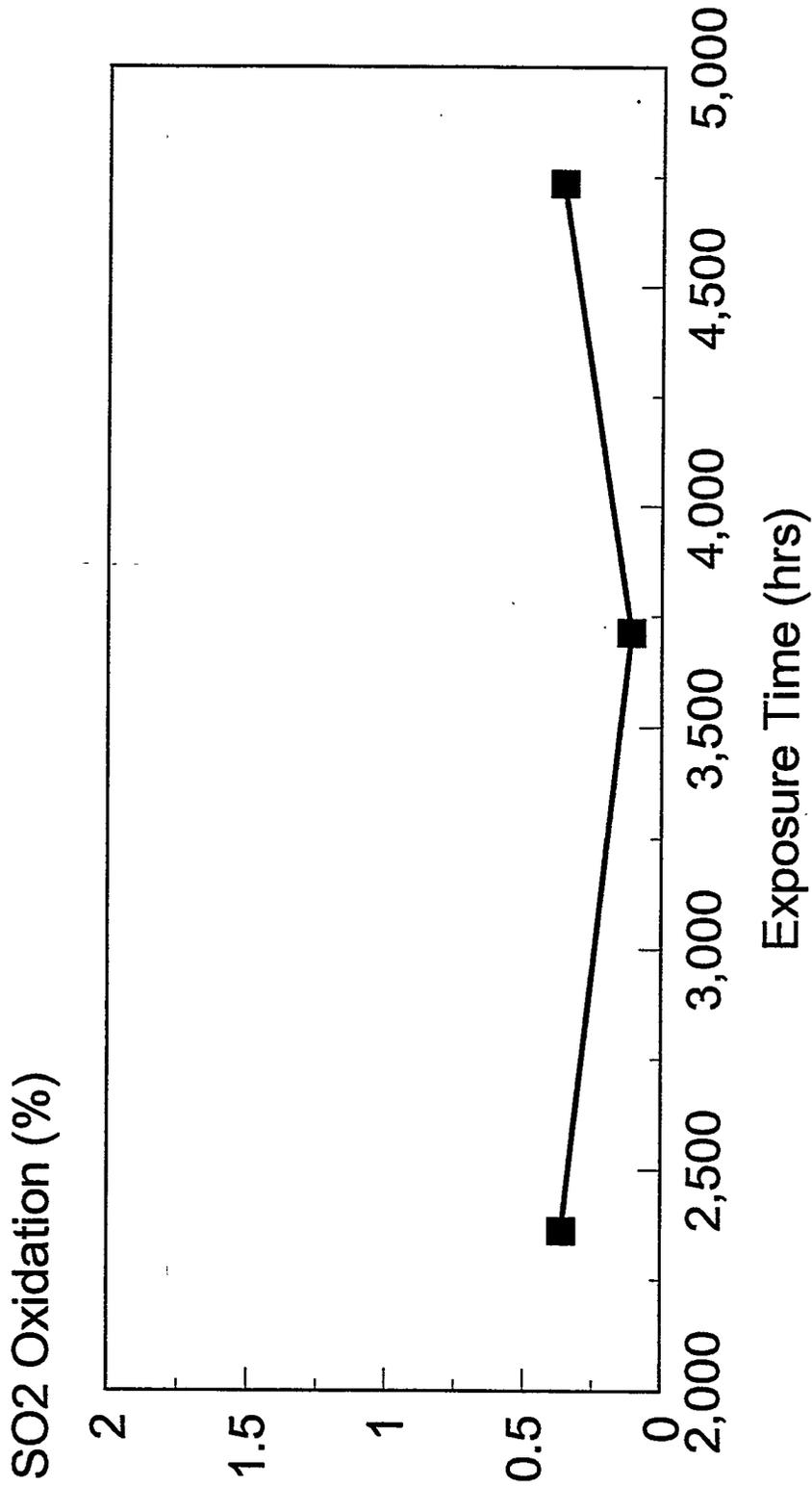
# Figure 5.4-33 SO2 Oxidation VS. Exposure Time



Hitachi Zosen  
NH3/NOx=0.8, 700F, 400 SCFM

# Figure 5.4-34

## SO2 Oxidation VS. Exposure Time

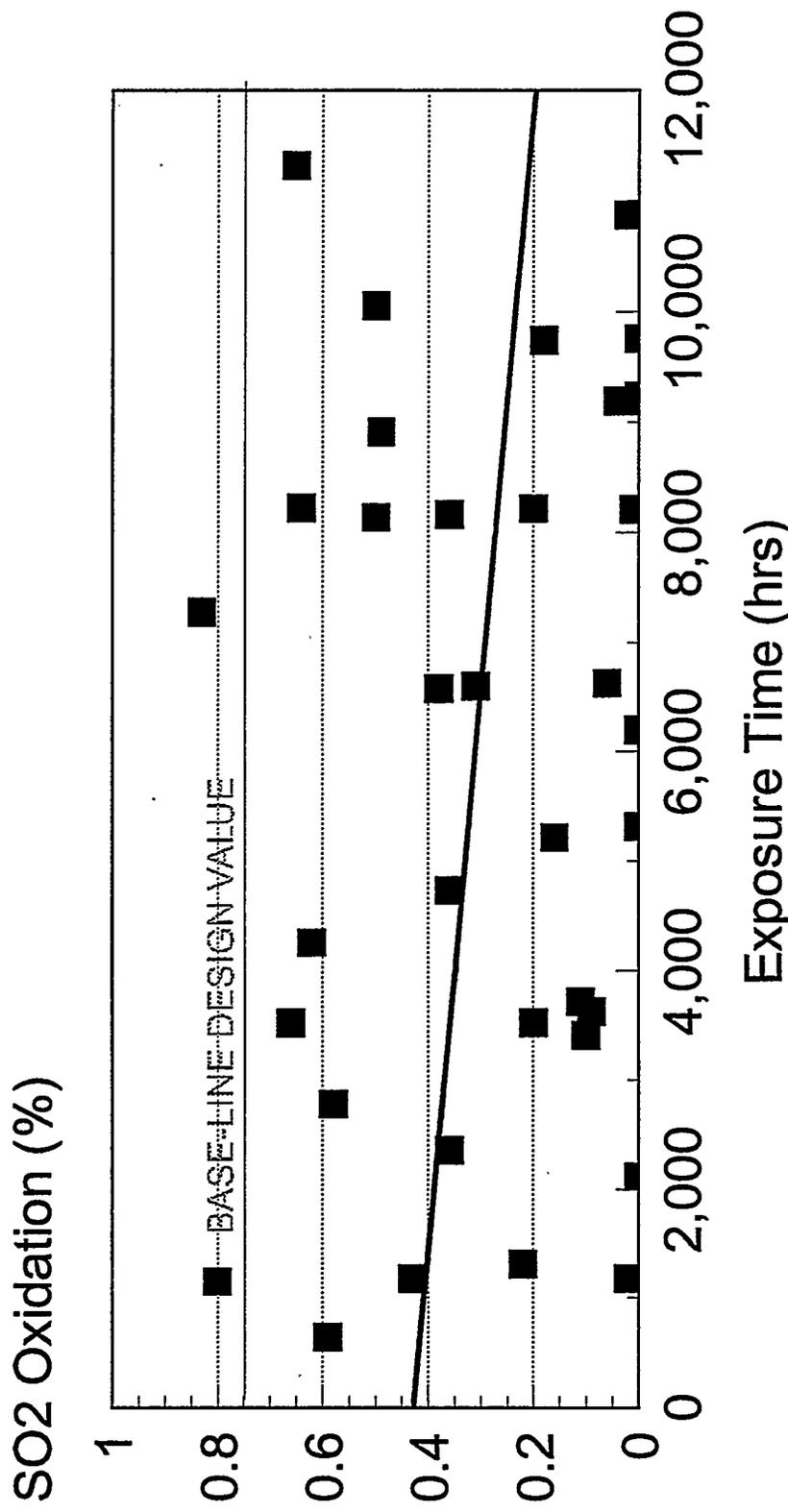


Cormetech Low-Dust

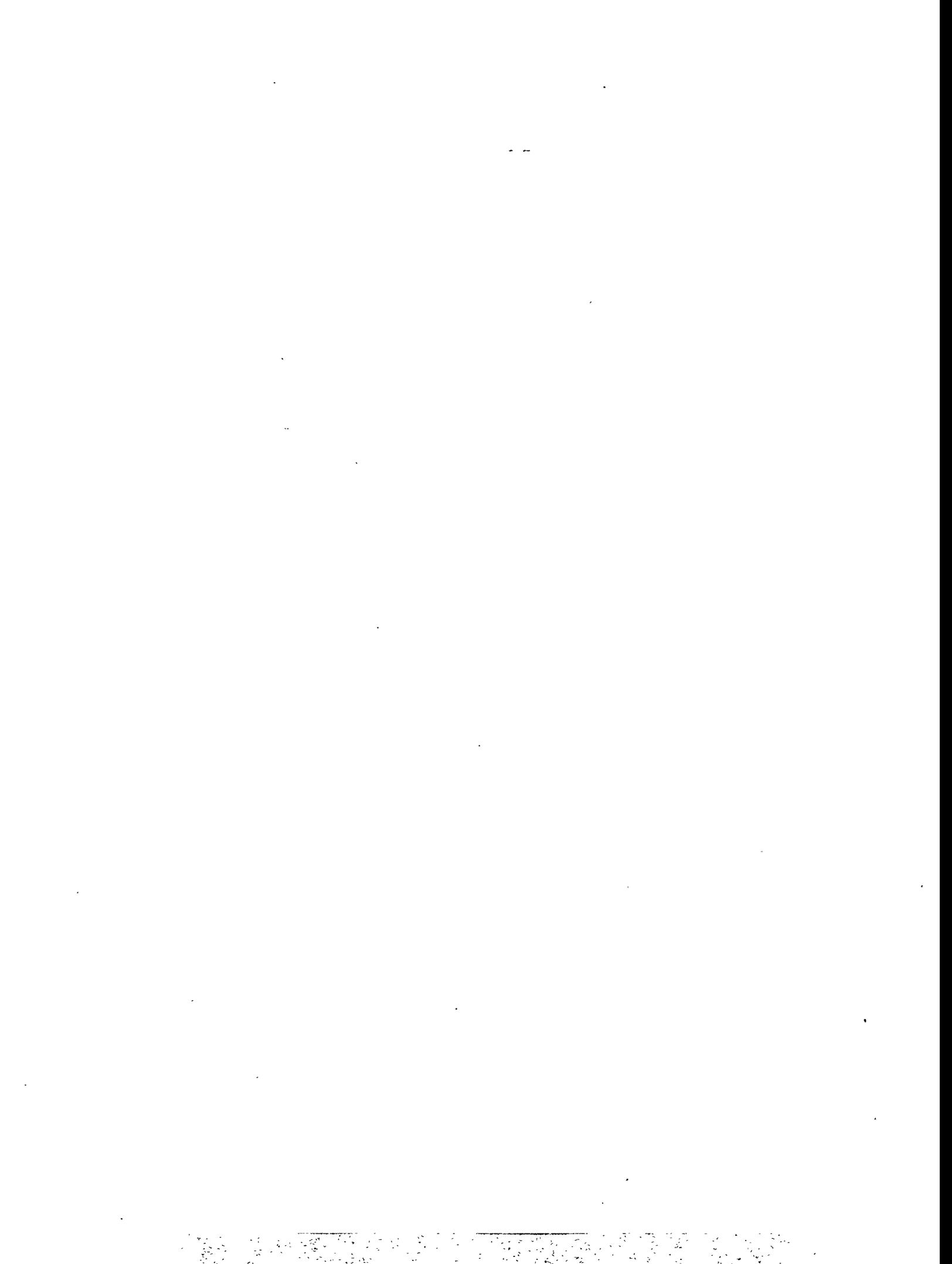
NH3/NOx=0.8, 700F, 400 SCFM

# Figure 5.4-35

## SO2 OXIDATION VERSUS EXPOSURE TIME AT BASE-LINE CONDITIONS

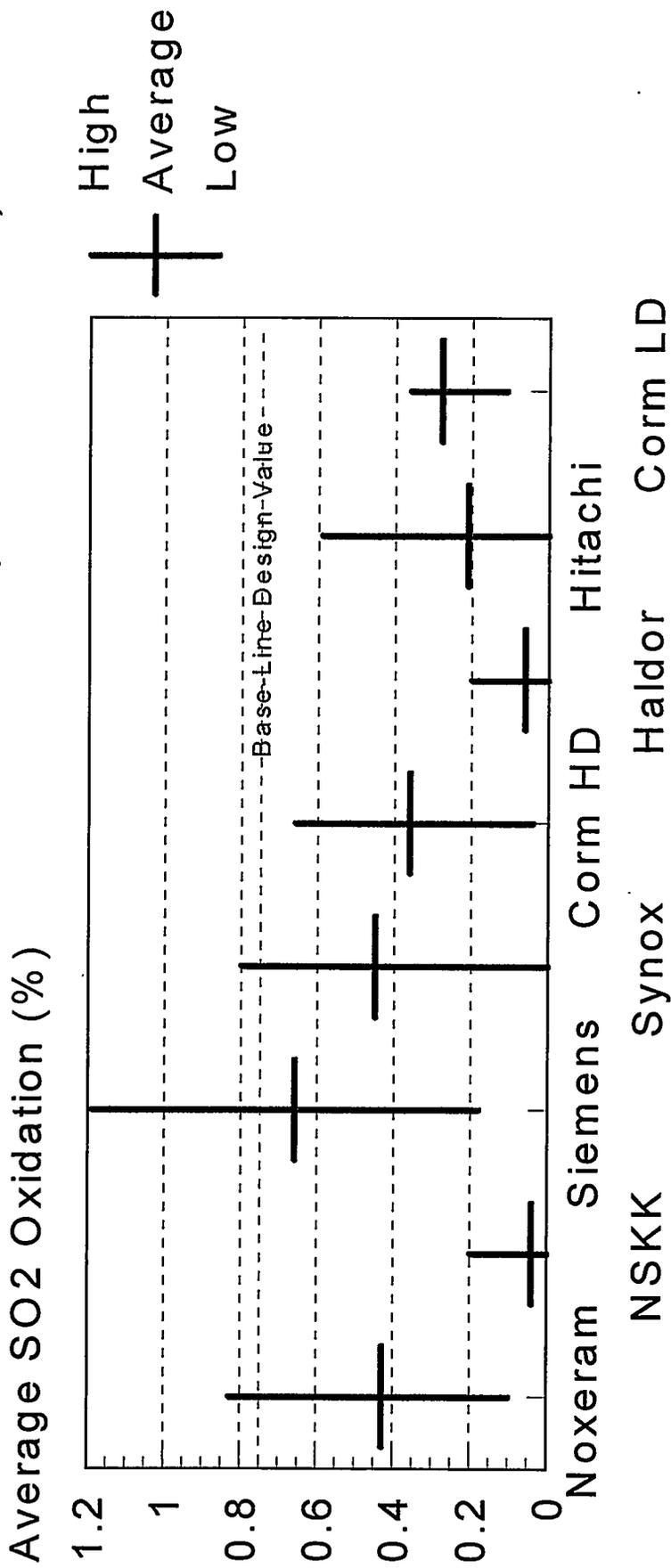


Values are for the combination of all reactors  
NH3/NOx=0.8, 700F, 100% Of Design Flow



# Figure 5.4-36

## Average SO<sub>2</sub> Oxidation (Base-Line)

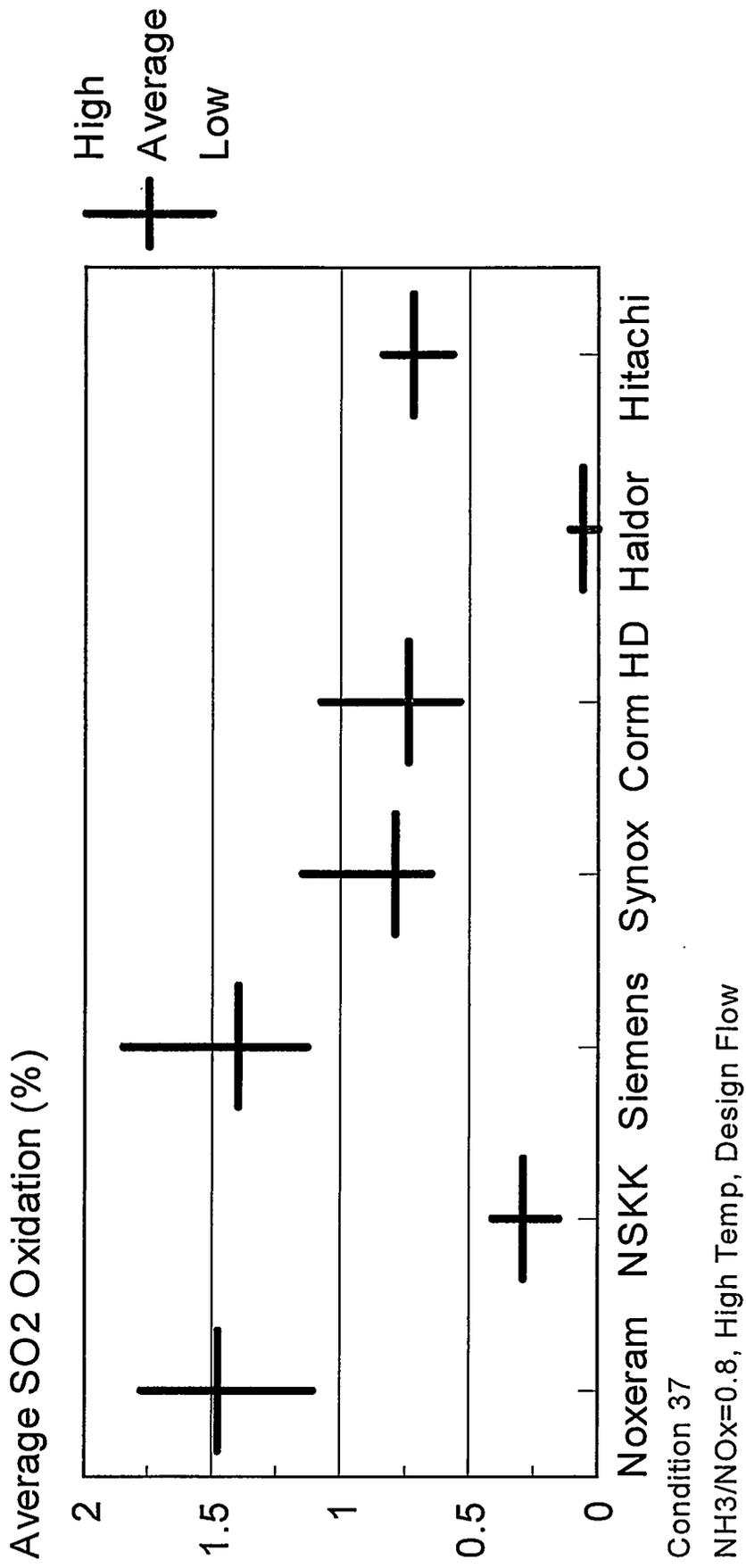


Condition 22  
 NH<sub>3</sub>/NO<sub>x</sub>=0.8, Design Temp, Design Flow



# Figure 5.4-37

## Average SO2 Oxidation





## **5.5 Air Preheater Evaluation**

The analysis of the test facility air preheaters is divided into three main areas: 1) manual test series evaluation, 2) continuous long-term data evaluation, and 3) evaluation by ABB Air Preheater, Inc. These three combine to form an overall assessment of the performance of air preheaters operating in conjunction with SCR technology.

### **5.5.1 Manual Air Preheater Test Series Evaluation**

Three manual test series were performed on each of the facility air preheaters during the life of the project. These manual tests were performed by SRI as part of certain parametric test sequences performed on the facility SCR reactors. Appendices N through P contain the detailed results of these test series. Summaries of the three series follow.

#### **5.5.1.1 First Manual Air Preheater Test Series**

The first series of manual tests on the facility air preheaters was conducted during late May and early April of 1994. Detailed results of these tests are reported in Appendix N. The air preheater testing included the determinations of particulate mass concentration and measurements of the concentrations of sulfur dioxide, sulfur trioxide, hydrogen chloride, and ammonia with manual sampling methods. Ammonia samples were segregated into solid and gas-phase fractions to characterize the gas/solid phase partitioning of ammonia across the air preheaters. Tests were performed at the inlet and outlet of each of the three air preheaters (except for mass concentration measurements at the outlet of the reactor C air preheater). The fly ash (particulate) catches from the mass concentration measurements were further analyzed in the laboratory to determine particle size distributions, ash mineralogy, and ash resistivity.

#### **5.5.1.1.1 Ammonia Concentrations**

Concentrations of ammonia were measured simultaneously at each of the three air preheater inlet and outlet test locations. The tests were conducted so as to differentiate between gas-phase and solid-phase ammonia. The majority of the ammonia was found in the solid phase. Most of the gas phase ammonia concentrations were below the detection limit, especially at the air preheater outlets. A measurable increase in ammonia in the solid phase was detected during operation at the higher  $\text{NH}_3/\text{NO}_x$  ratio during operation at Test Condition 24 (1.8 to 6.7 ppm (v) dry @ 3%  $\text{O}_2$  at Test Condition 24 high  $\text{NH}_3/\text{NO}_x$  ratio) versus 0.2 to 1.0 ppm (v) dry @ 3%  $\text{O}_2$  at Test Condition 22 (base-line) on reactors B and C).

#### **5.5.1.1.2 $\text{SO}_2$ and $\text{SO}_3$ Concentrations**

Concentrations of sulfur dioxide and sulfur trioxide were measured simultaneously at the air preheater inlet and outlet test locations of reactors A, B, and C during operation at base-line.  $\text{SO}_3$  inlet concentrations ranged from 8 to 19 ppm(v) dry @ 3%  $\text{O}_2$ , while  $\text{SO}_3$  concentrations at the reactor outlets ranged from 5 to 11 ppm(v) dry @ 3%  $\text{O}_2$ . Reductions in  $\text{SO}_3$  concentration across the air preheaters ranged from 37.5% on reactor B to 42.1% on reactor A. Within the tolerance of the standard deviations for the average  $\text{SO}_2$  concentrations, there was no measurable change in  $\text{SO}_2$  concentration across any of the three air preheaters. Air preheater inlet  $\text{SO}_2$  concentrations averaged  $2044 \pm 41$  ppm(v) dry @ 3%  $\text{O}_2$ , while the air preheater outlet  $\text{SO}_2$  concentrations averaged  $2095 \pm 34$  ppm(v) dry @ 3%  $\text{O}_2$ .

#### **5.5.1.1.3 HCl Concentration**

Measurements of the concentration of hydrogen chloride were conducted simultaneously at the inlet and outlet of each of the three large reactor air preheaters. All HCl

concentrations fell within the range of 221 to 233 ppm(v) dry @3% O<sub>2</sub>. There was no measurable change in HCl concentration across any of the three air preheaters.

#### **5.5.1.1.4 Mass Concentration**

Mass concentration was measured simultaneously at the inlet and outlet of the air preheaters on reactors A and B. Mass concentration was measured only at the inlet to the heat pipe air preheater on reactor C.

The average air preheater inlet mass concentrations ranged from  $3.42 \pm 0.12$  (reactor B) to  $3.84 \pm 0.17$  gr/dscf (reactor C). The reactor A inlet and outlet average mass concentration values were within one standard deviation of each other, while the reactor B average outlet mass concentration was 19% lower than the reactor B average inlet mass concentration.

#### **5.5.1.1.5 Particle Size Distributions**

The particulate collected in the Method 17 thimbles during the reactor inlet and outlet mass concentration tests was analyzed using a Shimadzu Model SA-CP4 Centrifugal Particle Size Analyzer to determine particle size distribution. The mass median diameters (Stokes' diameters) of the fly ashes ranged from 9.9 to 11.2 micrometers. The Stokes' or physical diameter is based on the assumption of spherical particles and the true, or actual, particle density. No significant change in mass median diameter across the air preheaters was evident in these data.

#### **5.5.1.1.6 Ash Mineralogy**

Fly ash samples collected during mass concentration tests at the air preheater inlet and outlet test locations were submitted for ash mineralogy tests. Fly ash samples were available for air preheater inlets on reactors A, B, and C and for the air preheater outlets

on reactors A and B (no test ports were available on the outlet of APH C). No fly ash samples were collected at the outlet of the reactor C air preheater. There were no significant differences in the chemical constituents of the fly ash between the air preheater inlets and outlets or among the three air preheaters.

#### **5.5.1.1.7 Ash Resistivity**

Laboratory measurements of ash resistivity were conducted on fly ash samples collected at the inlet and outlet of the three large reactor air preheaters, except the outlet of the reactor C air preheater. The resistivity/temperature relationships for the five ash samples are very similar. For all of the ash samples the peak in the resistivity, ranging from  $4.5 \times 10^{11}$  to  $1 \times 10^{12}$  ohm-cm, occurred at about 300 °F. These ash resistivities are similar to those measured during previous tests on ashes collected from the Unit 5 ESP inlet duct.

#### **5.5.1.2 Second Manual Air Preheater Tests Series**

The second series of manual tests on the facility air preheater was conducted at the beginning (June 1994) and end (October 1994) of the third sequence of parametric testing on the SCR reactors. Detailed results of these tests are presented in Appendix O. The tests in June 1994 (SO<sub>2</sub>, SO<sub>3</sub>, and particulate mass concentrations) were specifically conducted to establish a set of base-line performance values. (The air preheaters had been washed and a partial replacement of baskets had occurred on the two rotary air preheaters (A and B) during the May/June 1994 outage).

The air preheater testing included the determinations of particulate mass concentration and measurements of the concentrations of sulfur dioxide, sulfur trioxide, hydrogen chloride, and ammonia with manual sampling methods. Ammonia samples were segregated into solid and gas-phase fractions to characterize the gas/solid phase partitioning of ammonia across the air preheaters. Tests were performed at the inlet and outlet of each of the two rotary air preheaters and the outlet of the reactor C air preheater. Only the outlet of the

reactor C air preheater was sampled, due to the absence of an appropriate sampling location at the air preheater inlet.

#### 5.5.1.2.1 Ammonia Concentrations

At the air preheater inlets, during measurements conducted in October 1994, the ammonia present was divided roughly equally between gas phase and solid phase. At the air preheater outlets, the gas phase ammonia concentrations were below the detection limit, indicating that nearly all of the ammonia present had partitioned to the solid phase.

As expected, there was a measurable increase in ammonia concentration in both the gas and solid phases at the air preheater inlets during operation at the high  $\text{NH}_3/\text{NO}_x$  ratio at Test Condition 24 compared to Test Condition 22. At both parametric operating conditions, slip ammonia partitioned mostly to the solid phase at the air preheater exit after being cooled while passing through the air preheater.

#### 5.5.1.2.2 $\text{SO}_2$ and $\text{SO}_3$ Concentrations

In June 1994  $\text{SO}_3$  inlet concentrations (at base-line) ranged from 10 to 19 ppm(v) dry @ 3%  $\text{O}_2$ , while  $\text{SO}_3$  concentrations at the reactor outlets ranged from 10 to 16 ppm(v) dry @ 3%  $\text{O}_2$ . Reductions in  $\text{SO}_3$  concentration across the air preheaters ranged from 0% on reactor B to 11% on reactor A to 32% on reactor C. Within the tolerance of the standard deviations given for average  $\text{SO}_2$  concentrations, there was only a slight increase in  $\text{SO}_2$  concentration across the individual air preheaters. The reason for this slight increase in concentration is not known. Air preheater inlet  $\text{SO}_2$  concentrations averaged  $2038 \pm 191$  ppm(v) dry @ 3%  $\text{O}_2$ , while the air preheater outlet  $\text{SO}_2$  concentrations averaged  $2143 \pm 179$  ppm(v) dry @ 3%  $\text{O}_2$ .

In October 1994, SO<sub>2</sub> and SO<sub>3</sub> concentrations were measured at the split inlet upstream of the three large reactors. The average SO<sub>2</sub> concentration was 1880 ± 11 ppm(v) dry @ 3% O<sub>2</sub> and the average SO<sub>3</sub> concentration was 1.3 ± 0.01 ppm(v) dry @ 3% O<sub>2</sub>.

During the October 1994 tests, SO<sub>3</sub> concentrations at the air preheater inlets ranged from 3.8 to 21.7 ppm(v) dry @ 3% O<sub>2</sub>, while SO<sub>3</sub> concentrations at the air preheater outlets ranged from 7.3 to 15.6 ppm(v) dry @ 3% O<sub>2</sub>. Changes in SO<sub>3</sub> concentrations across the air preheaters ranged from factors of 0.72 on reactor A to 2.52 on reactor B to 1.78 on reactor C.

Within the tolerance of the standard deviations given for the average SO<sub>2</sub> concentrations, there were measurable reductions in SO<sub>2</sub> concentrations across the individual air preheaters. The reason for these rather large decreases in SO<sub>2</sub> concentrations is not known. SO<sub>2</sub> concentrations changed by factors of 0.75 (reactor A), 0.85 (reactor B), and 0.76 (reactor C). Overall, air preheater inlet SO<sub>2</sub> concentrations averaged 1,957 ± 71 ppm(v) dry @ 3% O<sub>2</sub>, while the air preheater outlet SO<sub>2</sub> concentrations averaged 1,539 ± 165 ppm(v) dry @ 3% O<sub>2</sub>.

#### **5.5.1.2.3 HCl Concentrations**

Air preheater inlet HCl concentrations, measured in October 1994, fell within the range of 92.8 to 101 ppm(v) dry @ 3% O<sub>2</sub>. Air preheater outlet HCl concentrations fell within the range of 81.1 to 93.1 ppm(v) dry @ 3% O<sub>2</sub>. The decrease in HCl concentration across the air preheaters ranged from 7.8% on reactor B to 14.9% on reactor C. The specific cause for this reduction in HCl concentration across the reactor air preheaters is not known at this time.

#### **5.5.1.2.4 Mass Concentrations**

The average air preheater outlet mass concentrations, measured during base-line performance tests in June 1994, were  $2.48 \pm 0.12$  gr/dscf for the reactor A air preheater and  $2.34 \pm 0.04$  gr/dscf for the reactor B air preheater. Mass concentration was not measured at the outlet of the reactor C air preheater.

#### **5.5.1.3 Third Manual Air Preheater Test Series**

The third series of manual tests on the facility air preheater was conducted in November and December of 1994. Detailed results of these tests are presented in Appendix P. Air preheater testing included the determinations of particulate mass concentration (inlet and outlet of reactor A and B air preheaters) and measurements of the concentrations of sulfur dioxide, sulfur trioxide, hydrogen chloride and ammonia (inlet and outlet of reactor A, B and C air preheaters). All tests were conducted with manual sampling methods.

Ammonia samples were segregated into solid and gas-phase fractions to characterize the gas/solid phase partitioning of ammonia across the air preheaters. In general, simultaneous tests for gaseous species were performed at the inlet and outlet of each of the three air preheaters. In addition, ash mineral analyses and the measurement of the concentrations of twenty trace metals were conducted on the fly ash samples collected at the inlet and outlet of the air preheaters on reactor A and B. Also, a portion of the air preheater outlet fly ash samples from reactors A and B were submitted for laboratory resistivity measurements.

##### **5.5.1.3.1 Ammonia Concentrations**

Concentrations of ammonia were measured simultaneously at each of the three air preheater inlet and outlet test locations during December 1994. The ammonia concentration tests conducted downstream of catalyst layer 3 (air preheater inlet) and at the air preheater outlets on reactors A, B, and C were designed to segregate the ammonia

into gas and solid phases. All three air preheaters were tested with the reactors operating at Test Conditions 22 and 24. Test Condition 22, the base-line or normal long-term operating condition, has a flow rate of 5,000 wscfm, a flue gas temperature of 700 °F, and a  $\text{NH}_3/\text{NO}_x$  ratio of 0.8. The operating parameters for Test Condition 24 are the same, except that the  $\text{NH}_3/\text{NO}_x$  ratio is 1.0.

At the inlet of each air preheater the volumetric concentration of ammonia was generally split evenly between the gas and solid phases under both test conditions. Unfortunately, the ash sample from the reactor C air preheater inlet and outlet at Test Condition 22 were both contaminated and could not be analyzed. As expected, at the air preheater outlet almost all of the ammonia was present in the solid phase. For all three reactors at Test Condition 22 the gas-phase ammonia concentration at the air preheater outlet was below the detection limit. This is true also for reactor A at Test Condition 24, but not for the other two reactor air preheaters, which had measurable concentrations of gas-phase ammonia. This was a direct result of a higher inlet concentration.

The ratio of inlet to outlet concentrations of ammonia based on the estimated solid-phase ammonia concentrations on a weight basis are generally similar in magnitude to those ratios calculated from the solid-phase ammonia concentrations calculated from the ammonia train test data. It should be noted that the possibility exists that some gas-phase ammonia may have reacted with sulfur trioxide present in the flue gas, as the gas stream cooled in the probe, to form ammonium bisulfate or ammonium sulfate. Other reactions involving chlorides, etc., are also possible. These reaction products would be collected with the solid-phase ammonia sample even though the ammonia was in the gas-phase in the duct. This possible sampling error would cause the solid-phase concentrations to be high.

#### 5.5.1.3.2 SO<sub>2</sub> and SO<sub>3</sub> Concentrations

SO<sub>3</sub> concentrations at the air preheater inlets ranged from  $2.3 \pm 0.9$  to  $20.7 \pm 2.6$  ppm(v) dry @ 3% O<sub>2</sub> while SO<sub>3</sub> concentrations at the air preheater outlets ranged from  $5.8 \pm 0.5$  to  $16.0 \pm 1.9$  ppm(v) dry @ 3% O<sub>2</sub>. The SO<sub>3</sub> concentration across the reactor A air preheater decreased by a factor of 0.8, while the SO<sub>3</sub> concentrations across reactor B and C air preheaters increased by factors of 1.5 and 2.5, respectively. Air preheater inlet SO<sub>2</sub> concentrations averaged  $1,845 \pm 58$  ppm(v) dry @ 3% O<sub>2</sub>, while the air preheater outlet SO<sub>2</sub> concentrations averaged  $1,852 \pm 66$  ppm(v) dry 3% O<sub>2</sub>. Within the tolerance of the standard deviations given for average SO<sub>2</sub> concentrations, there was no statistical difference in the concentrations of SO<sub>2</sub> at the inlet and outlet of each of the air preheaters.

#### 5.5.1.3.3 HCl Concentrations

Air preheater inlet HCl concentrations fell within the range of  $228 \pm 17$  to  $262 \pm 10$  ppm(v) dry @ 3% O<sub>2</sub>. Air preheater outlet HCl concentrations fell within the range of  $237 \pm 12$  to  $258 \pm 8$  ppm(v) dry @ 3% O<sub>2</sub>. The HCl concentrations were essentially identical between the air preheater inlet and outlet; however, the absolute concentrations were higher for reactor B compared to reactor A (5.6%) and for reactor C compared to reactor B (5.9%).

#### 5.5.1.3.4 Particulate Mass Concentrations

The average air preheater inlet mass concentration was  $3.21 \pm 0.49$  gr/dscf on reactor A and  $3.62 \pm 0.29$  gr/dscf on reactor B. The average air preheater outlet mass concentration was  $2.66 \pm 0.04$  gr/dscf on reactor A and  $2.42 \pm 0.05$  gr/dscf on reactor B. The mass concentration was lower at the air preheater outlet compared to the air preheater inlet by factors of 1.2 and 1.5 for reactors A and B, respectively.

#### **5.5.1.3.5 Fly Ash Resistivity**

The reactor A and B air preheater outlet fly ashes are composed of a moderate resistivity ash ( $5 \times 10^{10}$  ohm-cm @ 291 °F). The resistivity for this ash is a factor of almost ten lower than that for the Unit 5 hot-side ESP inlet fly ash collected during Task 1 testing in early 1993 ( $3.9 \times 10^{11}$  ohm-cm @ 293 °F).

#### **5.5.1.3.6 Fly Ash Mineral Analysis**

The chemical composition of the reactor A and B inlet and outlet fly ashes were very similar and the concentrations of the various compounds were typical of fly ash from high-sulfur coal.

#### **5.5.1.3.7 Metals Extractions**

Metals extractions were performed on fly ashes from the reactor A and B air preheater inlet and outlet. The metals of interest included antimony, cesium, copper, molybdenum, rubidium, tin, zinc, beryllium, barium, cadmium, cobalt, chromium, nickel, strontium, manganese, vanadium, mercury, arsenic, selenium, and lead. There was essentially no enrichment or depletion of the metal concentrations across the air preheaters, except for selenium and mercury. The concentrations of these two metals increased by an order of magnitude or greater across the air preheater. This can be explained because of the transition from gas-phase to solid-phase for these elements as cooling occurred within and across the air preheater.

### **5.5.2 Continuous Long-Term Air Preheater Evaluation**

The following table shows the average operational parameters for the three test facility air preheaters on a quarterly basis. These values represent averages of data acquired while the air preheaters were at or near base-line operation.

Table 5.5-1 Average Air Preheater Operational Parameters

| Parameter            | Quarter   | APH A | APH B | APH C |
|----------------------|-----------|-------|-------|-------|
| Gas flow rate (SCFM) | 3rd - '93 | 4712  | 4778  | 5321  |
|                      | 4th - '93 | 4544  | 4629  | 5226  |
|                      | 1st - '94 | 4998  | 5004  | 5103  |
|                      | 2nd - '94 | 4996  | 4947  | 4953  |
|                      | 3rd - '94 | 4982  | 5018  | 5018  |
|                      | 4th - '94 | 4932  | 5002  | 4939  |
|                      | 1st - '95 | 4972  | 4954  | 4967  |
|                      | 2nd - '95 | 5540  | 5128  | 5233  |
| Air flow rate (SCFM) | 3rd - '93 | 5070  | 4150  | 5910  |
|                      | 4th - '93 | 4026  | 3500  | 6010  |
|                      | 1st - '94 | 4491  | 3943  | 6770  |
|                      | 2nd - '94 | 5080  | 4463  | 7721  |
|                      | 3rd - '94 | 4687  | 4437  | 8035  |
|                      | 4th - '94 | 4009  | 3772  | 6834  |
|                      | 1st - '95 | 3914  | 3716  | 6396  |
|                      | 2nd - '95 | 4109  | 4565  | 10166 |
| Inlet gas temp. (°F) | 3rd - '93 | 643   | 648   | 659   |
|                      | 4th - '93 | 663   | 661   | 664   |
|                      | 1st - '94 | 677   | 672   | 667   |
|                      | 2nd - '94 | 673   | 673   | 675   |
|                      | 3rd - '94 | 675   | 667   | 672   |
|                      | 4th - '94 | 675   | 667   | 673   |
|                      | 1st - '95 | 662   | 669   | 670   |
|                      | 2nd - '95 | 667   | 671   | 665   |
| Exit gas temp. (°F)  | 3rd - '93 | 324   | 309   | 315   |
|                      | 4th - '93 | 313   | 308   | 307   |
|                      | 1st - '94 | 319   | 338   | 297   |
|                      | 2nd - '94 | 305   | 338   | 299   |
|                      | 3rd - '94 | 300   | 300   | 300   |
|                      | 4th - '94 | 300   | 300   | 317   |
|                      | 1st - '95 | 299   | 299   | 320   |
|                      | 2nd - '95 | 300   | 300   | 300   |
| Inlet air temp. (°F) | 3rd - '93 | 100   | 100   | 100   |
|                      | 4th - '93 | 73    | 73    | 73    |
|                      | 1st - '94 | 72    | 72    | 72    |
|                      | 2nd - '94 | 88    | 88    | 88    |
|                      | 3rd - '94 | 94    | 94    | 94    |
|                      | 4th - '94 | 79    | 79    | 79    |
|                      | 1st - '95 | 69    | 69    | 69    |
|                      | 2nd - '95 | 97    | 97    | 97    |
| Exit air temp. (°F)  | 3rd - '93 | 593   | 577   | 533   |
|                      | 4th - '93 | 605   | 588   | 508   |
|                      | 1st - '94 | 605   | 598   | 474   |
|                      | 2nd - '94 | 594   | 591   | 459   |
|                      | 3rd - '94 | 584   | 575   | 422   |
|                      | 4th - '94 | 592   | 596   | 423   |
|                      | 1st - '95 | 572   | 583   | 423   |

Table 5.5-1 (Cont'd) Average Air Preheater Operational Parameters

|   |           |      |       |      |
|---|-----------|------|-------|------|
|   | 2nd - '95 | 584  | 520   | 345  |
| Gas side press. drop (in. H <sub>2</sub> O) | 3rd - '93 | 3.73 | 3.26  | 1.75 |
|   | 4th - '93 | 4.31 | 5.27  | 2.31 |
|   | 1st - '94 | 7.26 | 5.90  | 1.63 |
|   | 2nd - '94 | 7.67 | 4.74  | 1.85 |
|   | 3rd - '94 | 7.12 | 3.99  | 2.57 |
|   | 4th - '94 | 7.06 | 4.69  | 5.39 |
|   | 1st - '95 | 5.68 | 8.48  | 9.02 |
|   | 2nd - '95 | 5.96 | 4.34  | 6.60 |
| Air side press. drop (in. H <sub>2</sub> O) | 3rd - '93 | 1.66 | 1.51  | NA   |
|   | 4th - '93 | 1.87 | 1.75  | NA   |
|   | 1st - '94 | 2.51 | 2.34  | NA   |
|   | 2nd - '94 | 2.97 | 2.14  | NA   |
|   | 3rd - '94 | 3.21 | 1.84  | NA   |
|   | 4th - '94 | 2.99 | 1.95  | NA   |
|   | 1st - '95 | 2.29 | 3.30  | NA   |
|   | 2nd - '95 | 2.70 | 2.04  | NA   |
| Air/Gas diff. press. (in. H <sub>2</sub> O) | 3rd - '93 | 0.58 | 0.42  | NA   |
|   | 4th - '93 | 0.48 | 0.48  | NA   |
|   | 1st - '94 | 0.50 | 0.50  | NA   |
|   | 2nd - '94 | 0.50 | 0.50  | NA   |
|   | 3rd - '94 | 0.51 | 0.50  | NA   |
|   | 4th - '94 | 0.52 | 0.51  | NA   |
|   | 1st - '95 | 0.51 | 0.52  | NA   |
|   | 2nd - '95 | 0.52 | 0.53  | NA   |
| Inlet gas O <sub>2</sub> (% wet)            | 3rd - '93 | 4.92 | 4.43  | 3.96 |
|   | 4th - '93 | 5.24 | 5.84  | 5.79 |
|   | 1st - '94 | 5.02 | 4.94  | 5.43 |
|   | 2nd - '94 | 4.64 | 4.15  | 4.65 |
|   | 3rd - '94 | 5.52 | 6.21  | 6.27 |
|   | 4th - '94 | 5.45 | 6.38  | 6.14 |
|   | 1st - '95 | 4.95 | 5.86  | 5.55 |
|   | 2nd - '95 | 5.01 | 5.62  | 6.57 |
| Exit gas O <sub>2</sub> (% wet)             | 3rd - '93 | 7.07 | 8.73  | NA   |
|   | 4th - '93 | 6.89 | 7.72  | NA   |
|   | 1st - '94 | 8.37 | 7.40  | NA   |
|   | 2nd - '94 | 7.02 | 7.32  | NA   |
|   | 3rd - '94 | 8.21 | 8.69  | NA   |
|   | 4th - '94 | 8.53 | 9.24  | NA   |
|   | 1st - '95 | 8.30 | 9.26  | NA   |
|   | 2nd - '95 | 9.23 | 10.19 | NA   |

The data contained in the previous table, along with other operational data, have been compiled in the following figures which outline the air preheater performance over the life of the project. Figures 5.5-1 through 24 show average temperatures, flow rates, and pressure drops for the three test facility air preheaters on a quarterly basis. In addition,

major operational events are depicted on the plots to show effects of the events on major operational parameters.

Figure 5.5-1

Air Preheater Trend Data for 3rd Quarter 1993  
Train A

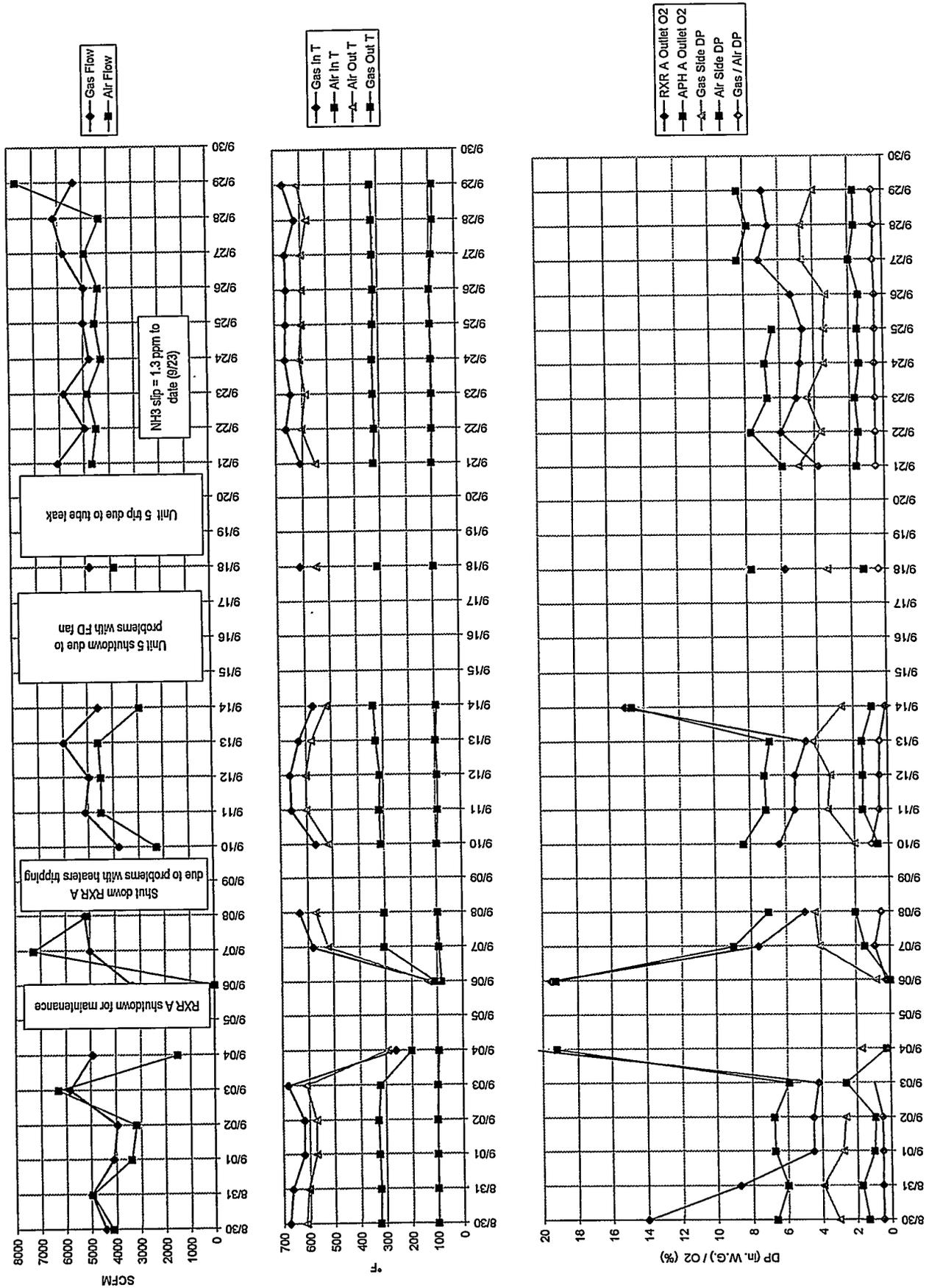


Figure 5.5-2

Air Preheater Trend Data for 3rd Quarter 1993  
Train B

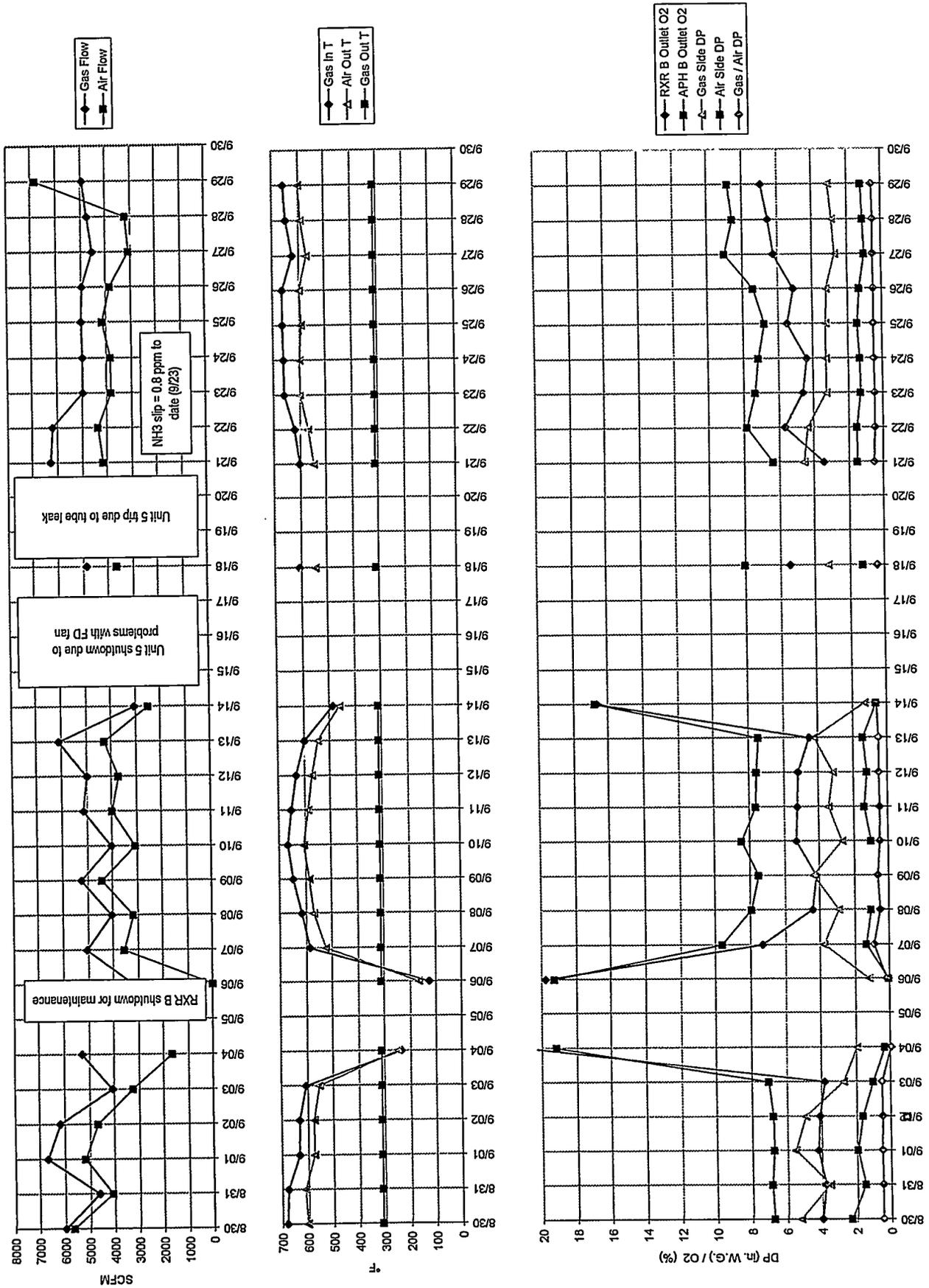


Figure 5.5-3

Air Preheater Trend Data for 3rd Quarter 1993  
Train C

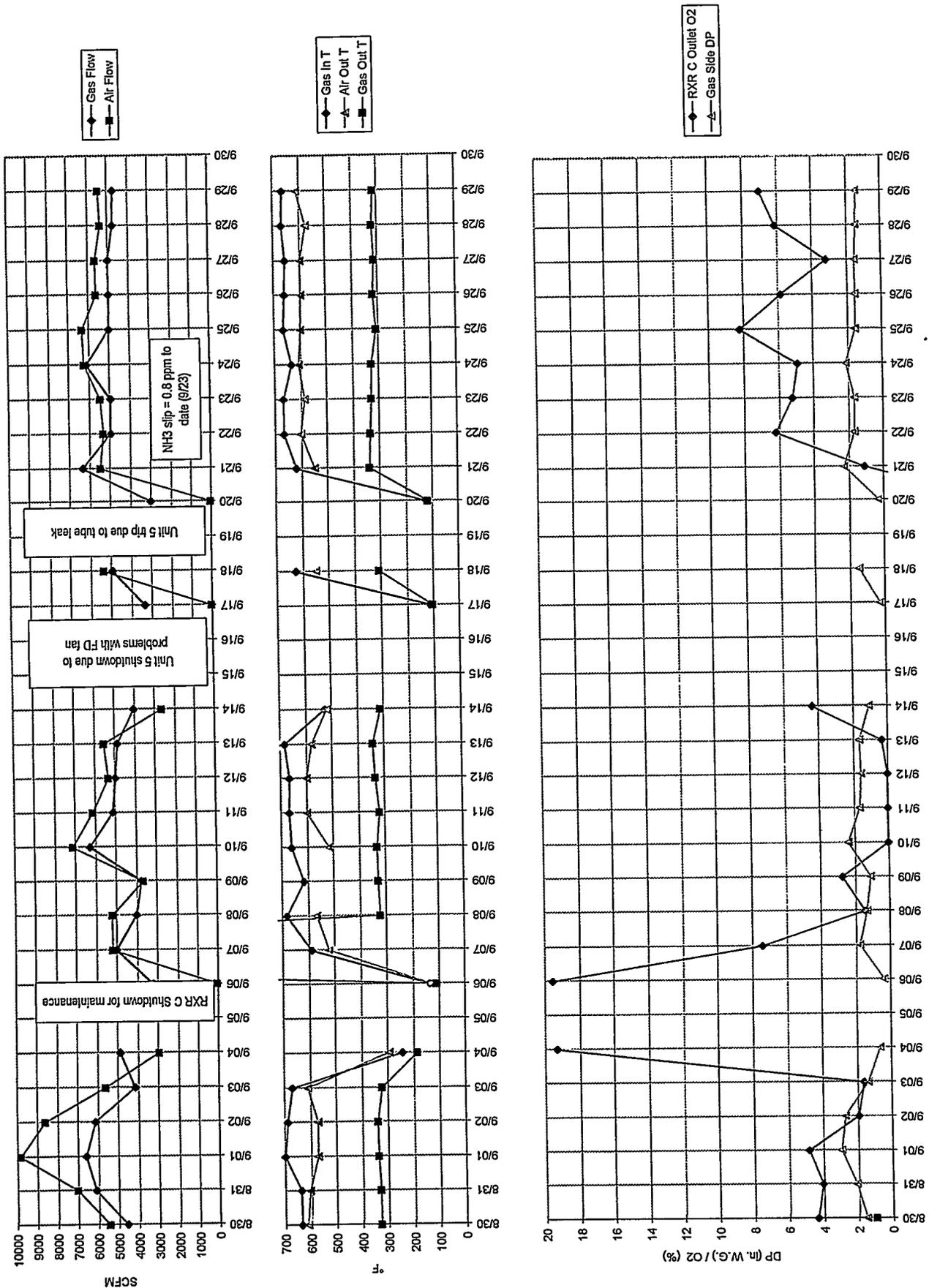


Figure 5.5-4

Air Preheater Trend Data for 4th Quarter 1993  
Train A

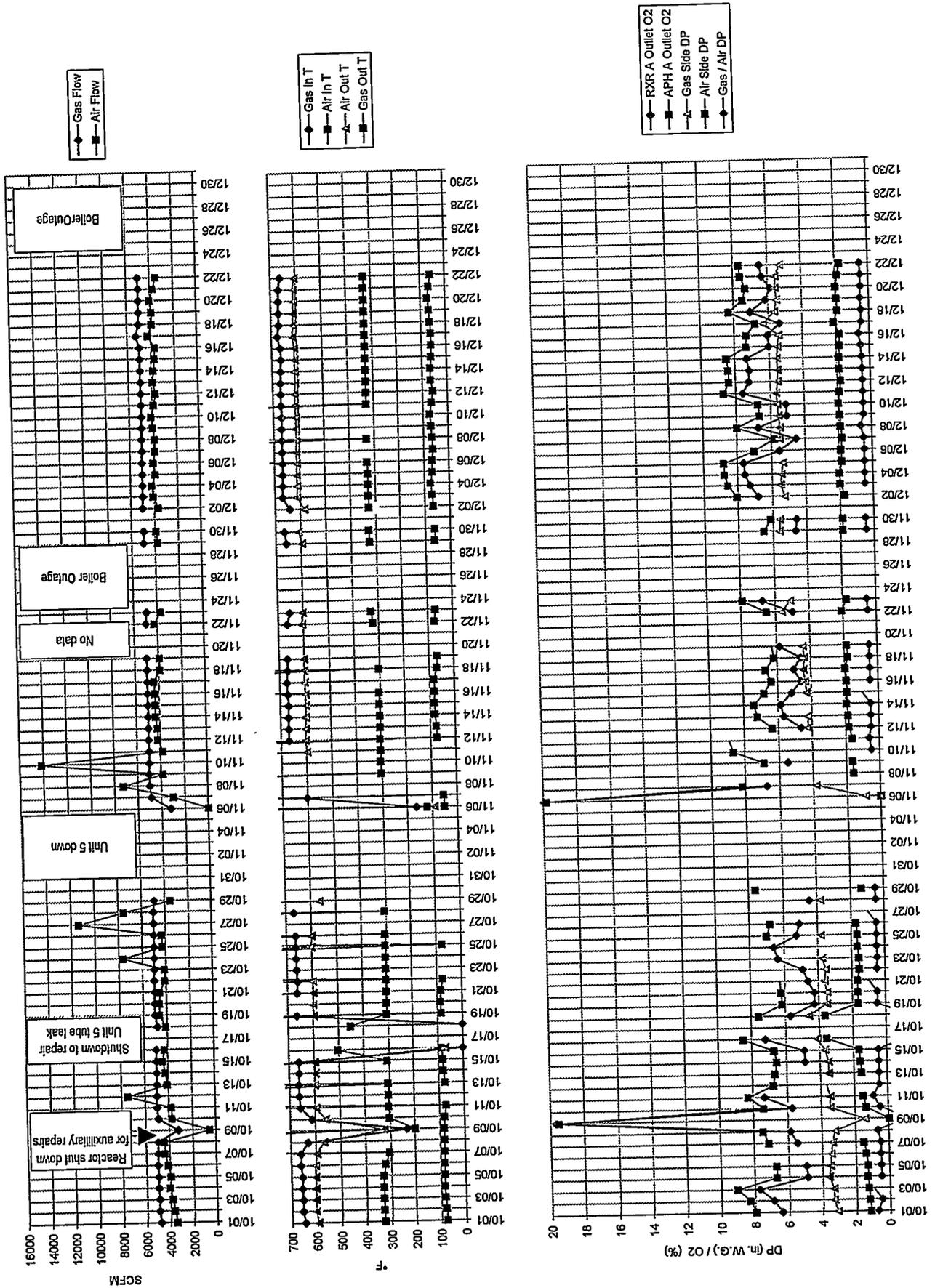


Figure 5.5-5

Air Preheater Trend Data for 4th Quarter 1993  
Train B

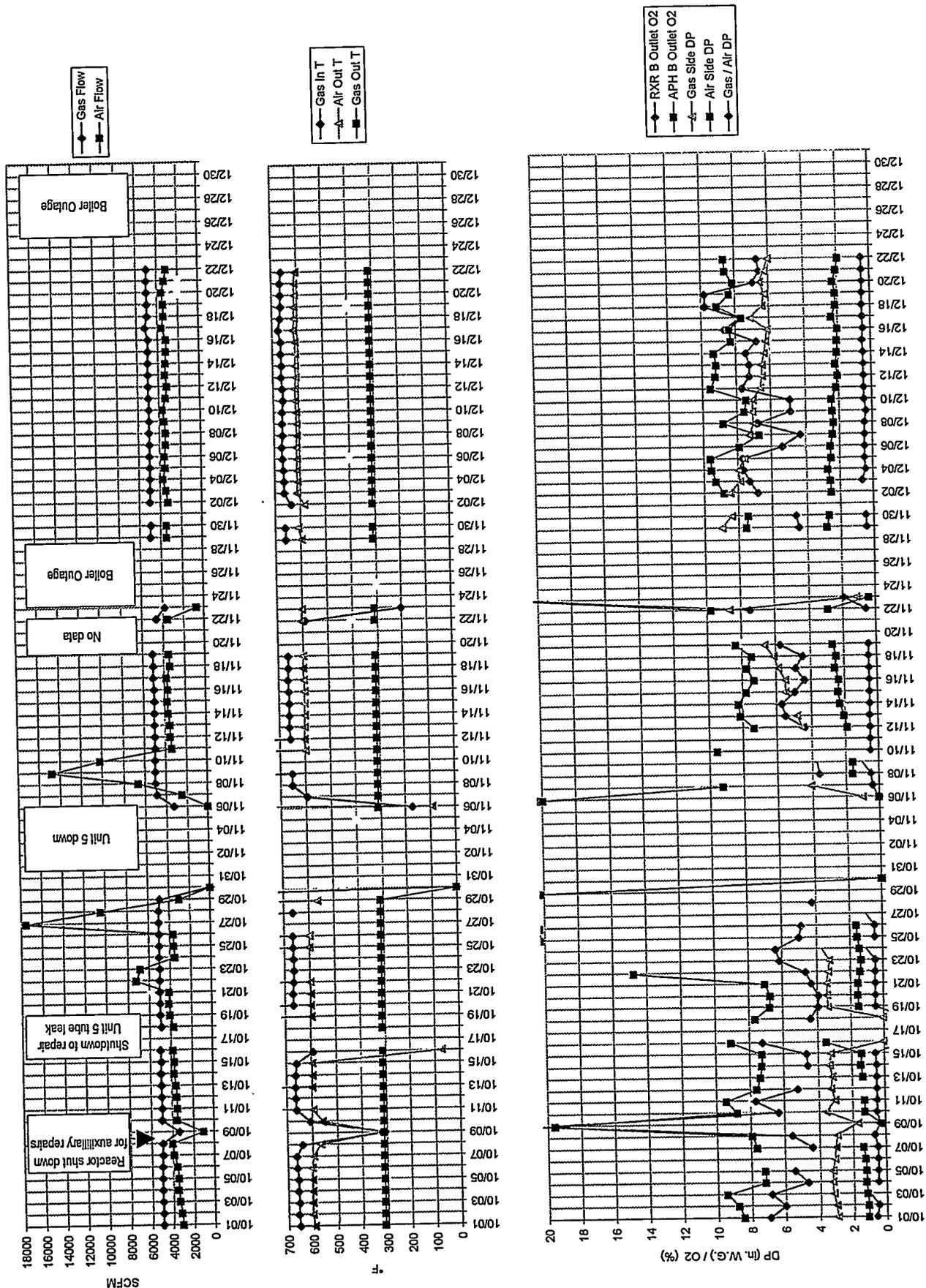


Figure 5.5-6

Air Preheater Trend Data for 4th Quarter 1993  
Train C

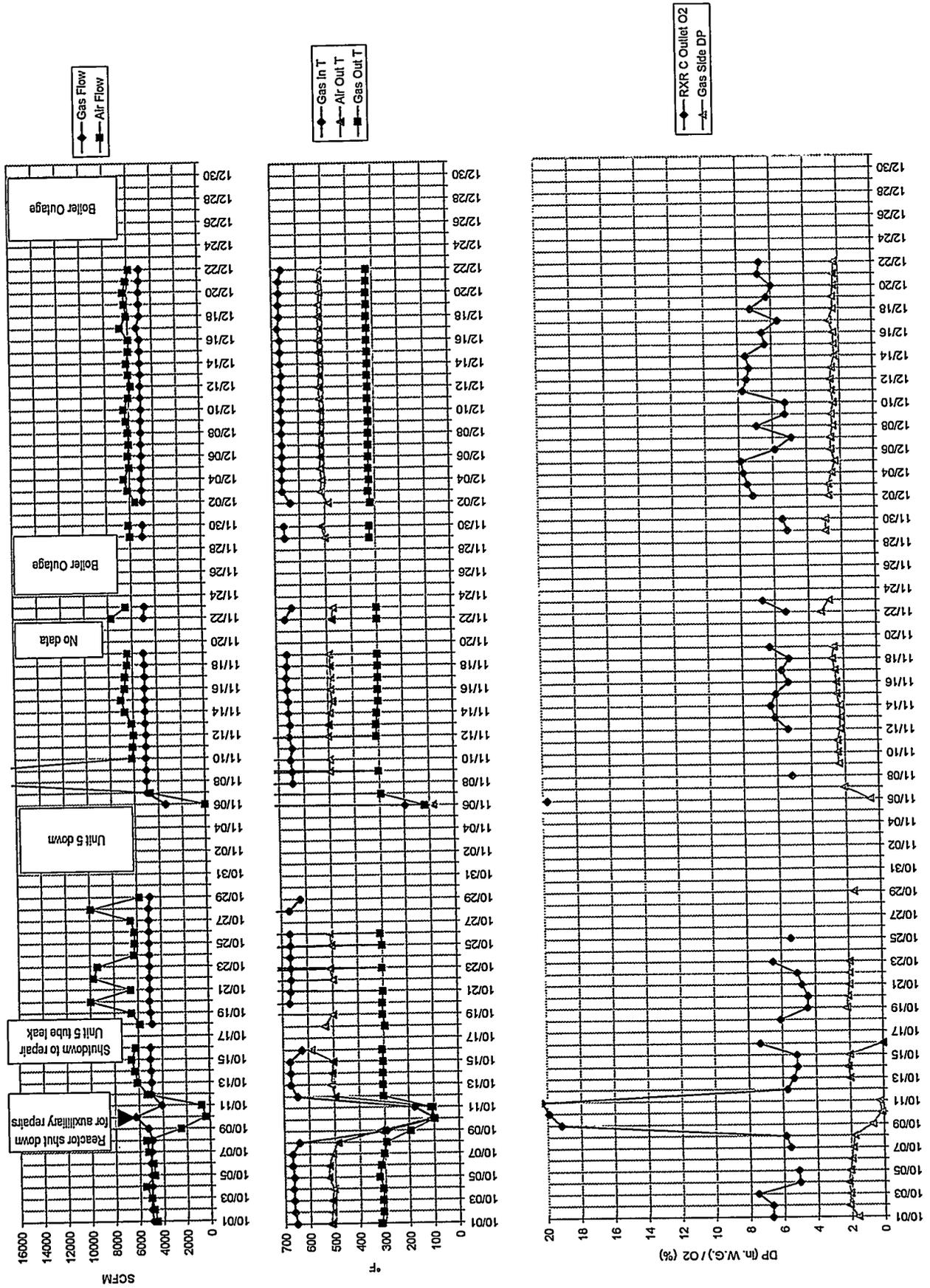


Figure 5.5-7

Air Preheater Trend Data for 1st Quarter 1994  
Train A

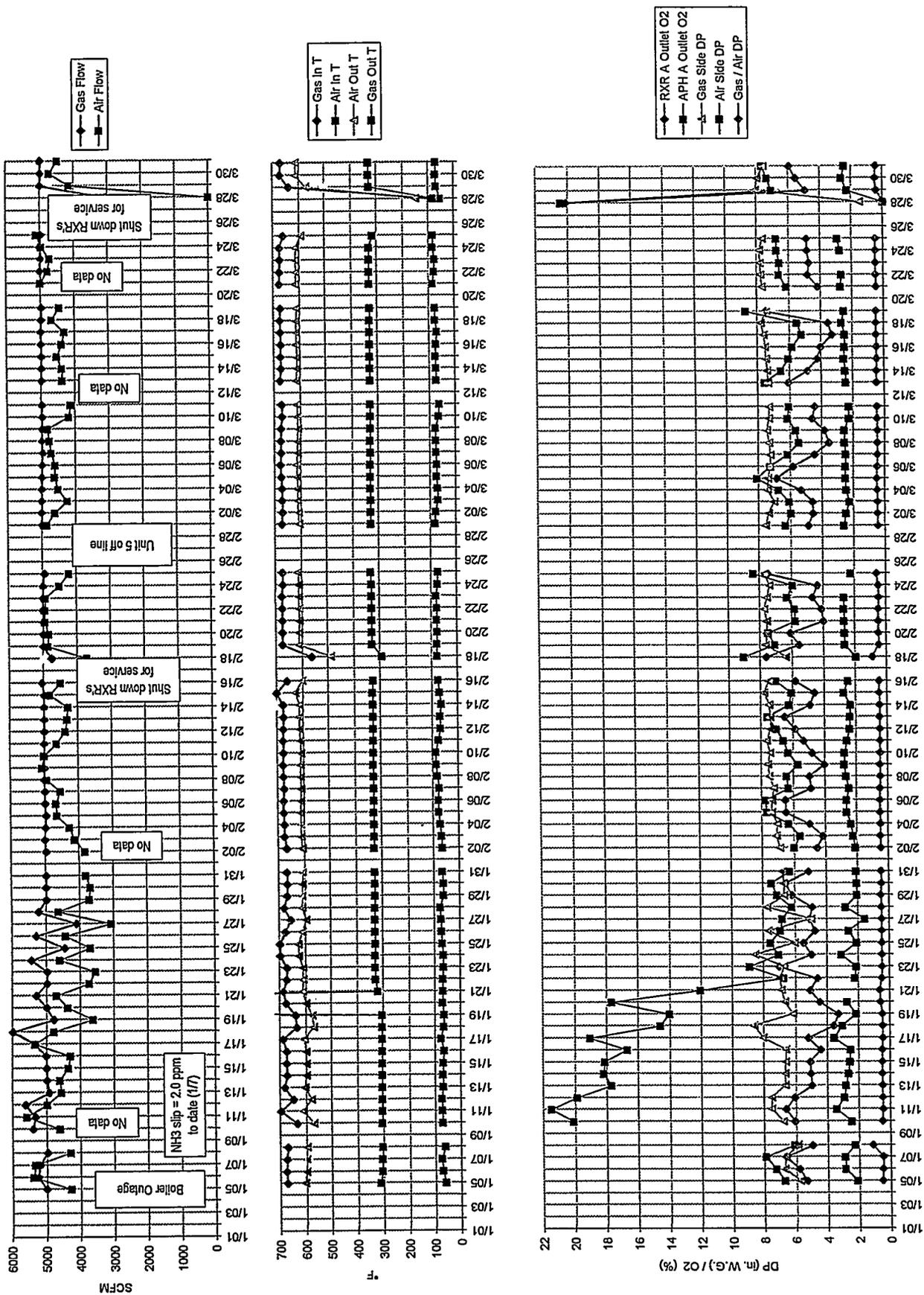
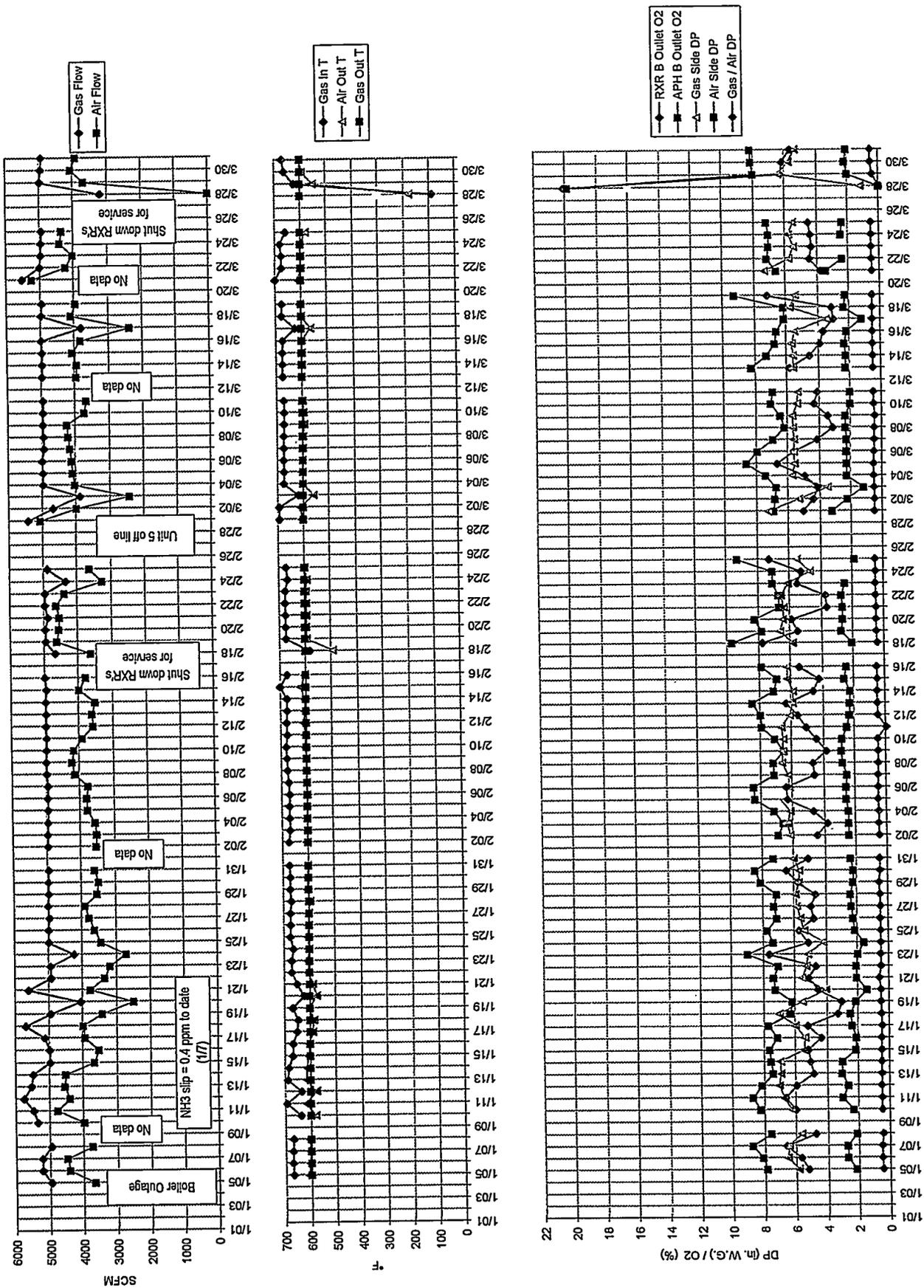


Figure 5.5-8

Air Preheater Trend Data for 1st Quarter 1994  
Train B



Air Preheater Trend Data for 1st Quarter 1994  
Train C

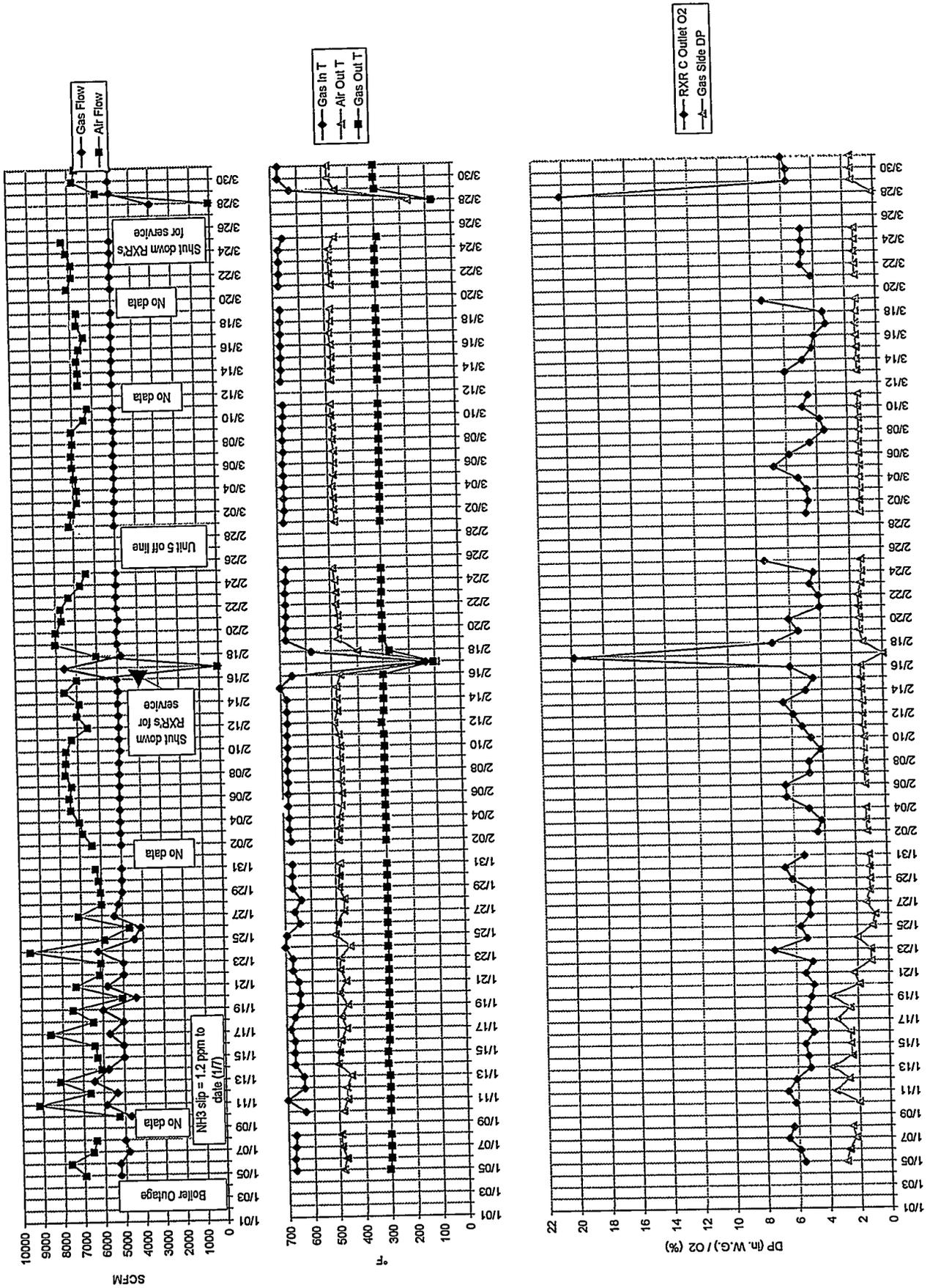
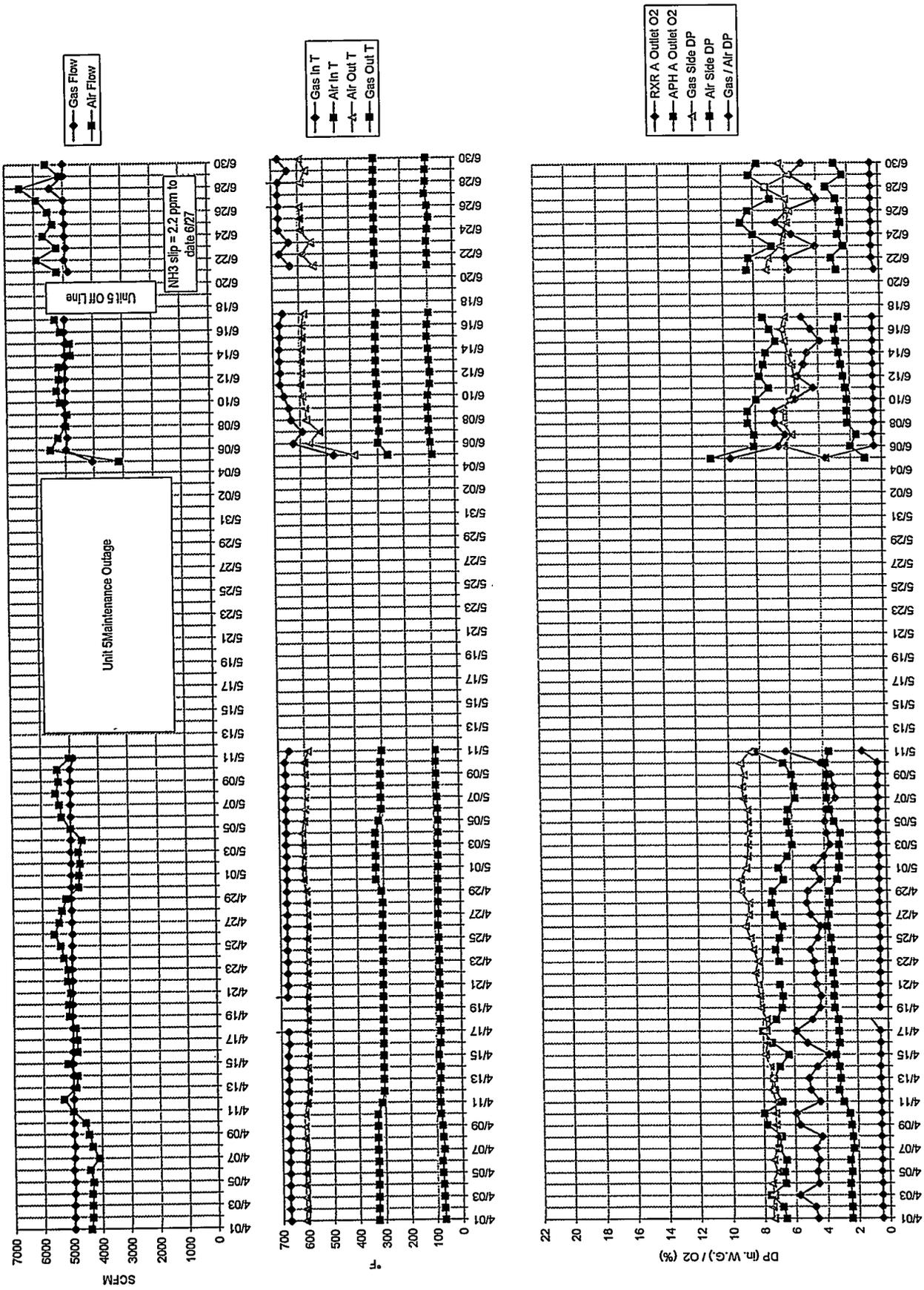


Figure 5.5-9

Figure 5.5-10

Air Preheater Trend Data for 2nd Quarter 1994  
Train A



Air Preheater Trend Data for 2nd Quarter 1994  
Train B

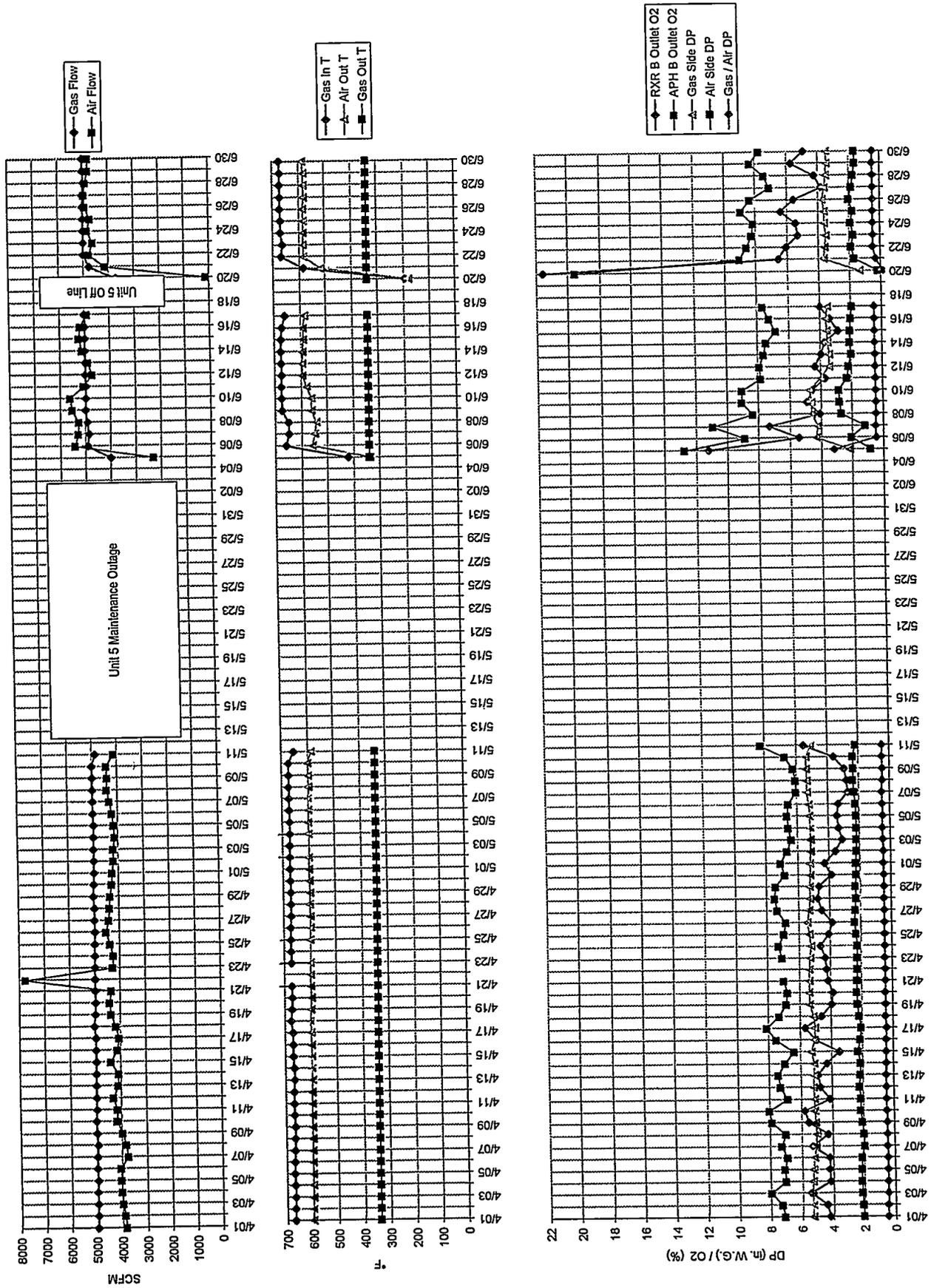


Figure 5.5-11

Figure 5.5-12

Air Preheater Trend Data for 2nd Quarter 1994  
Train C

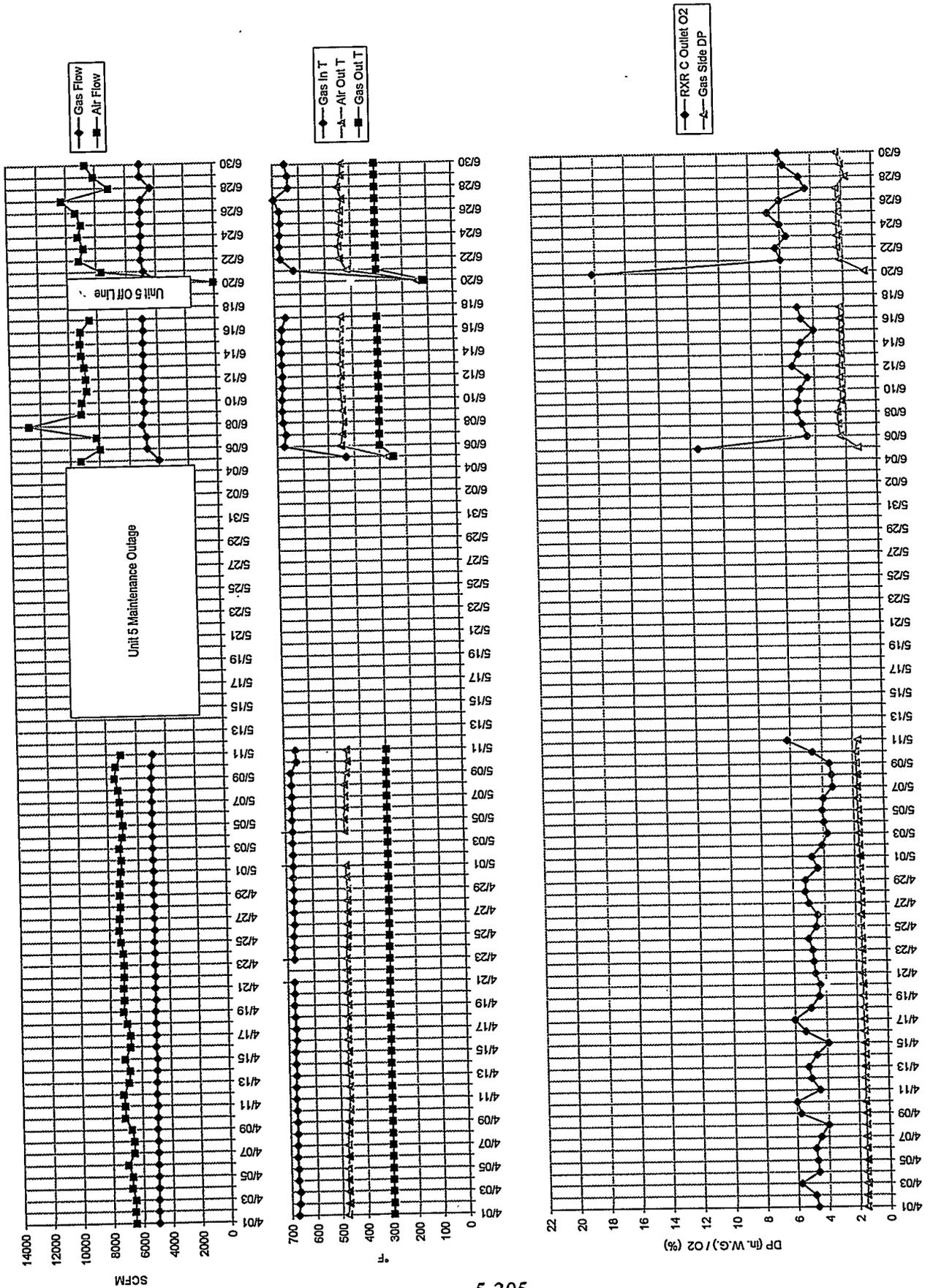


Figure 5.5-13

Air Preheater Trend Data for 3rd Quarter 1994  
Train A

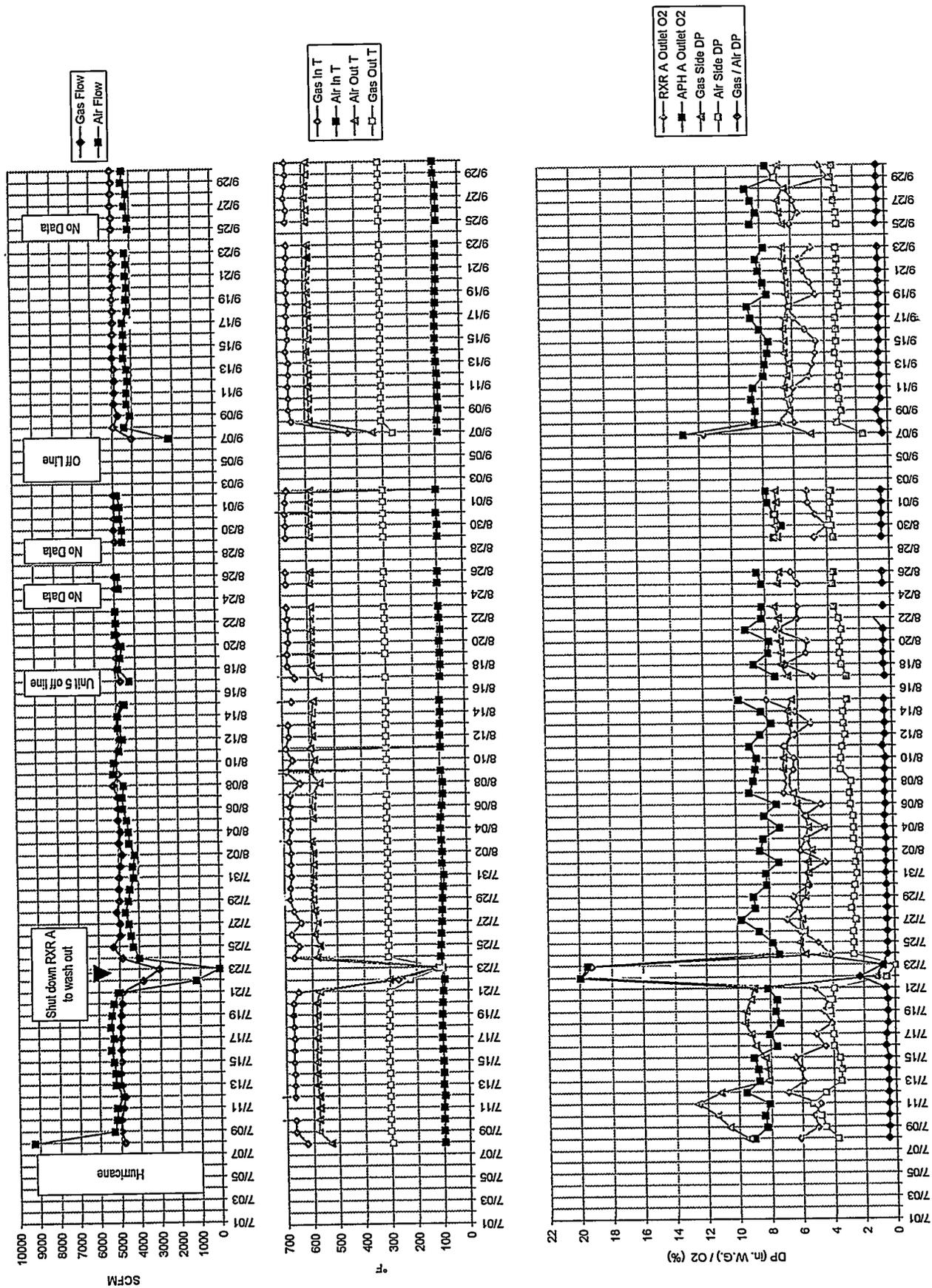


Figure 5.5-14

Air Preheater Trend Data for 3rd Quarter 1994  
Train B

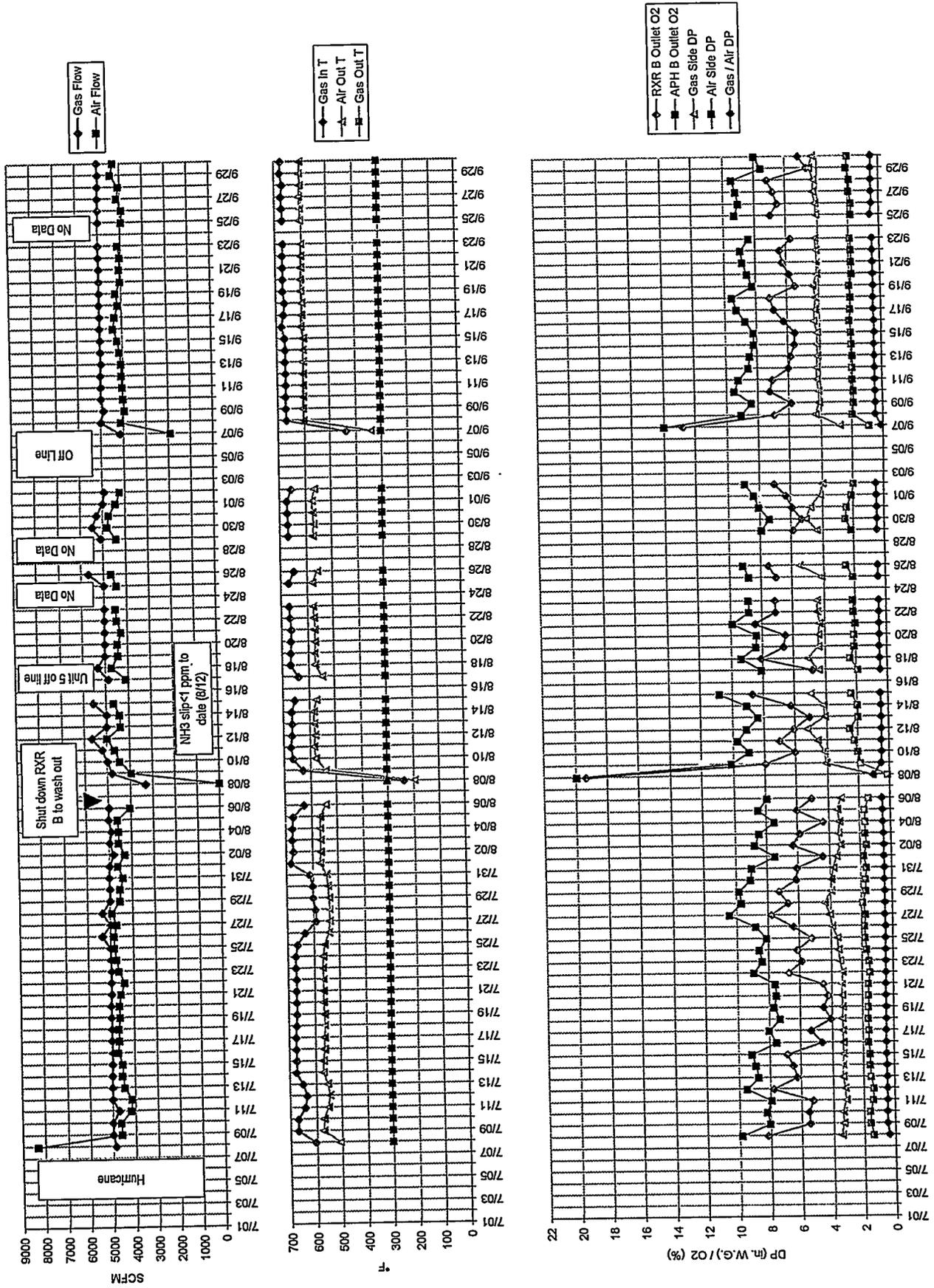
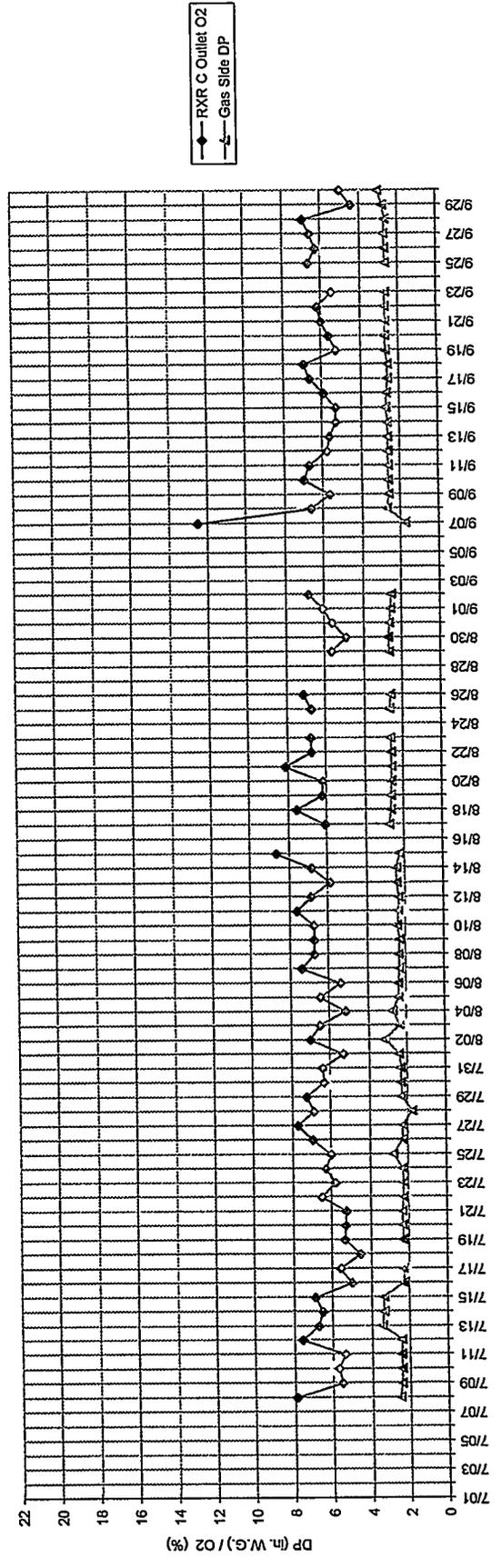
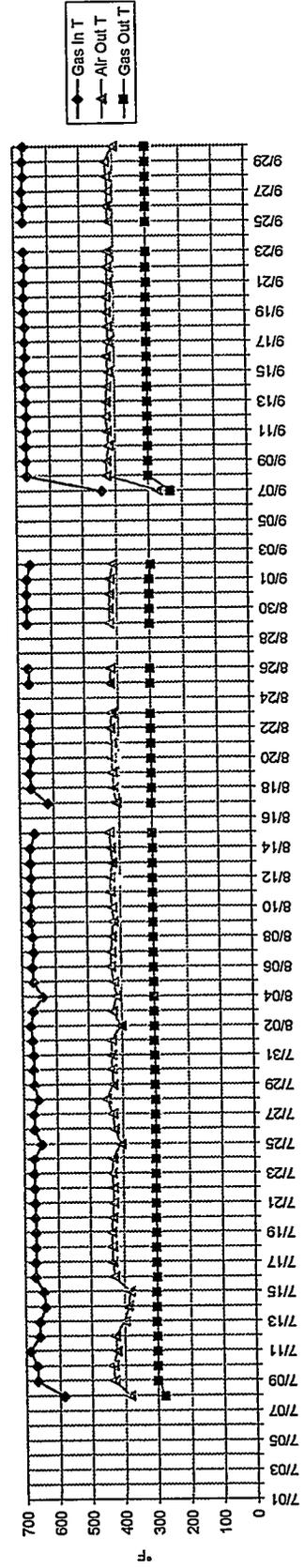
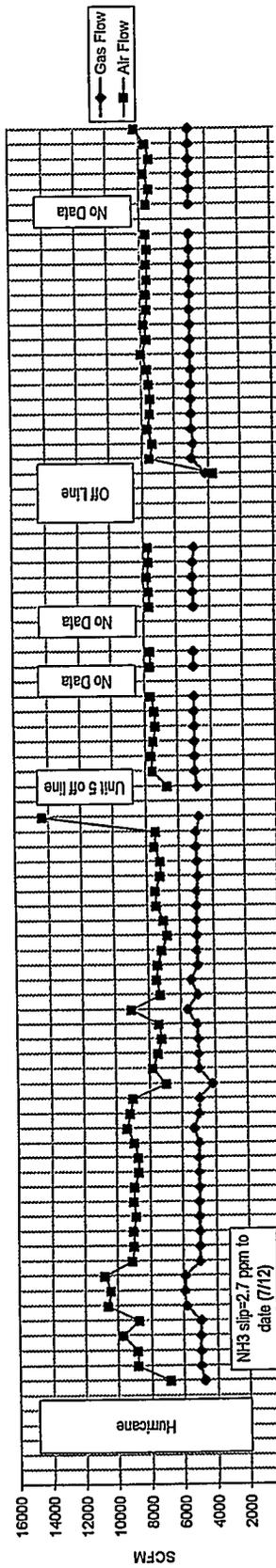


Figure 5.5-15

Air Preheater Trend Data for 3rd Quarter 1994

Train C



Air Preheater Trend Data for 4th Quarter 1994  
Train A

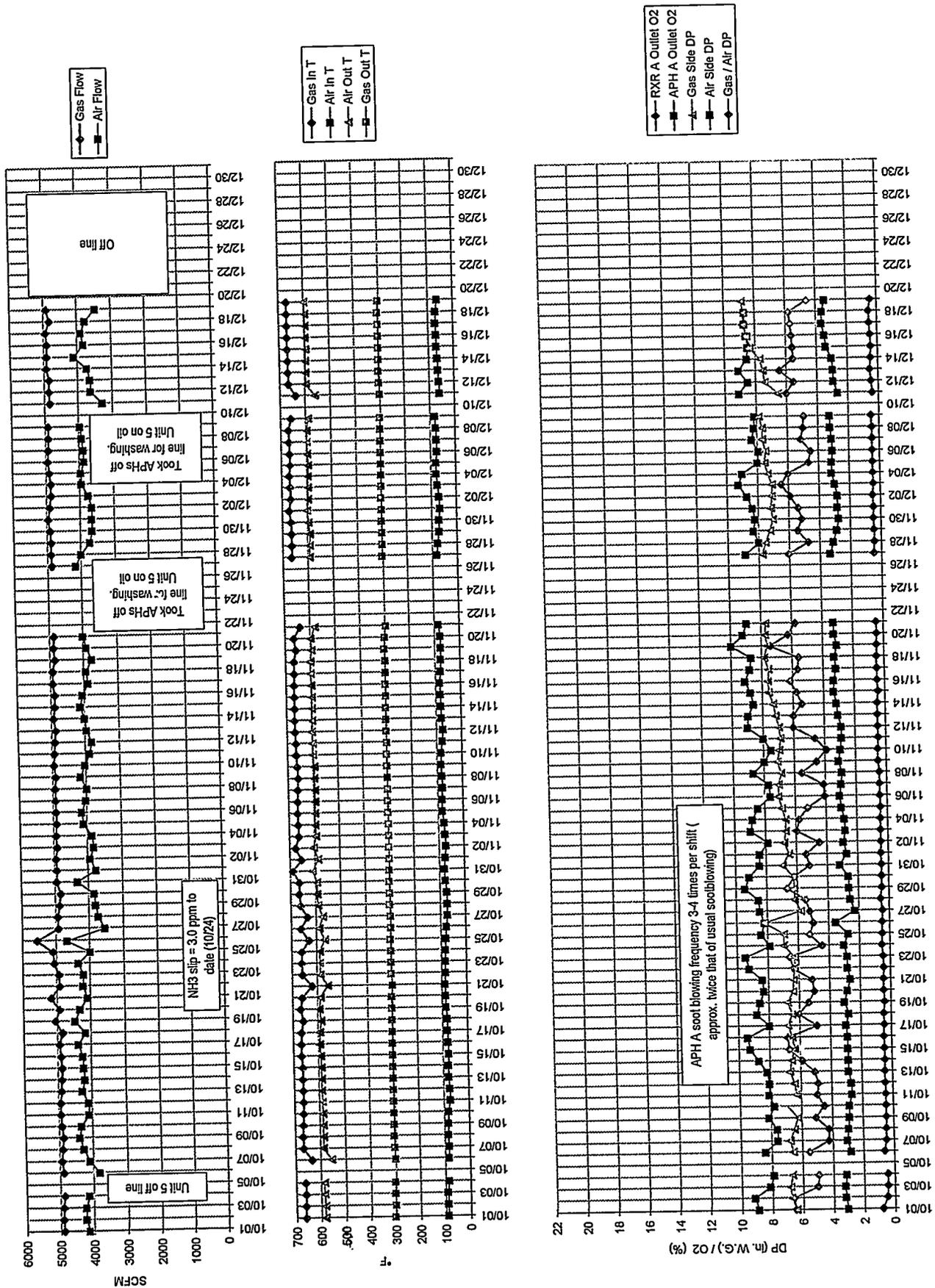


Figure 5.5-16

Figure 5.5-17

Air Preheater Trend Data for 4th Quarter 1994  
Train B

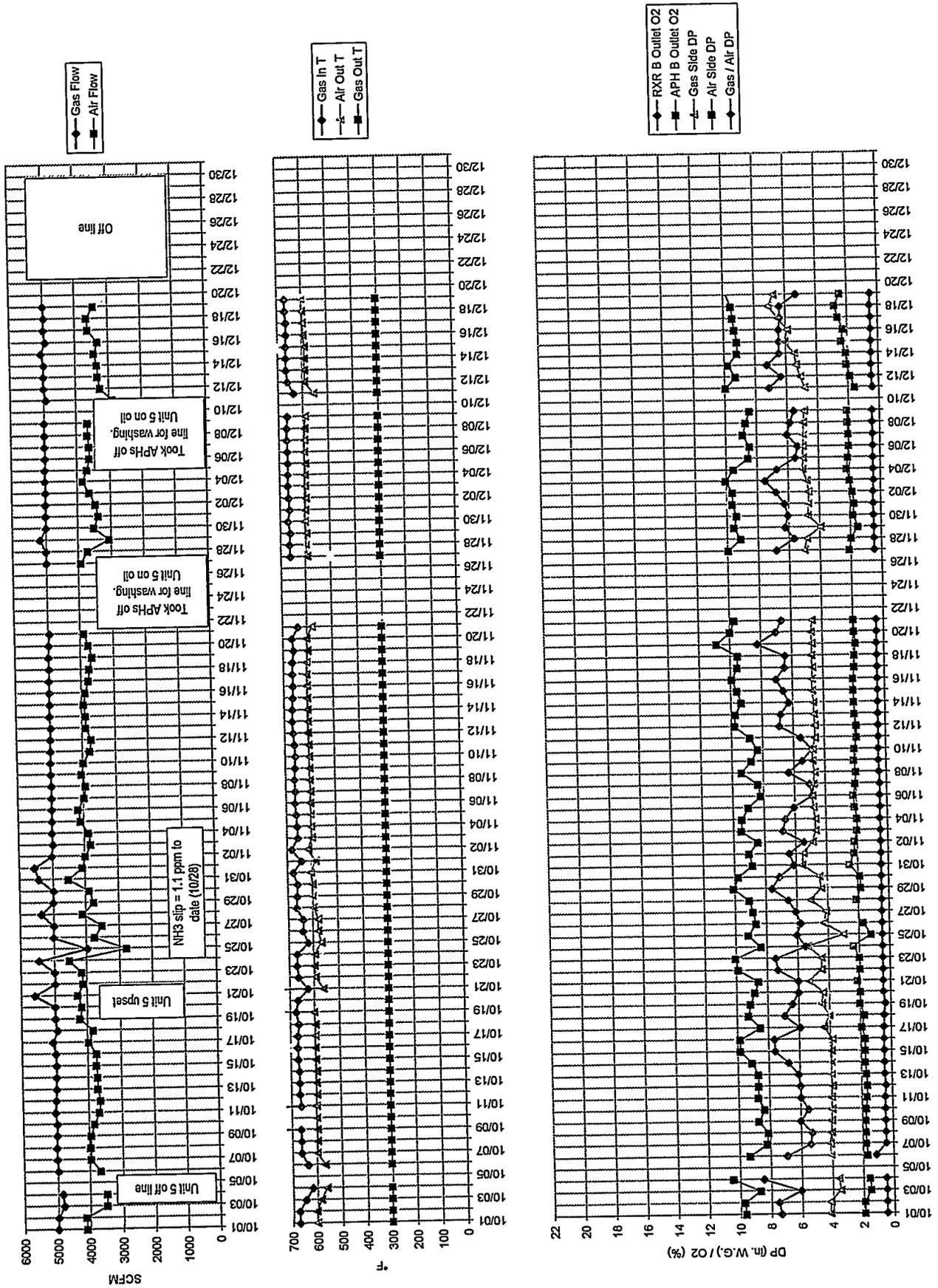


Figure 5.5-18

Air Preheater Trend Data for 4th Quarter 1994  
Train C

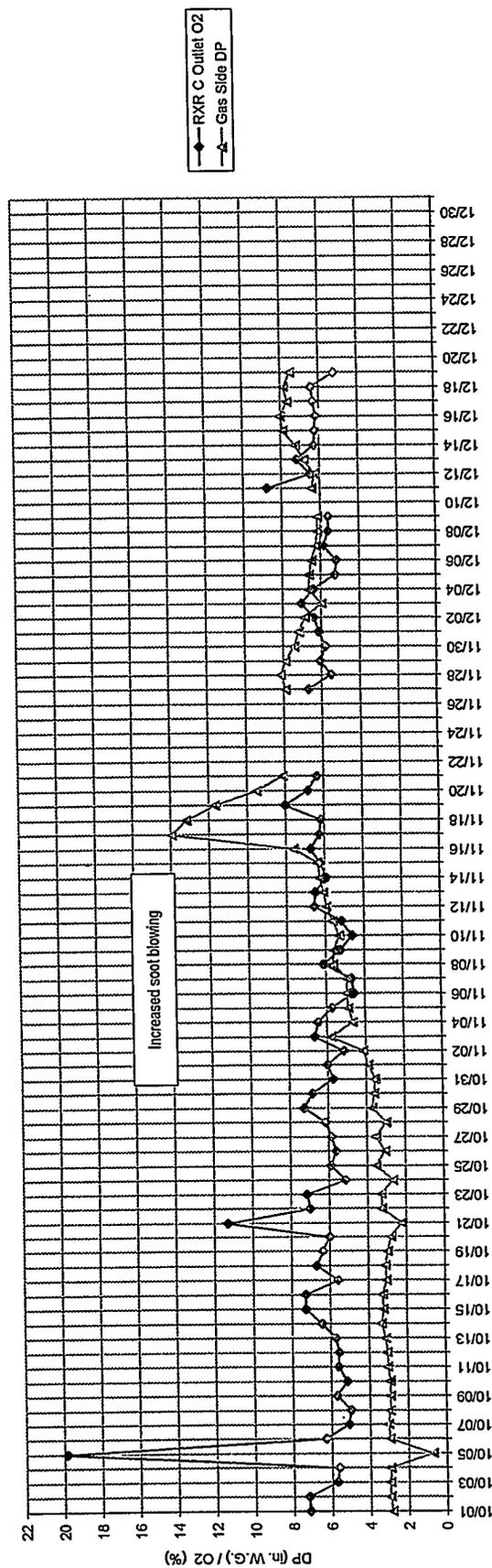
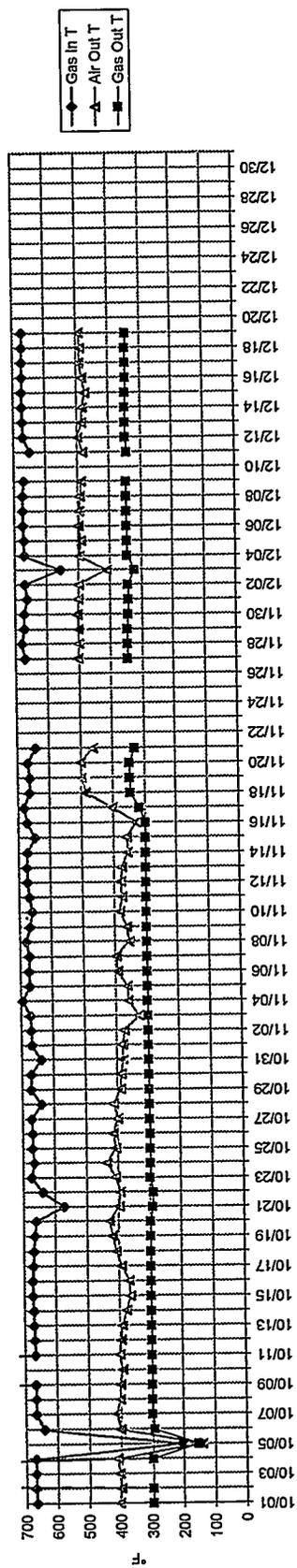
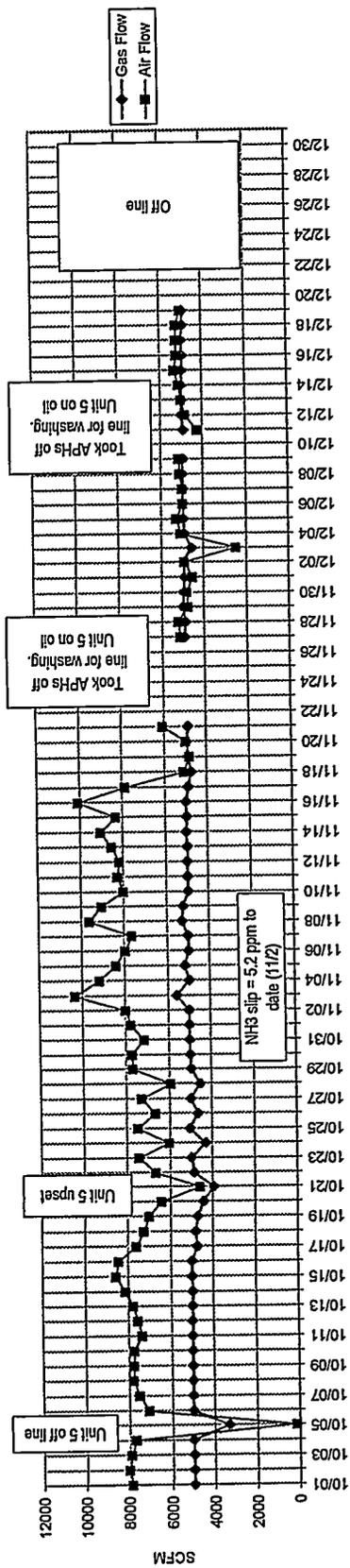
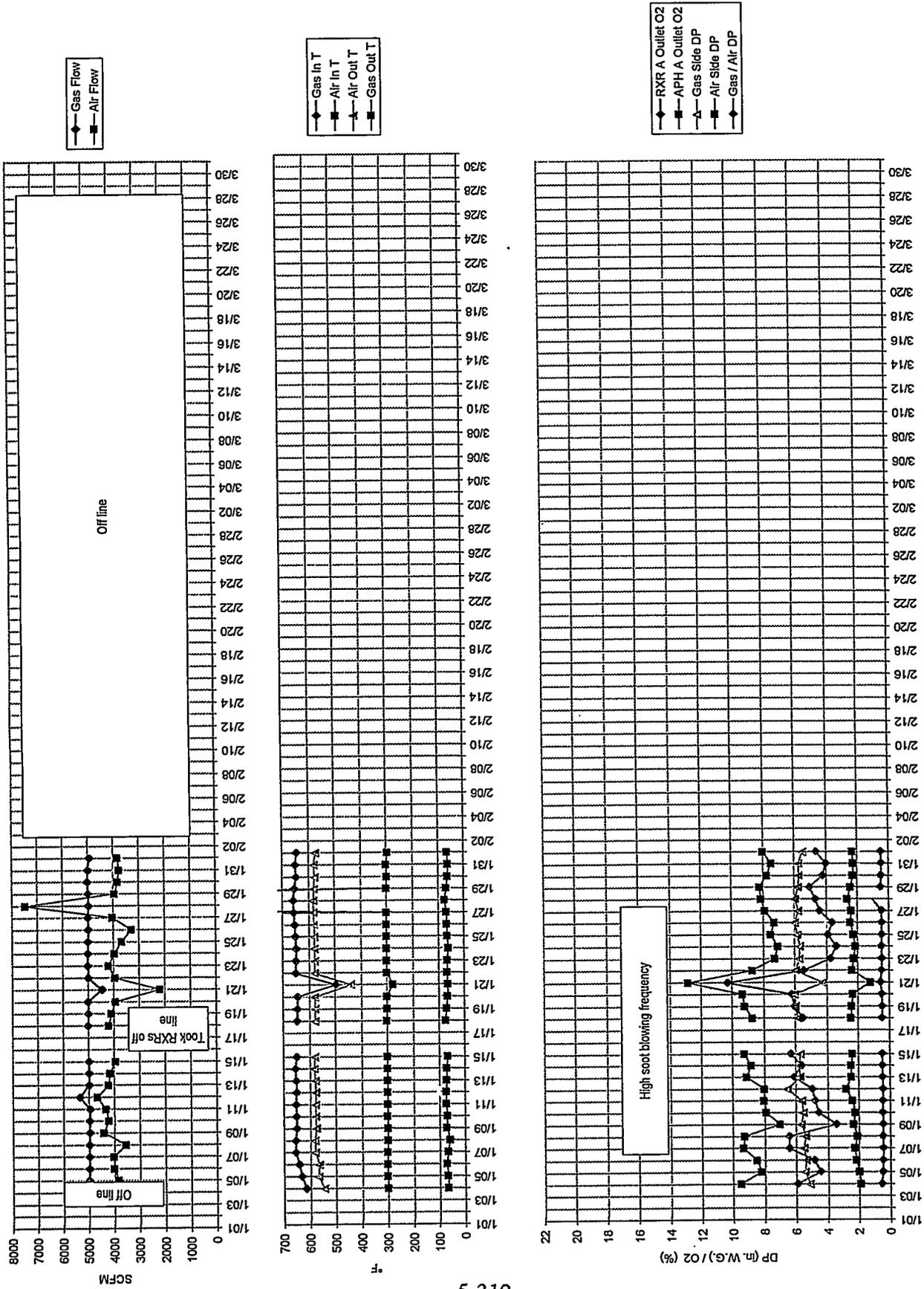


Figure 5.5-19

AIR Preheater / reno nana for '1st quarter' 1999  
 Train A



Air Preheater Trend Data for 1st Quarter 1995  
Train B

Figure 5.5-20

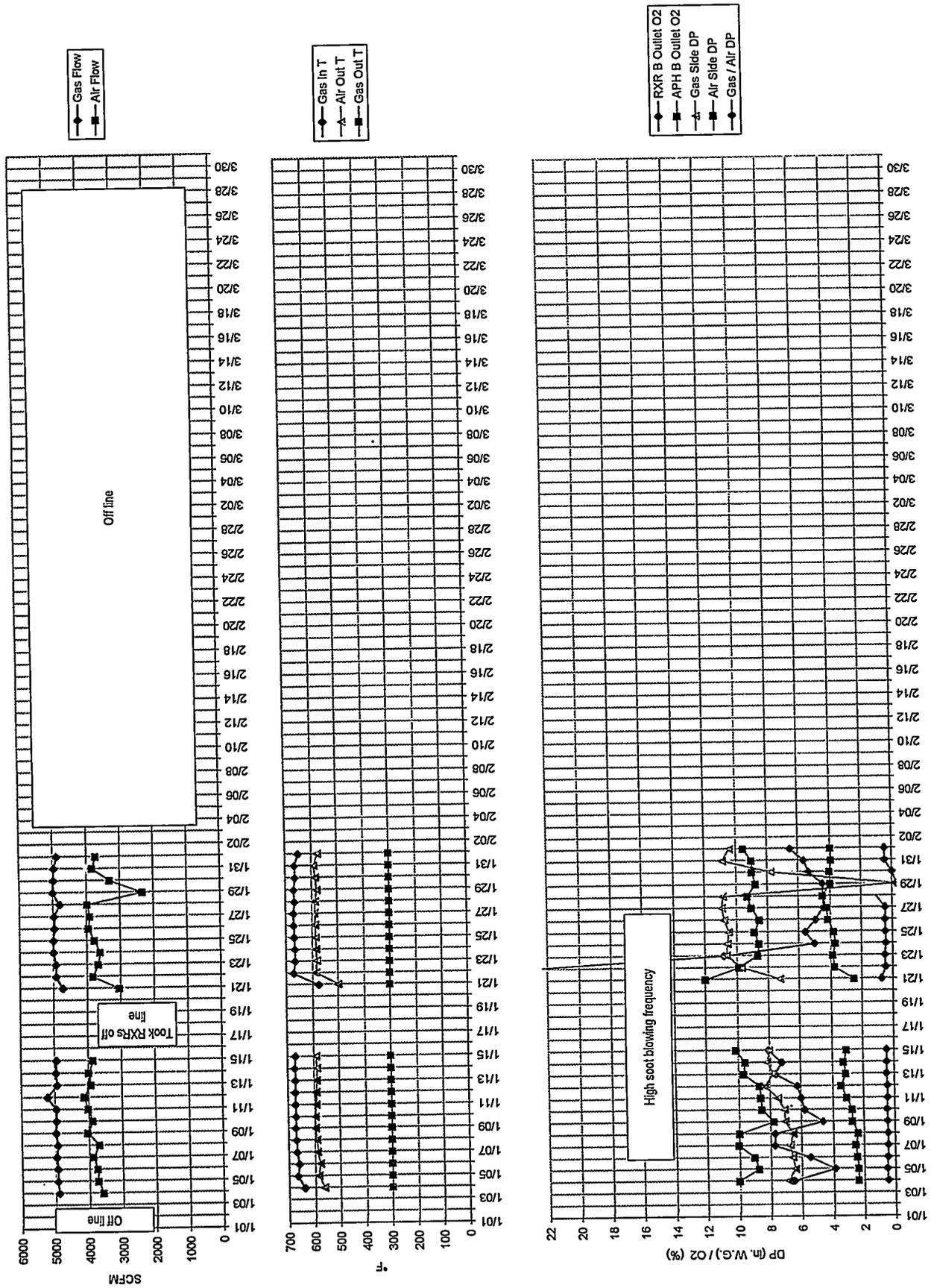


Figure 5.5-21

Air Preheater Trend Data for 1st Quarter 1995  
Train C

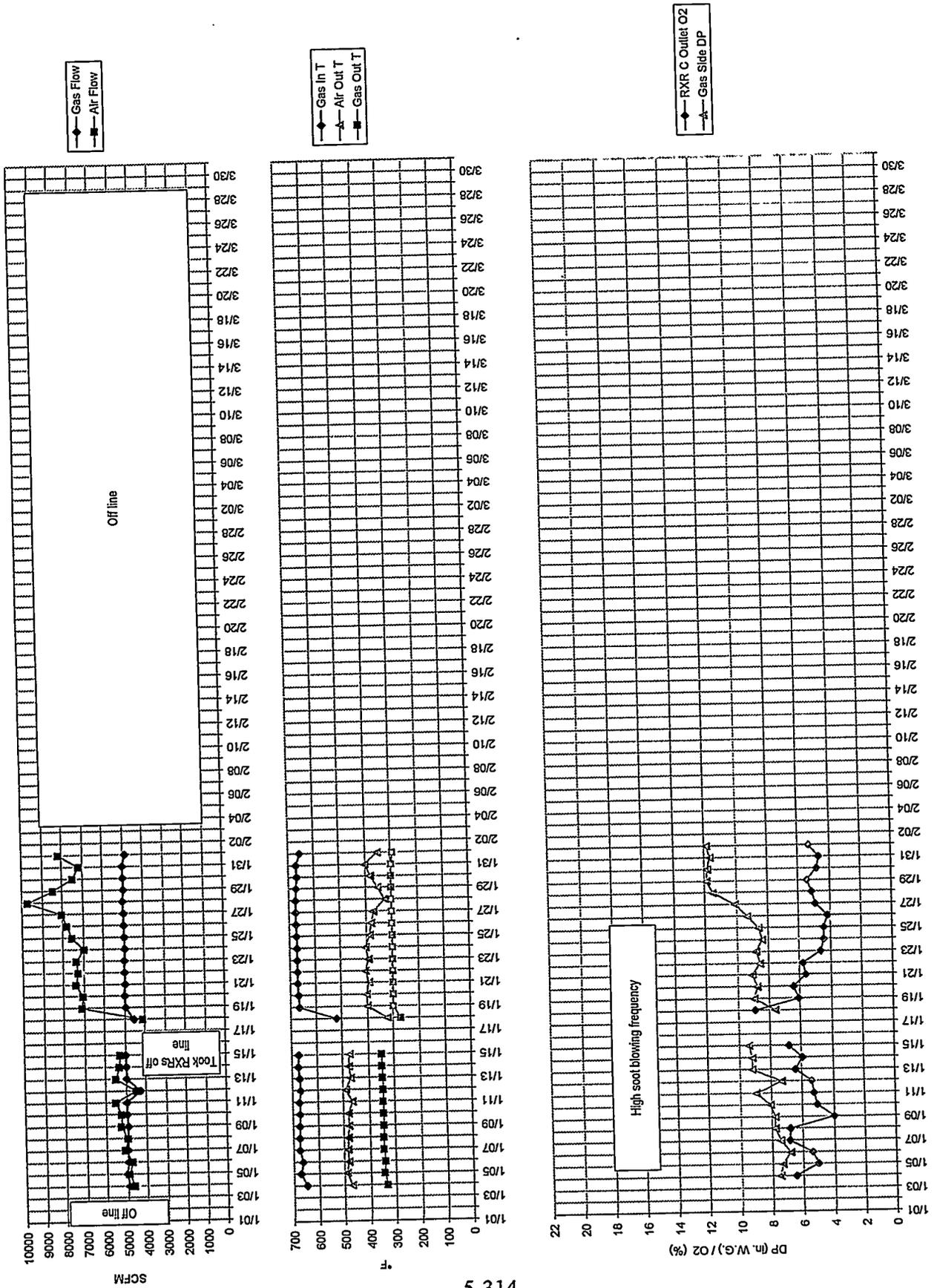


Figure 5.5-22

Air Preheater Trend Data for 2nd Quarter 1995  
Train A

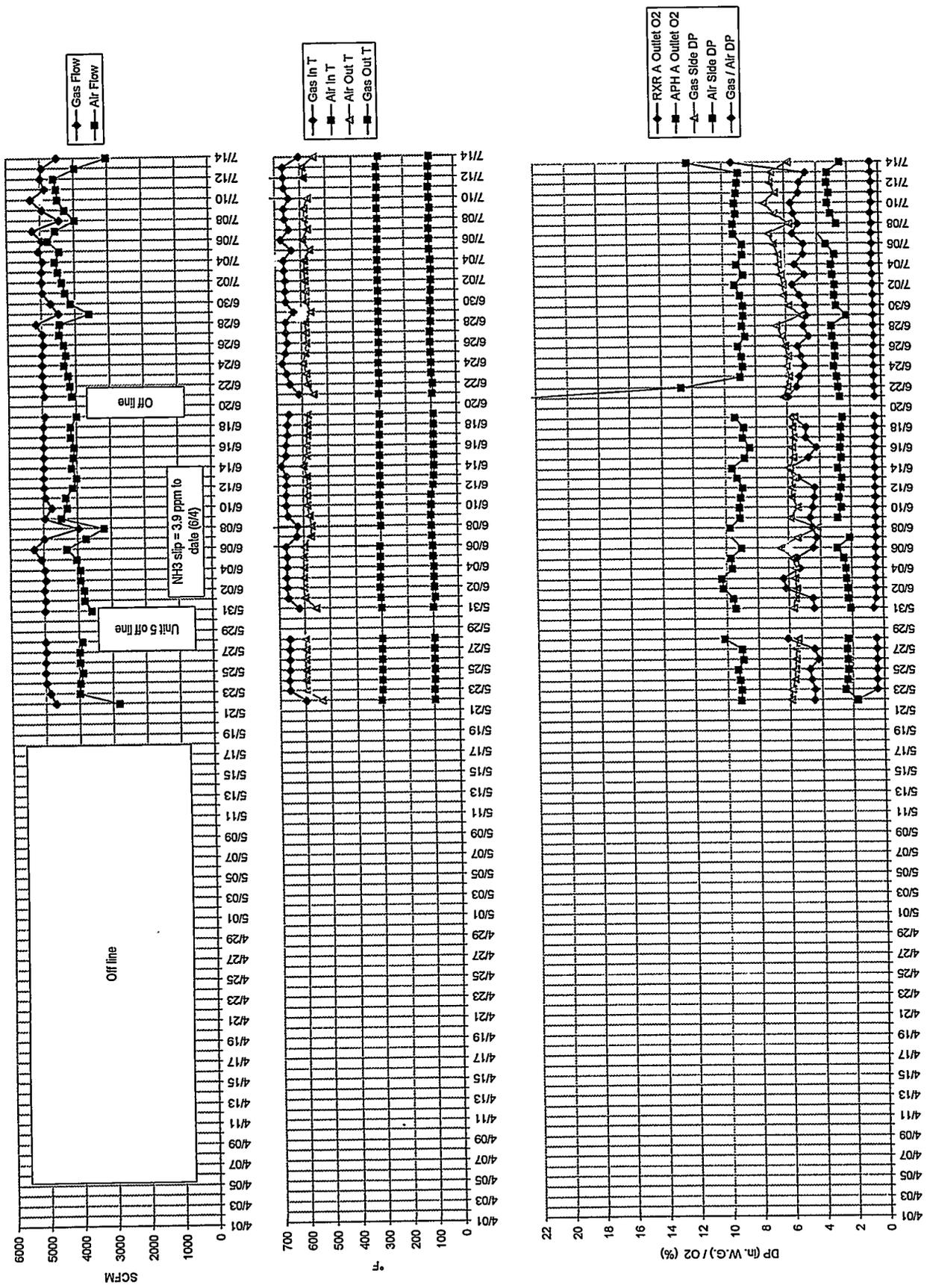
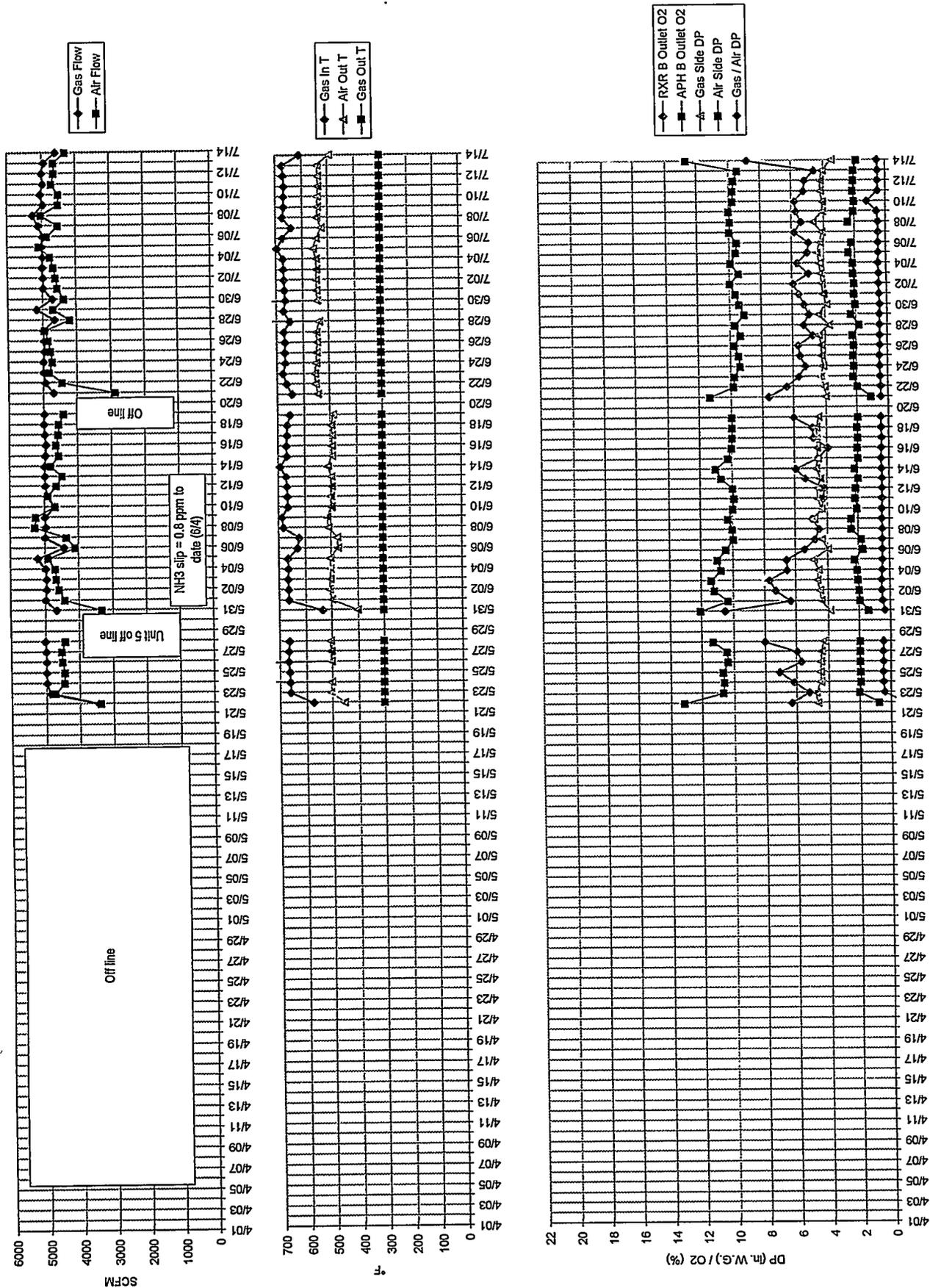


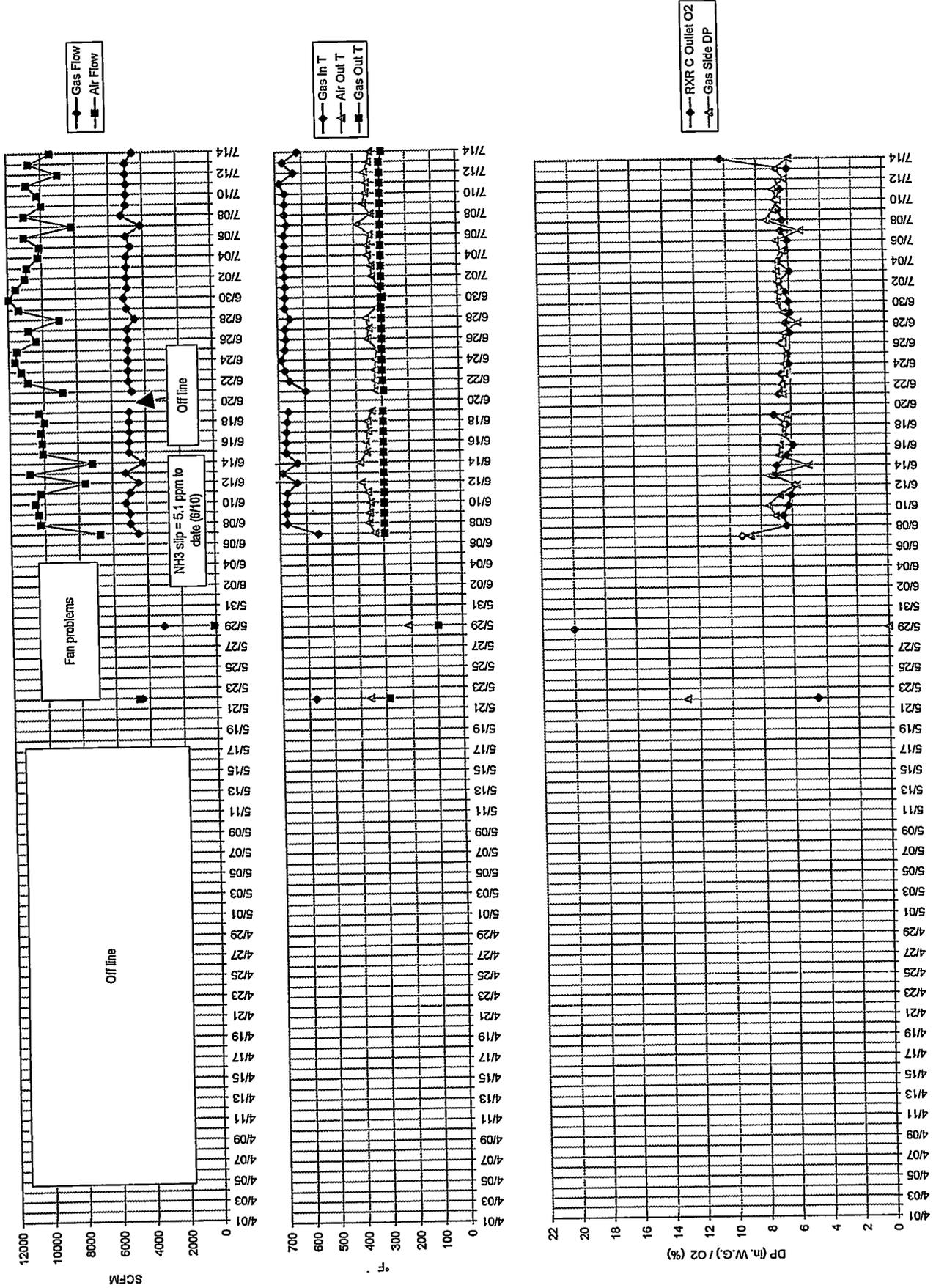
Figure 5.5-23

Air Preheater Trend Data for 2nd Quarter 1995  
Train B



Air Preheater Trend Data for 2nd Quarter 1995  
Train C

Figure 5.5-24



### 5.5.3 Air Preheater Evaluation by ABB Air Preheater, Inc.

The ABB air preheater evaluation is divided into two reports: 1) Final Test Report, contained in Appendix Q and 2) Corrosion Testing Results, contained in Appendix R.

As measured by the drop in number of transfer units (Ntu) from the initial values to the final values, the thermal performance of air preheaters A, B, and C dropped by about 11%, 7%, and 25%, respectively. The fact that air preheater B seemed to deteriorate less than the others is attributed to the fact that air preheater B received significantly less NH<sub>3</sub> slip than the other two air preheaters (see Table 1, Appendix Q). It is believed that air preheater C deteriorated the most because it is a recuperator, and is therefore, more sensitive to a given amount of fouling than a regenerator.

As one would expect, the gas side pressure drops were more sensitive to the degree of fouling and plugging than the Ntu values were. In general, all three air preheaters showed generally steady increases in gas-side pressure drop ( $\Delta P_g$ ) during the test period, punctuated by occasional spikes which may have been caused by system upsets such as a sootblower failure.

In general, the high  $\Delta P$ 's could be reduced by aggressive cleaning methods, including sootblowing at four hour intervals, thorough water washing, and occasional increases in the gas outlet temperature. It was not possible, however, to maintain the original, clean  $\Delta P$  of any of the air preheaters. The air and gas Euler (Eu) numbers for air preheater A increased by 145% and 115%, respectively, from the beginning of the test to the end. For air preheater B, the increases in both Eu numbers were in the 50-55% range.

Although the 3 layer air preheater appeared to perform better than the 2 layer air preheater, it cannot be concluded that the 3 layer design is superior to the 2 layer design. This is because the 2 layer air preheater received much more NH<sub>3</sub> than the 3 layer air preheater -- possibly as much as four to five times more. Given this significant difference

in operating conditions, the 2 layer air preheater performed remarkably well, and might very well have done better than the 3 layer design if the concentration of  $\text{NH}_3$  into the two regenerators had been equal.

The Q-Pipe® air preheater seemed to steadily lose thermal performance with time during most of the test, although a partial recovery was achieved during months 19-20. It is possible that some part of this performance loss may have been due to the loss of some of the heater pipes in the unit as a result of the sootblower jet penetrating the tube wall and the consequent loss of heat transfer fluid from those pipes. However, the majority of the drop in Ntu is believed to be attributable to fouling of the finned tubes on the gas side.

The report (Appendix R) dealing with the corrosion tests on various heat transfer surface materials used in air preheaters A and B recommends that enameled heat transfer surface should be used for Ljungstrom® air preheaters when ammonia and sulfur compounds are both present in the gas stream.

Table 2, Appendix Q, summarizes the changes in Ntu, air-side Euler number ( $\text{Eu}_a$ ), and gas-side Euler number ( $\text{Eu}_g$ ) for the three air preheaters. It compares worst case values and final values to initial values of all three parameters based on Figures 6-13 of the appendix. Worst case increases in  $\text{Eu}_g$  varied from 185% up to 320%. Worst case increases in air-side pressure drop ( $\Delta P_a$ ) varied from 245% up to 345%. Final air and gas Eu numbers were about 115-145% higher than initial values on air preheater A, and about 50%-55% higher on air preheater B. This is roughly consistent with the declines in Ntu (final vs. initial) of 11% for air preheater A and only 7% for air preheater B, since the air preheater with the higher increase in Eu (air preheater A) also had the greater loss of Ntu.

## 5.6 Catalyst Supplier Descriptions and Laboratory Test Results

The laboratory testing program for the project was described in Section 3.3 of this report. Appendix D contains an example laboratory testing protocol agreed upon by SCS and the

individual catalyst suppliers. Many of the tests performed are proprietary. However, the catalyst deactivation as a function of exposure time is the most critical parameter measured and is presented here. Catalyst deactivation was measured, using samples collected from the test facility at roughly three-month intervals over the life of the test program. The total catalyst exposure time is shown in Table 5.6-2. Deactivation studies were carried out by performing a series of tests in the individual laboratories at various operating conditions. The nominal conditions for those tests are shown below in Table 5.6-3.

Table 5.6-2 Total Catalyst Exposure Time

| Catalyst              | Reactor Designation | Total Exposure Time (hrs.) |
|-----------------------|---------------------|----------------------------|
| Grace (Noxeram)       | A (large)           | 11012                      |
| NSKK                  | B (large)           | 11859                      |
| Siemens               | C (large)           | 11632                      |
| Grace (Synox)         | D (small)           | 10151                      |
| Cormetech (high-dust) | E (small)           | 10151                      |
| Haldor Topsoe         | F (small)           | 10175                      |
| Hitachi Zosen         | G (small)           | 7293                       |
| Cormetech (low-dust)  | J (small/low-dust)  | 5363                       |

Table 5.6-3 Laboratory Test Conditions

| Test No. | Temp. (°F) | AV<br>(Nm <sup>3</sup> /m <sup>2</sup> h) | Inlet NO <sub>x</sub><br>(ppmv) | NH <sub>3</sub> /NO <sub>x</sub> | SO <sub>2</sub> (ppmv) |
|----------|------------|---|---------------------------------|----------------------------------|------------------------|
| 1 (base) | 700        | 50  | 400                             | 1.0                              | 2000                   |
| 2        | 700        | 50  | 400                             | 0.6                              | 2000                   |
| 3        | 700        | 50  | 250                             | 1.0                              | 2000                   |
| 4        | 640        | 50  | 400                             | 1.0                              | 2000                   |
| 5        | 700        | 20  | 400                             | 1.0                              | 2000                   |
| 6        | 700        | 20  | 400                             | 1.0                              | 1000                   |

The determination of catalyst activity ( $k$ ) is based on the application of laboratory experimental data to a simplified kinetic correlation as follows (see [Appendix D](#)).

$$1/k_a = 1/(\eta)(k_i)S_g + 1/(k_g)(a_m)$$

where:  $k$  = first-order apparent rate constant, [time<sup>-1</sup>]

$\eta$  = effectiveness factor accounting for pore diffusion

$k_i$  = intrinsic rate constant, [mass\*(internal surface area)<sup>-1</sup>\*(time)<sup>-1</sup>]

$S_g$  = internal catalyst surface area per mass of catalyst

$k_g$  = mass transfer coefficient, [mass\*(geometric surface area)<sup>-1</sup>\*(time)<sup>-1</sup>]

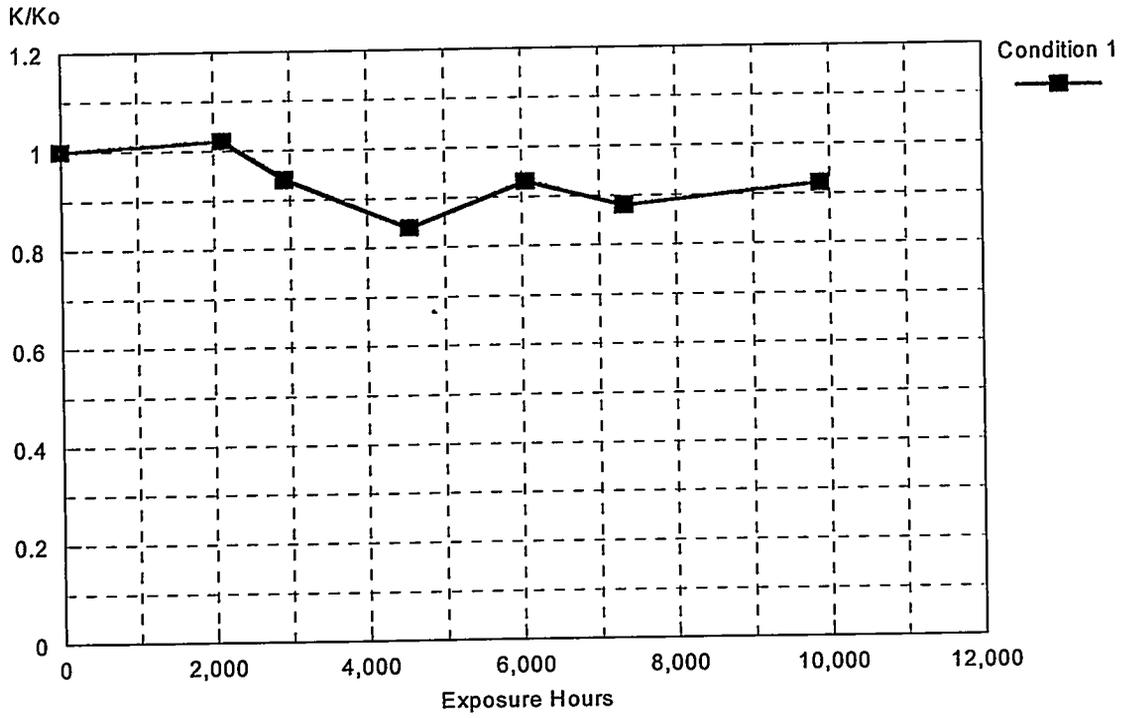
$a_m$  = external (geometric) surface area per mass of catalyst

SCS requested that the laboratory tests be conducted at conditions where the contribution of mass transfer resistance, expressed by  $1/(k_g)(a_m)$ , was less than 10% of  $1/k$ . In practice, this was difficult for some suppliers; and contributions to apparent activity ( $k$ ) may have been greater, especially under certain conditions. In addition, some suppliers may have used a slightly modified expression from that shown above to determine their particular apparent activity. The relative activity ( $k/k_o$ ) is determined by taking the ratio of measured activity at some exposure time to the activity of fresh catalyst. This ratio tends to remove some of the variability between the various definitions and measurement conditions of laboratory activity. However, since differences do exist between the laboratory activity data with respect to contributions from mass transfer and activity definition, the data is most useful in comparing a particular catalyst's activity decline over time rather than comparing activity declines from one catalyst to another. Also, laboratory catalyst deactivation data may not be directly applicable to the determination of installed catalyst life in a commercial installation, even though the data may be based on catalyst samples from that particular installation. This is due to the significant differences in operating conditions (and thus mass transfer contributions) between the commercial installation and the laboratory. Consequently, the data are often used to make comparisons to other operating installations with known commercial lives to predict the commercial catalyst life in that particular installation.

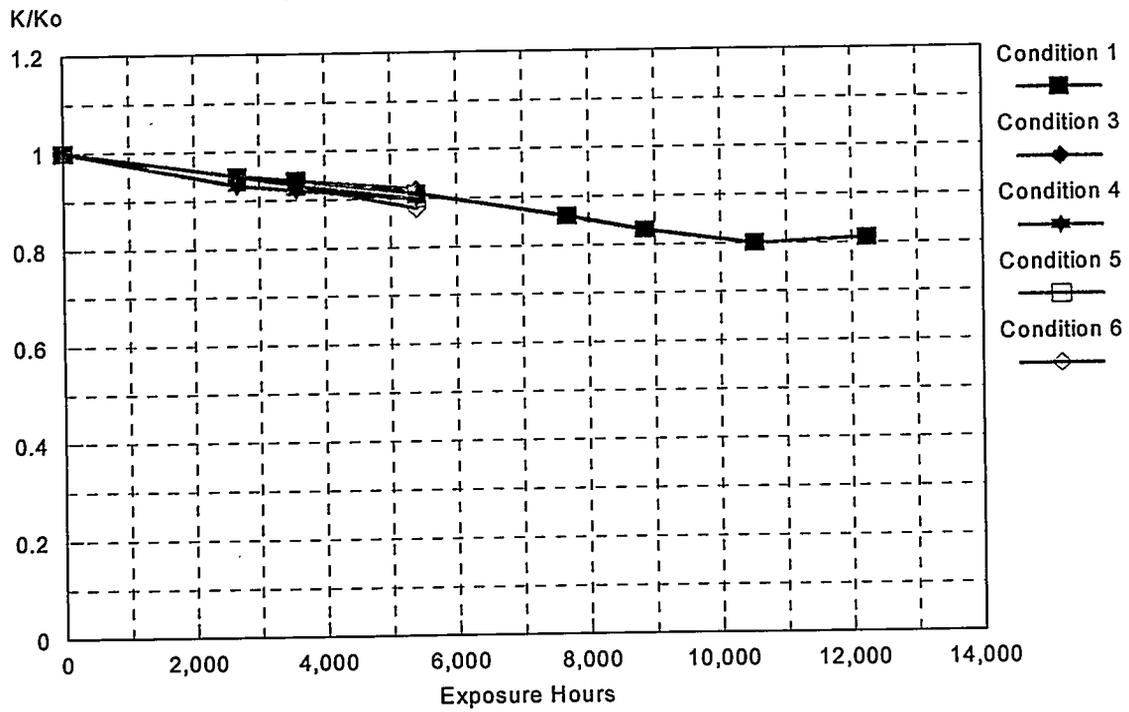
Figures 5.6-1 through 5.6-8 show the relative deNO<sub>x</sub> activity ( $k/k_0$ ) of the first catalyst bed for each of the test facility catalysts according to test condition. In general, most test conditions were designed to minimize contributions from mass transfer and therefore determine intrinsic deactivation (test conditions 1-4). However, test conditions at lower space velocities (test conditions 5 and 6) more closely mimic the actual operating conditions in a full scale application and may be more appropriate in determining the effects on a full scale installation due to deactivation. In most cases, for a given amount of catalyst deactivation, high area velocities exhibit a greater loss in deNO<sub>x</sub> efficiency than would low area velocities. Although some scatter is present in the plots, the general trend of the deactivation is similar to that of catalyst suppliers for installations in Europe and Japan. Activity at 12,000 hours can be extrapolated to be roughly 80 to 90% of initial catalyst activity. This finding is significant because it demonstrates that no severe deactivation is taking place with the U.S. coal application and that deactivation of the catalyst would be manageable.

Figures 5.6-9 through 5.6-14 show catalyst deactivation on a supplier basis. This allows the apparent deactivation to be compared for each test condition on a catalyst specific basis.

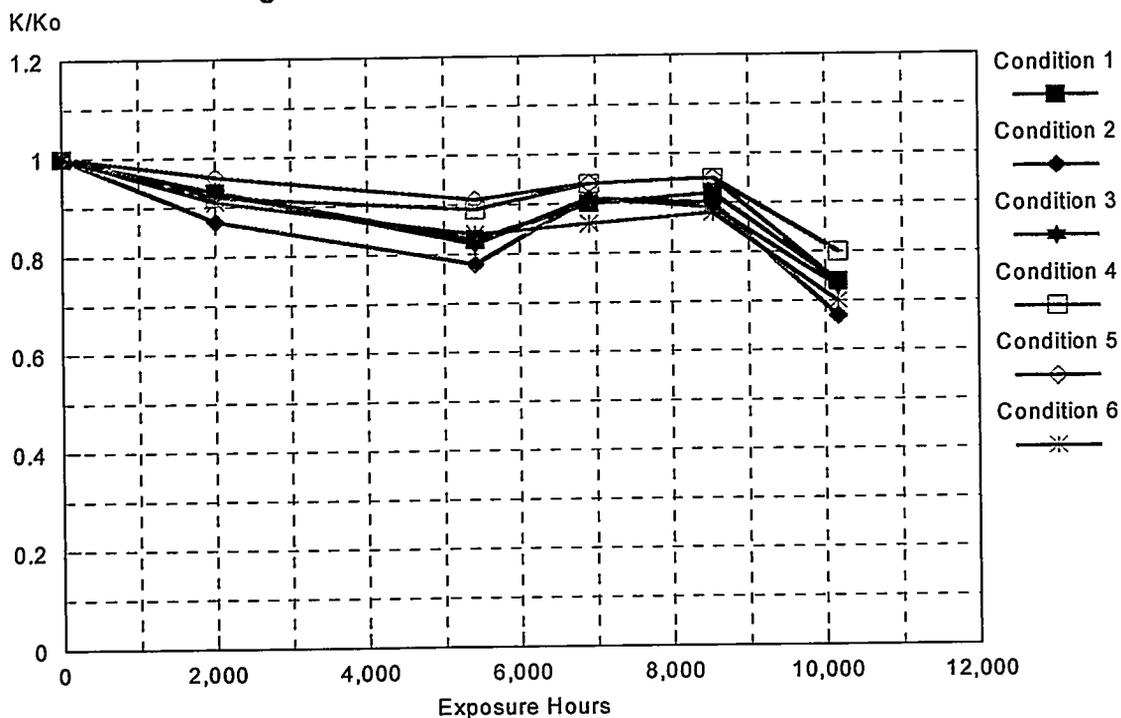
**Fig. 5.6-1 K/Ko vs Exposure Time (Grace Noxeram)**



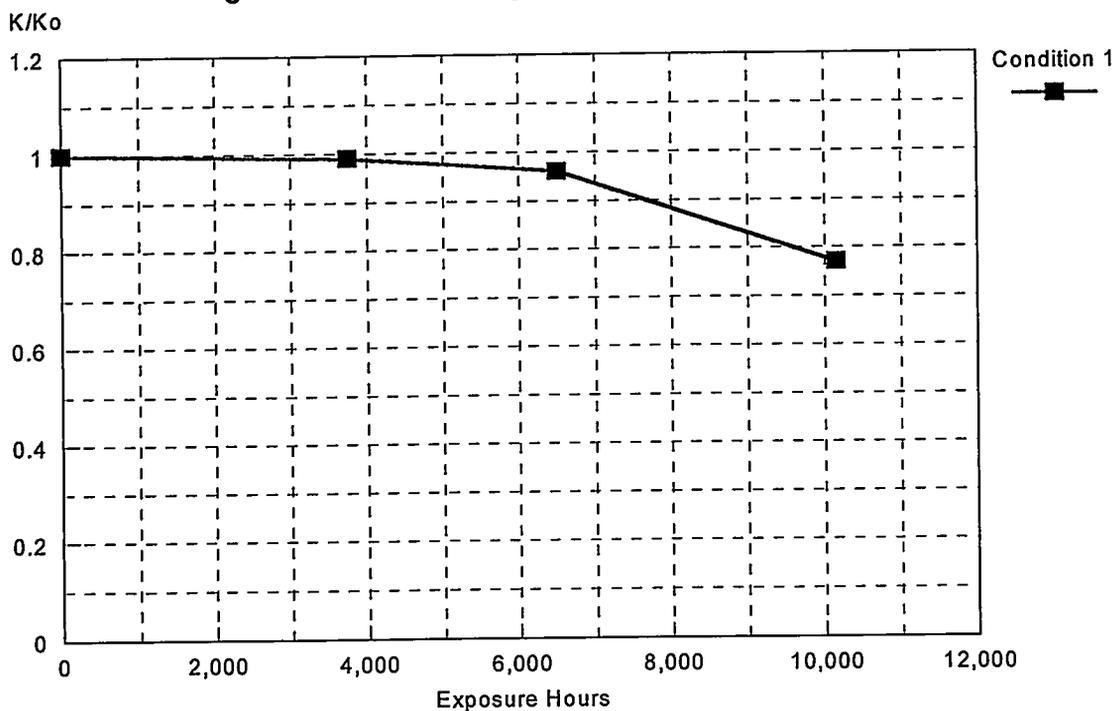
**Fig. 5.6-2 K/Ko vs Exposure Time (NSKK)**



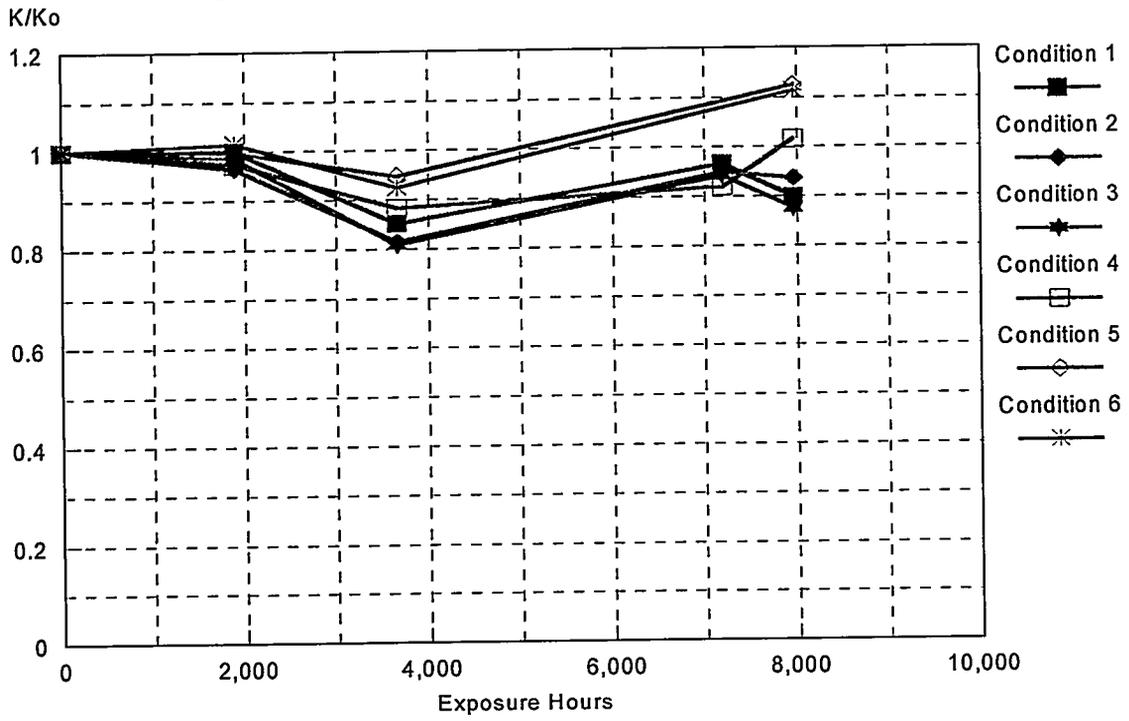
**Fig. 5.6-3 K/Ko vs Exposure Time (Siemens)**



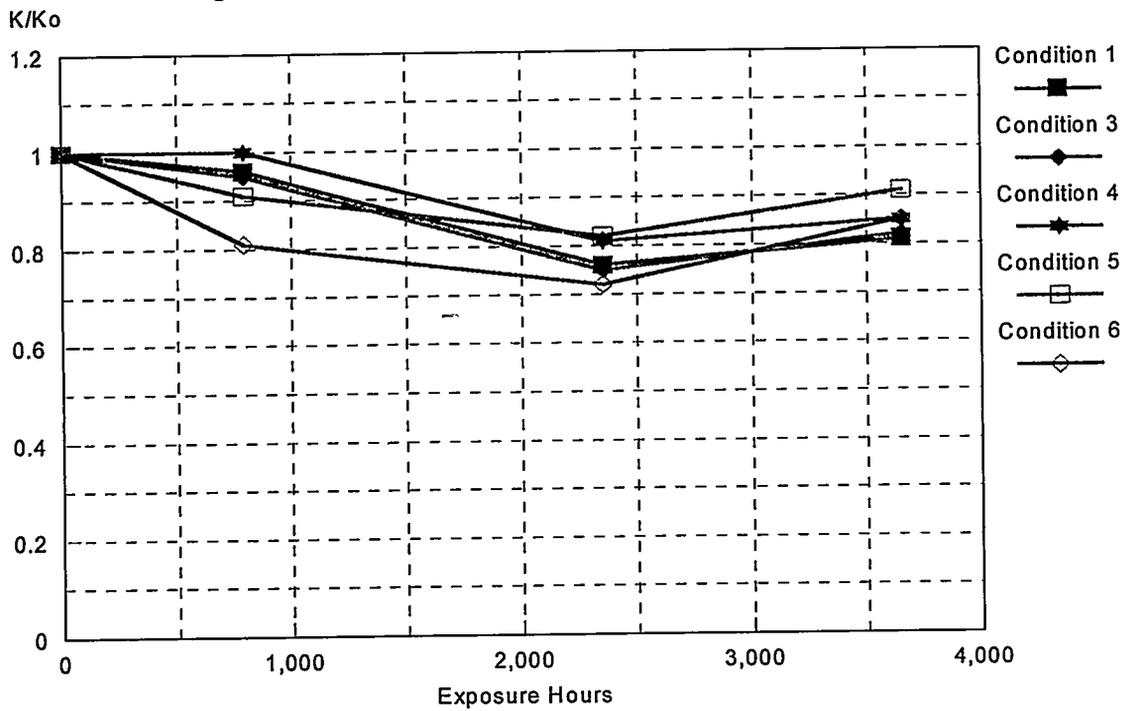
**Fig. 5.6-4 K/Ko vs Exposure Time (Grace Synox)**



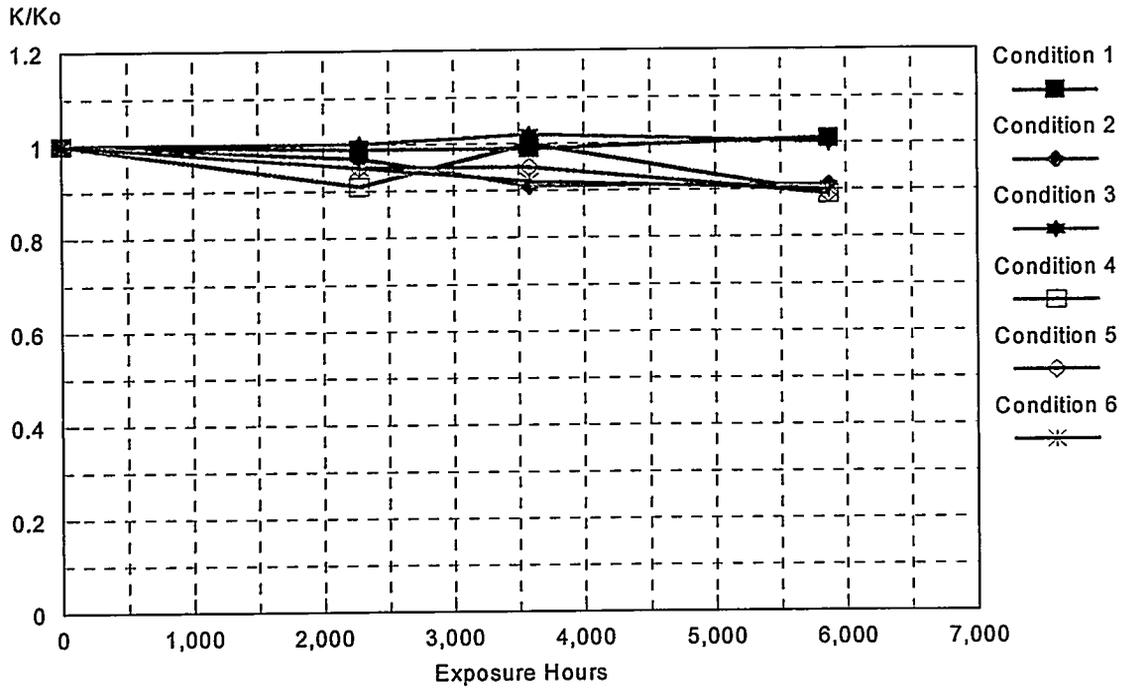
**Fig. 5.6-5 K/Ko vs Exposure Time (Cormetech HD)**



**Fig. 5.6-6 K/Ko vs Exposure Time (Haldor Topsoe)**

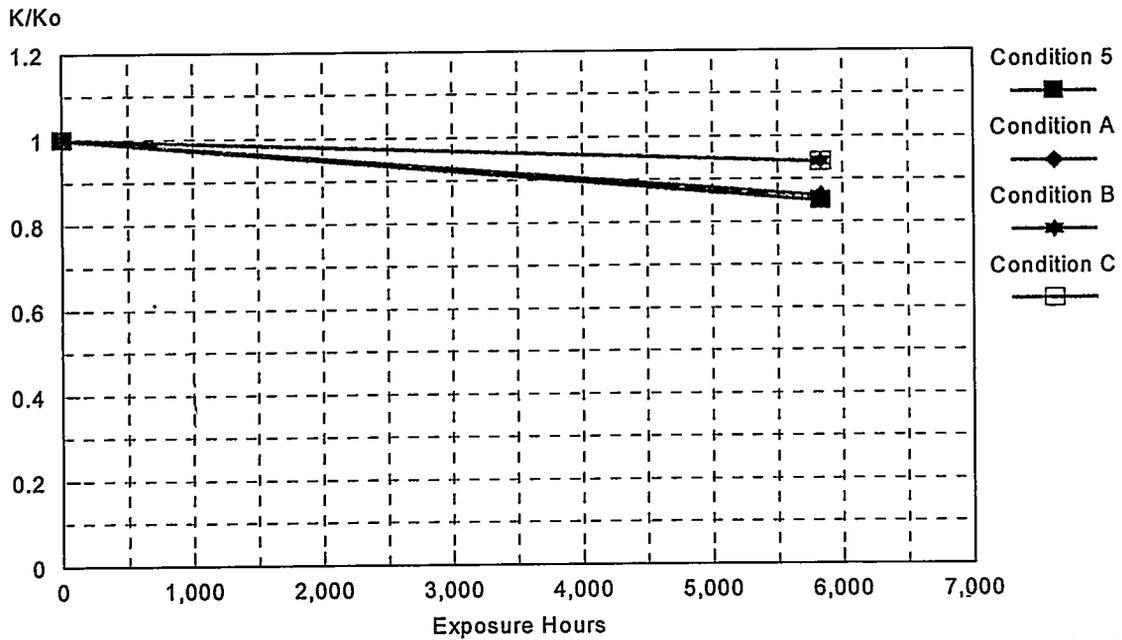


**Fig. 5.6-7 K/Ko vs Exposure Time (Hitachi Zosen)**



Note: Data based on second catalyst bed coupons

**Fig. 5.6-8 K/Ko vs Exposure Time (Cormetech LD)**



Condition A: AV=22 Nm<sup>3</sup>/hr, T=640 F, NH<sub>3</sub>/NO<sub>x</sub>=1.0  
 Condition B: AV=11 Nm<sup>3</sup>/hr, T=700 F, NH<sub>3</sub>/NO<sub>x</sub>=1.0  
 Condition C: AV=22 Nm<sup>3</sup>/hr, T=700 F, NH<sub>3</sub>/NO<sub>x</sub>=0.6

Fig. 5.6-9 Composite K/Ko vs Time for Cond. # 1

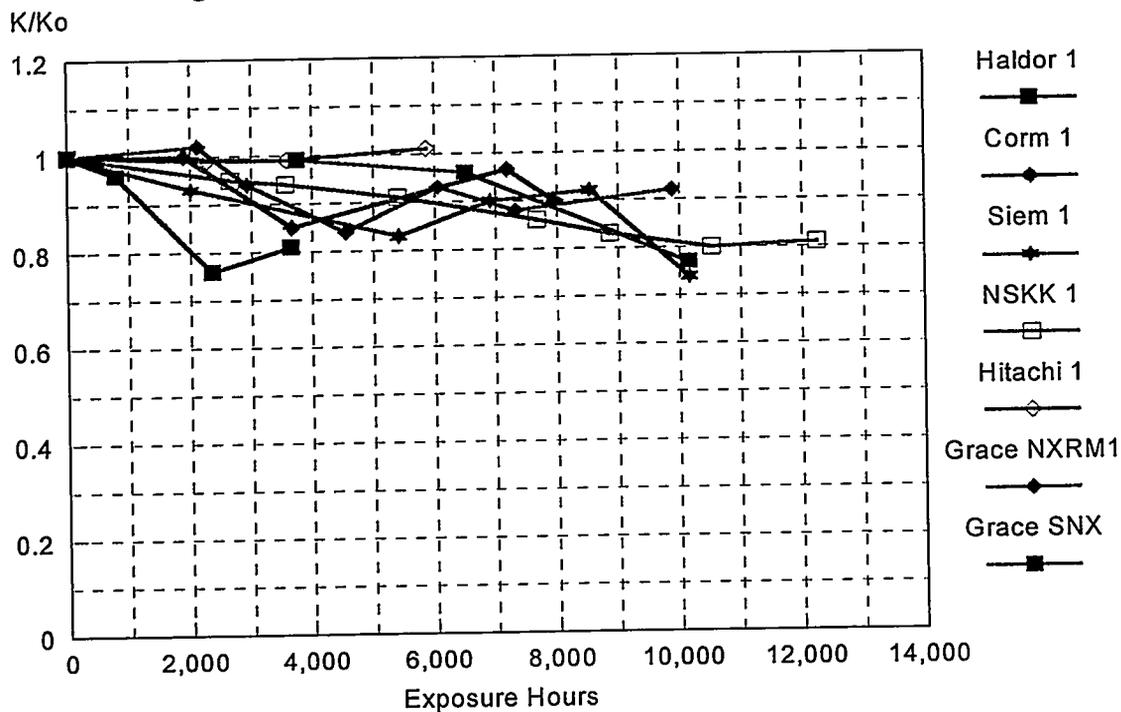
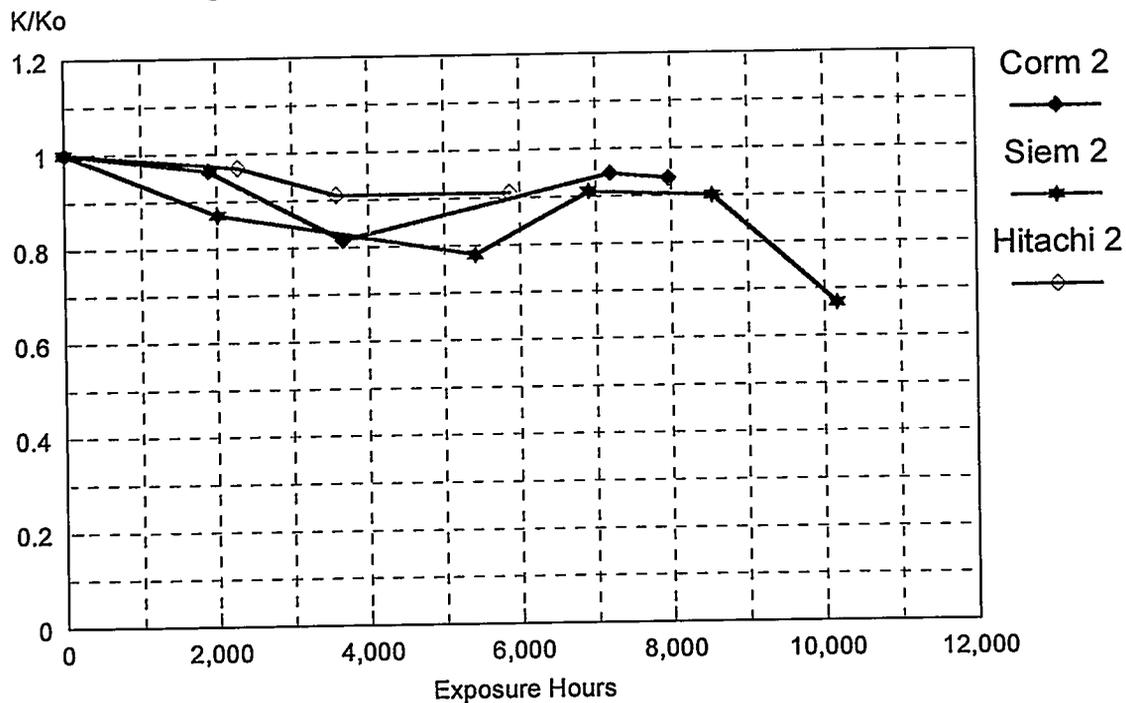
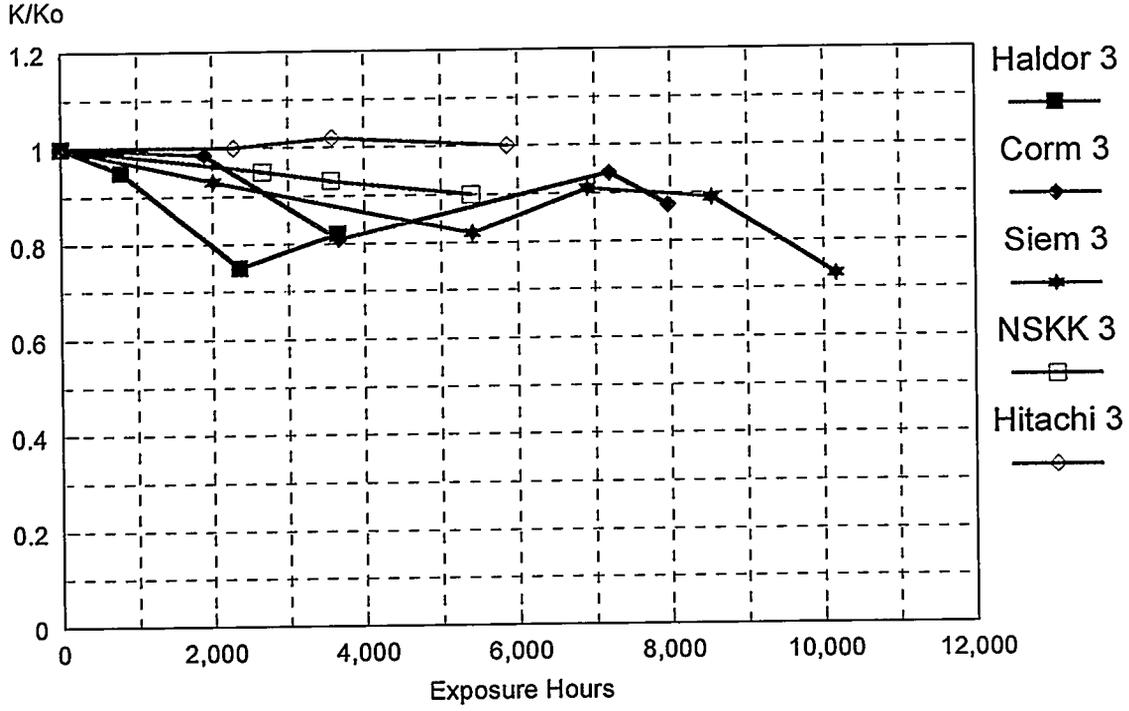


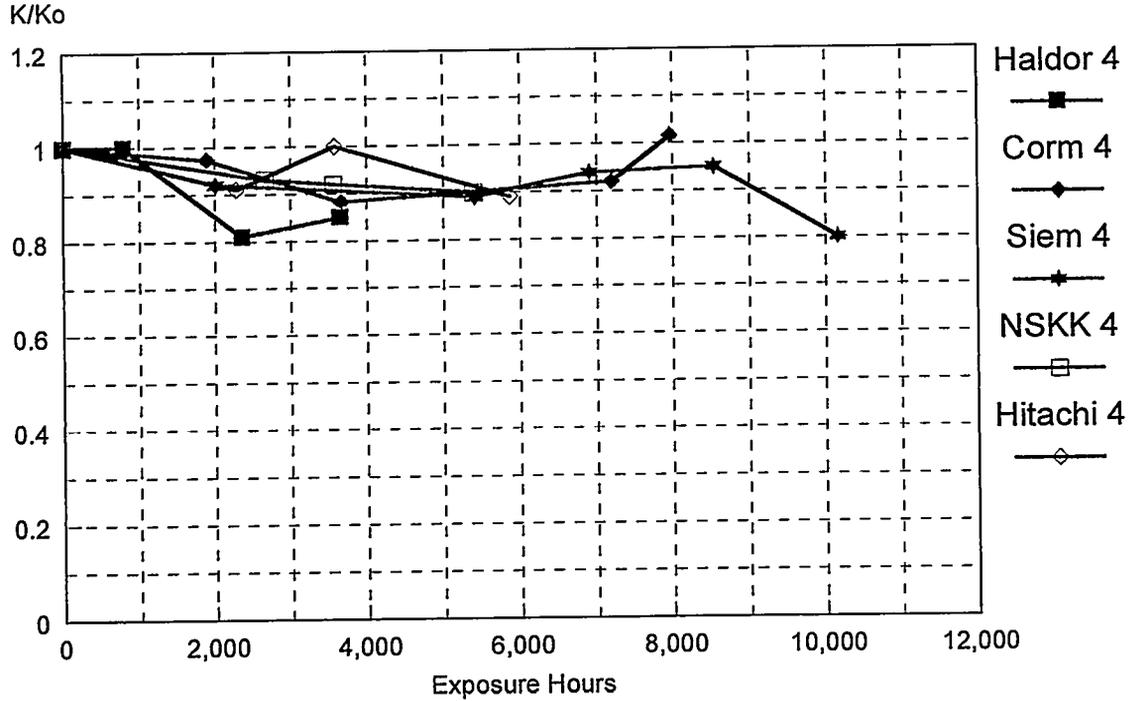
Fig. 5.6-10 Composite K/Ko vs Time for Cond. # 2



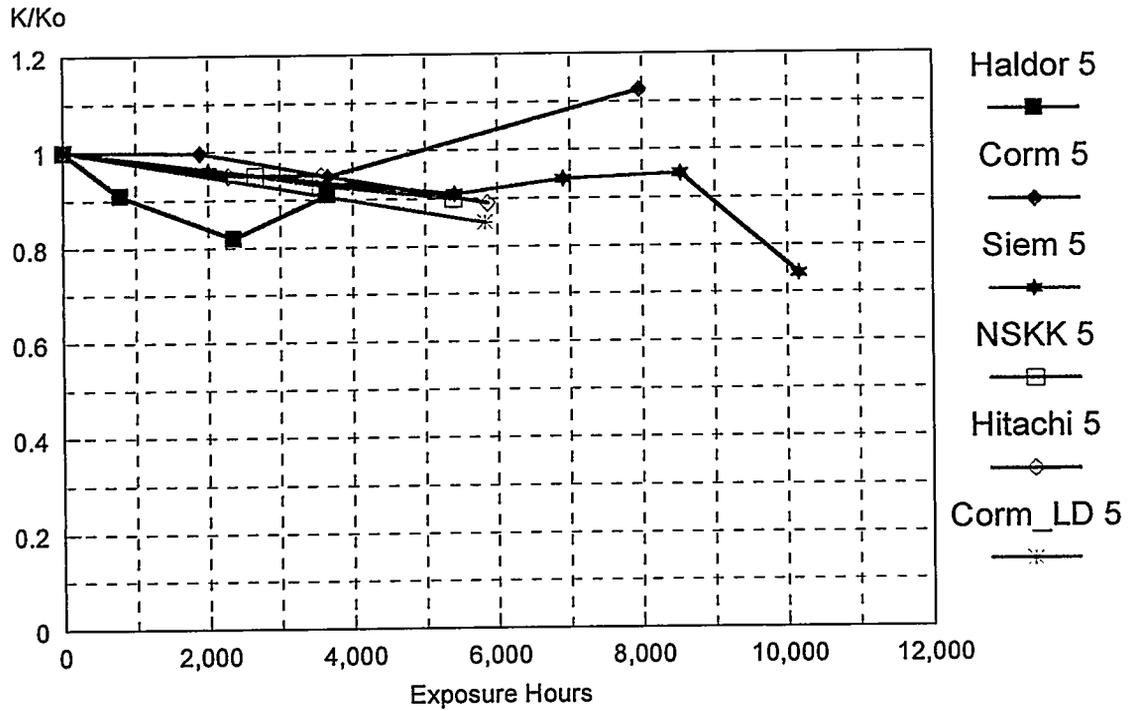
**Fig. 5.6-11 Composite K/Ko vs Time for Cond. # 3**



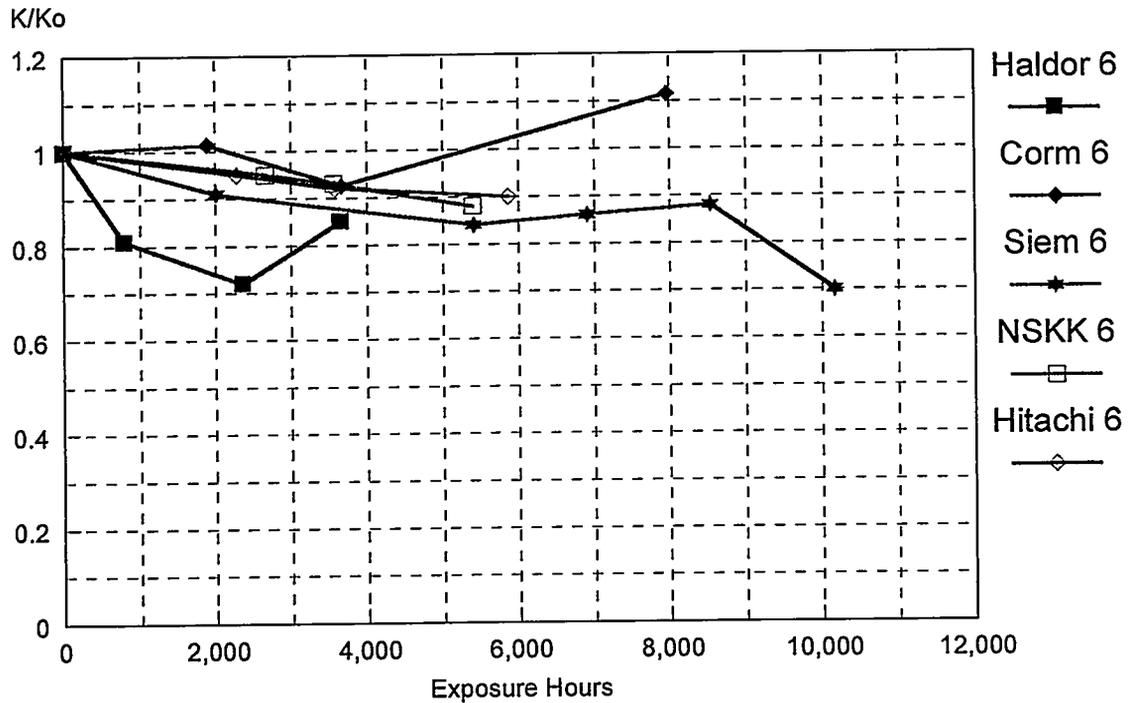
**Fig. 5.6-12 Composite K/Ko vs Time for Cond. # 4**



**Fig. 5.6-13 Composite K/Ko vs Time for Cond. # 5**



**Fig. 5.6-14 Composite K/Ko vs Time for Cond. # 6**



The following discussions present, where possible, the individual catalyst supplier's interpretation of the results of their laboratory studies. In addition, where available, general advertised information on each catalyst supplier is presented including current catalyst offerings, experience, services offered, etc. (Similar to published sales brochures.) This information has been provided directly from the suppliers and does not necessarily represent the views of the authors of this report.

### **5.6.1 W.R. Grace & Co. - Reactors A and D**

#### **5.6.1.1 General Advertised Information**

W.R. Grace & Co. offers advanced technology products tailored to meet the specific emission control needs of a wide range of industrial and power generation applications. Grace currently offers catalysts and systems for the control of carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), and volatile organic compounds (VOC) from stationary and automotive sources. Grace's Camet catalyst system produced in Hiram, Ohio features a metal monolith substrate uniquely designed of corrugated stainless steel which is coated with highly active catalyst and offers high CO, NO<sub>x</sub>, and VOC reduction at low pressure drops. Grace TEC Systems' facility in DePere, Wisconsin also offers systems for VOC control including thermal, catalytic and regenerative oxidizers.

For further information, please contact W.R. Grace & Co. under:

Dr. Mohit Uberoi  
Washington Research Center  
7379 Route 32  
Columbia, MD 21044  
Tel: 410-531-4272  
Fax: 410-531-4491

## 5.6.2 Nippon Shokubai Company, Ltd. - Reactor B

### 5.6.2.1 General Advertised Information

#### DeNO<sub>x</sub> Catalyst of Nippon Shokubai Co., Ltd.

Nippon Shokubai Co., Ltd. (NSCL) started research and development on the SCR catalyst in 1973. Since then, extensive research and development have been conducted on the unique catalyst compositions, shapes, and industrial production technology. In 1979, NSCL's SCR catalysts which have excellent deNO<sub>x</sub> activity with low SO<sub>2</sub> oxidation rate, very light weight, and high durability were commercialized by NSCL's own technology. They can be applied to utility and industrial boilers, heaters burning coal, oil or gas, gas turbines, engines burning gas or oil, and waste incinerations. More than 11,000 m<sup>3</sup> of NSCL's SCR catalyst have been installed and operated successfully in many electric power stations and industrial plants in Asia, Europe, and the USA.

Testing results at the SCS/DOE SCR Project proved NSCL's outstanding performance including high deNO<sub>x</sub> activity, very low SO<sub>2</sub> oxidation rate, low pressure drop, high resistance to erosion by dust, high resistance to catalyst poisons, and long life. It is concluded that the NSCL's SCR catalyst can be applied to the control of NO<sub>x</sub> emissions from High Sulfur Coal fired boilers in the United States.

## NSCL's DeNO<sub>x</sub> Catalyst Features

Not only the unique catalyst composition but also the highly automated production process and intensive quality control system contribute to the superior performance of NSCL's SCR catalysts.

- High DeNO<sub>x</sub> Activity
- Low SO<sub>2</sub> Oxidation Rate
- High resistance to SO<sub>x</sub> and dust
- Light weight
- Small pitch (3mm~) and thin wall (Open rate ~79%) honeycombs (large contact area and low pressure drop)
- Wide temperature range (350 °F - 1022 °F)
- High resistance to erosion
- Good thermal stability

For further information concerning Nippon Shokubai, please contact;

Mr. Kazuo Tsuchitani  
Manager, Technology Development  
P.O. Box 5407  
Chattanooga, TN 37506-0407  
Tel: 423-624-6496  
Fax: 423-629-0531

### **5.6.2.2 Laboratory Testing Results**

Results for two catalyst formulations (HC and HC-A) were presented by NSKK. This was possible because all replaced catalyst coupons were of the HC-A type. This allowed for future samplings of these replacement coupons and for laboratory data to be collected on these. The following text is a summary of testing results and conclusions reached by Nippon Shokubai.

Testing of Nippon Shokubai's SCR catalysts (HC and HC-A) exposed at Plant Crist was conducted with respect to deNO<sub>x</sub> activity, SO<sub>2</sub> oxidation, and such physical properties as specific surface area, pore volume, strength, etc. DeNO<sub>x</sub> activity decrease with exposure time was within the range of that experienced in Japan and Germany. Results of the

laboratory deNO<sub>x</sub> activity test were in good agreement with the parametric tests at Plant Crist. Influence of ABS/AS on the catalyst activity was not apparent. Significant SO<sub>2</sub> oxidation rate change was not observed. HC-A type catalyst for medium dust emission from coal fired boilers showed less activity loss with exposure time than HC type catalyst. Less masking of HC-A catalyst surface by the ash substance was considered to be the main reason for the better activity change behavior. Considering the dust content in the flue gas and the relative activity change results obtained in this testing, application of HC-A type catalyst for emissions from coal fired boilers may be possible. An initial specific surface area decrease was observed. However, the surface area decrease is not considered to be significant enough to affect the deNO<sub>x</sub> performance. Catalyst plugging and abrasion were not significant problems. The catalyst was also analyzed chemically to observe the relationship between catalyst deactivation and accumulated trace species. Deposition of Al, Ca, Fe, S, and Si substances on the catalyst surface was found. Increase of such surface deposition with exposure time was observed. Catalyst bulk analysis showed slight increases of such possible catalyst poisons as As, Ca, and K. However, deactivation of the catalyst was considered to be mainly due to the masking by the ash substance over the catalyst surface.

After reviewing the used catalyst condition and the results obtained during this program, NSKK had the impression that the SCR reactor was well-designed and operated properly. NSKK concluded that the SCR catalyst also can be applied for the control of NO<sub>x</sub> emissions from high-sulfur coal-fired boilers in the United States.

### **5.6.3 Siemens - Reactor C**

#### **5.6.3.1 General Advertised Information**

**Selective catalytic reduction** is the most effective large-scale process known today for reducing nitrogen oxide emissions from furnaces, incineration plants and industrial

process-plants. Catalysts for the SCR process have been produced by Siemens/KWU since 1987.

*SINOx® Plate-type* catalysts are an in-house development of KWU designed especially for deployment in dust-laden flue gases directly downstream of coal-fired boilers. With this product Siemens/KWU has secured a major share of the market in Europe, and has therefore accumulated extensive experience which has made Siemens one of the world's most competent partners in this technology. This expertise has also enabled Siemens to post major successes in introducing the technology in the USA. For example, Siemens booked eight orders for the supply of plate-type catalysts for coal-fired power plants and has an almost 90% share of the market in this field. These also include the first SCR retrofit for a plant in the USA (PSNH Unit Marrimack 2, wet-bottom boiler). All the renowned SCR plant builders in the USA have been supplied with *SINOx®* catalysts. Operating performance data is positive and this will help to make SCR technology available for coal-fired plants in the USA, as it has already been proven in Europe.

*SINOx® Plate-type catalysts* have the following characteristics:

**Composition**

Stainless Steel Carrier

TiO<sub>2</sub>

V-oxide

Mo-oxide

Operating Temp. 300-430 °C

High resistance to fly ash erosion

Insensitivity to dust deposits

Low susceptibility to fly ash blockage

High thermal and mechanical resistance

Low pressure loss

The catalyst geometry is highly adaptable to individual plant conditions by modification of the catalyst geometry:

Specific surface area: 250 to 400 (550) m<sup>2</sup>/m<sup>3</sup>

Plate height: 500/550/570/600/625 mm

The design of the *SINOx® Plate-type* catalysts is tailored to the chemical and physical conditions of service. If necessary, Siemens/KWU performs additional customizing

studies to find the ideal catalytic converter for the application. However, the catalyst is not the sole key to finding the most economical and reliable solution. To name a few examples: full deNO<sub>x</sub> reactor efficiency depends on flue-gas flow pattern being conducive to uniform flue-gas velocities and distribution of the injected reducing agent over the entire reactor cross-section. On completion of commissioning, on-line process data must be collected to gain insights into the long-term behavior of the catalysts and to determine the optimum time of replacement.

Siemens/KWU scope of services in the field of SCR technology therefore covers:

**SCR consulting**

Optimization of SCR design  
NH<sub>3</sub> injection design  
Catalytic converter dimensioning  
Operating requirements

**Flow model tests**

Optimization of flue-gas flow  
Optimization of NH<sub>3</sub> injection  
Ductwork routing  
Prevention of fly ash deposition

**Commissioning/SCR inspections**

Catalyst installation  
Operating instructions  
Commissioning  
SCR plant inspections

**Catalyst management services**

Monitoring of catalyst behavior  
Catalyst replacement strategies

For additional information, please contact Siemens under:

Siemens AG, KWU F11 Kat  
P.O. Box 3220  
D-91050 Erlangen, Germany  
Mr. Ralph Sigling  
Tel.: ++49 9131 18 6169  
Fax.: ++ 49 9131 18 2786  
E-Mail: sigling@erls13.kwu.siemens.de

## **5.6.4 Cormetech, Inc. - Reactors E and J**

### **5.6.4.1 General Advertised Information**

Cormetech, Inc. is a leading environmental technologies company offering design, manufacturing, testing, and customer support services. From its modern headquarters near Research Triangle Park in Durham, North Carolina, Cormetech designs and manufactures the most proven technology for SCR systems and is successfully applied to 70% of all SCRs worldwide. Cormetech's ceramic, extruded, honeycomb catalysts provide maximum efficiency in nitrogen oxide (NO<sub>x</sub>) removal from coal-, oil-, and gas-fired stationary combustion systems. The honeycomb structure of Cormetech's high-surface area, titanium dioxide based catalyst maximizes catalytic activity while minimizing gas-flow resistance.

Each Cormetech installation is backed by a performance and life span guarantee. Furthermore, Cormetech works closely with operators to provide maintenance or investigative testing during planned shut-downs. When the catalyst is ultimately in need of replacement, Cormetech offers both replacement and recycling services.

Cormetech services include SCR Catalyst Design, Engineering and Manufacture, Field Supervision and Engineering, On-Site Training, Catalyst Management, Catalyst Replacement, Flow Modeling, and Extensive Laboratory Testing. End users of Cormetech's technology include electric utilities, independent power producers, petroleum refiners, as well as chemical manufacturers. Cormetech has installed its SCR catalysts in over 125 units, encompassing over 11,000 MW of power generating capacity. Installations include coal, gas, and oil utility boilers, gas turbines, refinery boilers, industrial boilers, and diesel engines.

Cormetech SCR catalyst was installed in both Plant Crist's High Dust Reactor E and Low Dust Reactor J as part of the ICCT Catalyst Test. The SCR catalyst installed in both the

high-dust and low-dust applications performed above expectations. Both deNO<sub>x</sub> performance (catalyst deactivation) and SO<sub>2</sub> oxidation easily remained within design limits. The two layers of the high-dust reactor are expected to last up to 31,000 hours, while the expected life for the low-dust design is 21,000 hours due to higher design space velocity. The deactivation mechanisms are consistent with experience and within expectations. The test results showed the impact of high sulfur coal on Cormetech SCR catalyst is minimal, and that SCR is a viable technology for high sulfur coal applications.

For further information, please contact Cormetech under;

Mr. Reda S. Iskandar  
Vice President - Sales and Marketing  
Cormetech, Inc.  
5000 International Drive  
Durham, North Carolina 27712  
Tel: 919-620-3003  
Fax: 919-620-3001

#### **5.6.4.2 Laboratory Testing Results**

The following text is a summary of conclusions reached by Cormetech, Inc., based on the laboratory test results.

##### **5.6.4.2.1 Reactor E - High-Dust**

1. Overall the SCR catalyst installed in the high-dust application performed above expectations. Both deNO<sub>x</sub> performance (catalyst deactivation) and SO<sub>2</sub> oxidation easily remained within design limits.
2. Two layers of catalyst are more than sufficient to meet the design requirements of the test; however, due to initial concern over the small scale of the project and somewhat unknown effects of firing high sulfur U.S. coal on the SCR catalyst, a third layer of catalyst was installed. Upon design of a full scale facility a space velocity more closely related with an equivalent two (2) layer system should be used (approx. 4000). The two layers are expected to last up to 31,000 hours.

3. In general, the deactivation mechanisms are consistent with experience. However, the potential impact of iron compounds on surface contamination warrants further study.

#### **5.6.4.2.2 Reactor J - Low-Dust**

1. Overall, the SCR catalyst installed in the low-dust application performed above expectations-even when considering margin for as much as 30% plugging of the catalyst. DeNO<sub>x</sub> performance (catalyst deactivation) and SO<sub>2</sub> oxidation easily remained within design limits. SO<sub>2</sub> oxidation increased significantly; however, further testing is necessary to determine if the increase is true or if the catalyst is emitting accumulated SO<sub>3</sub>.
2. The catalyst bed is expected to last at least 20,000 hours.

### **5.6.5 Haldor Topsoe - Reactor F**

#### **5.6.5.1 General Advertised Information**

##### Catalyst Description

The Topsoe DNX-362 catalyst is based on a porous fiber reinforced TiO<sub>2</sub> carrier impregnated with V<sub>2</sub>O<sub>5</sub> and WO<sub>3</sub>. The result is a catalyst with a porous structure having the active components finely dispersed on the entire surface area, ensuring a large number of active sites. The special way of manufacturing the catalyst allows for a comparatively low content of V<sub>2</sub>O<sub>5</sub> which keeps the SO<sub>2</sub> oxidation at a low level. The catalyst has a reinforced front edge which eliminates erosion.

The DNX-catalyst series are the results of Topsoe's own developments, which started back in the beginning of the 1980s. Thus, Haldor Topsoe is able to supply DNX catalyst world-wide, as they are not limited by licenses.

### Technical Service

The backbone in Topsoe's technical service program is an extensive contact to the industry. New requirements of the catalyst from the industry can be investigated by Topsoe's research facilities, and also engineering aspects can be dealt with intensively by Topsoe's engineering experts. This close contact to the industry enables Topsoe to improve products as well as to develop models for catalyst performance predictions.

Topsoe's engineers communicate regularly with catalyst users to discuss operation and experience. Based on operating data, Topsoe makes performance checks and evaluates the state of the catalyst. Through predictions it can be determined when catalyst replacement or installation of additional catalyst will be advantageous and economic in light of the client's requirements and operating philosophy.

In addition, the Topsoe program comprises supervision of loading , start-up, optimization of the operation, and training of personnel.

### Industrial Experience

Topsoe has delivered catalyst for pilot scale to full scale industrial units treating flue gas flows from 10,000 to 2,200,000 Nm<sup>3</sup>/hr, with design deNO<sub>x</sub> efficiencies ranging from 80% to more than 98%.

In all of the more than 30 references, the performance has fulfilled the highest expectations with respect to:

- high NO<sub>x</sub> removal activity
- low SO<sub>2</sub> oxidation
- low pressure drop
- low deactivation
- high mechanical stability

References are distributed on application areas shown below:

| Boilers |             |               | Engines          |                    |              | SNOX™                       | Other     |
|---------|-------------|---------------|------------------|--------------------|--------------|-----------------------------|-----------|
| Gas     | Gas/<br>Oil | Coal<br>(Oil) | Diesel<br>(land) | Diesel<br>(marine) | Dual<br>Fuel | Coal, Oil,<br>Coke, Lignite | Chemicals |
| 2       | 1           | 3             | 9                | 6                  | 3            | 6                           | 2         |

As can be seen from the table, Topsoe is experienced within practically any SCR application area. For boilers, Topsoe has delivered catalyst for demonstration units and up to 600 MW power plants.

Topsoe was the first ever to equip ships with deNO<sub>x</sub> systems.

Conclusions from the SCS/DOE SCR-project

The DNX-362 has demonstrated a very high and stable deNO<sub>x</sub> activity and almost zero SO<sub>2</sub>-oxidation activity. In addition there has been no tendency of pluggage of the catalyst and no sign of erosion has been observed.

The conclusions are that the DNX-362 has fulfilled the expectations, and the experiences on a boiler burning US high-sulphur coal are very similar to previous experiences obtained from Danish power plants.

For further information concerning Haldor Topsoe, please contact;

Mr. Samuel H. Chidester  
Sales Manager  
Sulfuric acid and Environmental Catalysts  
Catalyst Division  
Haldor Topsoe, Inc.  
P.O. Box 58767  
Houston, Texas 77258-8767  
Tel: 713-480-2600 x.166  
Fax: 713-480-2021

### **5.6.6 Hitachi Zosen - Reactor G**

#### **5.6.6.1 General Advertised Information**

##### History in SCR

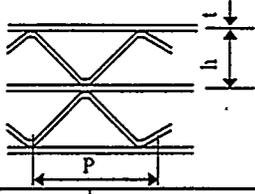
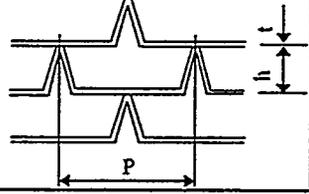
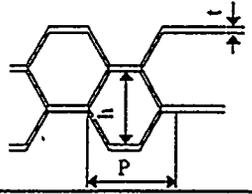
Hitachi Zosen, established at Osaka, Japan in 1881, as a leading company of engineering and manufacturing, has been covering a vast range of activities to meet the changing requirements of the world's communities and industries. In 1969, Hitachi Zosen started R&D programs for removing NO<sub>x</sub> with the SCR process and had successful results in: 1) developing and manufacturing effective catalysts, 2) construction of the world's first commercial NO<sub>x</sub> removal plant in 1975, and 3) completion of the largest-scale NO<sub>x</sub> removal plant in the world in 1985. Hitachi Zosen is determined to continue the pursuit of higher technology in SCR.

## Catalyst

Hitachi Zosen has developed various types of catalysts: NO<sub>x</sub>NON 300 (pellet), NO<sub>x</sub>NON 500/600(metal plate) and the latest NO<sub>x</sub>NON 700. NO<sub>x</sub>NON 700 is a new ceramic type catalyst (CP catalyst) having the following features:

- Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, TiO<sub>2</sub>, V<sub>2</sub>O<sub>5</sub>, WO<sub>3</sub> composition for higher performance in various applications,.
- High-Density honeycomb structure for less catalyst volume,
- Thin ceramic sheet for lighter weight and less pressure loss, and
- Higher activity for wider temperature range.

At present Hitachi Zosen can supply NO<sub>x</sub>NON 700 with three different configurations as shown below.

| TYPE          | S TYPE  |   | P TYPE   | H TYPE  |
|---------------|---|---|--|---|
| CONFIGURATION |  |   |  |  |
| DIMENSION     | H (mm)  | 3.7/5.0                                       | 5.5  | 4.0   |
|               | P (mm)  | 7.5/8.4                                       | 30   | 7.0   |
|               | t (mm)  | 0.3   | 0.4  | 0.4   |
|               | AREA  | 1020/820<br>(m <sup>2</sup> /m <sup>3</sup> ) | 420  | 550   |
| APPLICATION   |   |   | GAS FIRED  |   |
|               |   |   | OIL FIRED  |   |
|               |   |   | COAL FIRED   |   |

Hitachi Zosen can also supply various services in the SCR field. For more detailed information, please contact Hitachi Zosen as follows.

Attn. Mr. Doi  
Manager, Plant Business Dept.  
Hitachi Zosen U.S.A. LTD.  
767 Third Avenue, 17th Floor  
New York, NY 10017

Attn: Mr. N. Matsumoto  
Manager, Plant Engineering and Design Dept.  
Hitachi Zosen Corporation  
3-40, Sakurajima 1-chome  
Konohana-ku, Osaka 554  
JAPAN

Tel: (212) 355-5650  
Fax: (212) 308-4937

Tel: 81-6-465-3053  
Fax: 81-6-465-4015

#### 5.6.6.2 Laboratory Testing Results

Hitachi Zosen supplied NO<sub>x</sub>NON 700 P type catalyst for the high dust small reactor G at the SCR project. General results from the test facility at Plant Crist and also the laboratory tests of catalyst samples sent back from Plant Crist to Hitachi Zosen's laboratories showed nearly the same performance as was expected for deNO<sub>x</sub> rate, SO<sub>2</sub> conversion rate, and operating hour effects. Replacement of the catalyst damaged by manual sootblowing during the test shortened considerably the catalyst exposure hours to the flue gas. However, Hitachi Zosen concluded, with the test results covering the critical period for operating hour effects, that NO<sub>x</sub>NON 700 P type catalyst can be applied for flue gas NO<sub>x</sub> control with high-sulfur U.S. coal firing. Hitachi Zosen also confirmed that the special features of NO<sub>x</sub>NON 700 catalyst allowed for operation with almost no sootblowing.

## **5.7 Coal Analysis**

Summary tables of the coal analyses performed over the project life follow. Table 5.7-1 presents the data measured by Alabama Power Company Laboratories and contains primary coal constituents as well as some trace metals. Table 5.7-2 presents trace metal data measured at the University of Missouri-Columbia, Research Reactor Center using neutron activation analysis. Table 5.7-3 offers a comparison of data for species that were measured by both laboratories.

Table 5.7-1 Alabama Power/SCS Coal Analysis Data - As Burned Composites

| SCS ID No. | Test                  | Method                | Units    | 1st Qtr. 93 |        | 2nd Qtr. 93 |        | 3rd Qtr. 93 |        | 4th Qtr. 93 |        | 1st Qtr. 94 |        | 2nd Qtr. 94 |        | 3rd Qtr. 94 |        | 4th Qtr. 94 |        | 1st Qtr. 95 |        | 2nd Qtr. 95 |        | 1993    |        | 1994    |        | 1995    |        | Project Life |        |         |        |       |       |       |       |       |
|------------|-----------------------|-----------------------|----------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|-------------|--------|---------|--------|---------|--------|---------|--------|--------------|--------|---------|--------|-------|-------|-------|-------|-------|
|            |                       |                       |          | Average     | Sample | Average | Sample | Average | Sample | Average | Sample | Average      | Sample | Average | Sample |       |       |       |       |       |
|            | Moisture, Total       | ASTM D 3302           | % by Wt. | 11.46       | 10.56  | 10.56       | 10.40  | 10.05       | 9.58   | 11.74       | 11.46  | 11.86       | 12.42  | 10.58       | 10.45  | 11.16       | 10.45  | 11.16       | 11.04  | 10.87       | 10.45  | 11.16       | 10.45  | 11.16   | 10.45  | 11.16   | 10.45  | 11.16   | 10.45  | 11.16        | 10.45  | 11.16   |        |       |       |       |       |       |
|            | Ash                   | ASTM D 3180           | % by Wt. | 9.24        | 9.29   | 9.24        | 10.00  | 9.70        | 9.64   | 8.81        | 8.87   | 9.39        | 9.46   | 8.63        | 9.62   | 8.81        | 9.18   | 8.63        | 9.18   | 8.84        | 9.30   | 8.63        | 9.18   | 8.63    | 9.18   | 8.63    | 9.18   | 8.63    | 9.18   | 8.63         | 9.18   | 8.63    | 9.18   |       |       |       |       |       |
|            | Gross Calorific Value | ASTM D 3180           | Btu/lb   | 13328       | 13242  | 13242       | 13159  | 13259       | 13391  | 13284       | 13251  | 13143       | 13080  | 13459       | 13267  | 13268       | 13459  | 13267       | 13268  | 13364       | 13268  | 13459       | 13267  | 13268   | 13364  | 13267   | 13268  | 13364   | 13267  | 13268        | 13364  | 13267   | 13268  |       |       |       |       |       |
|            | Sulfur, Total         | ASTM D 3180           | % by Wt. | 2.83        | 2.95   | 2.95        | 2.94   | 2.47        | 2.82   | 2.69        | 2.57   | 2.49        | 2.24   | 2.79        | 2.64   | 2.79        | 2.64   | 2.79        | 2.64   | 2.79        | 2.58   | 2.64        | 2.79   | 2.64    | 2.79   | 2.64    | 2.79   | 2.64    | 2.79   | 2.64         | 2.79   | 2.64    | 2.79   | 2.64  | 2.79  |       |       |       |
|            | Sulfur, lb/MMBtu      | ASTM D 3180           | % by Wt. | 2.12        | 2.23   | 2.23        | 2.24   | 1.86        | 2.10   | 2.02        | 1.94   | 1.89        | 1.71   | 1.30        | 2.11   | 1.99        | 2.11   | 1.99        | 2.11   | 1.99        | 1.95   | 2.11        | 1.99   | 2.11    | 1.99   | 2.11    | 1.99   | 2.11    | 1.99   | 2.11         | 1.99   | 2.11    | 1.99   | 2.11  | 1.99  | 2.11  |       |       |
|            | Carbon                | ASTM D 3180           | % by Wt. | 75.05       | 74.93  | 74.93       | 74.32  | 74.82       | 75.22  | 74.95       | 74.69  | 74.17       | 74.26  | 75.74       | 74.67  | 74.67       | 74.67  | 74.67       | 74.67  | 74.67       | 74.82  | 74.67       | 74.67  | 74.67   | 74.67  | 74.67   | 74.67  | 74.67   | 74.67  | 74.67        | 74.67  | 74.67   | 74.67  | 74.67 | 74.67 | 74.67 |       |       |
|            | Hydrogen              | ASTM D 3180           | % by Wt. | 5.09        | 5.08   | 5.08        | 5.00   | 5.00        | 4.97   | 4.97        | 4.99   | 4.97        | 4.99   | 5.00        | 5.00   | 5.03        | 4.97   | 5.00        | 4.97   | 5.00        | 5.00   | 5.00        | 5.00   | 5.00    | 5.00   | 5.00    | 5.00   | 5.00    | 5.00   | 5.00         | 5.00   | 5.00    | 5.00   | 5.00  | 5.00  | 5.00  |       |       |
|            | Nitrogen              | ASTM D 3180           | % by Wt. | 1.52        | 1.56   | 1.56        | 1.56   | 1.62        | 1.59   | 1.57        | 1.60   | 1.59        | 1.60   | 1.58        | 1.58   | 1.58        | 1.58   | 1.58        | 1.58   | 1.58        | 1.58   | 1.58        | 1.58   | 1.58    | 1.58   | 1.58    | 1.58   | 1.58    | 1.58   | 1.58         | 1.58   | 1.58    | 1.58   | 1.58  | 1.58  | 1.58  | 1.58  |       |
|            | Oxygen                | ASTM D 3180           | % by Wt. | 6.27        | 6.19   | 6.19        | 6.18   | 6.89        | 6.77   | 7.01        | 7.29   | 7.39        | 7.45   | 7.31        | 7.31   | 7.31        | 7.31   | 7.31        | 7.31   | 7.31        | 7.31   | 7.31        | 7.31   | 7.31    | 7.31   | 7.31    | 7.31   | 7.31    | 7.31   | 7.31         | 7.31   | 7.31    | 7.31   | 7.31  | 7.31  | 7.31  | 7.31  |       |
|            | Carbon, Fixed         | ASTM D 3180           | % by Wt. | 51.43       | 51.21  | 51.21       | 51.33  | 52.33       | 53.75  | 53.21       | 53.04  | 53.52       | 53.42  | 54.48       | 53.42  | 53.42       | 53.42  | 53.42       | 53.42  | 53.42       | 53.42  | 53.42       | 53.42  | 53.42   | 53.42  | 53.42   | 53.42  | 53.42   | 53.42  | 53.42        | 53.42  | 53.42   | 53.42  | 53.42 | 53.42 | 53.42 | 53.42 |       |
|            | Volatiles Matter      | ASTM D 3180           | % by Wt. | 39.33       | 39.50  | 39.50       | 38.67  | 37.97       | 36.61  | 37.98       | 38.08  | 37.09       | 37.12  | 36.89       | 37.12  | 36.89       | 37.12  | 36.89       | 37.12  | 36.89       | 37.12  | 36.89       | 37.12  | 36.89   | 37.12  | 36.89   | 37.12  | 36.89   | 37.12  | 36.89        | 37.12  | 36.89   | 37.12  | 36.89 | 37.12 | 36.89 | 37.12 | 36.89 |
|            | Aluminum              | ASTM D 3682           | % by Wt. | 0.96        | 1.08   | 1.08        | 1.09   | 1.14        | 1.10   | 1.09        | 1.02   | 1.26        | 1.10   | 1.02        | 1.02   | 1.09        | 1.12   | 1.02        | 1.12   | 1.04        | 1.09   | 1.02        | 1.12   | 1.02    | 1.12   | 1.02    | 1.12   | 1.02    | 1.12   | 1.02         | 1.12   | 1.02    | 1.12   | 1.02  | 1.12  | 1.02  | 1.12  | 1.02  |
|            | Antimony              | ASTM D 3683           | mg/kg    | <1.0        | <1.0   | <1.0        | 4.3    | 5.5         | 3.1    | 1.5         | 2.1    | 4.3         | 3.6    | 4.2         | 3.4    | 2.8         | 4.0    | 3.2         | 4.0    | 3.2         | <1.0   | <1.0        | <1.0   | <1.0    | <1.0   | <1.0    | <1.0   | <1.0    | <1.0   | <1.0         | <1.0   | <1.0    | <1.0   | <1.0  | <1.0  | <1.0  | <1.0  | <1.0  |
|            | Arsenic               | Spec. Chem. Acta. 44B | mg/kg    | <1.0        | 1.5    | 1.5         | 43     | 51          | 75     | 29          | 38     | 35          | 22     | 36          | 53     | 33          | 33     | 33          | 33     | 33          | 33     | 33          | 33     | 33      | 33     | 33      | 33     | 33      | 33     | 33           | 33     | 33      | 33     | 33    | 33    | 33    | 33    | 33    |
|            | Barium                | ASTM D 3683           | mg/kg    | 43          | 36     | 36          | 51     | 75          | 29     | 38          | 35     | 22          | 36     | 53          | 33     | 33          | 33     | 33          | 33     | 33          | 33     | 33          | 33     | 33      | 33     | 33      | 33     | 33      | 33     | 33           | 33     | 33      | 33     | 33    | 33    | 33    | 33    | 33    |
|            | Beryllium             | ASTM D 3683           | mg/kg    | 2           | 3      | 3           | 3      | 3           | 3      | 2           | 2      | 3           | 2      | 2           | 3      | 2           | 2      | 2           | 2      | 2           | 2      | 2           | 2      | 2       | 2      | 2       | 2      | 2       | 2      | 2            | 2      | 2       | 2      | 2     | 2     | 2     | 2     | 2     |
|            | Cadmium               | ASTM D 3683           | mg/kg    | <1.00       | <1.00  | <1.00       | <1.00  | <1.00       | <1.00  | 0.23        | 0.24   | 0.30        | 0.22   | 0.13        | <1.00  | <1.00       | <1.00  | <1.00       | <1.00  | <1.00       | <1.00  | <1.00       | <1.00  | <1.00   | <1.00  | <1.00   | <1.00  | <1.00   | <1.00  | <1.00        | <1.00  | <1.00   | <1.00  | <1.00 | <1.00 | <1.00 | <1.00 | <1.00 |
|            | Calcium               | ASTM D 3682           | % by Wt. | 0.29        | 0.28   | 0.28        | 0.27   | 0.24        | 0.21   | 0.22        | 0.24   | 0.24        | 0.24   | 0.25        | 0.23   | 0.26        | 0.22   | 0.23        | 0.26   | 0.23        | 0.24   | 0.23        | 0.22   | 0.22    | 0.22   | 0.23    | 0.22   | 0.23    | 0.22   | 0.23         | 0.22   | 0.23    | 0.22   | 0.23  | 0.22  | 0.23  | 0.22  | 0.23  |
|            | Chlorine              | ASTM D 4208           | mg/kg    | 1514        | 1173   | 1173        | 1495   | 1139        | 1244   | 2577        | 2050   | 2705        | 3073   | 1400        | 1294   | 2144        | 1818   | 1767        | 1767   | 1767        | 1767   | 1767        | 1767   | 1767    | 1767   | 1767    | 1767   | 1767    | 1767   | 1767         | 1767   | 1767    | 1767   | 1767  | 1767  | 1767  | 1767  | 1767  |
|            | Chromium              | ASTM D 3683           | mg/kg    | 23          | 15     | 15          | 19     | 20          | 22     | 25          | 19     | 19          | 19     | 14          | 19     | 21          | 16     | 19          | 16     | 19          | 16     | 19          | 16     | 19      | 16     | 19      | 16     | 19      | 16     | 19           | 16     | 19      | 16     | 19    | 16    | 19    | 16    | 19    |
|            | Cobalt                | ASTM D 3683           | mg/kg    | 7           | 6      | 6           | 7      | 9           | 6      | 8           | 8      | 8           | 8      | 6           | 8      | 7           | 8      | 7           | 8      | 7           | 8      | 7           | 8      | 7       | 8      | 7       | 8      | 7       | 8      | 7            | 8      | 7       | 8      | 7     | 8     | 7     | 8     |       |
|            | Copper                | ASTM D 3683           | mg/kg    | 8           | 7      | 7           | 9      | 12          | 9      | 9           | 9      | 11          | 10     | 10          | 9      | 10          | 9      | 10          | 9      | 10          | 9      | 10          | 9      | 10      | 9      | 10      | 9      | 10      | 9      | 10           | 9      | 10      | 9      | 10    | 9     | 10    | 9     | 10    |
|            | Fluorine              | ASTM D 3761           | mg/kg    | 49          | 24     | 24          | 69     | 57          | 43     | 77          | 42     | 81          | 72     | 48          | 50     | 61          | 54     | 56          | 56     | 56          | 56     | 56          | 56     | 56      | 56     | 56      | 56     | 56      | 56     | 56           | 56     | 56      | 56     | 56    | 56    | 56    | 56    | 56    |
|            | Iron                  | ASTM D 3682           | % by Wt. | 1.16        | 0.97   | 0.97        | 1.11   | 1.15        | 1.28   | 1.15        | 1.00   | 1.06        | 1.10   | 0.85        | 1.08   | 1.12        | 0.92   | 1.08        | 1.12   | 0.92        | 1.08   | 1.12        | 0.92   | 1.08    | 1.12   | 0.92    | 1.08   | 1.12    | 0.92   | 1.08         | 1.12   | 0.92    | 1.08   | 1.12  | 0.92  | 1.08  | 1.12  | 0.92  |
|            | Lead                  | ASTM D 3683           | mg/kg    | 22          | 15     | 15          | 10     | 8           | 14     | 11          | 11     | 10          | 11     | 11          | 12     | 11          | 11     | 12          | 11     | 11          | 11     | 11          | 11     | 11      | 11     | 11      | 11     | 11      | 11     | 11           | 11     | 11      | 11     | 11    | 11    | 11    | 11    | 11    |
|            | Lithium               | ASTM D 3683           | mg/kg    | 4           | 6      | 6           | 6      | 10          | 7      | 9           | 7      | 16          | 18     | 11          | 11     | 10          | 13     | 9           | 10     | 13          | 9      | 10          | 13     | 9       | 10     | 13      | 9      | 10      | 13     | 9            | 10     | 13      | 9      | 10    | 13    | 9     | 10    |       |
|            | Magnesium             | ASTM D 3682           | % by Wt. | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.07   | 0.05        | 0.06   | 0.06        | 0.06   | 0.08        | 0.05   | 0.06        | 0.08   | 0.05        | 0.06   | 0.08        | 0.05   | 0.06        | 0.08   | 0.05    | 0.06   | 0.08    | 0.05   | 0.06    | 0.08   | 0.05         | 0.06   | 0.08    | 0.05   | 0.06  | 0.08  | 0.05  | 0.06  |       |
|            | Manganese             | ASTM D 3682           | mg/kg    | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05        | 0.05   | 0.05    | 0.05   | 0.05    | 0.05   | 0.05    | 0.05   | 0.05         | 0.05   | 0.05    | 0.05   | 0.05  | 0.05  | 0.05  | 0.05  |       |
|            | Mercury               | ASTM D 3684           | mg/kg    | <0.02       | 0.03   | 0.03        | 0.09   | 0.16        | 0.09   | 0.08        | 0.04   | 0.05        | <0.02  | 0.05        | 0.09   | 0.06        | 0.05   | 0.09        | 0.06   | 0.05        | 0.09   | 0.06        | 0.05   | 0.09    | 0.06   | 0.05    | 0.09   | 0.06    | 0.05   | 0.09         | 0.06   | 0.05    | 0.09   | 0.06  | 0.05  | 0.09  | 0.06  |       |
|            | Molybdenum            | ASTM D 3683           | mg/kg    | <0.02       | 7.7    | 7.7         | 13.3   | 4.0         | 7.7    | 5.8         | 8.7    | 8.7         | 8.7    | 8.7         | 8.3    | 7.1         | 8.3    | 7.1         | 8.3    | 7.1         | 8.3    | 7.1         | 8.3    | 7.1     | 8.3    | 7.1     | 8.3    | 7.1     | 8.3    | 7.1          | 8.3    | 7.1     | 8.3    | 7.1   | 8.3   | 7.1   | 8.3   |       |
|            | Nickel                | ASTM D 3683           | mg/kg    | 15          | 13     | 13          | 14     | 17          | 14     | 14          | 15     | 14          | 18     | 14          | 15     | 15          | 14     | 15          | 14     | 15          | 14     | 15          | 14     | 15      | 14     | 15      | 14     | 15      | 14     | 15           | 14     | 15      | 14     | 15    | 14    | 15    | 14    |       |
|            | Phosphorus            | ASTM D 3682           | % by Wt. | <0.01       | 0.03   | 0.03        | 0.06   | 0.03        | 0.01   | <0.01       | 0.01   | 0.01        | 0.01   | 0.01        | 0.01   | 0.01        | 0.01   | 0.01        | 0.01   | 0.01        | 0.01   | 0.01        | 0.01   | 0.01    | 0.01   | 0.01    | 0.01   | 0.01    | 0.01   | 0.01         | 0.01   | 0.01    | 0.01   | 0.01  | 0.01  | 0.01  | 0.01  |       |
|            | Potassium             | ASTM D 3682           | % by Wt. | 0.23        | 0.23   | 0.23        | 0.25   | 0.22        | 0.22   | 0.15        | 0.24   | 0.13        | 0.13   | 0.18        | 0.13   |             |        |             |        |             |        |             |        |         |        |         |        |         |        |              |        |         |        |       |       |       |       |       |

Table 5.7-2 Plant Crist Unit 5 Coal Analyses - 1993-95 Quarterly, As-Burned Composites  
 INAA Results from the University of Missouri-Columbia, Research Reactor Center, Dry Basis

| SCS ID No.<br>Test | Units    | 94-115        |               | 94-116        |               | 94-117        |               | 94-118        |               | 95-202        |               | 95-203        |         | 95-204  |         | 95-205  |         | 95-221  |         | 1993    |         | 1994    |         | 1995    |         | Project Life |           |
|--------------------|----------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------------|-----------|
|                    |          | 2nd Qtr. 1993 | 3rd Qtr. 1993 | 4th Qtr. 1993 | 1st Qtr. 1994 | 2nd Qtr. 1994 | 3rd Qtr. 1994 | 4th Qtr. 1994 | 1st Qtr. 1995 | 2nd Qtr. 1995 | 3rd Qtr. 1995 | 4th Qtr. 1995 | Average      | Std. Dev. |
| Aluminum           | % by Wt. | 0.99          | 0.93          | 0.98          | 0.86          | 0.86          | 0.95          | 0.95          | 1.07          | 1.06          | 1.07          | 0.97          | 0.97    | 0.99    | 0.99    | 0.97    | 1.06    | 0.91    | 0.91    | 0.91    | 0.97    | 0.97    | 0.99    | 0.99    | 0.97    | 0.97         | 0.07      |
| Antimony           | mg/kg    | 0.96          | 1.13          | 0.97          | 1.15          | 0.49          | 0.54          | 0.49          | 0.54          | 0.49          | 0.54          | 0.49          | 0.54    | 0.49    | 0.54    | 0.49    | 0.54    | 0.49    | 0.54    | 0.49    | 0.54    | 0.49    | 0.54    | 0.49    | 0.54    | 0.30         | 0.30      |
| Arsenic            | mg/kg    | 4.5           | 9.4           | 16.8          | 7.1           | 4.9           | 5.5           | 6.6           | 6.6           | 6.6           | 6.6           | 6.6           | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6     | 6.6          | 3.7       |
| Barium             | mg/kg    | 60            | 59            | 92            | 85            | 52            | 53            | 53            | 33            | 41            | 41            | 41            | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41      | 41           | 20        |
| Calcium            | % by Wt. | 0.26          | 0.28          | 0.17          | 0.19          | 0.19          | 0.09          | 0.11          | 0.11          | 0.12          | 0.12          | 0.12          | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12         | 0.07      |
| Cerium             | mg/kg    | 11.6          | 12.4          | 15.1          | 12.1          | 12.2          | 10.5          | 10.5          | 12.7          | 11.9          | 10.3          | 13.0          | 13.0    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9    | 11.9         | 1.4       |
| Chromium           | mg/kg    | 18.1          | 19.2          | 17.7          | 17.2          | 17.0          | 16.5          | 15.0          | 16.6          | 15.0          | 12.6          | 18.3          | 18.3    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8    | 16.8         | 1.9       |
| Cobalt             | mg/kg    | 3.06          | 3.51          | 4.95          | 4.01          | 3.66          | 3.29          | 3.47          | 3.47          | 3.65          | 2.86          | 3.84          | 3.84    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 3.61    | 0.61         |           |
| Cesium             | mg/kg    | 0.95          | 0.98          | 1.18          | 1.04          | 0.89          | 1.03          | 0.93          | 1.03          | 0.92          | 0.81          | 1.04          | 1.04    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.97    | 0.11         |           |
| Dysprosium         | mg/kg    | 0.77          | 0.95          | 1.16          | 0.83          | 0.92          | 1.05          | 0.91          | 1.05          | 0.91          | 0.78          | 0.96          | 0.96    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.85    | 0.13         |           |
| Europium           | mg/kg    | 0.24          | 0.22          | 0.32          | 0.21          | 0.21          | 0.20          | 0.21          | 0.25          | 0.21          | 0.20          | 0.26          | 0.26    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.21    | 0.04         |           |
| Europium           | mg/kg    | 0.59          | 0.64          | 0.61          | 0.56          | 0.53          | 0.49          | 0.55          | 0.55          | 0.53          | 0.47          | 0.61          | 0.61    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.53    | 0.05         |           |
| Europium           | mg/kg    | 1.16          | 1.21          | 1.18          | 1.21          | 1.03          | 0.94          | 0.99          | 1.18          | 0.96          | 0.68          | 1.18          | 1.18    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04    | 1.04         | 0.17      |
| Europium           | mg/kg    | 5.2           | 5.4           | 6.5           | 5.4           | 5.4           | 5.2           | 5.2           | 6.1           | 6.0           | 5.0           | 5.7           | 5.7     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 5.6     | 0.5          |           |
| Europium           | mg/kg    | 0.13          | 0.13          | 0.16          | 0.12          | 0.14          | 0.12          | 0.14          | 0.09          | 0.09          | 0.08          | 0.14          | 0.14    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.03         |           |
| Europium           | mg/kg    | 23.1          | 24.7          | 24.9          | 27.7          | 23.6          | 25.4          | 23.3          | 23.3          | 23.8          | 24.6          | 24.2          | 24.2    | 25.0    | 25.0    | 24.6    | 24.2    | 24.6    | 24.6    | 24.6    | 24.6    | 24.6    | 24.6    | 24.6    | 24.6    | 1.4          |           |
| Europium           | mg/kg    | 0.20          | 0.06          | 0.11          | 0.13          | 0.15          | 0.11          | 0.08          | 0.08          | <0.07         | <0.06         | 0.12          | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.05         |           |
| Europium           | mg/kg    | 13.0          | 11.9          | 12.6          | 11.9          | 13.6          | 8.9           | 4.3           | 4.3           | 3.7           | 3.9           | 12.5          | 12.5    | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 9.7     | 4.2          |           |
| Europium           | mg/kg    | 8.0           | 7.2           | 6.4           | 4.3           | 6.2           | 7.2           | 7.2           | 6.6           | 5.0           | 4.8           | 6.2           | 6.2     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 6.1     | 1.2          |           |
| Europium           | mg/kg    | <27           | <27           | <28           | <27           | 18            | 15            | 15            | 15            | 15            | 15            | <28           | <28     | 20      | 20      | 20      | 15      | 15      | 15      | 15      | 15      | 15      | 15      | 15      | 15      | <28          | ---       |
| Europium           | mg/kg    | 0.20          | 0.21          | 0.18          | 0.17          | 0.19          | 0.19          | 0.19          | 0.16          | 0.14          | 0.15          | 0.20          | 0.20    | 0.18    | 0.18    | 0.18    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.02         |           |
| Europium           | mg/kg    | 13.1          | 10.7          | 12.7          | 14.1          | 12.4          | 12.0          | 12.0          | 14.0          | 13.1          | 10.6          | 12.2          | 12.2    | 13.1    | 13.1    | 12.5    | 13.1    | 13.1    | 13.1    | 13.1    | 13.1    | 13.1    | 13.1    | 13.1    | 13.1    | 1.3          |           |
| Europium           | mg/kg    | 1.15          | 1.19          | 1.55          | 1.16          | 1.22          | 1.17          | 1.27          | 1.27          | 1.09          | 1.06          | 1.30          | 1.30    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 1.21    | 0.14         |           |
| Europium           | mg/kg    | 2.48          | 2.64          | 3.04          | 2.51          | 2.60          | 2.45          | 2.62          | 2.62          | 2.63          | 2.36          | 2.72          | 2.72    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 2.60    | 0.21         |           |
| Europium           | mg/kg    | 1.75          | 1.79          | 1.88          | 1.28          | 1.95          | 2.17          | 1.86          | 1.86          | 1.82          | 2.70          | 1.81          | 1.81    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 1.82    | 0.38         |           |
| Europium           | mg/kg    | 405           | 352           | 418           | 379           | 628           | 580           | 718           | 718           | 717           | 506           | 392           | 392     | 576     | 576     | 576     | 576     | 576     | 576     | 576     | 576     | 576     | 576     | 576     | 576     | 144          |           |
| Europium           | mg/kg    | <38           | <37           | 36            | <37           | 26            | 25            | 25            | 36            | 22            | 32            | <38           | <38     | 31      | 31      | 31      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | 27      | <38          | ---       |
| Europium           | mg/kg    | 0.10          | 0.15          | 0.18          | 0.11          | 0.12          | 0.12          | 0.12          | 0.14          | 0.13          | 0.11          | 0.14          | 0.14    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.12    | 0.02         |           |
| Europium           | mg/kg    | 0.14          | 0.15          | 0.18          | 0.10          | 0.15          | 0.17          | 0.17          | 0.18          | 0.09          | 0.09          | 0.16          | 0.16    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.15    | 0.04         |           |
| Europium           | mg/kg    | 1.64          | 1.74          | 2.07          | 1.66          | 1.63          | 1.57          | 1.89          | 1.89          | 1.70          | 1.54          | 1.82          | 1.82    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 1.69    | 0.17         |           |
| Europium           | % by Wt. | 0.07          | 0.06          | 0.05          | 0.04          | 0.06          | 0.06          | 0.06          | 0.06          | 0.05          | 0.05          | 0.07          | 0.07    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.06    | 0.01         |           |
| Europium           | mg/kg    | 3.34          | 2.96          | 3.57          | 3.13          | 3.92          | 2.85          | 2.85          | 3.35          | 1.10          | 1.28          | 3.29          | 3.29    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 2.81    | 1.08         |           |
| Europium           | mg/kg    | 50.0          | 54.0          | 42.0          | 45.0          | 37.9          | 36.8          | 36.8          | 33.0          | 27.1          | 27.3          | 48.7          | 48.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 38.7    | 9.4          |           |
| Europium           | mg/kg    | 0.46          | 0.53          | 0.64          | 0.47          | 0.49          | 0.50          | 0.54          | 0.54          | 0.50          | 0.40          | 0.54          | 0.54    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.50    | 0.07         |           |
| Europium           | mg/kg    | 49            | 29            | 57            | 76            | 44            | 64            | 64            | 28            | 44            | 63            | 45            | 45      | 47      | 47      | 47      | 45      | 45      | 45      | 45      | 45      | 45      | 45      | 45      | 45      | 20           |           |
| Europium           | mg/kg    | 54            | 44            | 41            | 40            | 41            | 24            | 24            | 21            | 21            | 21            | 46            | 46      | 32      | 32      | 32      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 22      | 34           | 12        |

< Less Than Detection Limit

Table 5.7-3 Comparison of APC Analyses Versus INAA Analyses, Dry Basis

| SCS ID No.<br>Test | AVG %<br>Difference | Units    | 2nd Qtr. 93 |      | 3rd Qtr. 93 |      | 4th Qtr. 93 |      | 1st Qtr. 94 |      | 2nd Qtr. 94 |      | 3rd Qtr. 94 |      | 4th Qtr. 94 |      | 1st Qtr. 95 |      | 2nd Qtr. 95 |       |
|--------------------|---------------------|----------|-------------|------|-------------|------|-------------|------|-------------|------|-------------|------|-------------|------|-------------|------|-------------|------|-------------|-------|
|                    |                     |          | APC Avg.    | INAA  |
| Aluminum           | 10.77               | % by Wt. | 1.08        | 0.99 | 1.09        | 0.93 | 1.14        | 0.99 | 1.10        | 0.86 | 1.09        | 0.98 | 1.02        | 0.95 | 1.26        | 1.07 | 1.10        | 1.06 | 1.02        | 0.91  |
| Antimony           | 29.46               | mg/kg    | <1          | 0.96 | <1          | 1.13 | 1           | 0.97 | 1           | 1.15 | 0.77        | 0.99 | 1.03        | 0.94 | 0.47        | 0.44 | <0.2        | 0.49 | 0.60        | 0.52  |
| Arsenic            | 73.47               | mg/kg    | 1.5         | 4.5  | 4.3         | 9.4  | 5.5         | 16.8 | 3.1         | 7.1  | 1.5         | 4.9  | 2.1         | 5.5  | 4.3         | 6.6  | 3.6         | 6.6  | 4.2         | 6.9   |
| Barium             | 41.20               | mg/kg    | 36          | 60   | 51          | 59   | 75          | 92   | 29          | 85   | 29          | 52   | 38          | 33   | 35          | 33   | 22          | 41   | 36          | 44    |
| Calcium            | 39.66               | % by Wt. | 0.28        | 0.26 | 0.27        | 0.28 | 0.24        | 0.17 | 0.21        | 0.18 | 0.22        | 0.10 | 0.22        | 0.09 | 0.24        | 0.11 | 0.25        | 0.12 | 0.23        | 0.11  |
| Chromium           | 20.98               | mg/kg    | 15          | 18   | 19          | 19   | 20          | 18   | 22          | 17   | 25          | 17   | 19          | 15.5 | 19          | 16.5 | 20          | 15.0 | 14          | 12.6  |
| Cobalt             | 60.83               | mg/kg    | 6           | 3    | 7           | 4    | 9           | 5    | 5           | 4    | 8           | 4    | 8           | 3.29 | 8           | 3.47 | 8           | 3.65 | 6           | 2.85  |
| Iron               | 17.91               | % by Wt. | 0.97        | 1.16 | 1.11        | 1.21 | 1.15        | 1.16 | 1.28        | 1.21 | 1.15        | 1.03 | 1.00        | 0.94 | 1.06        | 0.99 | 1.10        | 0.96 | 0.85        | 0.69  |
| Manganese          | 6.46                | mg/kg    | 0.03        | 0.20 | 0.09        | 0.06 | 0.16        | 0.11 | 0.09        | 0.13 | 0.08        | 0.15 | 0.22        | 0.24 | 0.24        | 0.23 | 0.23        | 0.24 | 0.24        | 0.24  |
| Mercury            | 61.99               | mg/kg    | 0.03        | 0.20 | 0.09        | 0.06 | 0.16        | 0.11 | 0.09        | 0.13 | 0.08        | 0.15 | 0.22        | 0.24 | 0.24        | 0.23 | 0.23        | 0.24 | 0.24        | 0.24  |
| Molybdenum         | 48.54               | mg/kg    | 13          | 13   | 13          | 12   | 4           | 13   | 13          | 12   | 6           | 14   | 9           | 0.04 | 0.05        | 0.08 | <0.02       | 0.07 | 0.05        | <0.06 |
| Nickel             | 32.24               | mg/kg    | 13          | <27  | 14          | <27  | 17          | <28  | 14          | <27  | 16          | 18   | 14          | 15   | 14          | 19   | 18          | 15   | 12          | 15    |
| Potassium          | 23.01               | % by Wt. | 0.23        | 0.20 | 0.25        | 0.21 | 0.22        | 0.16 | 0.22        | 0.17 | 0.15        | 0.19 | 0.24        | 0.19 | 0.13        | 0.16 | 0.16        | 0.14 | 0.13        | 0.15  |
| Selenium           | 16.18               | mg/kg    | <2          | 1.75 | 2           | 1.79 | <2          | 1.88 | 2           | 1.28 | 1.47        | 1.35 | 1.63        | 2.17 | 1.93        | 1.85 | 1.40        | 1.82 | 2.63        | 2.70  |
| Sodium             | 29.51               | % by Wt. | 0.06        | 0.04 | 0.07        | 0.04 | 0.06        | 0.04 | 0.06        | 0.04 | 0.06        | 0.06 | 0.06        | 0.06 | 0.08        | 0.06 | 0.09        | 0.07 | 0.07        | 0.05  |
| Titanium           | 14.41               | % by Wt. | 0.06        | 0.07 | 0.06        | 0.07 | 0.06        | 0.06 | 0.06        | 0.04 | 0.06        | 0.06 | 0.06        | 0.06 | 0.06        | 0.06 | 0.06        | 0.05 | 0.06        | 0.05  |
| Vanadium           | 3.39                | mg/kg    | 50          | 50   | 53          | 54   | 43          | 42   | 43          | 45   | 40          | 38   | 41          | 36.8 | 33.0        | 28   | 28          | 27.1 | 28          | 27.3  |
| Zinc               | 32.67               | mg/kg    | 35          | 49   | 30          | 29   | 30          | 57   | 34          | 76   | 32          | 44   | 51          | 64   | 35          | 28   | 52          | 63   | 23          | 17    |

< Less Than Detection Limit.

The quality of the coal remained relatively constant over the course of the project with the following exceptions.

- The total sulfur content of the coal dropped at the end of the project. The typical sulfur content ranged from about 2.5 to 3 percent until the beginning of 1995. From there on, the percentage of sulfur dropped continuously, reaching a minimum just above 1% at the end of the project.
- Arsenic content fluctuated several times. There was a significant increase in arsenic in September of 1993 which lasted until January 1994. In October of 1994, the level again jumped and remained unstable for the remaining life of the project. In both instances, the arsenic value more than doubled from its typical range of 1 to 2 ppm.
- The level of chlorine in the coal also varied several times. In June of 1993, a substantial one-month drop of 1000 ppm was observed. A 1500 ppm increase occurred in April of 1994. Once again, the level became unstable in October of 1994 and persisted until the end of the project. Chlorine content ranged from about 200 ppm to over 3000 ppm in the last seven months.

Analyses performed by the Alabama Power laboratory were compared with INAA analyses performed by the University of Missouri. The agreement between the two sets of analyses ranged from a 3 percent difference to over 70 percent. Agreement was good for aluminum, iron, manganese, selenium, titanium, and vanadium. Fair agreement was observed for antimony, barium, calcium, chromium, nickel, potassium, sodium, and zinc. The two methods did not agree well for arsenic, cobalt, mercury, and molybdenum.

## **5.8 Waste Stream Impacts**

The report contained in Appendix S summarizes the results of an SRI evaluation of the effects from SCR ammonia on ammonia volatilization, ammonia extraction, and metals extractability from fly ash. To conduct the laboratory study, samples of pre-reactor (ammonia-free) and post-reactor (ammonia-exposed) fly ash were collected at the Crist test facility on reactors B and C. The following discussions summarize the conclusions reached from the study.

### 5.8.1 Ammonia Extractability and Volatilization from SCR Fly Ash

Almost no ammonia volatilized from the SCR fly ash until a significant amount of water vapor was absorbed by the ash. A plausible mechanism for the apparent volatilization is that enough water was gained by the ash to form a moist layer with a pH high enough to evolve gas-phase ammonia from the ammonium compounds on the ash. Nearly all of the ammonia on the ash evolved to the gas phase in the closed-container experiments.

Ammonia concentrations in enclosed spaces depend on the ammonia concentration of the ash, the volume of air above the ash available for dilution, and the presence of a humid atmosphere.

The extraction of ammonia from fly ash seems to depend upon pH. Evidently, all or nearly all of the ammonia present was extracted in the buffered solutions at pH 4.7 and pH 6.2, but not all was recovered in alkaline unbuffered extracts. In the pH 6.2 buffer, however, the completeness of extraction seemed to fall off somewhat as the ratio of ash to buffer increased. At 3g of ash per 50 mL of pH 6.2 buffer, the amount of ammonia extracted was about 200  $\mu\text{g/g}$ , whereas at 1 g per 50 mL, the amount was near 250  $\mu\text{g/g}$ .

Ammonia concentration in the ash was much higher for the smaller particle sizes, but most of the total ammonia was found to reside with the larger particles simply because these comprise the vast majority of the ash mass. The implication is that very little slip ammonia will exit the process when high efficiency particulate emission controls are in place since all detectable ammonia is in the solid phase at the exit of the air preheaters and most of the ammonia is associated with the larger particle sizes which are most readily collected.

## **5.8.2 Metals Extractability from SCR Fly Ash**

The SCR ash samples were subjected to extraction with water, and the extracts were analyzed for each of 28 metals. This was done to ascertain whether exposure of the fly ash to ammonia vapor caused an enhancement of the metal's extractabilities under conditions resembling those that might exist in an ash pond.

Of the 28 metals included in the study, only 17 could be detected in the fly ash extracts. Of these 17 detectable metals, only barium underwent an increase in extractability following exposure to ammonia. The magnitude of the increase was found to depend directly on the magnitude of the  $\text{NH}_3/\text{NO}_x$  ratio in the SCR unit; however, the increase was slight for all  $\text{NH}_3/\text{NO}_x$  ratios tested. Of the 16 additional metals that could be detected in the fly-ash extracts, none displayed what were considered to be genuine enhancements in extractability, and several exhibited decreases in extractability as a result of exposure of the fly ash to ammonia. Although one of these metals - Se - displayed a large apparent increase in extractability on exposure to ammonia, it was concluded that the selenium found in the reactor-outlet sample extracts must have condensed from the gas phase onto the fly ash at the reactor outlet. Finally, a deliberate downward adjustment in the pH of one sample solution caused enhancements in the extractabilities of several metals, most notably Mg, but also Mn, Ca, As and Fe to a lesser degree.

## **5.9 Miscellaneous Test Results**

### **5.9.1 TCLP Analysis**

The following table outlines the results of TCLP analyses performed on fly ash samples from the SCR reactors at three times during the project life: (1) initial start-up of after catalyst loading in June 1993, (2) near the midpoint of operations in August 1994, and (3) near the end of operations in July 1995. These samples were taken as grab samples from the cyclone ash hoppers from each of the high-dust SCR reactors. The reactors were operated at base-line conditions at least 12 hours prior to sampling. All hoppers were

cleaned of ash prior to the period of base-line operation to insure that all ash acquired in the sampling was produced during reactor base-line operation.

To minimize costs, composite samples were generated from the individual reactor ash samples. Normally, composites were generated representing equivalent mass fractions from 1) reactors A, B, and C, 2) reactors D, E, and F, and 3) reactors G, H. In the case of the June 1993 sample, a single composite was generated from all of the reactor samples. A reference host unit hopper ash sample was also taken at the time of sampling the SCR cyclone hoppers. The reference ash samples were taken from the host unit hot-side electrostatic precipitator hoppers.

Table 5.9-1 TCLP Analysis - 6/21/93

| Sample            | Species (mg/L) |    |    |    |    |    |    |    |
|-------------------|----------------|----|----|----|----|----|----|----|
|                   | Ag             | As | Ba | Cd | Cr | Hg | Pb | Se |
| Unit #5 Reference | ND             | ND | ND | ND | ND | ND | ND | ND |
| A, B, C Composite | ND             | ND | ND | ND | ND | ND | ND | ND |

Table 5.9-2 TCLP Analysis - 6/28/93

| Sample                           | Species (mg/L) |    |    |    |    |    |    |    |
|----------------------------------|----------------|----|----|----|----|----|----|----|
|                                  | Ag             | As | Ba | Cd | Cr | Hg | Pb | Se |
| A, B, C, D, E, F, G, H Composite | ND             | ND | ND | ND | ND | ND | ND | ND |

NOTE: No test taken for Unit #5 Reference.

Table 5.9-3 TCLP Analysis - 8/25/94

| Sample               | Species (mg/L) |    |      |       |      |    |      |    |
|----------------------|----------------|----|------|-------|------|----|------|----|
|                      | Ag             | As | Ba   | Cd    | Cr   | Hg | Pb   | Se |
| A, B, C Composite    | ND             | ND | 0.33 | 0.020 | 0.08 | ND | 0.05 | ND |
| D, E, F, G Composite | ND             | ND | 0.29 | 0.015 | 0.04 | ND | 0.05 | ND |
| Unit #5 Reference    | ND             | ND | 0.30 | 0.024 | 0.04 | ND | 0.05 | ND |

Table 5.9-4 TCLP Analysis - 7/12/95

| Sample               | Species (mg/L) |    |      |       |      |    |    |    |
|----------------------|----------------|----|------|-------|------|----|----|----|
|                      | Ag             | As | Ba   | Cd    | Cr   | Hg | Pb | Se |
| Unit #5<br>Reference | ND             | ND | 0.24 | 0.024 | 0.01 | ND | ND | ND |
| A, B, C<br>Composite | ND             | ND | 0.24 | ND    | ND   | ND | ND | ND |
| D, E, F<br>Composite | ND             | ND | 0.24 | ND    | ND   | ND | ND | ND |
| G, H<br>Composite    | ND             | ND | 0.23 | ND    | ND   | ND | ND | ND |

Table 5.9-5 Analyzing Laboratory Reporting Limits

| Date    | Species Detection Limit (mg/L) |      |      |       |      |       |      |     |
|---------|--------------------------------|------|------|-------|------|-------|------|-----|
|         | Ag                             | As   | Ba   | Cd    | Cr   | Hg    | Pb   | Se  |
| 6/21/93 | 0.5                            | 0.5  | 10   | 0.1   | 0.5  | 0.002 | 0.5  | 0.1 |
| 6/28/93 | 0.5                            | 0.5  | 10   | 0.1   | 0.5  | 0.002 | 0.5  | 1   |
| 8/25/94 | 0.01                           | 0.05 | 0.01 | 0.005 | 0.01 | 0.002 | 0.05 | 0.1 |
| 7/12/95 | 0.01                           | 0.05 | 0.01 | 0.005 | 0.01 | 0.002 | 0.05 | 0.1 |

## 5.9.2 Ammonia Partitioning

As part of the three series of air preheater tests performed by SRI, the gas/solid phase ammonia partitioning was determined. Tables 5.9-6 through 5.9-8 show the results of these tests. These series of air preheater tests were previously discussed in Section 5.5.1 of this report. Detailed test descriptions are contained in Appendices N, O, and P.

### 5.9.2.1 First Test Series

Concentrations of ammonia were measured simultaneously at each of the three air preheater inlet and outlet test locations in May 1994. The tests were conducted so as to differentiate between gas-phase and solid-phase ammonia. All three air preheaters were tested with the reactors operating at Test Condition 22, the base-line operating condition. The reactor B and C air preheaters were also tested at Test Condition 24 ( $\text{NH}_3/\text{NO}_x = 1.0$ ); however, the reactor A air preheater was not tested at this condition because of concern that the air preheater might become plugged during operation with the higher inlet ammonia concentration.

The test data are summarized in Table 5.9-6. Table 5.9-6 also gives estimated solid-phase ammonia concentrations on a mass of ammonia per mass of ash basis. The values shown in the table were derived both from solid-phase ammonia measurements made at the same time the gas-phase measurements were made and mass concentration measurements made earlier at the same location. The ammonia partitioning between the gas and solid phases shown in the table are similar for the air preheaters on reactors B and C. These data show that ammonia partitioning at the inlet to the air preheater is roughly equal (on a flue gas volumetric basis or ammonia mass basis) between the gas and solid-phases on reactors B and C. On both reactors the partitioning shifts toward the solid-phase at the air preheater outlet. As expected, a significant increase in total ammonia concentration was measured during operation at the higher  $\text{NH}_3/\text{NO}_x$  ratio at Test Condition 24 for both the air preheater inlet and air preheater outlet on reactors B and C. The test run on the reactor A

air preheater at Test Condition 22 indicated a higher total ammonia concentration at the air preheater inlet than at the air preheater outlet with the ammonia strongly partitioned to the solid phase. The total ammonia measured at the reactor A air preheater outlet was less than one-half of the total ammonia measured at the air preheater inlet with the ammonia more evenly partitioned between the gas and solid-phases. The lack of ammonia mass balance closure suggests an error in the measurement so that this result should be disregarded until further testing is done. The original data summaries for these tests can be found in Table A-1 in Appendix N.

The last three columns in Table 5.9-6 show the estimated weight concentrations of ammonia on the ash. The column headed "Estimated Solid-Phase  $\text{NH}_3$ ,  $\mu\text{g/g}$ " indicates the solid-phase ammonia concentration calculated from the average solid-phase ammonia concentration shown in the table and the average mass concentration measured a month earlier. The next two columns are an attempt to estimate a confidence interval for these data based on the standard deviations of the triplicate mass trains and the triplicate ammonia runs. These calculations are based on the volumetric concentrations of the solid phase ammonia and the particulate, both expressed at the same temperature and pressure, i.e. standard conditions. The upper limit shown is the quotient of the mean volumetric concentration of solid-phase ammonia plus one standard deviation and the mean particulate volumetric concentration minus one standard deviation. The lower limit shown is the quotient of the mean solid-phase ammonia concentration (mass per unit volume) minus one standard deviation and the mean particulate mass concentration plus one standard deviation. These calculations give the largest spread that can be obtained from these data.

The ratio of inlet to outlet concentrations of ammonia based on the estimated solid-phase ammonia concentrations (weight basis) are generally similar in magnitude to those ratios calculated from the solid-phase ammonia concentrations calculated from the ammonia train test data. It should be noted that the possibility exists that some gas-phase ammonia may have reacted with sulfur trioxide present in the flue gas, as the gas stream cooled in

the probe, to form ammonium bisulfate or ammonium sulfate. Other reactions involving chlorides etc. are also probably possible. These reaction products would be collected with the solid-phase ammonia sample even though the ammonia was in the gas-phase in the duct. This possible sampling error would cause the solid-phase concentrations to be high.

Table 5.9-6 Ammonia Partitioning Test - First Series

| Reactor | Date       | $\frac{\text{NH}_3}{\text{NO}_x}$ | Air Preheater Location | Gas-Phase $\text{NH}_3$ , ppm(v), @ 3% $\text{O}_2$ , dry | Solid-Phase $\text{NH}_3$ , Equivalent ppm(v), @ 3% $\text{O}_2$ , dry | Estimated Solid-Phase $\text{NH}_3$ , $\mu\text{g/g}$ | Estimated Upper Limit Solid-Phase $\text{NH}_3$ , $\mu\text{g/g}$ | Estimated Lower Limit Solid-Phase $\text{NH}_3$ , $\mu\text{g/g}$ |
|---------|------------|-----------------------------------|------------------------|---|--|---|---|---|
| A       | 5/11/94    | 0.8                               | Inlet                  | $0.6 \pm 0.1$   | $3.3 \pm 0.2$  | 307   | 372   | 256   |
|         |            |                                   | Outlet                 | $0.6 \pm 0.1$   | $1.0 \pm 0.2$  | 108   | 139   | 84  |
| A       | Not tested | 1.0                               | Inlet<br>Outlet        |   |  |   |   |   |
| B       | 5/10/94    | 0.8                               | Inlet                  | < 0.4   | $0.2 \pm 0.01$   | 22  | 24  | 20  |
|         |            |                                   | Outlet                 | < 0.3   | $0.5 \pm 0.01$   | 65  | 70  | 61  |
| B       | 5/10/94    | 1.0                               | Inlet                  | $1.8 \pm 0.4$   | $1.9 \pm 0.5$  | 186   | 239   | 137   |
|         |            |                                   | Outlet                 | < 0.4   | $1.3 \pm 0.2$  | 162   | 189   | 137   |
| C       | 5/6/94     | 0.8                               | Inlet                  | $0.7 \pm 0.1$   | $0.6 \pm 0.1$  | 56  | 68  | 45  |
|         |            |                                   | Outlet                 | < 0.3   | $1.0 \pm 0.1$  | 116   | 137   | 99  |
| C       | 5/9/94     | 1.0                               | Inlet                  | $3.3 \pm 0.3$   | $3.8 \pm 0.5$  | 332   | 390   | 280   |
|         |            |                                   | Outlet                 | < 0.3   | $6.7 \pm 1.6$  | 746   | 1003  | 525   |

### 5.9.2.2 Second Test Series

In September and October of 1994, concentrations of ammonia were measured simultaneously at each of the three air preheater inlet and outlet test locations with the reactors operating at Test Condition 22, the base-line operating condition ( $\text{NH}_3/\text{NO}_x = 0.8$ ), and at Test Condition 24 ( $\text{NH}_3/\text{NO}_x = 1.0$ ). The ammonia testing protocol, designed to differentiate between gas-phase and solid-phase ammonia as described in Section 2, Appendix O was used.

The test data and estimated solid-phase ammonia concentrations on a mass of ammonia per mass of ash basis are presented in Table 5.9-7. The mass-basis ammonia concentrations shown in the table for the ash entering and exiting the air preheater were derived both from the solid-phase ammonia measurements conducted simultaneously with

the gas-phase measurements and mass concentration measurements made earlier at the same location. The ammonia partitioning between the gas and solid-phases shown in the table are similar for all three air preheaters. These data show that ammonia partitioning at the inlet to the air preheater is roughly equal (on a flue gas volumetric basis or ammonia mass basis) between the gas and solid-phases and that the ammonia shifts heavily to the solid-phase as it cools while passing through the air preheater.

As expected, the data in Table 5.9-7 show a significant increase in ammonia concentration in both the gas and solid-phase (except the gas-phase at the air preheater outlets) during operation at the higher  $\text{NH}_3/\text{NO}_x$  ratio at Test Condition 24. For the gas phase at the air preheater inlets, the range of concentrations at Test Condition 24 was 1.2 to 7.3 ppm(v) dry @ 3%  $\text{O}_2$ , while at Test Condition 22 the range of concentrations was 0.4 to 1.3 ppm(v) dry @ 3%  $\text{O}_2$ . For the solid-phase at the air preheater inlets the range of ammonia concentrations at Test Condition 24 was 1.4 to 6.5 ppm(v) dry @ 3%  $\text{O}_2$ , (188 to 887  $\mu\text{g/g}$  of ash), while at Test Condition 22 the range of ammonia concentrations was 0.4 to 2.0 ppm(v) dry @ 3%  $\text{O}_2$  (51 to 270  $\mu\text{g/g}$  of ash). The partitioning shifts heavily toward the solid-phase at the air preheater outlets. As expected, a significant increase in total ammonia concentration was measured during operation at the higher  $\text{NH}_3/\text{NO}_x$  ratio at Test Condition 24 (high  $\text{NH}_3/\text{NO}_x$ ).

Each ammonia sampling train was used to run a blank sample by sampling ambient air before each set of tests was run to demonstrate the integrity of the equipment. The original data summaries from these blank ammonia concentration tests can be found in Table A-1 in Appendix O. The original data summaries for the actual ammonia concentration tests at Test Conditions 22 and 24 can be found in Table A-2 in Appendix O.

Table 5.9-7 Ammonia Partitioning - Second Series

| Reactor | Date     | NH <sub>3</sub><br>NO <sub>x</sub> | Air<br>Preheater<br>Location | Gas-Phase<br>NH <sub>3</sub> , ppm(v),<br>@ 3%<br>O <sub>2</sub> , dry | Solid-Phase<br>NH <sub>3</sub> , Equivalent<br>ppm(v), @ 3%<br>O <sub>2</sub> , dry | Estimated<br>Solid-<br>Phase NH <sub>3</sub> ,<br>µg/g | Estimated<br>Upper Limit<br>Solid-Phase<br>NH <sub>3</sub> , µg/g | Estimated<br>Lower Limit<br>Solid-Phase<br>NH <sub>3</sub> , µg/g |
|---------|----------|------------------------------------|------------------------------|--|---|--|---|---|
| A       | 10/13/94 | 0.8                                | Inlet<br>Outlet              | 0.4 ± 0.1<br>< 0.6   | 0.7 ± 0.2<br>1.4 ± 0.2  | 87<br>191  | 119<br>222  | 58<br>163   |
| A       | 10/13/94 | 1.0                                | Inlet<br>Outlet              | 1.2 ± 0.3<br>< 0.6   | 1.4 ± 0.2<br>1.7 ± 0.1  | 188<br>233   | 226<br>252  | 152<br>215  |
| B       | 10/12/94 | 0.8                                | Inlet<br>Outlet              | 0.6 ± 0.1<br>< 0.5   | 0.4 ± 0.1<br>0.8 ± 0.1  | 51<br>119  | 61<br>134   | 41<br>104   |
| B       | 10/12/94 | 1.0                                | Inlet<br>Outlet              | 7.3 ± 6.3<br>< 0.5   | 4.9 ± 3.7<br>6.5 ± 5.5  | 692<br>923   | 1233<br>1731  | 170<br>141  |
| C       | 9/29/94  | 0.8                                | Inlet<br>Outlet              | 1.3 ± 0.4<br>< 0.5   | 2.0 ± 0.2<br>2.4 ± 0.2  | 270<br>324   | 314<br>359  | 228<br>291  |
| C       | 9/30/94  | 1.0                                | Inlet<br>Outlet              | 3.6 ± 0.5<br>< 0.5   | 6.5 ± 0.8<br>7.2 ± 3.5  | 887<br>990   | 1028<br>1523  | 755<br>491  |

### 5.9.2.3 Third Test Series

Concentrations of ammonia were measured simultaneously at each of the three air preheater inlet and outlet test locations during December 1994. All three air preheaters were tested with the reactors operating at Test Conditions 22 and 24. Test Condition 22, the base-line or normal long-term operating condition, has a flow rate of 5,000 wscfm, a flue gas temperature of 700 °F, and a NH<sub>3</sub>/NO<sub>x</sub> ratio of 0.8. The operating parameters for Test condition 24 are the same, except that the NH<sub>3</sub>/NO<sub>x</sub> ratio is 1.0. The test data are summarized in Table 5.9-8.

The ammonia concentration tests conducted downstream of catalyst layer 3 (air preheater inlet) and at the air preheater outlets on reactors A, B, and C were designed to segregate the ammonia into gas and solid phases. A heated (maintained at the flue gas temperature) fiberglass thimble in a quartz thimble holder outside the stack was attached downstream of the probe. The thimble filtered out the fly ash from the flue gas. The thimble containing the ash catch and the probe wash were placed in a separate container and analyzed separately for ammonia. This sample was considered to have contained the solid-phase ammonia from the volume of gas sampled. The Teflon sample lines connecting the

thimble holder to the impingers were rinsed and the rinse liquid, the impinger liquid, all inter-impinger connector rinses and a final, glass-wool plug (to capture any aerosols escaping from the last impinger) were placed in another sample container. This sample was considered to contain the gas-phase ammonia from the volume of flue gas sampled. In Table 5.9-8 the column headed "Gas-Phase NH<sub>3</sub>, ppm(v), @ 3% O<sub>2</sub>, dry" shows the results of the analysis of the impinger catches plus rinses. The next column, headed "Solid-Phase NH<sub>3</sub>, Equivalent ppm(v), @ 3% O<sub>2</sub>, dry" shows the results of the analysis of the ash catch and probe wash. The solid-phase concentration is expressed as an equivalent volumetric concentration (as though it were a gaseous constituent of the stream) to give a basis for the comparison of gas-phase ammonia and solid-phase ammonia.

At the inlet of each air preheater the volumetric concentration of ammonia was generally split evenly between the gas and solid-phases under both test conditions. Unfortunately, the ash sample from the reactor C air preheater inlet and outlet at Test Condition 22 were both contaminated and could not be analyzed. As expected, at the air preheater outlet almost all of the ammonia was present in the solid-phase. For all three reactors at Test Condition 22 the gas-phase ammonia concentration at the air preheater outlet was below the detection limit. This is true also for reactor A at Test Condition 24, but not for the other two reactor air preheaters, which had measurable concentrations of gas-phase ammonia. This was a direct result of a higher inlet concentration.

Of interest, also, in this test program was the solid-phase ammonia concentration expressed on a weight basis, typically as ppmv or µg/g (micrograms of ammonia per gram of ash). The method used to measure ammonia concentrations during these tests did not lend itself to expressing the solid-phase ammonia concentrations on a weight basis because ash weights were not measured. However, it was possible to obtain an estimate of the weight concentration of ammonia on the ash by assuming that the mass concentration during the ammonia tests on December 15, 16, and 20, 1994, was the same as that measured when mass concentrations were measured on November 8 and 9, 1994, at the

same sites. Detailed data summaries and analytical procedures are contained in Appendix P.

Table 5.9-8 Ammonia Partitioning - Third Series

| Reactor | Date     | NH <sub>3</sub><br>NO <sub>x</sub> | Air<br>Preheater<br>Location | Gas-Phase<br>NH <sub>3</sub> , ppm(v),<br>@ 3%<br>O <sub>2</sub> , dry | Solid-Phase<br>NH <sub>3</sub> , Equivalent<br>ppm(v), @ 3%<br>O <sub>2</sub> , dry | Estimated<br>Solid-<br>Phase NH <sub>3</sub> ,<br>μg/g | Estimated<br>Upper Limit<br>Solid-Phase<br>NH <sub>3</sub> , μg/g | Estimated<br>Lower Limit<br>Solid-Phase<br>NH <sub>3</sub> , μg/g |
|---------|----------|------------------------------------|------------------------------|--|---|--|---|---|
| A       | 12/15/94 | 0.8                                | Inlet                        | 1.2 ± 0.2  | 1.2 ± 0.2   | 125  | 167   | 94  |
|         |          |                                    | Outlet                       | < 0.3  | 3.9 ± 0.3   | 481  | 520   | 444   |
| A       | 12/14/94 | 1.0                                | Inlet                        | 2.9 ± 0.7  | 4.1 ± 1.1   | 424  | 634   | 271   |
|         |          |                                    | Outlet                       | < 0.4  | 6.0 ± 0.8   | 749  | 861   | 640   |
| B       | 12/16/94 | 0.8                                | Inlet                        | 0.9 ± 0.1  | 0.8 ± 0.2   | 76   | 103   | 54  |
|         |          |                                    | Outlet                       | < 0.4  | 3.1 ± 0.4   | 431  | 406   | 361   |
| B       | 12/16/94 | 1.0                                | Inlet                        | 17.4 ± 4.5   | 12.2 ± 5.1  | 1119   | 1723  | 604   |
|         |          |                                    | Outlet                       | 1.1 ± 0.8  | 12.9 ± 6.6  | 1792   | 2792  | 854   |
| C       | 12/20/94 | 0.8                                | Inlet                        | 4.0 ± 0.3  | Samples<br>Contaminated   |  |   |   |
|         |          |                                    | Outlet                       | < 0.3  |   |  |   |   |
| C       | 12/20/94 | 1.0                                | Inlet                        | 20.5 ± 1.8   | 14.6 ± 0.4  | 1420   | 1643  | 1242  |
|         |          |                                    | Outlet                       | 0.7 ± 0.5  | 18.0 ± 0.3  | 2367   | 2462  | 2277  |

### 5.9.3 Fly Ash Resistivity

Fly ash resistivity was measured in the laboratory on a fly ash sample collected in early 1993 at the Unit 5 hot-side ESP at high load conditions. The technique for measuring resistivity was based on the IEEE 548 (1984) test method, commonly referred to as a descending temperature method. The atmosphere in the laboratory oven holding the sample was controlled to a moisture content of 7.6%, comparable to that occurring in the actual Unit 5 flue gas. The peak resistance of  $3.9 \times 10^{11}$  ohm-cm occurred near 300 °F and declined to roughly  $1 \times 10^{18}$  ohm-cm near 800 °F. This is a relatively high resistivity ash and demonstrates the requirement for flue gas conditioning in cold-side ESPs treating ashes of this type, as well as the reason hot-side ESPs were selected for Crist Unit 5. The detailed data summary of this initial fly ash resistivity test can be found in Appendix G (Task 1 commissioning tests).

A second series of laboratory measurements of ash resistivity were conducted in September of 1994 on fly ash samples collected at the inlet and outlet of the three large reactor air preheaters, except the outlet of the reactor C air preheater. The detailed test data are shown in Appendix N (first test series air preheater tests). The resistivity/temperature relationships for the five ash samples are very similar. For all of the ash samples the peak in the resistivity ranging during the Task 1 base-line testing at the location of the SCR test facility inlet scoop was  $3.9 \times 10^{11}$  ohm-cm @ 293 °F. Based on these two measurements, the SCR process appears to have little or no effect on fly ash resistivity.

Fly ash resistivity was again measured in the laboratory on fly ash samples collected at the outlet of the air preheaters on reactors A and B in December of 1994. The atmosphere in the laboratory oven holding the samples was controlled to a moisture content of 7.9%, comparable to that occurring in the actual Unit 5 flue gas. This is a moderate resistivity ash. The resistivity for this ash is almost a factor of ten lower than that for the Unit 5 hot-side ESP inlet fly ash collected during Task 1 testing in early 1993 ( $3.9 \times 10^{11}$  ohm-cm @ 293 °F). Appendix P (Third Series Air Preheater Tests) contains the detailed data from these laboratory resistivity tests. The resistivity peaked at roughly  $5 \times 10^{10}$  ohm-cm near 300 °F and declined to roughly  $5 \times 10^7$  ohm-cm near 800 °F.

#### **5.9.4 High Velocity Catalyst Tests - Reactor H**

High velocity tests were performed on reactor H by modifying the reactor to produce linear velocities near 30 ft/s. A Cormetech catalyst was used for this testing, essentially the same offering as in reactor E. Testing on the catalyst was performed during the brief period of operations from June 1 through July 14. The tests were somewhat inconclusive due to the relatively short duration of operation. However, no significant erosion or fouling as compared to normal high dust applications was noted. Further long-term testing will be required to fully evaluate the high velocity application.

### 5.9.5 Continuous Ammonia Analyzers

The experience gained in this project highlighted the need for a continuous ammonia analyzer, especially in full-scale applications. As a result, an effort was made to determine what monitors were currently available and their applicability to normal conditions associated with SCR technology. It was desired that the monitor be capable of measuring ammonia on a continuous basis at ammonia levels commonly found at the SCR exit, i.e. < 5ppm. The ability to measure ammonia at this location would allow enhanced operation of the SCR since ultimately ammonia slip is the primary indication of reactor performance and, from a practical standpoint, sets the maximum attainable deNO<sub>x</sub> efficiency.

Unfortunately, none of the instruments tested were acceptable for the application. Both in-situ and extractive type systems were evaluated, but interferences from other flue gas components or the formation of ammonia by-products prevented the accurate determination of ammonia slip levels. Continued research is required to produce an acceptable continuous ammonia monitor which will meet both the analytical and durability requirements of SCR technology.

## 6.0 ECONOMIC EVALUATION

*(Detailed economic evaluation shown in Appendix T)*

Ultimately, the goal of any test facility is to gather information and gain experience to enable a more accurate performance evaluation as well as economic analysis when extrapolated to commercial size installations. From its inception, the SCS/DOE test facility was designed to minimize the uncertainty associated with application of pilot scale test results to a full scale installation. Significant resources have been expended to present realistic costs and performance expectations of SCR technology based on the results of the 2-year test program. It is anticipated that the economic analysis presented in this report will assist interested parties with evaluating SCR compared to other possible NO<sub>x</sub> control alternatives for future emission control requirements.

There are several regulatory and environmental drivers in various stages of consideration which may increase the likelihood of employing SCR technology in the future. Recent experience of applying SCR to new coal-fired installations has created regulatory precedent under New Source Review, which will affect future best available control technology (BACT) and lowest achievable emission rate (LAER) determinations for other new units. With one exception, these new installations are owned and/or operated by independent power producers (IPPs) who report that adopting SCR technology was necessary to quickly obtain the construction and/or operating permits.

The 1990 Clean Air Act Amendments (CAAA) mandated several NO<sub>x</sub> control requirements and regulatory reviews to reduce NO<sub>x</sub> emissions from utility boilers. Application of SCR to existing boilers is being considered for units located in areas designated under Title I (nonattainment provisions) for attainment of the ambient ozone standard. Recent efforts by the Ozone Transport Assessment Group (OTAG) have focused on NO<sub>x</sub> reduction strategies on a broader scale, encompassing all states in the central and eastern part of the United States. Results of the OTAG review may increase the likelihood for retrofits of SCR technology, particularly if emission averaging and NO<sub>x</sub> trading are allowed. Additionally, nationwide reductions in NO<sub>x</sub> mandated under Title IV

(acid rain provisions) will be required by the year 2000. In order to meet these additional NO<sub>x</sub> reductions, utilities are given flexibility in selecting the most suitable and cost-effective NO<sub>x</sub> control technologies for their situation.

This report is written from the perspective of a utility end user of SCR technology. As such, the results are meant to establish a range of financial exposure representative of most domestic electric utilities. It is recognized that there will be utility specific instances where the cost (or cost effectiveness) of SCR technology may be higher or lower than what is contained in this report as evidenced in previous papers representing diverse views regarding the cost of SCR technology. (refer to section 5.0 for a list of reference papers). In an effort to present the most effective economic evaluation possible, information was obtained and incorporated from several sources including:

- Test Facility Data - Measured data and operational lessons learned at the SCS/DOE test facility over the 2-year test program formed the basis of the technical performance estimates.
- Peer Review - Comments were solicited from cofunders, project participants, and independent consultants. The review cycle accomplished a key objective of obtaining peer review of the material as well as challenging the results based on differing viewpoints.
- Technology Suppliers - Analytical and engineering analysis received from vendor participants contributed greatly to the success of the project. The catalyst management plans presented in this report are based on vendor generated laboratory data of catalyst deactivation (k/ko) over time. Additionally, air preheater performance, material testing, and deposit analysis were supplied by the air preheater vendor.
- Full-Scale, Coal-Fired Experience - Results of the economic analysis are enhanced by incorporating current market trends based on SCS participation in one of the first commercial coal-fired SCR installations in the United States. Information from the other U.S. coal-fired SCR installations was also considered when developing the economic evaluation.

This section reports the results of a commercial-scale capital and O&M costs evaluation of SCR technology applied to a new facility, coal-fired boiler utilizing high-sulfur, U.S.

indigenous coal. The economic analysis presented in this report is not meant to supplant the need to perform site-specific financial analyses when evaluating SCR technology for a specific project. It is recognized that there will likely be project-specific constraints, sensitivity analyses, and market forces which no generalized economic analysis will be able to capture. Rather, the information reported herein reflects a macro-economic analysis of SCR technology based on historical data measured at the test facility, empirical laboratory data generated as a result of the test program, and consolidation of operational lessons learned tempered with the knowledge of the current commercial market trends.

The economic analysis presented herein determines the total capital, operating, and levelized costs for a 250 MW sized base case plant. Economic factors are calculated according to guidelines established by EPRI, taking into account financial parameters, such as the cost of capital, income tax rates, and the rate of inflation. Two different sets of factors are calculated to permit the economics to be presented either on a current dollar basis which includes the effect of inflation or constant dollar basis which ignores inflation. Reporting of the results are based on "General Guidelines for Public Design Report and Final Report" prepared by Burns and Roe Service Corporation for the U.S. Department of Energy Pittsburgh Energy Technology Center. The analysis also involves determining the sensitivity of the results to changes in inlet NO<sub>x</sub> concentration, NO<sub>x</sub> removal efficiency, and unit size.

The study conclusion shows the 250-MW base case (60% NO<sub>x</sub> removal) unit capital and first year O&M (in 1996 dollars) are \$13,415,000 (\$54/kW) and \$1,045,000, respectively. Levelized cost for the base case unit is \$2,500/ton on a current dollar basis and \$1,802/ton on a constant dollar basis. Busbar cost is 2.57 mills/kWh on a current dollar basis and 1.85 mills/kWh on a constant dollar basis.

For the new plant applications, total capital requirement for a 60 percent NO<sub>x</sub> removal design ranged from \$45/kW for a 700-MW unit to \$61/kW for a 125-MW unit.

Associated current dollar levelized cost ranged from \$2,165/ton to \$2,811/ton for the 700-MW unit and 125-MW unit, respectively.

Capital cost variation as a function of NO<sub>x</sub> removal for a 250-MW unit ranged from \$57/kW for an 80 percent design to \$52/kW for a 40 percent removal design.

Corresponding current dollar levelized cost ranged from \$2,036/ton to \$3,502/ton for the 80 percent and 40 percent removal cases, respectively.

Retrofit applications for a 60 percent removal design show a range of capital requirements from \$59/kW for an 880-MW unit size to \$87/kW for a 100-MW units size. There are two plants having capital requirements of \$130/kW and \$112/kW due to balanced draft conversion of the units. Levelized costs range from \$1,848/ton to \$5,108/ton on a current dollar basis.

The detailed economic evaluation is contained in Appendix T. However, a brief synopsis of the base case results follows.

### **6.1 Base Case Economics**

The economic estimates for the base case evaluation are based on application of high-dust, hot-side SCR configuration (i.e., located between the boiler economizer outlet and the air preheater inlet) to a new coal fired installation utilizing high-sulfur coal. The technical design premises used to prepare the economic analysis were selected to be representative of actual or anticipated plant configurations and NO<sub>x</sub> control requirements currently being permitted or likely to be permitted on coal-fired boilers in the United States. Thus, defining assumptions were selected in an effort to have broad utility applicability. The following section describes major features of the base case installation.

### 6.1.1 Base Case Definition

The base case represents a new, base-load 250 MW pulverized-coal power plant typical of the majority of new coal-fired projects currently under development, construction, or recently declared in commercial operation. It is felt that the unit size of 250 MW is consistent with future trends of new domestic power plants. The plant is located in rural area with minimal space limitations. The fuel is a high-sulfur bituminous Illinois No. 6 coal.

The plant will utilize a single, balanced-draft, pulverized-coal fired boiler complete with all required auxiliary equipment. The boiler will be designed to produce approximately 1,610,000 lb/hr of main steam at turbine inlet conditions of 2400 psig and 1000 °F. Utilizing current generation low NO<sub>x</sub> combustion systems, the boiler will produce a NO<sub>x</sub> emission rate of 0.35 lb/MBTU. For purposes of this study, it is assumed that tangentially-fired boilers and wall-fired boilers are interchangeable with respect to all thermal performance and flue gas constituents.

Coal will be delivered through gravimetric feeders to the pulverizers and then to the coal nozzles located in the furnace walls. Primary combustion air will flow through the pulverizers to transport the pulverized coal to the furnace. Secondary combustion air from the forced draft fans will be preheated in the air preheater and will then be ducted to the boiler windbox to be injected into the furnace at the burners and overfire air ports.

The flue gas will leave the boiler and enter a single, hot-side SCR. Flue gas flow is vertically downward through the reactor. The physical arrangement of the SCR is located directly above the air preheater. The SCR is designed as a "universal" reactor able to accept either (or both) plate type catalyst and honeycomb type catalyst. Ammonia injection will utilize stand alone dilution air fans rather than combustion air.

A single, trisector, Ljungstrom regenerative air preheater will be utilized to reclaim heat from the flue gas stream and transfer that heat to the primary and secondary air. Physical features of the air preheater are typical of what is commercially offered as a "deNO<sub>x</sub>" air preheater. The heater transfer surface arrangement will include hot, intermediate, and cold sections.

Sulfur dioxide removal is accomplished by a lime spray dryer FGD system. The FGD system will include two 50% absorber vessels equipped with rotary atomizers which produce very fine droplets to enhance the reactivity of the slurry. The absorber vessel shall be designed with sufficient residence time to ensure complete evaporation of the water and collection of the acid gases.

A reverse gas, fabric filter baghouse will be used which will collect the dried reaction products from the spray dryer as well as the fly ash produced in the boiler by the combustion of coal. The baghouse will be constructed in multiple compartments which will allow on-line cleaning and maintenance. Each compartment will be equipped with a single ash hopper. The dust laden gas enters the baghouse through an inlet manifold which spans the length of the baghouse and distributes the gas into the ash hoppers of each compartment containing filter bags. Once the flue gas enters the compartment, the gas velocity decreases causing particulate drop out in the ash hopper. As the gas travels upward, the particulate is deposited on the inside of each filter bag. Clean gas from each compartment passes to an outlet manifold which is common to all compartments. The clean gas passes out of the baghouse and to the ID fans for discharge out the stack.

The SCR reactor for this analysis includes three catalyst support layers plus a flow straightener (dummy bed). At time zero, two of the three catalyst support layers are loaded with catalyst. To optimize catalyst life, a spare (empty) catalyst support elevation inside the reactor is provided. The spare layer allows catalyst suppliers to develop optimized catalyst management plans which increase catalyst utilization. Thus, a fresh catalyst layer can be added to the reactor after the guarantee period when the ammonia

slip begins to exceed the guaranteed limit. The activity of the new catalyst combined with the residual activity of the existing catalyst restores the performance of the SCR and extends the next addition/replacement outage far beyond the initial guarantee interval.

Catalyst deactivation data was developed by periodically taking catalyst samples from the pilot reactors and returning the samples to the catalyst supplier. The catalyst supplier performed a standard test protocol to develop  $k/k_0$  vs. time trending. The catalyst management plan developed for the economic analysis is based on composite empirical laboratory data developed on test facility catalyst.

The catalyst management plan is based on a 16,000 hour (2 year) catalyst life guarantee period. After the initial guarantee period of 2 years, a new layer of catalyst is added to the reactor, thus, taking advantage of the residual activity in the initial layers to "boost" the performance of the SCR. The next addition of catalyst is required in project year 6 when one of the initial layers is replaced. Thus, catalyst is added and/or replaced after 2, 6, 9, 15, 18, 21, 24, and 27 years for a total of 9 times during the 30 year evaluation period. It should be noted that catalyst life projections of 30 years are speculative at best due to uncertainty of catalyst structural properties with exposure to flue gas for periods over 6 to 8 years.

## **7.0 CONCLUSIONS**

World-wide capacity utilizing SCR technology has reached nearly 100,000 MW. However, U.S. utilization of the technology is small (approximately 7,000 MW). Thus, the potential use of SCR technology is huge, representing nearly all installed and future fossil-fuel capacity in the domestic case. Of particular concern is coal-fired capacity, considering its current dominance in the U.S. generation mix. With coal-fired capacity as the focus, this project has demonstrated the applicability of SCR technology to boilers firing high-sulfur U.S. coal (with the findings presumably applicable to lower-sulfur U.S. coals). All catalyst offerings met the basic design criteria, i.e. meeting 80% deNO<sub>x</sub> rates with less than 5 ppm ammonia slip over the project life. Thus, SCR technology has been shown to be a viable option for achieving significant levels of NO<sub>x</sub> reduction on U.S. coal-fired installations.

### **7.1 SCR Technology Evaluation**

#### **7.1.1 SCR Catalysts**

One of the primary goals of this project was to demonstrate the applicability of several SCR catalyst designs to U.S. coal-fired boilers. All of the catalyst designs tested in the facility proved to be acceptable for the application and met the general performance criteria set forth for the catalysts at the onset of the project. However, major differences in the performance of the individual catalysts were noted. The performance differences included deNO<sub>x</sub> activity, SO<sub>2</sub> oxidation activity, pressure drop, fouling characteristics, and physical strength. Each of these performance parameters is addressed in the following discussion.

### 7.1.1.1 SCR Catalyst deNO<sub>x</sub> Activity

One of the primary purposes of the test program was to address the potential catalyst deactivation associated with U.S. high-sulfur coal application. Although a considerable experience base is present for foreign coals, little is known about the potential catalyst poisons and resulting catalyst deactivation of U.S. coals. The primary method of tracking this deactivation was via catalyst supplier laboratory tests. The results of these tests have shown that for all catalysts, deactivation rates are similar to those noted in European and Japanese installations. No unusual deactivation trends were noted and it appears that at least for the coals tested at this facility, catalyst poisoning and deactivation is similar in significance to other world-wide installations. As expected, the deNO<sub>x</sub> activity of the SCR test catalysts varied greatly with respect to bulk volume. This is an important parameter because the bulk volume (and weight) control to a large degree the physical size and structure of an SCR reactor and the resulting capital cost. The catalyst suppliers were given a great deal of latitude in specifying the volume of catalyst for their respective reactors. In some cases suppliers chose to minimize catalyst volume by designing a system which met, but did not exceed, performance requirements. In other cases, catalyst suppliers chose to increase catalyst volume to insure performance margin and thus exceed specifications. Honeycomb catalysts are generally considered to have high surface area when compared to plate-type catalysts (on a bulk volume basis) and would thus generally require less volume (although weight may be greater). However, it appears that installed catalyst design margin can be as significant to bulk catalyst volume as is the basic geometrical (honeycomb/plate) design. The bulk volumes offered in the test program by the various catalyst suppliers ranged from 82% to 120% of the average (excluding the low-dust catalyst). Geometric surface area ranged from 383 to 470 m<sup>2</sup>/m<sup>3</sup> or 88% to 108% of the average of 437 m<sup>2</sup>/m<sup>3</sup> (excluding the low-dust catalyst). Specific weight (bulk density) ranged from 16 to 39 lb/ft<sup>3</sup> or 61% to 148% of the average of 26.4 lb/ft<sup>3</sup>. Total weight ranged from 50% to 161% of the average. (All data have been normalized to flue gas flow rate to compensate for differences between the large and small reactors in bulk parameters.) Ammonia slip from all of the reactors combined averaged 1.8 ppm over

the life of the test program at base-line conditions. Individual reactor average slip values ranged from 35% to 197% of the overall average, again based on entire project life data under base-line conditions.

#### **7.1.1.2 SCR Catalyst SO<sub>2</sub> Oxidation Activity**

Unfortunately, the catalytic activity that results in deNO<sub>x</sub> activity also contributes to SO<sub>2</sub> oxidation activity. Since increased SO<sub>2</sub> oxidation is detrimental to equipment downstream of the SCR, the competing reactions tend to bound the catalyst design. In general, as requirements to minimize SO<sub>2</sub> oxidation relax, deNO<sub>x</sub> activity per volume of catalyst can be increased. The upper bound for SO<sub>2</sub> oxidation for the test facility catalysts was set at 0.75%. A wide range of SO<sub>2</sub> oxidation rates were exhibited by the various catalysts in the test program. In practice, some benefits may be realized by decreasing SO<sub>2</sub> oxidation past some arbitrarily chosen point, but these decreases are generally made at the expense of increasing catalyst volume. As with deNO<sub>x</sub> activity, the SO<sub>2</sub> oxidation margin chosen by the individual catalyst suppliers likely contributed significantly to the overall catalyst volume. It is difficult to determine the point of diminishing return for decreasing SO<sub>2</sub> oxidation as little full scale long-term operational data are available for U.S. boilers. Differences in SO<sub>2</sub> oxidation characteristics were very apparent between the catalyst suppliers ranging from near zero to 0.66 % SO<sub>2</sub> oxidation with an averaging of 0.31% SO<sub>2</sub> oxidation. However, these differences do not necessarily denote a difference in catalyst design expertise between the suppliers, but more likely reflect a philosophical decision as to the catalyst offering made. In practice, all suppliers would likely be able to meet a customer's specific SO<sub>2</sub> oxidation requirements.

#### **7.1.1.3 SCR Catalyst Pressure Drop**

Catalyst pressure drops are generally a function of catalyst geometry and volume. Honeycomb catalysts commonly have less open area than plate catalysts, resulting in increased pressure drop per unit length of catalyst. However, this is sometimes mitigated

by less volume of honeycomb catalyst required compared to plate catalysts. Thus, the overall reactor pressure drop must be considered when evaluating catalysts and neither the geometry nor the catalyst volume are exclusively controlling. Project life average pressure loss of the catalysts at the test facility ranged from approximately 1" to 3" H<sub>2</sub>O (based on the sum of catalyst bed pressure drop across all catalyst beds in each reactor, excluding the high-dust reactor). These values equate to a low of approximately 0.6 to a high of 1" H<sub>2</sub>O pressure loss per linear foot (unit height) of catalyst.

#### **7.1.1.4 SCR Catalyst Fouling Characteristics**

The fouling characteristics of SCR catalysts are important to the successful long-term operation of the reactor. In practice, the pressure drop across a catalyst increases slightly from new condition once the catalyst is placed in service. The pressure loss, however, should remain relatively consistent after the initial start-up of the reactor. Steadily increasing pressure drops over time indicate that a catalyst is either improperly designed for the application or that appropriate sootblowing steps are not being taken. Small reactors similar to those present in the test facility represent worst case scenarios for catalyst fouling due to the wall effects and space constraints preventing optimum sootblowing. However, the test facility pressure drop data show relatively stable pressure drop versus time for the catalysts. This indicates that the sootblowing procedures used in the test facility were effective. In the case of the low-dust reactor, more fouling was noted. This was not a result of catalyst design, however, but was the result of test facility design. Long duct runs with increased heating requirements and a less than optimum take-off scoop all contributed to large particulate material being passed through the low-dust reaction system. The catalyst was not designed for these conditions and fluctuation in the low-dust catalyst's pressure drop should not necessarily be construed as demonstrating the inapplicability of a low-dust configuration. Interestingly, due to the delicate nature of the Hitachi Zosen catalysts, no sootblowing was performed at all on this catalyst. This did not, however, adversely affect the fouling of this catalyst, as the extremely low facial area of the catalyst prevented fouling to a great degree. The plate-type configurations

demonstrated somewhat less fouling potential than did the honeycomb configurations, but neither configuration was unacceptable for the application.

#### **7.1.1.5 SCR Catalyst Physical Strength/Durability**

The harsh environment in which catalysts in coal fired applications must operate make high physical strength and durability a necessity for catalysts. Erosion of the catalyst can be worsened by areas of high velocity or high particulate as well as by erosion from sootblowing operations. Severe erosion in certain areas of a catalyst is accelerated by the fact that eroded areas tend to become the preferred flow path due to localized reduced pressure drop, thereby increasing the erosion potential in that particular area. In the case of some plate catalysts such as the Siemens, the catalyst support is steel, preventing significant erosion past the face of the catalyst. In the case of the Haldor Topsoe catalyst, a face hardening procedure appeared to enhance this catalyst's ability to withstand facial erosion. Little facial erosion was noted on the Hitachi Zosen catalyst likely due to the extremely small cross-sectional area of exposed catalyst face (due to extremely thin plates). The honeycomb catalysts also withstood erosion quite well, and the majority of erosion noted appeared to be due to aggressive sootblowing procedures (based on the erosion pattern). One exception to this finding however, was the Grace Synox catalyst. This special-design catalyst represents a significant deviation from other honeycomb catalysts currently marketed. The bimodal design resulted in a relatively soft material which showed significant erosion during the test program mainly indicated by the thinning of the catalyst walls. Also, some honeycomb dummy bed material initially used in the test facility was considerably less durable than the catalysts. This material exhibited the phenomenon previously discussed where erosion problems were exacerbated by channeling.

## **7.1.2 SCR Reactor Design**

The proper design of an SCR reactor is as important as the catalyst design. A poorly designed or poorly functioning reactor will limit the SCR process performance regardless of catalyst capability. Primary concerns in reactor design are ammonia/NO<sub>x</sub> distribution, velocity distribution, and particulate distribution.

### **7.1.2.1 NH<sub>3</sub>/NO<sub>x</sub> Distribution**

The ammonia/NO<sub>x</sub> distribution is critical to the efficient operation of an SCR reactor. Most full scale reactors operate with some NO<sub>x</sub> maldistribution and have tuning capabilities designed to match the injected ammonia distribution to the NO<sub>x</sub> distribution. The test facility reactors were designed to have smooth NO<sub>x</sub> distributions and, as a result, ammonia distributions were desired to be as uniform as possible. The test facility ammonia injection grids (25 points on the large reactors, 16 points on the small reactors) generated acceptably uniform ammonia distributions ( $\leq \pm 10\%$  about the average). Without a uniform ammonia-to-NO<sub>x</sub> distribution, areas within an SCR reactor can be created which have high relative ammonia-to-NO<sub>x</sub> ratios. Since little mixing occurs as the flue gas passes through the layers of catalyst, these areas of high ratios of ammonia-to-NO<sub>x</sub> can create excessive ammonia slip, reducing the deNO<sub>x</sub> efficiency and contributing to downstream equipment problems. Flow modeling of ammonia injection and periodic manual testing can be extremely valuable tools in insuring proper ammonia distribution within the reactor.

### **7.1.2.2 Velocity Distributions**

Minimizing velocity maldistributions within the SCR reactor is an important design criteria. Velocity maldistributions can make balancing NH<sub>3</sub>/NO<sub>x</sub> distributions difficult and most importantly can contribute to excessive erosion of the catalyst in high velocity areas. Further, low velocity areas within the reactor may contribute to fouling via ash deposition.

Particular care was taken in the design of the test facility reactors to insure uniform velocity distributions. Scale models were used to characterize velocity distributions since a number of complicated expansions/turns were required in the test facility reactor design. Turning vanes, baffles, and diffusers were incorporated to insure uniform velocity distributions. Subsequent evaluations of velocity distributions within the test facility showed good uniformity within all of the SCR reactors.

### **7.1.2.3 Particulate Distributions**

Similar to velocity maldistributions, poorly distributed particulate can cause areas of high erosion within SCR reactors. Much of the test facility reactor design aimed at smoothing velocity distributions also helped to insure flue gas mixing and thus promoted uniform particulate distributions. Several evaluations of particulate distributions within the SCR reactors were made, all showing relatively uniform distributions. In addition, particle size distributions were also measured. These measurements showed that the particle size distributions in the test facility reactors were similar to those from the host unit.

### **7.1.3 Commercial SCR Operational Recommendations**

The operation of the test facility reactors was in many ways ideal compared to conditions that might be experienced in a full-scale commercial SCR unit. This was due to the ability to closely control the test facility SCR reactors at various operating conditions, including the ability to operate the reactors on heated ambient air at various conditions. Of particular concern to commercial SCR units are start-up/shut-down periods. Specific recommendations for start-up/shut-down are made in the following sections based on operating experience gained at the test facility and deemed to be applicable to a commercial SCR unit.

### 7.1.3.1 Flue Gas Operation

In ideal situations the SCR unit will be equipped with a bypass (or partial bypass) to allow start-up of the generating unit prior to start-up of the SCR. This allows for controlled start-up of the SCR on flue gas once the generating unit has stabilized operations.

Unfortunately, this is sometimes not the case in commercial SCRs and thus the SCR unit is exposed to start-up conditions for the duration of generating unit start-up. In any event, adverse conditions can be minimized by appropriate operation steps. Typically, the initial phase of start-up and final phase of shut-down of an SCR unit is not a question of ammonia by-product formation, but rather of simple acid condensation. The primary objective of the start-up and shut-down procedures therefore is to minimize the time period during which the SCR unit resides in conditions promoting acid formation. Thus, the heat-up and cool-down of the SCR unit would normally be performed as quickly as possible, although care must be taken to avoid exceeding the maximum temperature ramp rate specified by the catalyst supplier. In cases where air purge is available, it is desirable to purge the reactor thoroughly after shut-down of the SCR unit thus preventing "bottling-up" of flue gas acid components. In cases where air purge is not available, a thorough boiler purge can help to minimize acid condensation within the SCR reactor.

In some situations, a boiler may be shut down for a very short duration. In which case, it may be desirable not to completely shut-down the SCR unit, but to simply isolate the SCR as much as practical until the boiler is again available. This scenario is most applicable to SCR units which are equipped with bypass capability. In this case, ammonia injection would be discontinued prior to bypassing the SCR reactor to allow residual ammonia to react/purge from the reactor. The reactor would then be isolated allowing for flue gas to bypass the unit. Typically the SCR has a large thermal mass and would thus retain significant temperature for as long as a weekend outage, depending on the size and construction of the unit. The decision whether to isolate the reactor or to completely shut down the reactor can be difficult since outage durations can often be difficult to estimate. There is some risk associated with the former option since an outage continuing past the

expected duration would leave a significant amount of flue gas to cool within the SCR reactor which would require purging to prevent substantial amounts of acid by-products.

### 7.1.3.2 Ammonia Injection

The point at which ammonia injection is begun or ceased is one of the primary factors in the optimum start-up or shut-down of an SCR unit. In the absence of strict regulatory requirements it is beneficial to delay ammonia injection until all generating unit components have reached their normal operating temperature. This prevents ammonia by-products from depositing on cold surfaces in various areas downstream of ammonia injection, including the SCR structure, catalyst, and air preheater. This delay also helps to insure that all areas of the catalyst have reached appropriate minimum operating temperature. In some cases, deposits of by-products will be eliminated once higher temperatures have been reached, but fouling with fly ash often prevents full destruction of the deposit resulting in permanent fouling. Unfortunately, regulations may require ammonia injection ( $\text{NO}_x$  control) prior to the attainment of normal system operating temperatures. In this case it is desirable to delay ammonia injection as much as possible. A possible mitigating step to help to minimize adverse effects from early ammonia injection would be short-term elevated temperature operation (as soon as practical) of equipment downstream of ammonia injection.

Shut-down procedures of an SCR unit follow the same principles as start-up procedures. Ammonia injection should be ceased as early as practical in the shut-down of a generating unit. This is very important because the ammonia adsorption characteristics of the catalyst tend to retain and slowly evolve ammonia for some time after ammonia injection has ceased. Thus, ammonia may be present for some period after discontinuing injection and will continue to potentially form by-products especially as equipment temperatures begin to decline.

### **7.1.3.3 Sootblowing**

Appropriate sootblowing procedures at the time of start-up/shut-down of a commercial SCR unit can help to minimize adverse effects from cycling due to the removal of ash deposits which may subsequently contribute to permanent fouling by combining with acid/ammonia by-products. In general it is desirable to clean SCR catalysts as much as possible prior to shut-down of the SCR unit and to coordinate this sootblowing with the boiler during unit shut-down. This helps to prevent ash cakes from hardening due to their exposure to acid and ammonia by-products during shut-down events. This also insures that the reactor is as clean as possible prior to restart of the unit, again helping to minimize ash hardening during adverse start-up conditions. In addition, it may be desirable to sootblow the SCR reactor shortly after proper operating temperature has been attained to aid in the dislodging of any fouling that may be present due to start-up conditions.

## **7.2 SCR Downstream Effects**

The test facility was developed to include an examination of downstream impacts of SCR. Most notably this included examining air preheater performance and possible changes in ash and the resulting waste characteristics.

### **7.2.1 Air Preheater Performance**

As measured by the drop in number of transfer units (Ntu) from the initial values to the final values, the thermal performance of air preheaters A, B, and C dropped by about 11%, 7% and 25%, respectively. The fact that air preheater B seemed to deteriorate less than the others is attributed to the fact that air preheater B received significantly less  $\text{NH}_3$  slip than the other two air preheaters. It is believed that air preheater C deteriorated the most because it is a recuperator, and is therefore more sensitive to a given amount of fouling than a regenerator. As one would expect, the gas-side pressure drops were more sensitive to the degree of fouling and plugging than the Ntu values were. In general, all three air

preheaters showed generally steady increases in gas-side pressure drop during the test period.

In general, the high  $\Delta P$ 's could be reduced by aggressive cleaning methods, including sootblowing at four hour intervals, thorough water washing, and occasional increases in the gas outlet temperature. It was not possible, however, to maintain the original, clean  $\Delta P$  of any of the air preheaters.

Although the 3 layer air preheater appeared to perform better than the 2 layer air preheater, it cannot be concluded that the 3 layer design is superior to the 2 layer design. This is because the 2 layer air preheater received much more  $\text{NH}_3$  than the 3 layer air preheater -- possibly as much as four to five times more. Given this significant difference in operating conditions, the 2 layer air preheater performed remarkably well, and might very well have done better than the 3 layer design if the concentrations of  $\text{NH}_3$  into the two regenerators had been equal.

The Q-Pipe® air preheater seemed to steadily lose thermal performance with time during most of the test. The majority of the drop in Ntu is believed to be attributable to fouling of the finned tubes on the gas-side.

Corrosion tests on various heat transfer surfaces showed that enameled heat transfer surfaces should be used for Ljungstrom® air heaters when ammonia and sulfur compounds are both present in the gas stream.

### **7.2.2 Environmental Impacts**

Evaluation of environmental impacts as a result of applying SCR technology included TCLP analyses, ash resistivity analysis, and a special study examining the effects of slip ammonia on waste streams. In addition, the project Final Environmental Monitoring Report contains information related to the effects of SCR technology on host facility air,

water, and solid waste streams. TCLP and resistivity analyses did not indicate that SCR technology caused any appreciable change in these parameters. This result was expected but had not been shown conclusively prior to this study. Ammonia volatilization was shown to occur quite readily on moist fly ash, but did not evolve easily from dry fly ash. This has important implications in the handling of fly ash associated with SCR. The study also showed that aqueous solution pH affected ammonia extraction, implying that wet handling of ash may be affected by solution pH. An increase in barium extractability was noted with ammonia containing fly ash, but no notable changes in other metal extractabilities were found. The results of these studies indicate that although no severe impacts were noted on waste streams, some changes in waste stream characteristics are likely to occur with the implementation of SCR technology. In particular, precautions may be necessary to protect individuals involved in the handling of fly ash due to ammonia evolution.

### **7.3 Low/High-Dust SCR Configuration**

The installation of the reactor J low-dust configuration allowed a comparison of low-dust to high-dust applications. The test results were somewhat inconclusive due to fouling problems associated with the design of the test facility low-dust reactor and extraction scoop, biasing the physical testing. The results did show that catalyst parameters such as deactivation, NO<sub>x</sub> reduction capability, and SO<sub>2</sub> oxidation were similar to the high-dust configuration. The results also showed that comparable NO<sub>x</sub> reduction could be accomplished with significantly less volume of catalyst (primarily due to the higher specific surface area of the low-dust catalyst). Physical characteristics such as fouling and pressure drop, however, were much more difficult to determine. The results showed that a low-dust configuration could be very sensitive to upsets in boiler/ESP operation. The small channel openings in the low-dust configuration present a particular problem during upset conditions where large amounts of particulate are forced through the catalyst. Since it appears that relatively short periods of operation at such upset conditions could be catastrophic to the catalyst, process design must unfortunately focus on mitigating the

effects of upset conditions. It is unclear as to the degree that upsets would be experienced on full scale installations as compared to the test facility experience. It is also unclear how these full-scale upsets would compare in severity to the test facility upsets. The study basically concludes that a low-dust configuration works well for the conditions for which it was designed, but to the degree that excursions from these design conditions occur, the catalysts could be adversely impacted.