DOE/MC/30056 --5400
(DE97002145)
Distribution Category UC-1 09

Utilization of Lightweight Materials Made From Coal Gasification Slags

Topical Report

July 8, 1996

Work Performed Under Contract No.: DE-FC21-94MC30056

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Praxis Engineers, Inc.
852 North Hillview Drive
Milpital, California 95035

Disclaimer

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

Table

Figure

ABSTRACT

The integrated gasification combined-cycle (IGCC) coal conversion process has been demonstrated to be a clean, efficient, and environmentally acceptable method of generating power; however, it generates solid waste materials in relatively large quantities, For example, a 400-MW power plant using 4000 tons of 10% ash coal per day may generate over 440 tons/day of solid waste or slag, consisting of vitrified mineral matter and unburned carbon. The disposal of these wastes represents significant costs. Regulatory trends with respect to solid waste disposal, landfill development costs, and public concern make utilization of solid wastes a high-priority issue. As coal gasification technologies find increasing commercial applications for power generation or production of chemical feedstocks, it becomes imperative that slag utilization methods be developed, tested, and commercialized in order to offset disposal costs.

Praxis is working on a DOE/METC funded project to demonstrate the technical and economic feasibility of making lightweight and ultra-lightweight aggregates from slags left as solid by-products from the coal gasification process. These aggregates are produced by controlled heating of the slags to temperatures ranging between 1600 and 1900°F. Over 10 tons of expanded slag lightweight aggregates (SLA) were produced using a direct-fired rotary kiln and a fluidized bed calciner with unit weights varying between 20 and 50 lb/ft^3. The slag-based aggregates are being evaluated at the laboratory scale as substitutes for conventional lightweight aggregates in making lightweight structural concrete, roof tiles, blocks, insulating concrete, and a number of other applications. Based on the laboratory data, large-scale testing will be performed and the durability of the finished products evaluated. Conventional lightweight aggregates made from pyroprocessing expansible shales or clays are produced for $30/ton, The net production costs of SLA are in the range of $22 to $24/ton for large systems (440 t/d) and $26-$30/ton for small systems (220 t/d). Thus, the technology provides a good opportunity for economic use of gasification slags.

EXECUTIVE SUMMARY

This document represents the Phase I Final Report (Topical Report No. 1) for the project entitled "Utilization of Lightweight Materials Made from Coal Gasification Slags." The objective of Phase I of the project was to demonstrate the technical and economic viability of producing lightweight aggregates (LWA) and ultra-lightweight aggregates (ULWA) from coal gasification slags. Conventional LWAS are typically produced by thermal processing of expansible clays and shales to achieve product unit weights in the 40-55 lb/ft^3 range. They are used to produce lightweight structural concrete, blocks, and roof tiles. Conventional ULWAS are typically produced by pyroprocessing perlite ore to make products with unit weights in the 4-12 lb/ft^3 range. They are used to make insulating concrete and loose fill insulation, and for horticultural and other applications. During Phase 1, we successfully demonstrated the production of expanded slag lightweight aggregates (SLA) which can be used as substitutes for conventional LWAS and ULWAs. Engineering data collected during pilot plant operation demonstrated the technical feasibility of producing LWA and subsequently utilizing all size fractions of the product in various end-use applications. Laboratory-scale tests were performed to demonstrate the use of the expanded slag aggregates in several applications including structural concrete, roof tiles, and loose fill insulation. All of the technical objectives of Phase I have been met, as described below by task.

A detailed **Laboratory and Economic Analysis Plan** was developed under Task 1.1 and used throughout Phase I as a guide to test planning and implementation of the project goals.

Under Task 1.2, Production **of Lightweight Aggregates from Slag,** two slag samples generated from two different coal feedstocks were tested. A 20-ton sample of the primary slag (Slag 1) was obtained from a source which has requested confidentiality. Prior to collecting the bulk sample of Slag I, a small advance sample was collected, processed for char removal, and tested for its expansion characteristics using a laboratory muffle furnace, These tests confirmed the amenability of the slag to thermal processing, and the decision to proceed with collection of the 20-ton sample was made. A 1-ton sample of the second slag (Slag Ii), which was available from a previous project, was used for confirmatory purposes. This sample, obtained from TVA's gasification facility at the National Fertilizer Development Corporation (NFDC) located in Muscle Shoals, AL, was generated from an Illinois coal feedstock.

Using a procedure finalized during laboratory testing, the bulk slag sample was processed for char removal, and the char-free slag was screened into three size fractions: +10M, 10 x 50M, and 50M x 0. To ensure that the slag is utilized in its entirety, the 50M x 0 fines were extruded to produce coarse aggregates after mixing with a clay binder. Laboratory-scale tests confirmed that this approach was feasible and tests at the pilot scale were planned accordingly for both slag samples. A portion of the recovered char was used for tests to upgrade its calorific value, and the products were evaluated for recycle to the gasifier and for use as a kiln fuel.

Pilot Operation of Direct-Fired Kilns for Slag *Expansion.* Two direct-fired rotary kilns (3-ft x 30-ft and 1-ft x 15-ft) were used to conduct the expansion tests and produce SLA at the pilot scale. Fuel Oil No. 2 was selected as the kiln fuel for this program. However, coal could be used in a commercial kiln to lower energy costs. The kiln fuel oil burner was adjusted to obtain a starting hot zone temperature of 1500°F (816°C). The feed system was set to deliver a slag feed rate of 500 lb/hour for the larger kiln and 50 lb/hr for the smaller kiln. Although these feed rates are half of the rated capacity of the pilot kilns, they were selected because they provide sufficiently long operating times to generate all the required operating data including the temperature vs. density relationship. The following materials were tested:

- 1/4” x 10M slag fraction to produce fine structural aggregates
- 10x 50M slag fraction to produce roof tile aggregates
- Extruded 50M x O slag fines mixed with 20% by weight of a clay binder to produce coarse structural aggregates
- Extruded 50M x O slag fines using a 50/50 slag/clay blend
- A control sample of extruded clay to produce conventional LWAs.

Initial tests were conducted using the 1/4” x IOM size fraction of Slag 1 in the large kiln. After allowing the operating conditions to stabilize for 30-60 minutes, product samples were taken every 15 minutes for measurement of the unit weight. Since the unit weight of the product is a function of the kiln hot zone temperature, this was adjusted as necessary to obtain a product of the desired unit weight. Temperature changes were generally limited to 15-20°F increments and maintained for 60 minutes. This procedure was followed, increasing the temperature until the desired product unit weight was achieved, Steady-state conditions were maintained until all of the slag was processed. The product unit weight was measured every 30 minutes as part of operational quality control. All operating conditions were recorded every 30 minutes.

The small kiln was used for pyroprocessing of slag/clay pellets. Its vibratory feed system was set at a delivery rate of 50 lb/hour using 80/20 slag/clay pellets made from minus 50M fines of Slag 1. Operating information was collected and recorded for each production run or phase, defined as the expansion of a single size fraction to produce a specific unit weight product.

Operation of both kilns was successful and no problems were encountered when changing the feed materials and product unit weights as a function of temperature. Large quantities of lightweight products ranging in unit weight between 22 and 50 lb/ft^3 were made in the kilns from different size fractions of Slag 1. The kiln system stack flow was monitored continuously for SO_2, NO_X, CO, $C0_2$, and 0_2. SO_2 emissions were the highest during processing of the 50M x O extruded fines (80/20 slag/clay) because sulfur tends to be concentrated in the slag fines. NO_x emissions were 30-40 ppm, with the upper end of the range measured during processing of the pelletized fines at higher temperatures.

Pilot Operation of Fluidized Bed Expander for Slag *Expansion.* In subsequent testing targeted at producing ULWAs, a fluidized bed expander was used to produce expanded slag in both discrete particle and extruded form. Products with unit weights as low as 16 lb/ft^3 were produced from +50 mesh Slag 1. Granulated Slag I/clay pellets and Slag n/clay pellets (generally 4 x 20 mesh) were processed to produce LWA products with a minimum unit weight of 30 lb/ft^3.

Under Task 1.3, **Data Analysis of Slag Preparation and Expansion,** material balances were developed around the kiln and fluidized bed operations. Operational material losses were between 3 and 8%, with the lower end of the range occurring for the smaller kiln.

The expanded slag products were characterized for size distribution, chemical composition, unit weight, moisture absorption, and RCRA leachability. Leachability tests were conducted on the SLA prepared for use in the roof tile application. Since this material must be comminuted to minus 6 mesh to meet the requirements for lightweight roof tile aggregates, it would be the most leachable of the samples prepared for applications testing. Test results indicated that this sample was within the RCRA leachability limits.

Laboratory-scale applications-oriented testing of SLA as a substitute for LWA and ULWA was conducted. The SLA aggregates were prepared to meet the particle size and unit weight requirements of selected applications by crushing and blending products of various sizes and unit weights. Procedures describing the mix designs to be used and applicable ASTM standards were developed and provided to selected test laboratories who used them to prepare test specimens incorporating SLA as a substitute for conventional LWAS and ULWAs. The applications tested are listed below:

- Structural concrete (three SLA products)
- Lightweight concrete masonry units (lightweight blocks, 2-3 blends)
- Insulating concrete
- Lightweight roof tile aggregate (three SLA products)
- Loose fill insulation
- Horticultural applications,

Under Task 1,4, Economic Analysis of Expanded Slag Production, the costs of producing SLA were developed and compared with those for conventional LWAS and ULWAs. Production costs include capital costs for a modern facility located at the gasifier site and capable of handling approximately 220 tons per day of slag generated by a 200-MW integrated gasification combined-cycle (IGCC) facility. Operations include processing the raw slag for char removal and kiln processing of the slag to produce LWAS from +50M slag and pelletized LWAS from the minus 50M fines after mixing with an expansible clay binder and extruding, Fifty percent of the energy required for pyroprocessing is assumed to be supplied by the recycled char, with the remaining 50% supplied by coal, which is easily available on site. The economic analysis was carried out for two different pyroprocesses, i.e., a rotary kiln and a fluidized bed expansion system. Capital costs for the facility are depreciated over 20 years. Necessary utilities are assumed to be available at prevailing market rates at the gasifier site. A 15% contingency is allowed for capital costs.

These studies indicate that the costs of production of SLA are $30.06/ton for the rotary kiln process and $26.48/ton for the fluidized bed process, When these numbers are modified to reflect the $151ton avoided costs of slag disposal, the economics of SLA production improves further, and payback periods of around five years are achieved.

SLA production costs were also compiled for a 440-t/d facility, which is closer in capacity to the 400-500-t/d LWA facilities that are profitably operated commercially, Production costs were reduced significantly for both the rotary kiln and the fluidized bed processes to $24.40 and $21.87 per ton of product, respectively. These costs compare very favorably with current LWA production costs of about $30/ton.

Economic analyses were conducted for both processes at the two levels of production. These analyses indicate that SLA production is economically attractive at the larger scale without factoring in the avoided costs of disposal. The economics are exceptionally attractive when these costs (up to $1 5/ton) are taken into account. The costs of production are close to those of conventional LWAS for the rotary kiln and slightly lower for the fluidized bed system. Production costs at the smaller scale are economically attractive when the avoided costs of disposal are factored in.

1.0 PROJECT OBJECTIVES, SCOPE, AND METHODOLOGY

1.1 Overview

Gasification combined-cycle (GCC) technology is an emerging technology that utilizes coal for power generation and production of chemical feedstocks. However, the process generates a waste stream consisting of vitrified ash (slag) and some unconverted carbon. In previous projects, Praxis investigated the utilization of slags for a wide variety of applications and concluded that it would be extremely difficult for "as-generated" slag to find large-scale acceptance in the marketplace even at no cost because the materials it could replace were abundantly available at very low cost. It became apparent that a more promising approach would be to develop a variety of value-added products from slag that meet specific industry requirements. This approach was made feasible by the discovery that slag undergoes expansion and forms a lightweight material when subjected to controlled heating. The technology to produce lightweight (LWA) and ultra-lightweight aggregates (ULWA) from slag was subsequently developed by Praxis with funding from the Electric Power Research Institute (EPRI), Illinois Clean Coal Institute (ICCI), and internal resources.

Praxis will complete Phase I of the project "Utilization of Lightweight Materials Made from Coal Gasification Slags" under DOE/METC Cooperative Agreement No. DE-FC21-94MC30056 on 14 June 1996. Primary funding for the project is provided by DOE's Morgantown Energy Technology Center (METC) with significant cost sharing by EPRI, ICCI, and a number of industry partners. The major goals of the project are to demonstrate the production of lightweight and ultra-lightweight aggregates (LWA and ULWA) from two samples of coal gasification slag at the large pilot scale, evaluate the performance of the slag-based lightweight aggregates (SLA) in a number of applications (lightweight blocks, roof tiles, insulating concrete, etc.), and study the economics of commercial production of these products using SLA. This document summarizes the results of the Phase I work in accordance with contractual requirements.

1.2 Project Objectives

The major objectives of the project are to demonstrate the technical and economic viability of commercial production of LWA and ULWA from slag and to test the suitability of these aggregates in a number of end-use applications. The specific objectives of Phase I were to produce LWA and ULWA from two different slags at the large pilot scale and to study the performance of the SLA products in several commercial applications (i.e., roof tiles, lightweight structural concrete, insulating concrete, loose fill insulation, and horticultural products). The technical objectives of the project can be summarized as follows:

Phase 1 Objectives:

- Develop and demonstrate the technology of producing slag-based lightweight aggregates (SLA) at the pilot scale (500 lb/hour) and collect operational and emissions data.
- Produce a large batch (10 tons) of LWA and ULWA from slag.
- Perform a comparative evaluation of the quality of the expanded slag aggregates vs. conventional LWAS by conducting laboratory-scale tests in accordance with ASTM or Perlite Institute procedures.
- Demonstrate that the char recovered from the slag can be recycled to the gasifier or used as a fuel in the slag expansion process or a boiler.

- Perform environmental characterization of expanded slag products to confirm their safety prior to being used as substitutes for conventional LWAS and ULWAs.
- Conduct the preliminary economics of SLA production using a computer model.

At the end of the project, a detailed technology package comprising SLA production process and design information and economic analyses will be produced.

1.3 Scope of Work

The project scope consisted of collecting a 20-ton sample of slag (primary slag), processing it to remove the char, and subjecting it to pyroprocessing to produce expanded slag aggregates of various size gradations and unit weights, ranging from 12 to 50 lb/ft^3. A second smaller slag sample was used for confirmatory testing. The expanded slag aggregates were then tested for their suitability in manufacturing precast concrete products (e.g., masonry blocks and roof tiles) and insulating concrete at the laboratory scale. These products were evaluated using ASTM and industry test methods, Technical data generated during production and testing of the products were used to assess the overall technical viability of expanded slag production.

In addition, a market assessment was made based on an evaluation of both the expanded slag aggregates and the final products, and market prices for these products were established in order to assess the economic viability of these utilization technologies. Relevant cost data for physical and pyroprocessing of slag to produce expanded slag aggregates were gathered for comparison with (i) the management and disposal costs for slag or similar wastes and (ii) production costs for conventional materials which the slag aggregates would replace. This formed the basis for an overall economic evaluation of expanded slag utilization technologies.

A summary of the tasks performed in Phase I is given below:

Task 1.1	Laboratory and Economic Analysis Plan Development: Development of a detailed work plan for this phase of the project.
Task 1.2	Production of Lightweight Aggregates from Slag: Selection and procurement of project slag samples, slag preparation including screening and char removal, and slag expansion in a direct-fired kiln and fluidized bed expander. Preliminary laboratory-scale studies were conducted before bulk samples of expanded slag were collected for processing. The char recovered from the slag preparation operation were evaluated for use as a kiln fuel and gasifier feed. Environmental data were collected during preparation and expansion of slag.
Task 1.3	Data Analysis of Slag Preparation and Expansion: Analysis and interpretation of project data, including development of material and energy balances for slag processing and product evaluation.
Task 1.4	Economic Analysis of Expanded Slag Production: Economic analysis of the utilization of expanded slag by determining production costs for slag-based LWAS and ULWAS. An estimated market value was established for the various expanded slag products. Expanded slag production costs were

compared with the costs of disposal and management of slag as a solid waste.

Task 1.5 **Reports:** Preparation and delivery of topical, financial status, and technical progress reports in accordance with the Statement of Work.

The objective of Phase II is to conduct field studies to test the performance of expanded slag aggregates used as substitutes for conventional materials in various end-use applications, including masonry blocks, roof tiles, insulating concrete, and loose fill insulation. Other applications may also be identified during the course of this work. Mix designs will be formulated and tested by refining the mix designs or material proportions developed in Phase 1. Commercial manufacturing practices, standards, and equipment will be used during Phase II. The economic analyses conducted in Phase I will be further refined using the new data.

1.4 **Project** Methodology

The project methodology was as follows:

- Build on developmental work done under previous EPRI-funded projects to produce LWA from slag, ICCI-funded projects to produce ULWAs from slag, and internal studies to identify potential applications for expanded slag aggregates,
- Obtain the participation of potential users and producers of slag-based products throughout the project in order to familiarize them with the capabilities of the new products.
- Seek the involvement of slag generators in order to keep them informed of the potential for utilizing slag as an alternative to disposal.
- Use conventional LVVA production methods and equipment as much as possible in order to minimize the process development and commercialization time frame and increase product acceptability to LWA and ULWA manufacturers and end-use industries.

The project team consists of Praxis Engineers, Inc., Fuller Company, Pennsylvania State University, and Texaco's Montebello Research Laboratory. Praxis, the prime contractor, is responsible for overall program management, test planning, implementation, and data analysis. Fuller, an established pyroprocessing equipment and process development company, performed all work relating to testing and production of the slag-based lightweight aggregates. Penn State prepared the raw slag for pyroprocessing by screening it and removing its char content. Texaco evaluated the potential for recycling the recovered char to the gasifier and also assisted in estimating slag disposal costs. In addition, a number of potential users (e.g., roof tile and block manufacturers) and LWA and ULWA manufacturers participated in the project.

2.0 RESULTS AND DISCUSSION

Task 1.1 Laboratory and Economic Analysis Plan

A detailed project work plan, called the "Laboratory and Economic Analysis Test Plan," was developed to plan the activities to be carried out in Phase 1. The work plan followed the Phase I task breakdown listed below:

Task 1.1: Laboratory and Economic Analysis Plan
Task 1.2: Production of Lightweight Aggregates from Slag
Task 1,3: Data Analysis of Slag Preparation and Expansion
Task 1.4: Economic Analysis of Expanded Slag Production
Task 1.5: Final Report

The work plan provided details of the work to be done at the subtask level. The quantities of materials required were estimated and their sources identified. Test plans for both laboratory confirmatory testing and pilot plant operation were drawn up. All of the data requirements were identified. A summary of these planning activities is given below.

Slag ***Selection Criteria and Sample Quantity Estimation and Procurement***

The project scope required the procurement of two slag samples for the project, a large primary sample and a second smaller sample to be used for confirmatory testing. The primary project slag sample was to be used as the feed material during the bulk of the pilot-scale demonstration tests and to produce a large batch of slag-based lightweight aggregates (SLA).

The following criteria were used for selection of the project slag samples:

- Must have suitable expansion characteristics
- Coal feedstock should be a major low-cost (high-sulfur) U.S. coal
- Sufficient quantities of the slag must be available
- One of the two slags should be derived from an Illinois coal feed, as requested by the Illinois Clean Coal Institute which is providing cost sharing to the project.

Based on these criteria, the slag selected as the primary sample was derived from an eastern bituminous coal whose supplier has requested confidentiality. The quantity of the primary slag required was estimated at 20 tons, based on the estimated 10 tons of expanded slag aggregates required for the manufacture of end-use products such as blocks and roof tiles. The breakdown of this estimate is given in Table 1. The 2:1 ratio of the feed to the finished product takes into account the amounts of slag required for trial runs, temperature vs. density studies, and the potential for producing off-grade products during these runs. The second slag sample, derived from an Illinois real, was obtained from TVA's gasification facility at the National Fertilizer Development Corporation (NFDC) located in Muscle Shoals, AL.

Table 1. Estimated Product Requirements for Evaluation of Expanded Slag Applications

Item	Application/Objective	SLA Products
1	Lightweight block production	4 tons
2	Roof tile production	3 tons
3	Construction applications - insulating concrete - loose fill insulation	 ½ ton ½ ton
4	Agricultural applications	½ ton
5	Industrial applications	½ ton
6	Lightweight concrete	1 ton
	Total	10 tons

Provision was made for both of the slag samples to be processed for char removal prior to expansion at Pennsylvania State University's Mineral Processing Laboratory. In addition, the recovered char would be upgraded and evaluated as a kiln fuel.

Laboratory and Pilot Expansion Testing

The pilot plant kiln tests were planned with the objective of utilizing all the size fractions of slag to meet the various size and unit weight requirements of targeted commercial products. The tests planned for laboratory confirmatory studies are identified in Table 2. Preparations were made for the bench-scale expansion work to be conducted at Fuller Company and Silbrico Corporation facilities using the various slag samples that were processed for char removal, as shown in Table 2. In addition, arrangements were made to obtain a small advance sample of Slag 1, for which expansion data were not available, for testing at the laboratory scale at Fuller and Silbrico prior to obtaining the bulk sample.

Table 2. Laboratory- and Pilot-Scale Tests Planned

	Product	Unit Wt, lb/ft^3	Test Batches
Slag I (primary slag)			
10x 50M (advance sample)	Fine LWA	30-50	8
1/4" x 10M	Coarse LWA	50	2
I0 x 50M	Fine LWA	30-50	6
I0 X50M	Fine LWA	<12	6
Minus 50M, pelletized	Coarse LWA	50	4
Slag II (second slag)			
1/4" x 10M	Coarse LWA	50	2
I0 x 50M	Fine LWA	30-50	2
I0 x 50M	Fine LVVA	< 12	4
Minus 50M, pelletized	Coarse LWA	50	2

Pilot-scale test runs paralleled those planned at the laboratory scale. These tests cover the applications listed in Table 1 by generating LWA and ULWA products (identified in Table 2) using various size fractions of slag.

Arrangements were made to have the following equipment available for the project test work:

1. Slag processing for char removal at a rate of 75-100 lb/hour
2. Screening of prepared slag in three sizes at a rate of 50 lb/hour
3. 3-ft dia. x 30-ft direct-fired rotary kiln (500-1000 [b/hour) with baghouse and off-gas analysis
4. 1-ft dia. x 15-ft direct-fired rotary kiln (50-100 lb/hour) with baghouse and off-gas analysis
5. 6-inch-diameter fluidized bed calciner with baghouse
6. Extruder to pelletize 50M x O slag fines into 3/4" pellets at 50 lb/hour
7. Granulator to crush the slag or pellets to meet product size requirements at 50 lb/hour
8. Other laboratory equipment (crushers, etc.) used in a semi-batch mode.

The objectives of Task 1.1 were fully met as the work plan was used as a tool for test planning, development, and implementation.

Task 1.2 Production of Lightweight Aggregate from Slag

Task 1.2.1 Procurement of Slag *Samples*

Based on the slag selection criteria established in Task 1.1, arrangements were made to procure 80 drums (over 20 tons) of the primary slag (Slag 1) from a gasification facility which has requested confidentiality. Prior to collecting the bulk sample, a small advance sample was obtained and tested for its expansion characteristics. These tests indicated that the slag could be expanded in a controlled manner, with unit weights between 25 and 50 lb/ft^3.

Upon completion of the confirmatory tests, a bulk sample of Slag I was obtained from normal gasifier operations. The sample was homogenized and the freestanding water was allowed to drain out before packing in eighty 55-gallon drums. Seventy drums were shipped to Penn State for char removal and ten were saved as a reserve sample.

One ton of the second sample (Slag II) which was available with Praxis from a previous project was shipped for kiln testing. This slag, derived from an Illinois coal feedstock, had been obtained from TVA's NFDC facility in Muscle Shoals, AL..

Task 1.2.2 Preparation of Slag for Kiln Processing

The need for slag preparation was established in previous Praxis projects where the unconverted carbon in the slag, termed char, was found to impede pyroprocessing. Slag preparation consists of removing the char from the slag, screening the char-free slag into size fractions to meet the feed size specifications of the target aggregate products, and mechanically dewatering the prepared slag. In addition, a portion of the recovered char was processed to upgrade its heating value or carbon content in order to assess its potential for reuse as a gasifier feed or boiler fuel.

The slag was wet-screened at 1/4" and 10-mesh sizes. The plus 1/4" material, primarily rocks, was discarded, As the 1/4" x 10-mesh fraction contains little char, it did not need further preparation and was dried, stored in drums, and set aside for kiln processing. The minus 10-mesh material, which

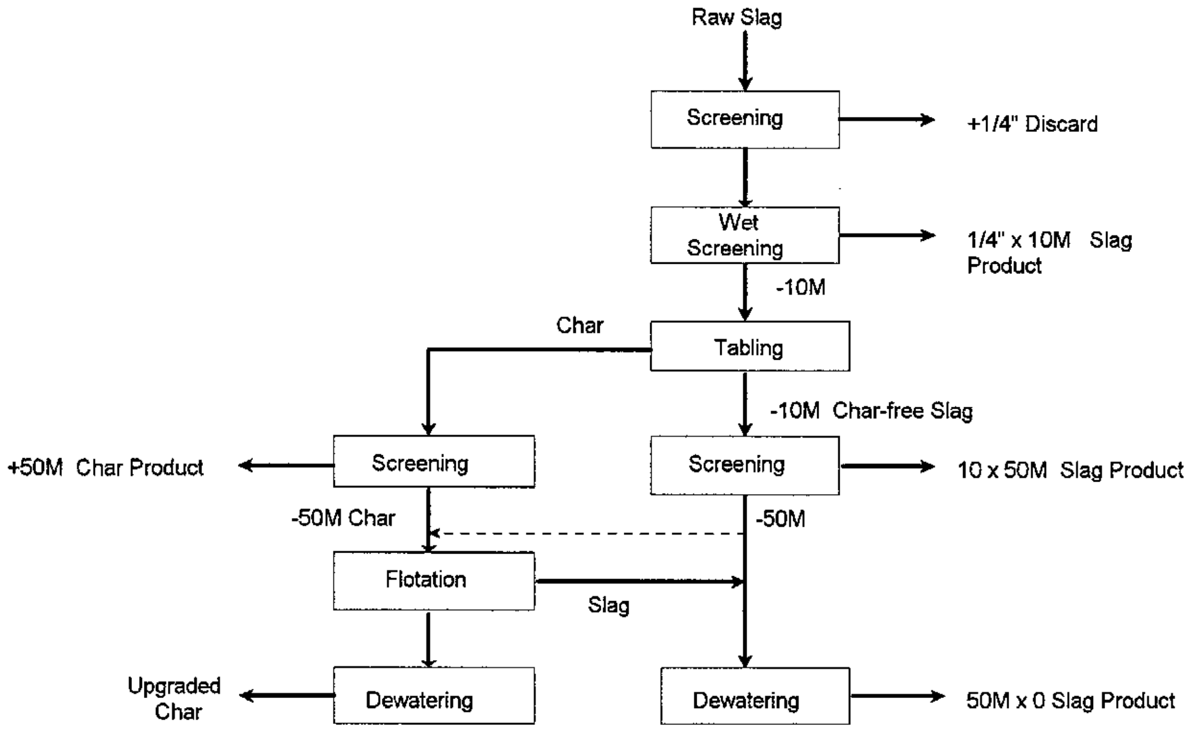


Figure 1. Slag Preparation and Char Removal

contains char, was processed on a shaking table for char removal. A flow diagram developed from earlier work used for this application is given in Figure 1.

Representative samples of the slag feed, prepared slag, and recovered char were analyzed in accordance with ASTM C 114 for loss on ignition (LOI) in three size fractions: 1/4" x 10M, 10 x 50M, and 50 x 0. The results are given in Table 3. After preparation and char removal, the slag was dried and screened for use as kiln feed for the following products:

- 1/4" x 10-mesh fraction for expansion to produce coarse aggregates
- 10 x 50-mesh slag for expansion to produce fine aggregates
- Minus 50-mesh slag for pelletization to make coarse aggregates.

In addition, a mass balance for each product stream was developed to estimate char recovery on a dry basis. All feed and product samples were analyzed for composition, particle size distribution, and loss on ignition.

Table 3. Ash Content of Slag Feed, Prepared Slag, and Char

Size	**Raw Slag** (I 00%)		Prepared Slag (68.2%)		Recovered Char **(31.8%)**	
	Wt%	**Ash%**	Wt%	**Ash%**	**Wt%**	**Ash%**
1/4" x 10M	**31.9**	100.0	38.79	101.1	0.1	34.5
IO x 50M	38.3	81.7	44.10	100.9	36.4	31.9
50M *x* O	29.9	83,6	17.11	101.3	63.5	60.9
Total	100.0	84.9	100.00	101.0	100.0	50.3

Task 1.2.3 Laboratory Confirmatory Studies for Slag Expansion

The major objective of this task was to determine the expansion characteristics of the two project slags for production of expanded aggregates, including the following:

- Identify kiln operating conditions (temperature and retention time) for slag expansion to the desired unit weight
- Confirm the suitability of the direct-fired rotary kiln and fluidized bed expansion methods for the project slags
- Determine the slag size fraction that may be expanded in the kiln as a single feed
- Select the pelletizing conditions and binder requirements for extrusion of fines,

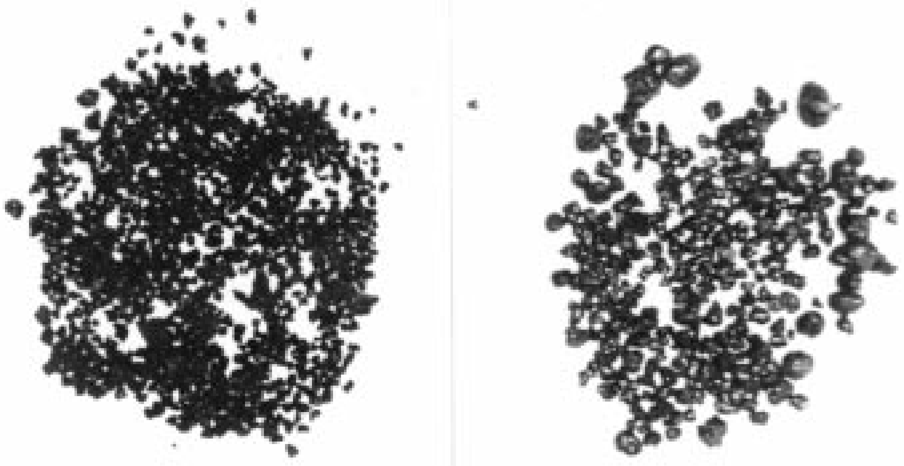
Bench-scale expansion tests using discrete particles of two project slags were conducted as part of this task as a confirmatory step before making the final selection of the project primary slag. Tests conducted using +10M and 10 x 50M size fractions of the Slag I advance sample confirmed that it could be expanded in a controlled manner to produce products with unit weights ranging between 22 and 64 lb/ft^3. Photographs of the prepared slag and expanded slag products are shown in Figure 2. These results confirmed the work done previously by Praxis on a number of other slags. It was also established that in order to meet aggregate specifications the minus 50-mesh slag fines need to be subjected to size enlargement, i.e., extrusion followed by pelletization, prior to expansion. Therefore the slag fines were mixed with an expansible clay as a binder, extruded, and pelletized for expansion testing.

As part of this task, studies were also conducted to evaluate the suitability of an expansible clay binder sample selected for the project. An expansible clay was selected since it can participate in the expansion process, is abundantly available at low cost, and offers the following advantages:

- Good binding capability
- Similar expansion characteristics to those of slag
- Source is located close to the commercial gasifier where the slag is generated and expanded.

Figure 2
Discrete Particle Slag I Feed and Products

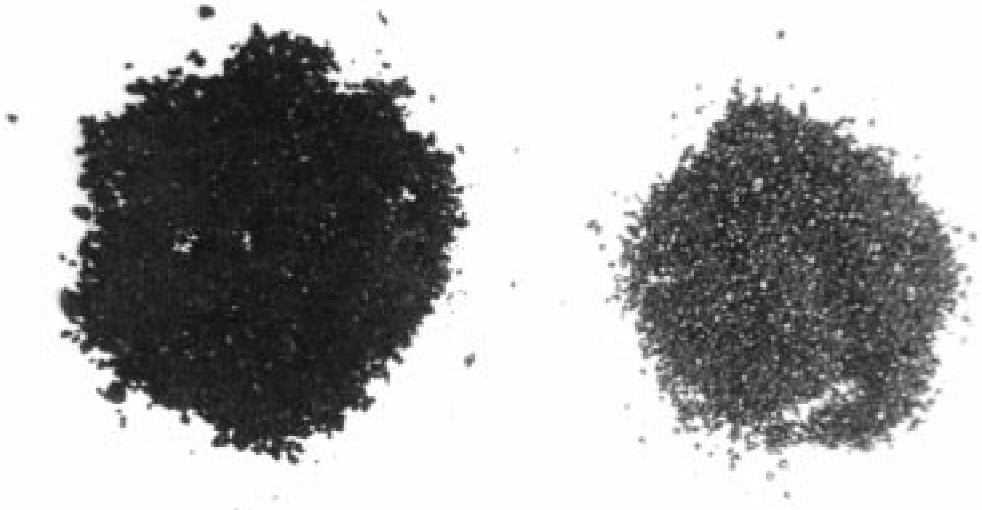
Praxis Lightweight Aggregate Study



+10M SLAG I COMPOSITE FEED
11-13-95, 950931

+10M SLAG I 30 LB/CF PRODUCT
11-13-95, 950931

+10 Mesh Slag I



10x50M SLAG I COMPOSITE FEED
11-14-95, 950932

10x50M SLAG I 40 LB/CF PRODUCT
11-14-95, 950932

10x50 Mesh Slag I

Based on these criteria, a clay sample was obtained from a commercial lightweight aggregate plant in Alabama and analyzed for its composition, which is provided in Table 4.

A composition analysis of the char-free slag was conducted at two sizes (+6M and -6M) and compared with that of the clay. The slag composition differs from that of the clay with respect to loss on ignition at 900°C and in three categories based on compounds of interest: (i) silica, (ii) alumina, and (iii) flux compounds, which include oxides of iron, calcium, magnesium, potassium, and sodium.

Table 4. Chemical Analysis of Prepared Slag and Clay Sample Repotted as Oxides

Material	Clay	+6M Slag	-6M Slag
SiO_2	58.41	43.36	43.14
Al_2O_3	17.99	27.29	27.15
Fe_2O_3	6.90	22.36	22.05
CaO	1.85	4.65	4.56
MgO	2.37	1.08	1.08
K_2O	2,44	1.85	1.86
Na_2O	0.92	0.51	0.52
s o .	1.36	0.65	0.82
cl”	0.05	0.02	0.03
LOI @ 900°C	7,69	-1.73	-1.04
Total	99,76	100.04	100.17

In order to compare the composition of these materials, these analyses were recalculated on an LOI-free basis. As may be seen in Table 5, the slag samples have a lower silica content and higher alumina content than the clay.

Table 5. Reconstituted Silica, Alumina, and Flux Contents of Slag and Clay

	Clay	**+6M Slag**	-6M **Slag**
SiO_2	64.4	42.9	43,0
Al_2O_3	19.8	27.0	27.0
Flux compounds	15.8	30.1	30.0
Total	100.0	100.0	100.0

The considerably higher total flux compounds (including iron) in the slag samples explains, as shown in later test data, the lower expansion temperature (<1600°F) for slag compared to clay, which typically expands in the 1800-2200°F range. Too wide a gap between the respective expansion temperatures of slag and clay could produce aggregates with inadequate strength.

Laboratory expansion of slag fines combined with expansible clays was conducted to evaluate the following issues related to commercial production of slag-based LWAS:

- The potential for blending slag fines with an expansible clay
- The feasibility of producing coarse aggregates from slag fines using the minimum amount of clay binder
- The feasibility of blending slag and clay together to make extruded pellets that have good strength following pyroprocessing.

The slag size selected for this work was minus 50 mesh, based on previous experience, and the clay size was 20 mesh. Mixtures of slag and clay starting at 50/50 and proceeding with reducing proportions of clay were tested in a bench-scale extruder. Extrusion with slag-to-clay ratios of 50/50, 60/40, and 70/30 was successful. The product containing the lowest proportion of clay was made with extremely high energy draw, and attempts to extrude an 80/20 mixture using a laboratory extruder were unsatisfactory. The extrusion tests indicated that a highly plastic clay is ideal and that lower quantities of clay can be used when it is comminuted to a fine size (minus 50 mesh). H was also noted that higher proportions of slag in the mix made the material somewhat abrasive, causing notable wear in the barrel of the bench-scale extruder. Moisture requirements for extrusion of each mix were determined as follows:

50/50 slag/clay	21.40%
60/40 slag/clay	12.15%
70/30 slag/clay	11.36%

The three extruded mixture products were fired in an electric muffle furnace to allow visual inspection of the product at 1800°F, 1900°F, and 2000°F after a 15-minute preheat at 1000°F for each sample. The results are illustrated in Figure 3, which consists of photographs that show the products from pyroprocessing of 3/8"-diameter extruded pellets. These results show that all mixes expanded extremely well with uniform internal structure, with the best results being achieved at 1900°F and 2000°F. There were no signs of fusion or stickiness, as was expected based on the chemistry study reported earlier,

While expansion tests were conducted using each slag/clay mix, a full series of burn test runs was conducted using the 50/50 mixture. The results were as follows:

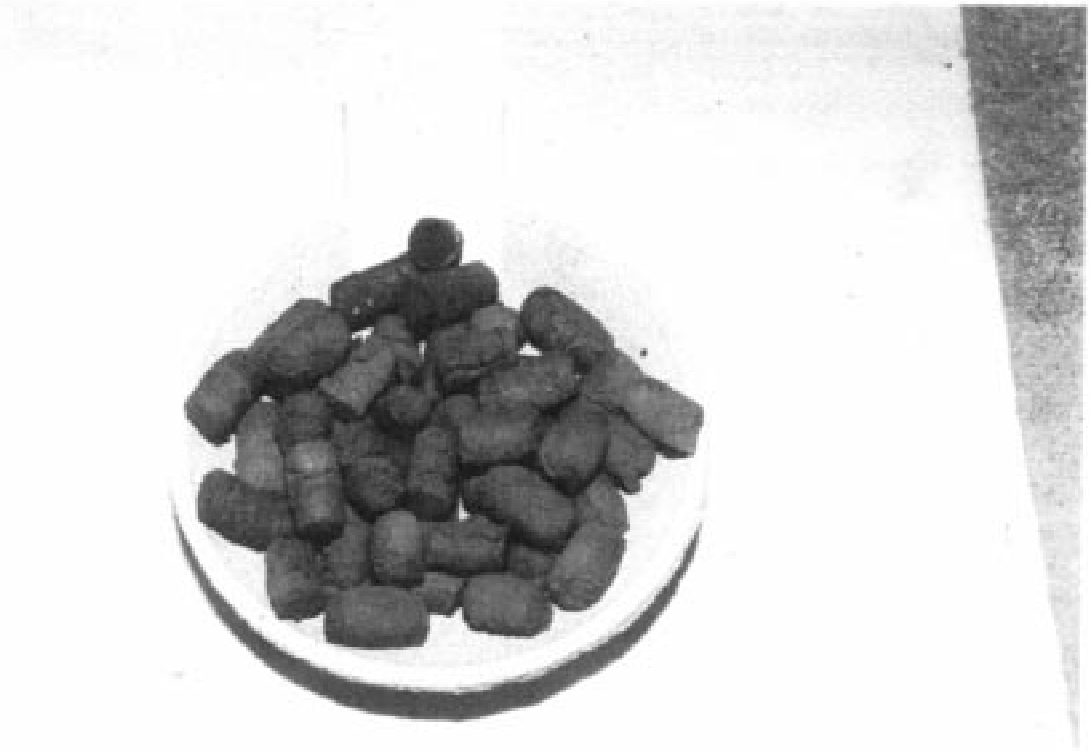
Extrusion moisture	21 .4%
Dry unit weight (unburnt 3/8” diam. pellets)	52,5 lb/ft^3
Preheat @ 1000°F	15 minutes
Firing time @ 1900°F	15 minutes
Product unit weight	29.16 lb/ft^3
Volume expansion	1.3 to 1

Confirmatory tests were also run successfully for Slag II. Following these tests, arrangements were made to prepare the kiln feed for pilot-scale production of expanded slag.

Figure 3
Pyroprocessed 3/8" Extruded Pellets

MUFFLE BURN TESTS - EXTRUDED MIXTURES

BURN TESTS ALL THREE BLENDS



50/50 MIX-COMPLETE CUP BURN - 1900°F

Task 1.2.4 Production of Expanded Slag Products Using-a Direct-Fired Kiln

The objective of this task was to demonstrate pilot-scale production of lightweight aggregates from slags using a direct-fired rotary kiln. This method was selected because it is a proven process and parallels that conventionally used for pyroprocessing of expansible shales and clays. Large batches of expanded slag aggregates were produced from various fractions of coarse slag and from pelletized slag fines. Two different sizes of kilns were used: a 3-ft diameter x 30-ft long kiln and a I-ft x 15-ft kiln.

The size fractions that were tested in the direct-fired kiln are:

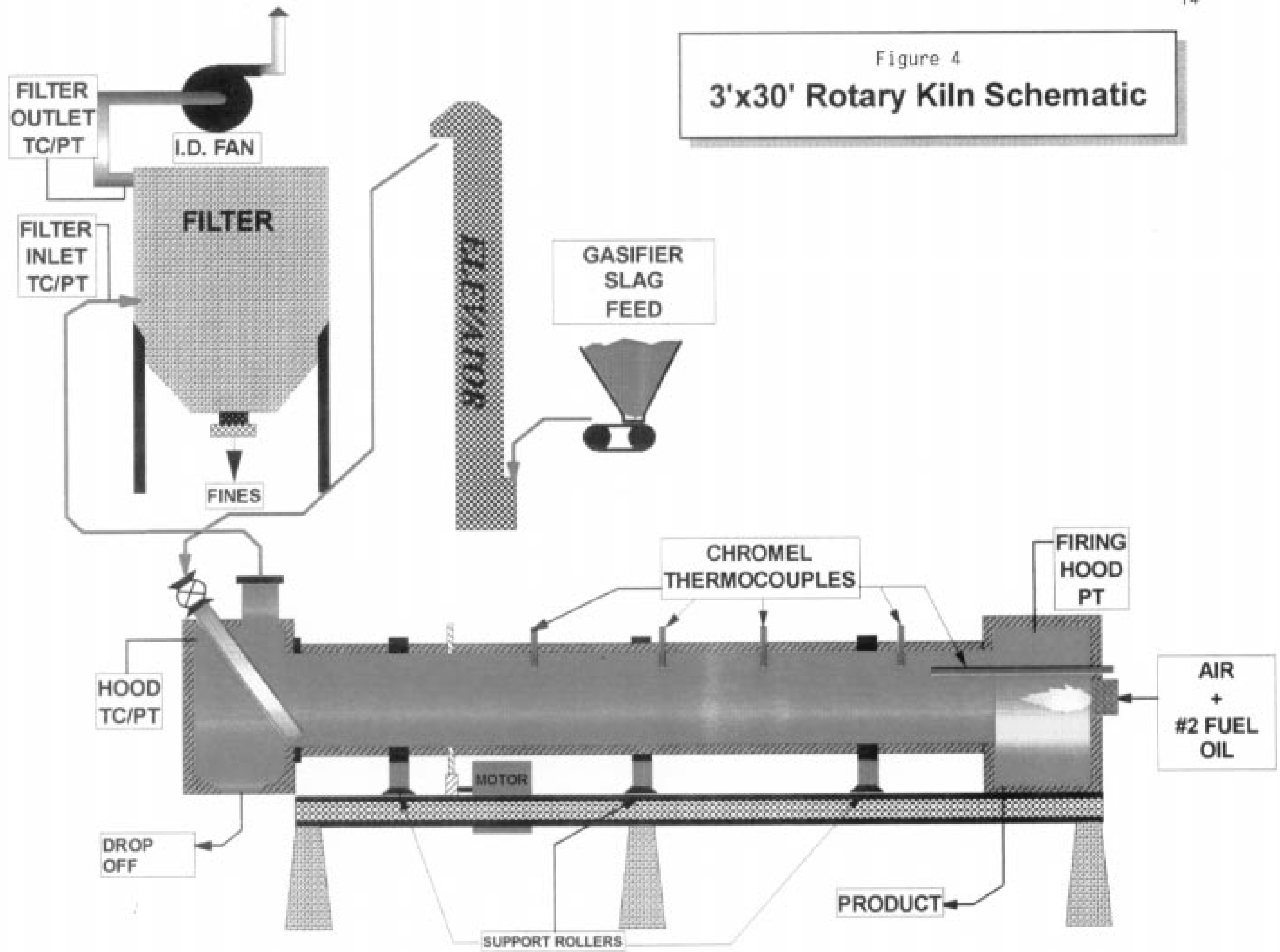
- 1/4” x 10M fraction to produce coarse aggregates
- 10x 50M fraction to produce fine aggregates
- 1/4” x 50M fraction to demonstrate the ability of the kiln to accept both of these fractions simultaneously, thus establishing that they do not need to be screened
- 50M x O fines fraction extruded with clay to make coarse aggregates,

The slag fines were pelletized by extruding the material in an 8“ diameter extruder using an expansible clay binder. Pellets were made by crushing the binder to minus 50 mesh and blending it with the minus 50-mesh slag in a rotary cement mixer. Water was added to the sample during mixing to obtain the plastic qualities necessary for extrusion, In addition to an all-clay control sample, pellets containing two differing ratios of slag to clay were produced: 80:20 and 50:50. These blends were extruded to produce pellets ½" in diameter and %-1” in length, The pellets were then pyroprocessed to form coarse-sized lightweight aggregates.

First, a 3-ft diameter x 30-ft long direct-fired rotary kiln was commissioned at Fuller’s R&D facility prior to conducting pilot expansion tests for the primary slag (Slag l). A schematic of the direct-fired rotary kiln is shown in Figure 4. The kiln rotational speed was set at 2.6 rpm to provide a total material residence time of 30 minutes. This was based on a kiln slope of 3/8"/ft and a material angle of repose of 35°, Fuel oil No, 2 containing 0.25% sulfur was selected as the kiln fuel for this program. The kiln was preheated for 6 hours to obtain a starting hot zone temperature of 1500°F (816°C). Based on the fuel oil flow rate and a kiln exit oxygen concentration of 10%, the kiln exit gas velocity was calculated at be at approximately 10 ft/sec.

Figure 4

3'x30' Rotary Kiln Schematic



The following measurements were taken during the pilot runs:

- Feed, product discharge, and baghouse fines rates
- Off-gas temperature at six locations across the kiln and at the baghouse inlet
- External shell temperature at four locations
- Fuel firing rate
- Off-gas flow
- Continuous gas analyses for SO_2, NO_X, CO, CO_2 and O_2
- Gas sampling from the kiln exit gas and baghouse inlet streams for CO, CO_2 and O_2 on a periodic basis
- Product unit weight at 15-minute intervals.

The 1 -ft x 15-ft direct-fired rotary kiln was used to conduct pilot expansion tests to process the second slag (Slag II) and extruded pellets made from the minus 50M fines from Slag 1. The smaller kiln was selected because it can be operated at a lower feed rate (50-100 lb/hour) thus increasing the operating period. This, in turn, allows expansion studies to be conducted using smaller quantities of feed materials thus conserving the project slag samples.

Test runs were conducted using the matrix given in Table 6, with each slag feed designation representing one continuous run. For convenience, data on the fluidized bed expander tests (Task 1.2,5) are also included in Table 6.

Test runs were carried out in phases defined as a time period representing a set of distinct operating conditions aimed at achieving a particular product density. The 3-ft x 30-ft kiln operation consisted of the following phases:

- 1/4” x IOM: Phases 1A (50 lb/ft^3), 1 B (40 lb/ft^3), 1C (35 lb/ft^3)
- 10X 50M: Phases 2A (50 lb/ft^3), 26 (40 lb/ft^3), 2C (35 lb/ft^3)
- 1/4” x 50M: In Phase 2D, a 50/50 blend of the 1/4” x IOM and 10x 50M feeds was processed to produce a 40 lb/ft^3 product.

Table 6. SLA Products from Direct-Fired Kiln and Fluidized Bed Expander

Slag/Size Tested	**Direct-Fired Kiln Testing**		**Fluidized Bed Expander Testing**	
	Unit Weight lb/ft^3	**Quantity Produced b**	**Unit Weight lb/ft^3**	**Quantity Produced b**
Slag 1: +10M	28-67	5810	24-73	66
Char injection	--	--	16-26	89
Slag 1: 10x 50M	34-58	5404	--	--
Slag 1: +50M	38	500	16-58	113
Extruded Slag I/Clay				
80/20	**27-62**	**447**	--	--
50/50	21-42	383	--	--
0/100	18-41	369	--	--
Extruded Slag I/Clay				
(Granules)	--	--	**30-60**	90
80/20 4 *x* 20M	--	--	37-42	106
80/20 4 *x* 30M	--	--	31-65	77
50/50 4 *x* 20M M	--	--	43-66	24
Slag II: +10M	**22-82**	**643**	--	--
Extruded Slag n/Clay				
(Granules)				
50/50 4 *x* 20M	--	--	33-63	40

Once the operating conditions to make products of each targeted density were defined, the kiln was operated at those conditions. Kiln operating conditions were monitored; data for the large kiln are given in Table 7,

Extruded pellets made from slag fines combined with clay were tested in the 1-ft x 15-ft rotary kiln. In the smaller kiln, the pellets could be fired at a higher temperature and slower feed rate than in the larger kiln. The kiln operating conditions were monitored, and the data are presented in Table 8. The small kiln operation consisted of the following phases:

80/20 pellets:	Phases 3A (30 lb/ft^3), 3B (40 lb/ft^3)
50/50 pellets:	Phases 4A (20 lb/ft^3) 4B (30 lb/ft^3), 4C (40 lb/ft^3)
All-clay pellets:	Phases 5A (30 lb/ft^3), 5B (40 lb/ft^3), 5C (20 lb/ft^3)
Slag II (+1 OM):	Phases 6A (30 lb/ft^3), 6B (30-50 lb/ft^3), 6C (20 lb/ft^3)
Drop-off	In Phase 2E, slag collected from various transfer points during large kiln operation was processed to produce 40 lb/ft^3 material.

Kiln product samples were taken every 15 minutes and measured for loose unit weight as a first step in quality control and to provide feedback data for selecting kiln operating conditions to achieve the targeted product unit weights. All test products and final bulk products were labeled and packed in 55-gallon drums for shipping. Based on the data collected, energy and mass balances were prepared with special emphasis on fuel requirements on a per-ton-of-product basis and SO_2 and NO_X generation.

Expanded slag product densities were measured as a function of kiln hot zone temperature. Figure 5 shows the density vs. temperature relationship for slag in discrete particle form, and Figure 6 shows this relationship for slag in extruded pellet form, These data indicate that the product density can be controlled as a function of temperature for slag in discrete particle form as well as pelletized slag fines.

Table 7. Direct-Fired Rotary Kiln Average Operating/Process Conditions (3-ft x 30-ft System)

Test Phase	**1A**	**1B**	**1C**	2A	2B	**2C**	2D	2E
Feed Size, Slag I	**1/4" x IOM**			**IO x 50M**			**1/4" x 50M**	**Drop Off**
Feed rate, lb/h	500	670	525	500	590	590	610	610
Unit Wt, lb/ft^3	50	40	34	50	40	35	38	38
Temperature, 'F								
Hot zone	1520	1590	1925	1585	1650	1800	1650	1685
Kiln #1	1520	1580	1960	1575	1650	1825	1650	1680
Kiln #2	1400	1445	1720	1450	1535	1665	1530	1560
Kiln #3	1340	1380	1580	1375	1455	1560	1460	1490
Kiln #4	1275	1320	1500	1310	1390	1490	1395	1425
Kiln exit	1160	1175	1350	1155	1240	1295	1235	1260
Calciner	850	880	980	850	900	930	890	900
BH inlet	380	375	400	--	--	--	--	--
BH outlet	340	325	340	260	270	255	245	250
Pressure at **BH** outlet, "WG	**-4.2**	**-8**	**-13.3**	**-3.7**	**-4,1**	**-4.2**	**-4.2**	**-4.3**
Gas Analysis								
Kiln exit, %O$_2$	12.4	12	8.6	12.1	11.6	9,9	11.9	11.6
Kiln exit, ppm CO	3	2	2	44	71	47	27	62
BH inlet, %O$_2$	17	16.5	14,4	17	16.4	15.7	16.5	16.5
No. 2 fuel oil, gal/h	13	12.2	16.2	12,8	13.6	15.4	13.3	13.8

Table 8. Direct-Fired Rotary Kiln Average Operating/Process Conditions (1-ft x 15-ft System)

Test Phase	**3A**	**3B**	**4A**	**4B**	**4C**	**5A**	**5B**	**5C**	**6A**	**6B**	**6C**
Feed Type	**80/20 Pellets**		**50/50 Pellets**			**0/100 Pellets**	**0/100 Pellets**	**0/100 Pellets**	**+10M Slag II**	**+10M Slag II**	**+10M Slag II**
Feed rate lb/h	73	100	97	97	100	98	96	96	100	100	100
Unit Wt, lb/ft^3	30	40	22	30	40	30	40	18	30	30-50	22
Temperature, °F											
Hot zone	2110	2000	2050	1980	1900	1900	1770	***	166	1645	1820
Kiln #1	2130	2000	2100	2050	1940	1925	1875	2230	1650	1640	1860
Kiln #2	1975	1900	1945	1900	1825	1795	1700	1940	1525	1450	1740
Kiln #3	1810	1755	1730	1710	1650	1605	1525	1750	1340	1250	1490
Kiln #4	1805	1750	1695	1680	1660	1580	1505	1750	1375	1300	1540
Kiln #5	1610	1525	1480	1460	1460	1380	1325	1610	1225	1125	1450
Kiln #6	1475	1380	1350	1340	1325	1250	1200	1520	1145	1075	1375
Kiln exit	1425	1375	1355	1350	1345	1300	1280	1430	1210	1175	1335
Filter inlet	845	810	825	825	825	800	765	840	650	625	790
Filter outlet	325	325	340	340	330	315	320	330	280	285	310
Pressure at filter outlet, "WC	-2.7	-2.7	-2.7	-2.7	-2.75	-2.7	-2.7	***	-2.7	-2.65	-2.75
Gas Analysis											
Kiln exit, %O_2	5.7	6.9	5.9	7.5	9.6	8.9	9.7	***	9.5	10.5	9.8
Kiln exit, ppm CO	74	160	112	267	10	708	602	***	>1000	406	43
Filter, inlet, %O_2	12	13.7	11.7	12.4	13.4	13.5	14.1	***	15.6	15.8	13.3
No. 2 fuel oil, gal/h	5.91	5.43	5.49	5.07	4.6	4.4	4.2	***	3.3	3.1	4.6

Figure 5

Hot Zone Temperature vs. Product Density
Slag I Rotary Kiln Processing

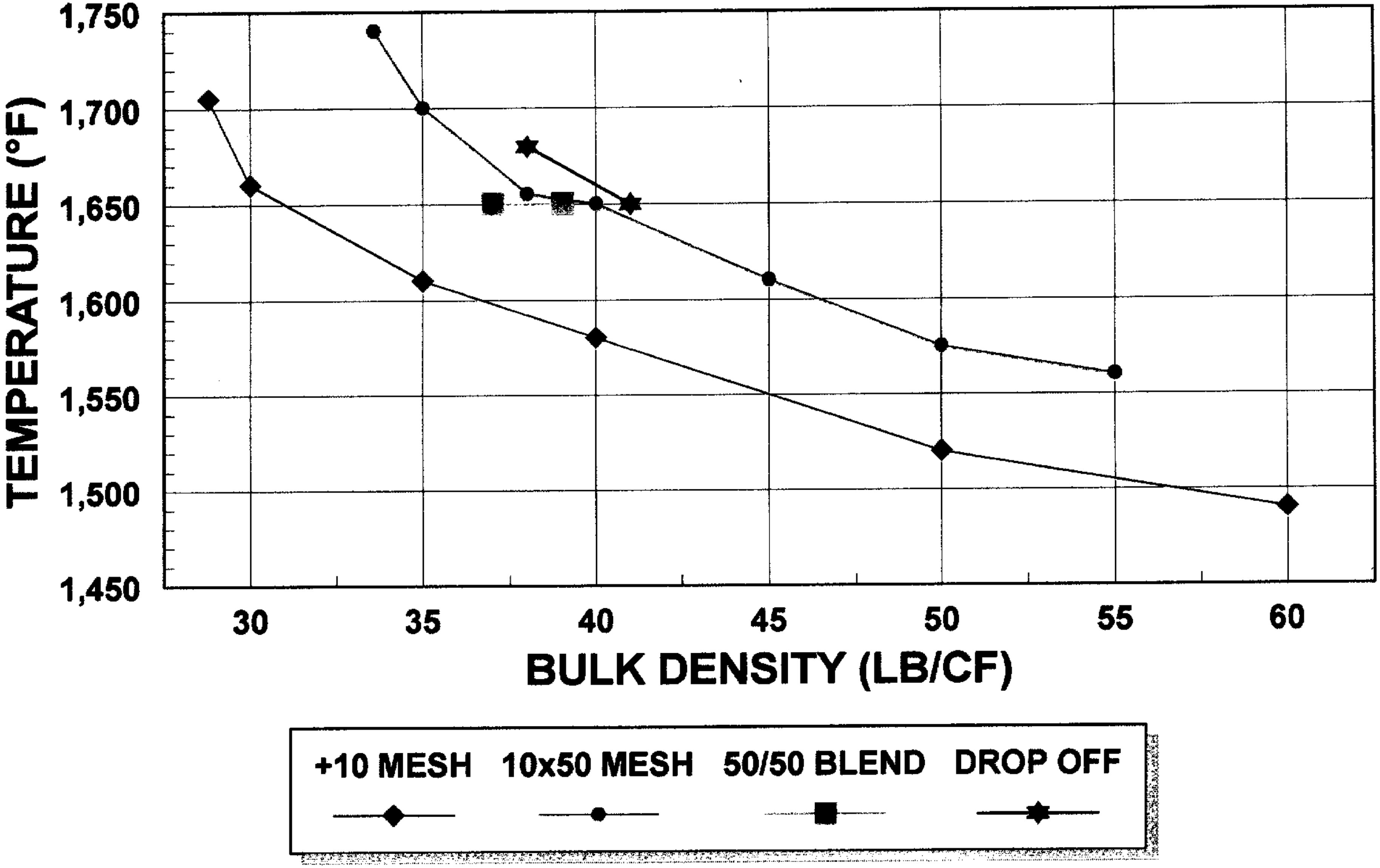
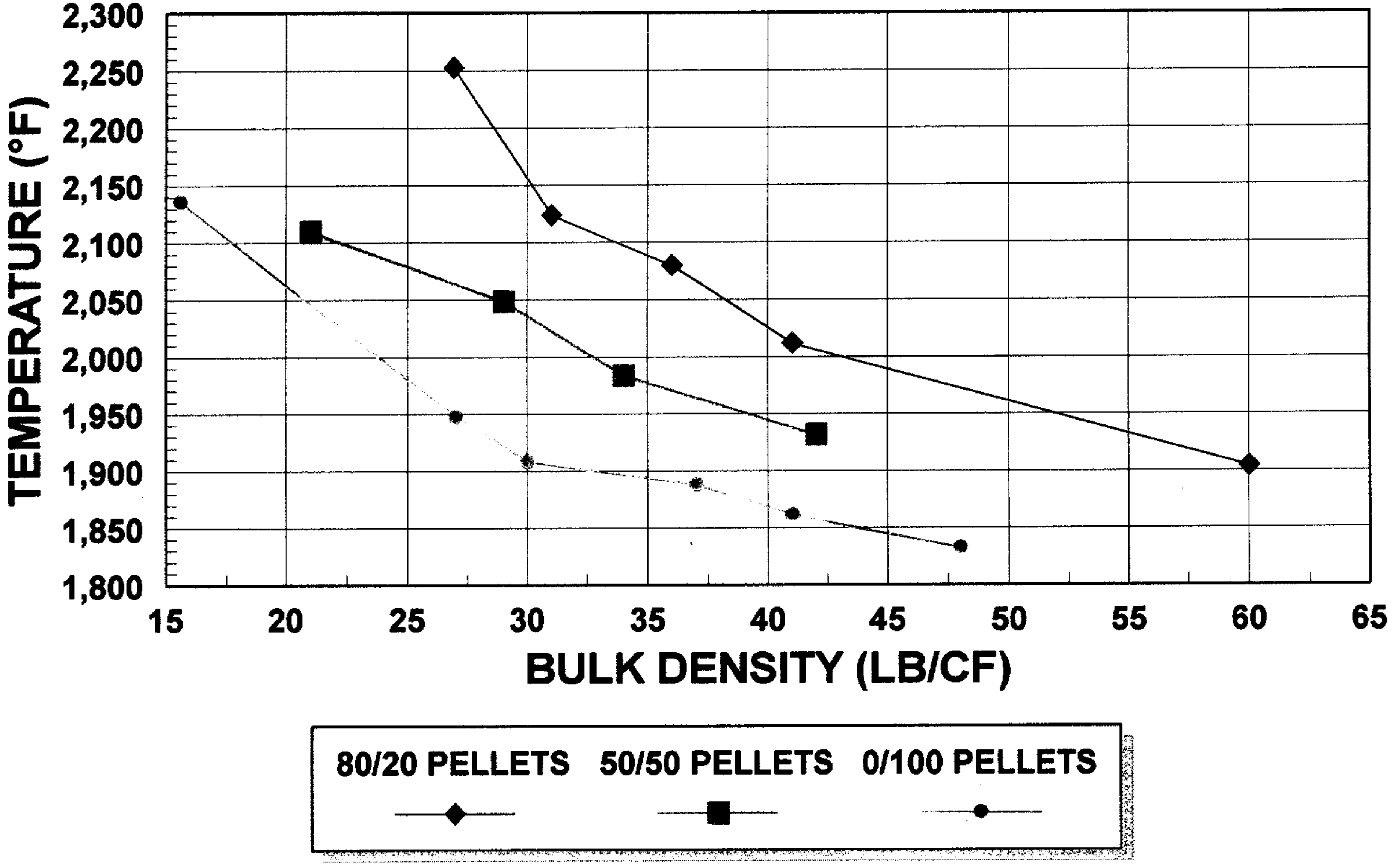


Figure 6

Hot Zone Temperature vs. Product Density
Extruded Pellet Rotary Kiln Processing



Task 1.2.5 Production of Expanded Slag Products Using a Fluidized Bed Expander

Both direct- and indirect-fired kilns were originally planned to be tested for expansion of various size fractions of slag in discrete particle form and as pelletized fines. However, a change order was approved by METC to allow use of a fluidized bed expander (calciner) instead of an indirect-fired kiln as the former offers numerous advantages including higher energy efficiency. In the fluidized bed expander, high-temperature combustion products are bubbled through a bed of the feed material. Additional fuel (#2 fuel oil) is injected into the fluidized bed immediately above the air distribution plate. The excellent mixing and thermal transfer characteristics of the fluidized bed provide a uniform thermal profile through the bed without formation of a high-intensity flame. This mechanism of combustion provides excellent bed temperature control, maximizes system capacity, and has the added benefit of reducing the formation of nitrous oxides. The superficial fluidization velocity is maintained at a level not exceeding 110% of the minimum fluidization velocity to generate an actively fluidized bed while minimizing particle entrainment and particle attrition. A schematic of the fluidized bed expander is shown in Figure 7.

The objectives of this task were to study the production of LWA and ULWA from slag using a fluidized bed expander and to generate large samples of expanded slag and pelletized slag for further testing and evaluation. In addition, the potential for using char recovered from the slag as a fuel was to be investigated.

A 6-inch fluidized bed calciner at Fuller's R&D facility was used for this purpose. The samples that were tested in the fluidized bed expander were +50M Slag I (combined +1 OM and 10 x 50 M), +1 OM, and extruded slag/clay pellets. Since it is difficult to process large pellets in this equipment, the pellets were crushed in a granulator to generate 4 x 20M or 4 x 30M fractions. The fines were returned to the extruder. The granulated material approximates the size gradation of LWAS used to make blocks and roof tiles.

The fluidized bed expander was operated at conditions selected during preliminary testing, and followed a test matrix similar to that utilized for direct-fired kiln testing. Target product unit weights were between 12 and 50 lb/ft^3. The particle size of the feed was changed in order to observe its effect on product density at different temperatures and fluidized bed operation. The results and operating conditions for the fluidized bed system are given in Table 9.

Figure 8 shows product density measurements as a function of temperature. The temperature/density profile of Slag II is much steeper than that of Slag I and Slag 1 pelletized fines. Pellet density could be controlled to a desired value as a function of temperature. However, the temperature/density profiles of slag/clay blends are different from those of the slag and the clay when expanded individually, These results confirm the feasibility of producing expanded slag particles and pellets in a fluidized bed expander.

Figure 7

6" Diameter Bench-Scale Fluid Bed Reactor

Specifications

Bed Height:	*3 ft*
Feed Height (Above Grid):	*2 ft*
Inside Diameter:	*0.5 ft*
Temperature:	*+1420°C*
Fuel:	*Gas/Oil*

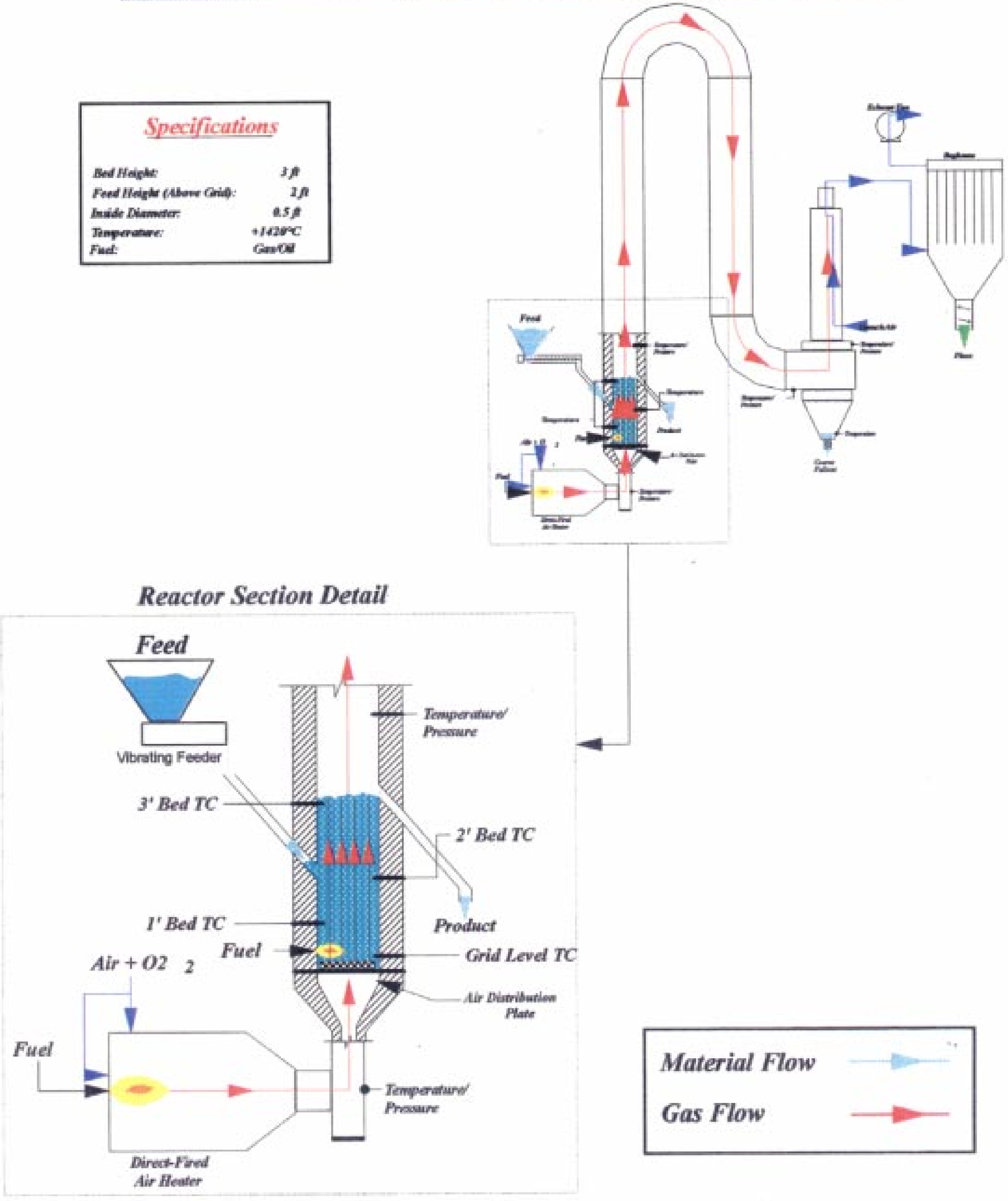
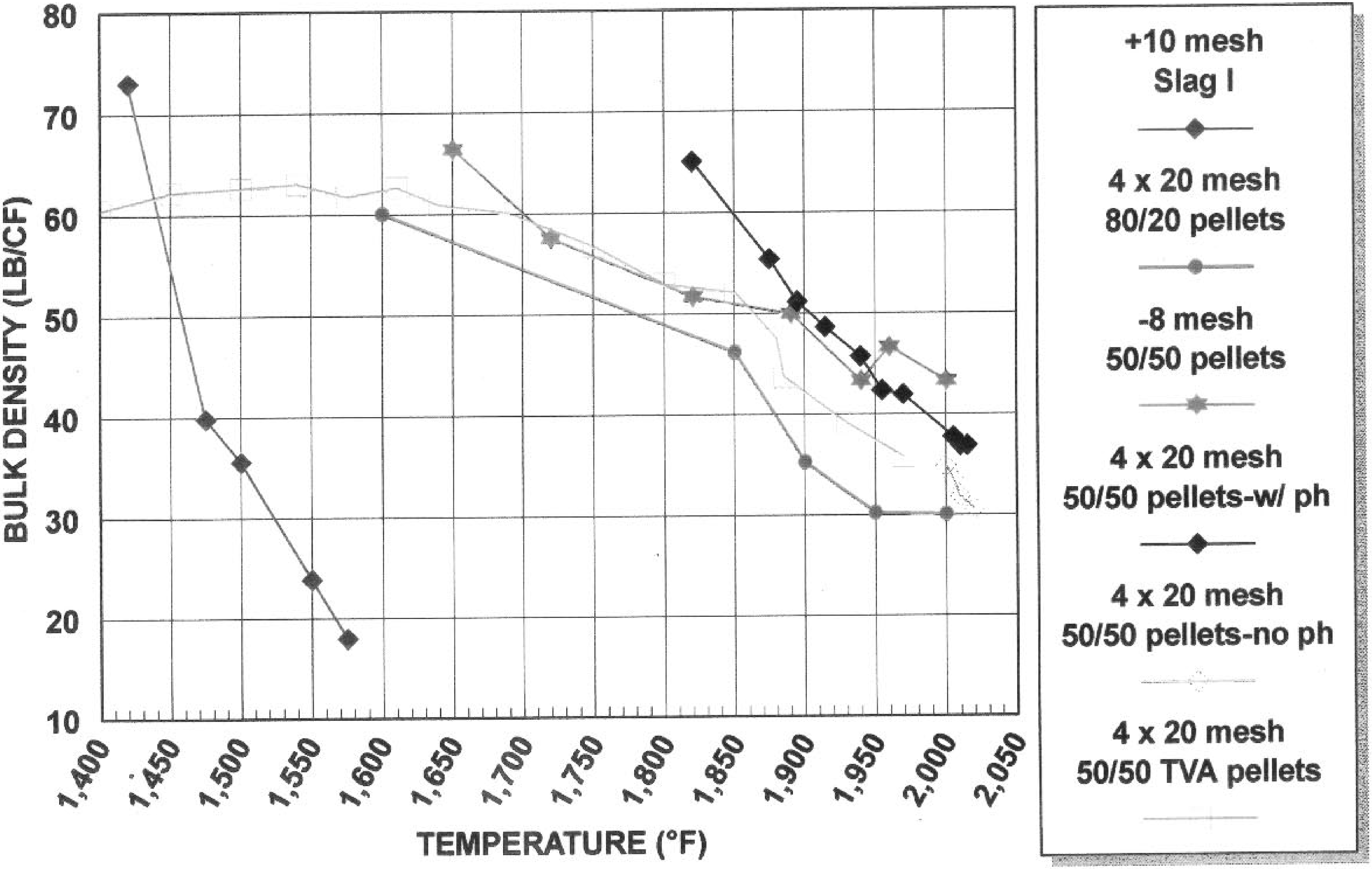


Table 9, Average Operating Conditions (6" Fluidized Bed System)

Phase	**76**	**7C**	8A	86	9	10	**11A**	**116**	12	13
Feed Type/Feed Size	Slag I +50M		Slag I +10M		80/20 Slag I/ Clay 4 x 20M	50/50 Slag I/ Clay -8M	50/50 Slag I/Clay 4 x 20M		50/50 Slag II/ Clay 4x20M	80/20 Slag I/ Clay 4 x 30M
Feed rate, lb/h	38	38	56	40	31	30	32	32	30	30
Unit weight, lb/ft^3	28	16	36	18	30	43	39	31	33	41
Temperature, "F										
Plenum	1750	2100	1565	1610	1960	2135	1980	2035	1855	1770
Grid level	1475	1575	1475	1535	1895	1895	1960	1975	1690	1920
1' bed level	1500	1650	1475	1540	1945	1960	2015	2015	2020	1920
2' bed level	1425	1525	1475	1545	1915	1935	2010	2010	1655	1865
3' bed level	1375	1450	1470	1575	1820	1840	1960	1960	1530	1745
Freeboard	1125	1225	1390	1530	1675	1580	1840	1860	1400	1525
BH inlet	80	80	105	115	160	85	110	135	105	95
Pressure,"WC										
Plenum	23.2	20	32	30	27	15	28	26	28	34
Freeboard	-0.1	-0.5	-0.5	-0.3	-0.1	-0.6	0	-0.2	-0.3	-0.3
Gas Analysis										
Plenum, %O$_2$	18.3	***	12.9	12.1	14.6	29.7	21.6	22.7	**	14,1
Freeboard, %O$_2$	16.3	***	**	**	12.0	22.5	14,7	16.6	**	12.4
Freeboard, ppm CO	>1000	***	**	**	830	>100	980	683	**	o
No. 2 fuel oil, gal/h	<0.25	<0.25	0.22	0,32	0.10	0.43	0,36	0.32	0.36	0.20
Natural gas, SCFH	105	105	87	87	107	102	120	122	113	**117**

Figure 8

Product Density vs. Fluid Bed Temperature



Task 1.2.6 Evaluation of Char as By-Product

The objective of this task was to determine the feasibility of recycling char to the gasifier and/or using it as a kiln fuel during slag expansion,

Upgrading Char. The objective of this subtask was to generate a char concentrate containing less than 20% ash (i.e., 80% carbon) from the char recovered from the slag, Since the char recovered from the tabling operation has an ash content of approximately 40-50%, this step is designed to enhance the value of the char and make it more acceptable as a fuel in kiln processing or as a gasifier recycle stream. Samples of char were processed for ash rejection using a froth flotation process, Initial tests were conducted to establish flotation conditions and collector and frother requirements. A 50-lb char flotation concentrate containing 30% ash was generated from the char recovered from the tabling operation. A portion of the product was evaluated as a recycle stream to the gasifier and the remainder was evaluated as a fuel during slag expansion,

Evaluation of Char as Fuel during Slag Expansion. The char was subjected to thermogravimetric (TGA) analysis. The results are shown in Figure 9. This test helps identify heat release from the char as a function of temperature. As may be seen in the figure, significant weight loss begins to occur at 600°C (1 110°F), and a residual weight of 60% is recorded at about 750°C (1380°F). Since the char sample contains 50% ash, little carbon remains in the sample at this temperature. Therefore, heat release from the char occurs between 1100 and 1400°F, which is considerably below the expansion temperature of slag (1600°F), Therefore, theoretically, the char could be utilized during slag expansion. This premise was tested in the fluidized bed pilot plant, as described below.

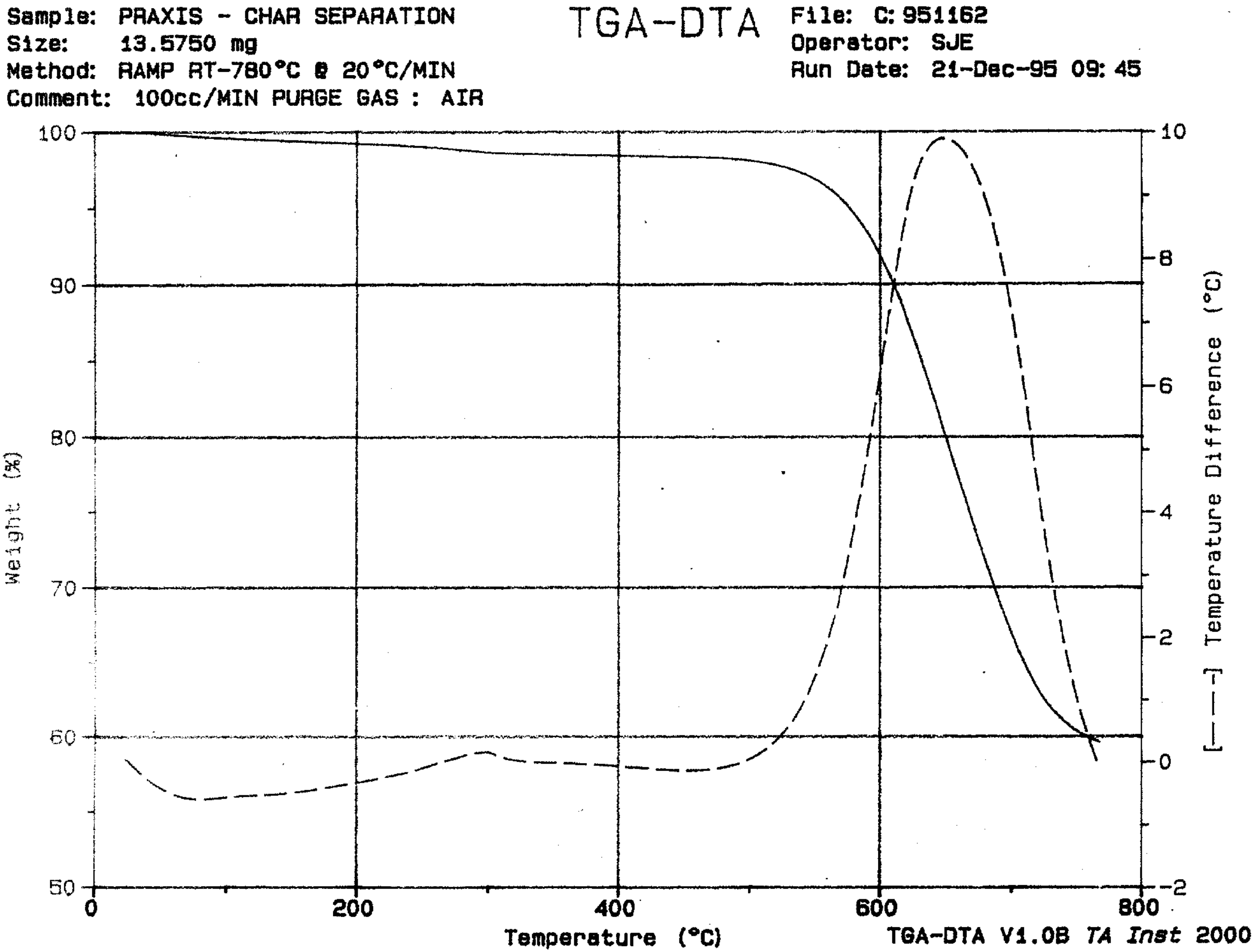
Samples of as-recovered char containing 50% ash and upgraded char containing 30% ash were tested by Fuller as fuels during slag expansion in the fluidized bed expander. Direct injection of the char as fuel did not produce any noticeable heat contribution to the process as the reaction kinetics of the relatively coarse particles were insufficient to oxidize the carbon in the short residence time offered by the process. Further testing utilizing a micronized char sample (>90% minus 200 mesh) was conducted but the results were inconclusive because of problems with plugging of the char feed tube during the time scheduled for these tests. However, the system operated for a short period of time prior to shutdown. This work will be included in Phase II testing. It is anticipated that particle size reduction of the char would facilitate its use as fuel in the fluidized bed.

Evaluation of Char for Gasifier Recycle: Two char samples, containing 50% ash and 30% ash respectively were provided to Texaco for gasification evaluation at their Montebello Research Laboratory. They have completed the evaluation and their report is in preparation.

The objectives of Task 1.2 were accomplished successfully, It has been shown that by careful control of pyroprocessing parameters LWAS of various sizes may be produced from slag using pilot-size equipment. In particular, the following was accomplished:

- Preparation of slag (char removal) prior to expansion
- Use of slag fines by means of extrusion with a clay binder
- Successful expansion of two slags in both discrete particle and pelletized form using two different methods of expansion
- Demonstration that the size and unit weight of the LWA products can be controlled as desired

Figure 9
Thermogravimetric Analysis of Char Sample



Sample: PRAXIS - CHAR SEPARATION
Size: 13.5750 mg
Method: RAMP RT-780°C @ 20°C/MIN
Comment: 100cc/MIN PURGE GAS : AIR

TGA-DTA

File: C: 951162
Operator: SJE
Run Date: 21-Dec-95 09: 45

- Recording of various environmental data during pyroprocessing of slag
- Evaluation of recovered char as a fuel for slag pyroprocessing and as a gasifier feed.

Task 1.3 Data Analysis of Slag Preparation and Expansion

The objective of this task was to analyze the results of all the test work and summarize the project findings for each major area.

Task 1.3.1 Energy and Material Balances

Process energy and material balances were developed for the two major unit operations: (i) processing of slag for char recovery, and (ii) pyroprocessing of slag. The results are discussed below,

Processing S/ag for Char Recovery. The mass balance around the char removal system, based on 100 lb of raw slag feed, is presented in Table 10. Slag samples were collected during processing of the primary slag sample. Analyses of two test runs (i.e., tests 31 and 32) and tests on the advance sample, which represent typical operational data with respect to the ash content of the feed, char, and slag streams, are presented in this table. The table shows that slag products consisting of 100°A ash were recovered at yields of 66-680A. Also, a char product containing 45-54°A ash was recovered during the process, The yield from the advance sample was slightly higher.

Table 10. Mass Balance Around Char Removal System

	Screening				Tabling						Product Yield %
	Raw Slag		+6M Slag Product		Feed Slag		Char		Product Slag		
Test No.	Wt lb	Ash %	Wt lb	Ash %	Wt lb	Ash %	Wt lb	Ash %	Wt lb	Ash %	
31	100.0	83.5	0.0	0.0	100.0	83.5	31.7	46,9	68.3	100.5	
32	100.0	84.9	0.0	0.0	100.0	64.9	34,3	54,6	65.7	100.7	65.7
AS*	100.0	86.1	11.1	100.2	88.9	74.7	25.7	45.1	63.2	100.2	74.3

* Advance slag sample processed for char removal prior to collecting the bulk 20-ton sample.

Pyroprocessing of Slag for Expansion. A summary of the material balances for rotary kiln and fluidized bed operations was compiled for both sizes of direct-fired kiln systems and the fluidized bed system. Measurement accuracy, provided in Table 11, is determined utilizing calculated loss-free material weights to account for the potential volatilization of components such as moisture, carbonates, etc. The highest mass balance differential was 8.7% due to weighing inaccuracies and losses associated with sample handling; this is considered an acceptable level for a pilot-scale operation. The material balances for the fluidized bed system are also reported in Table 11.

Table 11. Material Balances for Rotary Kiln & Fluidized Bed Operation

Pilot Kiln	Feed	Material, lb		Difference, % (Loss-Free)
		In	out	
3' x 30'	+10M Slag I	7335	6865	-6.4
3' x 30'	10x 50M Slag I	6609	6112	-7.5
l' X15'	80/20 Slag I	498	471	-5,3
l' X15'	50/50 Slag I	412	397	-3.8
l' X15'	0/1 00 (clay)	415	403	-2.9
l' X15'	+10M Slag II	728	672	-7.6
6" Fluid bed	+50M Slag I	180	175	-2.8
6" Fluid bed	+10M Slag I	181	174	2.1
6" Fluid bed	80/20 Slag I/Clay (4x 20M)	142.4	129.8	-7.4
6" Fluid bed	50/50 Slag I/Clay (-8M)	90	84.7	1.9
6" Fluid bed	50/50 Slag I/Clay (4x 20M)	134.1	114.3	-6.4
6" Fluid bed	50/50 Slag n/Clay (4x 20M)	120	101.1	-8.7
6" Fluid bed	80/20 Slag I/Clay (4x 30M)	180	161	-5.1

Energy balances were calculated for each phase of the kiln and fluidized bed pilot plant operation. A summary of the results is given in Table 12.

Rotary kiln energy balances were formulated using measured gas/material mass flow rates and temperatures. Heat lost through radiation and convective transfer to the atmosphere was calculated using measured kiln shell temperatures determined by infrared analysis. Shell losses accounted for 36-48% of the total fuel input to the process. Energy balances representing pilot kiln operation generally demonstrated an acceptable level of accuracy when comparing the total energy input and output, with the exception of Phase 3B where the difference is 11 .7%. The specific reason for this deviation could not be established. Energy balances for pilot fluidized bed operation were determined using a radiative transfer rate calculated by difference. The calculated radiative losses from the pilot fluidized bed process ranged between 39 and 76% of the total energy input. This method was required because the short duration of testing did not allow for complete thermal equilibrium of the refractory lining.

Table 12. Energy Balances for Rotary Kiln and Fluidized Bed Operation

Pilot System	Phase	Energy in MBtu/h		Energy in MBtu/ton		Difference (%)
			O		O	
3’ x 30’	**1B**	**1.67**	**1.71**	**5.13**	**5.27**	**+2.4**
3’ x 30’	2B	1.85	1.87	6.92	6.98	+1.1
I’ X15’	3B	0.691	0.545	17.26	13.62	-21.1
I’ X15’	4C	0.613	0.574	14,43	13.50	-6.4
I’ X15’	5B	0,557	0.536	15.47	14.89	-3.8
I’ X15’	6A	0.441	0.439	10.03	9.99	-0.5
6“ Fluid bed	7C	0.11	0.11	6.02	6,02	0
6“ Fluid bed	8B	0.119	0.119	10.14	10.14	0
6“ Fluid bed	9	0.12	0,12	7.38	7.38	0
6“ Fluid bed	10	0.151	0.151	35.72	35.72	0
6“ Fluid bed	11B	0.157	0.157	12.49	12.49	0
6“ Fluid bed	12	0.126	0.126	9.19	9.19	0
6“ Fluid bed	13	0,109	0,109	9.11	9.11	0

Process heat consumption values for pilot operations were calculated using the measured fuel net energy contribution and product mass flow rates. The process energy requirements in these tests were higher than those expected for commercial operations because of the disproportionate loss of process energy through radiative transfer due to the scale of the pilot kilns and fluidized bed, coupled with the lack of heat recovery systems.

Task 1.3,2 Environmental (Emissions) Data for Slag Expansion

Under this subtask, the air emissions, effluent discharge water, and solid waste generated by the slag expansion process were measured. This involved listing the quantity and quality of the following:

- Particulate emissions during char removal and kiln processing
- Gaseous emissions (NO_X, SO_2, CO) during kiln operation.

The rotary kiln temperature profile for the second day of full operation covering Phases 2A, 2B, 2C, 2D, and 2E and emissions for this period is shown in Figure 10, which also shows the density measurements of the products. Table 13 provides the emission levels for all phases of the pilot kiln operations. Figure 11 provides the stack gas analysis for one full day of operation. Emissions of NO_X, CO_2 and SO_2 were not monitored for the fluidized bed system as emissions levels are expected to be similar to or lower than those in rotary kilns. The kiln $S0_2$ emissions are in the range of 13-30 ppm for the discrete particle pilot runs covered by Phases 1A, 1 B, and 2A-2D. However, these emissions increased to 38-90 ppm when the extruded slag fines were processed. This reflects the higher sulfur content in the 50M x O fines compared to the +50-mesh slag. In addition, the higher temperature required for pellet expansion allowed volatilization of a higher percentage of the feed sulfur. The SO_2 emissions for Phase 3B were 140 ppm, which is unusually high compared to other phases. This is attributed to a measurement error for the fuel rate. A portion of the SO_2 emissions resulted from the sulfur content of the kiln fuel (Fuel Oil No. 2) which contained 0.25% sulfur. The use of natural gas as the fuel in a commercial plant would provide a means of reducing fuel-related emissions.

NO_x emissions during the kiln operations were in the range of 25-40 ppm during the entire program and were generally a function of the temperature of operation.

Table 13. Direct-Fired Rotary Kiln Emissions

Phase	Material	Product Rate	Stack Flow	SO_2		NO_x		c o ,	
		lb/h	DSCFM	ppm	lb/ton	ppm	lb/ton	0/	lb/ton
S									
1A	+10M	496	1785	13	0.94	33	1.716	--	--
1B	+10M	650	1526	14	0.661	35	1.187	2,3	746
2A	IO x 50M	475	1815	26	1.997	32	1,767	2,3	1215
2B	IO x 50M	535	1811	30	2.041	35	1,712	–	--
2C	1/4" x 50M	555	1829	30	1.987	35	1.666	--	--
2D	Drop off	533	1885	19	1.351	35	1.788	--	--
3A	80/20 pellets	62	618	90	18.03	40	5.761	2.8	3858
3B	80/20 pellets	80	702	140	24.69	36	4.564	2.7	3275
4A	50/50 pellets	82	588	60	8.648	35	3.626	3.2	3172
4B	50/50 pellets	82	586	75	10.77	35	3.614	2.9	2865
4C	50/50 pellets	85	546	55	7.101	32	2.97	2.5	2220
5A	0/1 00 pellets	74	537	40	5.834	32	3.355	2.5	2508
5B	0/1 00 pellets	72	527	38	5.591	32	3.384	74	7478
S									
6A	+10M	88	518	10	1.183	25	2.126	1.8	1465
6B	+10M	88	505	13	1.5	22	1.824	1.8	1428
6C	+10M	88	578	15	1.98	33	3.132	2.3	2088

Figure 10

Rotary Kiln Process Temperature Profile
14 November 1995

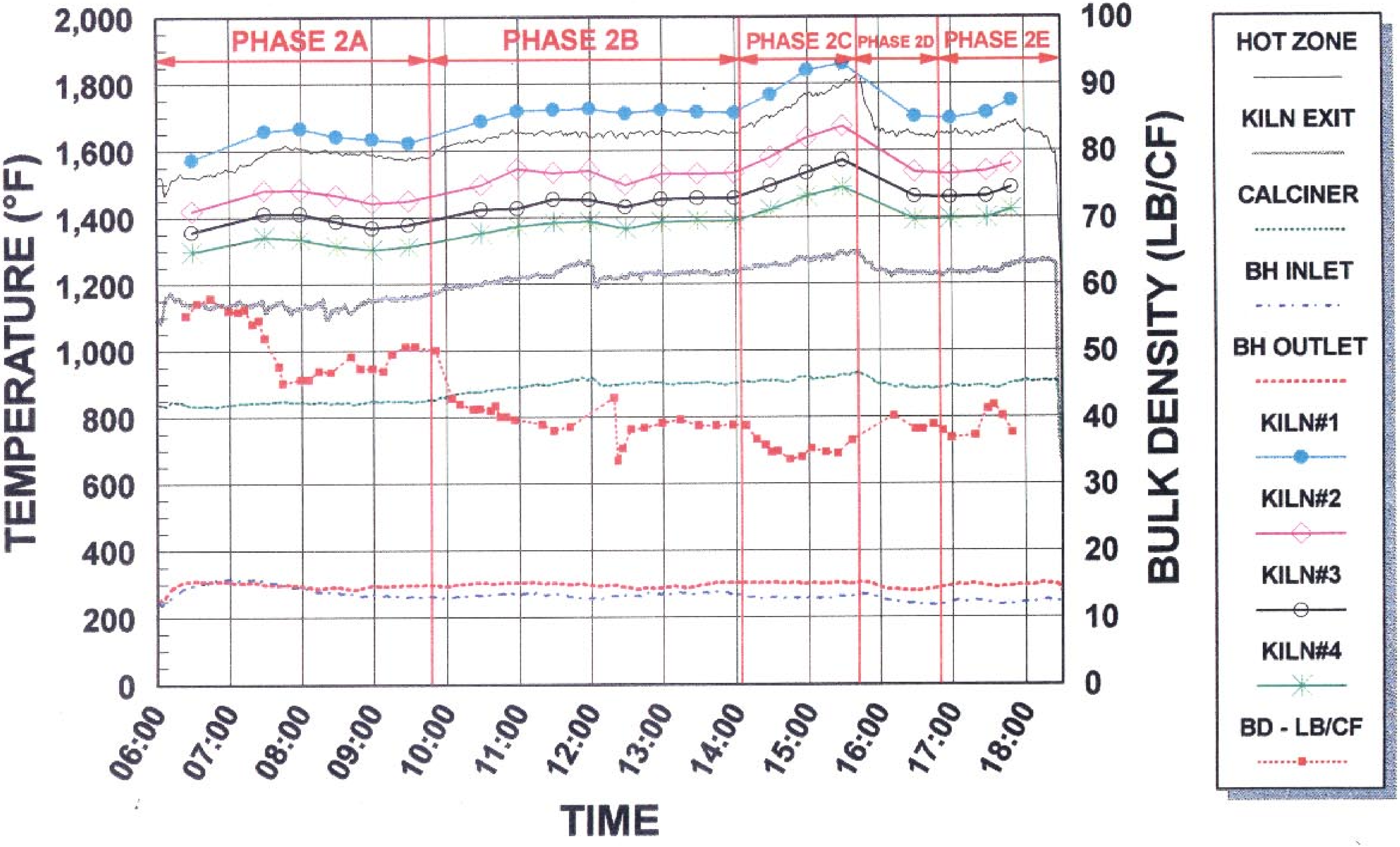
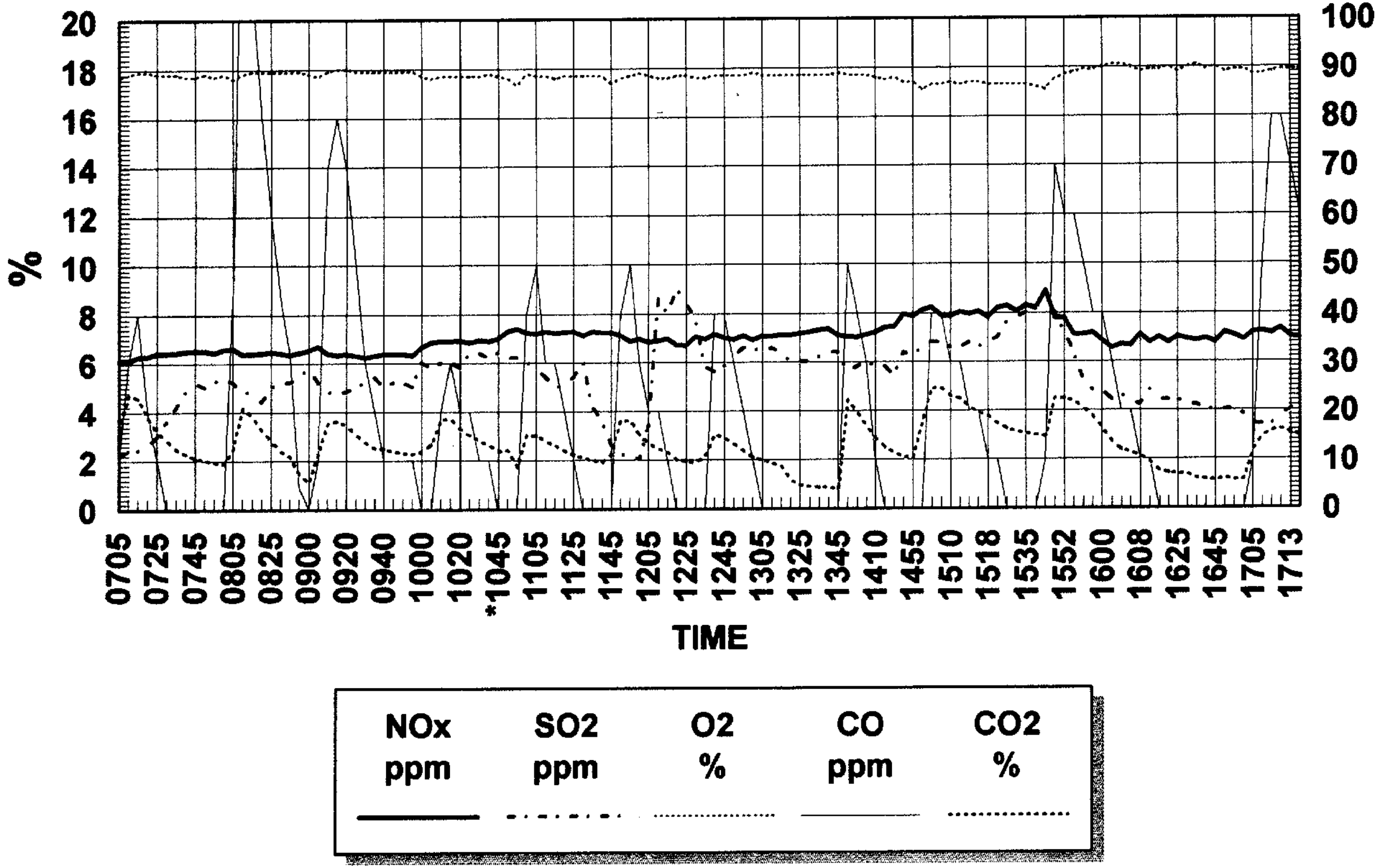


Figure 11

Stack Gas Analysis from Rotary Kiln Testing
14 November 1995



Task 1.3.3 Engineering Evaluation of Lightweight and Ultra-Lightweight Expanded Slag Production

The objective of this task was to evaluate the technical viability of expanded slag (SLA) production techniques compared to the production of the corresponding conventional materials. The criteria used for this technical assessment included the following:

- Environmental acceptability of expanded slag products
- Technical viability of expanded slag production
- Suitability of the expanded slag products for the target applications.

As a first step in evaluating the environmental acceptability of the raw, prepared, and expanded slag, the Slag I feed and products were subjected to chemical analysis, the results of which are given in Table 14. A similar analysis for the slag/clay blends and Slag II is given in Table 15.

Table 14. Chemical Analysis **of Slag I Feed and Products**

Sample/ Phase	**Slag Feed**				**Expanded Slag Products**		
	1/4” x o (Raw)	**1/4” x IOM (1B)**	**10X** 50M (26)	-50M	**1B**	**Baghouse**	**2B**
LOI @ 105°C	0.5	0	0	0	0	0	0
SiO_2	34.7	42.48	42.45	30.91	41.07	34.07	42.51
Al_2O_3	21.82	26.64	26.53	25.13	25.7	23.38	26.99
Fe_2O_3	17.2	21.11	20.68	24	20.41	5.14	20.88
CaO	3.85	4.61	4,52	4.91	4.57	15.88	4.6
MgO	0.93	1.11	1.11	1.07	1.14	1.42	1.15
K_20	1.5	1.82	1.82	1.67	1.82	0.88	1.85
Na_2O	0.43	0.47	0.45	0.42	0.71	0.76	0.47
SO_3	1.61	0.62	0.72	2.76	0.59	4.03	0.57
P_2O_5	0.74	0.84	0.83	0.8	0.82	0.33	0.86
TiO_2	1.24	1.49	1.46	1.43	1.45	0.89	1.49
Mn_2O_3	0.09	0.1	0.1	0.11	0.1	0.08	0.1
LOI @ 900°C	**15.74**	**-1.42**	**-0.75**	**-0.72**	**1.49**	**12.92**	**-1.49**
Carbon	17.94	0.03	0.9	0.4	0.04	--	0.01
Total	99.85	99.87	99.92	100.49	99.87	99.78	99.98

Table 15. Chemical Analysis of Slag/Clay Blends and Products

Oxides	**Feed**				**Kiln Products**				**Fluidized Bed**
	80/20 Pellets	**50/50 Pellets**	**0/100 Pellets**	**Slag II**	**80/20 Pellets (Baghouse)**	**50/50 Pellets (Baghouse)**	**0/100 Pellets**	**Slag II (Baghouse)**	**Slag I Product**
LOI @105°C	4.6	6.5	8.95	0.32	0.27	0.4	0	0.32	0
SiO_2	42.95	47.72	57.22	48.77	42.76	46.37	62.32	46.39	42.14
Al_2O_3	23.61	21.23	17.06	18.39	21.16	21.53	18.92	16.05	26.81
Fe_2O3	20.3	15.74	7.45	19.96	17.82	16.71	8.63	18.86	20.92
CaO	4.14	3.25	1.74	6.39	7.26	4.59	1.82	6.34	4.67
MgO	1.34	1.72	2.48	1.01	3.12	3.4	2.66	1.76	1.16
K_2O	1.84	2.03	2.38	1.96	1.69	1.87	2.6	1.8	1.84
Na_2O	0.42	0.48	0.63	0.78	0.6	0.53	0.59	0.87	0.44
SO_3	2.42	1.9	1.02	0.6	2.42	1.88	0.94	1.16	0.57
P_2O5	0.67	0.47	0.13	0.21	0.76	0.57	0.16	0.25	0.84
TiO_2	1.3	1.08	0.72	0.94	1.16	1.21	0.8	0.93	1.47
Mn_2O_3	0.11	0.12	0.13	0.15	0.11	0.12	0.14	0.15	0.1
LOI @ 900°C	1.17	4.19	8.85	0.75	1.03	1.13	0.22	5.38	-1.17
Total	100.27	99.93	99.81	99.91	98.89	99.91	99.8	99.94	99.79

Environmental Acceptability of Expanded Slag Products. Major environmental issues with regard to utilization of a new aggregate are (i) leachability and (ii) adverse reactivity when blended with other aggregates. A sample of expanded slag was prepared to match the particle size distribution required for lightweight roof tile aggregates and subjected to elemental analysis and RCRA/TCLP testing in accordance with EPA SW-846. The results of the TCLP test are given in Table 16, along with the elemental analysis of the SLA sample used for the test. The SLA sample selected was the "worst case" scenario because extensive size reduction of expanded aggregates is needed to meet the size requirements, thus potentially making it the most leachable SLA product. The results indicated that TCLP leachate heavy metals concentrations, given in mg/l, were considerably lower than the RCRA maximum allowable concentrations.

Table 16. Analysis of SLA Crushed for Lightweight Roof Tile Application and TCLP Results

Element	**SLA Sample (mg/kg)**	**TCLP Result (mg/l)**	**RCRA TCLP Max. Allowable Cone. (mg/l)**
Antimony (Sb)	<().5	<().()3	1
Arsenic (As)	<6.0	0.018	5
Barium (Ba)	106	0.5	100
Beryllium (Be)	<().7	<0.()()5*	0.007
Cadmium (Cd)	<0.3	<0.02*	1
Chromium (Cr)	157	<(3.03*	5
Lead (Pb)	<6	<0.05*	5
Mercury (Hg)	<0.007	<0.()()()07*	0.2
Nickel (Ni)	26	<0.03*	70
Selenium (Se)	<0.5	<0.007*	1
Silver (Ag)	1	<0.02*	5
Thallium (Tl)	<().5	<0.005*	7
pH of TCLP Extract		3.12	

* Concentration was below the detection limit.

Technical Viability of Expanded Slag Production. The technical viability of expanded slag production was evaluated in comparison with that of conventional LWAS. The findings are given below:

- Controlled expansion of both slag samples to produce SLA products with units weights of 40-50 lb/ft^3 was demonstrated.
- The direct-fired rotary kiln was shown to be a suitable method for SLA production in both discrete particle form as well as after blending with clay.

- Production of SLA products for use as substitutes for ULWAS was demonstrated successfully, with product unit weights of 18 lb/ft^3 being achieved. While this is above the typical 4-12 lb/ft^3 range produced by expansion of perlite, it is possible to produce lower-unit-weight products from slags that contain low amounts of flux compounds,

- All of the equipment used for the production of conventional LWAS and ULWAS is directly usable for expansion of slag.

Suitability of Expanded Slag Products for Target Applications. In order to conduct a systematic evaluation of the expanded slag aggregates for various applications, Praxis prepared a test plan, "Laboratory Evaluation of Expanded Slag Aggregates," which included a detailed procedure for preparation and testing of slag-based lightweight aggregates (SLA) for their suitability as aggregates for various lightweight (LWA) and ultra-lightweight (ULWA) aggregate applications.

Laboratory-scale applications-oriented testing of SLA as a substitute for LWA and ULWA was initiated. This work involved preparation of SLA samples to meet the particle size and unit weight requirements of various applications, and entailed grinding and blending of SLA products of various sizes and unit weights. Sizing and blending of the SLA products to the target applications was conducted at Fuller. The specific applications are listed below:

- Structural concrete (three SLA products)

- Lightweight concrete masonry unit (lightweight blocks, 2-3 blends)

- Insulating concrete

- Lightweight roof tile aggregate

- Loose fill insulation

- Horticultural application,

The specifications and tests planned are given in Table 17,

Table 17. Applications Tests and Expanded Slag Samples to be Used

	Conventional Aggregates		Expanded Slag Product Sample	
	Target Size/Specifications	Unit Wt lb/ft^3	Slag	Slag/Clay Pellets
LWA Applications				
Structural concrete	(i) 3/4” coarse **LWA,** ASTM C-330	50	--	50/50
	(ii)3/8”combined **LWA,** ASTMC-330	50	1/4” x **50M**	--
	(iii) 3/4” pilot plant **LWA**	50	--	0/1 00
CMU concrete	Fine (-4M) LWA	50	1/4” x 50M	50/50
Roof tile concrete	-6M LWA (size gradation given by manufacturer)	40	1/4” x 50M Crushed (4 samples)	50/50 Crushed
ULWA Applications				
Insulating concrete	**ASTM C-332 Group II (45-90** lb/ft^3 concrete)		**3/8” x O combined**	**--**
Loose fill insulation	ASTM C-549	<12	-4M	--
Horticulture	Expanded perlite size range	<12	IO x 50M	--

Procedures describing key industrial practices were developed and ASTM standards provided to various laboratories selected to test SLA as a substitute for conventional LWAS and ULWAS. The tests and mix designs involved in testing structural applications are summarized here.

Testing of SLA for Structural Lightweight Concrete Applications. The objective of this test program was to develop mix designs to produce sand and SLA-based cement concretes with a compressive strength of 2500-4000 psi and corresponding unit weights in the 115-105 lb/ft^3 range. This can be accomplished by varying the proportion of the cement relative to the SLA. The SLA samples to be tested are identified in Table 18. In addition, a control sample of commercially available structural aggregates was also tested during the materials testing program identified under items (i) and (ii) in Table 17, As maybe seen in Table 18, testing of SLA as 3/4” coarse aggregates involved demonstration of three strength levels (complete matrix) whereas other samples were tested at only one level of cement.

Table 18. Tentative Cement Levels for Testing SLA as Structural Aggregate

SLA Products to be Tested	Tentative Cement Level, SacksNard^3
(i) 3/4” SLA (50/50 slag-clay pellets) as 3/4” coarse LWA	5½, 6%, and 7½
(ii) 1/4” x 50M SLA crushed as 3/8” combined LWA	One level of cement
(iii) Expanded 3/4” clay pellets produced during the pilot program	One level of cement

Exploratory tests were conducted to establish the appropriate sand, water, and cement requirements in order to achieve the target mechanical properties. The strength and unit weight of the resulting concrete were measured and, using these results, final mix designs were developed for the various expanded slags, These mix designs were used to complete the final batches of tests listed below:

Test 1: Evaluation of Pelletized (50/50) SLA as 3/4" Coarse Aggregates
Test 2: Evaluation of SLA as 3/8" Combined Aggregates
Test 3: Evaluation of Extruded Clay as 3/4" Coarse Aggregates

Evaluation of Expanded Slag as Roof Tile Aggregates. Three different kinds of aggregates were tested for 7-day compressive strength using standard ASTM C 109 practice for testing mortars: (i) 100% expanded slag, (ii) 50/50 expanded slag/clay, and (iii) a 100% clay control sample provided by a commercial roof tile manufacturer. The SLA products were crushed to match the size gradation of the commercial sample prior to use in the tests, Typically, a roof tile mix uses a cement-to-aggregate ratio of 1:2.5, along with various additives such as accelerators and superplasticizers. In order to mimic products available in the market for purposes of comparison, two different kinds of accelerators and a common commercial superplasticizer were evaluated. The accelerators tested were calcium chloride dihydrate ($CaCl_2 \bullet 2H_2O$) and sodium silicate.

The 100% slag aggregates and the 50/50 slag/clay aggregates were sized by Fuller to be comparable to the clay aggregates used by roof tile manufacturers.

During the experimental stage, all the aggregates were used in their saturated surface dry (SSD) condition as defined by ASTM. The moisture content of the three aggregates in their SSD condition was measured and recorded.

Because the specific mix formulations used by roof tile manufacturers are considered proprietary information, many experiments were conducted with varying amounts of accelerator, superplasticizer, and water/cement (w/c) ratios with the goal of obtaining the highest 7-day compressive strength without the use of excess additives. Three 2" x 2" x 2" mortar cubes were cast and cured in a wet box (relative humidity of ~70%) for 2 hours and then steam-cured at ~60°C for 4 hours, The cubes were demolded and returned to the wet box for further curing to 7 days. The cubes were then weighed and broken in compression. A summary of the formulations and 7-day compressive strengths is presented in Table 19.

The highest 7-day compressive strength for the expanded slag specimens was 2806 psi, which is 83% of the highest compressive strength obtained for the expanded clay samples. Visual inspection of the crushed slag-based cubes revealed that the cement/aggregate interface was sound and that failure was chiefly due aggregate breakage. This was confirmed by the specimens containing 50/50 slag/clay.

The unit weight of the 100% expanded slag specimens ranged between 91 and 98 lb/ft^3, that of the 50/50 specimens was between 102 and 105 lb/ft^3, and that of the 100% clay control specimens was between 91 and 101 lb/ft^3.

These experiments also showed that the mechanical behavior of the samples is greatly affected by the water/cement ratio but not by the type of accelerators used. Typically, in cement systems, lowering the water/cement ratio improves strength if care is taken to keep the mix workable. However, in the case of the expanded slags, the water/cement ratio had to be kept relatively high (>0.35) in order to have the cement paste coat all the particles and keep the structure together.

Table 19. Formulations and 7-Day Compressive Strength **of Roof Tile Samples**

Aggregate Type	$CaCl_2 \bullet H_2O$ (Wt% of cement)	Super-plasticizer (Wt% of C m	Mortar Unit Wt **(lb/ft^3)**	Water/ Cement Ratio	SSD (%)	7-day Compressive Strength
Expanded slag	2	5,5	90.5	0.26	18	668
Expanded slag	2	5	92.3	0.29	18	934
Expanded slag	2	2	92.6	0.32	18.5	2303
Expanded slag	2	2	93.3	0.35	18.5	2806
Expanded slag	2	2	96.8	0.38	17.4	2028
Expanded slag	2	2	97.1	0.41	17.4	1743
Expanded slag	2	1.5	98.3	0.38	17.4	2650
Expanded slag*	2	1.5	101.7	0.38	18	2432
Control**	2	2	109.3	0.38	17	2011
Control**	2	2	108.7	0.41	17	2802
Control**	2	2	105.3	0.45	17	3390
Control**	2	2	105.2	0.50	17	3106
50/50 slag/clay	2	1.5	105.2	0.35	26	2303
50/50 slag/clay	2	1.5	101,9	0.38	26	1917
50/50 slag/clay	2	1.5	101.8	0.41	26	1736

* 1 % sodium silicate was added for this test.
** Control aggregate was produced at a commercial kiln and provided by a roof tile manufacturer.

Evaluation of Expanded* Slag Aggregates *in Insulating Concrete. Expanded slag aggregates with a unit weight of 26 lb/ft^3 produced using the fluidized bed expander were crushed and prepared in accordance with ASTM C 332. In order to evaluate expanded slag for use as an aggregate in insulating concrete, specimens were made for testing of compressive strength and thermal properties. Using the mix proportions for perlite insulating concrete reroofing as a guide, 2“ cubes and a 12” x 12” x 1“ slab were made using 3/8’ x O expanded slag according to the following formula:

Aggregate:	3/8” x O expanded slag, 26 lb/ft^3
Type I cement:	800 g
Water:	640 g
Air-entraining agent:	8,3 g
10-mm polypropylene fibers:	8 g
Aggregate-to-cement ratio:	4:1
Water-to-cement ratio:	0.8 by weight.

The sample was mixed in accordance with ASTM C 109 and cured in a 98% relative humidity chamber set at 25°C. After 7 days, the cubes were removed for compressive testing until failure. The highest 7-day compressive strength achieved was 175 psi, and the unit weight of the samples was approximately 51 lb/ft^3. The 28-day compressive strength of the specimen was 230 psi, which is lower than the requirement of 350 psi. However, this strength level should be easily achievable through optimization of the cement-to-water ratio.

The 12” x 12” x 1“ slab will be tested for thermal properties by a subcontractor.

Testing of Expanded Slag Aggregates for Use as Loose Fill Insulation. Expanded slag produced using the fluidized bed was screened in accordance with ASTM C 549 for use as loose fill insulation. The SLA was then shipped to a commercial testing laboratory for testing of its thermal properties, the results of which are not yet available.

Task 1.3.4 Commercial Production of Expanded Slag Lightweight Aggregates

Numerous pilot-scale evaluations performed for this project have demonstrated the feasibility of producing expanded slag lightweight aggregates (SLA) from gasifier slag. Based on test data and utilizing experience in commercial application of pilot technology, a commercial process has been developed for processing of slag to recover char (shown in Figure 12) and production of SLA (shown in Figure 13). The commercial system includes equipment to perform the following processing steps: (1) slag preparation/char removal, (2) drying/sizing, (3) extruding (slag/clay pelletization only), (4) thermal treatment and expansion, (5) product heat recovery, and (6) product sizing. It should be noted that the two figures illustrate possible arrangements for performing the required functions and that the commercial flowsheet is not limited to the equipment shown. For example, the rotary kiln could be replaced by a fluidized bed calciner system.

Slag Preparation and Char Removal. Raw slag from the gasifier is wet screened to wash and remove the +10M fraction. As material evaluations have indicated the char to be primarily present in the -10M fraction, the +10M slag does not require beneficiation and can bypass subsequent beneficiation steps. The -10M fraction is conveyed to the gravity separator where the primary char/slag separation is performed. The beneficiated -1 OM slag discharged from the separator is dewatered (vacuum drum shown) and then conveyed with the +1 0M fraction to the rotary dryer.

The char discharge from the gravity separator is fed to a second separator (hydrosizer) to remove the remaining slag component and increase the carbon content for use as a fuel. The slag fines collected from the separator may be discarded or combined with the -IOM slag stream from the gravity separator, The slag fines (-50M) are conveyed to the rotary dryer (see Figure 13).

Pyroprocessing. The +1 OM and -1 OM beneficiated slag fractions are conveyed to the rotary dryer unit. This unit, operating in a counterflow configuration, utilizes waste heat from the rotary kiln unit to dry the slag. The dryer product moisture content can be varied by adjusting the material residence time through dryer shell rotational speed changes. The free-flowing slag discharged from the dryer is split at 50M using a vibrating screen, and the two fractions are retained in storage bins (+50M and -50 M), The capacity of the -50M slag bin permits storage of this fraction for a period of 20 days, during which time the +50M fraction is expanded in the rotary kiln.

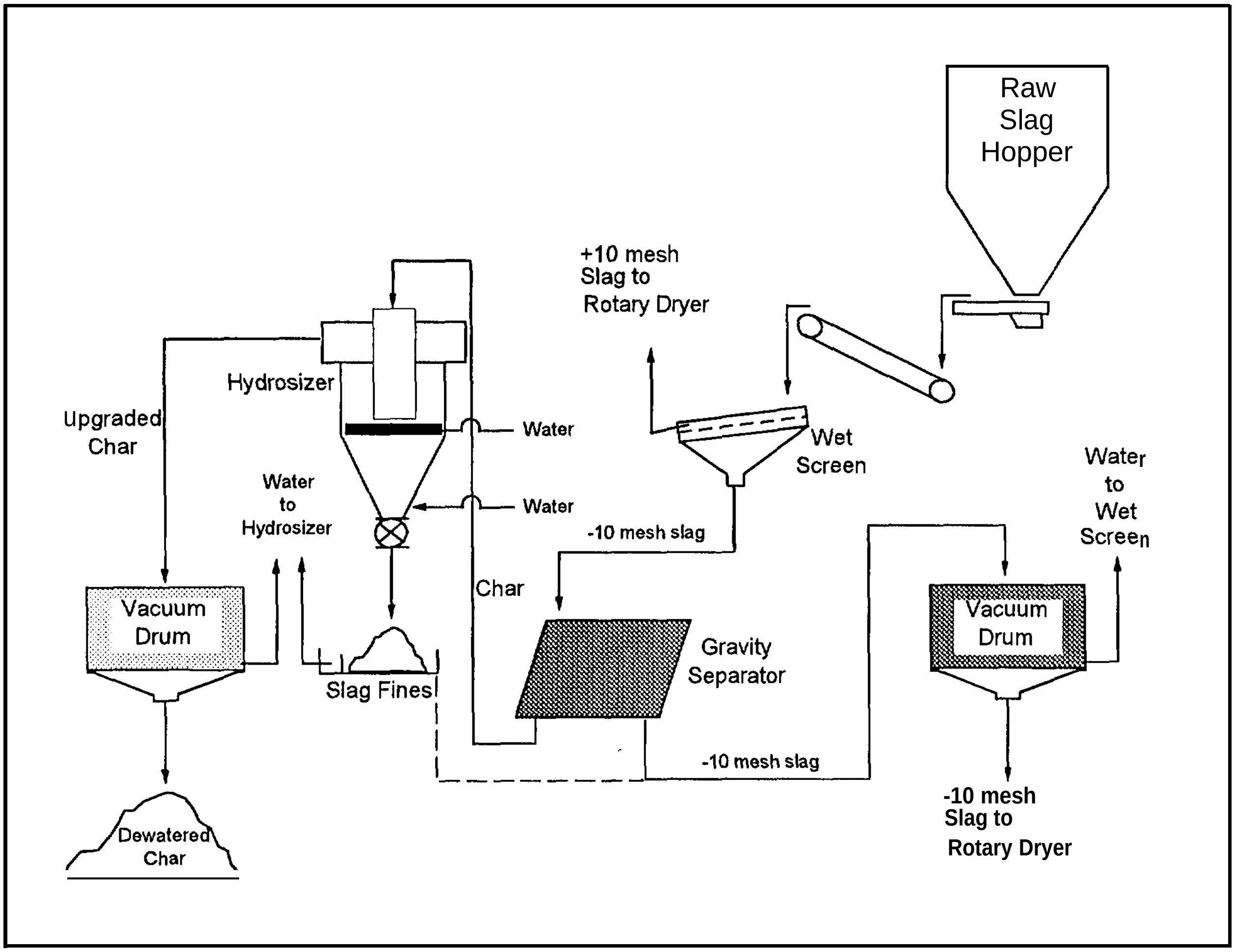


Figure 12. Commercial Slag Preparation and Char Removal Process

Likewise, the capacity of the +50M slag storage bin is sufficient to store this fraction for a period of 10 days, during" which time the -50M slag fines are processed.

During the operation to expand the +50M fraction, the slag is metered from the storage bin to a conveyor that feeds the rotary kiln. The kiln operates in a counterflow configuration, with fuel introduced at the end opposing the feed input location. The temperature and material residence time are varied by adjusting fuel input and the kiln rotational speed to obtain the desired slag product unit weight, The expanded slag is discharged from the kiln directly into a heat recovery device (rotary cooler, shown in Figure 13). The primary airstream is directed through the cooler to recovery 80°/0 of the product energy. This recovered energy is then utilized to preheat the air for the rotary kiln.

Expanded slag discharged from the cooler is conveyed to a crushing device such as a cone crusher. This device can be set to generate a number of particle size distributions to meet market requirements. Several storage bins are utilized to hold products of several different size specifications.

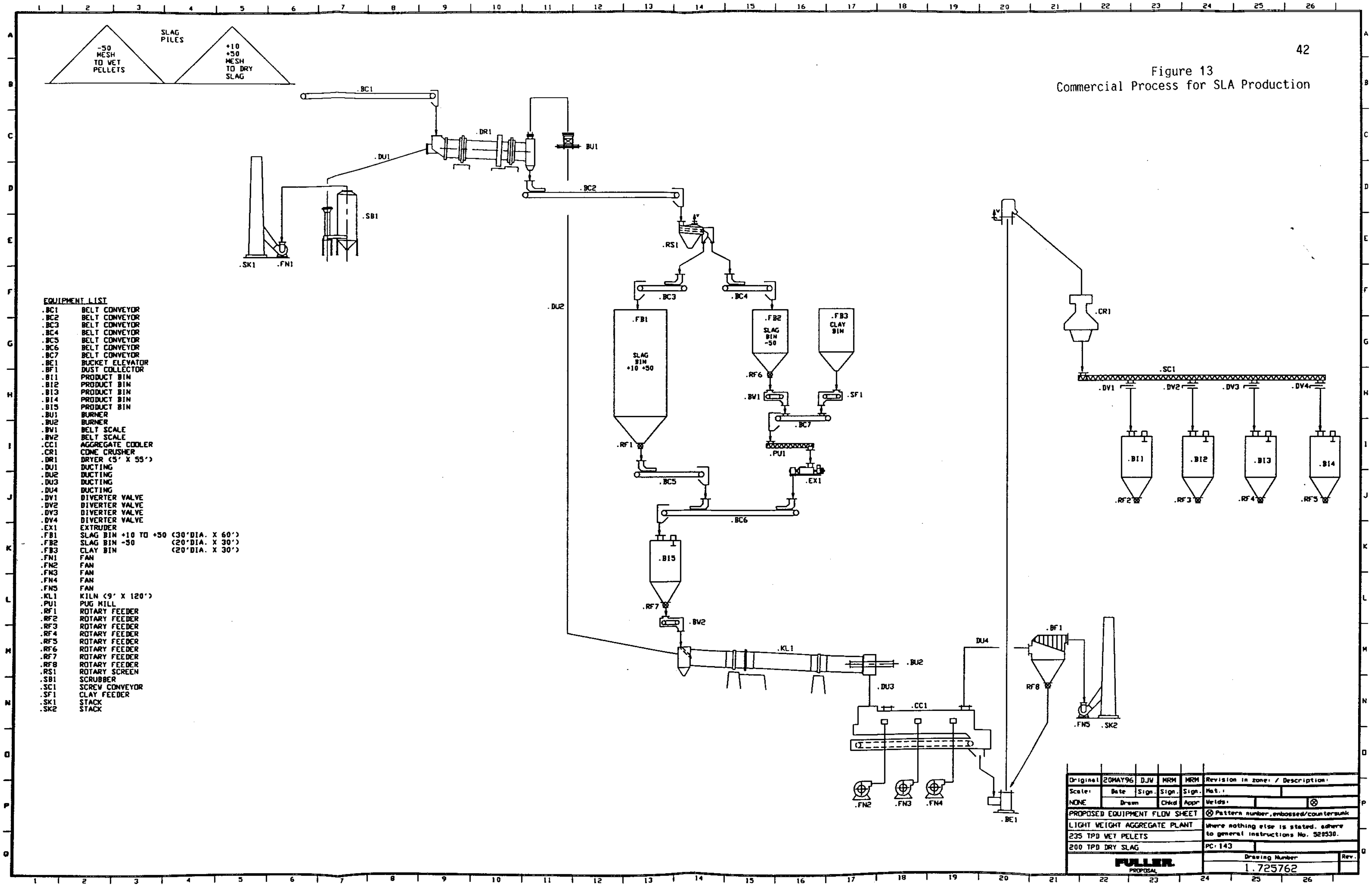


Figure 13
Commercial Process for SLA Production

EQUIPMENT LIST

.BC1	BELT CONVEYOR
.BC2	BELT CONVEYOR
.BC3	BELT CONVEYOR
.BC4	BELT CONVEYOR
.BC5	BELT CONVEYOR
.BC6	BELT CONVEYOR
.BC7	BELT CONVEYOR
.BE1	BUCKET ELEVATOR
.BF1	DUST COLLECTOR
.BI1	PRODUCT BIN
.BI2	PRODUCT BIN
.BI3	PRODUCT BIN
.BI4	PRODUCT BIN
.BI5	PRODUCT BIN
.BU1	BURNER
.BU2	BURNER
.BW1	BELT SCALE
.BW2	BELT SCALE
.CC1	AGGREGATE COOLER
.CR1	CONE CRUSHER
.DR1	DRYER (5' X 55')
.DU1	DUCTING
.DU2	DUCTING
.DU3	DUCTING
.DU4	DUCTING
.DV1	DIVERTER VALVE
.DV2	DIVERTER VALVE
.DV3	DIVERTER VALVE
.DV4	DIVERTER VALVE
.EX1	EXTRUDER
.FB1	SLAG BIN +10 TO +50 (30'DIA. X 60')
.FB2	SLAG BIN -50 (20'DIA. X 30')
.FB3	CLAY BIN (20'DIA. X 30')
.FN1	FAN
.FN2	FAN
.FN3	FAN
.FN4	FAN
.FN5	FAN
.KL1	KILN (9' X 120')
.PU1	PUG MILL
.RF1	ROTARY FEEDER
.RF2	ROTARY FEEDER
.RF3	ROTARY FEEDER
.RF4	ROTARY FEEDER
.RF5	ROTARY FEEDER
.RF6	ROTARY FEEDER
.RF7	ROTARY FEEDER
.RF8	ROTARY FEEDER
.RS1	ROTARY SCREEN
.SB1	SCRUBBER
.SC1	SCREW CONVEYOR
.SF1	CLAY FEEDER
.SK1	STACK
.SK2	STACK

Original	20MAY96	BJW	MRM	MRM	Revision in zone: / Description:	
Scale:	Date	Sign.	Sign.	Sign.	Mat.:	
NONE	Drawn		Chkd	Appr	Welds:	⊗
PROPOSED EQUIPMENT FLOW SHEET					⊗ Pattern number, embossed/countersunk	
LIGHT WEIGHT AGGREGATE PLANT					Where nothing else is stated, adhere to general instructions No. 520530.	
235 TPD WET PELETS						
200 TPD DRY SLAG					PC: 143	
FULLER PROPOSAL					Drawing Number 1.725762	Rev.

During the operation to process the -50M slag fraction, the fines are metered to a mixing/extruder unit where they are combined with clay. The high-speed mixing section sizes the clay and produces a uniform mix of slag and clay. Additional water may be added during this mixing procedure to improve extruding properties. This mix is then compressed through a die to produce extrusions that are cylindrical in cross-section. The length of the extruded pellets can be adjusted by varying the speed of the cutting device mounted on the discharge of the extruder. The extrusions are conveyed to a surge bin which then meters the pelletized material to the rotary kiln. The remainder of the processing circuit (cooling and sizing) is as described for the expanded slag product.

Based on the SO_2 emission data from pilot-scale operations, a wet scrubber is utilized to remove sulfur oxides from the process off-gas stream. The addition of scrubbing media may only be required during processing of the -50M slag fines due to the higher sulfur content of this fraction. The scrubber would operate utilizing a water charge during processing of the +50M fraction for the purpose of particulate removal.

Fluidized Bed Pyroprocessing. The pilot test program demonstrated the feasibility of utilizing a fluidized bed process for the production of SLA from discrete particle slag and pelletized slag. The fluidized bed expander and material preheater units would replace the rotary kiln in the flowsheet depicted in Figure 13. In addition, a granulator is required to size the extruded pellets, and the +1/4" slag fraction would be removed during the char removal process to produce a feed suitable for fluidization.

The energy requirements for a commercial-scale rotary kiln system based on a preliminary analysis are shown in Table 20, Estimated heat consumption would be lower for slag expansion than for most similar-sized existing commercial expanded clay systems due to the lower process temperature requirements and installation of improved heat transfer/recovery technology. Heat consumption decreases as the capacity of the rotary kiln process is increased to over 400 t/d. If a fluidized bed system were to be installed instead of a rotary kiln system, heat consumption would be even lower due to exceptional gas/material thermal transfer efficiency, improved temperature control, reduced excess air, and improved insulating properties.

Table 20. Commercial-Scale Slag Expansion System Fuel Requirements (MBtu Per Ton of Feed)

Feed	Rotary Kiln		Fluidized Bed	
	200 tid	>400 t/d	200 t/d	>400 t/d
Coarse slag, 71%	2.1	1.4	2.5	2.5
Extruded fines, 29%	2.8	1.8	2.5	2.5
Combined	2.3	1.52	2.5	2.5

Task 1.4 Economic Analysis of Expanded Slag Production

This task is repotted at length in Section 3 below.

Task 1.5 Reports

This task is aimed meeting the repotting requirements of METC throughout the project. The reports that have been provided to METC as per the schedule include the following:

- Laboratory and Economic Analysis Plan. This document comprising the project work plan was prepared as part of Task 1,1 and submitted to METC as per the project requirements.
- Technical Progress Reports. Six quarterly Technical and six quarterly Status Reports have been submitted to date as per the project requirements.
- Topical Report. The subject report is the final report for this phase of the project.

3.0 ECONOMIC ANALYSIS OF EXPANDED SLAG PRODUCTION (TASK 1.4)

The objective of this task is to develop capital and operating cost estimates for commercial production of slag-based lightweight aggregates (SLA) and to study the process economics. This effort involved developing a process flowsheet based on pilot plant operations data generated during the project, compiling a list of the process equipment needed for physical and pyroprocessing of slag to produce marketable lightweight aggregate products, and developing equipment-factored capital costs estimates, Two sizes of SLA production plants were considered in this study, as described below:

- Plant to process slag generated from a gasifier facility with a 200-MW equivalent capacity. Such a facility typically uses 2,000 tons/day of bituminous coal containing 10% ash. Depending upon the carbon conversion rate, this facility may generate 220 tons/day of slag containing 10% char. This approximates the size of a number of existing gasifiers in the United States.

- Plant to process slag generated from a gasifier facility with a 400-MW equivalent capacity. Such a facility would typically use 4,000 tons/day of bituminous coal containing 10% ash, Depending upon the carbon conversion rate, this facility may generate 440 tons/day of slag containing 10% char. This would approximate the feed capacity of a typical commercial LWA plant that currently uses expansible clays.

Since the commercial SLA production plant is assumed to be located “across the fence” from a gasifier facility, water and power requirements are assumed to be available at market cost at the site. The SLA production facility will consist of two sections, namely, (i) slag receiving and processing section for recovery of char and (ii) pyroprocessing section for SLA production. Coarse (+1O mesh) slag will be used to produce SLA in discrete particle form, and the fines will be used to produce extruded pellets, The facility includes product crushing equipment and product storage and handling bins sized in accordance with modem LWA industry practices. Major process equipment costs have been estimated based on the above assumptions, and used to prepare equipment-factored capital cost estimates for such plants, The capital and operating costs thus generated have an accuracy of ±25%, which is considered sufficient for conducting first-level economic assessments. Slag expansion process energy requirements were estimated by Fuller based on the pilot operations data generated during the project. Labor and other costs were estimated based on industry experience. A computer worksheet was developed and used to conduct economic evaluations of various alternative scenarios, as discussed in subsequent sections.

3.1 Costs of Production of Slag-Based LWA and ULWA (Task 1.4.1)

As a first step, the costs of production of various expanded slag products were estimated for two different sizes of commercial-scale plants. The design criteria for a plant processing slag from a 200-MW capacity gasifier are given in Table 21, Similarly, material balances were generated for the 440-t/d system and are provided in the same table.

Table 21. Design Criteria for Plant Processing of Gasifier Slag

Criteria	**200 MW**	**400 MW**
Coal usage, #d	**2000**	**4000**
Coal ash, %	10	10
Operation, days/year	365 @ 90% availability	Same
Slag generated	220 t/d (72,270 t/y)	440 t/d (144,540 t/y)
Processing yield, %	73.3	73.3
Prepared slag	161.3 t/d (52, 987 t/y)	322.6 t/d (105,974 t/y)
Char primary concentration, t/d	58.7	117.4
Char concentration (fuel), t/d	17.6	35.2
Reject slag (disposal), t/d*	41.1	82.2

*Reject slag and char are assumed to be disposal streams for purposes of this evaluation. However, these materials are currently being evaluated for use with fine slag to make extruded pellets.

The following assumptions were made in projecting SLA production costs:

- Expanded slag products with unit weights ranging between 20 and 50 lb/ft^3 would be produced by controlling the expansion temperature. SLA product densities would be targeted to match the requirements of most LWA applications and selected ULWA applications.

- The char recovered from the slag is assumed to provide 50% of the fuel requirements for pyroprocessing using a rotary kiln. In a fluidized bed system, the char would provide up to **80%** of the fuel requirements. Fuel requirements for the two sizes of plants would be as follows:

Case	**Slag Feed (t/d)**	**Fuel**	**Fuel Rate (MBtu/ton of feed)**	**Btu from Char (%)**
Al: Small rotary kiln	220	Coal/char	2.32	50
A2: Large rotary kiln	440	Coal/char	1,8	50
B1: Small fluidized bed	220	Bunker C/char	2.5	80
B2: Large fluidized bed	440	Bunker C/char	2.5	80

- Coal is the preferred fuel for a rotary kiln system because it is relatively cheap and readily available at the gasifier site. The cost of 11,500 Btu/ton coal delivered at the site is assumed at $30/ton or $1 .30/MBtu. Oil would be the preferred fuel for a fluidized bed expander system. The cost of Bunker C oil is assumed at $2.80/MBtu.

- A plant useful life of 20 years is assumed, and a straight-line depreciation method is used in assessing plant capital expenses.
- Plant capital costs are allowed a contingency of 15%.
- The cost of borrowing capital is assumed at 8%, and the interest expenses are applied to operating costs.

Slag Lightweight Aggregate Production Costs Using a Rotary Kiln. Based on the assumptions given above, SLA production costs were compiled for two plant sizes for both the kiln and fluidized bed pyroprocessing methods. Table 22 provides estimated costs generated by Praxis for production of SLA at 220 t/d and 440 t/d feed capacity from similar (rotary kiln) processing systems. The table also provides current conventional LWA production costs which were compiled based on a survey of four plants. The costs compiled for the slag processing plant assume that the necessary capital is borrowed at 8% interest. As may be seen in the table, the cost advantages for the slag-based operation are provided by (i) the ability to use char as a fuel in the kiln to meet 50% **or more of the total** energy requirements and (ii) the absence of mining costs. The disadvantages are: (i) high interest on capital expenses and (ii) the inability to take advantage of economies of scale in a small operation. However, a larger plant servicing the output of a 400-MW capacity gasifier would be able to use a large rotary kiln of a comparable size to those used in most commercial LWA operations.

Table 22. Comparative Per Ton Costs of Producing LWAS from Slag

Cost Item	**Shale. $/ton**(1)	**Slag $/ton**(2)	**Slag, $/ton**(3)
System type	Large rotary kiln	Small rotary kiln (Al)	Large rotary kiln (A2)
Fuel	Oil	Coal/char	Coal/char
Mining and preparation	6.00		
Transport ore to plant	0.50		
Processing Costs			
Clay binder		**1.45**	1.45
Labor (M&O)	6.23	7.50	6.25
Fuel	5.09	2.12	1.64
Power	1.37	1.35	1.35
M&S	1.85	1.94	1.48
Other	1.11	1.10	1.10
Overhead	2.24		
Depreciation	5.71	5.62	4.28
Interest on capital	not known	8.99	6.85
Total	30.10	30.07	24.40

(1) Fuller survey of four LWA plants; mining costs added later.
(2) Praxis estimate for 220 t/d raw slag system.
(3) Praxis estimate for 440 t/d raw slag system.

Slag-Based Ultra-Lightweight Aggregate Production Costs Using a Fluidized Bed Expander. In Table 23, the estimated costs for producing SLA using the fluidized bed method are presented alongside those for conventional ULWA production. This estimate is based on information provided by a leading manufacturer of expanded perlite. We have produced expanded slag products with unit weights as low as 18 lb/ft^3.

Table 23. **Comparative Per Ton Costs of Producing ULWA from Slag**

Cost item	**Perlite, \$/ton(1) 4-6 lb/ft^3**		**Slag, \$/ton(2) 15-16 lb/ft^3**
Processing method	Vertical shaft furnace	Small fluidized bed (B1)	Large fluidized bed (B2)
Mining and preparation	40.00		·
Shipping ore to plant	40.00		
Processing Costs			
Binder for fines		1.45	1.45
Labor	12.00	7.50	6.25
Fuel	8,00	1.34	1.29
Power	4.50	1.35	1.35
M&S	3.00	1.70	1.29
Other, loading	2.00	1.10	1.10
Overhead	10.00		·
Depreciation	4.75	4.63	3.52
Interest	unknown	7.41	5.63

(1) Silbrico data.
(2) Praxis estimate for slag.

In comparing the production costs of expanded slag with those of expanded perlite, a volumetric correction may need to be applied to the slag because it has a considerably higher unit weight. As may be seen in the table, the production costs of expanded slag would be lower than those of conventional perlite-based ULWAS. However, the equivalent SLA product has higher strength which can provide many advantages.

3.2 Market Assessment of Conventional LWA and SLA (Task 1.4.3)

The objectives of this subtask are to obtain an initial assessment of the market value of various conventional LWA products targeted for substitution by slag and to estimate the market value of the corresponding expanded slag products. The market value of the LWA is used to estimate the projected value of the SLA. As a first step, various trade associations and major users of LWA and ULWA were contacted to obtain price structures and marketing information. Contacts with these organizations allowed us to estimate accurately the current sale prices of various aggregates. These contacts included:

- Expanded Shale, Clay and Slate Institute
- Perlite institute
- National Concrete Masonry Association,

Conventional Lightweight Aggregate Production, Costs, and Markets. Development of a market assessment for SLA included identification of the current market for conventional LWAS and ULWAS and specific applications for which SLA would be an acceptable substitute. According to U.S. Bureau of Mines data, shown in Table 24, production and consumption of lightweight materials was 7.6 million tons in 1991, including expanded shale production of 3.96 million tons. These products are typically sold for $35-$50 per ton. The current annual production of lightweight and ultra-lightweight materials is estimated at 10 million tons. This excludes fly ash, which has a unit weight of 70 lb/ft^3 and is also used as a medium lightweight material.

Consumption and production of these materials is greatly dependent on production and transportation costs. Therefore, if cheaper by-product materials can be used to produce these products—especially at lower energy requirements—consumption will be significantly increased.

Table 24. U.S. Production of Expanded Shales, Clays, and Volcanic LWAS

Mineral	1990	1991
Shales and clays, million yd^3	18.58	17.6
Shales and clays, million tons	4.18	3.96
Pumice, pumicite, million tons	0.487	0.441
Volcanic cinders, scoria, million tons	3.2	3.2
Total, million tons	7,87	7.6

Conventional Ultra-Lightweight Aggregate Production, Costs, and Markets. Conventional ULWAs have unit weights in the range of 4-12 lb/ft^3 and are produced by thermal expansion of perlite and vermiculite ores at temperatures of 1600-2000°F. Their low unit weight and thermal conductivity (as low as 0.35 Btu-in/h-°F at a loose weight of 2.5 lb/ft^3) make ULWAs ideal insulating materials for loose fill insulation and aggregates for the manufacture of insulating concrete and numerous other insulation applications. Other applications for expanded perlite include filtration media, industrial fillers, abrasive in cleaners and polishes, soil amendment for horticulture, carrier of chemicals for pesticides and fertilizers, and acoustic material.

U.S. Department of the Interior production and consumption figures **for expanded perlite and vermiculite are given in Table 25. The actual domestic consumption of perlite ore in 1991 was 595,000 tons, which takes into account the import of 60,000 tons and export of 32,000 tons. The drop in production in 1991 is related to increased prices and softening demand due to the decline in industrial and commercial construction activity. The total market value of the 498,000 tons of**

finished products made from expanded peditewas $101,695,000 or$204 perton. Expanded perlite typically retails at $2.00/ft^3, which corresponds to $500/ton based on an average unit weight of 8 lb/ft^3 for the expanded products. The consumption of these materials is also highly sensitive to their costs of production; the availability of low-cost alternate feedstocks such as slag could increase the consumption of these materials.

Table 25. U.S. Production of Perlite and Vermiculite

Mineral	1988	1989	1990	1991
Perlite, tons	576,000	601,000	635,000	567,000
Vermiculite, tons	304,000	275,000	230,000	185,000
Total ULWA raw material, tons	880,000	876.000	865.000	752.000

Economics of Production of ULWA from Slag. Slag has been demonstrated to produce an expanded aggregate which may be used as a substitute for ultra-lightweight aggregates (ULWA) for some applications. The technical and economic advantages of producing ultra-lightweight aggregates from slag include the fact that, being a waste material, it is available at no or low cost. Prepared perlite ore, in contrast, sells at $40 per ton which includes the high costs for transportation from New Mexico to various production facilities. In comparison, no mining costs are involved for slag, energy requirements for expansion may be lower than those for perlite expansion, and the avoided disposal costs may be a major factor favoring its utilization,

Assessment of Market Price of SLA. In order to establish sale prices of SLA to be used to make various products, a market survey of the prices of structural LWAS was conducted by contacting manufacturers. The prices varied considerably by region, as indicated below:

Location	$/yd^3	$/ton
East coast	17.00	25.00
Midwest	20.00	30.00
West coast	30.00	44.00
Average	22.33	33.00

Prices also varied for each application due to a number of factors such as quality and size preparation. Typical prices quoted for major applications are given in Table 26.

Table 26. Market Survey of Prices of Lightweight Aggregates

Application	LWA Price ($/ton)	SLA Price ($/ton)	SLA Product
Block aggregate	37.00	30,00	IO x 50M SLA
Structural concrete	45.00	35.00	Extruded fines
Roof tiles	50.00	40,00	Extruded fines
Expanded perlite	150.00	40.00	+10M SLA

As a new product would command a lower price, the sale prices for slag-based aggregates were established at $30/ton for block aggregates, $35/ton for structural aggregates, and $40/ton for roof tile and ultra-lightweight aggregate applications. Using a product mix based on the percentage of coarse and fine slag, the weighted average price of SLA was estimated at $34.75/ton. This price was used for purposes of economic evaluation of SLA production.

3,3 Solid **Waste Management Costs (Task 1.4.2)**

The objectives of this subtask are to compile solid waste management costs for slag from a gasifier on a $/ton and $/ft^3 basis. These avoided costs are used as credits in the economic evaluation of expanded slag. Solid waste management costs typically include the following:

- Site preparation
- Handling and transportation
- Storage and compaction
- Land reclamation
- Runoff, drainage, and seepage monitoring,

Solid waste management costs are very site-specific due to transportation and site-related costs. Therefore, they vary considerably depending on the distance over which the solid waste has to be transported for disposal. They also vary on a regional basis depending on the availability of land for solid waste disposal. Thus, disposal costs in the northeastern United States would be the highest due to the limited availability of disposal sites. Our information is that typical utility waste disposal costs range between $10 and $20 per ton. For purposes of this analysis, a value of $1 5/ton is used as the disposal cost. Since these avoided costs would provide a substantial savings to the gasifier operation, this amount could potentially be made available to the slag aggregate production facility as a tipping fee per ton of slag,

3,4 Economic Evaluation (Task 1.4.4)

An economic analysis of SLA production was conducted for two production capacities using two alternative pyroprocessing methods. The four case studies developed to study the process economics are:

- Case Al: Small rotary kiln plant for SLA production using the slag output from a 200-MW equivalent gasifier generating 220 t/d of slag
- Case A2: Large rotary kiln plant for SLA production using the slag output from a 400-MW equivalent gasifier generating 440 t/d slag
- Case 61: Small fluidized bed plant for SLA production using the slag output from a 200-MW equivalent gasifier generating 220 t/d slag
- Case 62: Large fluidized bed plant for SLA production using the output from a 400-MW equivalent gasifier generating 440 t/d of slag.

A computer model was developed to compile the capital costs and conduct overall economic analyses for various case scenarios for the production of slag-based lightweight products. The worksheet covers the following issues:

- Capital costs for slag handling, preparation, pyroprocessing, and contingencies
- Direct operating costs (operating and maintenance labor, maintenance materials, consumables, and other costs)
- Indirect costs (depreciation, interest on capital)
- Credit for avoided costs of disposal of slag
- Costs for producing SLA and impact of credit for avoided disposal costs
- Economics (payback period and return on investment based on market prices commanded by conventional LWA products.

The economic advantages of slag-based lightweight aggregates over conventional materials are that no mining costs are involved and pyroprocessing costs are almost identical. Since slags expand at a lower temperature than shales, they require 50% less energy during the thermal processing step. Adjustments were made for various items where additional costs are incurred for slag expansion. The preliminary economics of production of slag-based lightweight aggregate vs. conventional LWA based on data generated during pilot kiln operation are summarized in Table 27. The data indicate that the production costs of slag-based lightweight aggregates are essentially the same as those for conventional LWAS.

As maybe seen in Table 27, SLA production costs for the small rotary kiln (Case Al) at $30,06/ton are close to the production costs of conventional LWAS. Being a small operation, this case does not benefit from economies of scale and would not be profitable unless the avoided costs of slag disposal are taken into account. For Case A2, the projected production costs are $24.40/ton, which is fairly competitive with production costs at typical conventional LWA plants.

Cases B1 and B2, based on use of small and large fluidized bed systems, respectively, would be considerably more competitive due to lower capital and operating costs. Therefore, such systems should be considered for commercial SLA production, especially for lower-capacity plants. The economics for the larger-sized plant (B2) are especially attractive if the avoided costs of slag disposal are taken into account, as indicated by the payback period of under three years,

Table 27. Economic Analysis Summary

	Case A1	**Case A2**	**Case B1**	**Case B2**
System	Small rotary kiln	Large rotary kiln	Small fluid bed	Large fluid bed
System fuel	Coal/char	Coal/char	Bunker C/char	Bunker C/char
Slag feed, t/d	220	440	220	440
Pyroprocessing feed, t/d	188	377	188	377
Fuel rate, MBtu/t	2.32	1.80	2.50	2.50
Fuel costs, $/MBtu	1.30	1.30	2.68	2.68
Fuel from char, %	30	30	80	80
Capital costs, $	6,960,375	10,600,000	5,735,625	8,700,000
Pyro throughput, t/y	61,921	123,841	61,921	123,831
Direct O&M costs, $	15.45	13.27	14.44	12.73
Indirect costs, $	14.61	11.13	12.04	9.14
Total SLA production cost, $	30.06	24.40	26,48	21.87
Avoided disposal credit, $	-14,23	-14.23	-14.23	-14.23
Net SLA production cost, $	15,83	10.17	8.89	7,64
Total sales revenues, $	2,151,106	4,302,213	2,151,106	4,302,213
Projected gross margin, $/y	1,119,200	2,956,143	1,341,312	3,270,074
Average sale price, $/t	34.74	34.74	34.74	34.74
Projected gross margin, $/t	18.91	24.57	25.85	27.10
Payback period, years	6.2	3.6	4.6	2.7
Return on investment, %	16.1	27.9	23.4	37.6

4.0 **CONCLUSIONS**

The primary objectives of the Phase I experimental work were to demonstrate the feasibility of producing lightweight and ultra-lightweight aggregates with unit weights ranging between 15 and 50 lb/ft^3 from the primary slag (Slag 1) and to generate a sufficient quantity of expanded slag lightweight products (SLA) for use in Phase II. The technology was also demonstrated for a second slag (Slag 11) derived from an Illinois coal feedstock. Another goal was to utilize all size fractions of the slag, including fines, for production of slag-based lightweight aggregates (SLA). This was accomplished via the extrusion of slag fines with a clay binder prior to pyroprocessing. Other goals included the collection of engineering data (energy consumption, material balances, and emissions) from pilot plant operations. The findings of the Phase I work are presented in this report. Specific conclusions based on the work conducted in Phase I are given below.

Slag Processing for Char Removal. The project slag samples were successfully processed to remove the char content which has been proven to be deleterious for expansion.

- Char-free slag was recovered at yields of approximately 66%. A char product containing 45-54% ash was also recovered and was evaluated as a potential gasifier feed and kiln fuel.

- The char recovered from the first-stage separation was upgraded successfully to 70°A carbon (30°A ash). This material can be utilized as a substitute for 50% of the fuel in a rotary kiln and 80% of the fuel in a fluidized bed system. The remaining slag from the upgrading step can be recycled to the slag stream thus increasing yield.

SLA Production in a Direct-fired Rotary Kiln. Slag expansion using a direct-fired rotary kiln was accomplished in two forms: (i) expansion of coarse (1/4" x 50M) slag in discrete particle form, and (ii) expansion of pellets made from extruded slag fines mixed with an expansible clay binder.

- Expansion of the 1/4" x 50-mesh size fraction of Slag l was demonstrated to be feasible in the rotary kiln as a single size interval. The slag could also be expanded in any other size interval within this range to meet the specific requirements of a product.

- Density vs. temperature studies were conducted and product unit weights could be varied in the 30-50 lb/ft^3 range by means of temperature control. It was feasible to further reduce the product unit weight below 20 lb/ft^3 but not without potential fusion problems.

- The +10-mesh Slag II sample was expanded to produce a product with a unit weight of 20-30 lb/ft^3 at a temperature of 1450-1500°F.

- The slag expansion temperature is 300-400°F lower than that typically required for expansible clays and shales and represents significant energy savings.

Expansion testing of the pelletized slag fines using an expansible clay binder had two objectives: (i) demonstration of the use of clay as a binder, and (ii) demonstration that the clay can be blended with slag fines for expansion. Both of these objectives were met. The following conclusions can be drawn from this work:

- Size enlargement of extruded pellets made from minus 50-mesh slag mixed with 20-50% by weight of an expansible clay binder was successful. The size of the resulting aggregates can be controlled during extrusion.

- The use of higher proportions of slag resulted in lower pellet moisture, which would have a major effect on overall process fuel requirements, with greater use of slag lowering fuel costs.

- The firing temperature for the 80/20 and 50/50 slag/clay blends tested is approximately 1800-1900°F, which is higher than the expansion temperature of slag by itself but lower than that of clay. There was no indication of fusion with any of the extruded mixtures fired up to 2000" F.

- Expanded products with unit weights ranging between 27 and 33 lb/ft^3 were produced. The expansion temperature for these samples was nearly 200°F lower than that typically required for conventional expansible clay pellets, which represents considerable energy savings for slag expansion.

- Successful expansion of pelletized slag/clay blends in a 50:50 ratio indicates that these two materials can be blended to produce lightweight aggregates.

Production of LWA and ULWA **Using Fluidized Bed Expander.** The fluidized bed expansion method was selected to demonstrate the production of lower unit weight products because of its improved energy efficiency and better temperature control. A lower product unit weight can be obtained because particles do not come into contact with a high-intensity flame as occurs in the rotary kiln system. The objectives were to demonstrate the suitability of this expansion method and to test the acceptability of the recovered char as a fuel in the bed. These objectives were met, and the following specific conclusions were drawn:

- The various slag size fractions were expanded in discrete particle form in a pilot-scale fluidized bed expander to produce LWAS with unit weights ranging between 18 and 26 lb/ft^3.

- Extruded 1/2" slag/clay pellets made from minus 50-mesh slag fines were granulated to 8 x 20M to produce aggregates for block and roof tile applications, The product unit weight was limited to a minimum of 30 lb/ft^3.

- An attempt was made to test the use of char in the fluidized bed expander. However, the char feed tube became plugged and the results were inconclusive in the time budgeted for use of the pilot facility.

Laboratory Evaluation of SLA for Various Applications. The SLA products were characterized in preparation for demonstration in various end-use applications. The results of RCRA testing indicated that the TCLP leachate heavy metals concentrations were considerably lower than RCRA requirements. In addition, SLA product samples were prepared for laboratory evaluation for various applications in accordance with ASTM standards.

Roof Tiles. Three different kinds of aggregates were tested for possible application of SLA in roof tiles, Two different expanded aggregates (i.e., expanded slag and 50/50 slag/clay extruded pellets), along with a commercial LWA as the control, were tested for compressive strength as per ASTM C 109. Specimen 2" x 2" x 2" cubes were cast, steam-cured for 4 hours, and tested for compressive strength at 7 days. An aggregate-to-cement ratio of 2.5 was used, and a commercial accelerator and superplasticizer were added, The results are as follows:

- The 7-day compressive strength of the specimen made from 100% slag at 2800 psi is about 83% of the strength of the specimen made from commercial aggregate. The unit weight of the SLA specimen at 93 lb/ft^3 was 87°/0 of that of the conventional aggregate specimen. If a higher proportion of sand were used in the SLA mix design, both strength and unit weight would increase.

- The unit weight of the 100% slag and 50/50 slag/clay concrete specimens was 102 lb/ft^3. The strength of the 100% slag specimen is comparable to that of the 50/50 slag/clay mix.

Insulating Concrete. SLA was used to make a specimen of insulating concrete to test its insulating properties. The unit weight of the specimen was 51 lb/ft^3 and its 7-day strength was 175 psi. This work is still in progress.

In addition, the insulating properties of SLA as loose fill material are being studied,

Viability of Commercial SLA Production. The pilot test program conducted in Phase I confirmed that SLA products with unit weights ranging between 20 and 50 lb/ft^3 can be produced. These products meet the unit weight requirements of almost all LWA applications and selected ULWA applications. Two method of slag expansion (rotary kiln and fluidized bed calciner) were demonstrated successfully using 100% slag, blends of slag and conventional LWA, and expansible clays. The technical and commercial advantages of utilization of slag to make lightweight aggregates may be summarized as follows:

- No mining costs are involved in procuring the raw material.

- The expansion temperature of slag is lower than that of conventional clays and shales and thus energy requirements are lower.

- Char recovered from the slag can be used to provide 50-80% of the fuel requirements for slag expansion, depending on the expansion system selected.

- Slag may be used for most LWA and selected ULWA applications, thus giving it as wide a market as conventional materials.

- Slag can be expanded by itself or after blending with expansible clays, This would enable the use of slag as a substitute for conventional expansible clays and shales in existing LWA plants.

- First-generation gasification plants generating 200-300 tons/day of slag could use the fluidized bed expansion method rather than the rotary kiln in order to be more profitable. Alternatively, slag could be trucked to an existing LWA production plant. The economics of this alternative will be studied in Phase II of the project.