Component Level Modeling of Materials Degradation for Insights into Operational Flexibility of Existing Coal Power Plants

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Acknowledgements: DOE Fossil Energy

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Outline

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Introduction

Project Objective and Team

Project Approach to Meet Technical Targets

Task 2.0 - Collect boiler/steam turbine plant operating data

- **Subtask 2.1 – *Boiler/Heat exchanger component down-selection and requirement definition***
- **Subtask 2.2 – *Steam turbine component down-selection and requirement definition***

Task 3.0 – Fireside corrosion/steam oxidation/creep modeling of superheater/reheater tubes

Task 4.0 – Water droplet erosion modeling for low pressure (LP) steam turbine blade

Task 5.0 - Modeling Data Validation and Scale-up Opportunities

- **Subtask 5.1 – *Constitutive model/tool validation***
- **Subtask 5.2 – *Component design/analysis for scale-up opportunities***
- ***Subtask 5.3 - Techno-economic analysis for model output***

Project Schedule and Milestones

Synergistic research for component level modeling for insights into operational flexibility of existing coal power plants

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Project information

PI: Anand Kulkarni

Funder: DOE Office of Fossil Energy (FE) – NETL Crosscutting

Strategic Partner: Siemens Gas and Power, Cranfield University

Total Project Funding: $937.5K ($750K Federal/$187.5K Cost share)

Project Details

- **Generate CFD/FE models for the prediction of deposition/erosion/corrosion around the fireside surfaces of a superheater/reheater boiler/heat exchanger tube.**
- **Generate CFD/FE models predicting the extent of steam oxidation within a heat exchanger tube or steam pipe, and the impact that plant cyclic operation will have on oxide spallation.**
- **Generate CFD/FE models for multiphase fluid flow predicting water droplet erosion for last stage low pressure turbine blade.**
- **Determine the impact of plant operations (fuel/operational flexibility), validated with service feedback data using plant and pilot-scale rig data (where available), on the response/trends of the three component/material CFD/FE models generated.**

Technical Highlights

Funding Opportunity Objective		Objective of the Proposed Work
Advanced modeling tools for existing power plant issues and mitigation	⇨	Component level modeling utilizing computational fluid dynamics for materials degradation for existing coal power plant issues
Insight into existing coal plant challenges and mitigation solutions	⇨	Modeling activities will focus on 1) Creep/fireside corrosion/erosion/steam oxidation in superheaters/reheaters and steam pipework and 2) water droplet erosion resulting in fatigue failure of last stage steam turbine blades
Materials degradation for operational flexibility	⇨	Multidisciplinary models for for solid particle impingement/ oxide scale exfoliation within the boiler tubes and dropler impingement in steam turbine to be evaluated with stress changes due to cyclic operations
Analytics results from model validated from plant data	⇨	Validation of modeling results via service run data (destructive metallurgical analysis) to correlate model and design assumptions to actual power plant performance

The proposed innovation is in developing a computational fluid dynamics/finite element (CFD/FE) modeling toolkit for the component level models to tackle multidisciplinary failure mechanisms occurring concurrently for extreme environment materials. Lifetime assessment in such environments also needs to account for the unit-specific analyses, operational history and fuel feedstock; this can only be obtained by destructive analysis of components. This, in turn, enables validation of the model toolkits utilizing service feedback data, improving the probability of time/temperature dependent life prediction.

Project Approach for Component Modeling for Existing Power Plants

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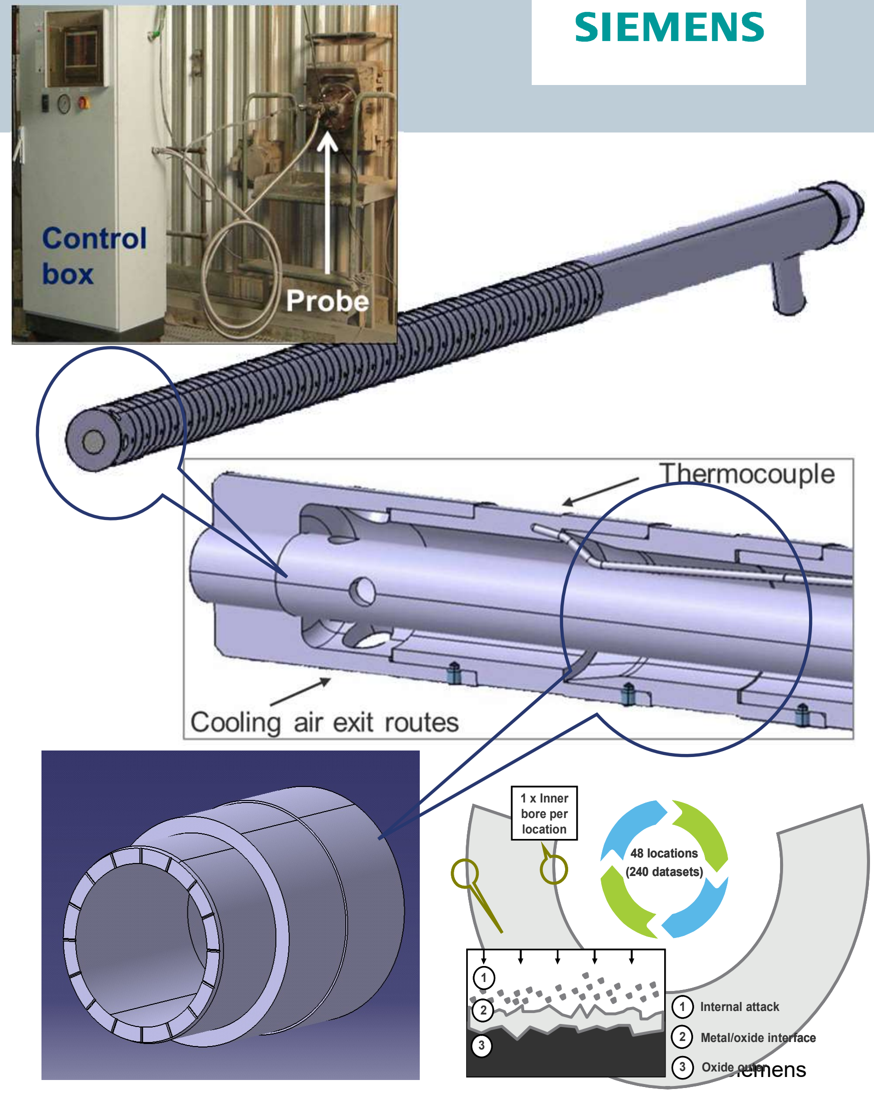
Year 1	Year 2	Year 3
Computational CFD/FE toolkit Framework	Model simulation for Multidisciplinary failure mechanisms	Heat exchanger and steam Turbine Component model Validation with plant data
Technical Progress Computational CFD/FE for failure mechanisms observed. Plant operations data for existing power plants as input for computational simulations	**Technical Progress** Computational tools developed for life calculations to accommodate baseload and cyclic operations Basis for design alternative to operational flexibility	**Technical Progress** Validation of CFD/FE computational models with plant data Validated life assessment methodology for heat exchanger and steam turbine
Go / No-Go CFD/FE toolkit framework with plant operations data and component performance and issues	**Go / No-Go** Develop one stop tool interface for model liking to design data and FEA package for component model analysis	**Program Success** Integrated framework established for robust life prediction assessment for operational flexibility and future plans

Task 2.0 - Collect boiler/steam turbine plant operating data

- **Data gathered on plant component materials degradation to establish CFD/FE model framework**
- **Data from exposures previously carried out in UK power plants (e.g. Tilbury, Ironbridge, Ratcliffe) for ‘Innovate UK’ projects (ASPECT and ASPIRE), EU NEXTGENPOWER project and earlier superheater/reheater tube monitoring**
- **Data include fireside corrosion damage measurements from inspections of heat exchanger tubes operated in pulvisered coal fired power plants as well as temperature-controlled probes of materials/components installed in plants for evaluation.**
- **Datasets gathered includes fuel compositions and operating environments – but every exposure has gathered different sets of exposure parameters**
- **Datasets allow the range of exposure conditions and alloy/coating fireside corrosion in superheater/reheater tubes in historic coal-fired UK pulverised fuel power stations to be quantified**
- **These data feed into the development/validation of fireside corrosion model (part of Task 3.2).**



Subtask 3.0: Fireside degradation

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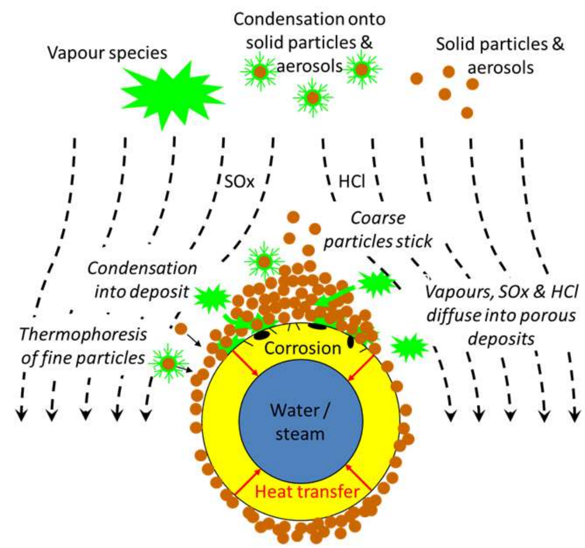
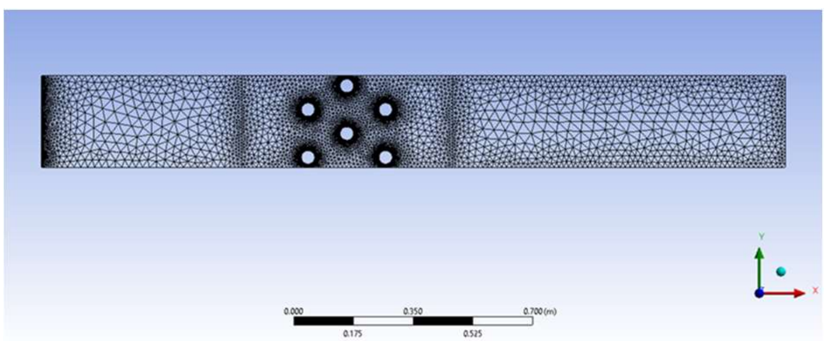
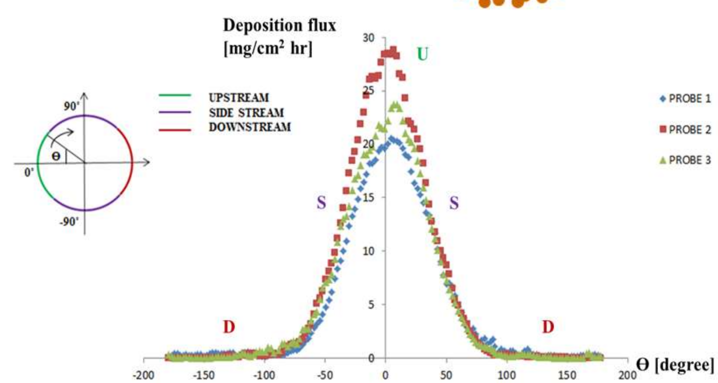
- Starting point was 2D Fluent deposition model incorporating multiple deposition mechanisms (via user defined functions, UDFs) applied to 3 tubes
- 2D Fluent CFD model for deposition in a pilot-scale combustion unit has been reconfigured into a 3D geometry with increasing numbers of tubes:
  - Images on this/next slide show 2D 6 and 12 tube versions
  - Images on the next slide show 3D 6 tube versions
  - Trials are underway using the 3D mesh and the existing UDFs for multiple deposition mechanisms







Subtask 3.0: Fireside degradation – Scaleup of rig configuration

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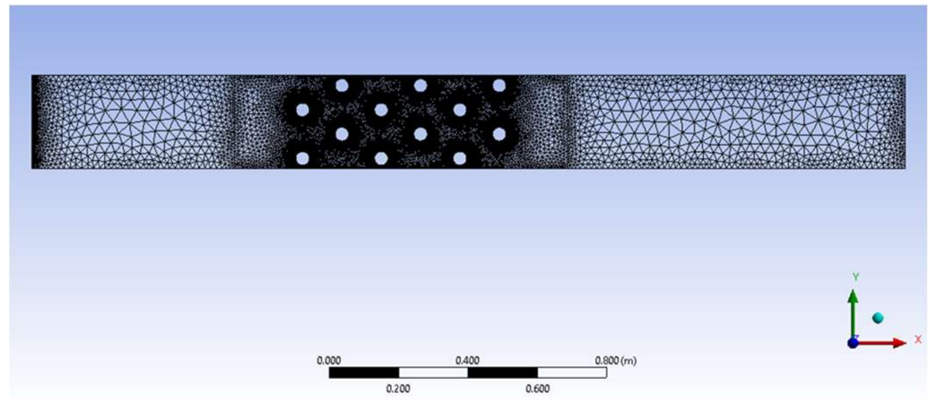
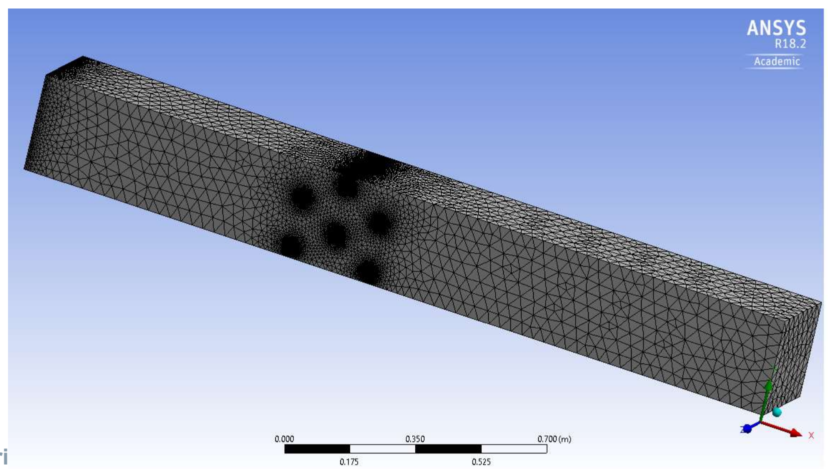
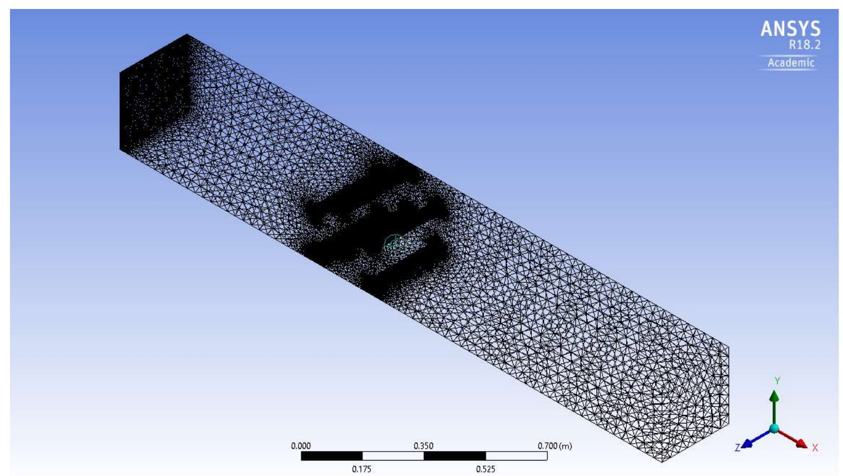
- Vapour deposition parts of existing UDFs are being expanded from just sodium sulphate to include more of the sodium and potassium species found in coal combustion environments
- Initially model using existing test rig geometry – as data already exists for validation – extend to layouts of heat exchanger tubes in UK power plants used in previous research.







Subtask 3.0: Fireside degradation – model development

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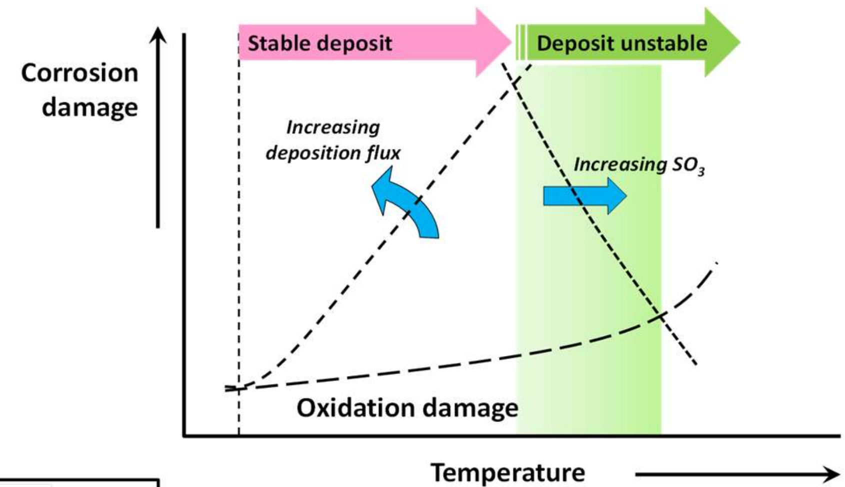
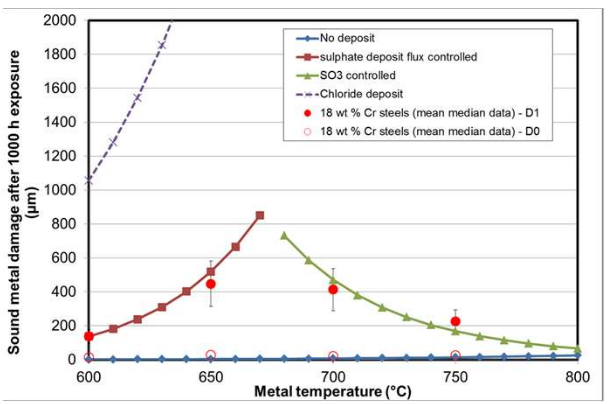
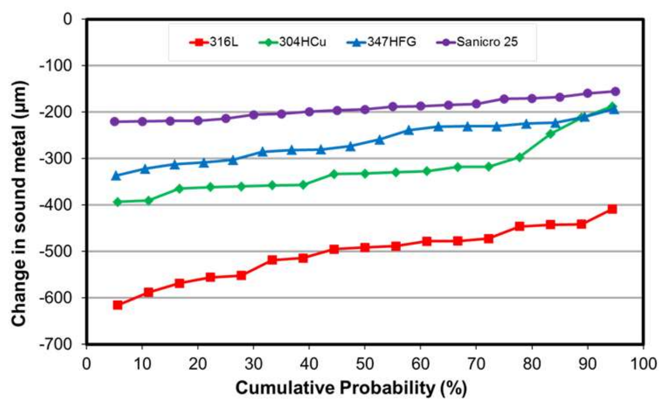
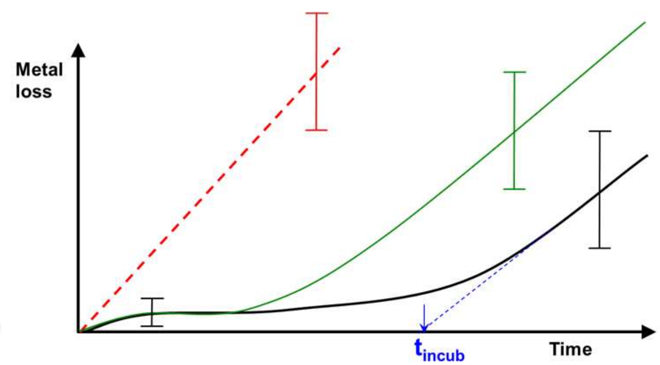
- Development of equations for fireside corrosion models, in terms of metal losses, to link to output parameters in CFD codes (e.g. gas phase concentrations, deposition fluxes, metal surface temperature)
  - Initially focusing on 347HFG steel
  - Data from plant exposures (gathered in Task 2)
  - Data/modelling concepts from lab exposures



Accelerated (high flux) lab testing at 650 °C







Task 4.0 – Water Droplet Erosion Modeling for Low Pressure (LP) Steam Turbine Blade

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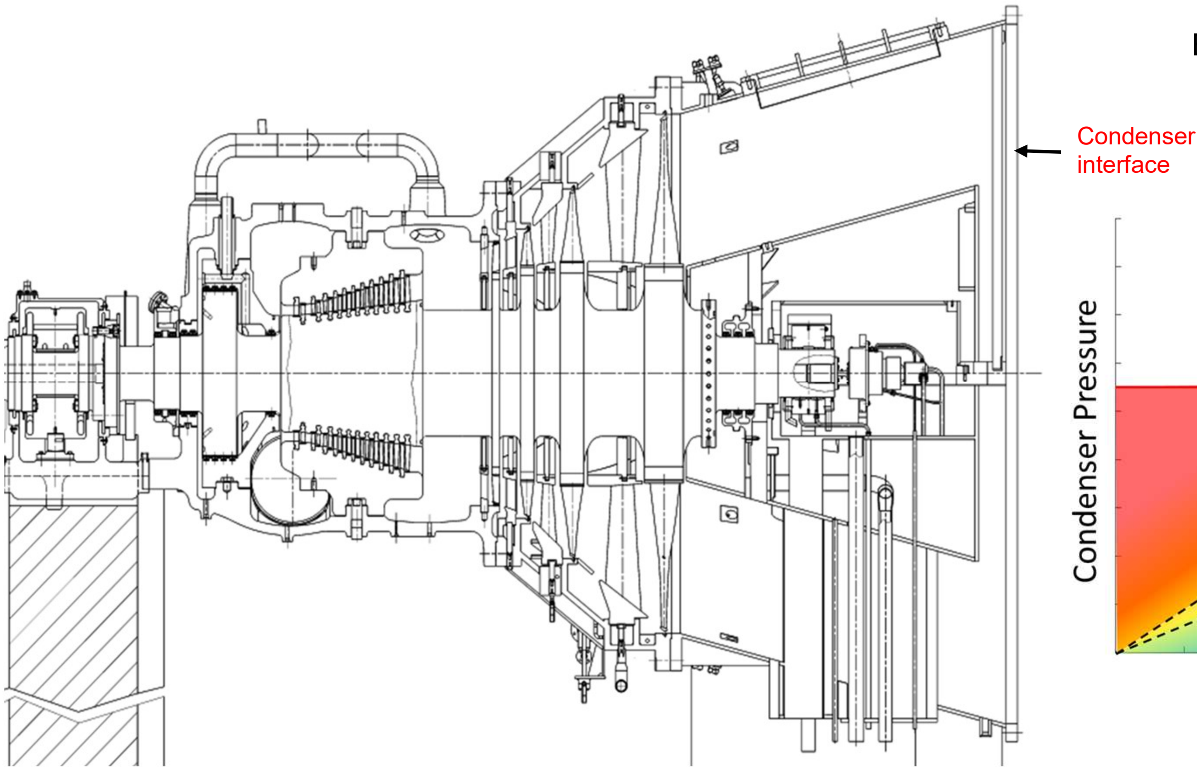
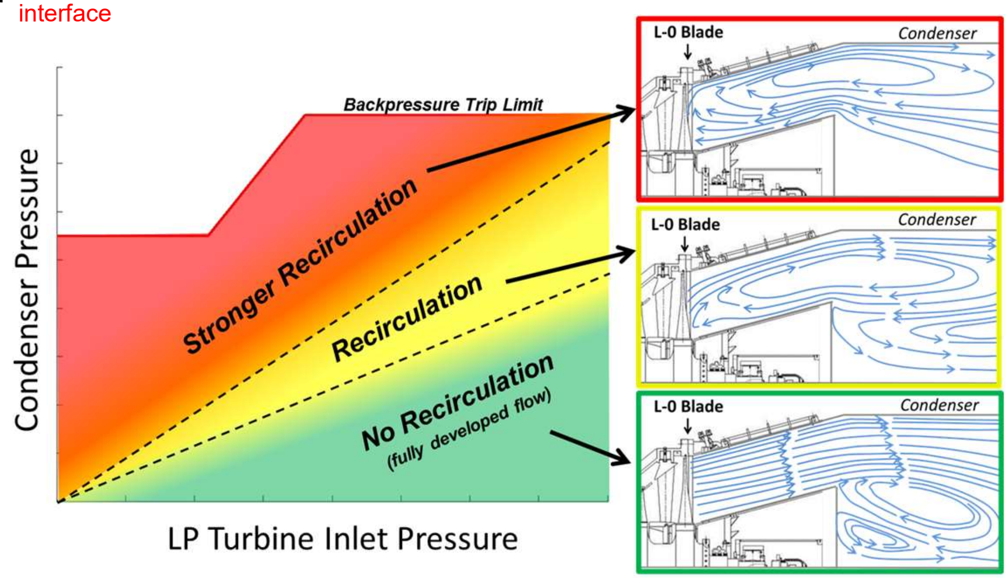


Exhaust Recirculation as a Function of LP Inlet Pressure and Condenser Pressure

(General illustration only. Not to scale)



In general, as backpressure increases for a given load, the potential for flow recirculation increases

10.3m² Titanium Blade Trailing Edge Erosion Background

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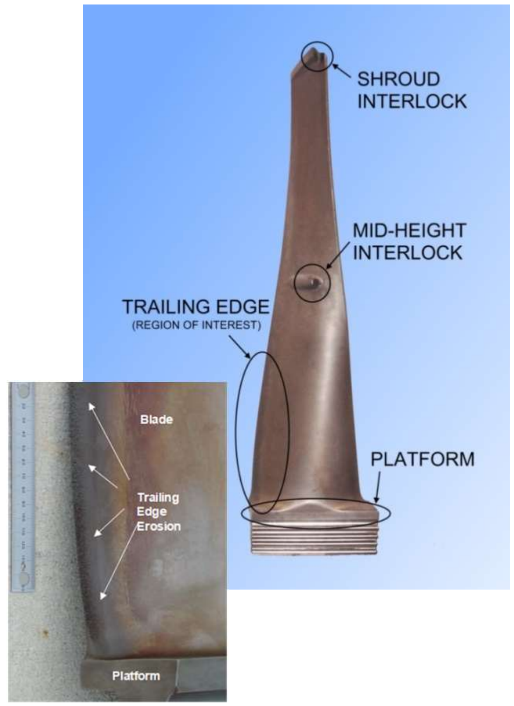
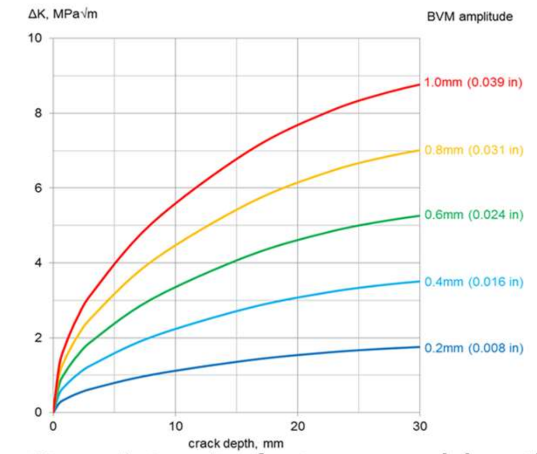
Trailing Edge Erosion

Observed on the convex surface of the airfoil on all current styles of last row titanium blades on some units.

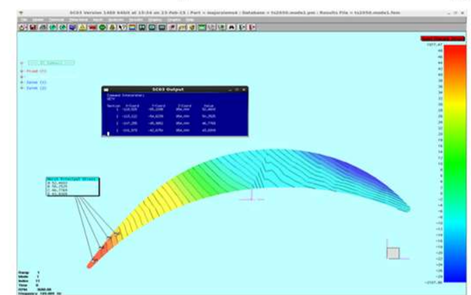
The erosion observed has varied, but in some cases has extended from the portion of the airfoil trailing edge just above the blade platform to as high as the mid-height interlock.

Blade airfoil cracks have been observed to initiate in the lower third of the airfoil.





Stress intensity factor vs crack length



Computed vibratory stress

Cracks originating in a heavily eroded region of the trailing edge have led to blade separation events on some units

10.3m² Titanium Blade Trailing Edge Erosion Contributors

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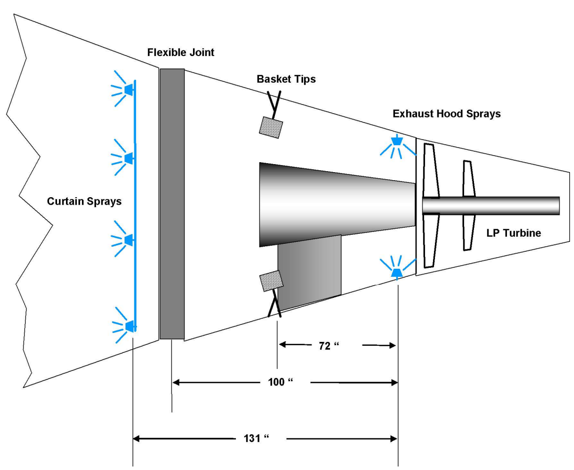
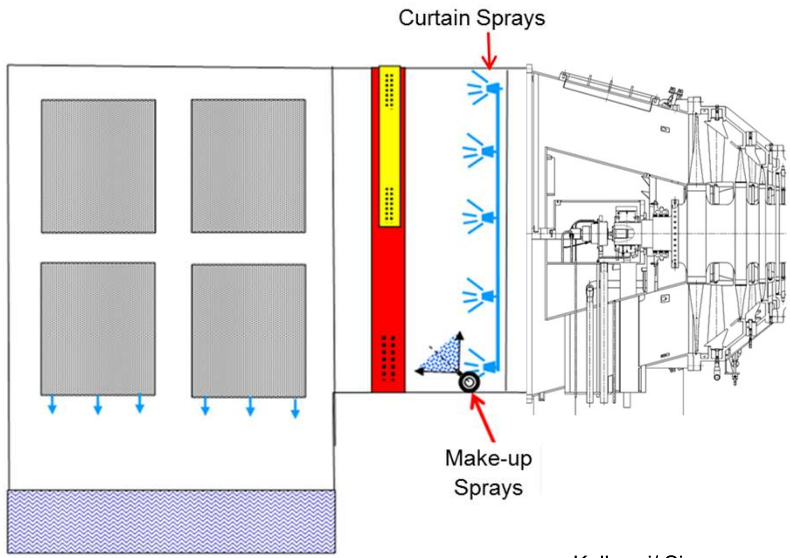
Downstream Moisture

- The layout and operation of the condenser, including the steam bypass system and the associated condenser spray systems, have been identified as factors in the amount of downstream moisture available to be recirculated back toward the turbine
- These spray systems, depending on their orientation and location in a particular unit, can provide the moisture necessary for erosion to occur



Curtain Sprays are located approximately 12 feet from the L-0 blades.

Nozzles are oriented away from the steam turbine..



Example Moisture Sources in Condenser

Kulkarni/ Siemens

Task 5.0 – Modeling Data Validation and Scale-up Opportunities

Global model

Simulate large portions of HSRG to capture thermal gradients:

- using homogenized models
- alternatively using beam elements (beam creation could be automated via scripts for large assemblies)

global deformations

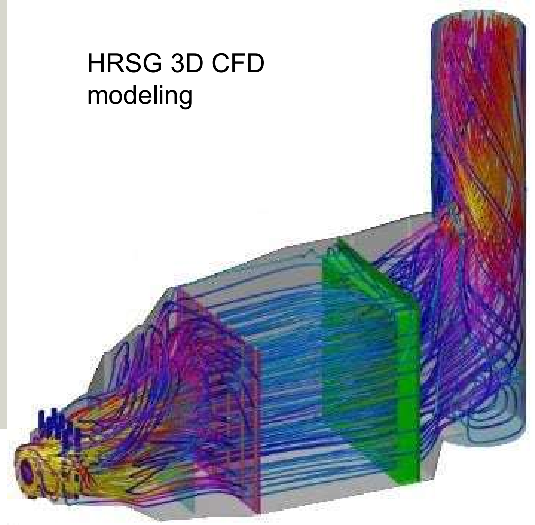
Submodels

Create detailed 3D models of separate tubes (or other points of interest) and apply global deformations as BC's.

HRSG 3D model

Tube bundles 3D arrangement

HRSG 3D CFD modeling



Milestones and Deliverables

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Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification method
	Year 1 (Oct 2019 – Sept 2020)		
3.1	Definition of heat exchanger detailed geometry and operating conditions	4/30/2020	Framework for modeling
2.0	Gather data on plant component materials degradation to establish CFD/FE model framework	7/15/2020	Technical report
4.1	Definition of steam turbine detailed blade geometry and operating conditions	6/30/2020	Framework for modeling
	Year 2 (Oct 2020 – Sept 2021)		
5.1	Component level models for heat exchanger tubes and steam turbine blades	11/30/20	Component models
3.1	Deposition / fireside corrosion / erosion / steam oxidation materials degradation model analysis for heat exchanger tubes for metal loss predictions	5/14/2021	CFD Modelling
4.2	Comparison of steam droplet erosion materials degradation models with plant / experimental data	9/15/2021	Technical report
	Year 3 (Oct 2021 – Sept 2022)		
3.2	Comparison of materials degradation models for heat exchanger tubes with plant / experimental data	12/15/21	Technical report
5.2	Validation of model toolbox for heat exchanger metal loss for baseload and cyclic operations	4/15/22	Technical report
5.2	Validation of model toolbox for steam turbine erosion and impact on fatigue life	6/15/22	Technical report
5.2	Validation of component level modeling for heat exchanger and steam turbine blade with existing plant data	8/31/2022	CFD/FE Modeling
6	Final technical report detailing component modeling activities for heat exchanger/steam turbine for existing power plant issues	9/30 /2022	Technical report

Milestone No.	Phase 1	Plan
2	**Gather data on plant component materials degradation to establish CFD/FE model framework** - Data report compiling insights into plant operations data and observed performance/issues after discussions with boiler manufacturers such as Babcock Power/Riley Power Inc, Doosan Babcock and plant operators such as Duke Energy, Emerson Power, Southern Electric, E.ON (now Uniper) and RWE to establish CFD/FE model framework	07/15/20
Milestone No.	**Phase 1**	**Plan**
5	**Deposition / fireside corrosion / erosion / steam oxidation materials degradation model analysis for heat exchanger tubes for metal loss predictions** - Demonstrate a CFD/FE modeling toolkit for heat exchangers to tackle multidisciplinary failure mechanisms occurring concurrently for extreme environment materials in coal power plants	05/14/21
Milestone No.	**Year 3**	**Plan**
10	**Validation of component level modeling for heat exchanger and steam turbine blade with existing plant data** Successfully conceive, develop, and demonstrate a validated life assessment methodology for baseload and cycle-based damage mechanisms for components of interest. Verify output with existing plant operational data].	08/31/22