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

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Acknowledgements

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Outline

Introduction

Project Objective and Team

Project Approach to Meet Technical Targets

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- **Subtask 2.1 – *Boiler/Heat exchanger component down-selection and requirement definition***
- **Subtask 3.2 – *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 team and expertise

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Anand Kulkarni, Siemens
Principal Investigator

Materials knowledge, Operational flexibility, Steam Turbines Field Experience, Design and analysis
Anand Kulkarni, Siemens
Bob Reynolds, Siemens
William McDonald, Siemens
- Materials performance
- Service/Field issues
- Modeling and simulations
- CFD/Heat transfer analysis
- Optimization expertise

Coal power boiler/heat exchangers, materials degradation in extreme environment, modeling and simulation
Nigel Simms, Cranfield University
Joy Sumner, Cranfield University
John Oakey, Cranfield University
- Coal power plant expertise
- Materials degradation in boilers
- Fireside corrosion/steam oxidation models
- Data analytics

Contract Administration
Kevin Go, Siemens
Kathy Sasala, Siemens
- Contract management

Financial Management
Terri Held, Siemens
- Financials, invoicing
- Subcontractor agreements

Senior Technical Advisors
Xavier Montesdeoca, Siemens
Michael Smiarowski, Siemens
- Steam turbine design and modifications

John Oakey, Cranfield
- Boiler design and performance expertise

Program Management
Jason Weissman, Siemens
- Risk analysis
- Program management

Team Member	Skill and expertise
Principal Investigator: Anand Kulkarni	Senior Key Expert; 25 years in research and technology in the area of materials/coatings for power systems, 10 years in materials needs for environmental and operational flexibility
Siemens Team: Bob Reynolds (BR) William McDonald (WM)	**BR**: Staff Scientist; 20 years' Computational Fluid Dynamics (CFD) experience in industry. Expert in various CFD applications including aerodynamics, conjugate heat transfer, Fluid-Structure Interaction, multiphase, phase change, reacting flow, Lagrangian particle tracking **WM**: Senior Engineer, Program Manager, 10 years' experience with design, service engineering and monitoring of steam turbines.
Cranfield Team: Nigel Simms (NS) Joy Sumner (JS) John Oakey (JO)	**NS:** Professor; 30 years' experience of power generation systems, Development of advanced higher efficiency and lower emission thermal power systems, Performance of components in conventional and advanced power systems. **JS:** Senior Lecturer, Expert in degradation of materials in coal and gas-fired power plants **JO:** 30 years' experience of power generation systems, with emphasis on the development of advanced higher efficiency and lower emission thermal power systems

The technical team is strong and has been working together for 15+ years

Project approach for component modeling for existing power plants

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Year 1 Computational CFD/FE toolkit Framework	**Year 2** Model simulation for Multidisciplinary failure mechanisms	**Year 3** 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

Development approach to advance technology

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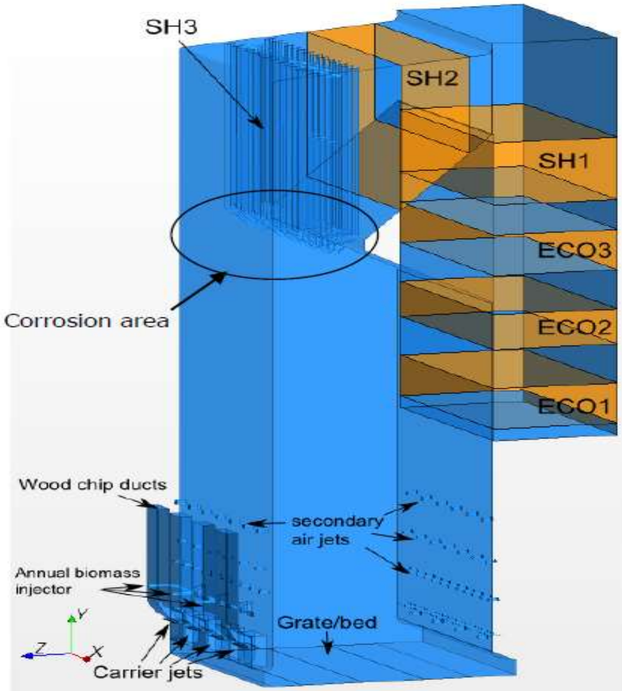
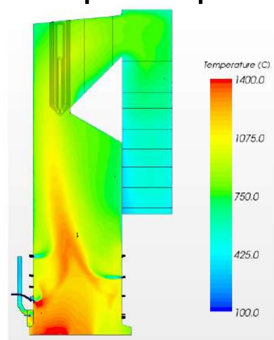
Simulated domain containing the boiler with super heater and economizers

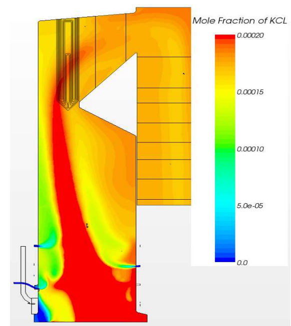


Svend S. Petersen, Master Thesis, 2012

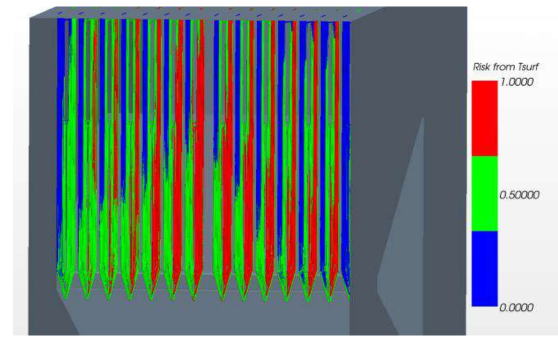
Temperature profile



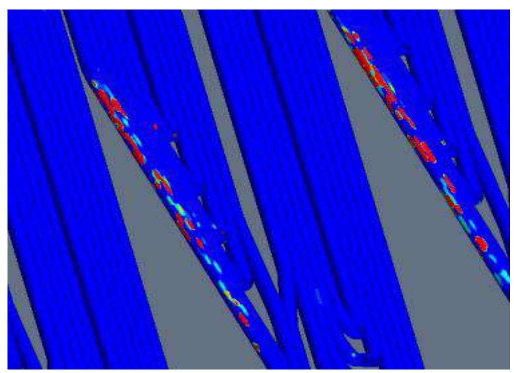
Concentration of KCl



corrosion risk on the SH3 surface



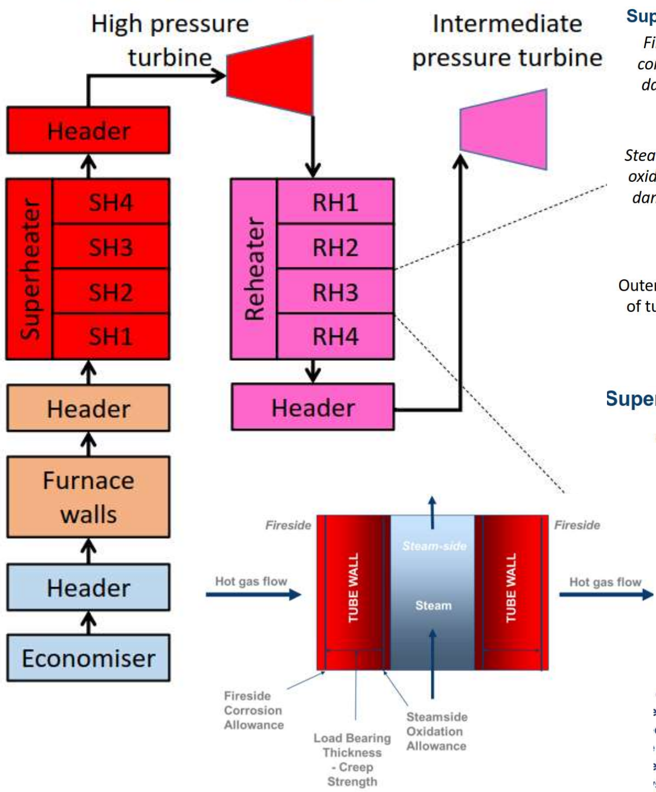
Prediction of ash buildup on SH3 on front side facing flow

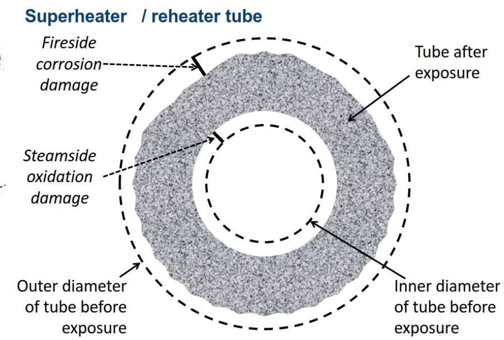


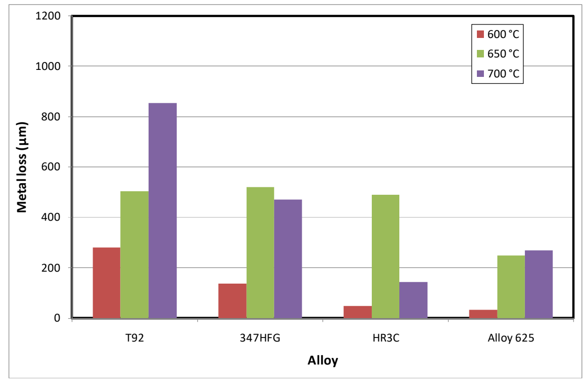
Simulation models for corrosion to predict localized high risk corrosion areas – Monitoring, Mitigation and Reduced repair costs/Forced Outages

Task 2.0 - Collect Boiler/Heat exchanger/Steam turbine plant operating data

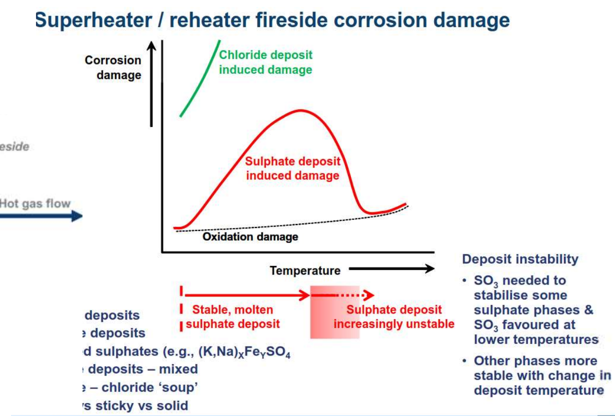
Part of steam circuit

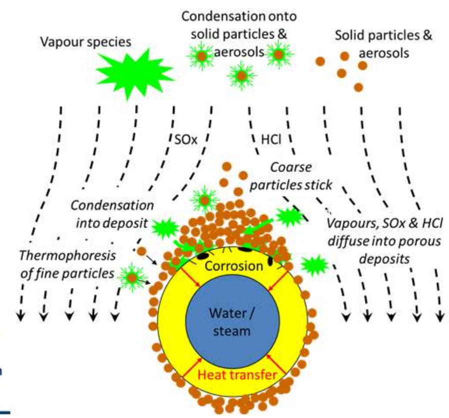






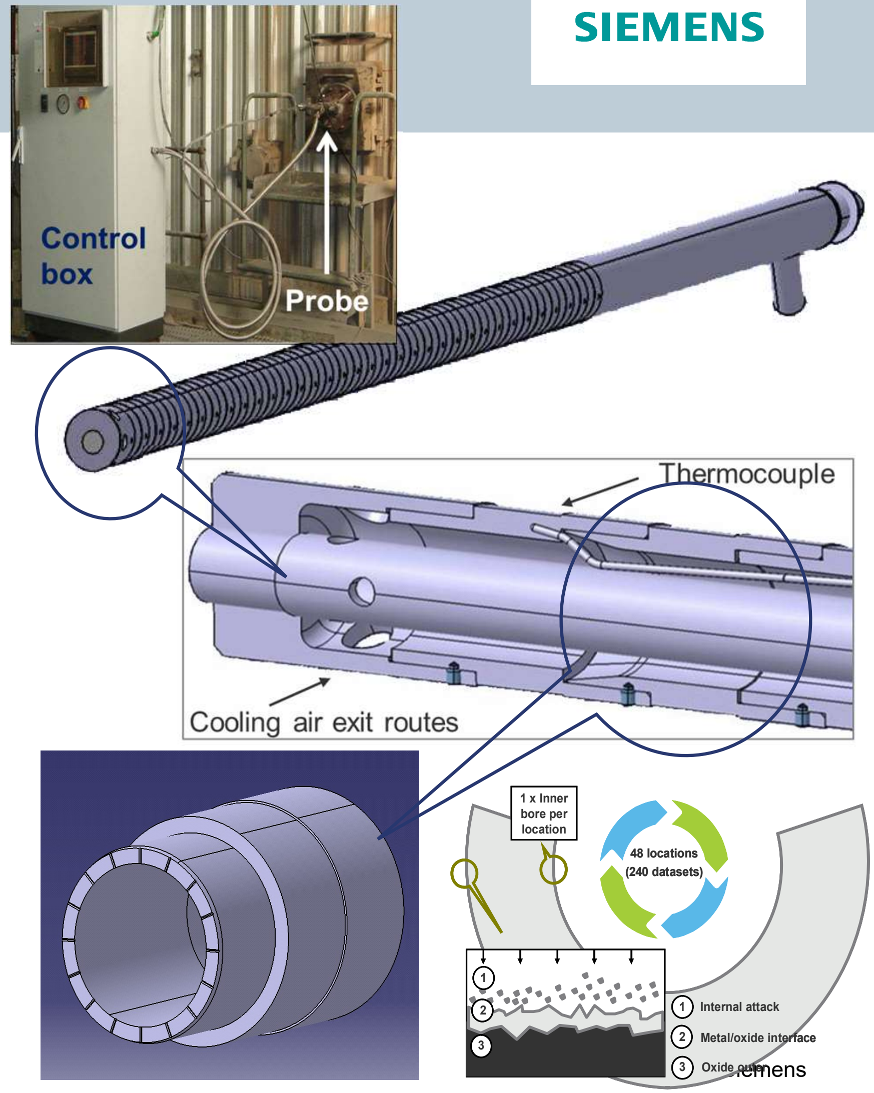
Simulated air-fired combustion gases





Fouling in heat exchangers

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).

Task 3.0 – Fireside corrosion/Steam oxidation/Creep modeling of Superheater/Reheater tubes

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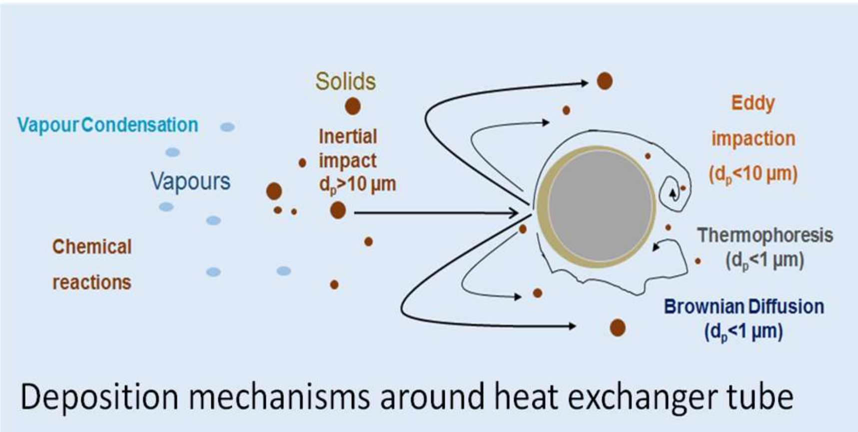
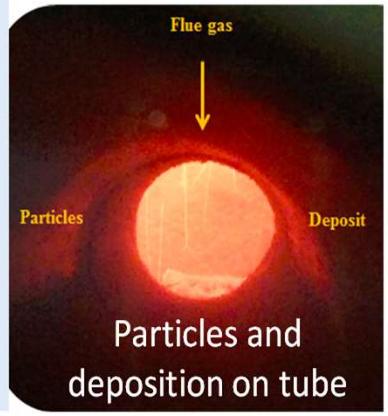
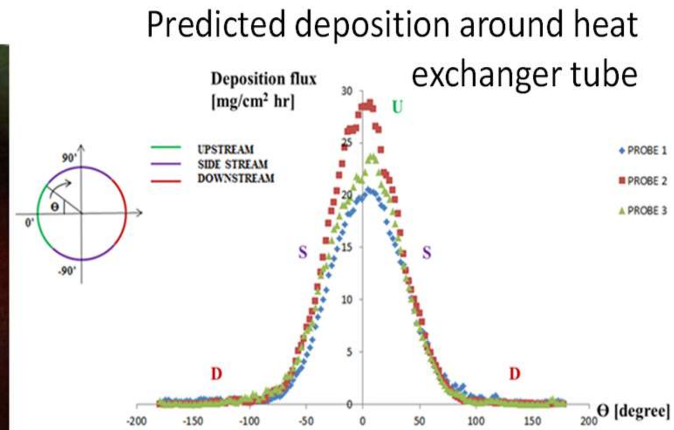
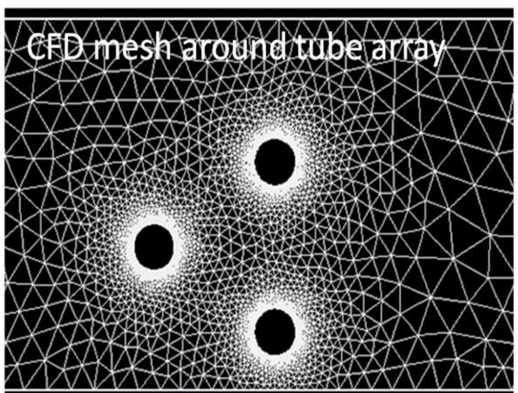
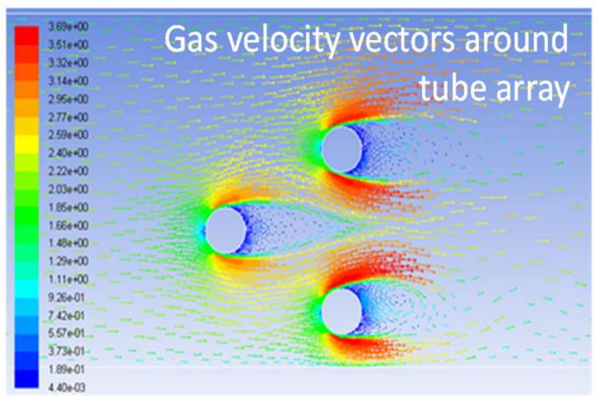
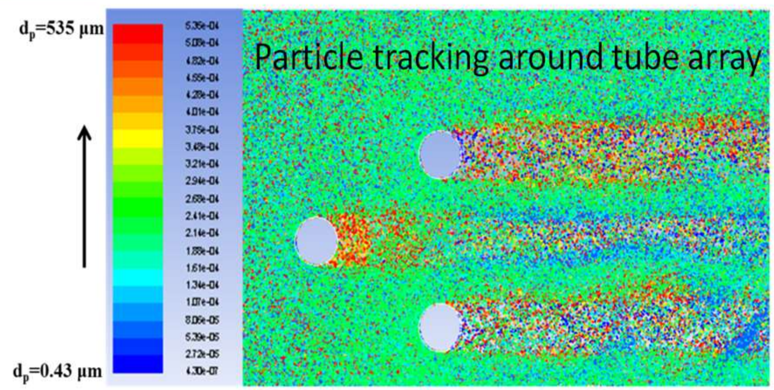








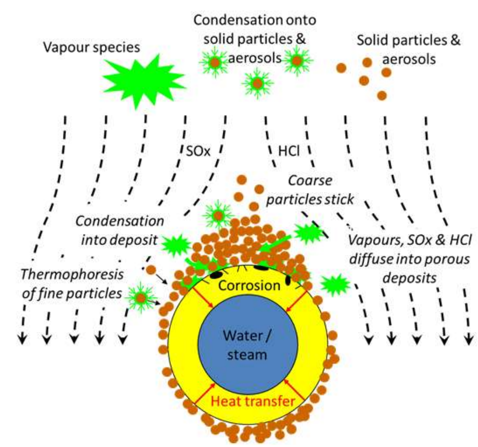


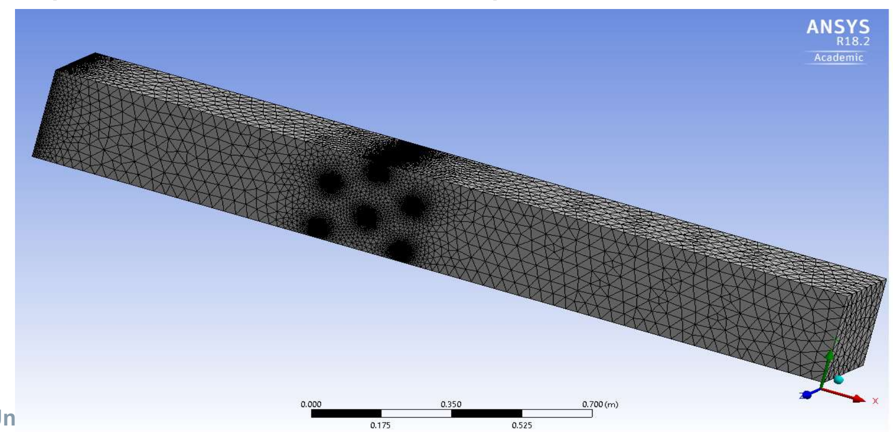


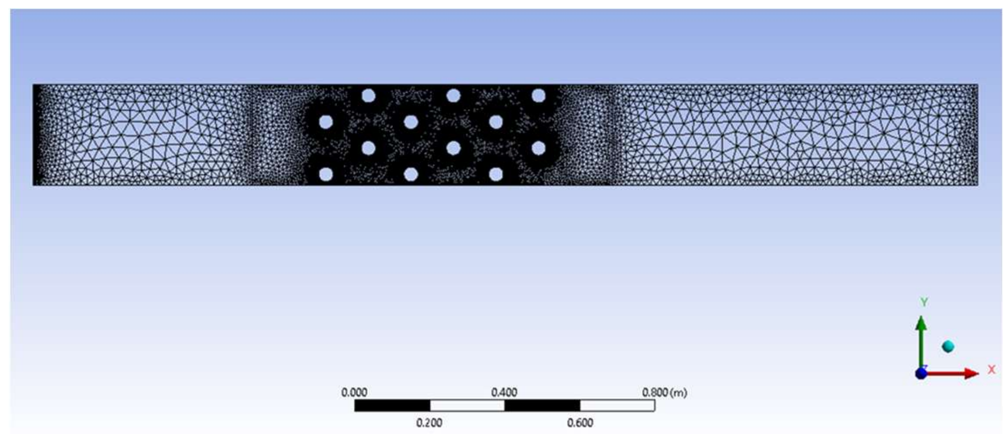
Updated - deposition modeling

Starting point: 2D Fluent deposition model

- Tube numbers increased from 3 to 12
- Model reconfigured from 2D to 3D geometry
- Alkali vapour condensation model updated with new parameters
- User defined functions (UDFs) updated and operations verified for both 2D and 3D cases
- Fluent code now on High Performance Computer (HPC)
- Siemens STAR-CCM+ software on desktop computer to investigate equivalent simulations compared to the Fluent







Effect of increased vapour condensation on deposition flux profiles: U= 2 m/s, Na_2SO_4= 1 ppm or 10 ppm

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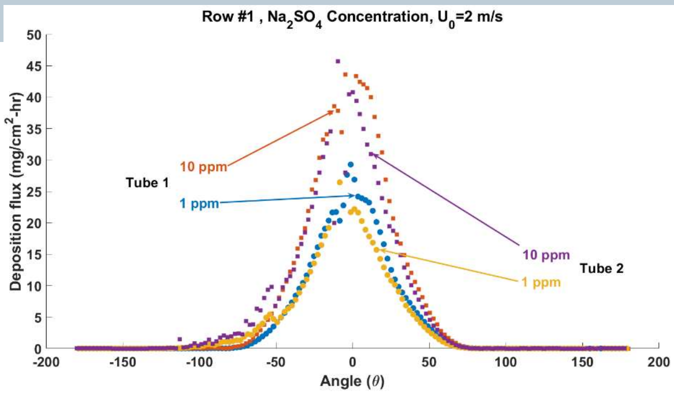
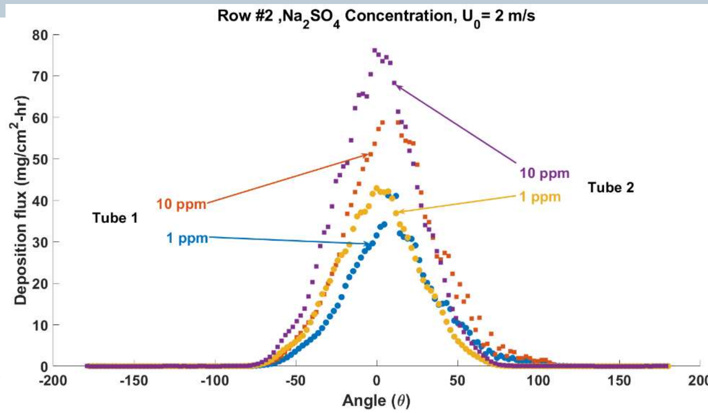
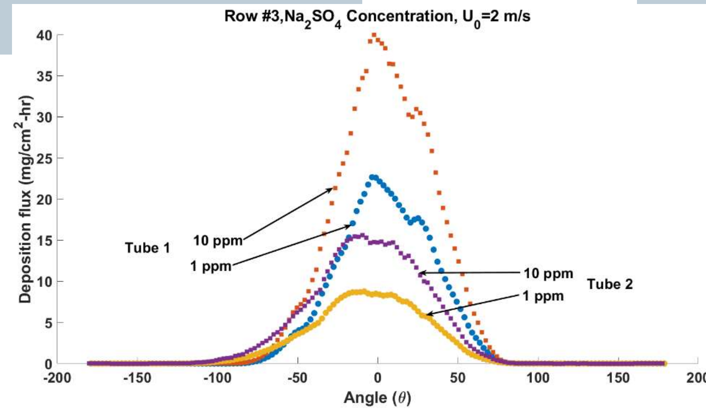
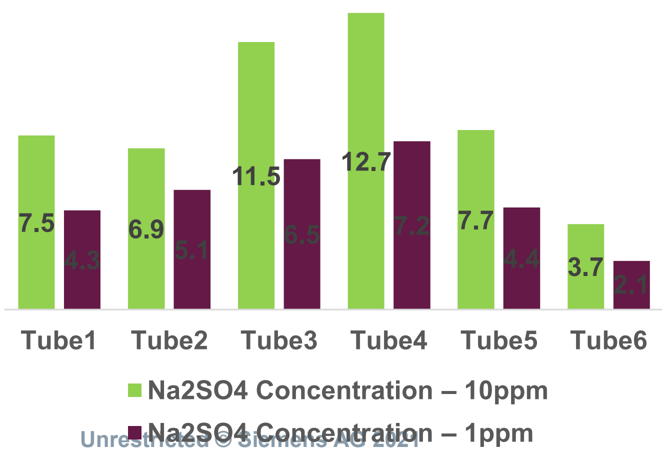


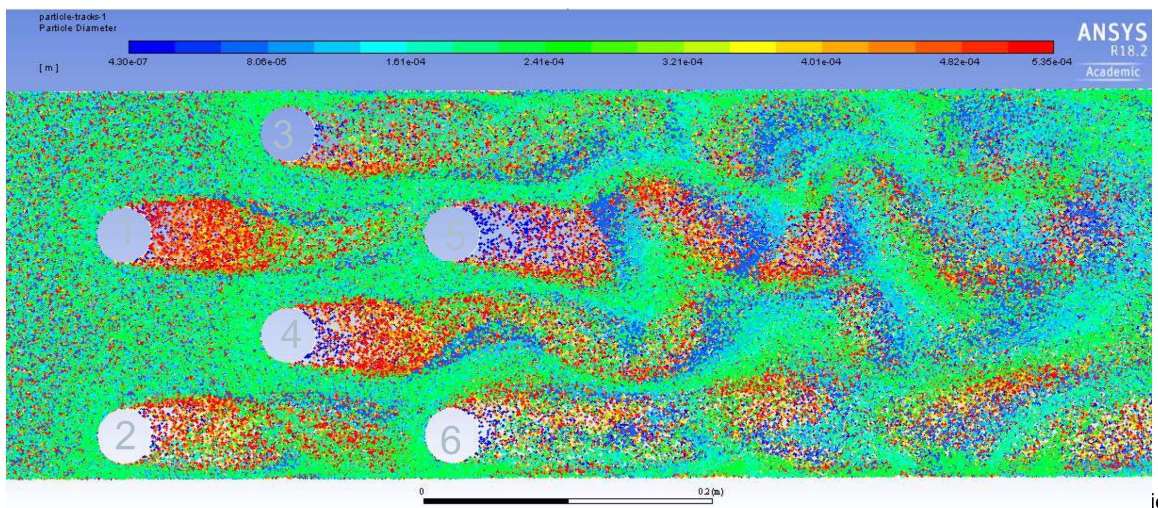




Mean Deposition Flux (mg/cm²-hr), U=2 m/s



Particle Diameter Distribution (for Na_2SO_4 = 10 ppm)



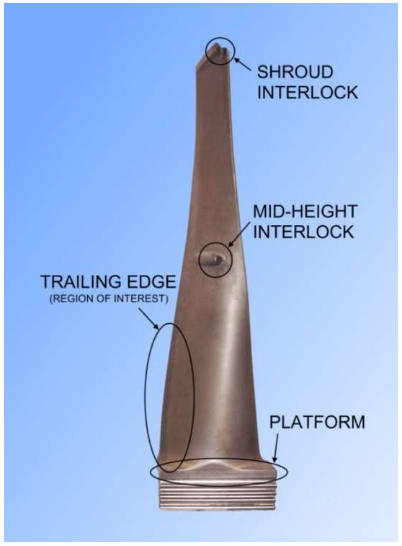
L0 Titanium blade trailing edge erosion
Background

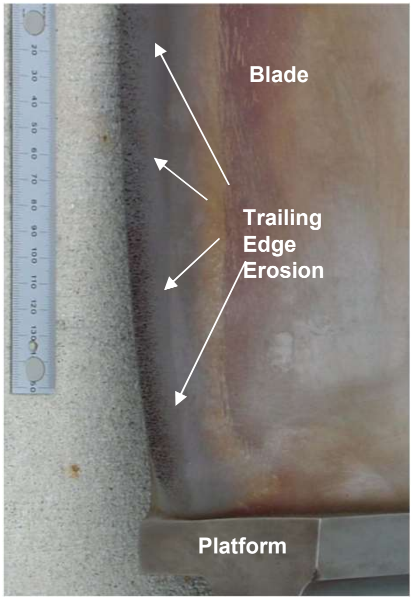
Trailing Edge Erosion

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.





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

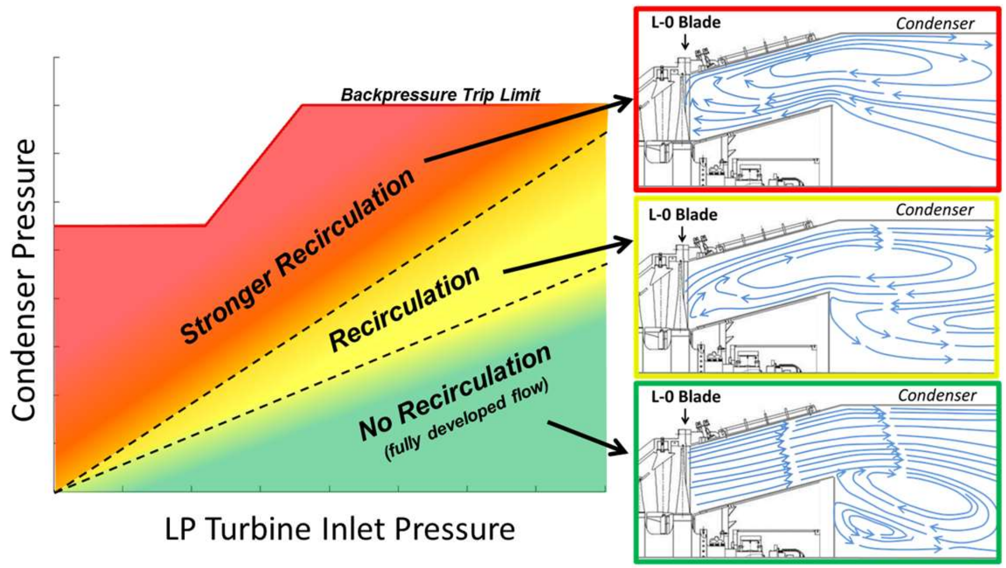
Titanium blade trailing edge erosion contributors

Exhaust Recirculation

- Recirculation can occur during low load or part load operation and is influenced by elevated backpressures
- Figure to right illustrates general relationship between steam turbine flow, condenser backpressure, and exhaust recirculation

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

Titanium blade trailing edge erosion contributors

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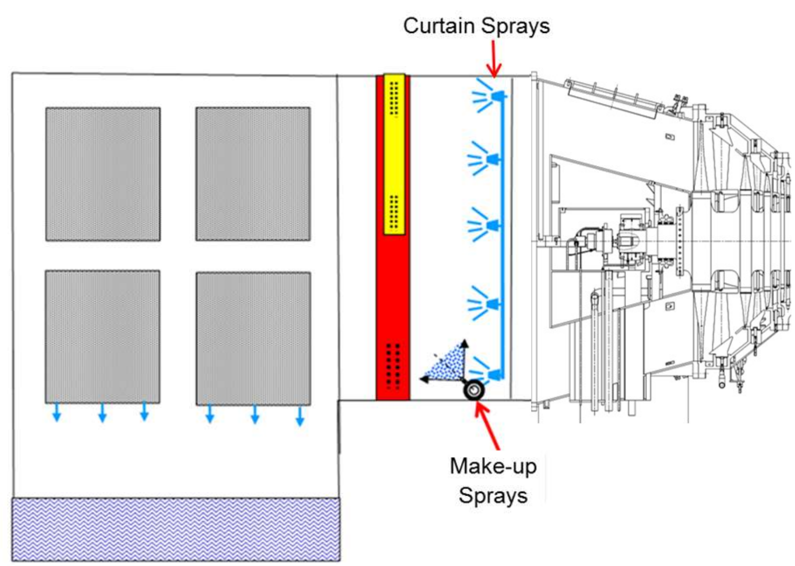
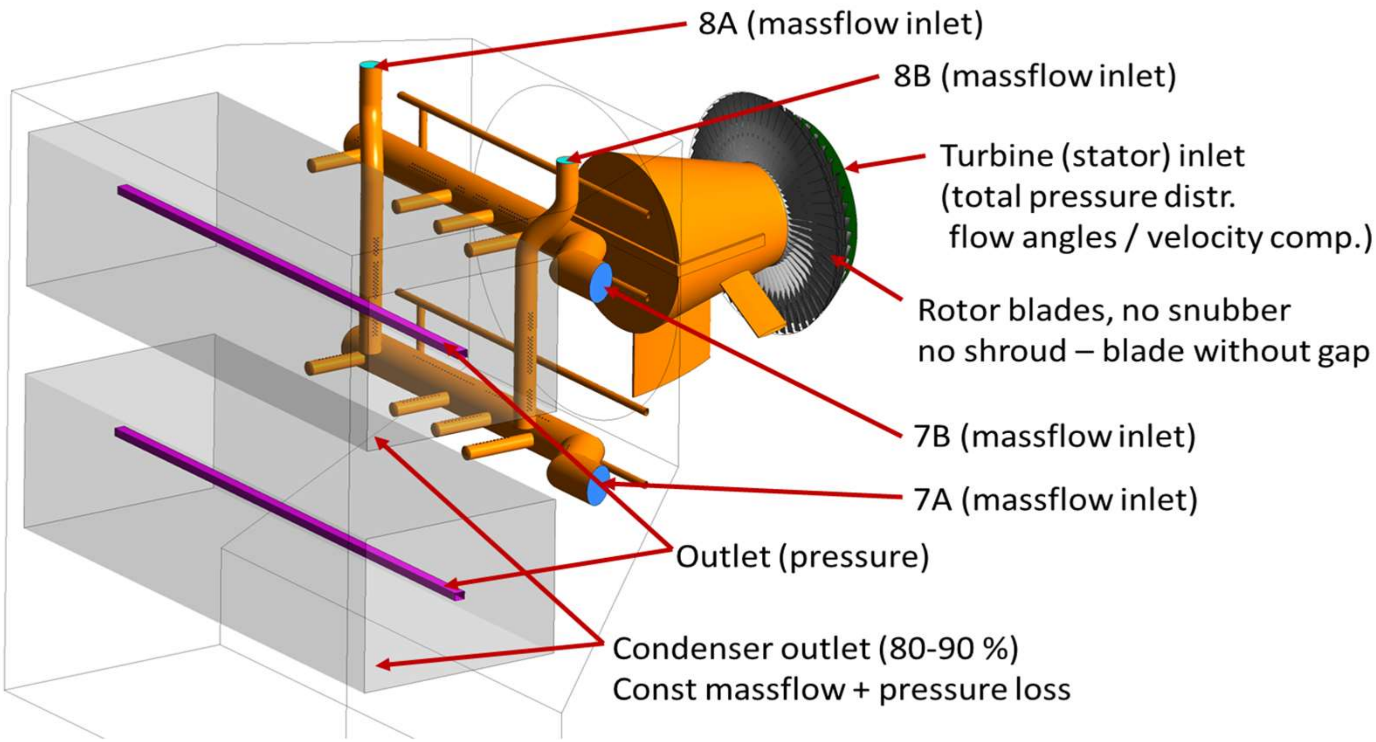
Downstream Moisture

- 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

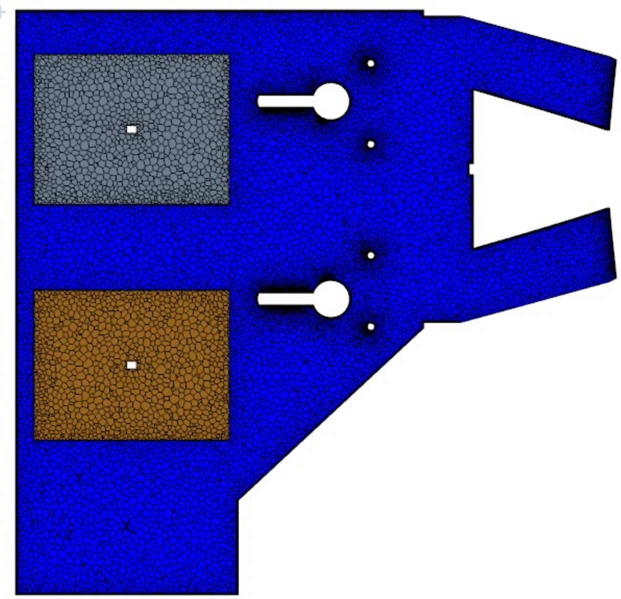
Example Moisture Sources in Condenser



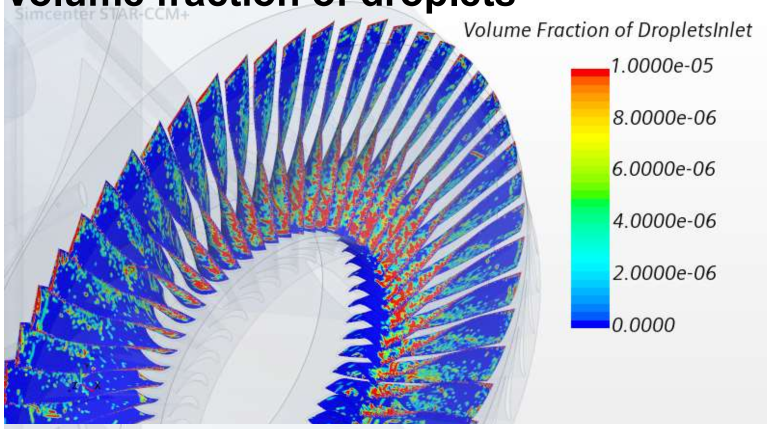
Model of curtain spray for water droplet studies

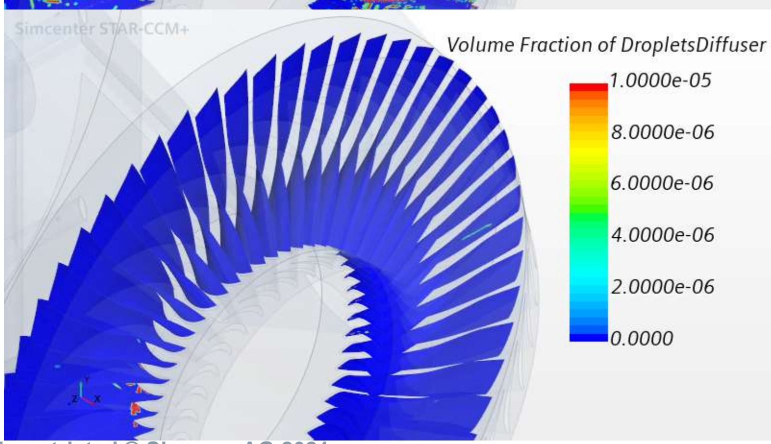


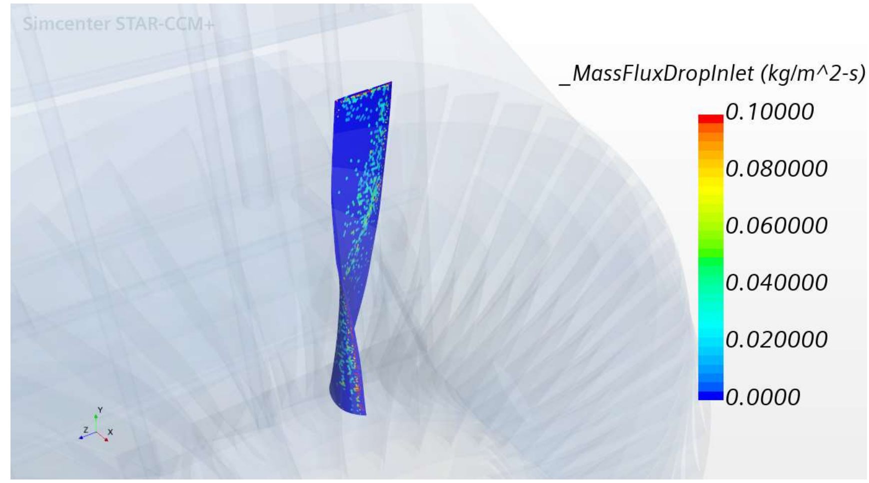
- Diffuser with struts
- Two Condensers
- Dilution pipes with inlets



Volume fraction of droplets







View from upstream side of the rotor, the droplets from the inlet mainly impact on the leading edge and close to the hub, while some droplets from the diffuser can be brought back to the turbine and impact the rotor blades close to the hub, no droplets from the curtain spray can be observed from this view.

Front View

Physics models for erosion

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- Erosion rate

The erosion rate is defined as the mass of wall material eroded per unit area per unit time. It is calculated on wall, baffle, and contact boundary faces by accumulating the damage that each particle impact does on the face.

- Oka correlation for erosion ratio

$$e_r = e_{90} g(\alpha) \left(\frac{v_{\text{rel}}}{v_{\text{ref}}} \right)^{k_2} \left(\frac{D_p}{D_{\text{ref}}} \right)^{k_3}$$

where:

- The angle function $g(\alpha)$ is defined as:

$$g(\alpha) = (\sin\alpha)^{n_1} (1 + H_v (1 - \sin\alpha))^{n_2}$$

with n_1, n_2, and H_v user-specified constants. Oka and others identify the value of H_v as the Vickers hardness of the eroded material in units of GPa.

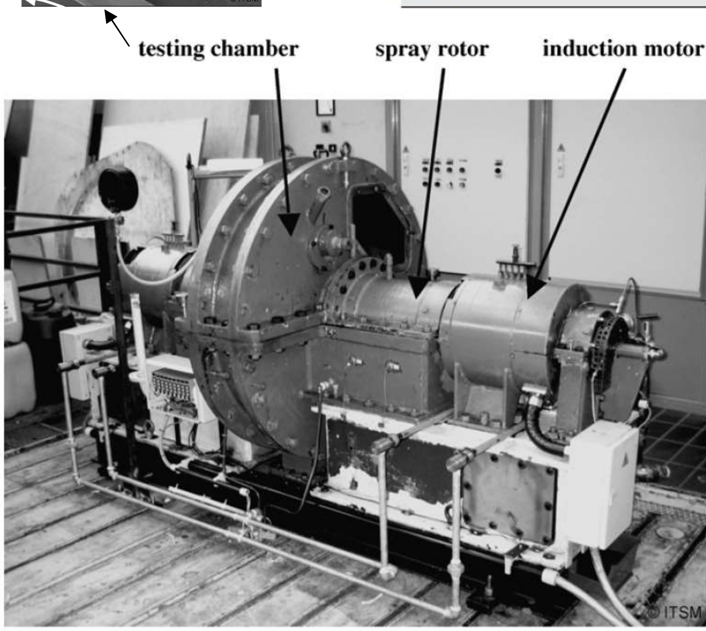
- v_{rel} is the magnitude of the relative velocity of the particle with respect to the wall.
- v_{ref} is the user-specified reference velocity.
- D_{ref} is the user-specified reference diameter.
- k_2 and k_3 are user-specified exponents.

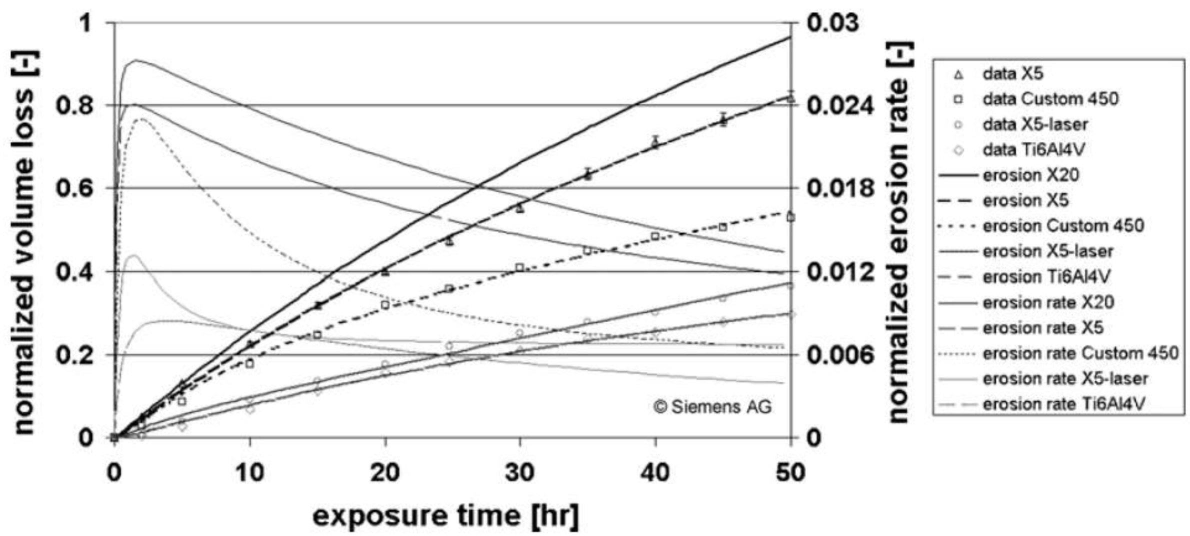
- Comparing with other erosion correlation models, Oka correlation has the advantage of accounting for both droplets' velocity and diameter
- The erosion rate e_r has the dimension of kg/m^2-s
- Revised erosion model parameters are needed for the materials systems
- Current, data digging for results of erosion testing for input into the model

Erosion data for model calculations

Table 2
Mechanical properties of specimen (at 313 K; standard testing conditions).

Material	Density [kg/m^3]	Surface hardness [HV-10]	Young's modulus E [GPa]	Modulus of resilience $U_r^*/U_{r\text{-}X20Cr13}^*$	Erosion resistance $R_{E,50}/R_{E,50\text{-}X20Cr13}$
X20Cr13	7.710	271	216	1.00	1.00
X5CrNiCuNb16-4	7.760	328	200	2.61	1.17
X5CrNiCuNb 16-4, laser treated	7.760	420	200	4.28*	2.58
X5CrNiMoCuNb 14-5-equiv	7.750	373	200	3.38*	1.78
Ti6Al4V	4.420	334	110	3.95	3.23





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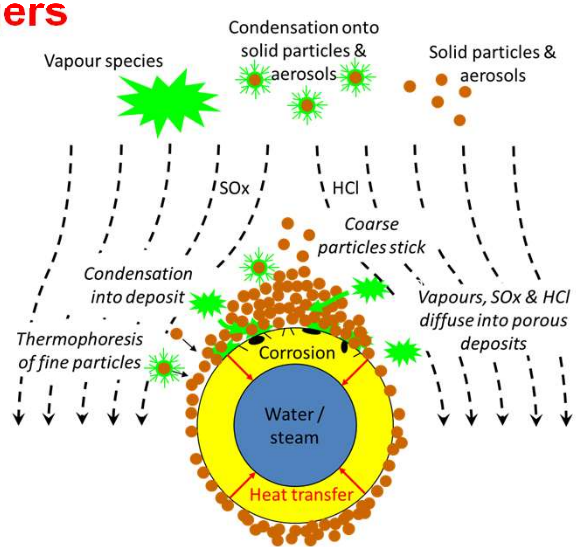
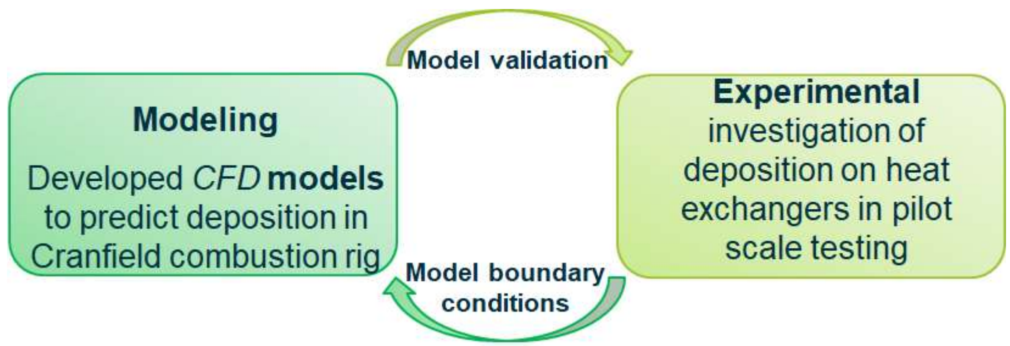
Boilers/Heat Exchangers



Deposition/corrosion around a heat exchanger tube

Fouling in heat exchangers

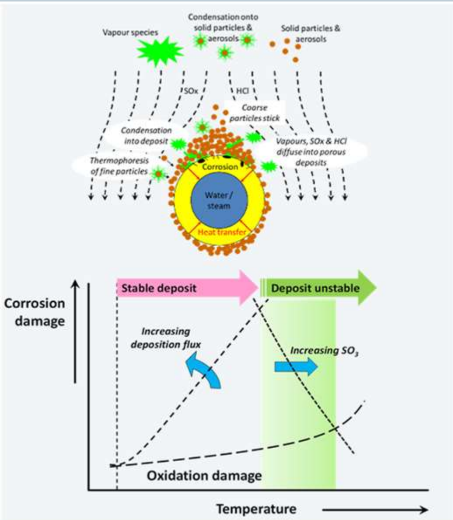
Deposit on real superheater tubes

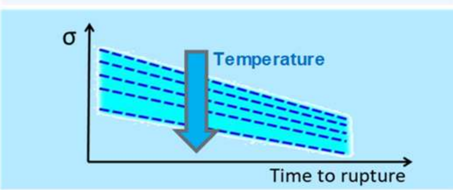


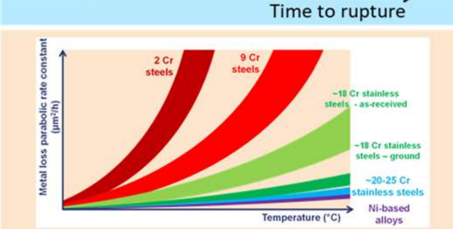
Flow (particulate/liquid) or droplet impingement/ assisted erosion for Casings, Compressor components/ HRSG/ Boiler tubes/ Steam turbines/ Piping

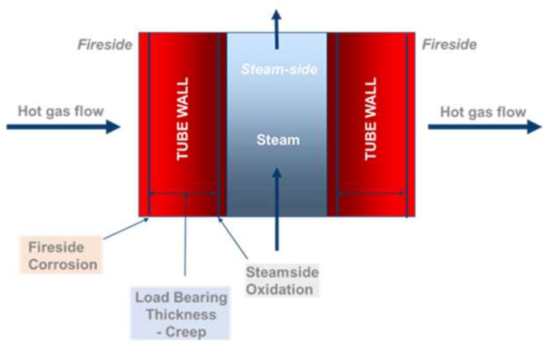
Model efforts of interest for Power Plant Upgrades (e.g. Fuel flexibility

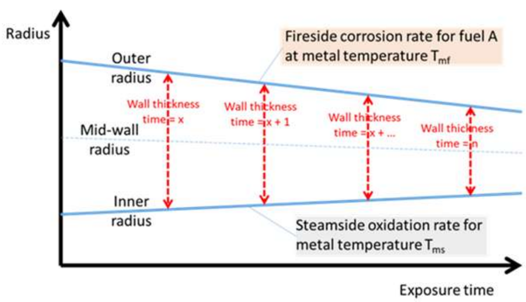
Techno-economic analysis

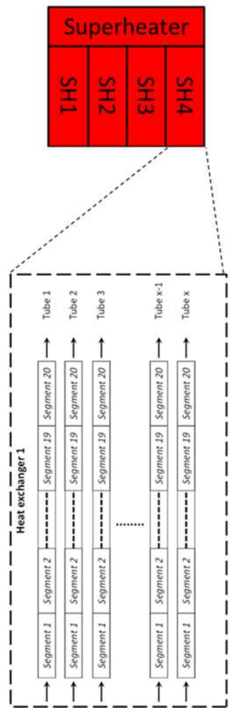


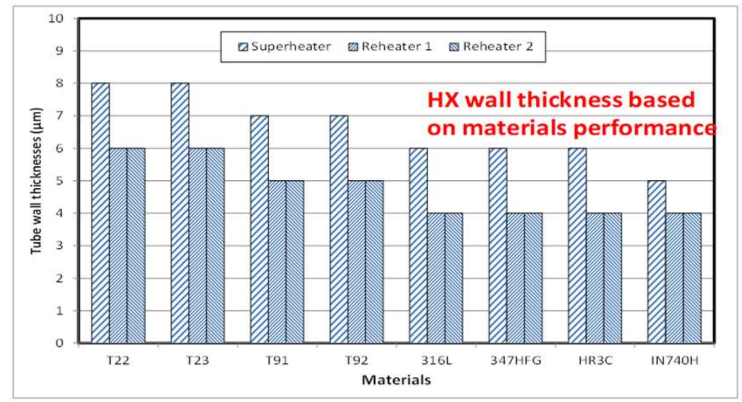


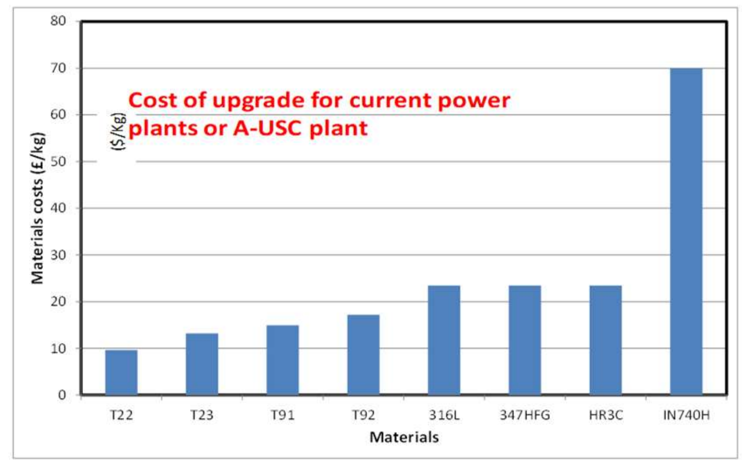












Project schedule

SIEMENS

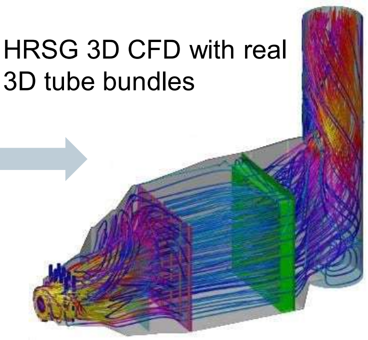
ID	Task Name	Duration	Start	Finish	Predece:
1	***Component level modeling of materials degradation for insights into operational flexibility of Existing Coal Power Plants***	784 days?	Tue 10/1/19	Fri 9/30/22	
2	**Task 1: Program Management and Planning**	784 days	Tue 10/1/19	Fri 9/30/22	
3	Update SOPO	30 days	Tue 10/1/19	Mon 11/11/19	
4	Kick-off Meeting	30 days	Tue 10/1/19	Mon 11/11/19	
5	Project Management	784 days	Tue 10/1/19	Fri 9/30/22	
6	Contract Administration and Cost Reporting	784 days	Tue 10/1/19	Fri 9/30/22	
7	Technical Reporting	784 days	Tue 10/1/19	Fri 9/30/22	
8	Progress Reports	784 days	Tue 10/1/19	Fri 9/30/22	
9	**Task 2.0 - Collect boiler/steam turbine plant operating data**	**207 days**	**Tue 10/1/19**	**Wed 7/15/20**	
10	**Task 2.1: Boiler/Heat exchanger component down-selection and requirement definition**	**206 days**	**Tue 10/1/19**	**Tue 7/14/20**	
11	Component performance requirements and design constraints	100 days	Tue 10/1/19	Mon 2/17/20	
12	Define design/manufacturing/physical constraints for observed failure mechanisms	106 days	Tue 2/18/20	Tue 7/14/20	11
13	**Task 2.2: Steam turbine component down-selection and requirement de**	**207 days**	**Tue 10/1/19**	**Wed 7/15/20**	
14	Component performance requirements and design constraints	100 days	Tue 10/1/19	Mon 2/17/20	11
15	Define design/manufacturing/physical constraints for observed failure mechanisms	106 days	Tue 2/18/20	Tue 7/14/20	14
16	**Gather data on plant component materials degradation to establish CFD/FE model**	**1 day**	**Wed 7/15/20**	**Wed 7/15/20**	**15**
17	**Task 3.0 – Fireside corrosion/steam oxidation/creep modeling of superheater/reheater tubes**	**547 days**	**Tue 11/12/19**	**Wed 12/15/21**	
18	***Task 3.1: Definition of heat exchanger***	**100 days**	**Tue 11/12/19**	**Mon 3/30/20**	
19	Evaluation of design conditions and operational data for heat exchang	50 days	Tue 11/12/19	Mon 1/20/20	
20	Compilation of materials matrix/properties and available experimenta	50 days	Tue 1/21/20	Mon 3/30/20	19
21	**Task 3.2: Fireside degradation model**	**200 days**	**Tue 3/31/20**	**Mon 1/4/21**	
22	Data analytics toolkit for deposits/erosion/corrosion failure mechanisı	100 days	Tue 3/31/20	Mon 8/17/20	20
23	Part damage model development for key components correlated to design/materials analysis	100 days	Tue 8/18/20	Mon 1/4/21	22
24	**Task 3.3: Steam oxidation and exfoliation model**	**200 days**	**Tue 3/31/20**	**Mon 1/4/21**	
25	Data analytics toolkit for deposits/erosion/corrosion failure mechanisı	100 days	Tue 3/31/20	Mon 8/17/20	20
26	Part damage model development for key components correlated to design/materials analysis	100 days	Tue 8/18/20	Mon 1/4/21	25
27	**Task 3.4: Creep model**	**93 days**	**Tue 1/5/21**	**Thu 5/13/21**	
28	Data analytics toolkit for multidisciplinary failure mechanisms run for cyclic loading	93 days	Tue 1/5/21	Thu 5/13/21	23,26
29	**Deposition / fireside corrosion / erosion / steam oxidation materials degradation model analysis for heat exchanger tubes for metal loss predictions**	**1 day**	**Fri 5/14/21**	**Fri 5/14/21**	**28**
30	Robust life prediction approach demonstrated with utilizing materials te	153 days	Fri 5/14/21	Tue 12/14/21	28
31	**Comparison of materials degradation models for heat exchanger tubes with plant / experimental data**	**1 day**	**Wed 12/15/21**	**Wed 12/15/21**	**30**
32	**Task 4.0: Water droplet erosion modeling for LP steam turbine blade**	**482 days**	**Tue 11/12/19**	**Wed 9/15/21**	
33	***Task 4.1: Definition of steam turbine blade***	**165 days**	**Tue 11/12/19**	**Mon 6/29/20**	
34	Evaluation of design conditions and operational data for steam turbin	80 days	Tue 11/12/19	Mon 3/2/20	
35	Compilation of materials matrix/properties and available experimenta	85 days	Tue 3/3/20	Mon 6/29/20	34
36	**Definition of Steam turbine detailed blade geometry and operating cond**	**1 day**	**Tue 6/30/20**	**Tue 6/30/20**	**35**
37	**Task 4.2: Water droplet erosion model**	**316 days**	**Tue 6/30/20**	**Tue 9/14/21**	
38	Data analytics toolkit for water droplet erosion failure mechanisms	150 days	Tue 6/30/20	Mon 1/25/21	35
39	Part damage model development for key components correlated to design/materials analysis	166 days	Tue 1/26/21	Tue 9/14/21	38
40	**Comparison of steam droplet erosion materials degradation models with plant / experimental data**	**1 day**	**Wed 9/15/21**	**Wed 9/15/21**	**39**
41	**Task 5.0: Modeling Data Validation and Scale-up Opportunities**	**1305 days?**	**Mon 10/2/17**	**Fri 9/30/22**	
42	**Task 5.1: Constitutive Model/Tool Development**	**274 days**	**Tue 11/12/19**	**Fri 11/27/20**	
43	Develop a data analytics framework capable of housing probabilistic design tool sets liked to finite element modeling of design parameters	140 days	Tue 11/12/19	Mon 5/25/20	
44	Deploy an integrated interface utilizing plant operational data and CFD/FE to predict remaining life of components for improved	134 days	Tue 5/26/20	Fri 11/27/20	43
45	**Component level models for heat exchanger tubes and steam turbine bl**	**1 day**	**Mon 11/30/20**	**Mon 11/30/20**	**44**
46	**Task 5.2: Component design/analysis for scale-up opportunities**	**784 days?**	**Mon 10/2/17**	**Thu 10/1/20**	
47	Fracture mechanics/heat transfer and CFD analysis demonstrated for multiple stages of components for boilers and steam turbines	359 days	Mon 11/30/20	Thu 4/14/22	44
48	**Validation of model toolbox for heat exchanger metal loss for baseload and cyclic operations**	**1 day**	**Fri 4/15/22**	**Fri 4/15/22**	**47**
49	**Validation of model toolbox for steam turbine erosion and impact on fa**	**1 day**	**Fri 4/15/22**	**Fri 4/15/22**	**47**
50	Demonstrate component modeling for optimization of design and service maintenance	98 days	Fri 4/15/22	Tue 8/30/22	47
51	**Validation of component level modeling for heat exchanger and steam turbine blade with existing plant data**	**1 day**	**Wed 8/31/22**	**Wed 8/31/22**	**50**
52	**Final Technical report detailing Improved materials/operational flexibility for improved power plant component**	**23 days**	**Wed 8/31/22**	**Fri 9/30/22**	**50**

Conclusions

- Efforts are underway to develop component level simulation model to predict localized high-risk areas for mitigations
- Scale up and validation of fireside corrosion model to industrial systems, based on fundamental understanding of materials behavior and failure mechanisms
- The CFD/FE framework will enable simulations for varied fuel compositions and operating environments of Boiler/HRSG tubes for risk mitigations and operational flexibility
- CFD/FE framework for L0 stage/exhaust area established for steam turbines with accurate steam droplet velocity and size distribution at the turbine inlet to improve the erosion prediction
- Extend model to include the full final row of turbine stage in order to include more accurate water droplet transport models up into final turbine stage (Lagrangian particle tracking and wall impingement)

HRSG 3D model

HRSG 3D CFD with real 3D tube bundles



Steam turbine droplet – exhaust recirculation