US-UK Energy Research Collaboration and The Hot Corrosion Project

ETN AGM - 15th March 2018

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Background to US-UK Collaboration

- **UK – US MOU on Collaboration in Energy Research renewed in 2000 and again in 2012**
  - ✓ Implementing Arrangement for Fossil Energy RTD signed 2003
  - ✓ Sets a framework for collaborative ‘tasks’ with named UK and US leaders
  - ✓ Phase 1 included collaborative tasks on:
    - Materials for Advanced Power Plants
    - Virtual Plant Simulation

- **Collaboration Framework**
  - ✓ Contributions from nationally-funded public domain research
  - ✓ Task proposals define equitable research collaboration
  - ✓ Detailed work program aligning UK and US activities to maximise exchanges and benefits
  - ✓ Exchange and sharing methodology based on EU COST Program
  - ✓ Dedicated Website for exchange of presentations, reports and data

- **Collaboration started April 2004**

Why Collaborate?

(Participant Perspective)

- Improved vision of industrial needs and national strategies
- Increased specialist knowledge pool
- Highly cost effective - small extra cost
- Critical review of methods & results
- Access to unique facilities
- Reduced risk of wasted effort
- Less time to develop design & modelling capability
- Improved quantity & quality of data
- Improved confidence in outputs

What is the Commitment?

- Agreement to contribute to common research questions agreed by Task partners
- Willingness to share data, to supply materials/parts and to undertake tests/examinations for other partners (at no cost)
- Attendance at collaboration meetings which are held every six months, alternately in the US and Europe. Could attend by teleconference, but this should be the exception.
- Provision of six-monthly reports/slides for presentation at the meetings
- Access to website for exchange of information (access is blocked if more than one meeting missed)

US–UK 'Advanced Materials' Program

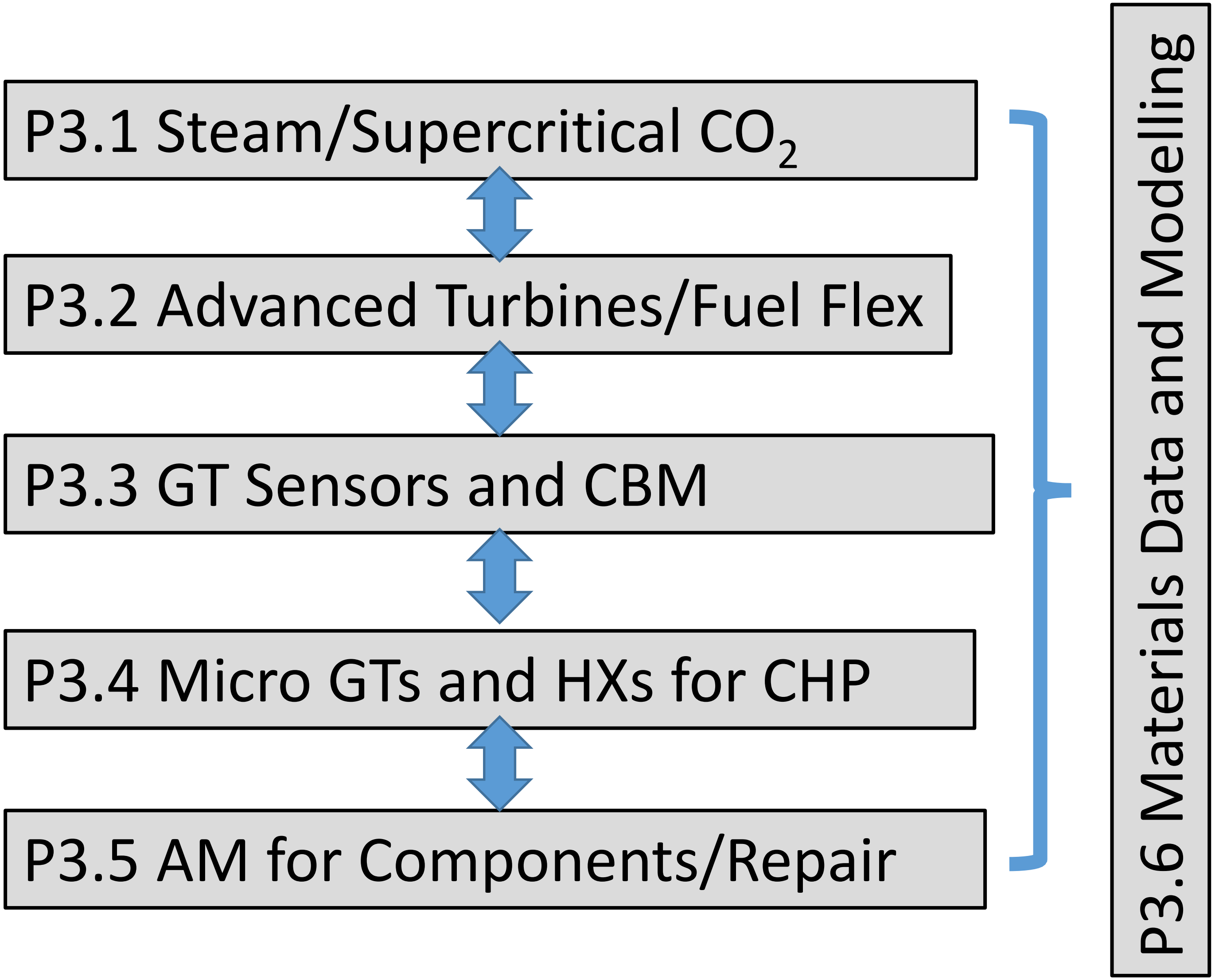
All tasks aimed at developing underpinning knowledge to support increased plant efficiency, reliability and reduced emissions

- Phase 1 (2004 – 2009):
  - Steam Oxidation
  - Boiler Corrosion & Monitoring
  - Gas Turbines Fired on Syngas and Other Fuel Gases
  - Oxide Dispersion-Strengthened (ODS) Alloys
  - Standards & Databases
- Phase 2 (2009 – 2016):
  - Steam Oxidation
  - Advanced Materials for Boilers and Oxy-combustion Systems
  - Gas Turbine Materials – Life assessment and Non-destructive Examination
  - ODS Alloy Applications

Currently completing Phase 2 Close-out Activities – Publications, 2-page Summaries

- Phase 3 (2016 - …)

Phase 3 Topics – Advanced Materials +



Genoa Meeting on ETN Involvement in US-UK Collaboration

Organisations participating in Genoa meeting:

- Adgas
- Ansaldo Energia
- Chromalloy UK
- City University
- ENEA
- EPRI
- Fogale Nanotech
- HIETA
- RSE
- Siemens
- Solar Turbines
- Uniper
- United Services Sweden
- University of Eindhoven
- University of Genoa
- University of Roma Tre
- University of Sheffield

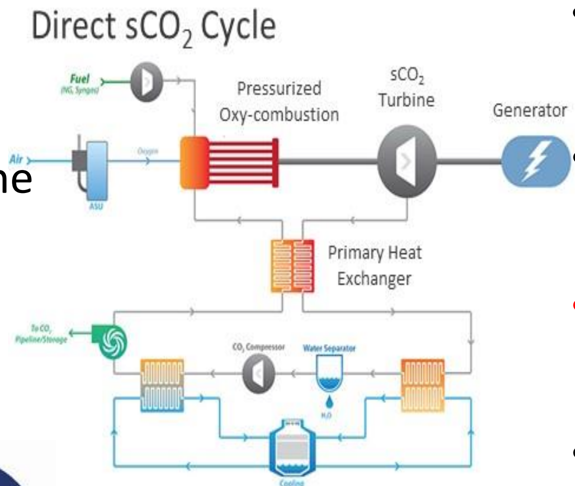
Potential ETN Member Contributions to Phase 3 Tasks

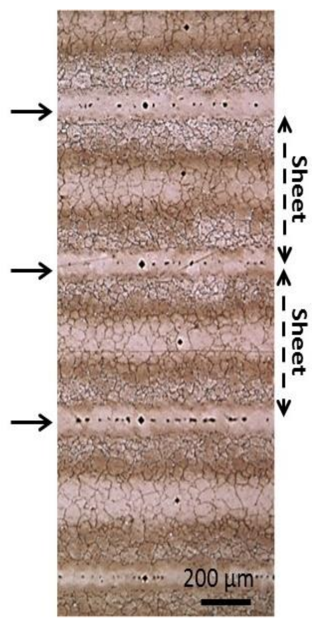
- Ansaldo Energia – Materials Data & Modelling
- Chromalloy UK – Additive Manufacturing, Coatings
- City University – Micro-turbines
- Fogale Nanotech – Vibration Monitoring
- HIETA – Additive Manufacturing/ Micro-turbines/Recuperators
- RSE – Ceramics and Coatings
- United Services Sweden – Anti-fouling Coatings – compressors, HXs, etc.
- University of Eindhoven – Micro-turbines, Combustion Stability, Modelling

Task 3.1: Corrosion in Supercritical Fluids

Supercritical & Elevated Pressure Systems

- Gas Turbine Compressors
- Regenerators
- Steam Boiler/Turbine
- Direct Cycle sCO_2
- Indirect Cycle sCO_2





Current Partners

National Energy Technology Laboratory
Cranfield University
Sandia National Laboratories
Oak Ridge National Laboratory
SIEMENS

Task Leads

UK: Nigel Simms (Cranfield)
US: Gordon Holcomb (NETL)

Key Objectives

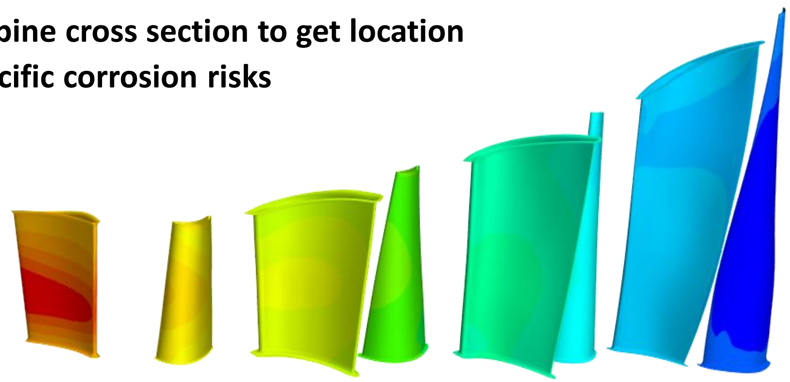
- Understand the effect of pressure on the oxidation of structural materials in **high-temperature supercritical fluids**
- Evaluate structural materials for corrosion resistance in low temperature environments (**dew point corrosion**)
- **Maximize the use of steel in gas turbine compressors** and sCO_2 systems, and this can include the use of coatings and liners
- Determine the importance and effect of **impurities** on oxidation
- Determine the effect of **surface finish** on the oxidation behaviour in steam and sCO_2
- Understand **reaction paths** of $H_2O/O_2/H_2$ (using isotopes) during steam oxidation
- Evaluate **oxidation microstructures from long-term power plant exposures**
- **Identify process environments for proposed power cycles** for design of corrosion tests
- **Include samples extracted from actual components** into oxidation and corrosion testing

Task 3.2: Computational corrosion modelling for fuel flexible turbines

Objective: **Development of predictive models for deposition, corrosion and component life assessment for fuel flexible gas turbines**

Concept

Turbine cross section to get location specific corrosion risks



Deliverables

Data collection of available historical public and corrosion tests, corrosion model infrastructure/ database development + software development

Predicted corrosion rates utilizing the levels of contaminant flux which allow extrapolation to high temperature/high pressure conditions to develop corrosion maps appropriate to a range of fuels

Validated and improved models for life prediction of alloys, corrosion resistant coatings and TBCs from isothermal and burner rig testing

Shared testing samples/data for model expansion/validation

Milestones

Complete initial parts of modelling activity for corrosion database with fuel/air contaminants for chosen specific materials/fuels – Dec 2018

Establishment of corrosion maps for metallic and ceramic systems – Sept 2019

Collection / generation of isothermal and burner rig test data for corrosion model and deposit characteristics from service run components for validation of model results – Sept 2020

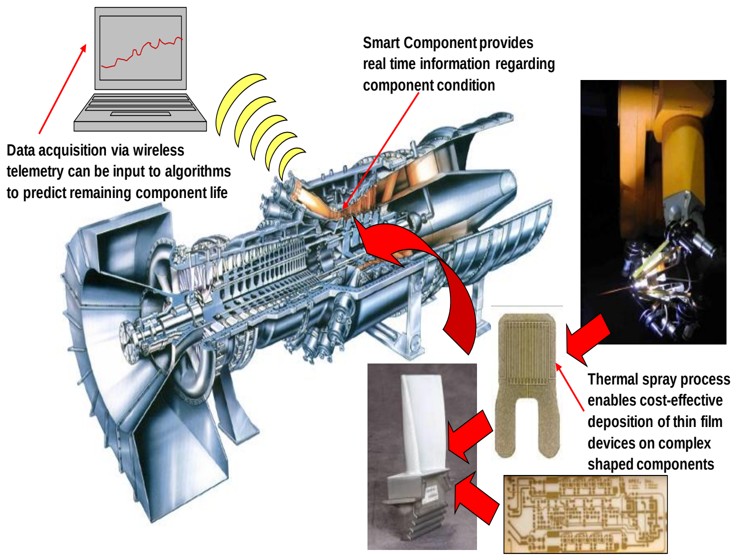
Team

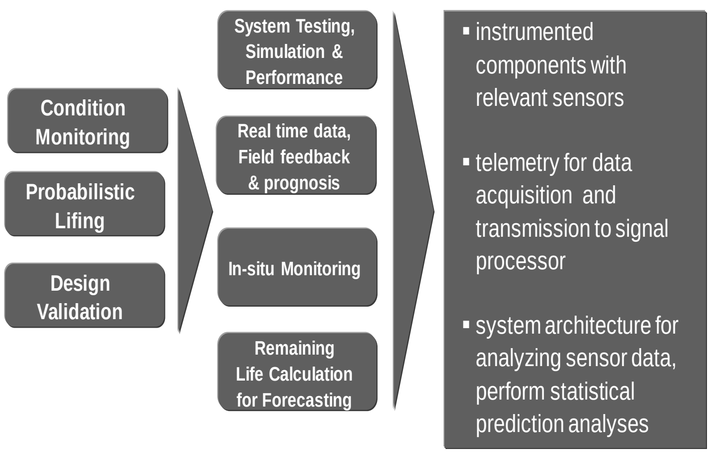
- US Task lead: Anand Kulkarni (Siemens)
- UK Task lead: Nigel Simms (Cranfield)
- Team:
  - Ken Natesan - Argonne National Laboratory (ANL)
  - Joy Sumner - Cranfield University
- ETN…

Task 3.3: Sensors and NDE

Objective: **Integrate durable, non-intrusive, ultra-high-temperature thermocouples (> 1200 °C) with high temperature wireless telemetry (> 550 °C) to enable materials prognostics and active condition monitoring in the hot gas path (HGP) of industrial gas turbines.**

Concept





Activities

Aim: Develop and engine test hardware and software technologies that will enable active condition monitoring to be implemented on hot gas path turbine blades in large industrial gas turbines.

Deliverables: Validation testing of sensor-wireless telemetry package in spin rig and advanced OBA model utilizing artificial intelligence

Demonstration of ceramic thermocouples that showed 10x improvement in emf output compared to metallic thermocouples

Developed a cutting edge SiC IC electronics/Improved wire-bond design capable of withstanding high centrifugal loading and induced power for > 550C wireless telemetry

OBA model development for damage models for life assessment

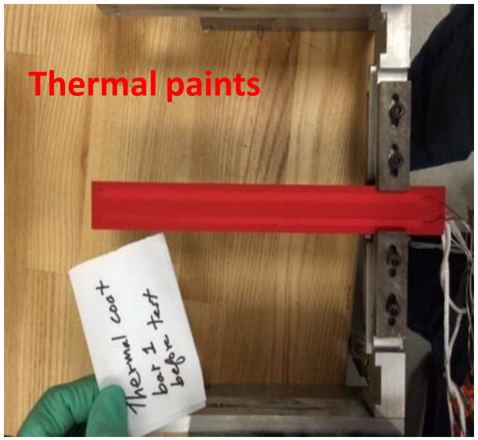
Team

- PI: Anand Kulkarni (Siemens)
- Team: Wolfspeed, Aerodyn, Siemens Energy, Curtiss Wright, Uni of Arkansas, Transtech

Task 3.3: Sensors and NDE

Objective: Standardization of sensor technologies for thermal measurement and NDE of turbine components

Concept



SiC Crystals

Deliverables

Round robin for temperature and heat flux measurements for gas turbines (thermal paints, TBCs, thermocouples, SiC crystals, non-contact, fibre grating sensors)

NDE/flash thermography for coating characteristics for quality/ performance evaluation for gas turbines.

Intrusive/ Non-intrusive inspection techniques, vibration monitoring for on-line or condition based monitoring of components

Standardization of sensor technologies/data analytics

Milestones

Precision, Accuracy and uncertainty for temperature/heat flux/thermal conductivity measurement techniques for gas turbines

Method for analyzing multi-layer materials from one-sided pulsed thermal imaging for coatings in gas turbines

Evaluation of uncertainties in diffusivity/conductivity measurements by laser flash to support standardization

3D microstructural characterisation and thermal property measurement of TBC's as a function of life to validation lifetime prediction methods

Team

- US Task lead: Anand Kulkarni (Siemens)
- UK Task lead: Tony Fry (NPL)
- Team:

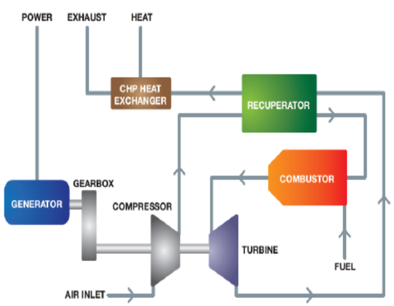
ANL, Others ..

SCS, Rolls Royce (thermal paints), Cranfield, Others…

Task 3.4: Micro-turbine Activities – under development

Objective: - To explore materials options for performance improvement of directly- and indirectly-fired micro-turbines

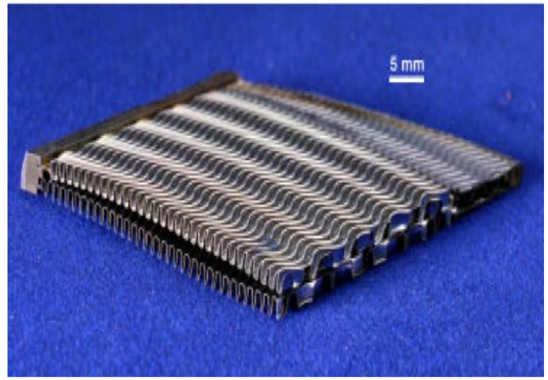
Concept



- Turbine and recuperator materials and sub-component trials – direct and indirect firing
- Recuperator materials properties – creep/fatigue, corrosion, - suitability inspection, etc.
- Focus on fuel-related issues

Deliverables

x



Copied from ORNL Report TM-2000/304

Milestones

x

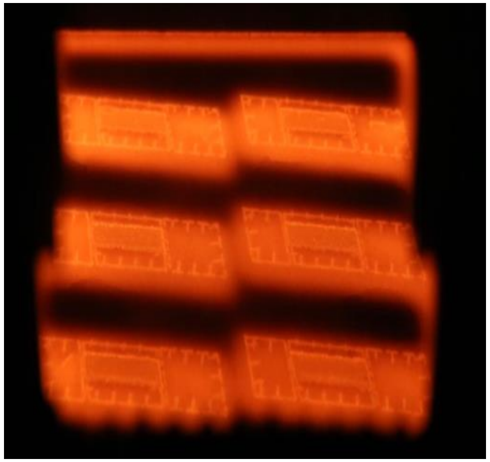
Team

- US Task lead: ???
- UK Task lead: Naser Sayma??, City University
- Team: to be completed – e.g. City University, Cranfield, ORNL?, NETL?, USDOE EERE Micro GT project? Capstone? Intelligent Power Generation? Aurelia? etc.

Task 3.5: Advanced Manufacturing & Repair

Objective: **Advanced manufacturing efforts to reduce significantly the cost associated with fabrication and repair of complex components**

Concept



Fabrication by additive manufacturing (AM) of near-net-shape high temperature components made of Ni-based (HastX/H282/CM247) or oxide dispersion strengthened (ODS) alloys along with modeling and simulation for process control.

Deliverables

Reducing cost or improving lifetime of thermal barrier coating (TBC) systems using novel manufacturing capabilities.

Development of laser-based processes for repair and joining. The project will evaluate laser stripping/cleaning and friction stir welding for Haynes 282/IN617 for gas turbine component.

Characterization, mechanical testing and corrosion evaluation of AM test samples and turbine components

Milestones

Create a database for Ni-based and ODS alloys fabricated by additive manufacturing (SLM, EBM, LMD)

Validate models predicting microstructure/properties to AM parameters

Demonstrate laser cleaning/stripping system for actual gas turbine components

Demonstration of prototype transition duct utilizing hybrid Laser cleaning/ friction stir welding technology for engine insertion

Team

- US Task lead: Sebastien Dryepondt (ORNL)/Anand Kulkarni (Siemens)
- UK Task lead: Gordon Tatlock – Uni. Liverpool
- Team:

Tony Fry (NPL), John Oakey (Cranfield), Simon Jones (Hieta)

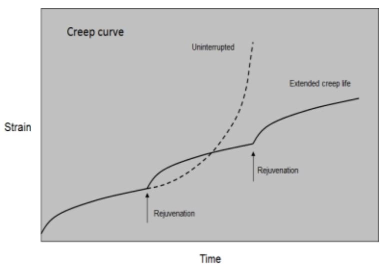
Glenn Grant (PNNL), Mike Kirka (ORNL)

ETN members?

Task 3.6: Materials Modelling and Data Management

Objective: **Cost effective materials and improved data analytics to accurately predict the remaining life of structural materials in existing plants**

Concept



- Open Access Materials Database – Boiler, Steam Turbine, Gas Turbine, HRSG, etc.
- Data quality rated for new, manufactured and aged parts
- Microstructure evolution
- Predictive Models – Creep, Fatigue, Corrosion, Residual Stresses, etc.
- Repair and Rejuvenation of properties

Deliverables

Demonstrate ability of modern data management and processing techniques to provide new insights into microstructure- processing - properties relationships of materials

Find and assess available data on residual stresses in weldments of structural alloys for advanced ultra-supercritical power plants

Demonstrate a data analysis framework housing deterministic and probabilistic design tool sets to automatically estimate component risk for multi-disciplinary failure mechanisms observed in fossil energy plants

Milestones

Development of Open Access Database

Report on the complementarity between deterministic models and probabilistic approach for A-USC/gas turbine conditions for materials data

Complete service feedback characteristics for Fe- and Ni- based Alloys/Coatngs/TBCs for correlation to time/temperature

Report on component lifetimes determined by microstructure characterization and property measurements versus lifetimes predicted by probabilistic models..

Team

- US Task lead: Vito Cedro (NETL)
- UK Task lead: John Oakey (Cranfield)
- Team:

  Siemens, ORNL, NETL

  Cranfield, NPL, Doosan Babcock, Granta Design, ETN?

Next US-UK Collaboration Workshop

- Tuesday 10th and Wednesday 11th April, Omni William Penn Hotel, Pittsburgh PA

(in parallel with the USDOE Cross-Cutting Technologies Contractors Conference – covers Sensors & Controls, Modelling & Simulation, Water Technologies, High-Performance Materials and Innovative Energy Concepts)

- sessions of 1½ to 2 hours with technical presentations on each task

- Webex teleconferencing links for those unable to attend

- ETN members offering contributions to Phase 3 tasks are welcome to attend to present their contributions, either in person or via webex

Hot Corrosion Project Update

- Hot corrosion is a complex form of high temperature corrosion resulting from a combination of factors

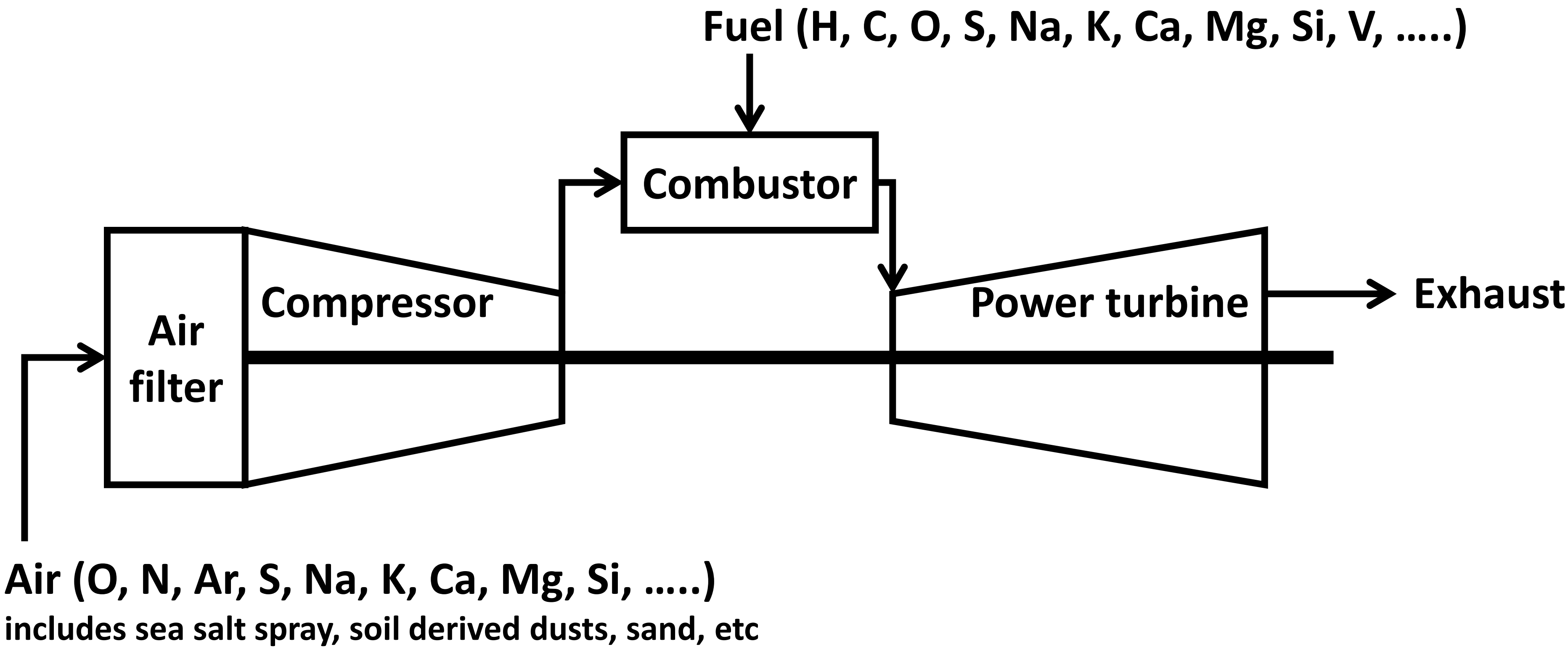
- In extreme cases, it can lead to dramatic failures of components as well as causing major reductions in performance

- Occurs between ~600 and 950 °C and requires molten surface deposit

- Commonly divided in a high temperature Type 1 damage morphology and a lower


Image: Total S.A Proprietary

Gas turbine – major inlet / outlet flows

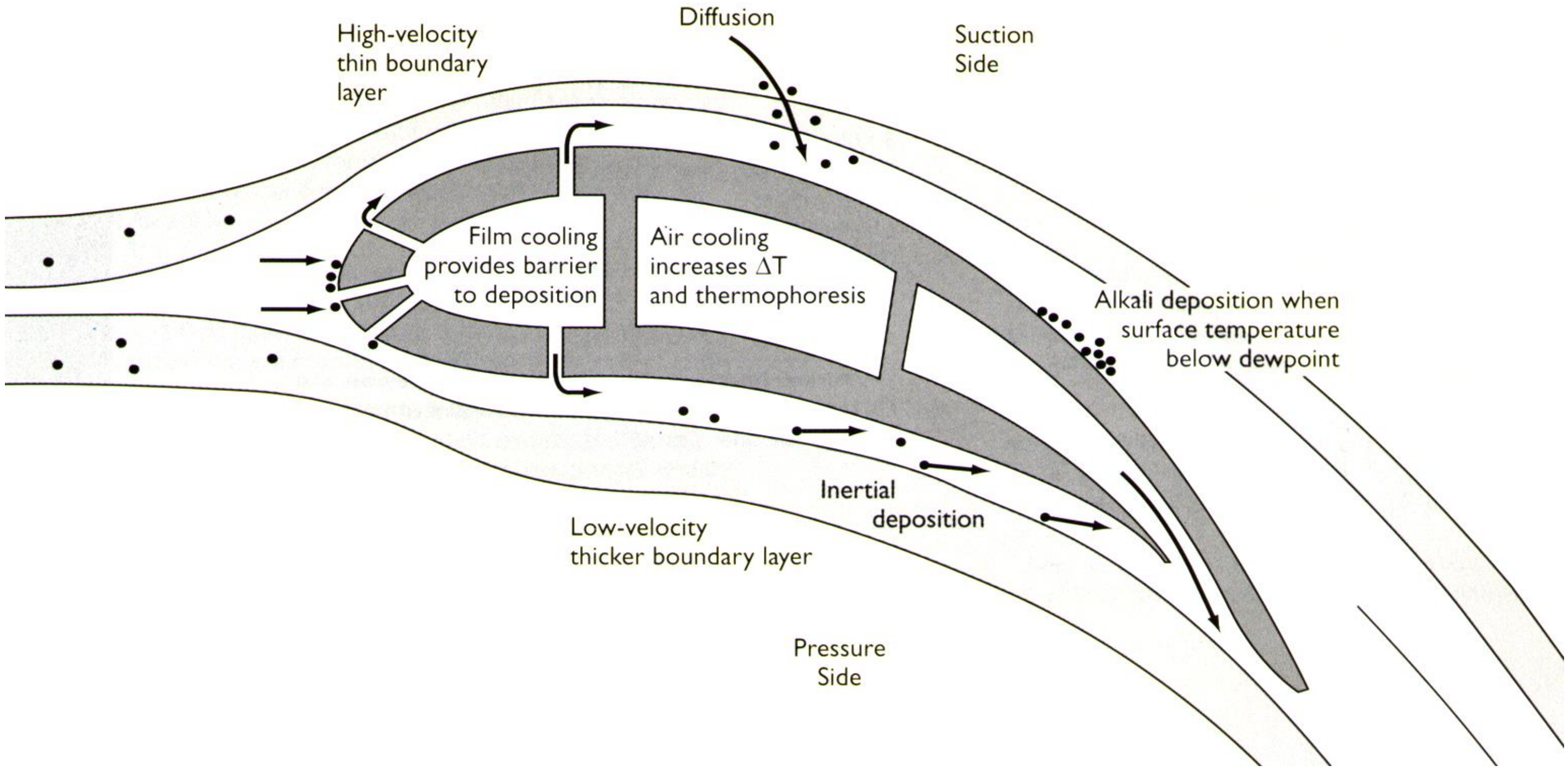


Permitted contaminants in fuels of different calorific values (example from one OEM)

ETN Global

Fuel type	Company Ref. Fuel	Biogas	Landfill gas		Poor quality nat. gas	Pipeline nat. gas	Refinery gases & LPG		
Net Calorific value (MJ/Kg)	48.16	4 - 10	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70-80
	Maximum allowable concentration from ALL sources on fuel equivalent basis, ppm (mass)								
V	1.00	0.08	0.20	0.40	0.60	0.80	1.00	1.20	1.40
Na + K	0.60	0.05	0.10	0.20	0.30	0.50	0.60	0.70	0.80
Ca + Mg	1.00	0.10	0.20	0.40	0.60	0.80	1.00	1.20	1.40
Pb	0.50	0.04	0.10	0.20	0.30	0.40	0.50	0.60	0.70
Zn	1.00	0.10	0.20	0.40	0.60	0.80	1.00	1.20	1.40
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S	3000	249	622	1240	1860	2490	3110	3730	4630
Li	0.50	0.04	0.10	0.20	0.30	0.40	0.50	0.60	0.70
SiO_2	0.04	0.003	0.008	0.016	0.024	0.032	0.042	0.05	0.058
F+ Cl+ Br+ I	1.00	0.10	0.20	0.40	0.60	0.80	1.00	1.20	1.40
Other non-combustibles Incl Ash	100	8	20	41	62	83	103	124	145

Deposition on Blades

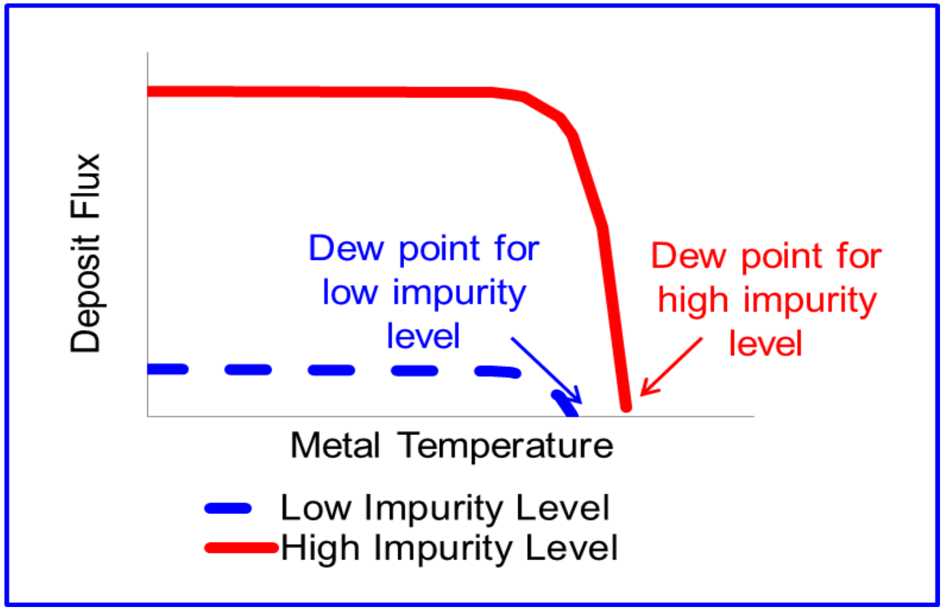


Deposition mechanisms:-

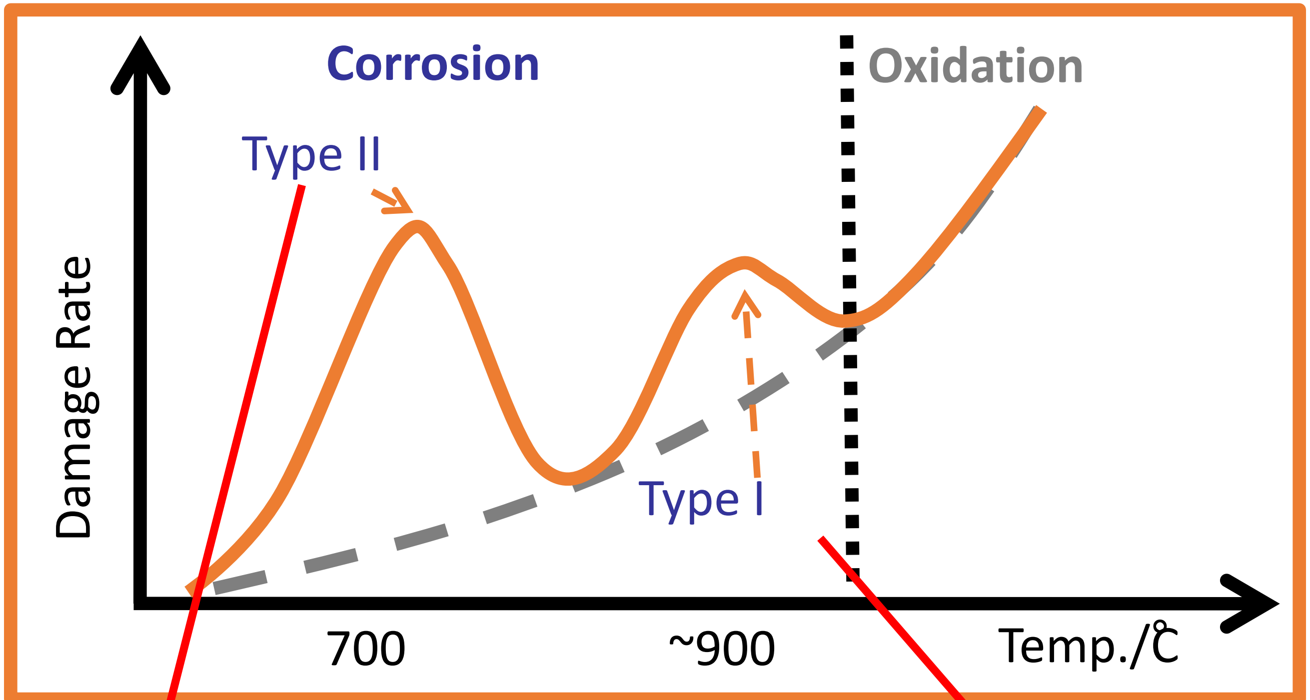
- Particle impaction, diffusion, thermophoresis, etc.
- Vapour condensation

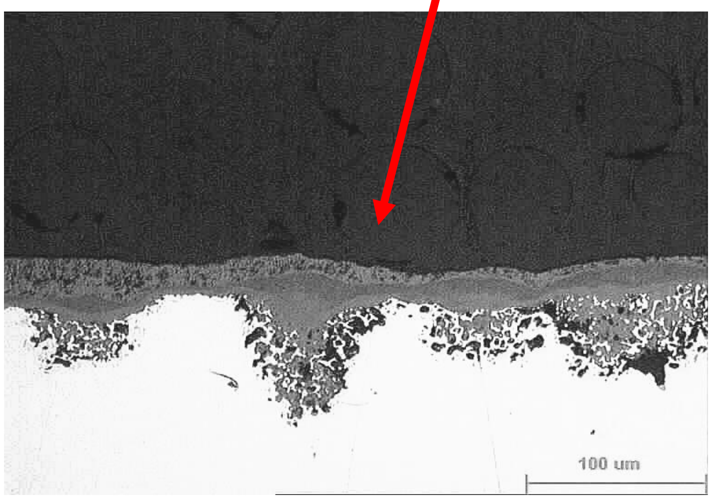
Vapour condensation: dew points

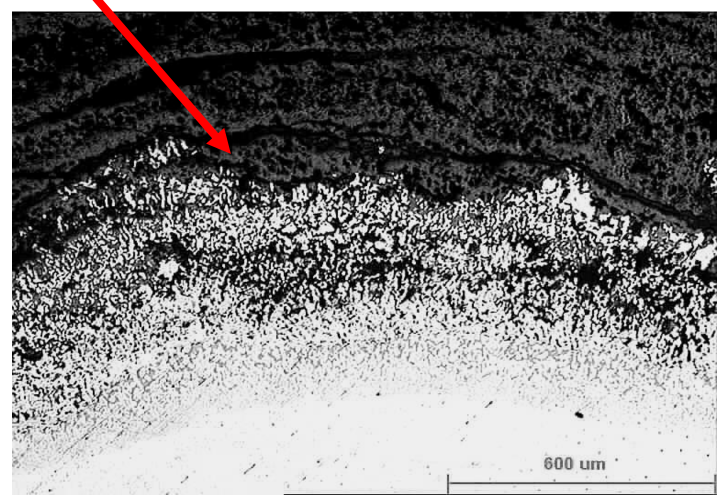
- What condenses onto a component surface in operation?
- Post-combustion:
  - Volatile, potentially corrosive compounds
  - S, Cl, Na, K, etc
- Condensation:
  - Hot gas stream
  - Cooled component
  - Occurrence depends upon dew point
- Dew point depends on:
  - Temperature (of gas & surface)
  - (Partial) pressure
  - Species concentration
- Can be calculated



Hot corrosion – propagation stages







The Cranfield ‘Phase 1’ Proposal

To achieve the necessary understanding of the problems being experienced, there is a need to establish a short-term project. The aims are:

- to bring together the available information from a number of hot corrosion problems where sufficient operating information is available
- to carry out thorough metallurgical investigations of the components provided, using a standardised approach (and provide confidential reports on each part examined)
- to provide an independent analysis of the findings to identify common features and differences
- to present this analysis to the ETN ‘Hot Corrosion’ group as a non attributable summary, discussing the mechanisms in play and options for remedial actions as a basis for follow-on studies to explore the merits and costs of potential

Proposed Project Format

- The project proposal will be developed between Cranfield and the ETN hot corrosion group members

- Each project partner will sign a separate confidentiality agreement with Cranfield, thus ensuring that any information exchanged is not released with the prior consent of the project partner

- The project will be funded on the basis of a fixed price for each damaged part & related information (details of GT, operating conditions, fuel(s), combustion air, etc.) provided to the project. For the project to start, at least 5 damaged parts will be needed. The price per part will be lower with more partners providing parts

- It will be possible for other partners to join the project at a later stage, subject to the agreement of the existing project partners to improve the developing knowledge base

Phase 1 Project Outline

Project set-up:

- Preparation of full project proposal for the short ETN industry project
- Potential project partners to identify their interests and proposed contributions, i.e. parts and data for the investigations
- Two-way confidentiality agreements and contract terms to be agreed with partners
- Partners to provide the parts and associated operating data

Phase 1 Project Outline

Project activities:

- Parts provided to be investigated and confidential reports on each part provided to the relevant project partner for review/approval.

  [additional investigations may considered where required and funding allows (could involve other independent organisations)]

(the parts should be components from machines where hot corrosion problems have occurred or are expected, but have not yet failed. Ideally, they should have a reasonably well-defined operating history (i.e. hours in service). It would also be very useful if an unused, equivalent component were also provided as a reference.)

- Once agreed quota of parts examined, Cranfield to analyse the findings, to consider remedial options with project partners and to prepare an overview draft report

- Project partners to approve disclosure of information in the draft report

Phase 1 Project Deliverables

- Each project partner to receive report on the damage / failures of their components (confidential to that partner)

- Draft summary report providing an overview of the findings and a proposal for Phase 2 studies to explore cost-effective remedial actions to be approved by the ETN Project Board following approval by all of the project partners

- Based on the findings from the study, the ETN Project Board:
  - to approve and issue a technical guidance note to members
  - to consider the scope and funding of possible Phase 2 studies (expected to involve a wide range of ETN members)

- Recommendations from the summary report to be included in the ETN Project Board's R&D Strategy Report

Current Status

- ETN and Cranfield have held discussions on the Phase 1 project proposal with prospective partners
- ETN has established an ETN ‘Hot Corrosion’ Working Group
- Currently, there are too few participants to initiate the project as planned. New simplified email survey being initiated to better define those with hot corrosion problems and to encourage their participation in the working group.

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