Fireside Corrosion and Steam Oxidation in Superheater / Reheater Tubes for Advanced Ultra-Supercritical Power Systems

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  - “Preparation for Commercial Demonstration Plant for 700 °C Operation”
  - DP 700 – Phase 1

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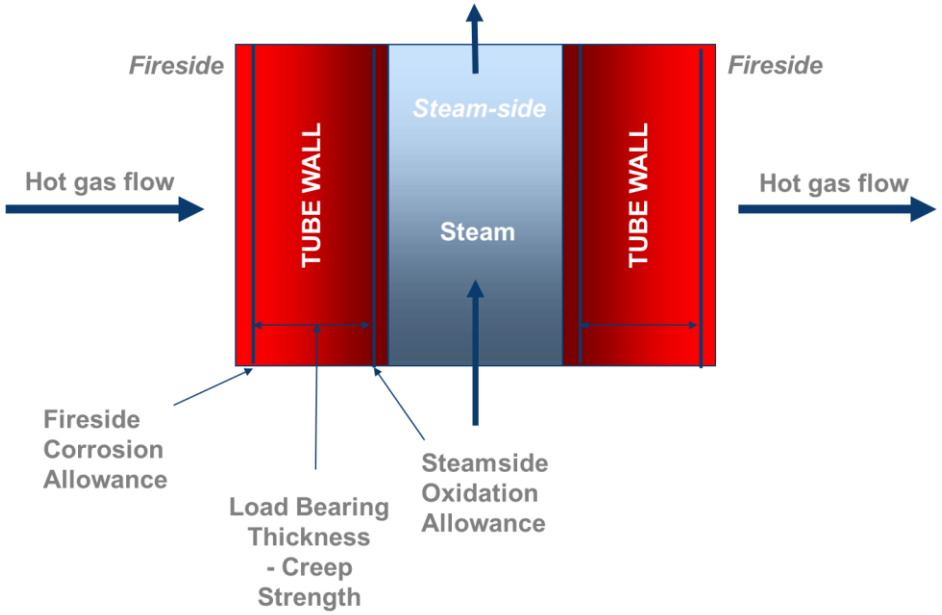
  - Database development
- Summary



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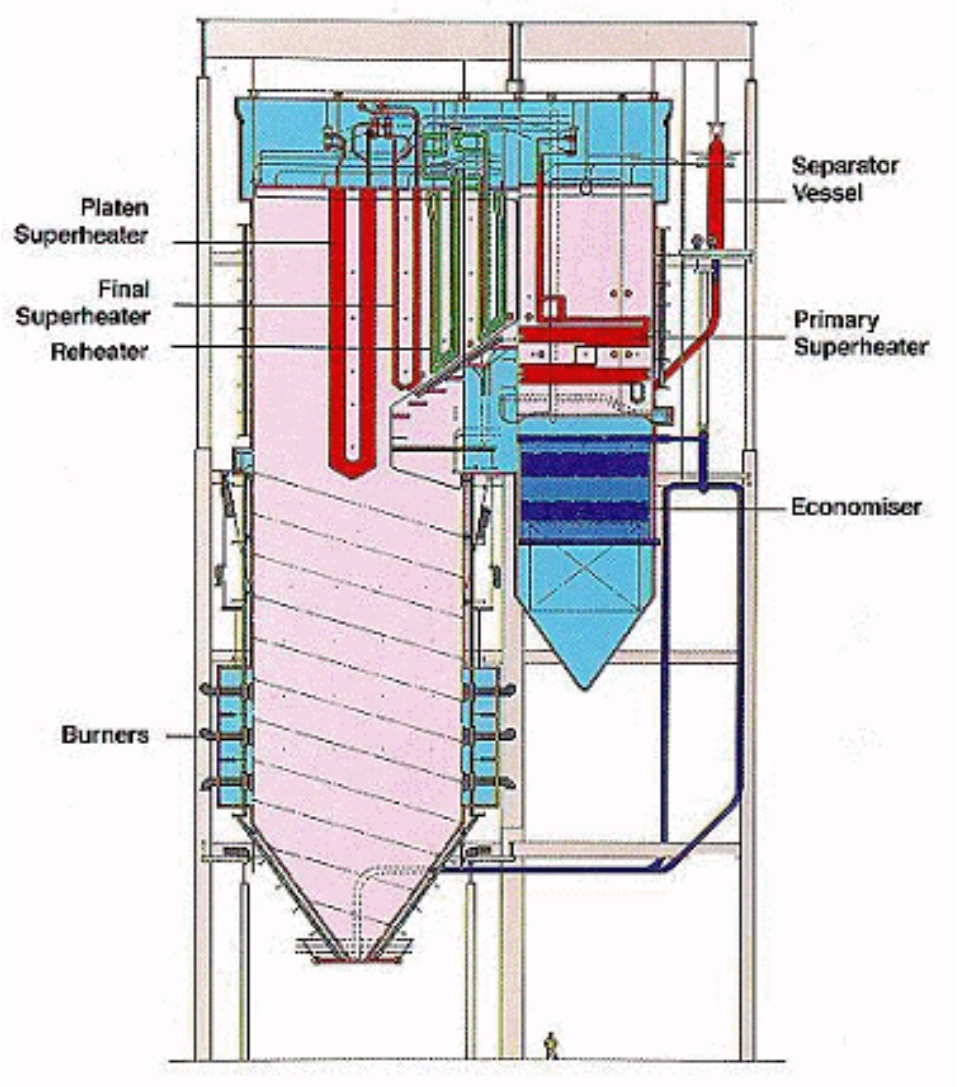
Advanced solid fuel fired combustion plants

- Higher efficiencies
- Higher component operating temperatures
- Lower emissions
  - CO_2, SOx, NOx, etc
- Carbon capture systems
  - Post-combustion capture
  - Oxy-firing
- Fuel flexibility
  - Wide range of coals
  - Co-firing with biomass
- Operational flexibility
  - Base load
  - Cyclic operation
    - To fit in with renewable energy generation



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Materials issues in advanced combustion plants (1)

More challenging component operating conditions:

- Higher steam operating temperatures and pressures
  - Heat exchangers – superheaters, reheaters, etc
  - Steam transfer pipes and control valves
  - Steam turbines
- Cyclic operation
  - May require far more frequent starts/stops from:
    - Hot, warm, cold
  - Would benefit from thinner components
    - New, more expensive alloys
- Wider range of fuels:
  - Local and world traded fuels:
    - Coals
    - Biomass for co-firing

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Materials issues in advanced combustion plants (2)

Potential materials degradation mechanisms

- Environmental
  - Steamside oxidation:
    - Scale growth; scale spallation; erosion / blockages
  - Fireside corrosion:
    - Superheaters / reheaters; boiler walls
  - Fireside erosion
- Mechanical
  - Creep
  - Fatigue
    - Low & high cycle fatigue (LCF & HCF); Thermo-mechanical fatigue (TMF)
  - Creep / fatigue
- Synergistic effects
  - Creep-corrosion
  - Corrosion-fatigue

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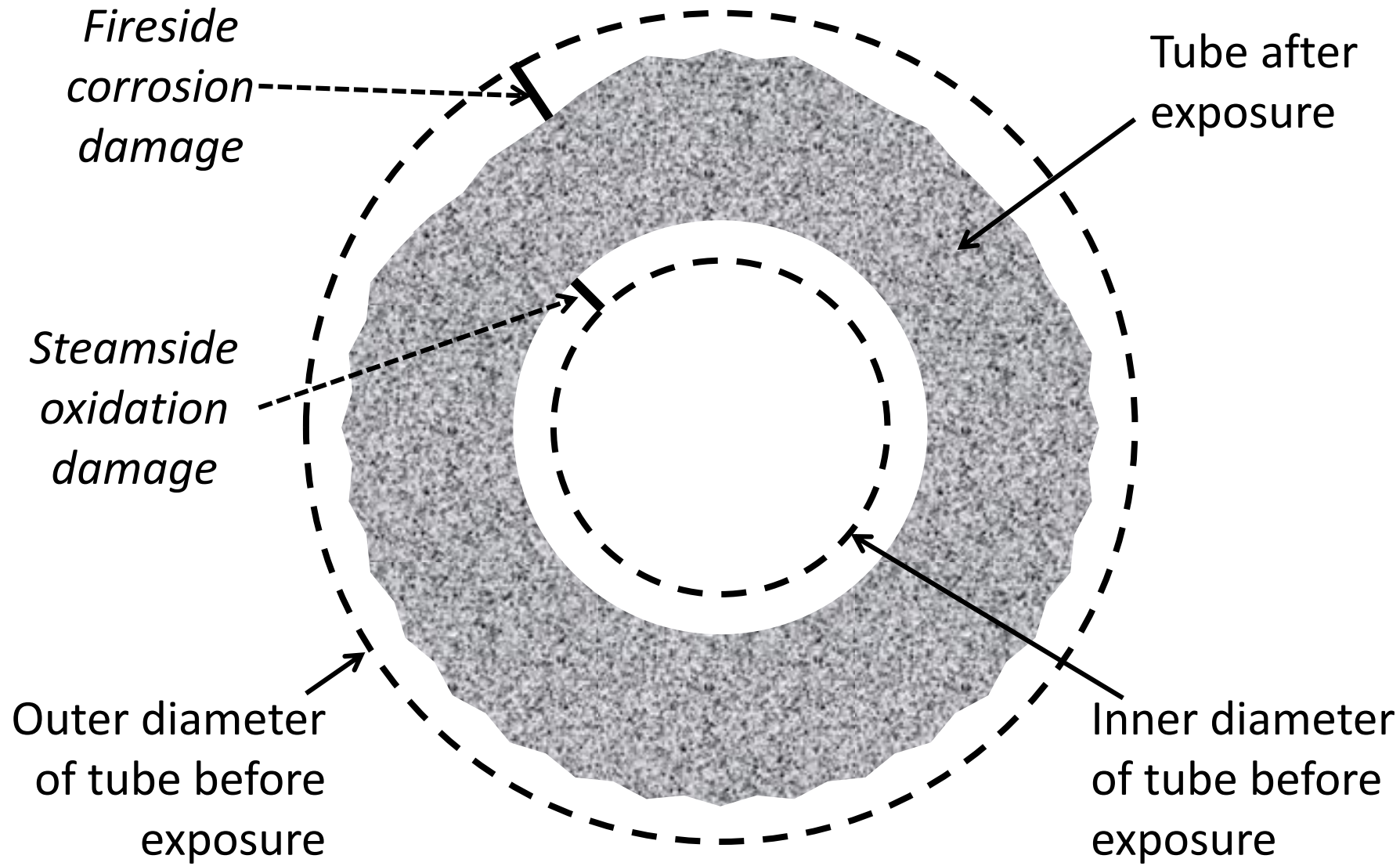
Superheater / reheater tube



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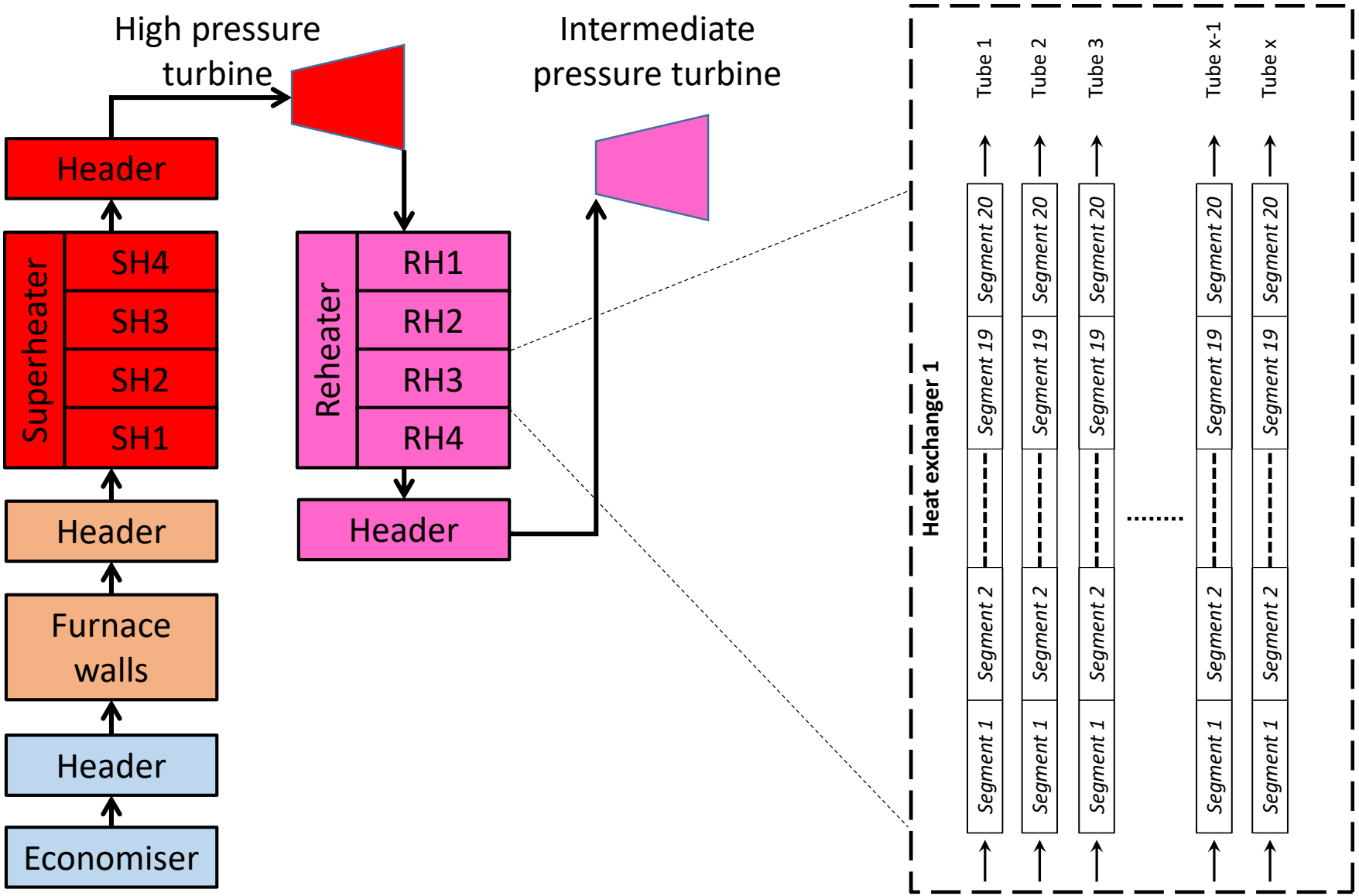
Part of steam circuit



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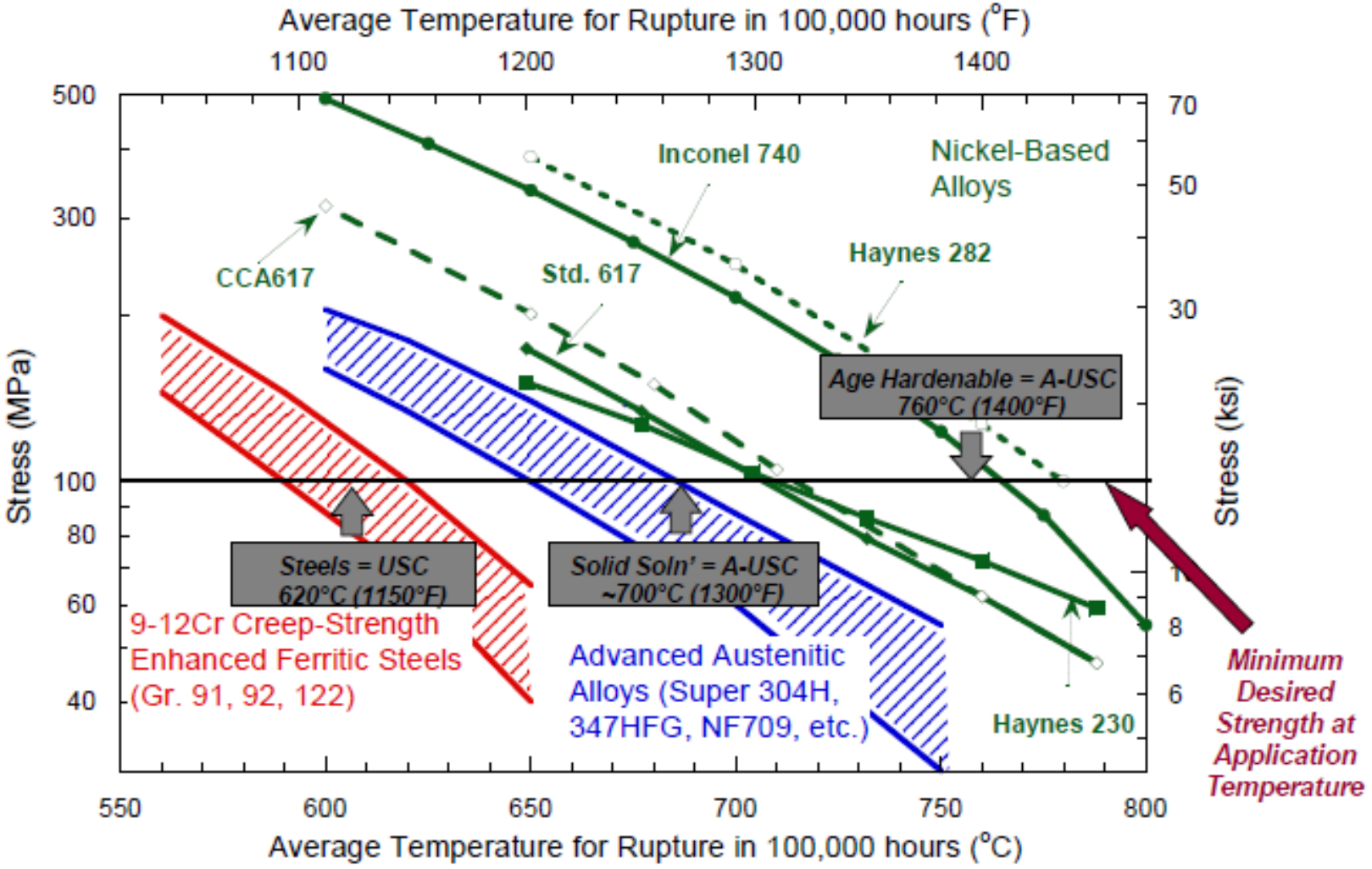
Candidate heat exchanger alloy 100,000 hour creep lives



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Materials issues in advanced combustion plants (3)

Candidate Materials

- Base alloys:
  - Ferritic steels: T24, T92
  - Austenitic steels: Sanicro 25, HR3C, 347HFG, 304HCu, 316L
  - Ni-based alloys: 740H, 282, 263, 617 (modified)

- Coatings
  - Fireside (HVOF application):
    - Ni-50Cr; NiCrAlY; FeCrAl; Alloy 625, etc
    - With and without sealants
  - Steamside
    - Aluminising treatments
    - Application using slurry coating or liquid ionic plating

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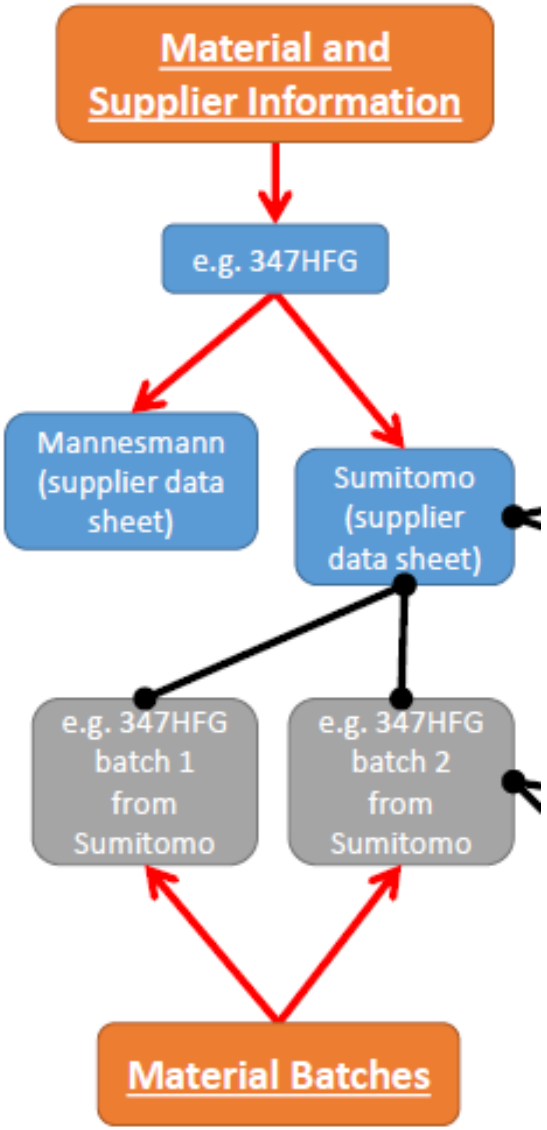
Component manufacturing issues

- Materials selection
  - Alloy / Coating (if required)
- Materials specifications
  - Compositions & microstructures
    - ranges, fine-tuning
  - Properties in final conditions & during lifetime
- Materials supply – variations
  - Composition range
  - Manufacturer
- Component manufacturing
  - Extrusion, bending, …
- Joining
  - Welding – similar vs dissimilar metals
- Non-destructive inspection
  - Methods & validation
  - Typical defects / criteria



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Steam oxidation

Historical data

- **Long duration plant data**
- **Component temperatures much lower than planned for advanced plants**
- **Alloys developed and select for use at lower temperatures**

Steam oxidation data needed for advanced plants

- **Higher component metal temperatures – up to 800 °C**
- **New alloys**
- **Potential data sources**
  - **Test loops – plant based**
  - **Pilot scale test rigs**
  - **Laboratory scale test rigs**
    - **Atmospheric pressure (and pressurised)**
- **Data quality – metal loss**
- **Data for modelling – to counter limitations in data sources**

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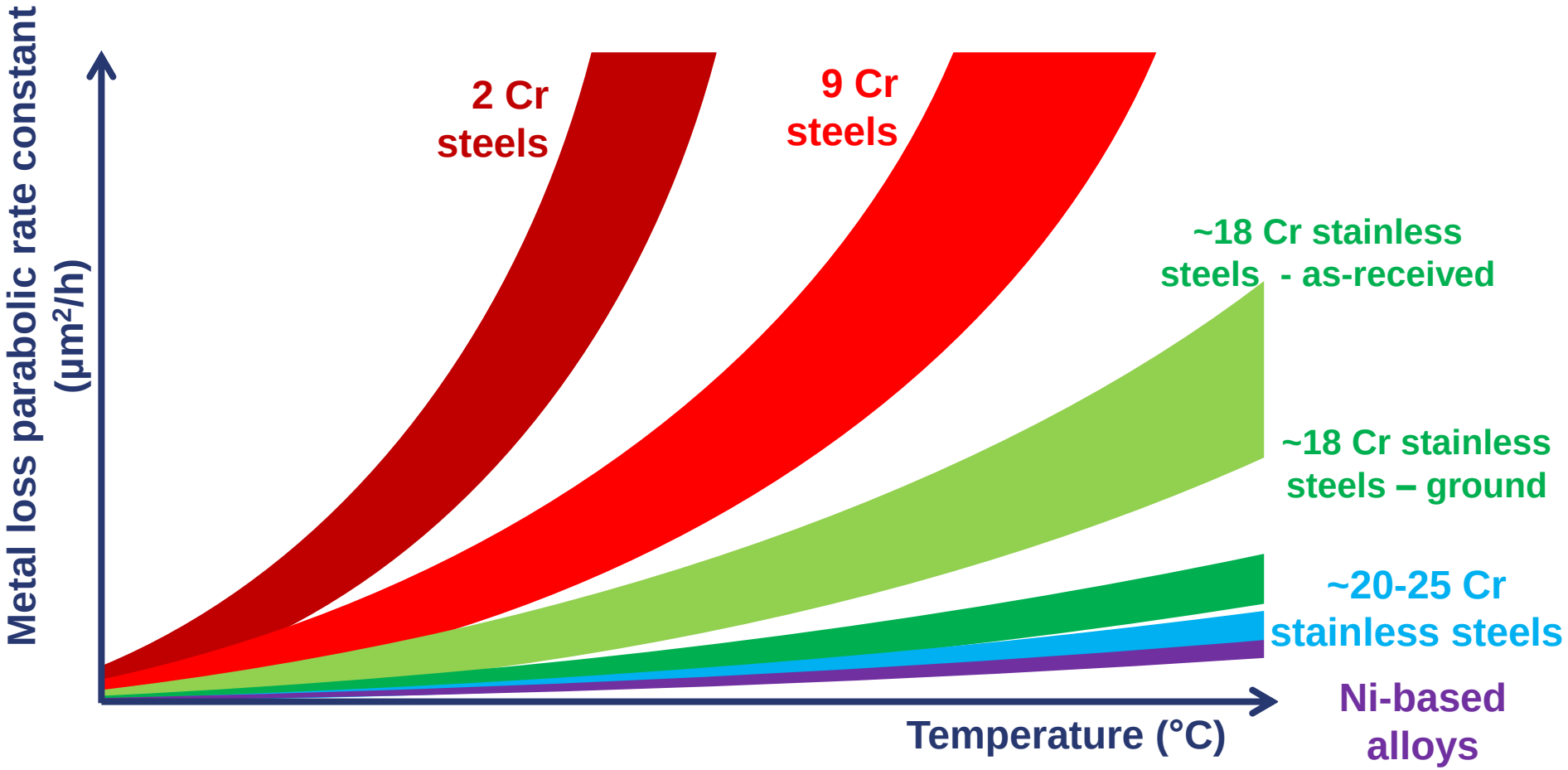
Steam oxidation



Issues:

- Spallation of oxide scales – especially from stainless steels
- Effects of surface finishes
- Reliability of potential coatings

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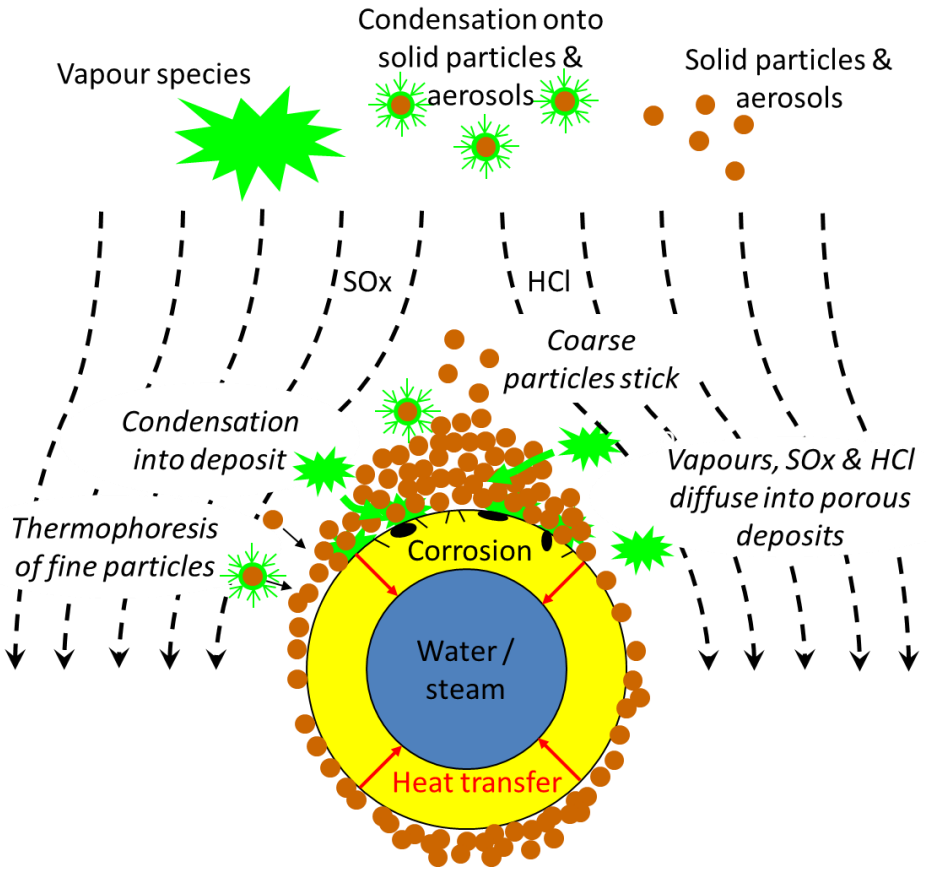
Plant operating conditions for heat exchanger tubes

- Fuel: coal / biomass
- Oxidant: air / oxygen
- Gas stream characteristics:
  - Gaseous species – e.g. SO_X, HCl, O_2, CO_2, H_2O, NO_X, N_2
  - Vapour species – e.g. Na, K compounds
  - Particles
    - From ash in fuel
    - Condensed vapour species
  - Gas temperature
- Heat exchanger characteristics:
  - Water / steam temperature (& pressure)
  - Metal temperature (& heat flux)
  - Deposit
    - Rate of formation (flux)
    - Composition



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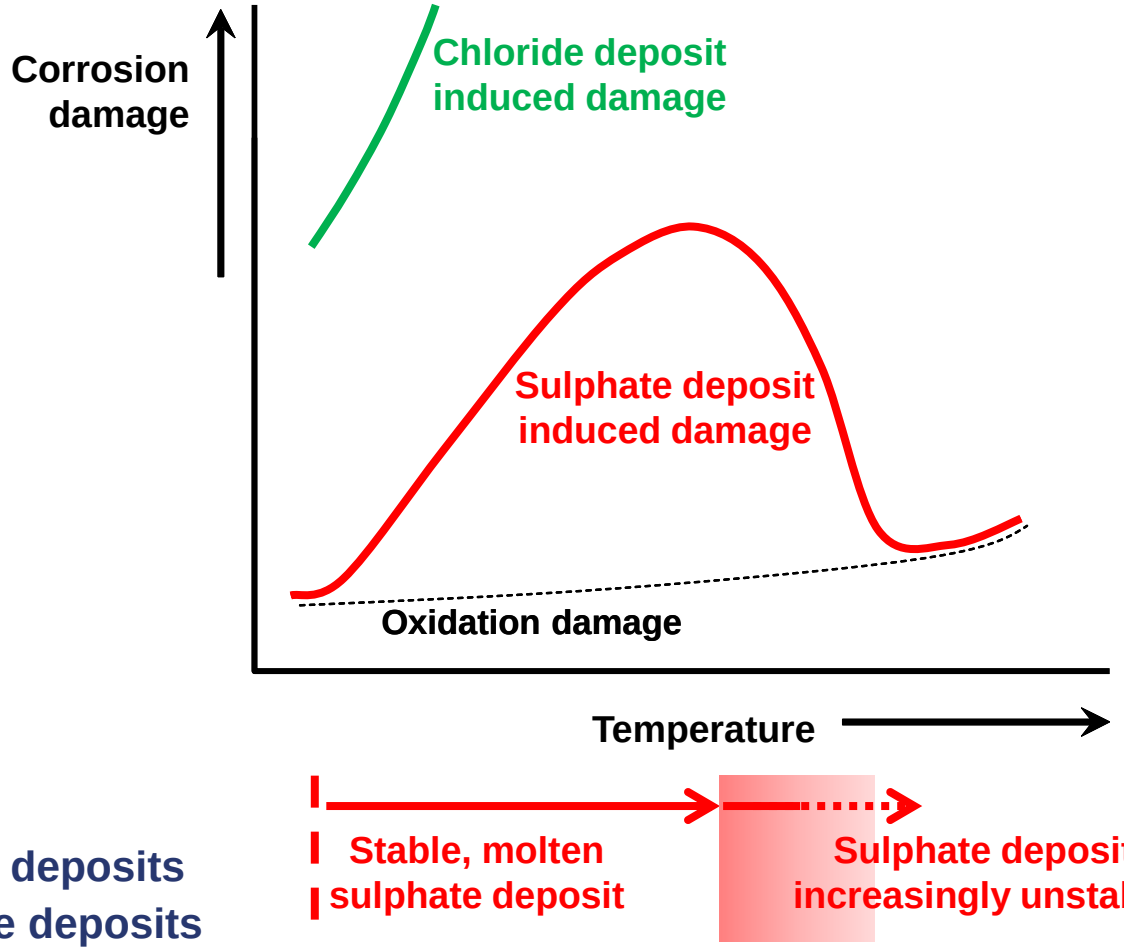
Superheater / reheater fireside corrosion damage



Corrosive deposits

- Sulphate deposits
  - Mixed sulphates (e.g., $(K,Na)_XFe_YSO_4$
- Chloride deposits – mixed
- Sulphate – chloride 'soup'
- Molten vs sticky vs solid

Deposit instability

- SO_3 needed to stabilise some sulphate phases & SO_3 favoured at lower temperatures
- Other phases more stable with change in deposit temperature

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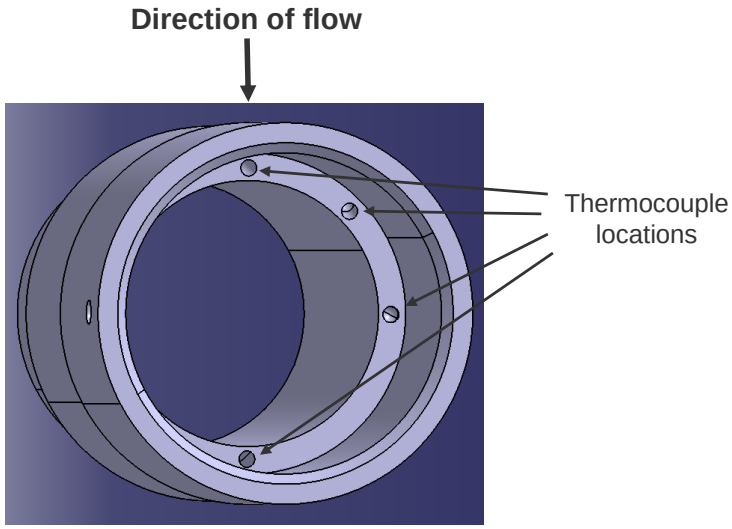
Fireside corrosion data

- Power plant derived data
  - Probes
  - Component inspections
  - Long exposures (usually)
  - Variable fuels
  - Variable operating conditions
- Pilot plant derived data
  - Probes
  - Short operating times – so need very accurate measurements
- Laboratory exposures
  - Smaller samples
  - Simulate specific environments
    - Gases
    - Deposits
    - Isothermal exposures
  - Often reported as mass change
  - Need accurate metal loss measurements for useful models



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Laboratory Hot Corrosion Tests

Critical parameters
- Metal temperatures
- Gas composition
- Deposit composition
- Deposition flux
- Coating / alloy compositions

Deposit recoat technique
- Simple ‘simulation’ of deposition flux
- Allows control of deposit composition
- Multiple deposit recoats (ideally >5)

Controlled atmosphere furnaces
- Specific gas compositions
- Alumina lined reactors
- Exposure temperatures controlled to +/- 3-5°C

Samples manufactured from tubes / bars
- Machined
  - Standard surface finish
  - Precision for dimensional metrology

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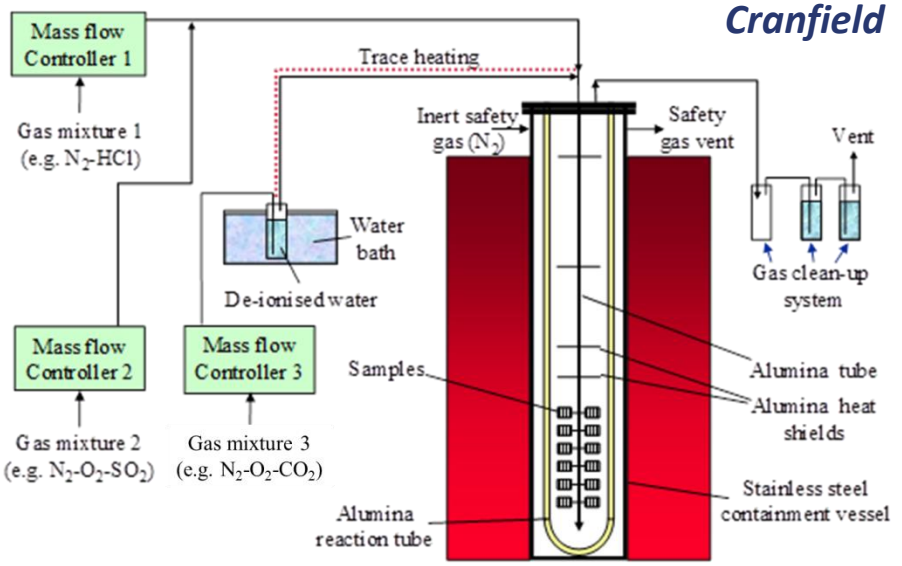
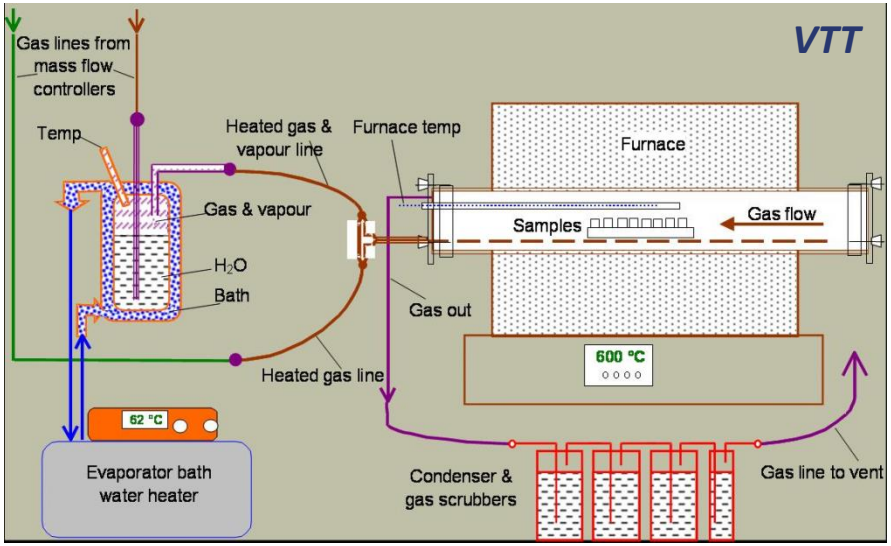


VTT



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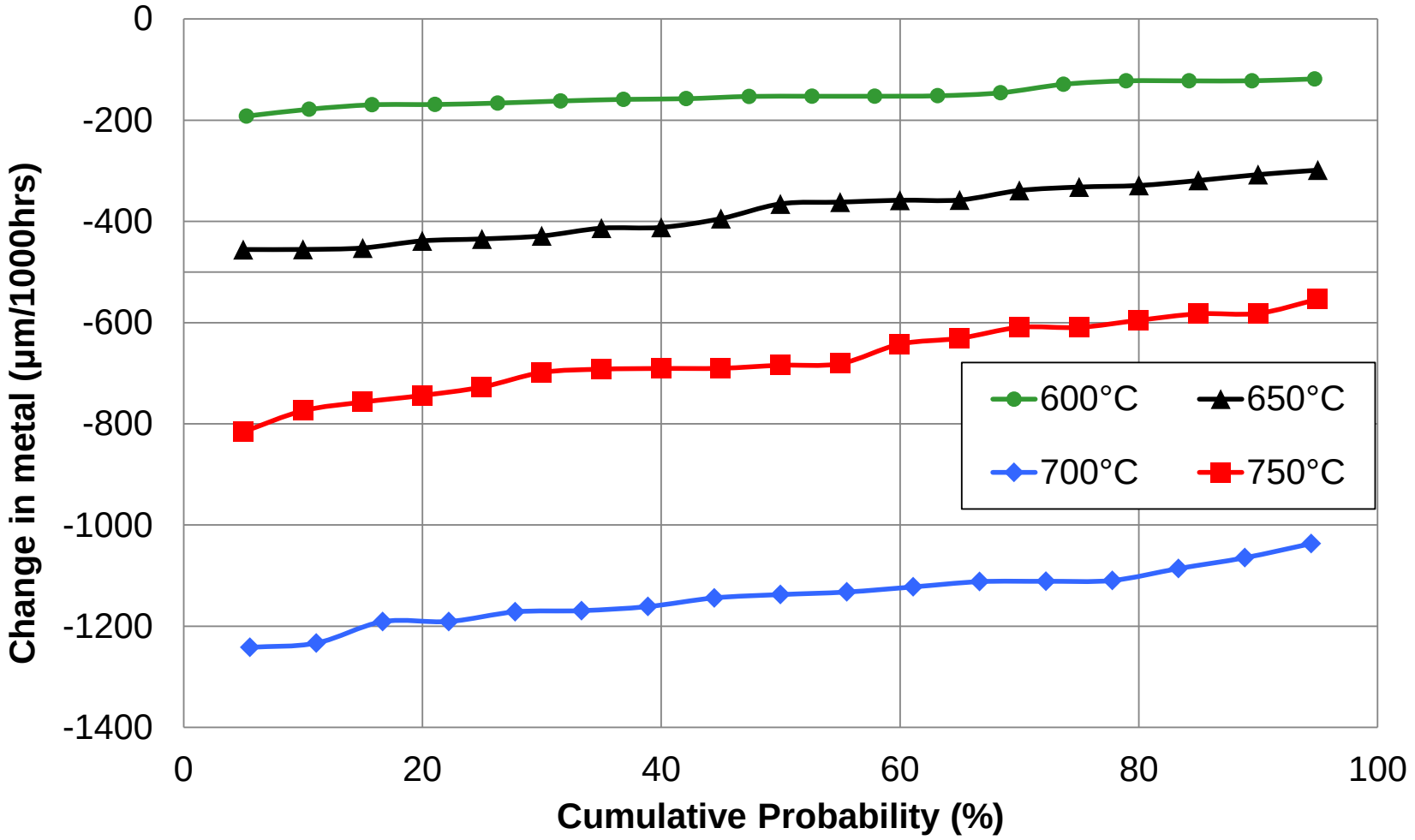
Fireside corrosion – examples of effect of temperature on metal loss distributions for alloy 347HFG



Alloy 347HFG covered with alkali iron sulphate deposit (D1) exposed to 59% CO_2/31%H_2O/4%O_2/6260vppm SO_2/1700vppm HCl for 1000h

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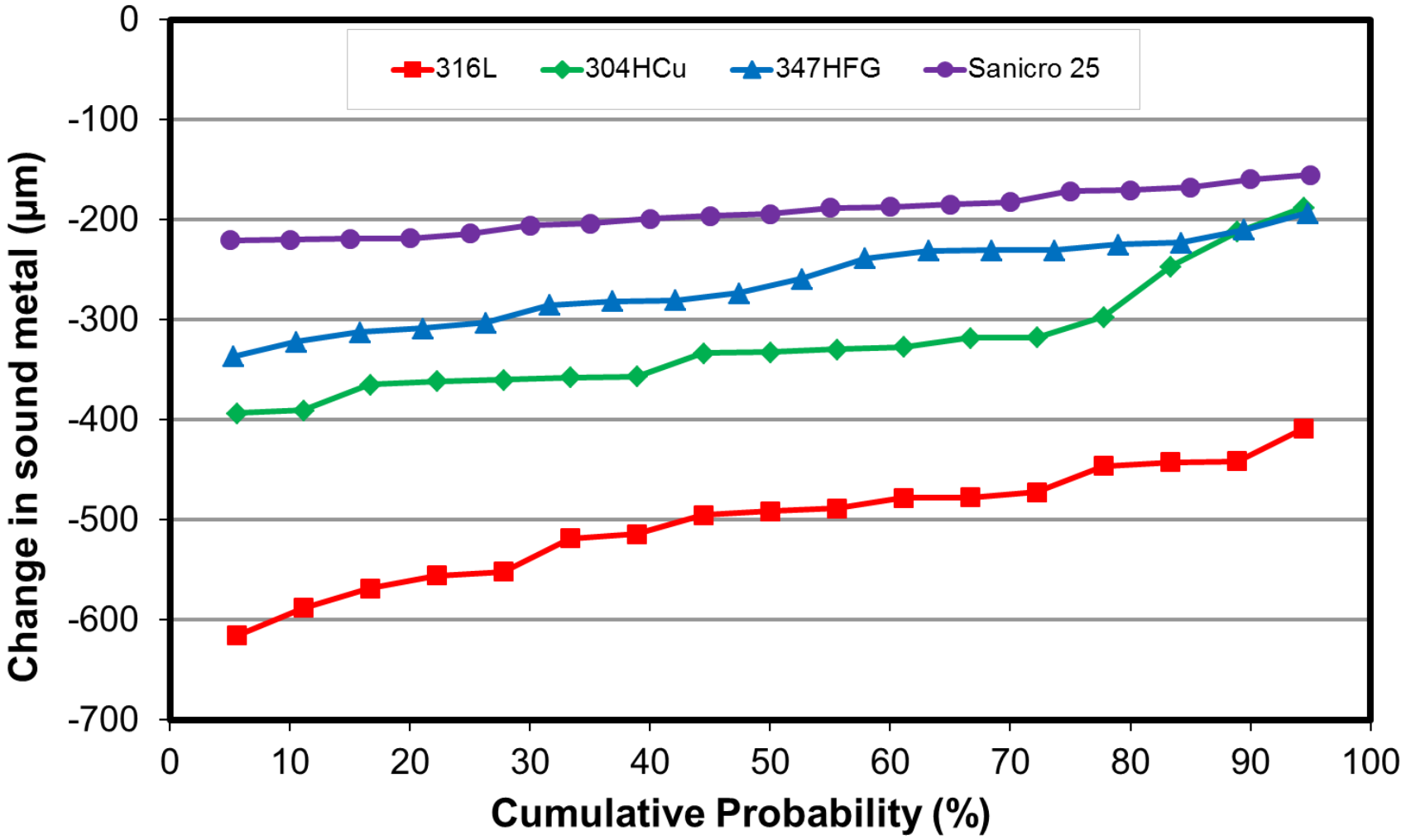
Fireside corrosion – examples of degradation of four stainless steels at 650 °C



Alloys covered with alkali iron sulphate deposit (D1) in simulated air-fired combustion gases for 1000h

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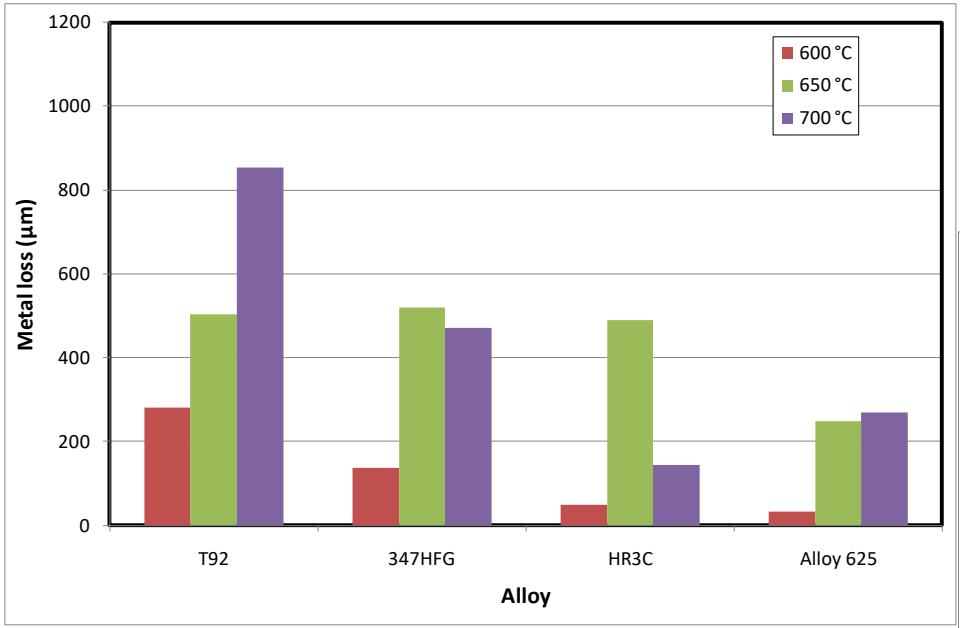
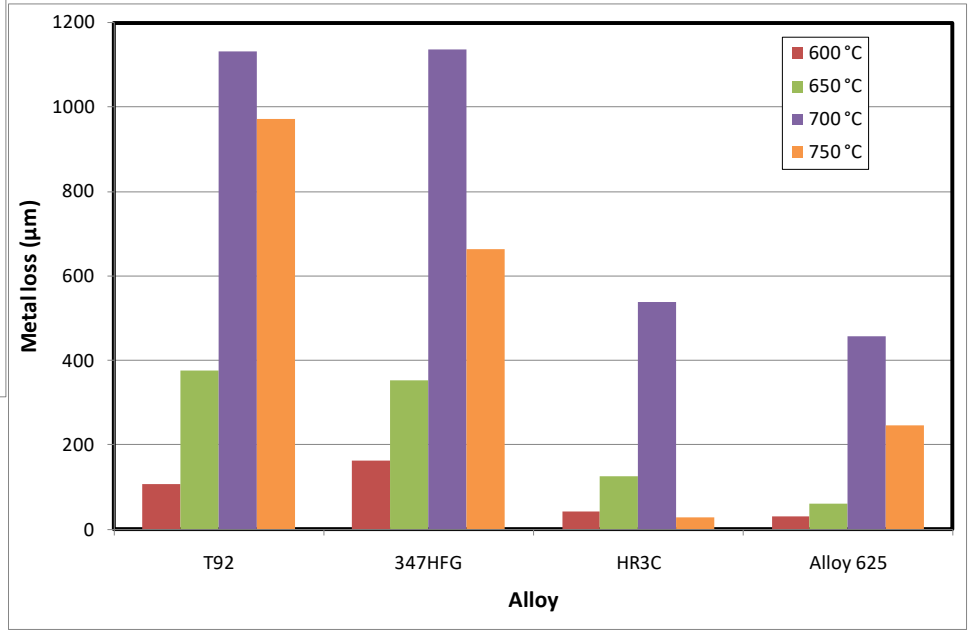
Fireside corrosion damage to alloys exposed with alkali iron sulphate (deposit D1)

(a) Simulated air-fired combustion gases



(b) Simulated oxy-fired combustion gases (hot gas recycle option)



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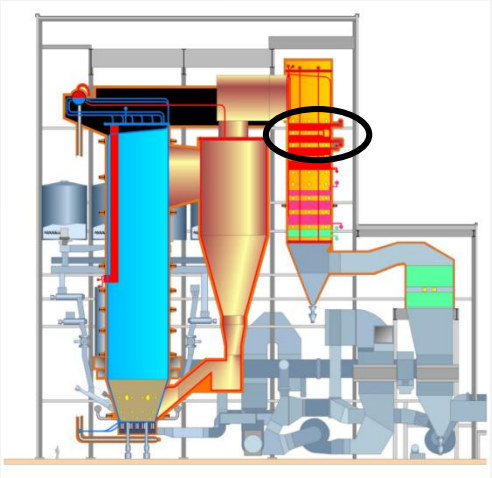
Plant exposures – tubes / probes

- Activities carried out by:
  - Doosan Babcock / VTT / DNV GL
- Power plants include:
  - E.ON / Ratcliffe – Coal – Pulverised fuel
  - E.ON / Stevens Croft – Biomass, CFBC
  - E.ON / Maasvlakte – Coal and 7% biomass (3.5% MBM and 3.5% biomass pellets)
  - RWE / Essent Amer 9 – Coal and 15% wood
  - RWE / Tilbury – Biomass – Pulverised fuel
  - GDF Suez Gelderland 13 – Coal
  - Alholmens Kraft – Biomass (forest residues, industrial wood and bark etc), peat, coal and 10 % SRF (solid recovered fuel) - CFBC

Plant Demonstration Trials by VTT

- corrosion testing and process monitoring by probe measurement



CFB boiler Alholmens Kraft, Pietarsaari, Finland
Biomass (forest residues, industrial wood and bark etc.), peat, coal and 10 % SRF (solid recovered fuel)

Trial	Coating	Spray
1-3	FeCr*	HVOF CJS
3	FeCr*	HVOF DJ
1-2	Ni-46Cr-2Si	HVOF CJS
3	Ni-46Cr-2Si	HVOF DJ
1	IN625	HVOF CJS
2	IN625	HVOF DJ

Trial	Coating	Spray
2	Ni-21Cr**	HVOF CJS
3	Ni-21Cr	HVOF DJ
3	NiCrAlY	HVOF DJ
3	NiCrAlY+ Al_2O_3	HVOF HV2000
1-2	NiCrTi	ARC

Trial	Substrate
1-3	T92
1-3	A263
3	A740

Trial	Duration
1	1300 h
2	5900 h
3	3400 h

*Fe-19Cr-9W-7Nb-4Mo-2Si-2C-B

**Ni-21Cr-9W-9Mo-4Cu-1C-1B

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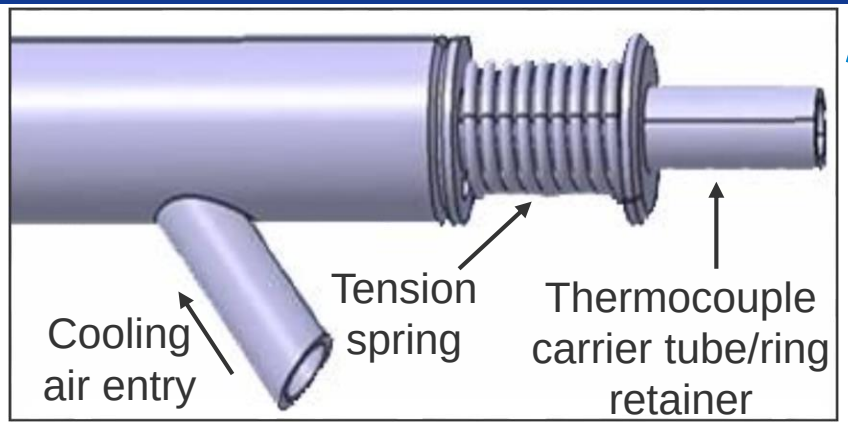
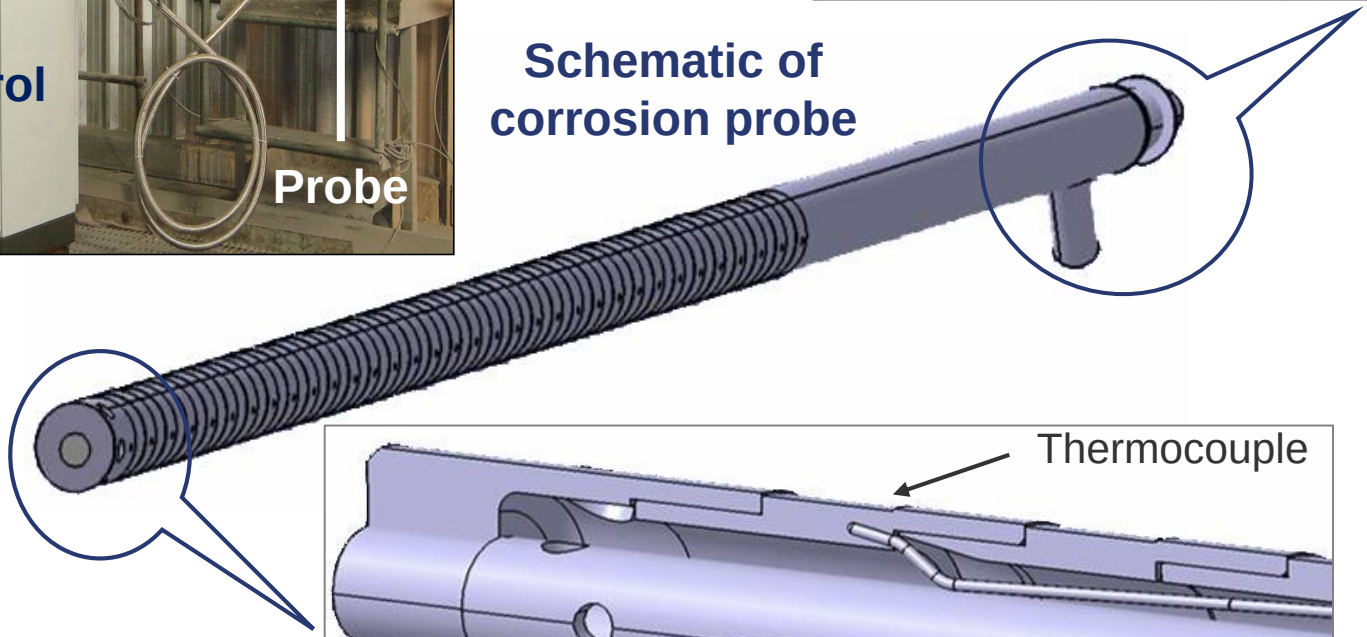
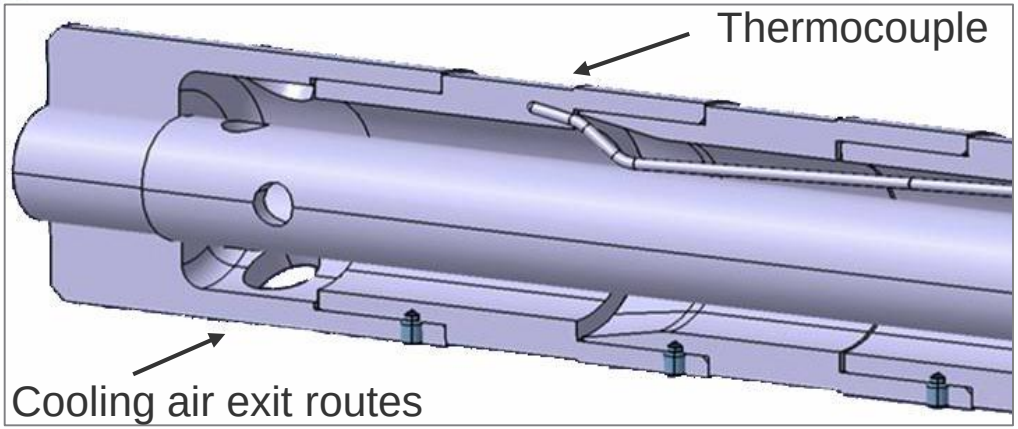
SEVENTH FRAMEWORK PROGRAMME

Doosan Babcock - Air-Cooled Corrosion Probe System at Tilbury PS



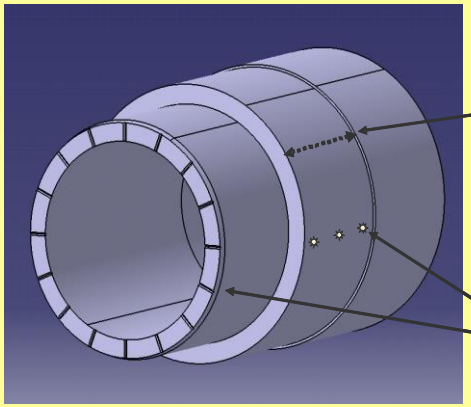
Schematic of corrosion probe





Experimental – Corrosion Probe

Pre-exposure measurements

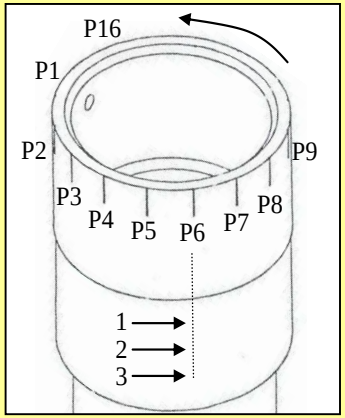


Area of interest

Measuring positions

3 Pitches across width

16 Circumference positions

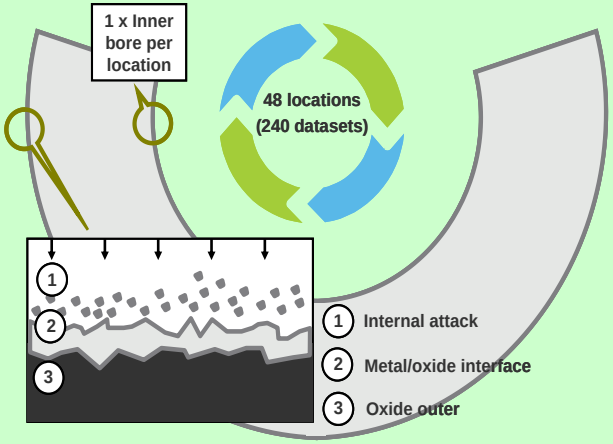


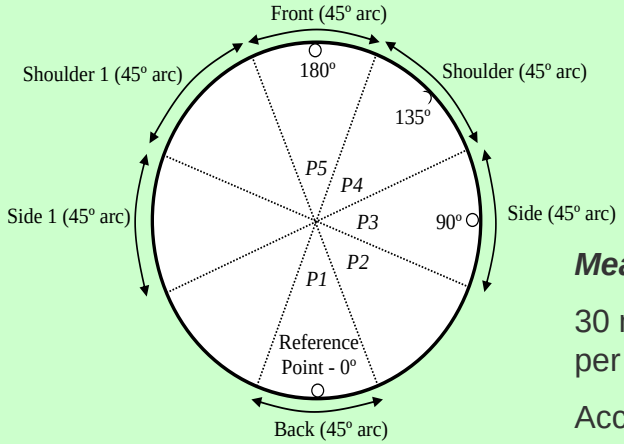
Max range across 48 measurements: 50 µm

Normally > 30 µm

Accuracy = +/- 4 µm

Post exposure measurements





Measuring

30 measurements per sector (240 total)

Accuracy = +/- 4 µm

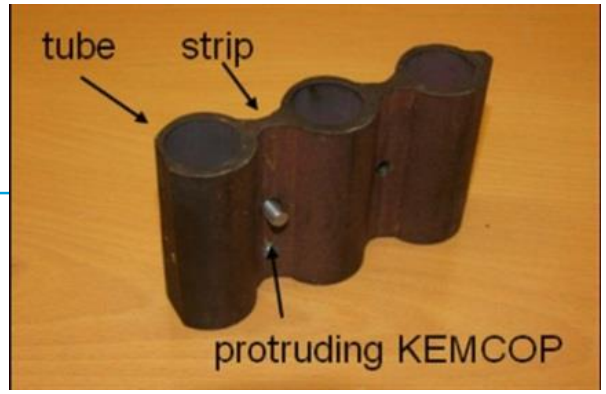
EU NEXTGENPOWER Programme

Plants

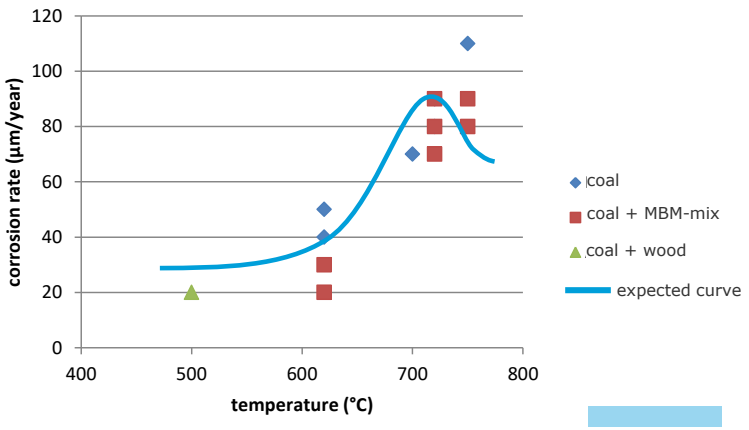
- E.ON Maasvlakte
- RWE / Essent Amer 9
- GDF Suez Gelderland 13

- Membrane wall corrosion: KEMCOPs
- Superheater corrosion: HT probe

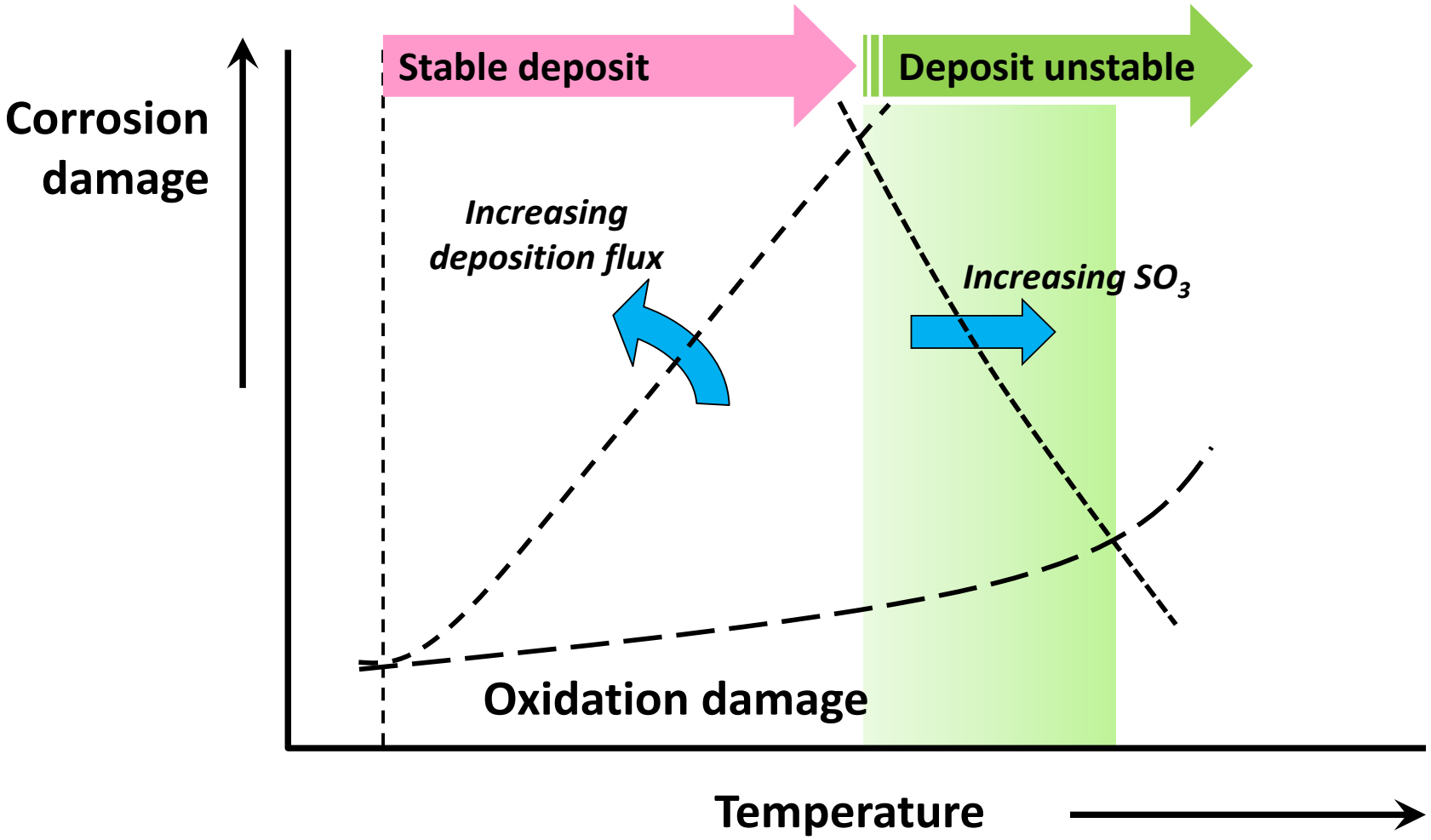
- Considered materials in DNV GL test programme
  - Membrane wall: 15Mo3, 10Cr9.10, T24, T92, Inconel 617, Nimonic 263
  - HT probe: 15Mo3, Nimonic 263, Alloy 740H



Nimonic 263



Key factors in fireside corrosion peaks and the effect of changes in exposure conditions for austenitic alloys



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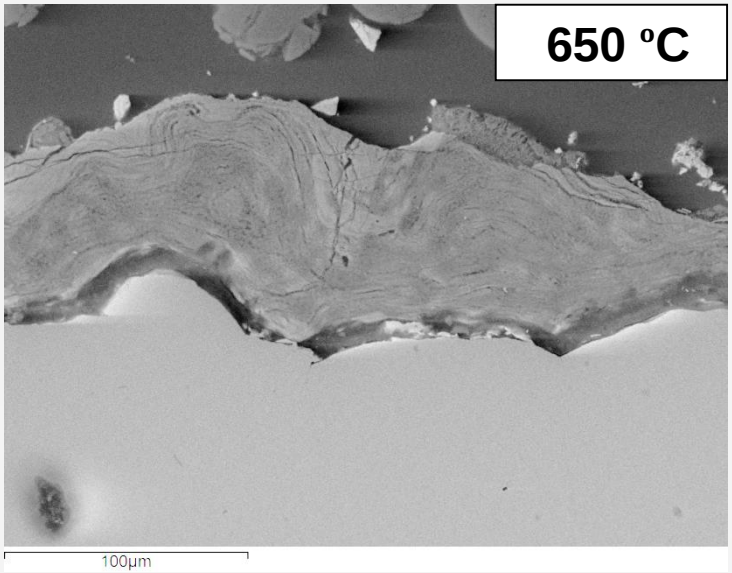
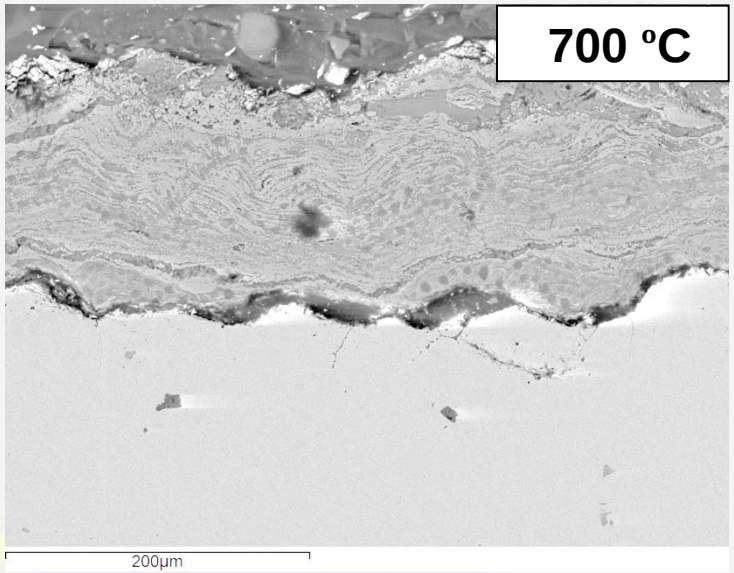
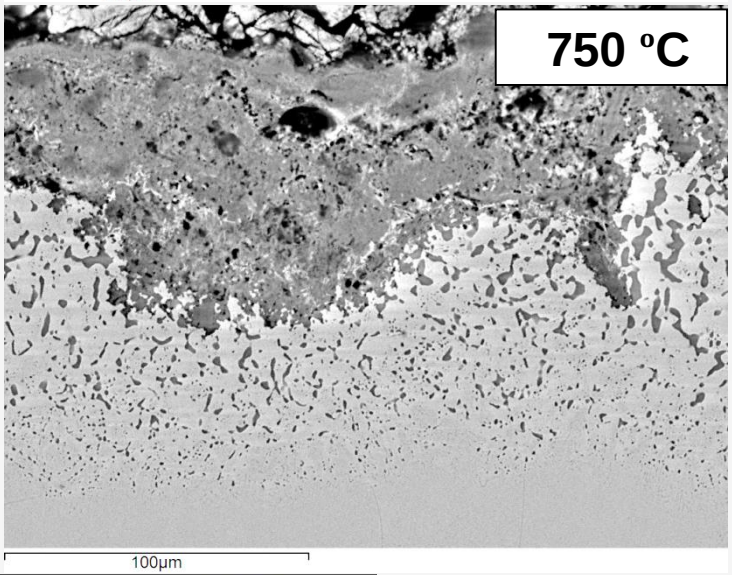
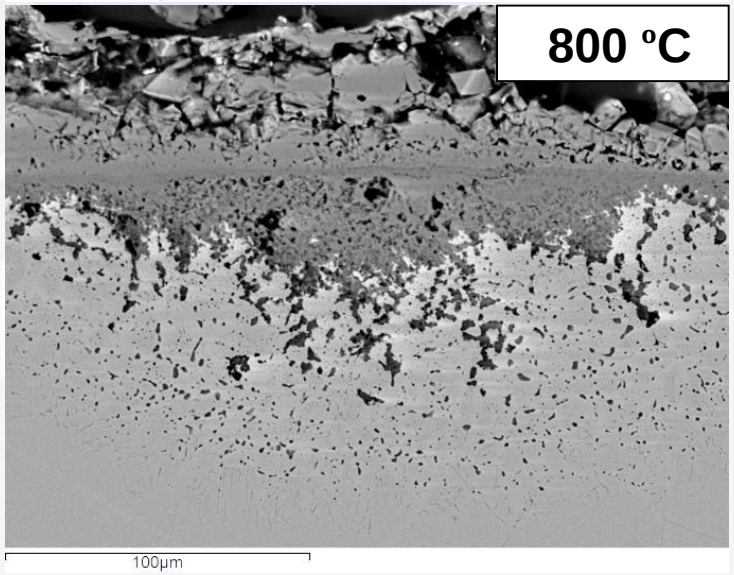
Alloy 263 – 1000 hours exposure at each temperature









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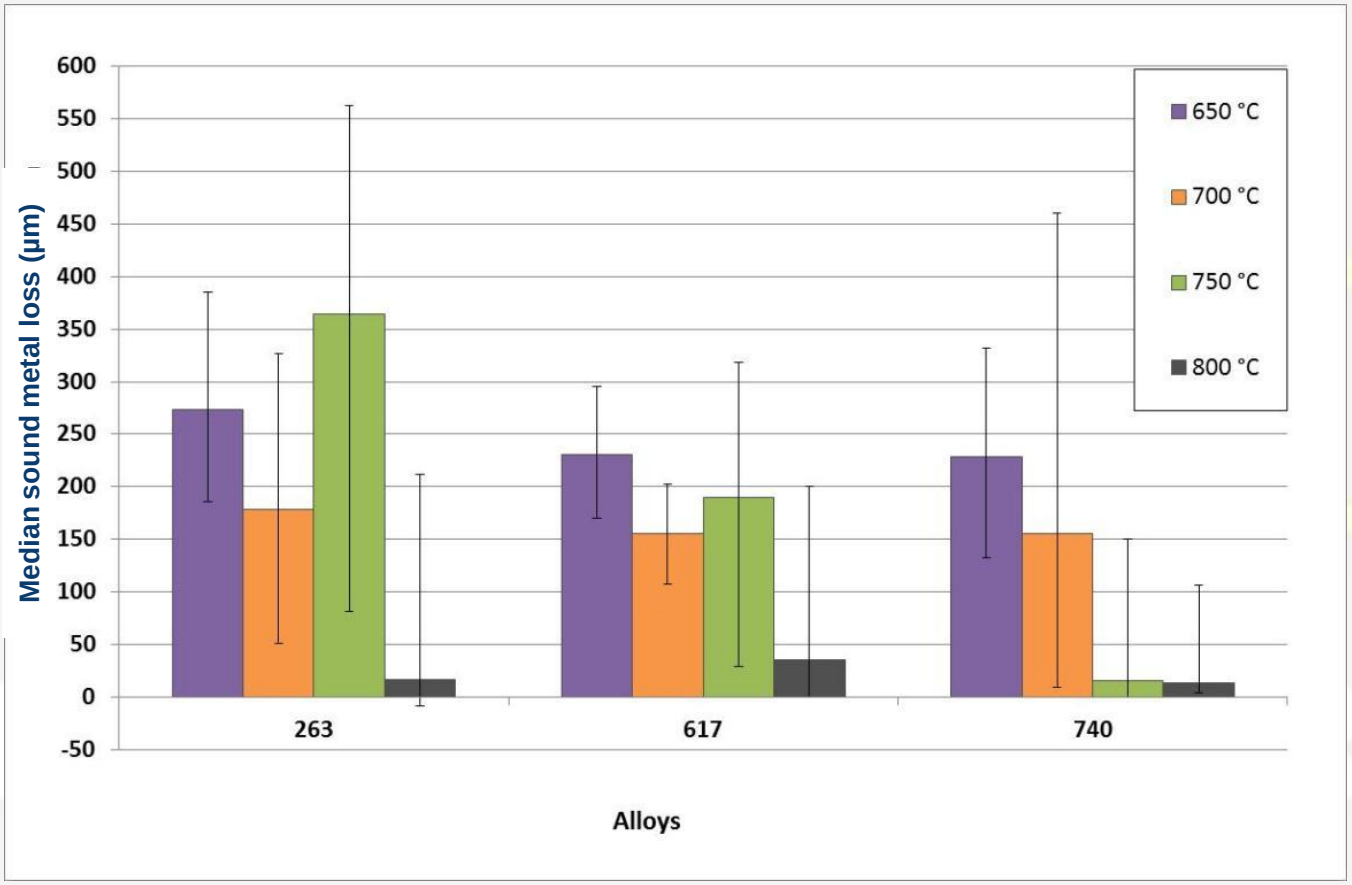
SEVENTH FRAMEWORK PROGRAMME

Median Metal Damage of Ni Alloys After 1000 h (Deposit D1)



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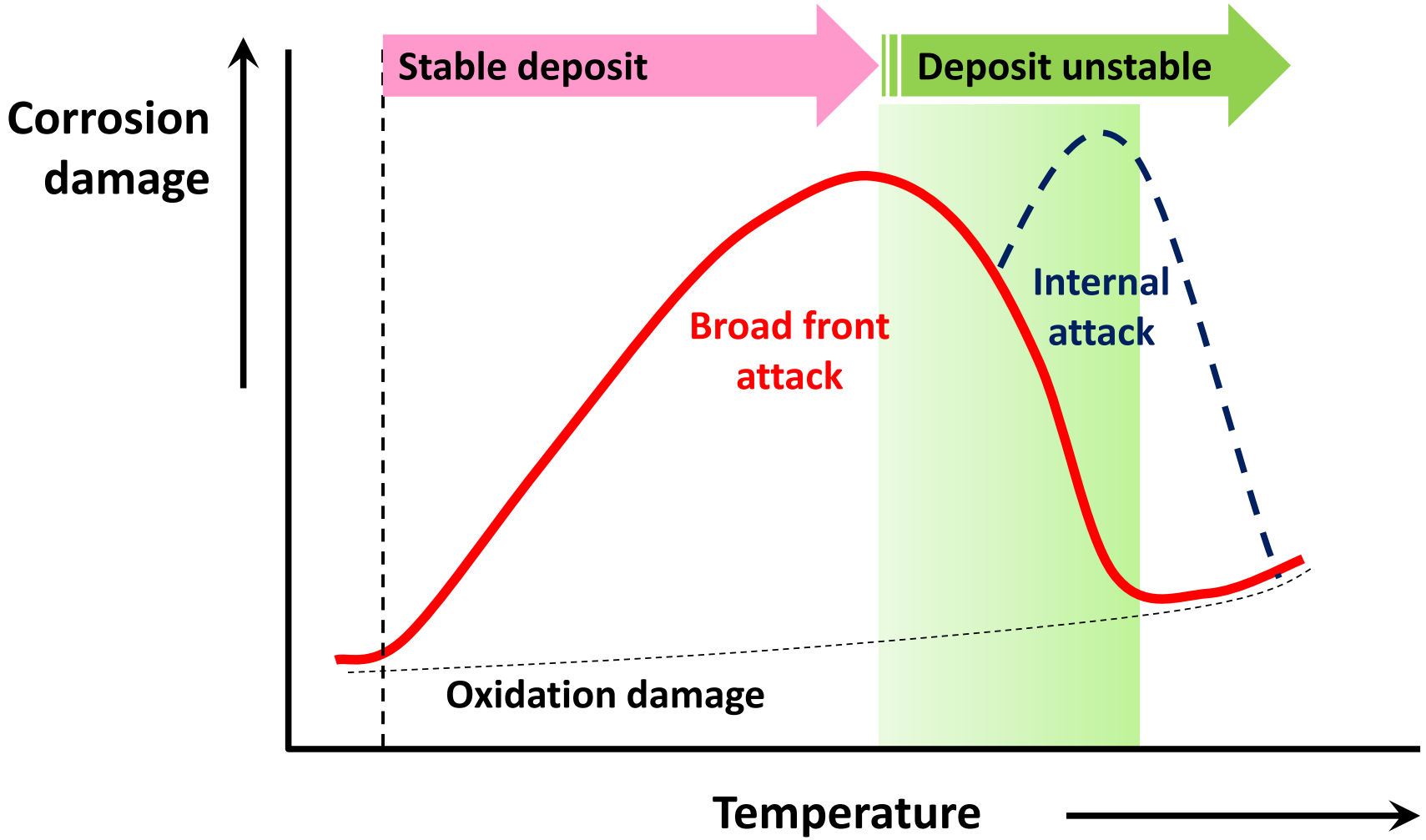
Fireside corrosion damage peaks for Ni-based alloys



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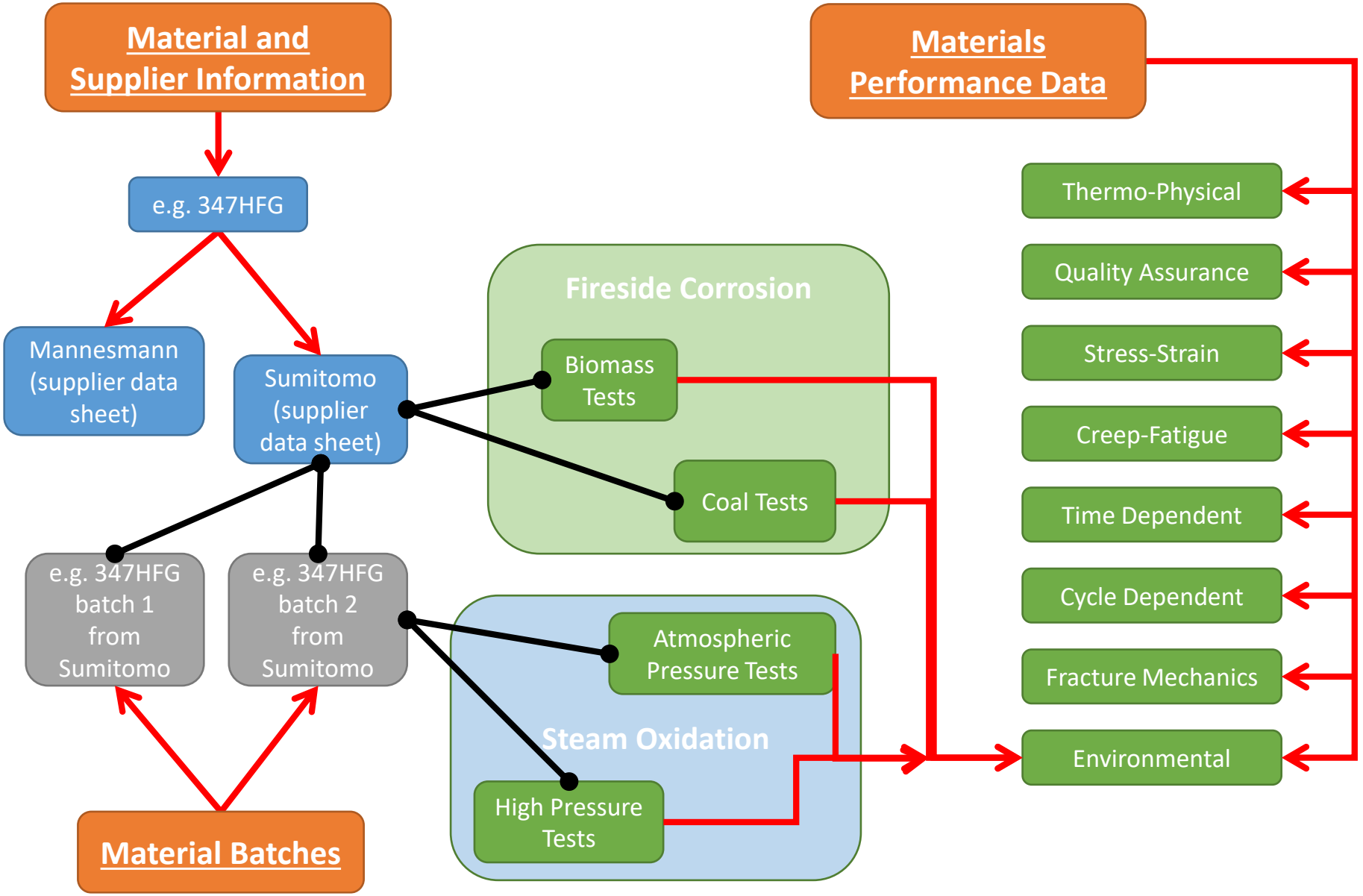
DP700 Project Database – Granta MI software



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DP700 Database

- Data Sources
  - Identify and review suitability of data for inclusion:
    - EU programmes – e.g. NextGenPower, MacPlus, etc.
    - National programmes – e.g. UK
    - International collaborations – e.g. UK-US
- Typical Data Required
  - Materials specification – composition, heat treatment, microstructure, etc.
  - Testing methods – standards, lab reference, environment, sample shapes and surface finish, etc.
  - Statistics – repeatability / reproducibility, error bands, systematic differences between sources, etc.
- Data given quality ranking depending on:
  - Use of standard test methods, detailed alloy composition provided, manufacturers data, etc

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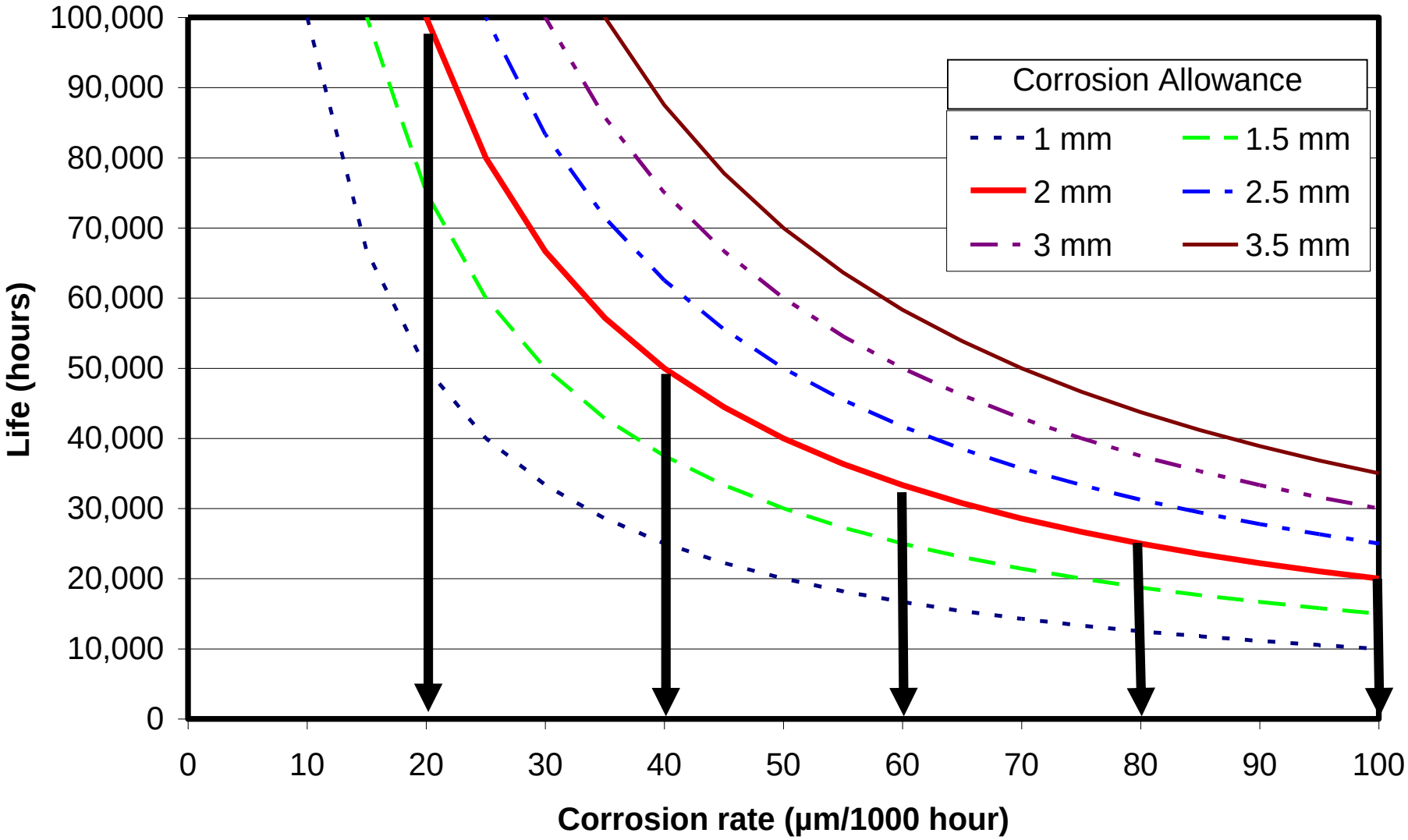
Approach 1 - Heat exchanger life, corrosion allowance, acceptable corrosion rates



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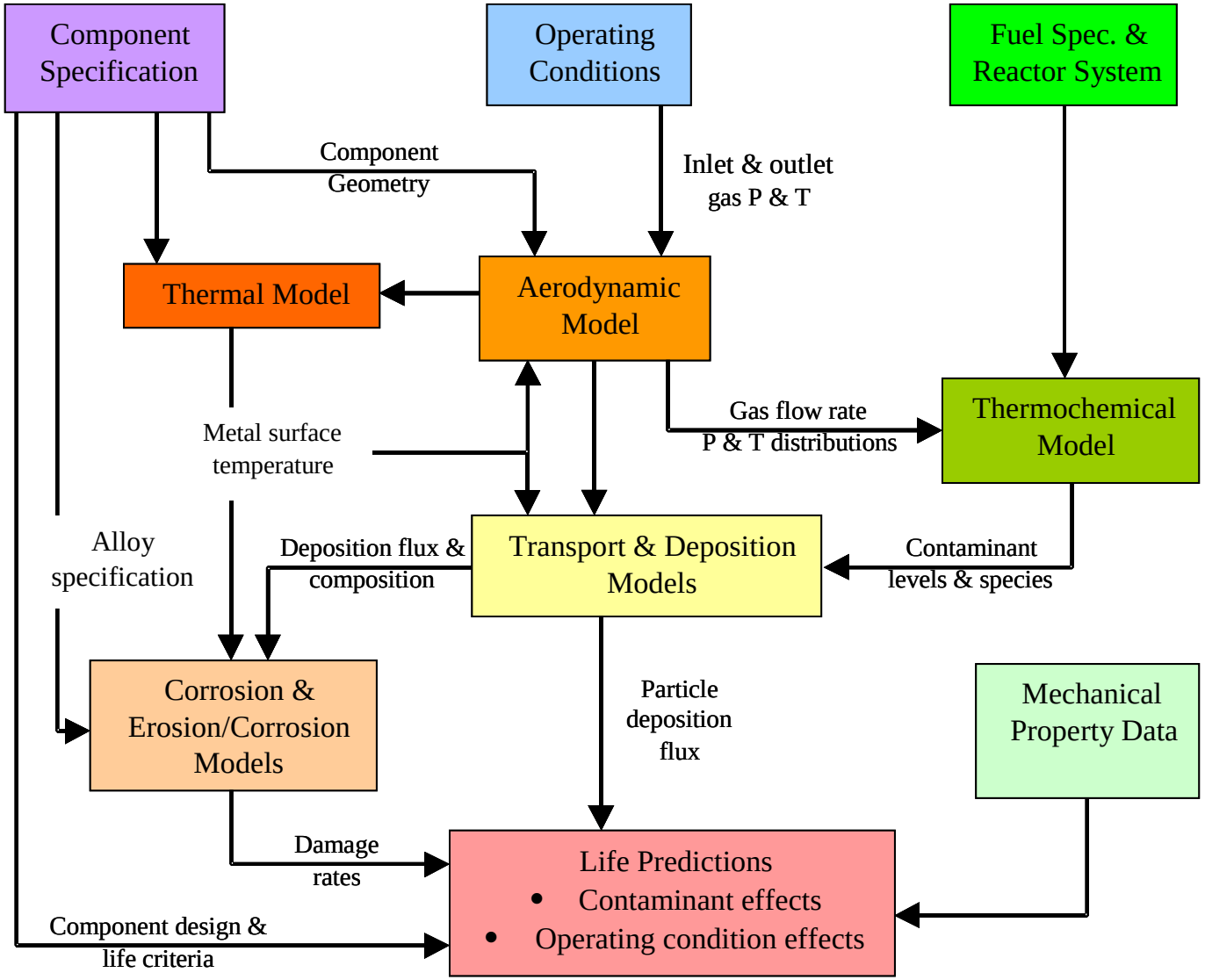
Approach 2 - Flow Diagram for Component Life Modelling



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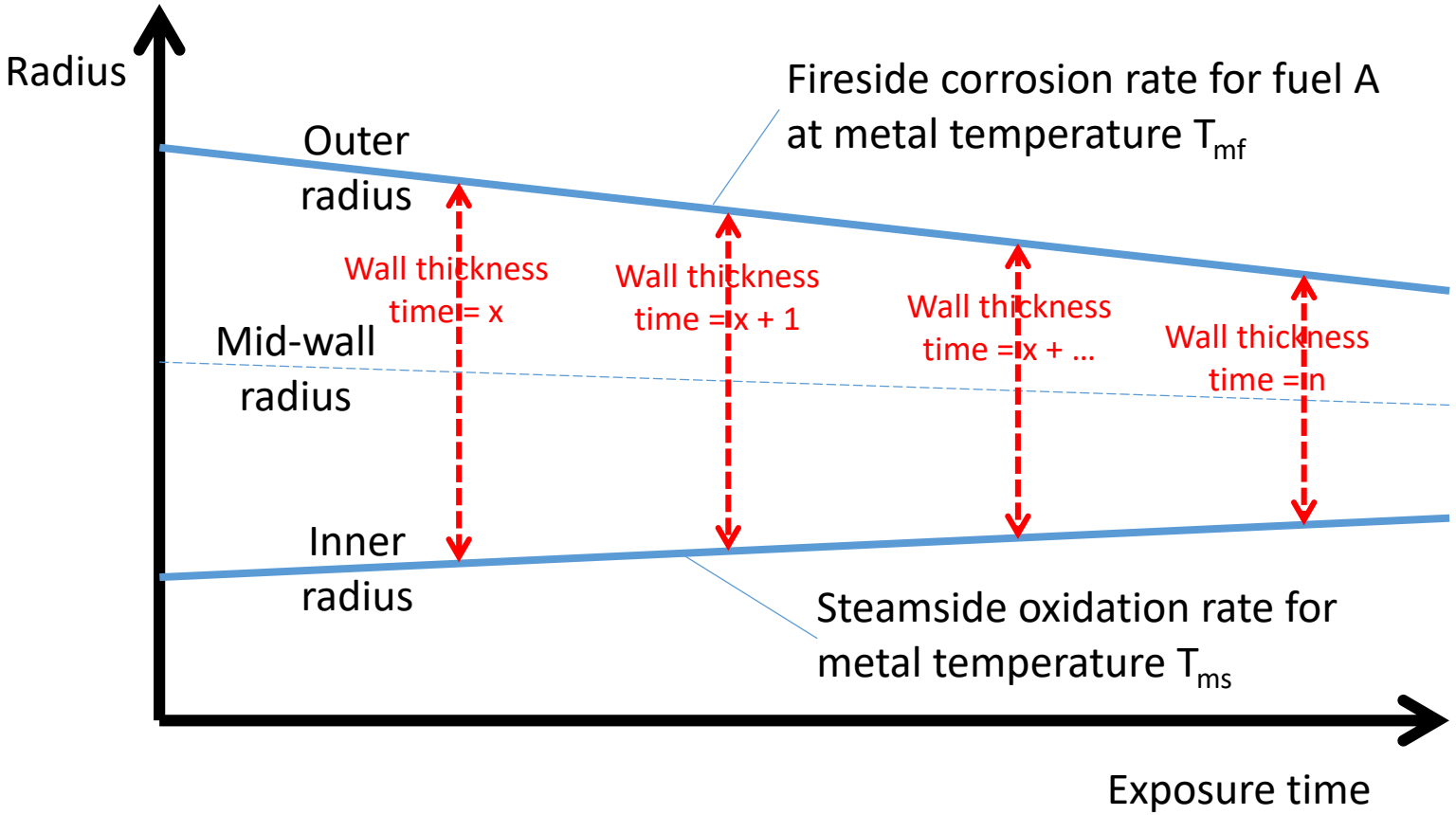
Development of model for environmental influences on heat exchanger degradation (1)



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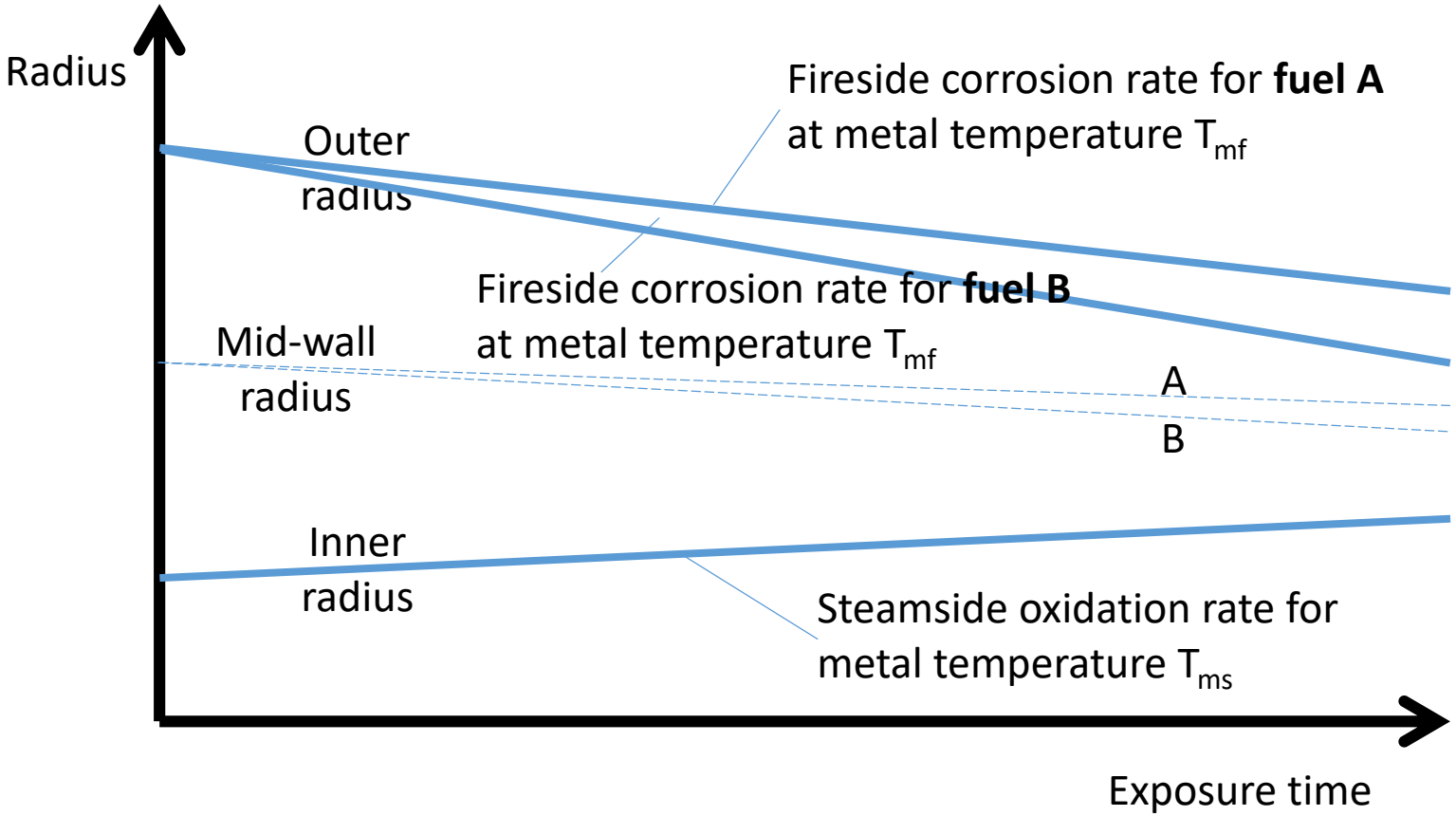
Development of model for environmental influences on heat exchanger degradation (2)



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Summary

- Operating conditions for steam system components in advanced solid fuel fired power plants will be significantly different from previous plants
- New materials have been / are being developed
- Limited data on materials exposed to the required operating conditions
- Detailed assessment needed for materials environmental degradation:
  - Steamside and fireside damage mechanisms
  - Sensitivity of damage development to:
    - Exposure conditions – component temperatures, fuels, etc
    - Materials compositions – e.g. batch and manufacturer variations
    - Component manufacturing processes – e.g. surface finish
  - Database being compiled of available materials performance data
  - Model development

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Thank you for your attention

Any questions ?

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