UK/US Collaboration in Energy R&D

Advanced Materials Program

FE Materials Conference
27th May 2010

Progress with Phase 2 Tasks

Approved Phase 2 Tasks

- Steam Oxidation
- Materials for Advanced Boilers and Oxy-combustion Systems
- Gas Turbine Materials Life Assessment and Non-Destructive Evaluation
- Oxide Dispersion Strengthened Alloys

1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
		▲	▲		▲	▲ ▲	▲ ▲	▲ ▲	▲ ▲	▲ ▲	▲			→

Phase 2 Task 1
Steam Oxidation

- What is the effect of pressure on the steam oxidation of alloys relevant to fossil-fuelled USC steam power plants?
- What is the effect of heat flux on steam oxidation and scale exfoliation on alloys relevant to fossil-fuelled USC steam power plants?
- What is the effect of specimen geometry on the oxidation kinetics, oxide scale morphology and spallation properties?
- Is chromia evaporation a concern in USC steam turbines?
- What is the agreed-upon standard laboratory test method for steam oxidation testing, and how can its validity be confirmed?
- Can a compendium of oxide microstructures provide useful information with respect to predicting component lifetimes and recognizing corrosion mechanisms?
- Can existing alloys be modified to be either castable or less expensive, while maintaining acceptable properties?

- **Partners**
  - **US – NETL, University of Pittsburgh, Carpenter Corporation**
  - **UK – NPL, Cranfield, Doosan Power Systems**
- **Integrated work programme developed**
- **First results – Pittsburgh May 2010**

Steam Oxidation Participants and Roles

	Laboratory Test		Alloy or Sample Supply	Modelling	Assessment of geometry & heat flux effects	Standardised test method	Measurement uncertainty	Power Industry Experience
	Ambient Pressure	Elevated Pressure						
NPL	■	■		■	■	■	■	
Cranfield	■	■		■	■	■		
Doosan	■		■		■	■		■
RWE	■							■
NETL	■	■	■	■		■		
Carpenter			■	■				■
UPitt	■			■		■		

Steam Oxidation Deliverables

- Review of the effect of pressure and heat flux on the steam oxidation
- Standard test method for steam oxidation testing
- Modified model of scale exfoliation for component lifetime prediction incorporating heat flux
- Reliable oxidation kinetics for candidate alloys including dependence on pressure, and heat flux
- Report on the inter-comparison exercise
- Database of information generated during the collaboration
- Verification of Cr evaporation model with respect to gas velocity
- Completion of ingot modelling (Mar 2011) and provide cast material samples (Jan 2012)
- Completion of alloy modelling and development of matrix of proposed compositions (Mar 2010), and provide material samples of alloys with best predicted performance and most promising data from initial testing (Jan 2012)

Phase 2 Task 2
Boiler Corrosion

What is the range of anticipated environments in advanced boiler systems? And how does oxy-fired ash differ from ash from air-fired systems?

What is the agreed-upon standard laboratory test method for boiler corrosion testing, and how can its validity be confirmed?

How can we further develop our understanding of the behavior of current and candidate materials for boilers operating under advanced conditions to become better informed for suitable material selection?

What is the performance of candidate coating systems for superheaters and reheaters in advanced boiler systems?

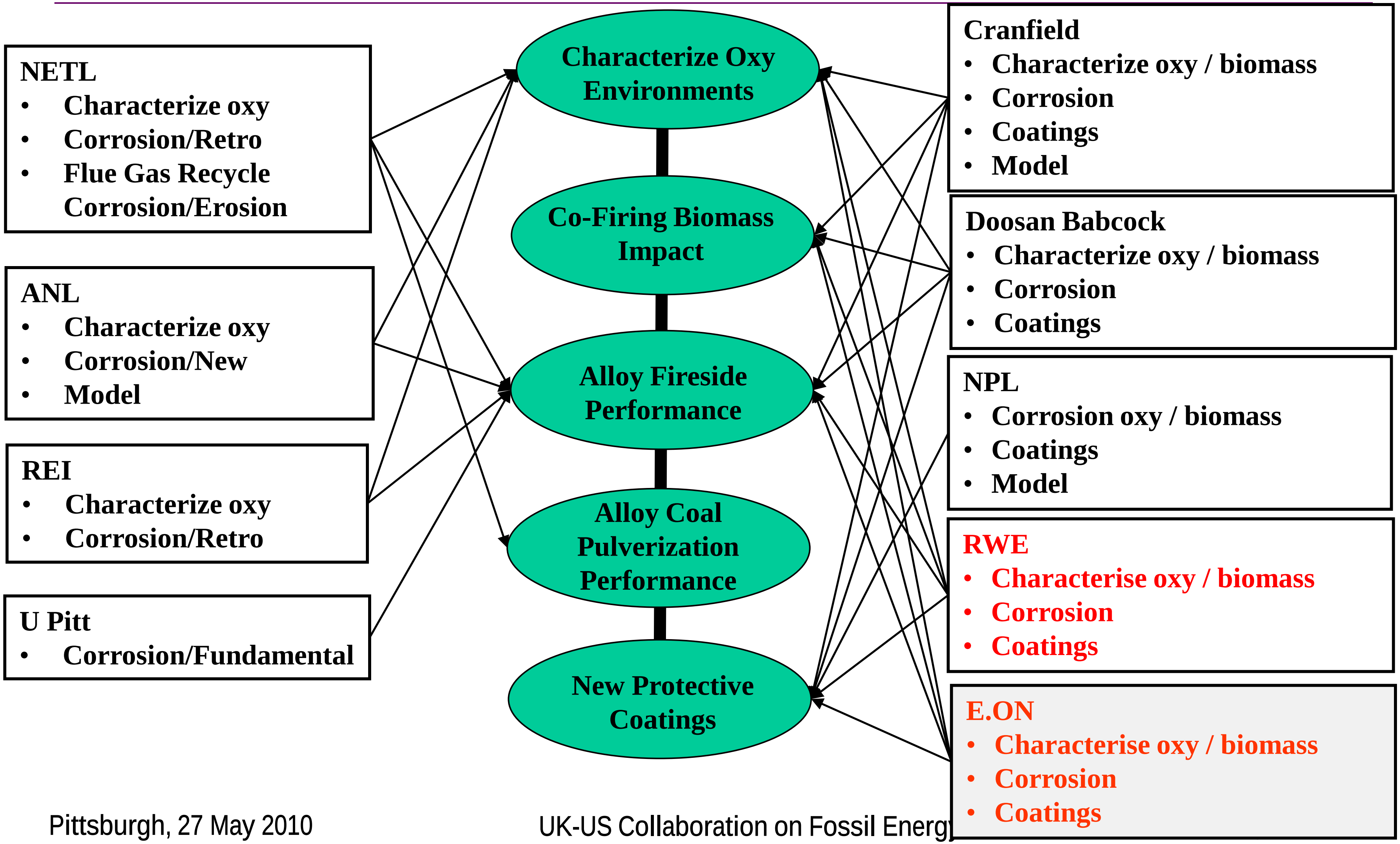
What is the performance of candidate piping systems in oxy-firing boilers for recycle flue gas?

What is the best way to share test results between collaboration partners?

- Partners
  - US – NETL, University of Pittsburgh, REI, ANL
  - UK – Doosan Power Systems, Cranfield, NPL
- Integrated work programme developed
- First results – Pittsburgh May 2010

Boiler Corrosion Participants and Role

	Environment Modeling & Characterization	Power Industry Experience	Standardized Test Method	Corrosion Tests		Coatings	Alloy or Sample Supply	Database
				Lab	Field			
NETL								
ANL								
REI								
UPitt								
Doosan								
Cranfield								
NPL								


NETL
• Characterize oxy
• Corrosion/Retro
• Flue Gas Recycle Corrosion/Erosion
ANL
• Characterize oxy
• Corrosion/New
• Model
REI
• Characterize oxy
• Corrosion/Retro
U Pitt
• Corrosion/Fundamental
Characterize Oxy Environments
Co-Firing Biomass Impact
Alloy Fireside Performance
Alloy Coal Pulverization Performance
New Protective Coatings
Cranfield
• Characterize oxy / biomass
• Corrosion
• Coatings
• Model
Doosan Babcock
• Characterize oxy / biomass
• Corrosion
• Coatings
NPL
• Corrosion oxy / biomass
• Coatings
• Model
RWE
• Characterise oxy / biomass
• Corrosion
• Coatings
E.ON
• Characterise oxy / biomass
• Corrosion
• Coatings

Deliverables I

- Report on the assessment of environments anticipated in advanced boiler systems.
  - Gas Composition from Process Models
  - Ash Characterization
  - Pilot Scale Testing (deposit compositions, deposition rates, gas compositions)
- Report on the inter-comparison exercise
- Compendium of materials performance data from laboratory and pilot plant exposures of candidate alloys for use in advanced boiler and oxy-fired power systems

Deliverables II

- Identification and performance of candidate coating systems for protection of superheaters/reheaters in advanced boiler systems
- Compendium of materials performance data from laboratory exposures for flue gas recycle piping in oxy-fuel boiler systems
- Database of information generated during the collaboration

Task 3: Objectives

Component life prediction

- Access materials performance in multiple simulated environments
- Develop models for deposition/gas phase chemistry along with thermo-kinetics for establishment of corrosion maps
- To use the modified models to predict alloy/coating degradation in specifically-designed tests
- To identify the fuel/operating conditions and the optimal candidate alloy and coating combinations

Non destructive evaluation

- Need to develop rapid and reliable NDE techniques for inspection of gas turbine hot gas path components
- Utilize 2D and 3D NDE technologies to establish their sensitivity and limitations in detecting degradation and delamination in EB-PVD and APS TBCs.
- A multi layered model of thermal diffusivity will be used to develop a methodology for measuring the thermal properties of TBC systems

Partners:

UK

Cranfield University
NPL
Siemens Turbomachinery

US

Siemens Energy
ANL
NETL Pittsburgh
ORNL

Component Life Prediction Activities

Materials Performance Evaluation

- To assess of the passage of contaminants (related to deposition, corrosion and erosion in gas turbines) through the hot gas paths of different IGCC system options; from gasifier through various gas cooling and cleaning options to the gas turbine.
- To identify the fuel/operating conditions and the optimal candidate alloy and coating combinations which are most appropriate to future power systems that use gas turbines fired on wide range of potential fuels.

Component Life Prediction

- To improve models for predicting the fate of trace contaminants within gas turbines (and the effect of fuel composition and turbine operating parameters), including linking deposition / gas phase chemistry models to the latest published versions of models for hot corrosion of alloys/coatings in gas turbines
- To develop a model capable of thermo-kinetic modelling of contaminant flux and extrapolation for high temperatures/high pressures for the establishment of corrosion maps for high temperature metallic and ceramic systems.
- To use the modified models to predict alloy/coating degradation in specifically-designed tests, and for available test cases to validate the model predictions

Non Destructive Evaluation

Develop rapid and reliable NDE techniques for inspection of gas turbine hot gas path components, coated with different types of TBCs.

- Two optical imaging methods (mid-IR reflectance and polarized optical backscatter) and pulsed thermal-imaging will be evaluated to establish their sensitivity and limitations in detecting degradation and delamination in EB-PVD and APS TBCs.
- 3D NDE technologies, including optical coherence tomography (OCT), confocal microscopy and thermal tomography (developed recently at Argonne), will be investigated for directly imaging the depth variation of the TBC degradation.
- The development of novel thermal barrier coatings (TBCs) with self-diagnostic properties will be continued, focusing on the development of remote luminescence sensing for monitoring the temperature of turbine component materials
- During the course of TBC cyclic testing, a fluorescence technique will be used to monitor the stresses developed in the thermally grown oxide of the TBC system, backed up by a simple thermography system to identify coating delamination locations
- A multi layered model of thermal diffusivity will be used to develop a methodology for measuring the thermal properties of TBC systems

Boundaries for Environmental Testing

Coal gasification feed information

Coal Gasification Processes				
Process		HTW	Shell	Texaco
Syngas Components				
H2	%vol	33.97%	31.42%	39.37%
CH4	%vol	3.92%	0.01%	0.06%
CO	%vol	43.84%	63.04%	45.39%
CO2	%vol	16.94%	1.00%	13.18%
N2	%vol	0.50%	3.41%	2.00%
Ar	%vol	0.00%	1.10%	0.00%
C2H6	%vol	0.83%	0.00%	0.00%
C2H4	%vol	0.00%	0.00%	0.00%
C3+	%vol	0.00%	0.00%	0.00%
H2S and COS*	%vol	0.00%	0.00%	0.00%
Total	%vol	100.00%	99.98%	100.00%
* H2S and COS	ppmv	20	20	20
Operating Characteristics				
Type		Fluidized Bed	Entrained flow	Entrained flow
Number of Gasifiers	Reactors	2	1	1
Coal feed type		Dry Crushed	Dry Pulverized	Slurry
Coal feeding system		Lockhopper screw conveyer	Lockhopper pneumatic	Pumping
Gasification temp (min)	C		1,500	1,260
Gasification temp (max)	C	1,000	2,000	1,540
Carbon conversion		93.00%	99.50%	98.50%
Gasifier lining		Refractory	Water Wall refactory	Refractory
Raw gas temp to SGC (min)	C	850	900	1,260
Raw gas temp to SGC (max)	C	900	900	1,540
Radiant SGC location		-	Above	Below
Radiant SGC design		-	Water Tube	Water Tube
Convection SGC		Fire tube	Water Tube	Water Tube
Dry particulate collection		cyclone filler	cyclone filler	-
Solid wastes		Ash/Char	Slag	Slag

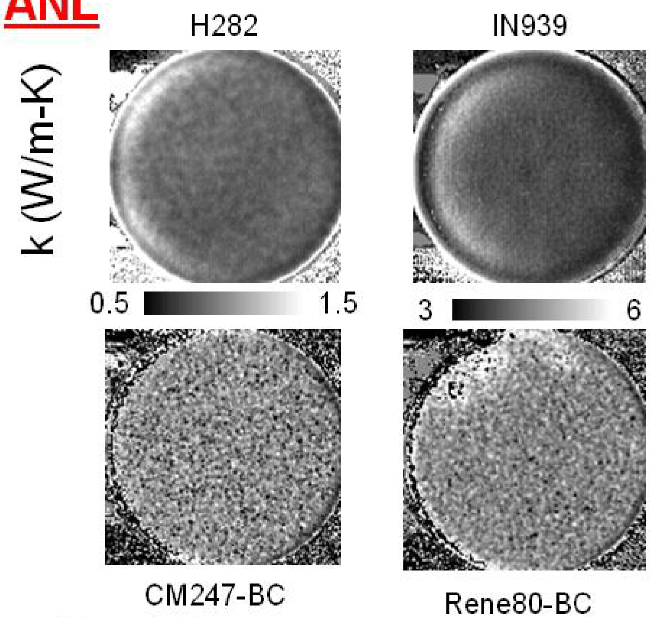
Contaminant analysis

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

Data being summarized to establish limits for gas compositions and contaminants for IGCC environments

NDE Efforts for TBC Characterization

ANL

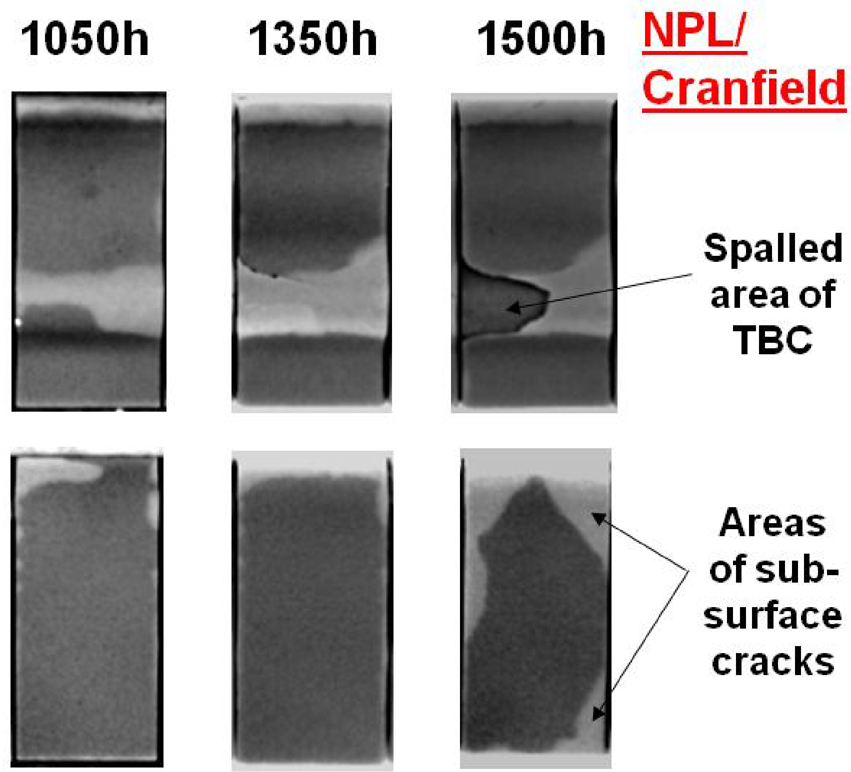


Predicted average properties:

Sample	k (W/m-K)
H282	0.887
IN939	0.804
CM247-BC	4.61
Rene80-BC	4.51

Initial TBC Characterization

Modified aerofoils exposed at 1000°C – raw thermographic images



TBC Characterization with Service Time

Phase 2 Task 4
ODS Alloys

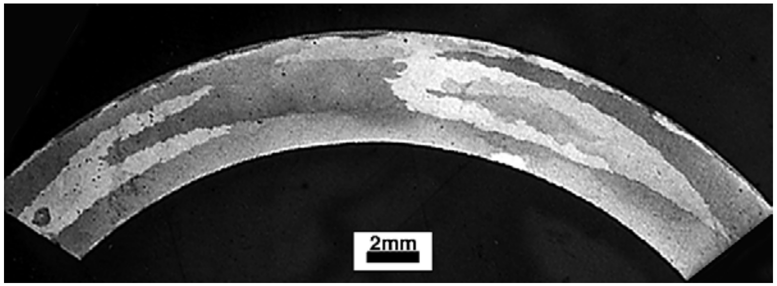
Aim - To produce a capped tube to header demonstrator as a step towards a single tube heat exchanger

- **Improve tube creep properties by a variety of forming means – (microstructure modifications achieved in the UK to be creep tested in the US)**
- **Achieve practical, tested ODS-ODS and ODS-dissimilar metal joints in a number of geometries**
- **Re-qualify commercial production of ODS alloys**
- **Investigate the effectiveness of selective laser melting to produce seam welds and layers**

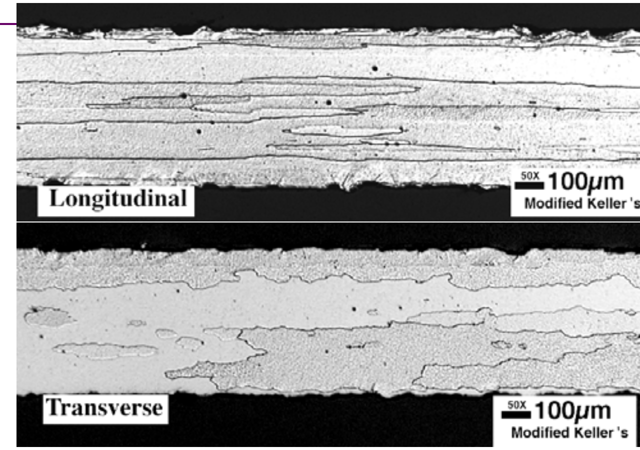
- Partners
  - US – UCSD, ORNL, Interface Welding, MER Corp, UNDEERC, Iowa State
  - UK – Liverpool University, TWI, Cranfield, RWE, Siemens
  - Dour Metal
- Integrated work programme developed
- First results – Pittsburgh May 2010

	Task 1 Alloy Properties	Task 2 Forming	Task 3 Joining	Task 4 SLM	Task 5 Coatings	Task 6 Braze Joints
UCSD	■	■	■			■
ORNL	■		■			■
Dour Metal	■					
Interface Welding			■			
MER Corp						■
UDEERC, ND						■
Iowa State, Iver	■					
Liverpool (UK)	■	■	■	■	■	
TWI (UK)			■			
Siemens (US)				■	■	
RWE (UK)				■	■	
Cranfield (UK)			■		■	

Task 1: ODS Tube Desired structure



ODM-751,Onion-skin grain structure



MA956, flow formed grain structure

In ODS MA956, coarse, secondary recrystallized, grain structure was only possible after extreme cold-working via flow forming.

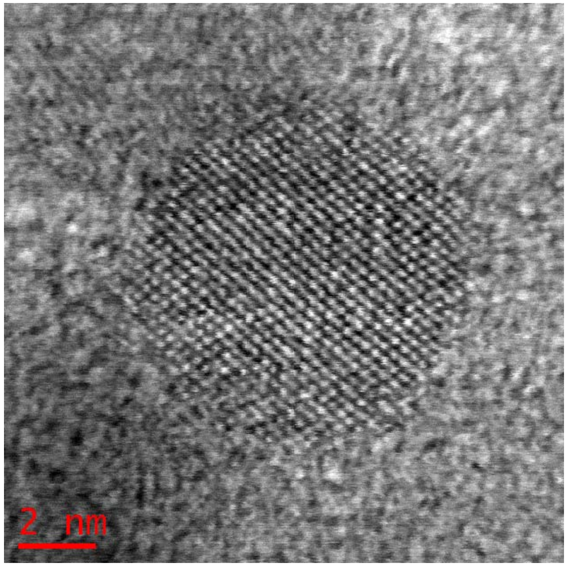
Flow forming does NOT produce any fibering.

Cold-work achieved via undesirable cross-section reduction. Explore alternates to preserve cross-section

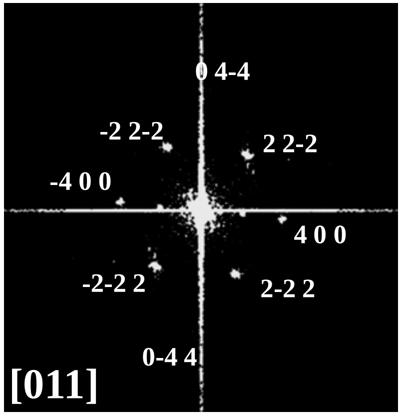
MA956, starting tube 0.25" thick wall. *flow formed* tube 0.03-0.04"

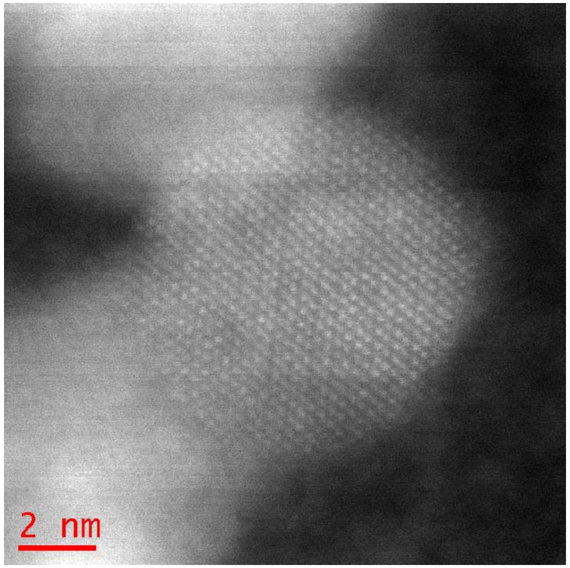
Task 4 ODS Alloys

High resolution electron microscopy to determine sequence of oxide dispersion transformations with time and temperature and link with secondary recrystallisation behaviour.



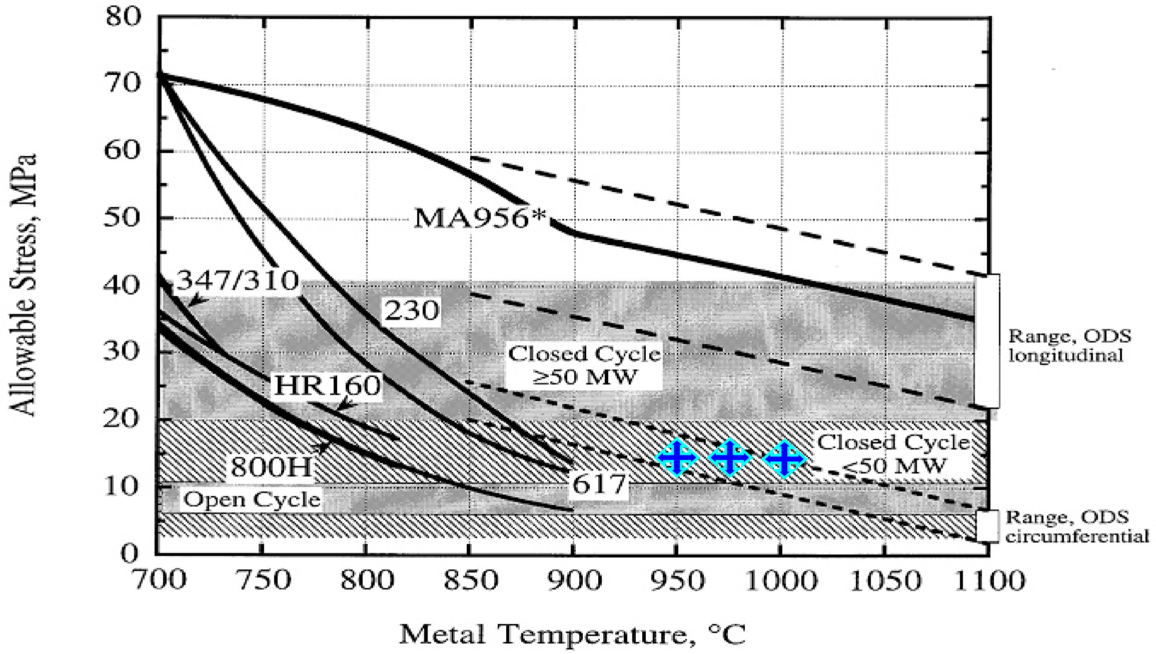
Cubic -Y_2O_3





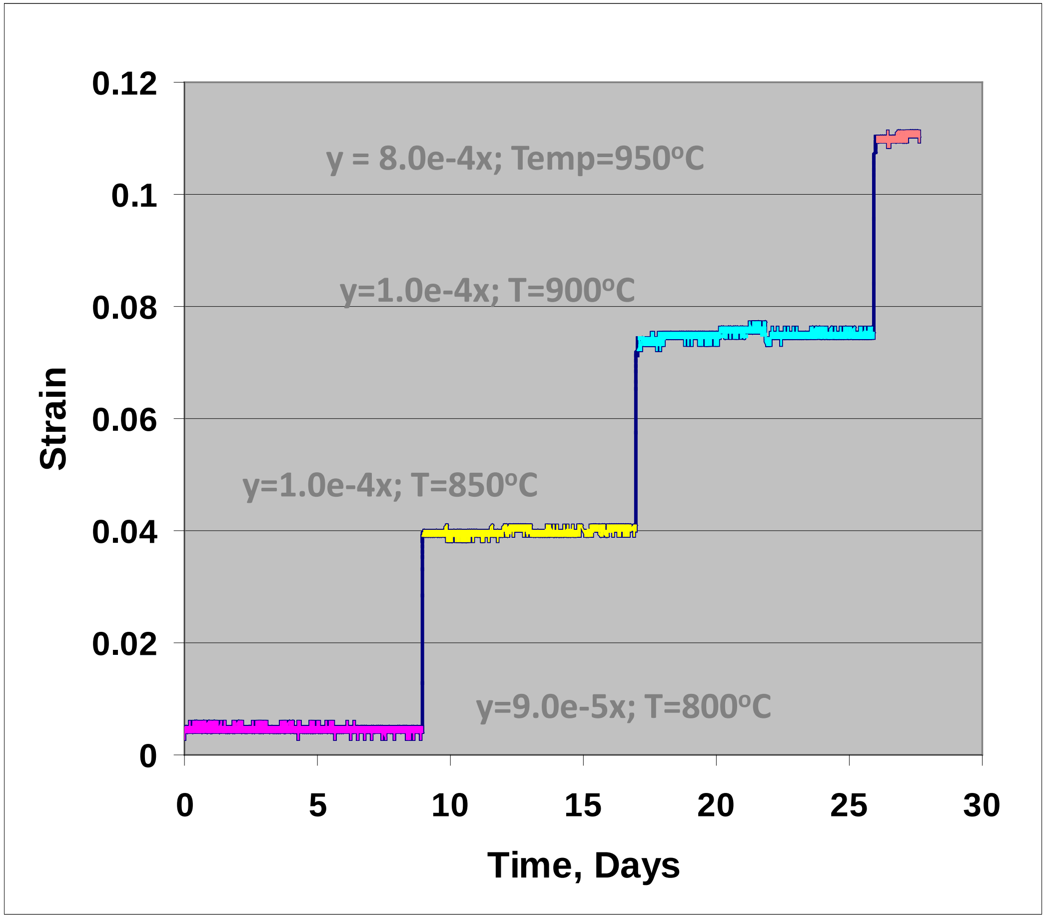
Task 2: Creep Life Assessment for New ODS Alloys

Objective: Establish long term hoop creep property database for ODS alloys
Data plotted upon a minimum of one year exposure at temperature & stress



Current hoop creep metrics for *flow formed* MA956 tubes

MA956 Tube Joint Incremental Creep Test



Joint #3, 2ksi Stress, Test in Air, OK

Phase 2
Next Steps

- Workshop – Pittsburgh, May 2010
- Workshop in the UK in Autumn 2010