Performance and Reliability Of Metallic Materials for Nuclear Fission Power Generation

PROMINENT

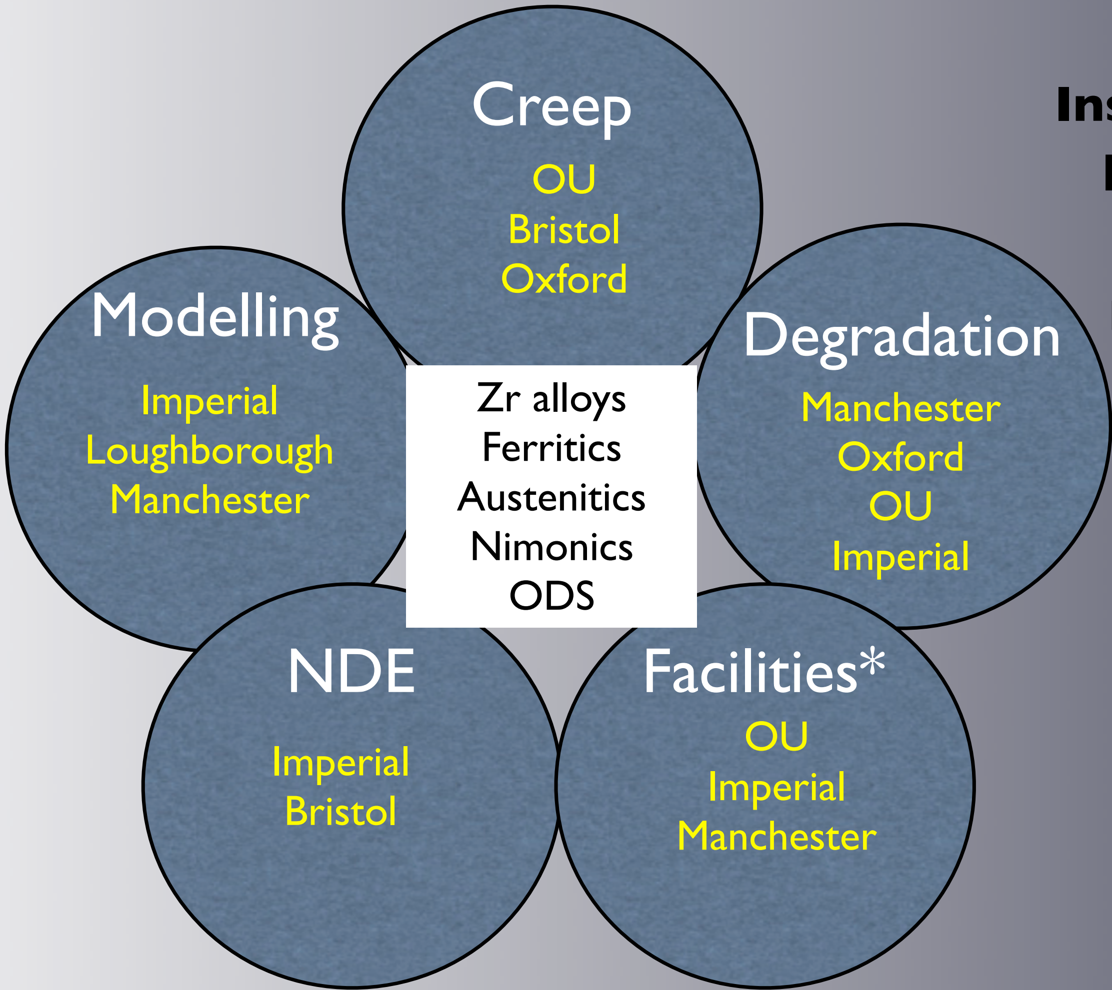
Summary and update

September 2014

Programme end-date March 2015

Industrial partners

Rolls-Royce
EDF
Westinghouse
Serco
AREVA
British Energy



Institutional partners

EPSRC
MOD
DIAMOND
DOE
INSS
INL
Saclay
Queen's
ANSTO
Los Alamos
Illinois
Orsay
Cincinnati
Berkeley

*Neutron and synchrotron

Our research challenges

- Challenge 1: Materials stability and degradation under in-service environmental exposure
  - 1.1 Radiation damage 3 projects
  - 1.2 IASCC 1 project
  - 1.2 Creep 2 projects
  - 2 Stability of zirconium 3 projects

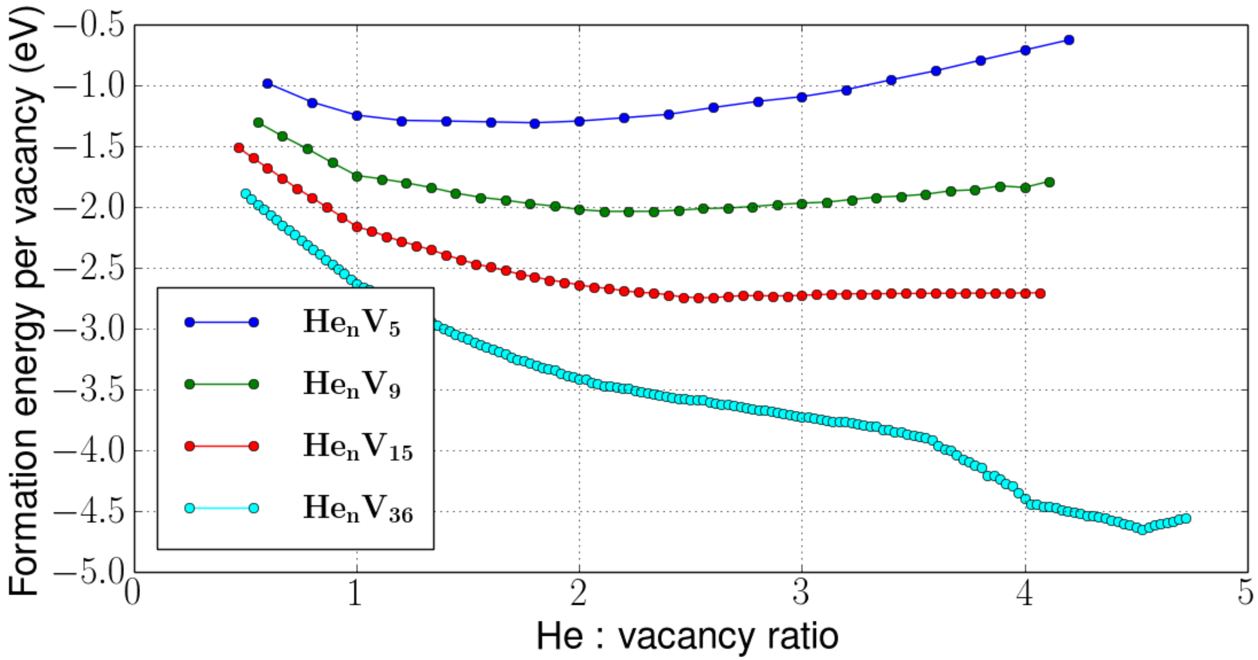
- Challenge 2: State Monitoring of Materials
  - Linear and non-linear monitoring techniques
    - 2 projects

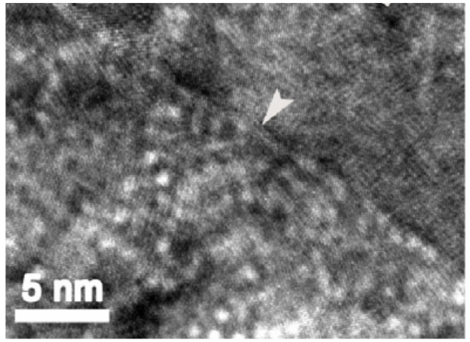
Looking ahead

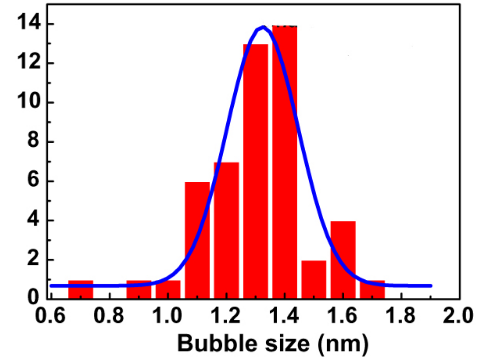
- Consortium grant runs through to a combined end-date of March 2015
- Research themes moving towards new programmes:
  - MUZIC 2
  - New metallics programmes
- Increasing focus on effects of irradiation damage
- Linking to other RCUK and industry-funded research programmes:
  - Platform grant at Oxford
  - UK-India projects
  - EDF High Temperature Centre
  - International collaborations

Mechanisms for He bubble formation in bcc Fe (Loughborough)

He bubbles form as a by-product of nuclear reactions. Experiments show that they can form within grains as well as on grain boundaries and that they have a preferred size.







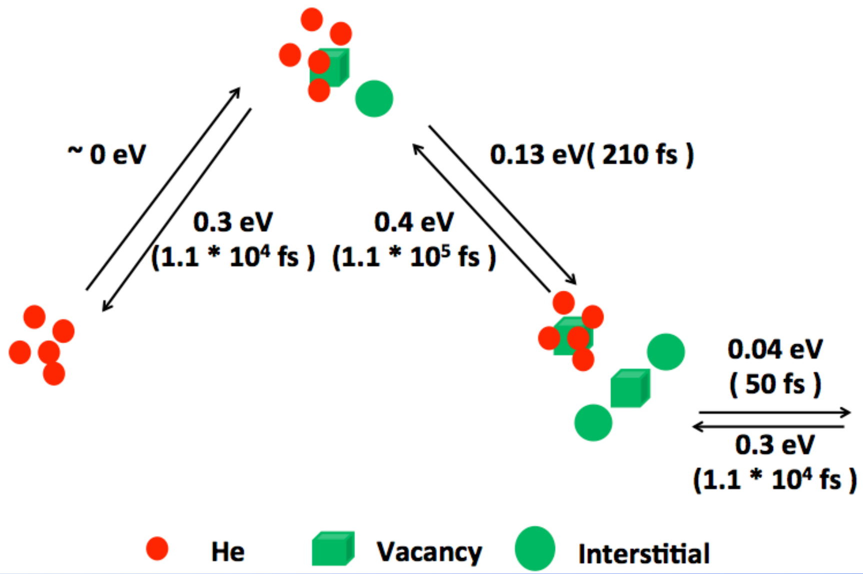
Yu et al JNM 425 2012 140

Static energy calculations show that the He: Vacancy ratio increases to about 4 : 1 for bubbles containing 36 vacancies ~ 1.5 nm in diameter

Mechanisms for He bubble formation in bcc Fe

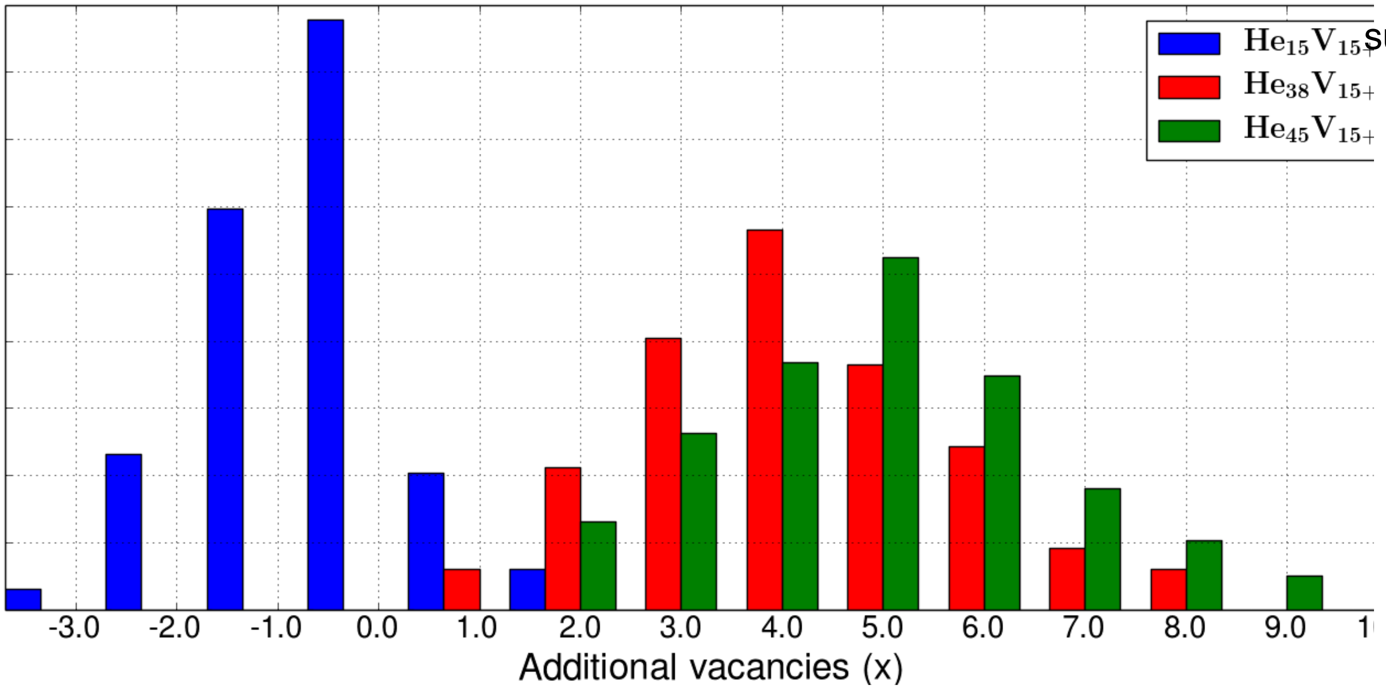
Typical energy barrier (eV)	He_2	He_3	He_4	He_5
To diffuse	0.12	0.2	0.48	-
To eject Fe into interstitial	-	-	0.3	0
To take over one vacancy	-	-	0.55	0.13

Small He clusters are highly mobile and aggregate into larger units. When they reach as size of 5 He, they eject an Fe interstitial and become effectively pinned.



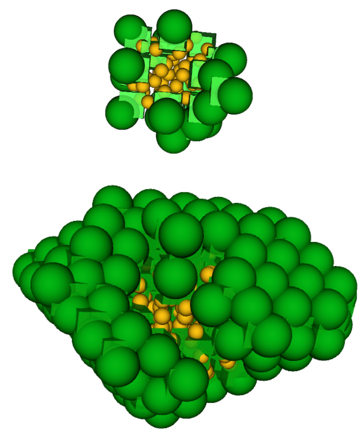
Mechanisms for He bubble formation in bcc Fe

Bubbles can attract vacancies from a collision cascade



sub-optimal He:V ratio
optimal
super optimal ratio

Result of adding/losing vacancies from 1 keV collision cascades



The strained region around He atoms (yellow spheres) for bubbles containing 60 (top) and 163 (lower) He atoms. Fe vacancies are green cubes. Interstitials are green spheres

University of BRISTOL

MANCHESTER 1824 The University of Manchester

The Open University

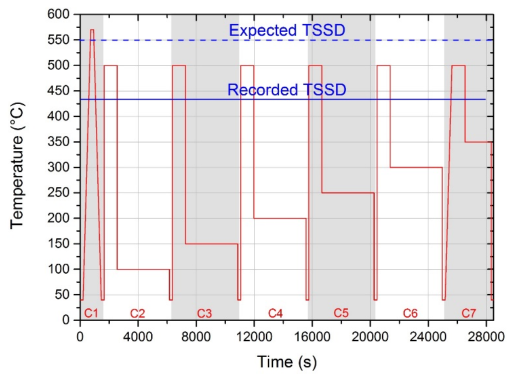
Precipitation of Hydrides in Nuclear Zr

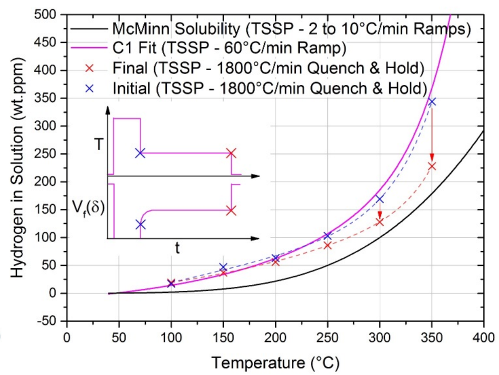
- Matthew S. Blackmur, Manchester

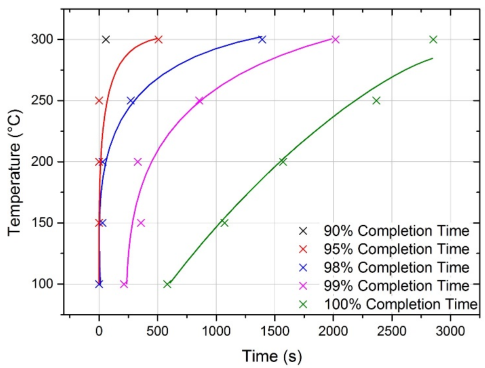
Precipitation Kinetics – SXRD + Modell

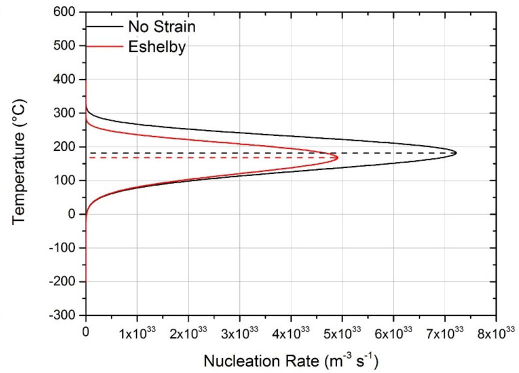
- Successful modelling of peak nucleation temperature, which cross compares with experimentally derived TTT diagram.

- Demonstration of kinetics limiting rate of precipitation at elevated temperature as source of discrepancy between TSSP and hydrogen in solution when quenching rapidly.









Imperial College London

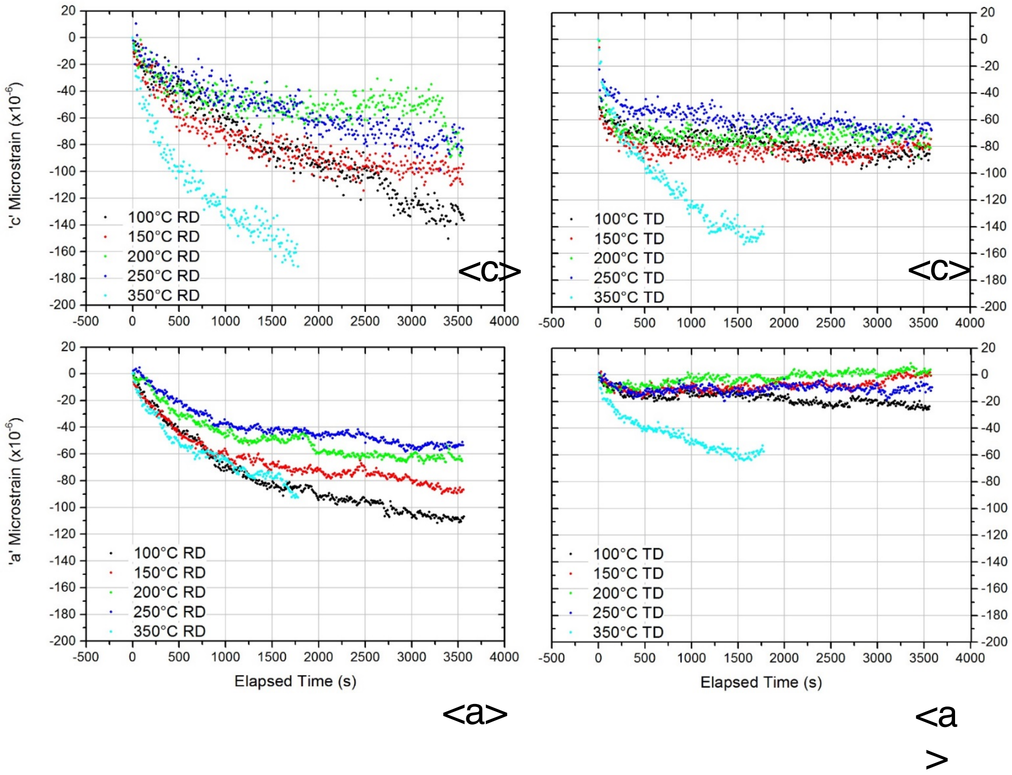
Loughborough University

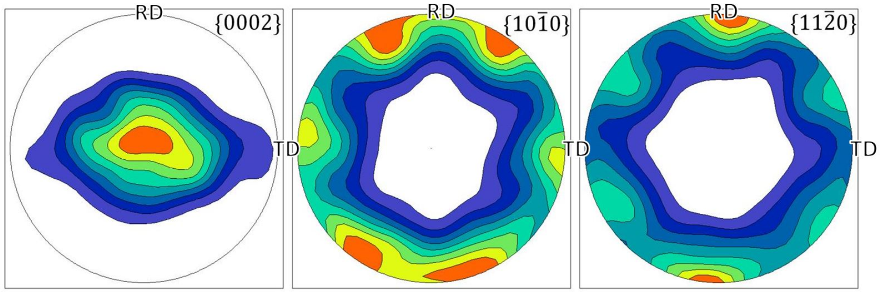
OxfordMaterials

Anisotropic Strain Evolution around Hydrides

- Mapping of strain in matrix (pictured) and hydride.
- Observation of strain evolution after all measurable precipitation is completed.
- Linking of deviations in directional strain to texture of matrix.
- Softer in RD direction where a greater alignment of slip systems occurs.

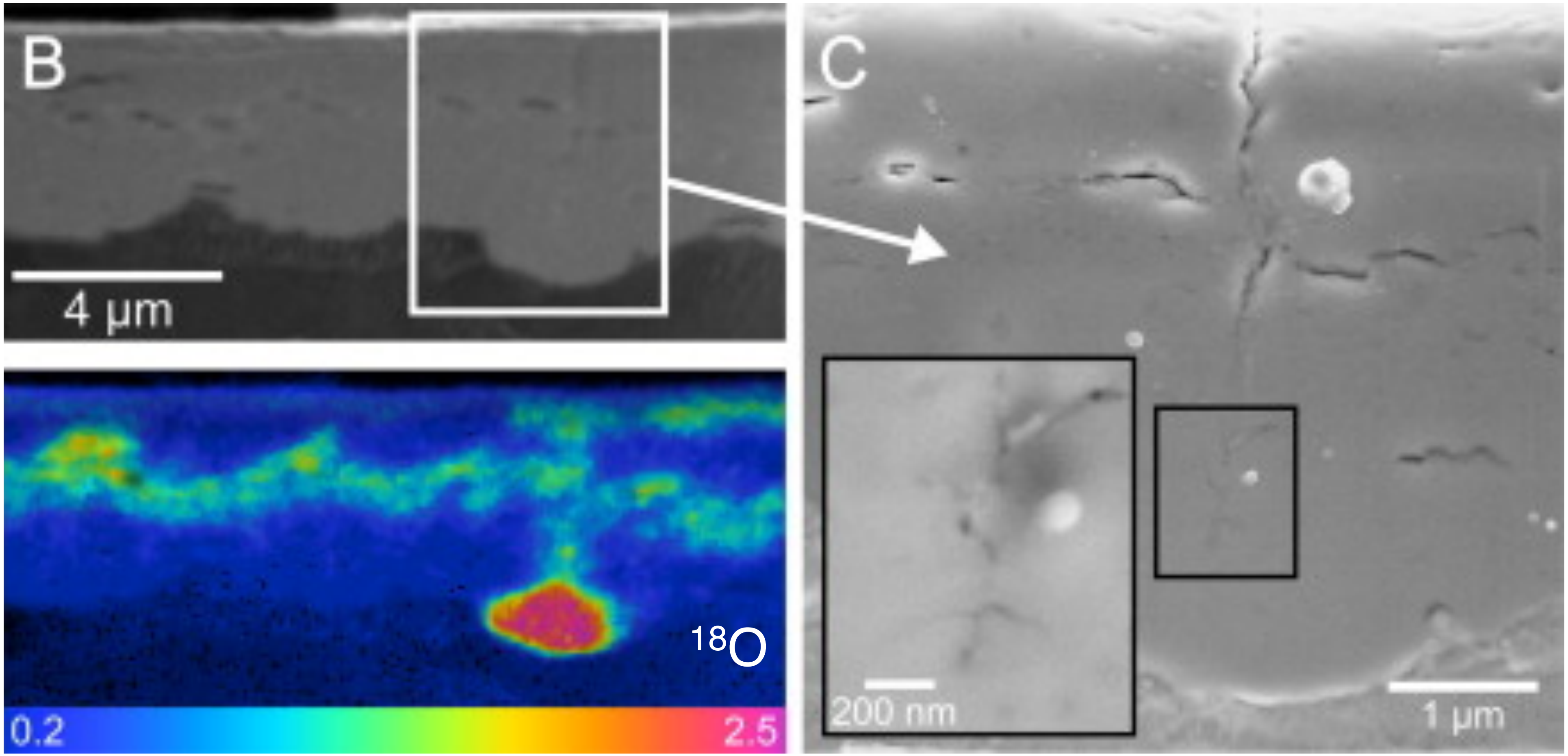
Rolling Direction | Transverse Direction



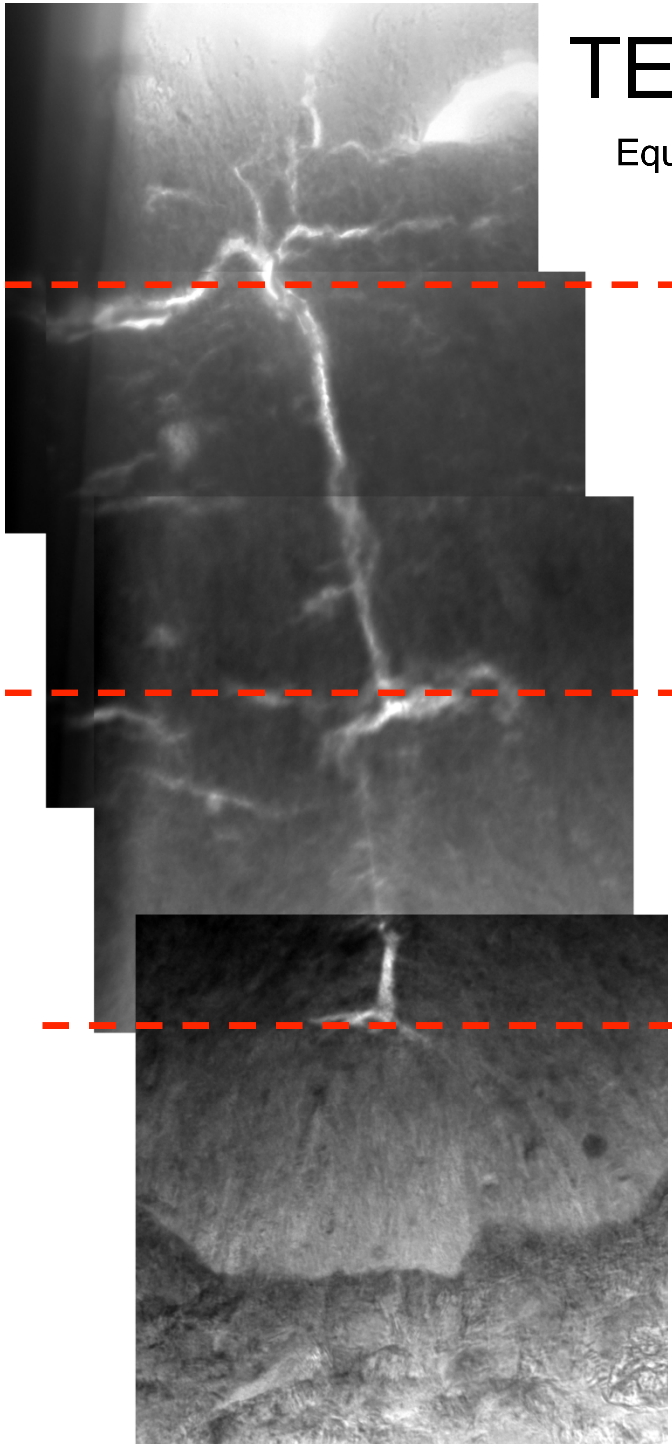


Sean Yardley: Oxford

Mechanisms of Oxidation in Zr alloys
SIMS analysis of chemistry and TEM of same area



TEM Analysis of 160+20 day ZIRLO

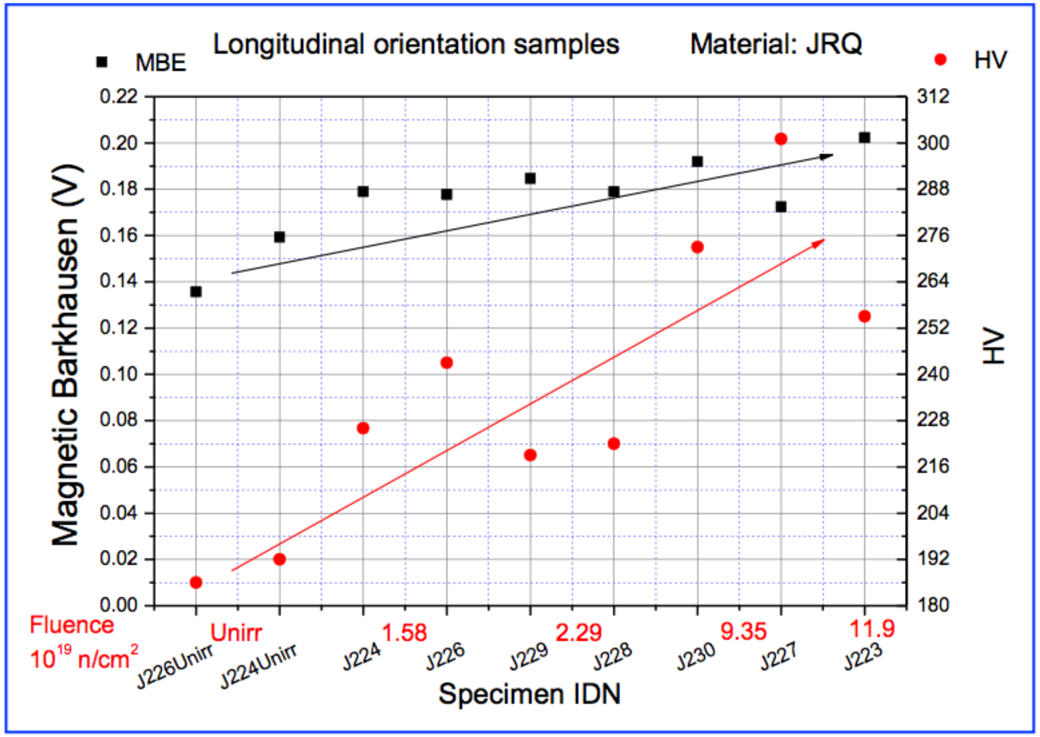


We can correlate microstructure and the local oxidation rate shown by SIMS experiments

Second project in Oxford on micromechanics of hydrides in Zr alloys (Howard Chan)

Magnetic technique development (OU/ Coventry)

- Correlation between Barkhausen noise and hardness increase from irradiation



THEME 3: State/NDE monitoring of materials in nuclear systems

Bristol: Xander Warren, Steve Best, A. Croxford

Evaluation of nonlinear ultrasonic parameters, very sensitive to damage precursors

Development of magnetic force microscopy

→Conventional Inspection finding defects with advanced techniques that are more sensitive to damage

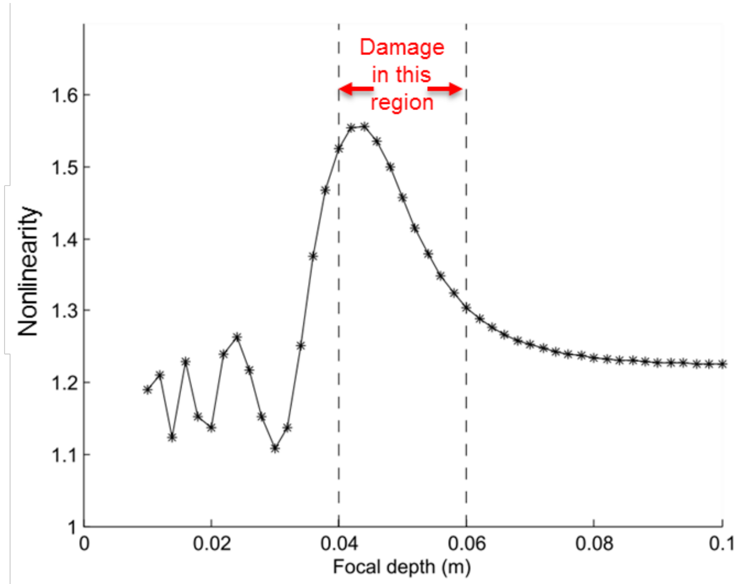
Imperial: A. Gajdacsi, F. B. Cegla

Monitoring of linear ultrasonic parameters

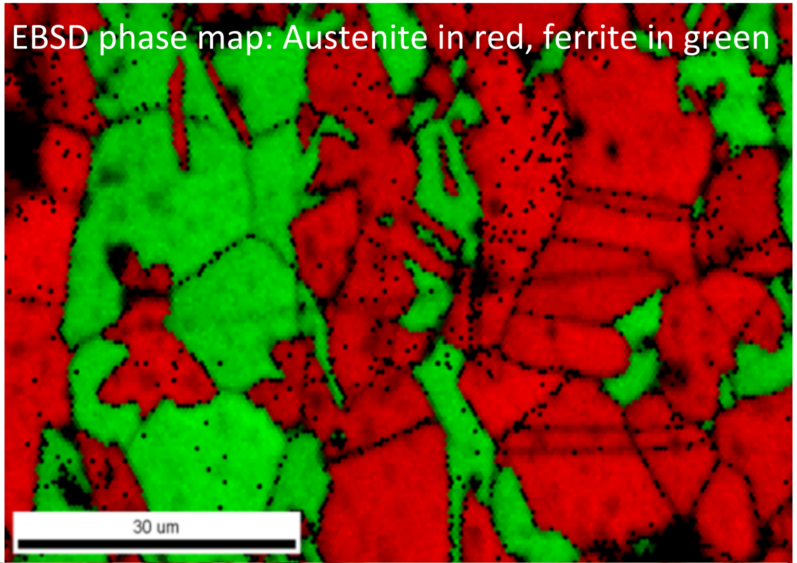
→ Monitoring much smaller changes than with conventional techniques in areas of concern

Bristol NDT report – Steve Best PhD student

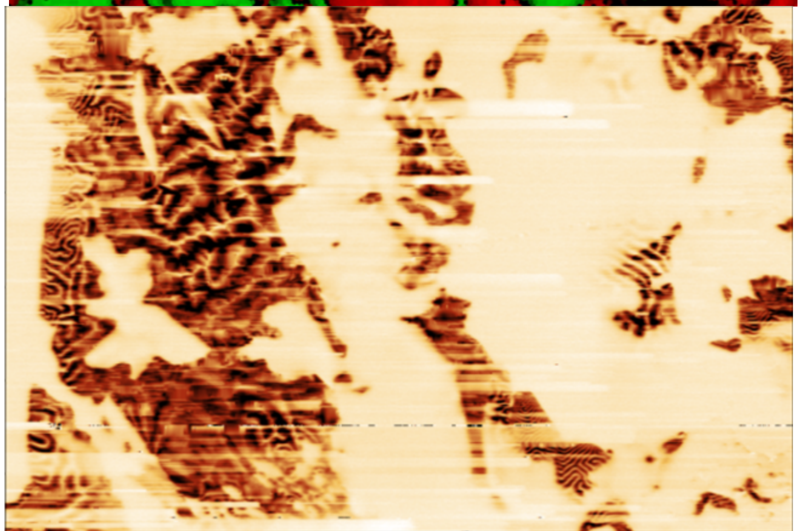
- Developed nonlinear techniques to allow the single sided use of nonlinear ultrasound, increasing its robustness and removing the need for permanently installing sensors
- In the final period developed techniques using phased arrays to localise nonlinearity
- Sweep focal spot through a specimen and measure nonlinear response
- Changes in the nonlinear response with depth indicate changes in damage
- First step to localising damage within a component
- Validated on machined section of steel bend specimen
- Steve Best has been awarded his PhD



Magnetic force microscopy



EBSD phase map: Austenite in red, ferrite in green



MFM map: Austenite in cream, ferrite in brown

- Magnetic force microscopy (MFM) developed into a viable and practical analysis technique for the quantification of ferrite in steels. The technique has mapping speeds comparable to EBSD, minimal preparation requirements and high reproducibility.

- Post-mortem studies on a creep cavitated ex-service Type 316H boiler header have revealed that creep cavities show a strong association with the residual δ-ferrite precipitates generated during casting. Of the 780 creep cavities studied, 56% were associated with ferrite – which comprises 2% of the volume fraction of the material. Of the δ-ferrite grains associated with creep cavities, 86% of the cavities site at the δ-γ-γ boundary junction.

Imperial- Overview

Aim: Map small changes of ultrasonic properties in a material as damage is being introduced

- Simulation and reconstruction of non-uniform Ultrasonic velocity by means of non-uniform temperature distribution

→This has been successfully demonstrated as part of this research programme (in simulation and experiment). Publication JNDE.

- Build rig to demonstrate damage growth and monitor while it is being introduced.

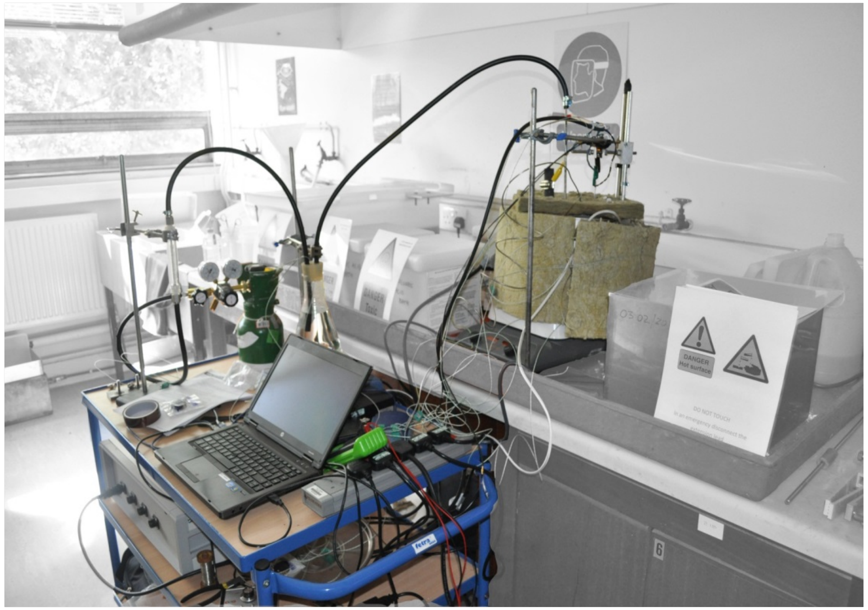
→Test rig built and problems with temperature stability encountered at high temperatures.

→Revisited stability at low temperatures and sensitivity to small changes (built corrosion rig).

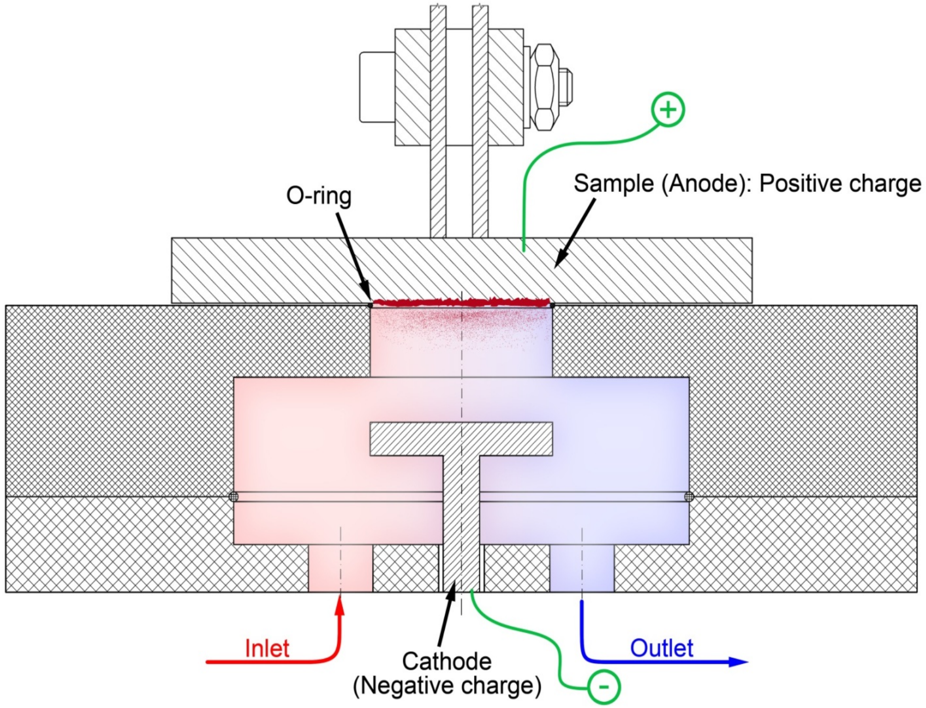
→ Current work is on exploring in depth the low temperature stability and we will then revisit high temperature experiments.

New test facilities

Experimental setup for electrochemically introducing material voiding (Hydrogen attack) at high temperatures

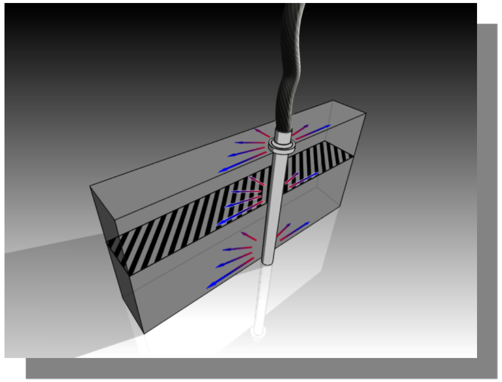


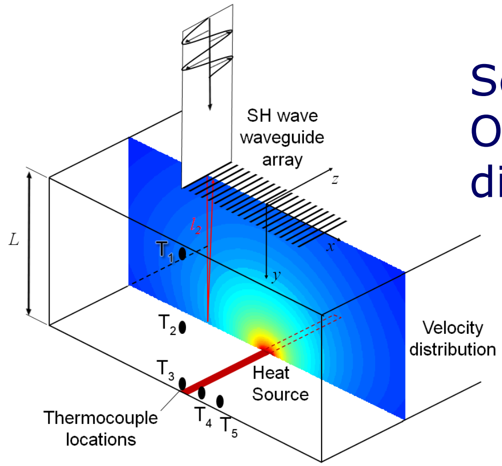
Low temp corrosion rig, detection of small changes



Preliminary results

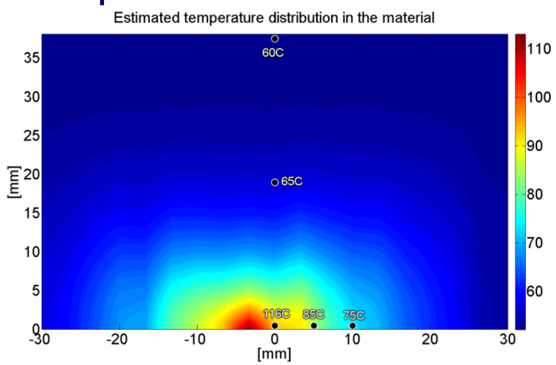
Schematic of heating element and steel test block



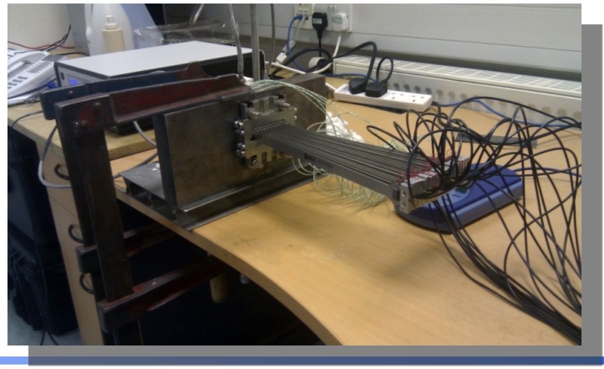


Schematic of position Of UT array and temp. distribution in steel test bloc

Experimentally retrieved temperature map.



Picture of experimental setup for transient heating to ~120°C.



Temperature reconstruction

- Local temperature changes as low as 5°C detectable (equivalent to 0.15% void fraction)

Corrosion rig

- Thickness loss of 1 [μm] detectable (0.01%) within 1 hour
- Precision of chemical controllability is the limit

High temperature voiding/Hydrogen Attack

- Lowering temperature gradient should enable us to measure changes using the ultrasonic sensor

Questions?