


# Structural integrity of the graphite cores in the UK AGR: A focus on life-extension

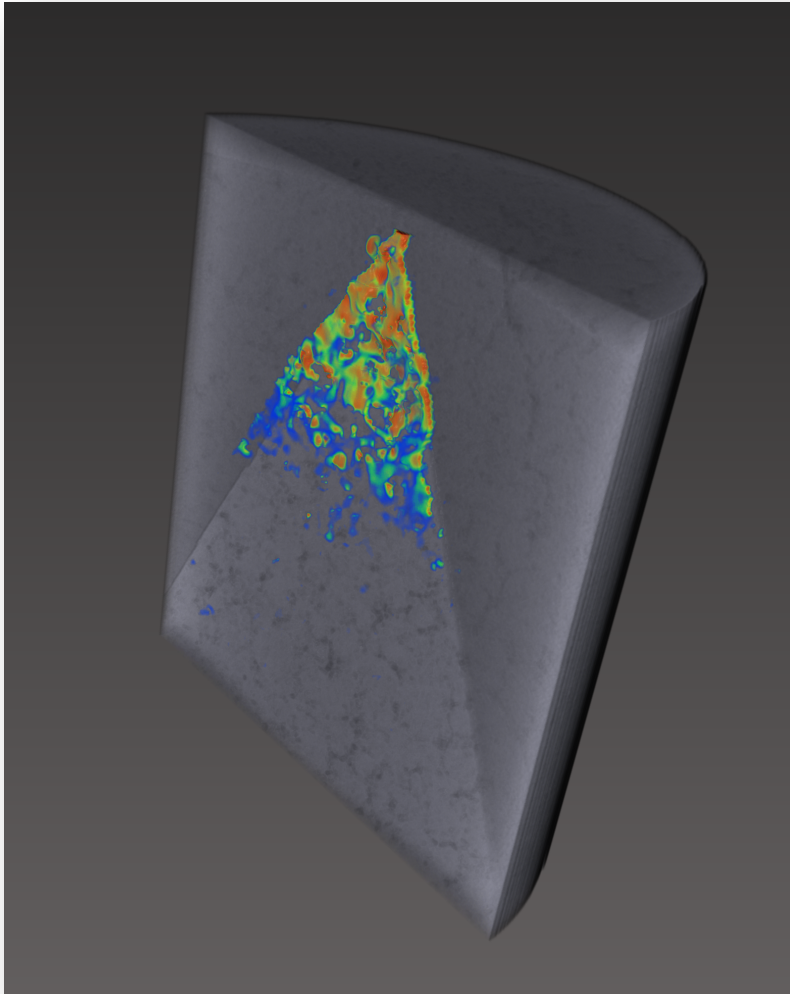
T.J. Marrow  
Department of Materials & Oxford Martin School, University of Oxford

[james.marrow@materials.ox.ac.uk](mailto:james.marrow@materials.ox.ac.uk)

*Cambridge—January 2013*

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Overview




*Why is ageing of nuclear plant an issue?*

*How does nuclear graphite age?*

*What approaches are taken to manage ageing?*

*Example of current research:  
Application of computed X-ray tomography and digital volume correlation (i.e. 3D digital image correlation)*

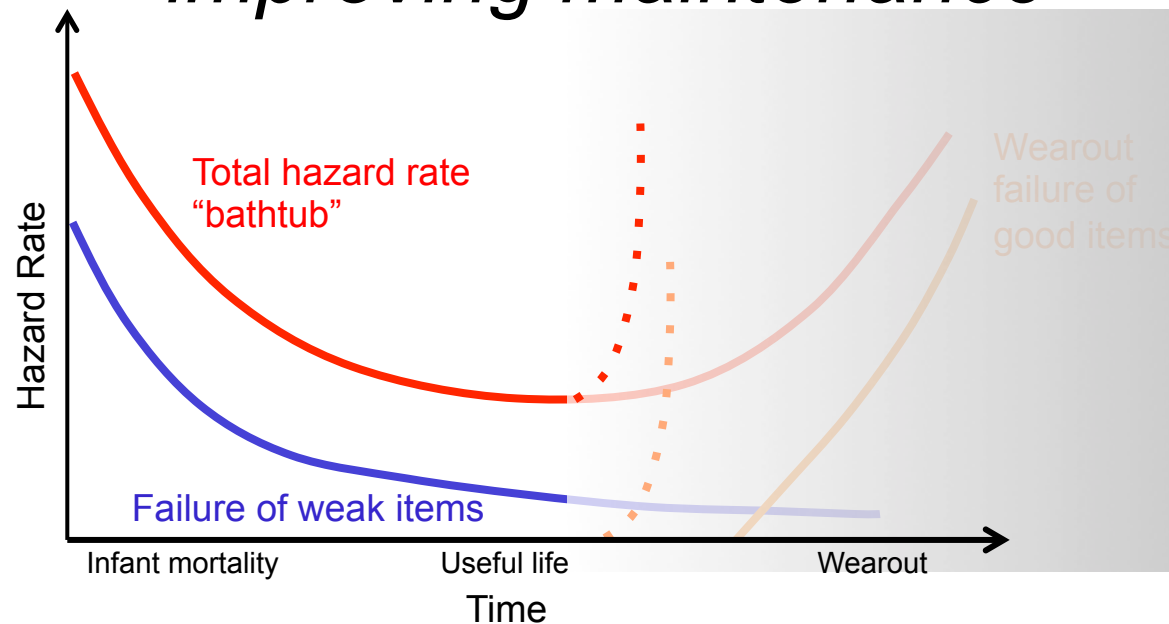
 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Structure of Talk

- Why extend reactor life?
- Why is graphite used in nuclear reactors?
- Effects of irradiation on nuclear graphite
- Nuclear safety principles
- An issue that may arise due to the ageing of graphite in the UK AGRs
- Some current research that is contributing to the managing of ageing nuclear graphite

# Plant Life Extension (PLEX)

- *“Revision of the original design life based by reviewing actual service conditions and ageing phenomena and improving maintenance”*

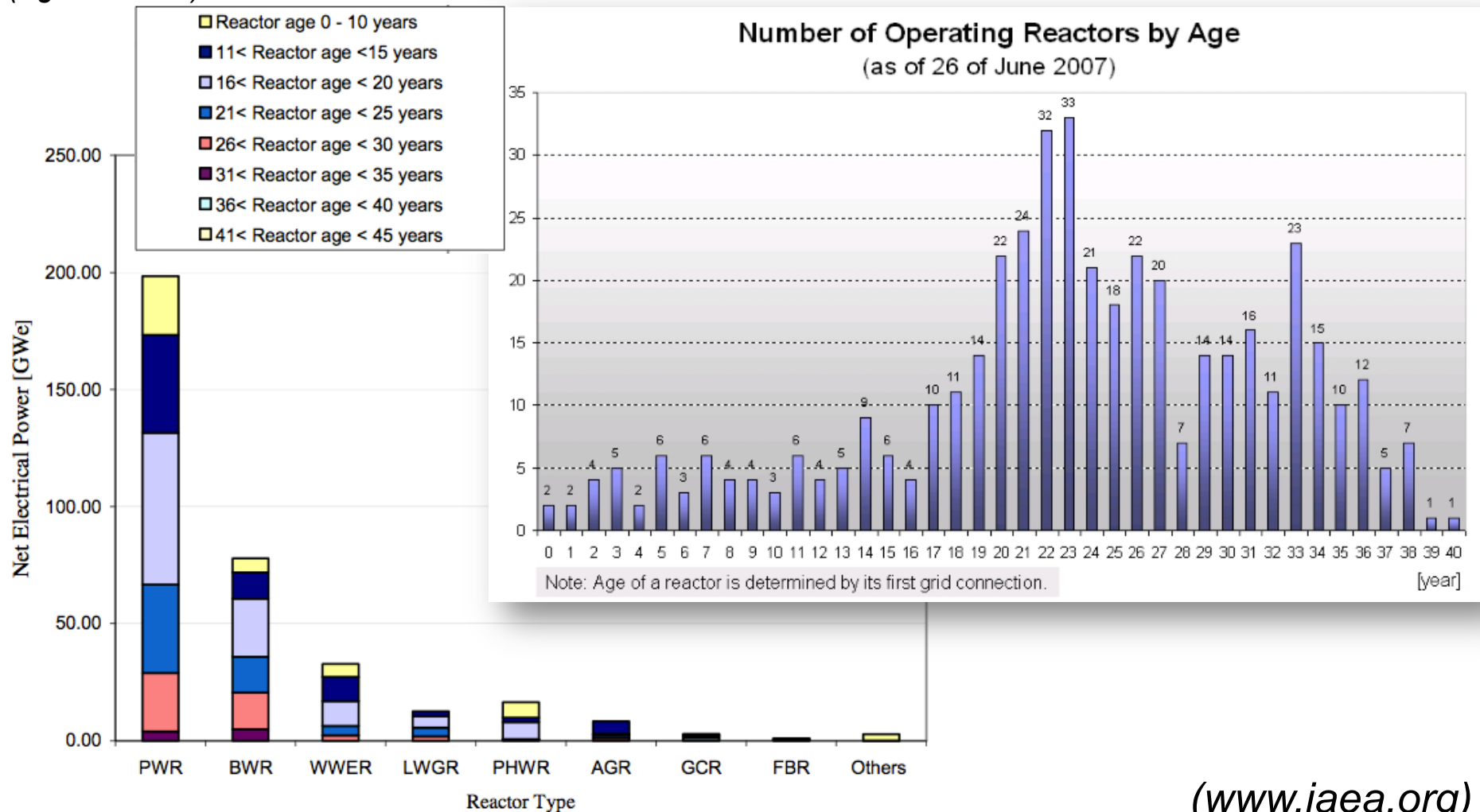


*Extension of life:  
economical method  
to meet the growing  
need for electricity  
and avoid investment  
in the construction of  
new installations*

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

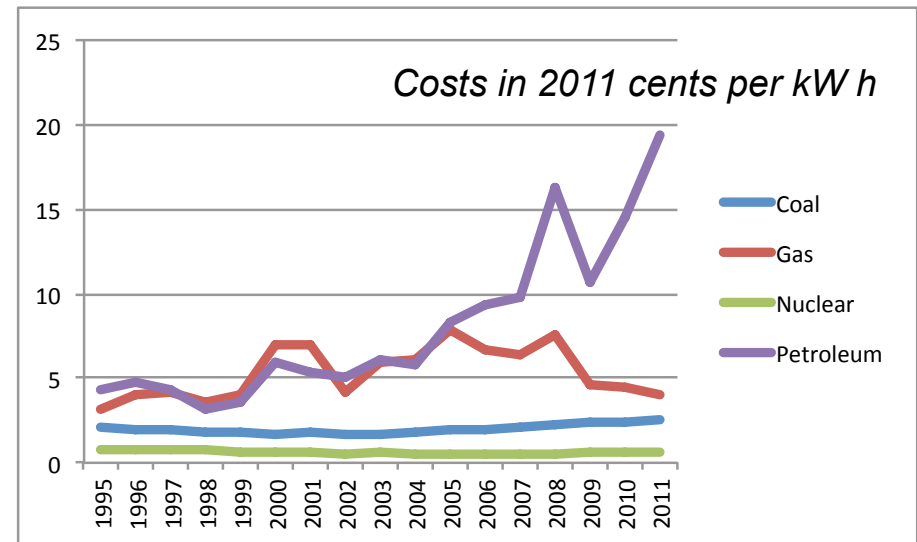
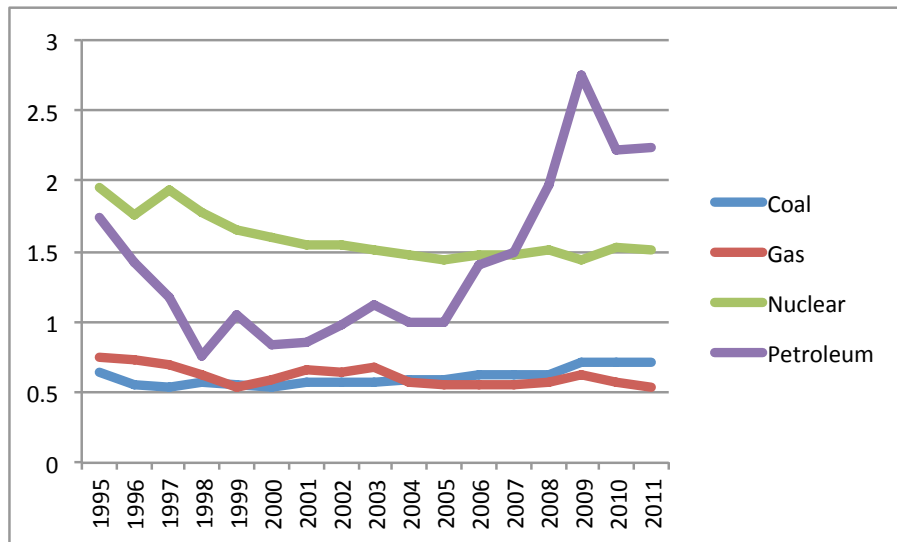
# Ageing of Nuclear Plant

(Ages in 2001)



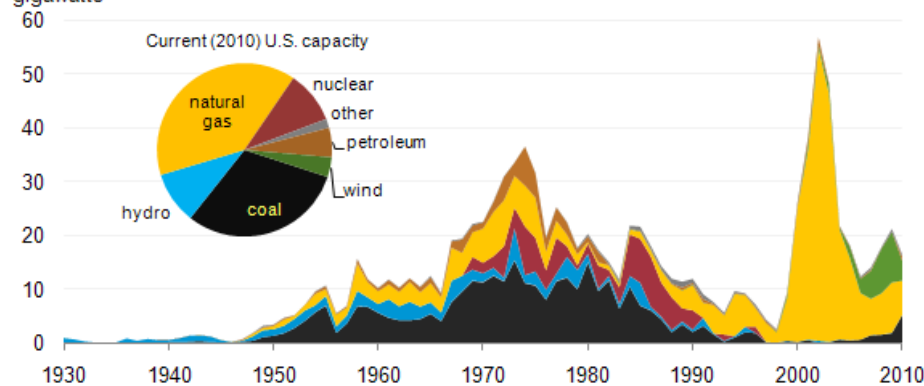
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Electricity Production Costs



## Operations and Maintenance

Current (2010) capacity by initial year of operation and fuel type  
gigawatts

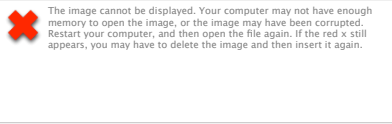


## Fuel

(USA Nuclear Energy Institute: NEI)

Old plant can be expensive to run, but nuclear is performing well

(U.S. Energy Information Administration)

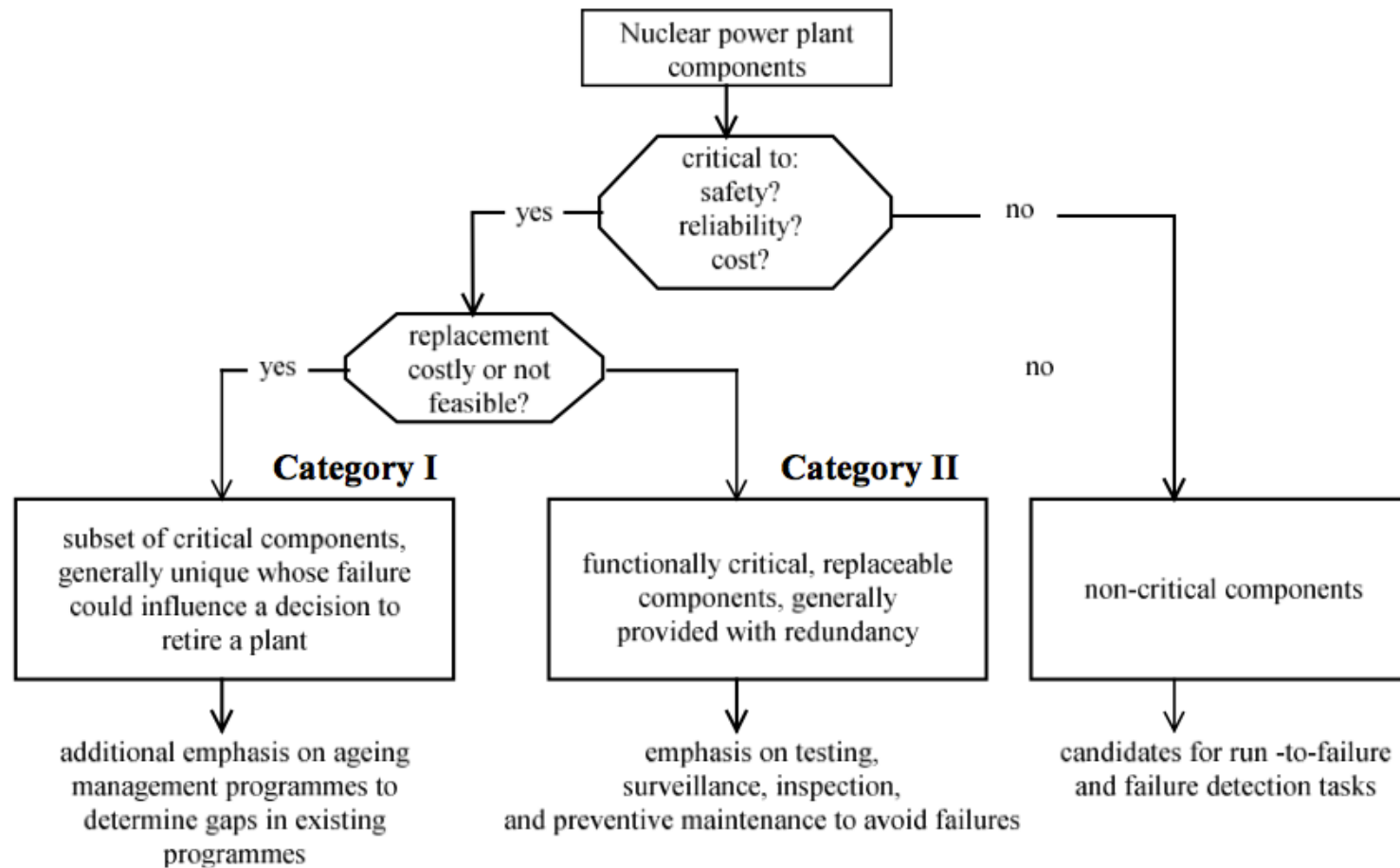


# PLEX Options

- Exchange of components
  - Costs usually are high
- Reduction of loads
  - Costs are moderate
- Reduction in safety margins
  - reducing conservatism can lead to longer lifetimes (at least theoretically)
  - Costs are usually relatively low

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Critical Components



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Materials Ageing Examples

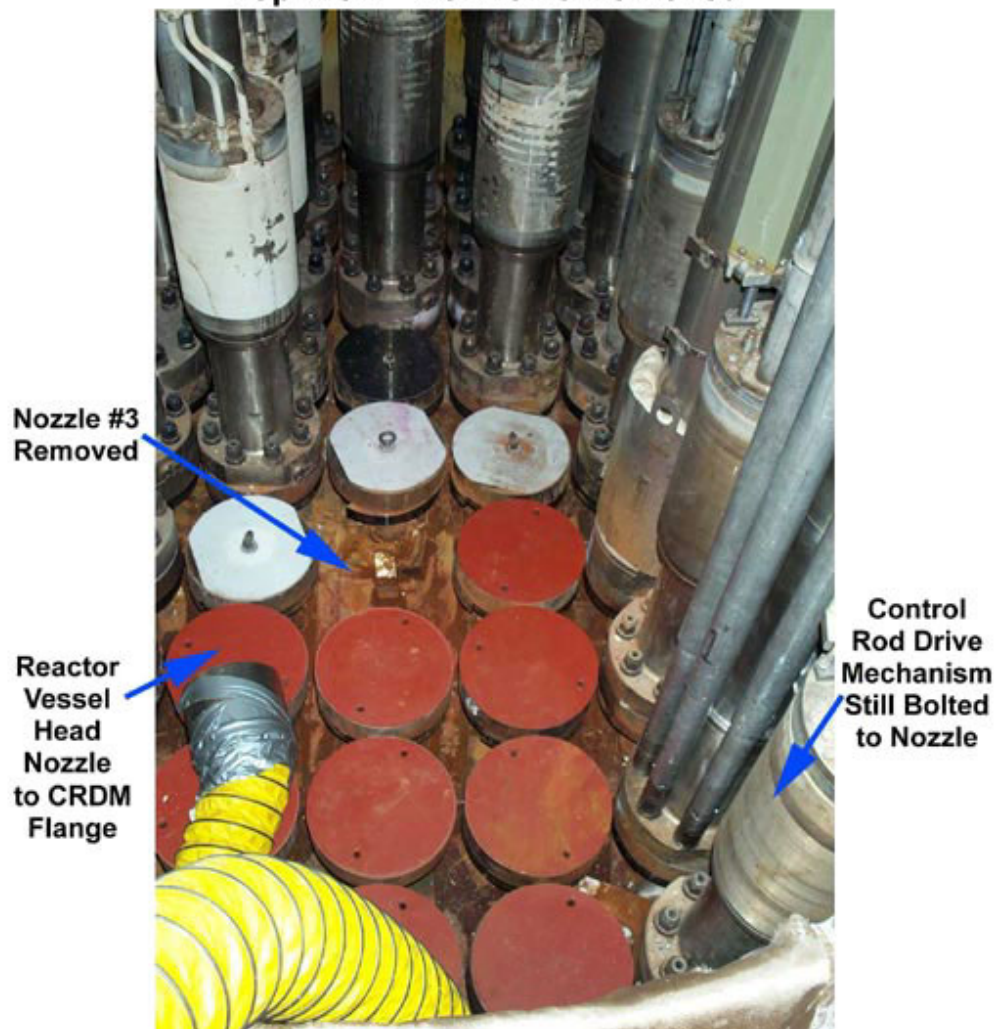
## Corrosion



Davis Besse  
(PWR, 900 MWe, 1977-, USA)



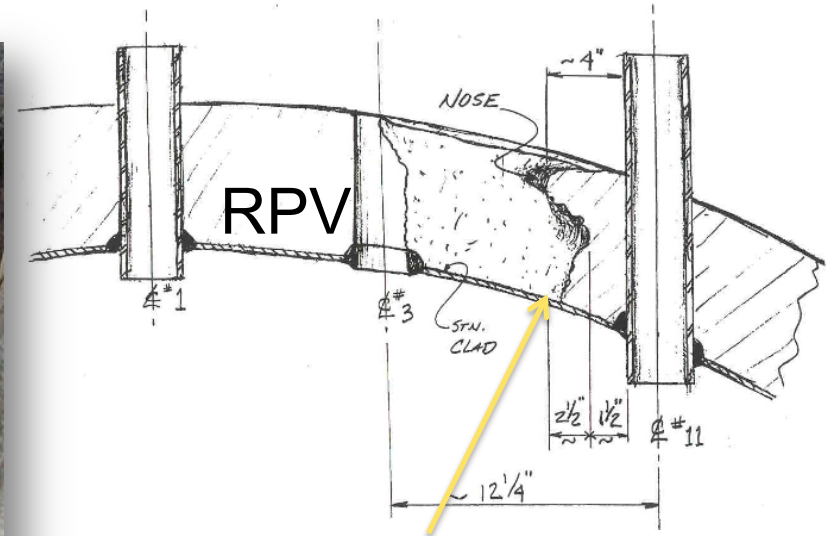
Davis Besse - Reactor Vessel Head Insulation  
Top View - Nozzle #3 Removed



([www.nrc.gov](http://www.nrc.gov))

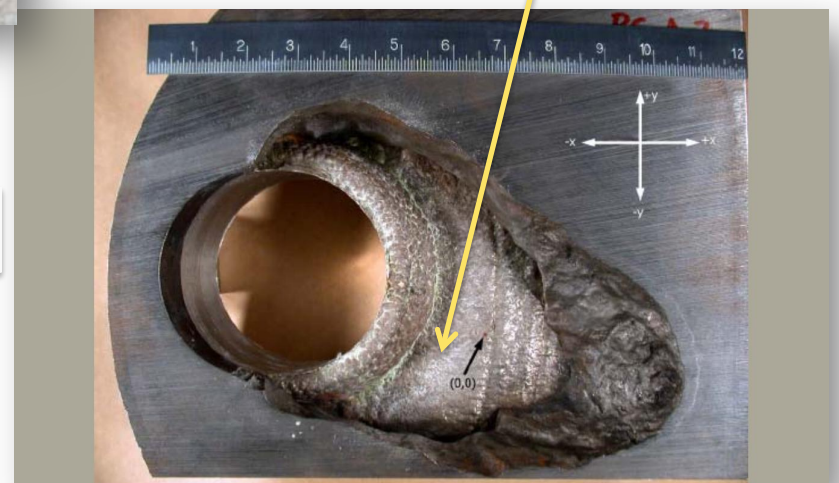
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Materials Ageing Examples Corrosion



Cladding (stainless steel)

This is an unusual degree of corrosion

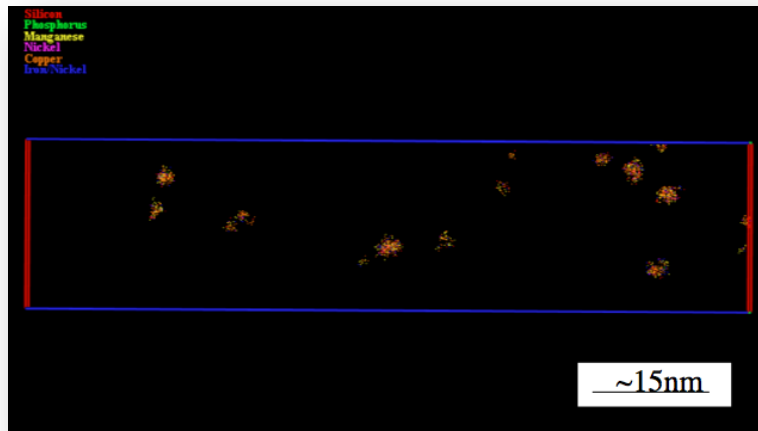
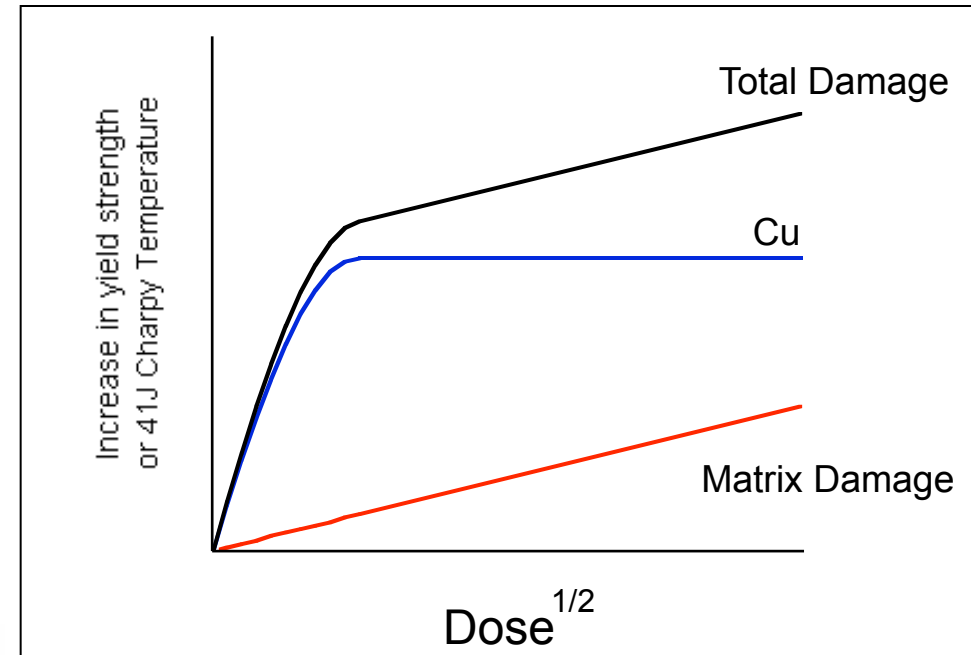


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

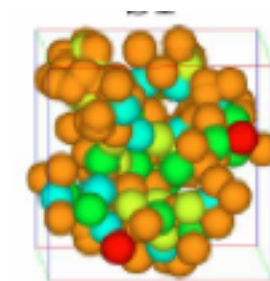
# Materials Ageing Examples

## Ferritic Steel Embrittlement

- Typically due to irradiation at  $< 0.3T_m$
- Accumulation of point defects and hardening precipitates
  - E.g. Cu clusters



Atom probe images of Cu clusters



Cu, Mn, Ni, Si, P, Fe

Hardening causes embrittlement

2nm

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Materials Ageing Examples

## Recovery Annealing of RPV

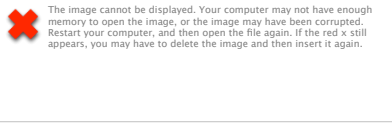


Bohunice (Slovakia, VVER)  
(~500 MWe) (~1980-)

RPV annealed at 475 –  
500°C for 160 h in 1993,  
using ~ 1MW radiant heater  
inserted into the core

(VVER = *Vodo-Vodyanoi Energetichesky Reactor*; *Water-Water Energetic Reactor* or **PWR**)





# Materials Ageing

- Irradiation, temperature and time can change the microstructure and properties of materials
- Prediction and monitoring and inspection are critical to safe and economic operation
- Many parts of the reactor can (and have been) replaced or repaired economically

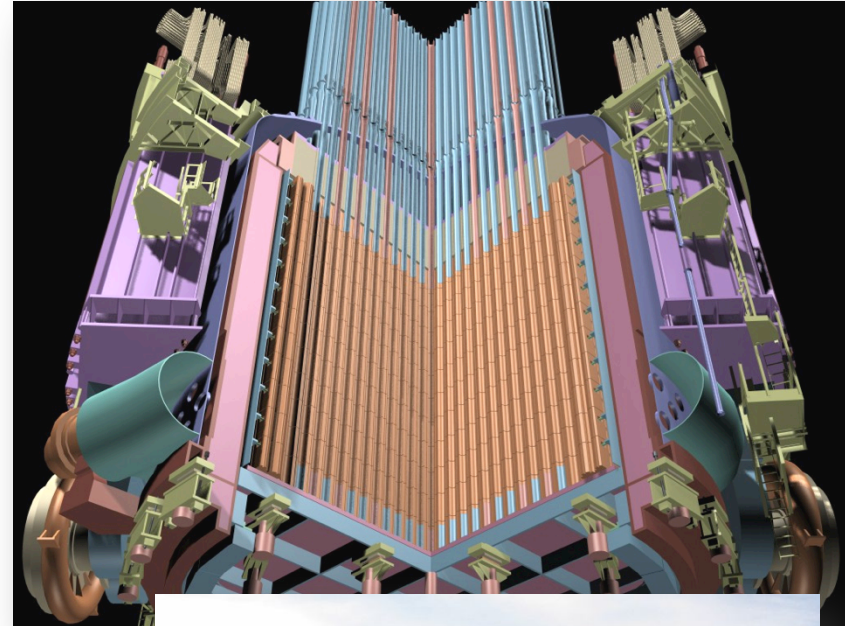
**The AGR graphite core cannot be replaced..**

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Advanced Gas Reactor (AGR)

- Generation II
- Graphite moderated
- CO<sub>2</sub> cooled
- Gas temp: ~640°C
- Gas pressure: ~40 bar
- Design Power
  - ~1500 MWt (thermal)
  - ~650 MWe (electrical)

Actual outputs are lower due to operational issues,  
e.g. Torness 625 MWe per reactor



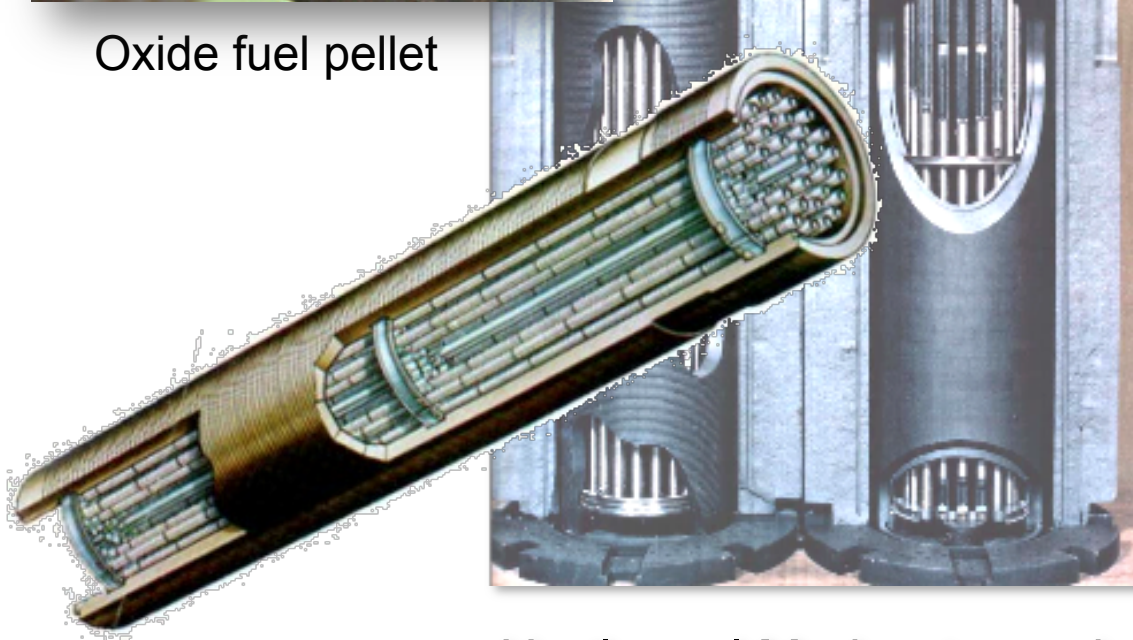
Torness (Scotland UK) (1988)  
(Built only in the UK)

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# AGR (Materials)



Oxide fuel pellet



([www.world-nuclear.org](http://www.world-nuclear.org)) Hartlepool Moderator and Fuel Element

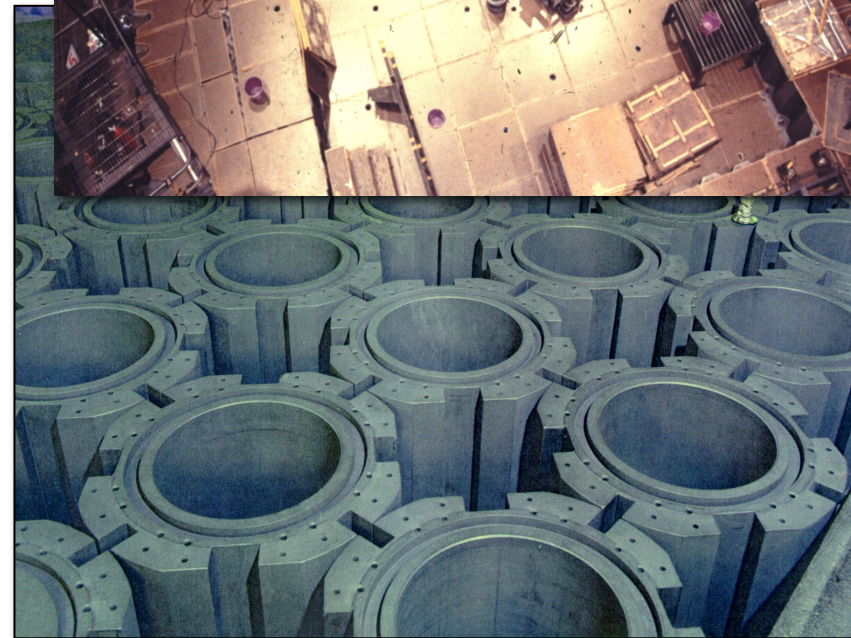
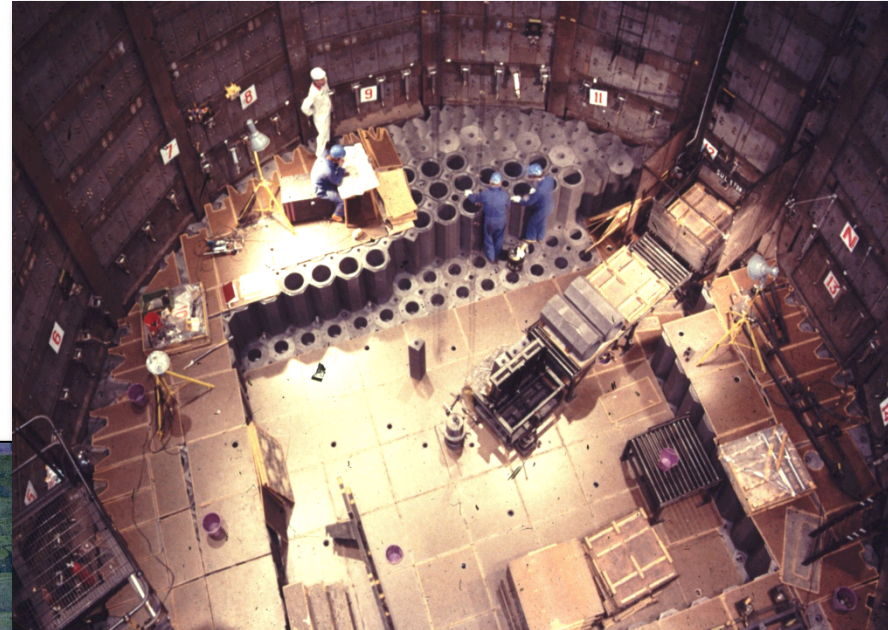
- Fuel Assembly

- Enriched  $\text{UO}_2$  fuel
- Clad in stainless steel
  - 20Cr/25Ni/6Nb
- Graphite Sleeve
  - Stainless steel for high temperature
  - Enriched fuel needed due to neutron absorption by cladding
  - Graphite sleeve to control coolant flow
- Low lifetime neutron dose in clad and sleeve (replaced when refuelling)

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# AGR (Materials)

- Moderator (and reflectors)
  - Graphite
  - High lifetime neutron dose
  - Not replaceable
- Pressure Vessel and Radiation Shield
  - Concrete
  - Low lifetime neutron dose
  - Not replaceable



Heysham 2/Torness (during construction)

# Graphite Core Requirements

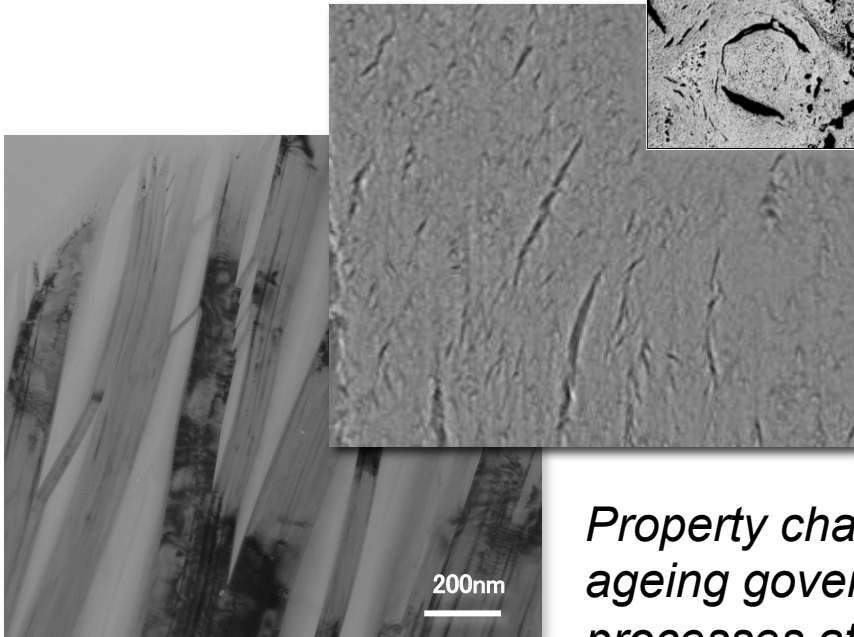
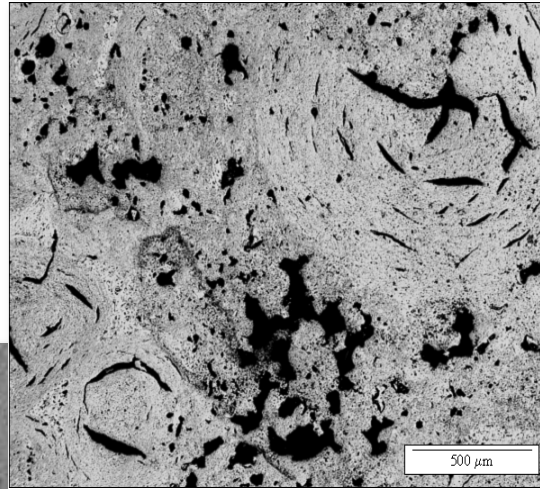
- Act as a moderator of fast neutrons
- Provide a stable geometric structure which would:
  - Provide passages in which fuel could be freely loaded and unloaded
  - Provide passages in which control rods could be freely inserted and removed
  - Provide passages to direct the coolant gas flow over the fuel to remove heat
  - Support its own weight

*(1965 Emeleus Committee)*

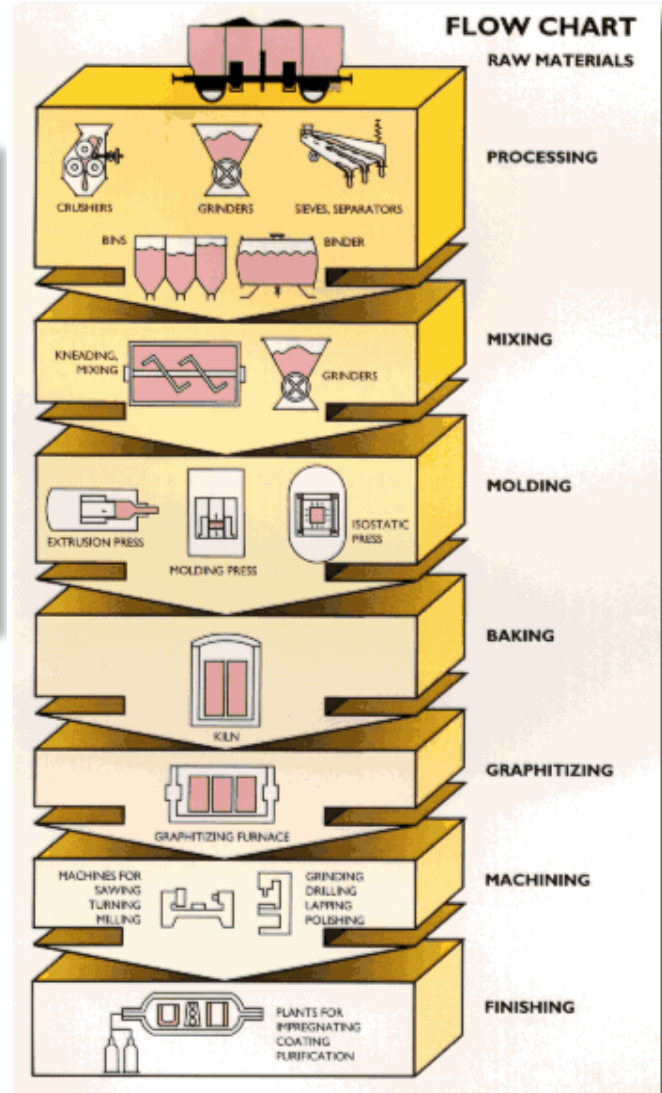
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Nuclear Graphite

Graphite properties are sensitive to microstructure (and processing)



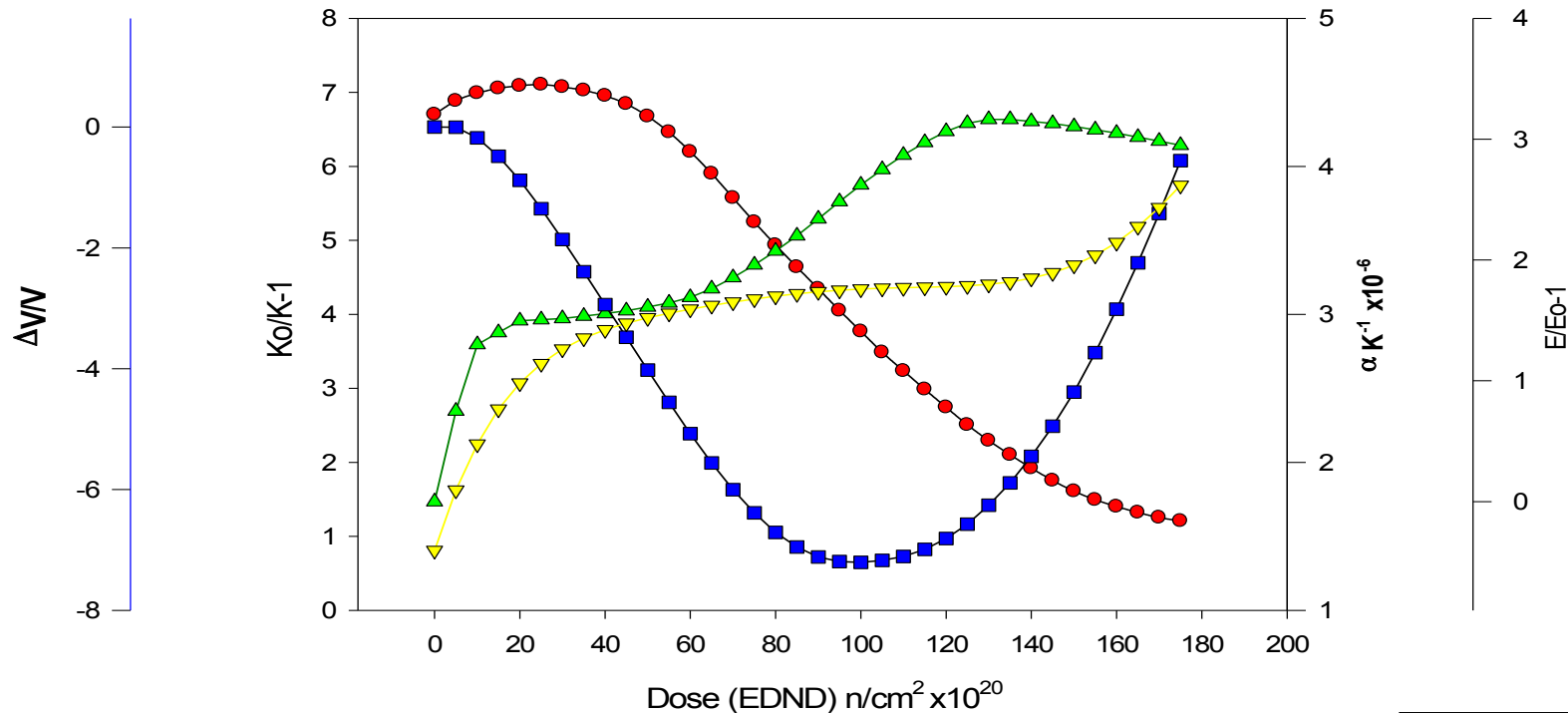
*Property changes with ageing governed by processes at the crystal level*



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

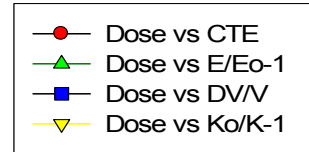
# Effects of Irradiation on Polygranular Graphite

Irradiation induced changes in Gilsocarbon at 550°C (EDT)



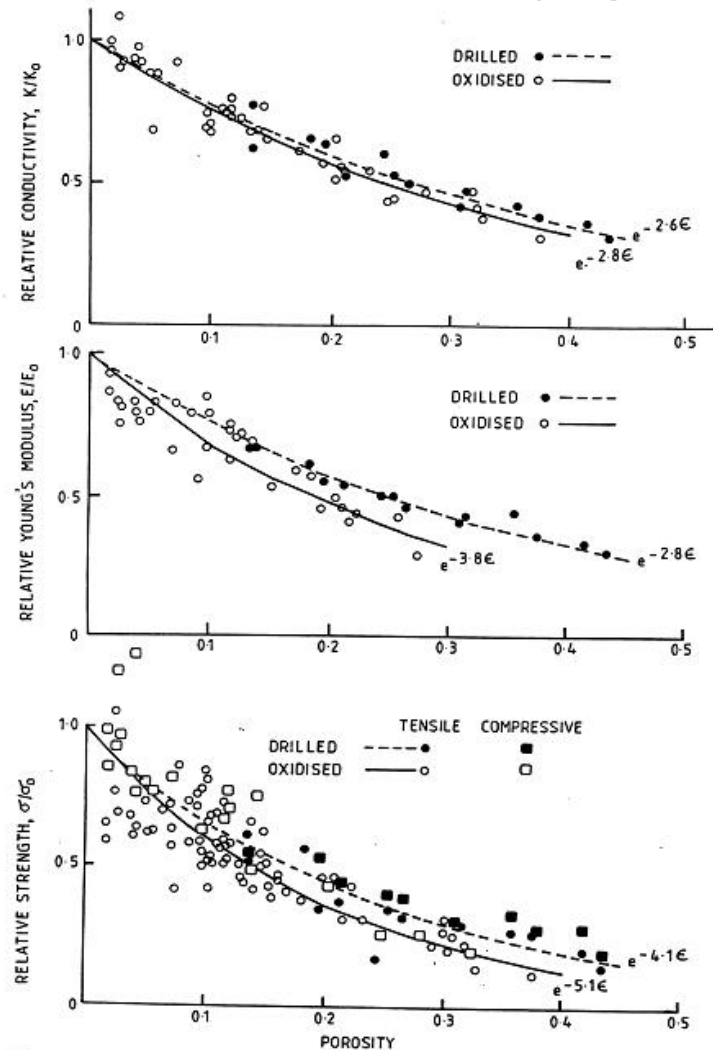
Thermal Expansion  
Young's Modulus

Dimensional Change  
Thermal Conductivity



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

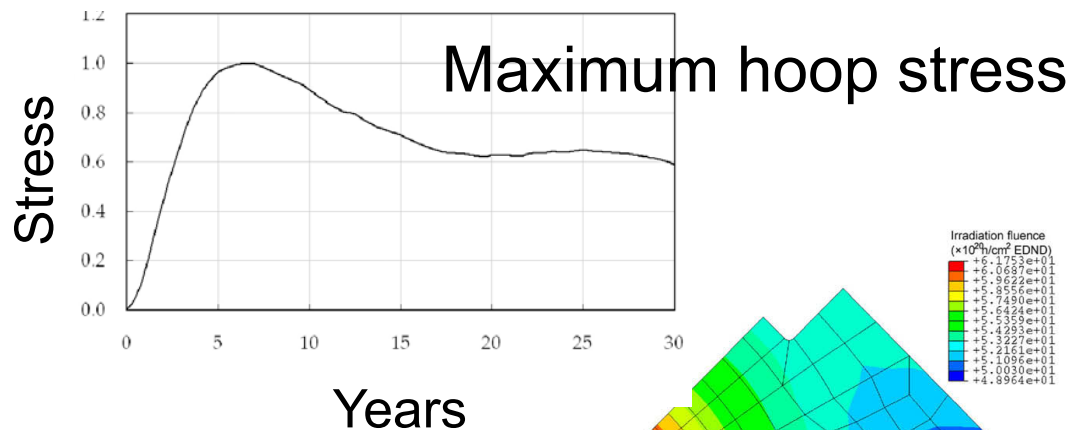
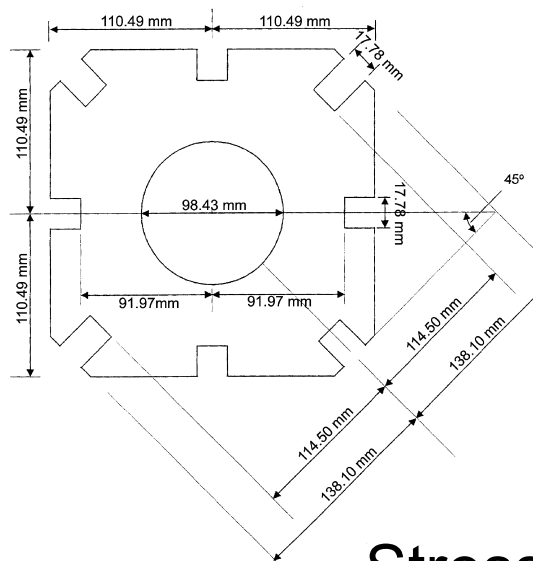
# Effects of Oxidation on Polygranular Graphite



- Oxidation
  - progressively reduces strength, modulus and thermal conductivity
  - depends on gamma dose, temperature, gas chemistry and initial state of the graphite

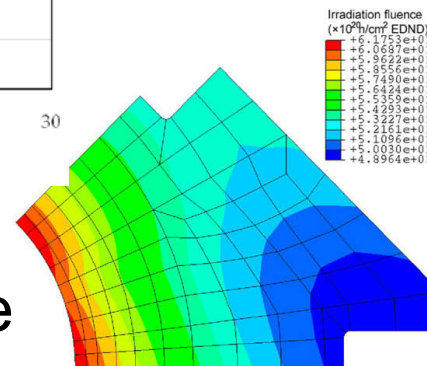
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Component Modelling



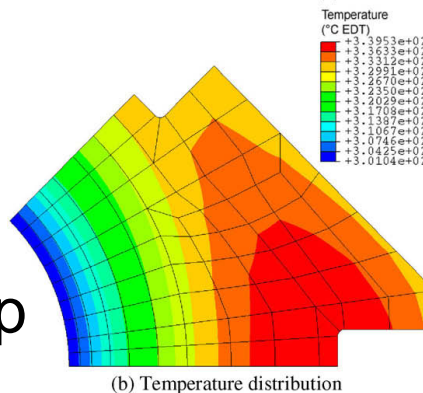
Stress development in Magnox graphite brick (at 30 years)

Dose

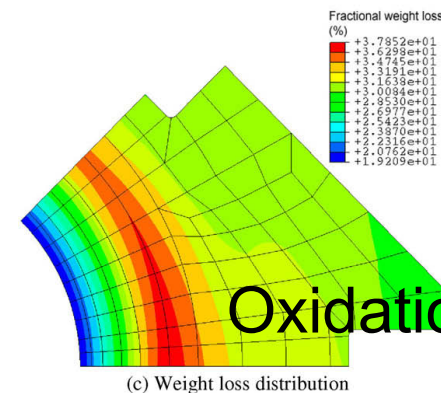



The locations of maximum stress and minimum strength vary with age

Temp




Oxidation



 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Ageing of Graphite: Regulation

- During reactor operation, graphite components oxidise and age due to interaction with the radiation environment
- This can lead to a reduction in graphite component strength and the potential for development of cracks in some of the graphite components
- Reactor licensees must demonstrate that the graphite reactor core can continue to be used safely as it ages

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Nuclear Safety Principles

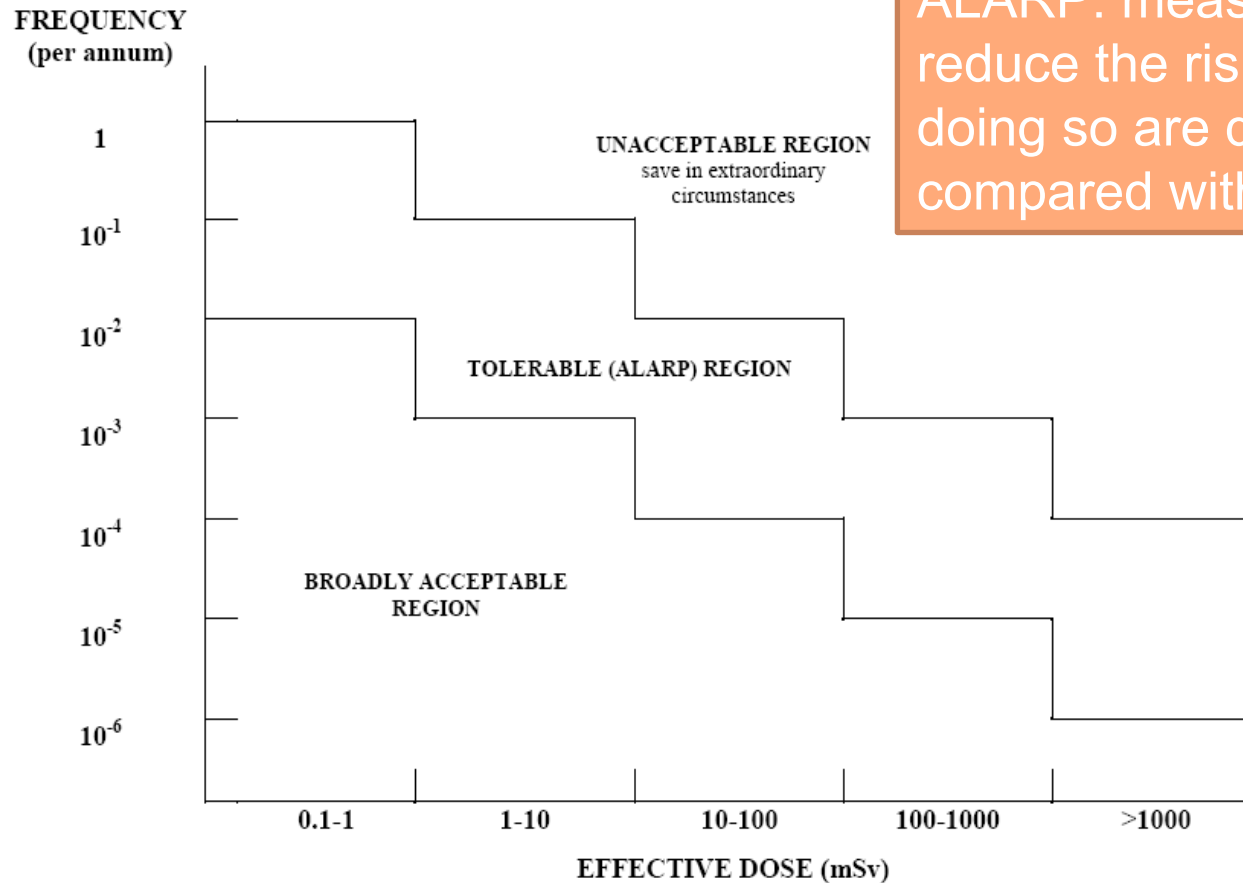
- Sound design concepts and proven design features
- Analysis of the potential failure modes for all conditions arising from design basis faults
- Use of proven materials
- Application of high standards of manufacture, including in-process inspection, and construction, for the materials and processes used
- High standards of quality assurance throughout all stages of design, procurement, manufacture, construction and operation
- Pre-service and in-service inspection to detect defects and component damage at sizes below those which have the potential for causing or developing into a failure mode, and to size these defects conservatively
- Provision of in-service plant and materials monitoring

**Some of the principles required to make a case for operation**

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

As Low As Reasonably Practical

# Levels of Risk and ALARP




ALARP: measures should be taken to reduce the risks unless the costs of doing so are disproportionately high compared with the risk averted

***Uncertainty reduces the operational time until the unacceptable region is reached***


Frequency/Effective Dose Relationships

Reducing uncertainty may increase reactor lifetime

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Multi-Legged Safety Case

- Safety Case Legs
  - Design
  - Manufacture, Construction & Commissioning
  - Component & Core Condition Assessment
  - Damage Tolerance Assessment
  - Consequences
  - Monitoring
  - Examination, Inspection, Surveillance, Sampling and Test
  - Redundant and diverse shutdown / hold-down systems
- An adequate case comprises:
  - Independent legs
    - Strong leg may offset weak leg
    - Strong leg may underpin another – not vice-versa
    - Contribution from each leg may vary through life
  - Redundant and diverse arguments
  - Avoidance of common underpinning data, assumptions or methodologies
  - **Burden of proof and the required robustness of case increases as component and core degradation increases**

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

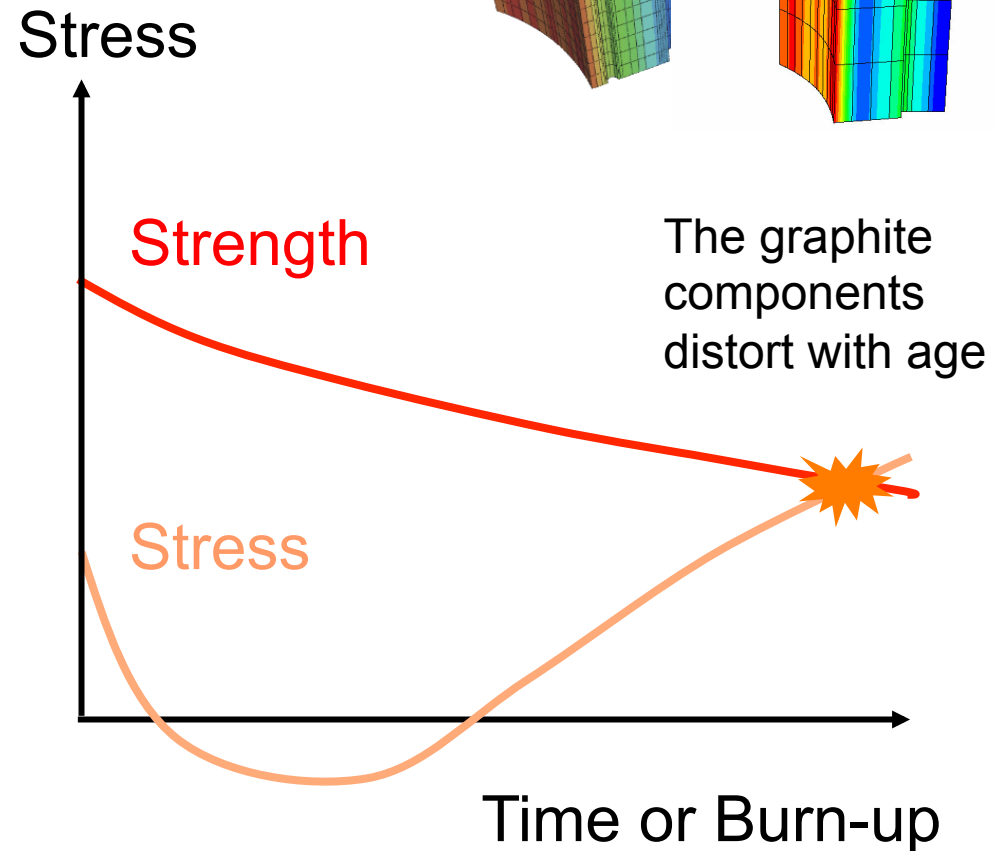
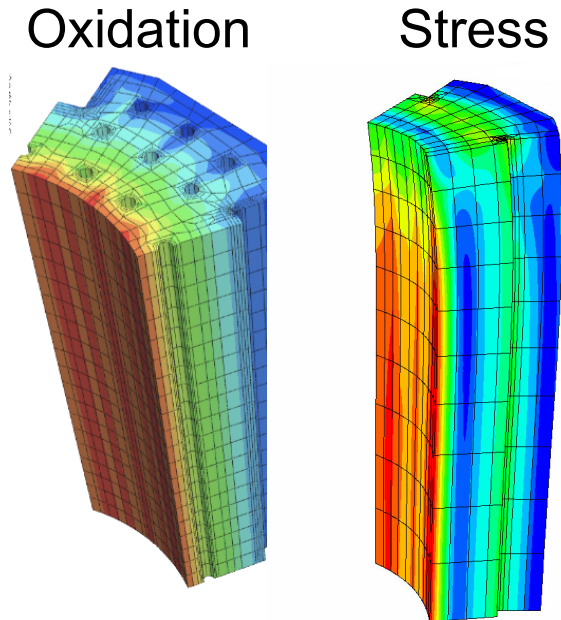
# Example: Core Condition

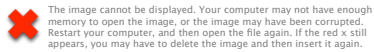
- Postulate types and degrees of graphite component degradation
  - Material property modelling and material properties data
  - Best estimate calculations of fuel brick stresses and distortions
  - Predictions of the timing and rates of brick cracking towards end of life

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# A potential mode of component degradation: Keyway Root Cracking

- Stress can become tensile with irradiation at some positions in the brick
- Strength reduces with radiolytic oxidation
- A simple crack initiation criterion is currently assumed: failure predicted when stress exceeds tensile strength
- Models can predict distributions of properties






# Questions that the regulator and the operator might ask themselves...


- When might the first brick crack?
  - What will be the fracture path?
  - Where will the crack start?
  - How will this be detected and with what reliability?
- How might the number of cracked bricks increase with time?
  - What is the confidence in the predictions and their bounds?
- How might the reactor core behave as the number of cracked bricks increases?
  - How might cracked bricks impact on reactor operation?
- What could happen in a seismic event?
  - How might a damaged core interact with the surrounding structure?

*And so on....*

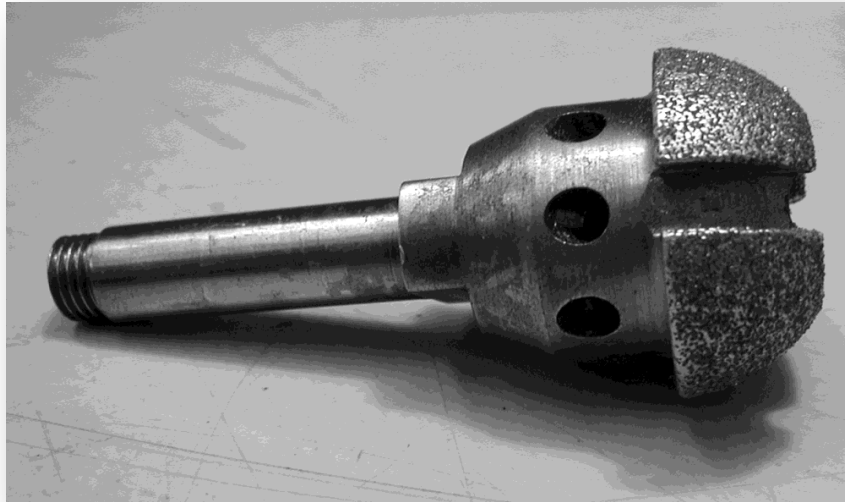
 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# What is needed to address these questions?

- Multi-scale modelling
  - From atomistic to whole core simulation
  - Statistical modelling
- Data
  - material properties, component tests.....
- Understanding of graphite properties and effects of ageing

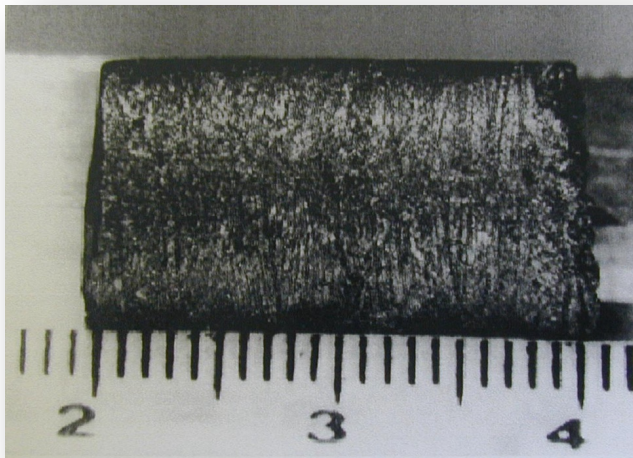
 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Example: Material Properties




Trepanning tool and trepanned core (Magnox)

Extracting test specimens from an operating reactor is not a trivial exercise!



Measurements to verify predictive models for oxidation and property changes; data may also support safety case

*Surveillance specimens are also important*

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

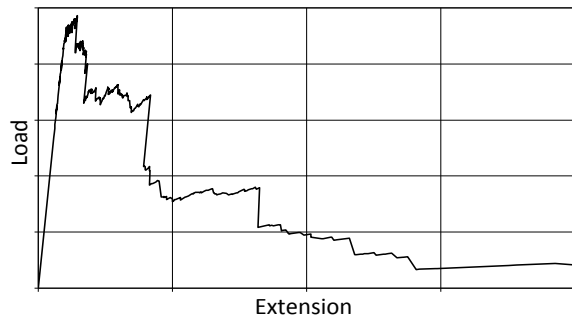
An example of current research

# GRAPHITE FRACTURE

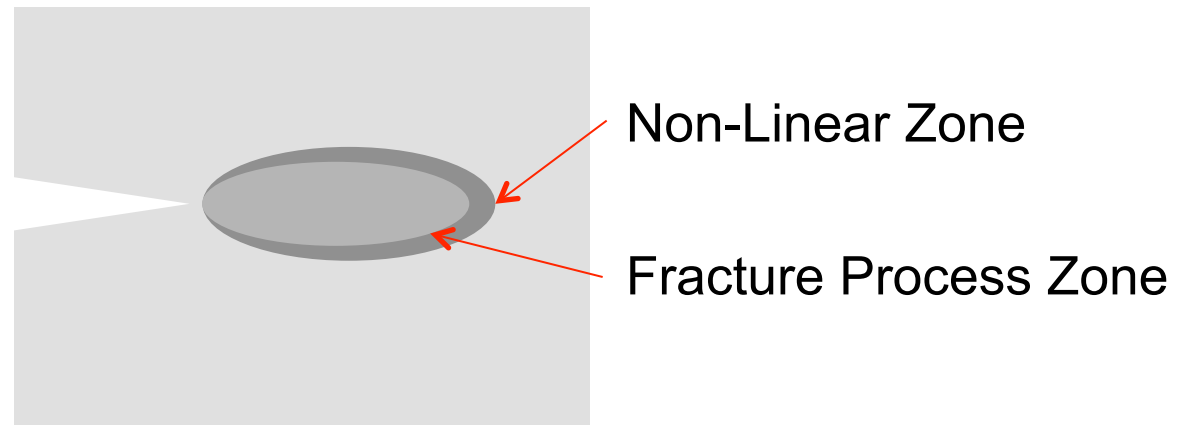
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Research Aim

- Fracture models are required that can predict the effects of microstructure on the *nucleation and propagation of critical defects at stress concentrations*
- Nuclear graphite is a quasi-brittle material



"Graceful" failure of a quasi-brittle material

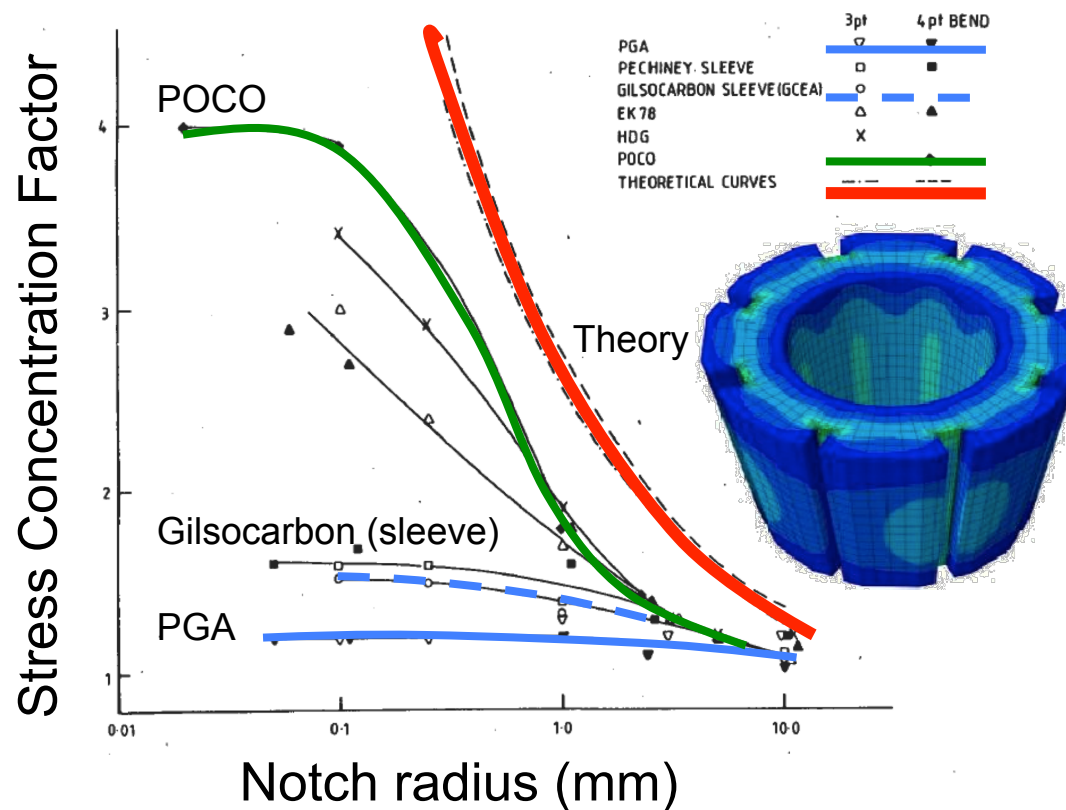


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Notch Sensitivity

Coarse grained graphites have low notch sensitivity

Does notch sensitivity change with age?



Stress concentration factor =

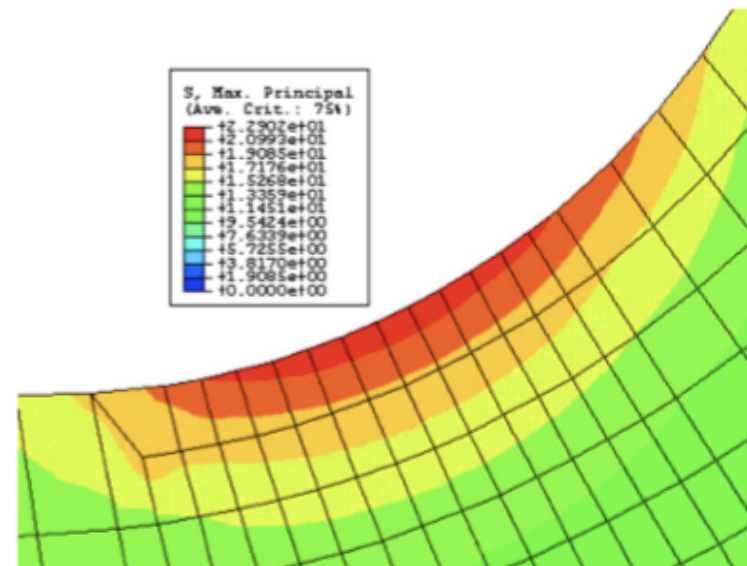
$$\frac{\text{Un-notched strength}}{\text{Notched strength}}$$

*Current assessments take a very conservative approach*

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Cohesive Zone Models for Graphite Fracture

- Micro-cracking occurs to relax elastic strains
  - Coarser microstructures contain larger microcracks
  - Mechanistic explanation for the effect of microstructure on strength
- Micro-cracking will occur at stress concentrations
  - Mechanistic explanation for the effect of microstructure on notch sensitivity
- Cohesive zone models can reproduce this behaviour



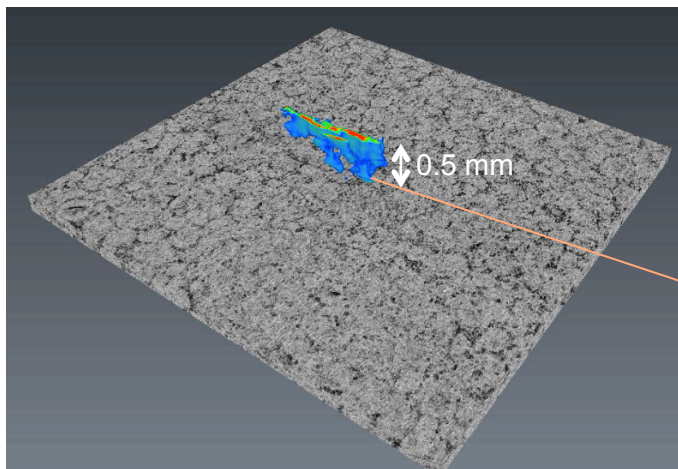
How is this behaviour affected by degradation of graphite?

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

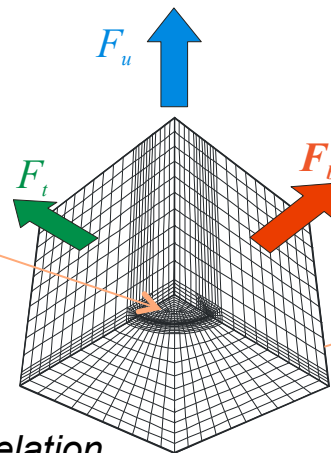
# Modeling Over Length Scales

- Unit Cell Model
  - Effect of constraint on propagation of intrinsic defects
- Cohesive Zone Model
  - Crack initiation and propagation from stress concentrations

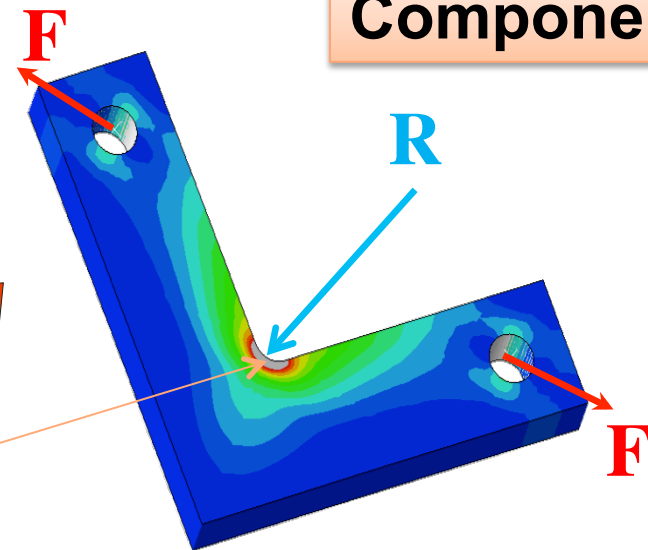
## Microstructure



*Crack nucleus revealed by digital volume correlation of computed X-ray tomography data (in-situ loading)*

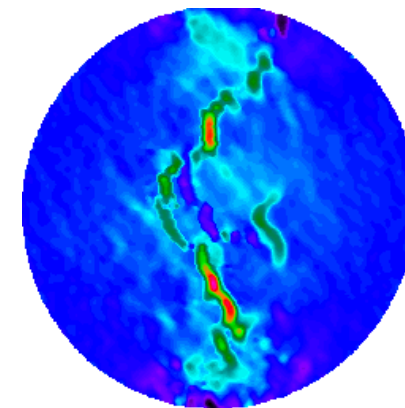
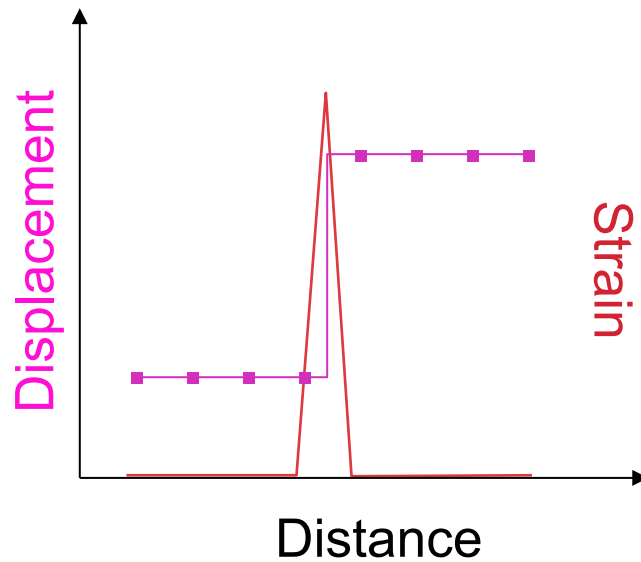
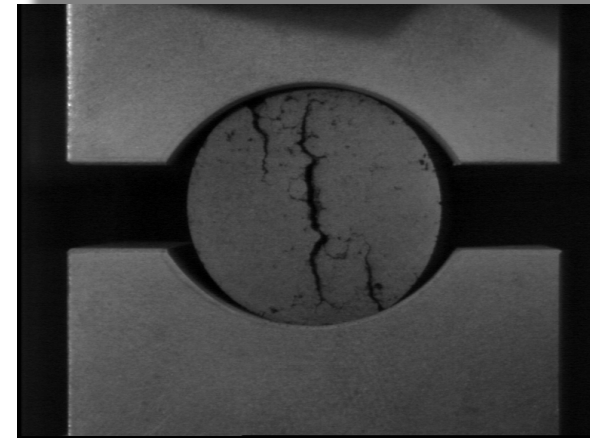
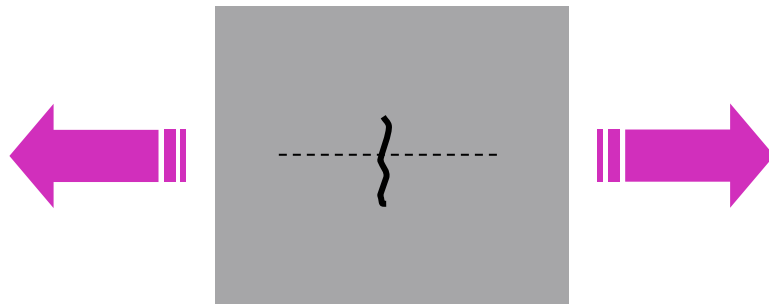


## Component



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Strain Mapping of Cracks

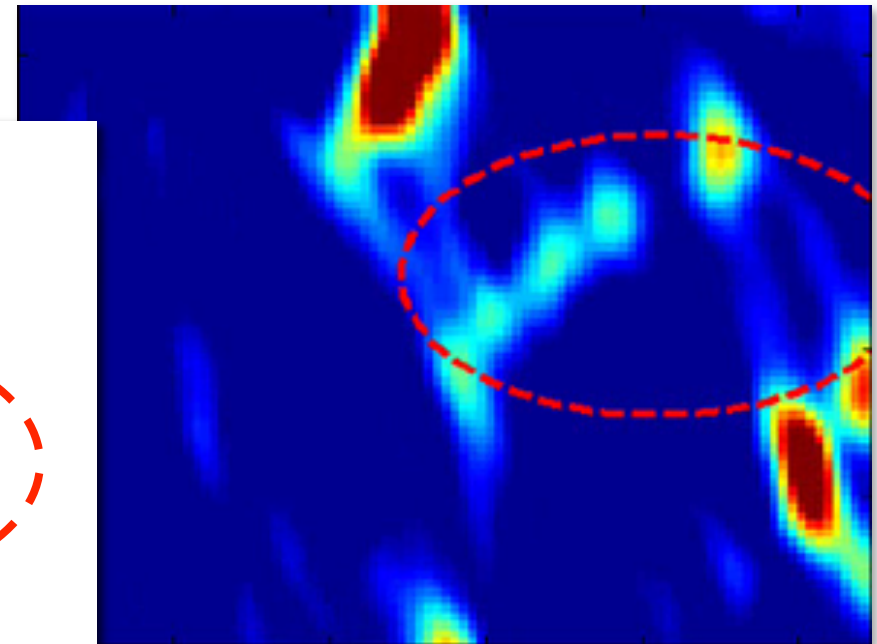
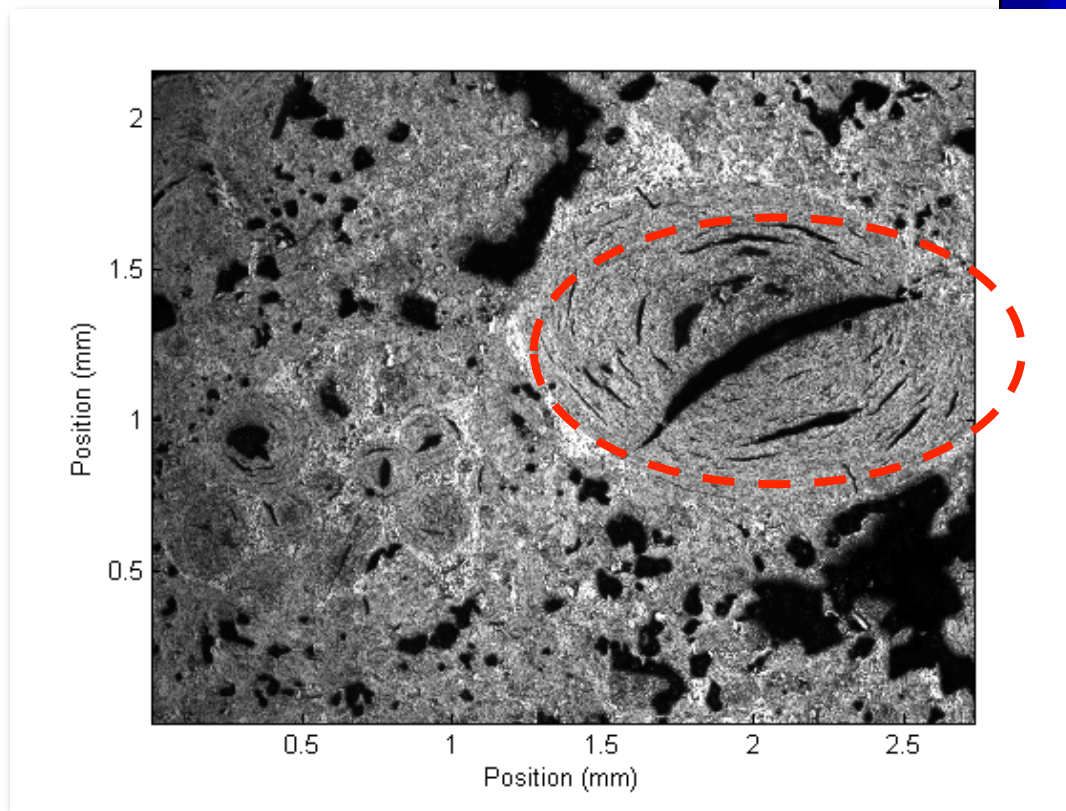


2D strain mapping


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Heterogeneous Deformation

## GilsoCarbon Graphite

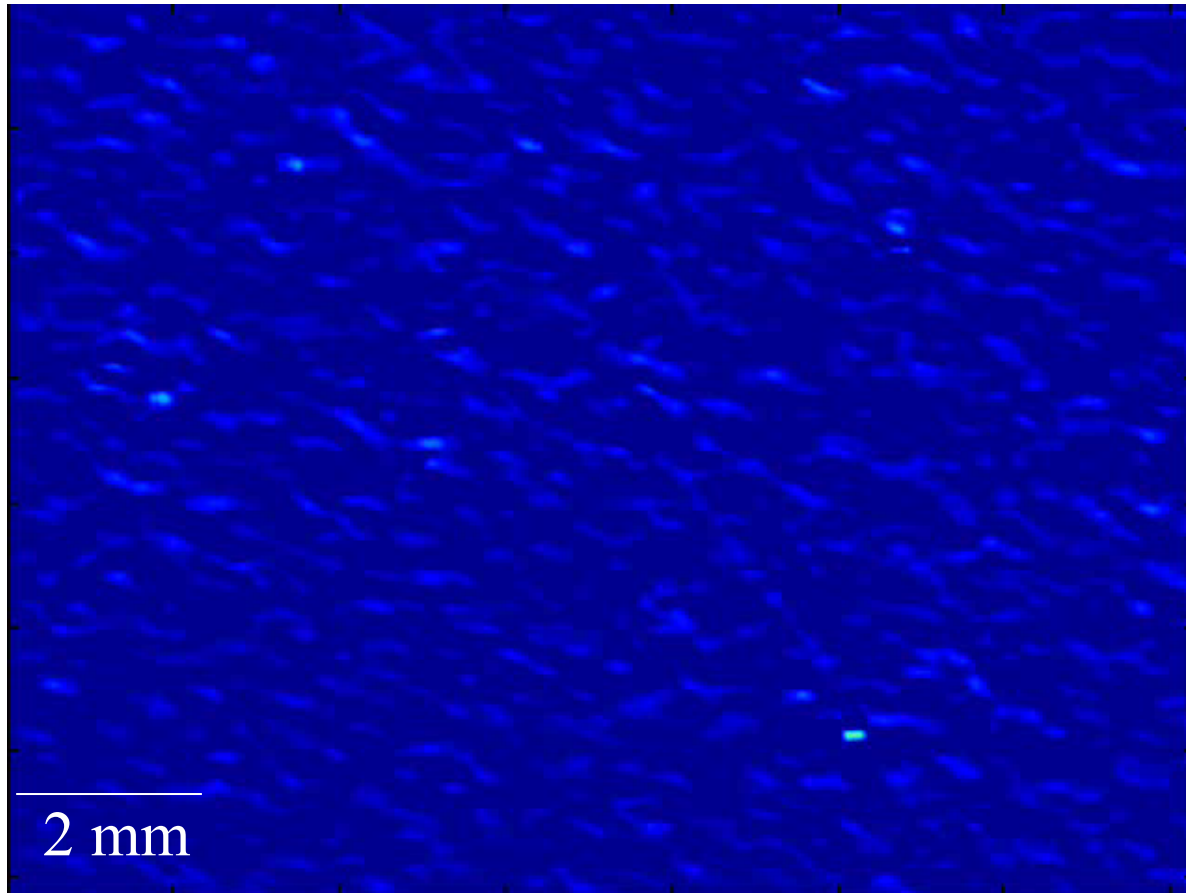


High strains associated with pores


 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Crack Nucleation in Graphite

Gilsocarbon Graphite




Tensile Loading

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

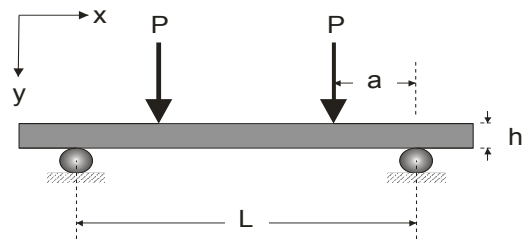
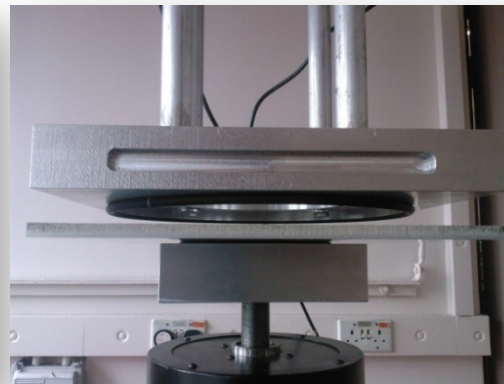
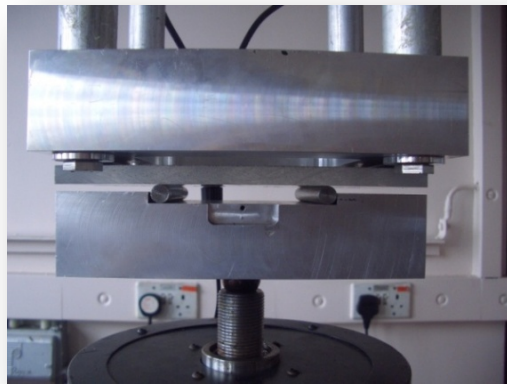
# Crack Nucleation - Summary

- Failure of the sample is preceded by propagation of a crack nucleus by the successive formation and coalescence of micro-cracks. These tend to be associated with significant porosity
- Final failure in small test specimens may depend on the development of instability in a single, stably propagating defect.

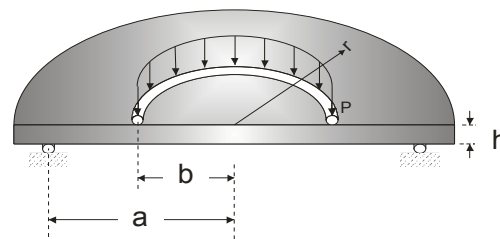
How do these defects behave in a larger sample?

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

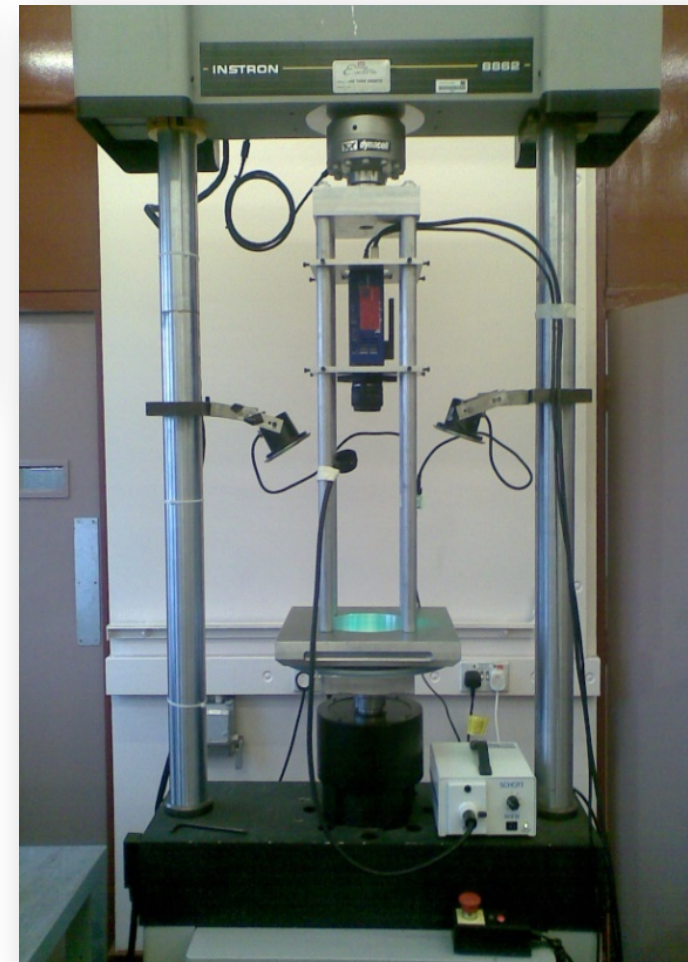
# In-Situ Observation of Fracture



Uniaxial

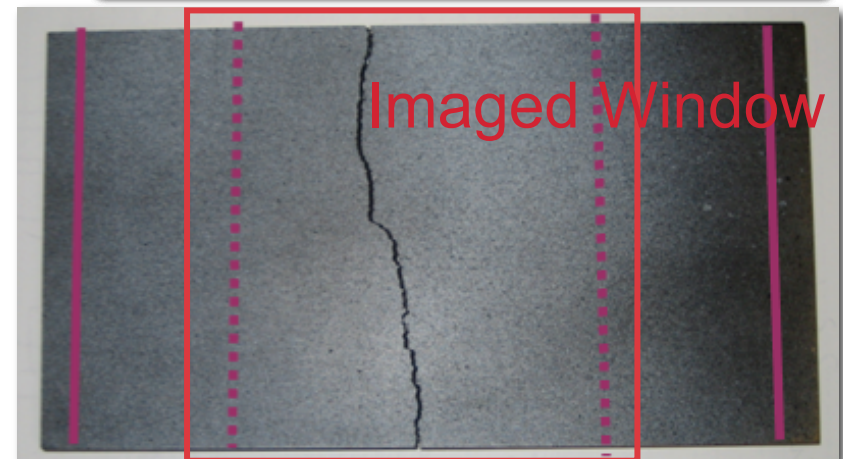
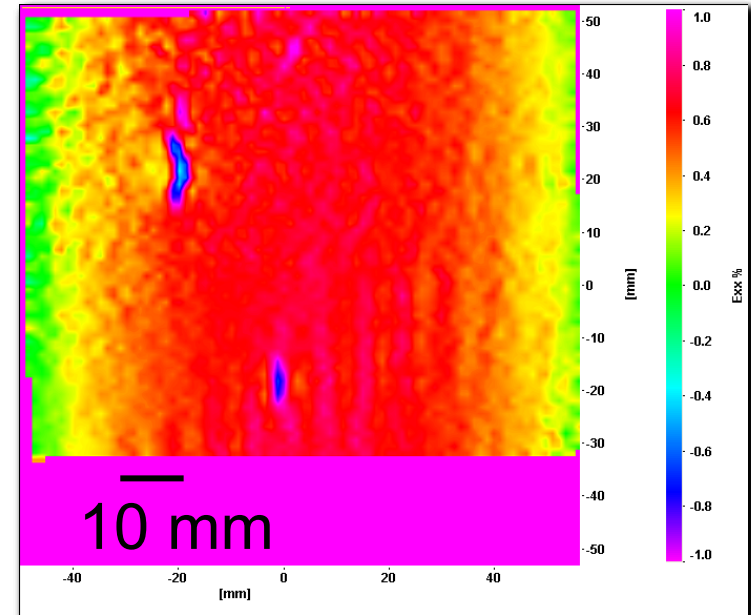
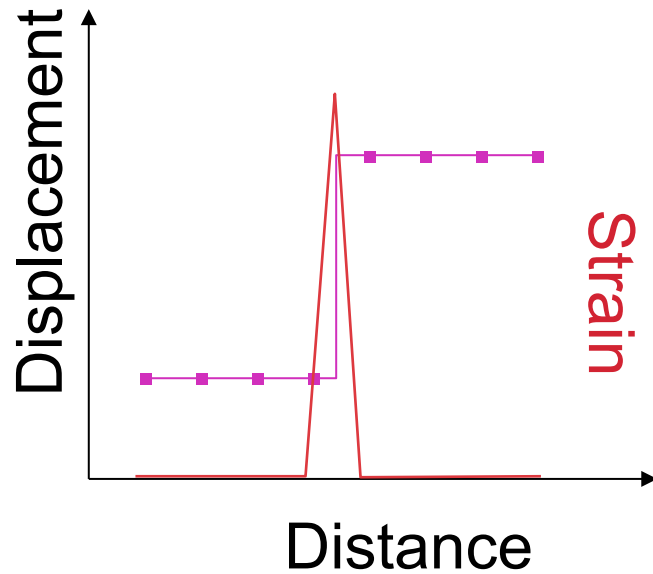
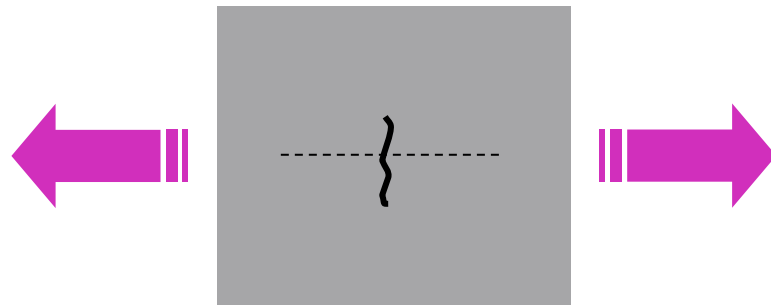


Equi-biaxial



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

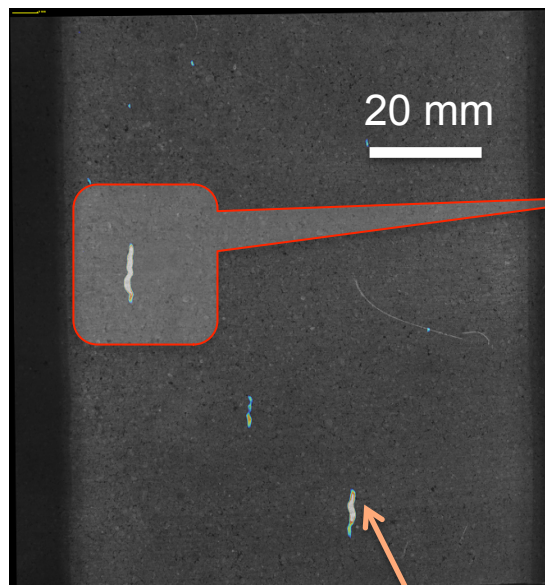
# Image Correlation of Cracks



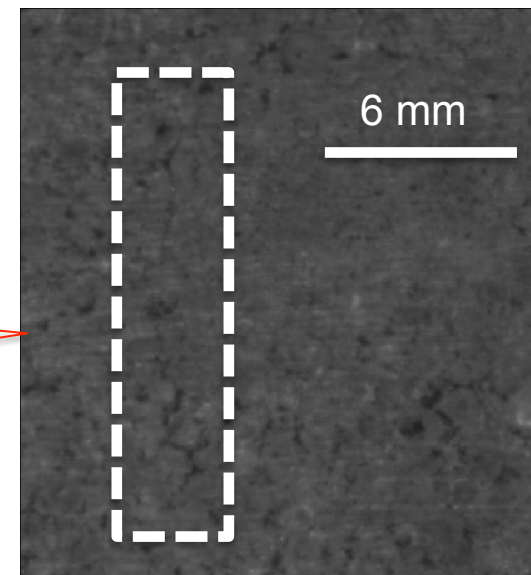
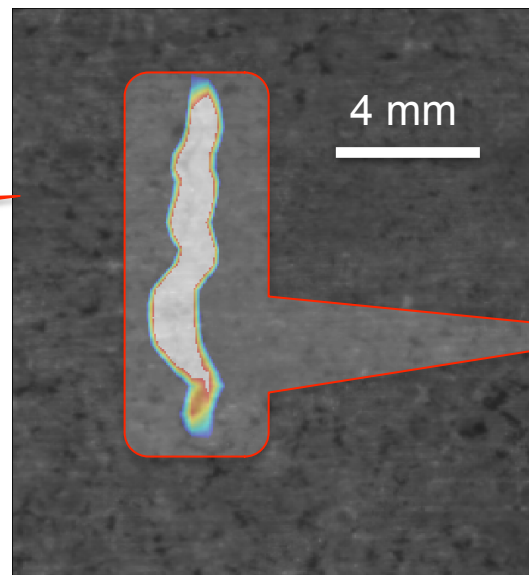
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Revealing Crack Nuclei

- Cracks *just* visible under load
- Digital Image Correlation reveals the crack



Failure Initiator



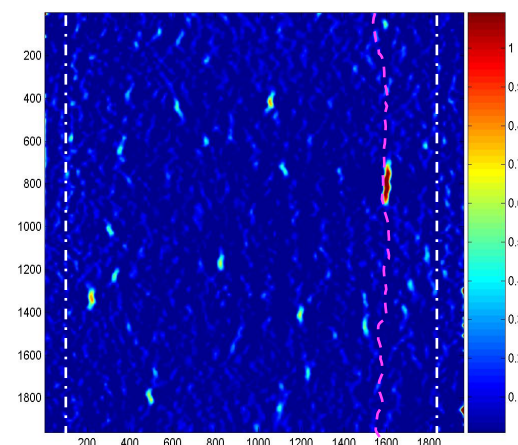
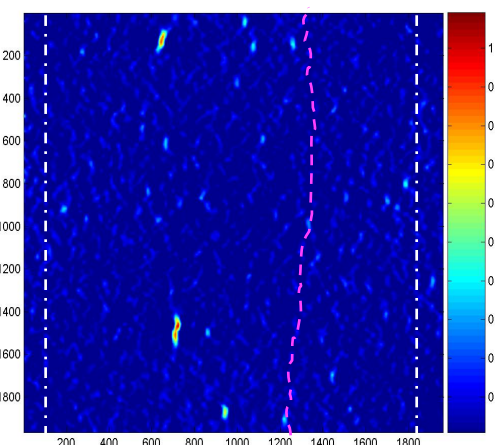
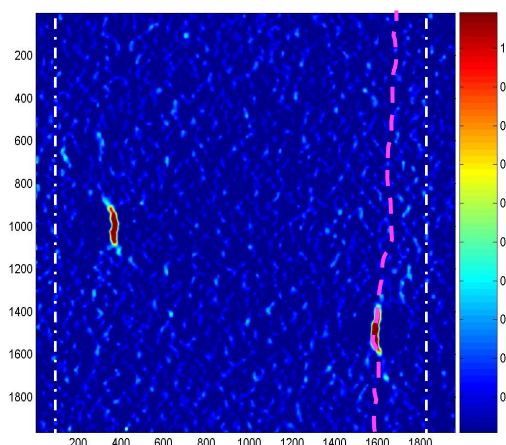
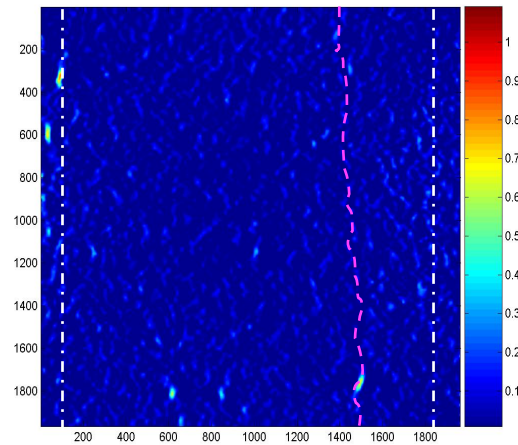
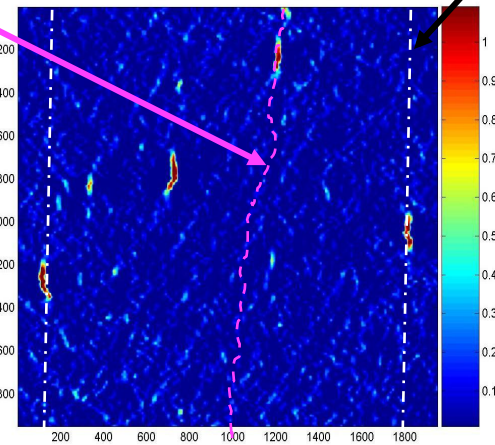
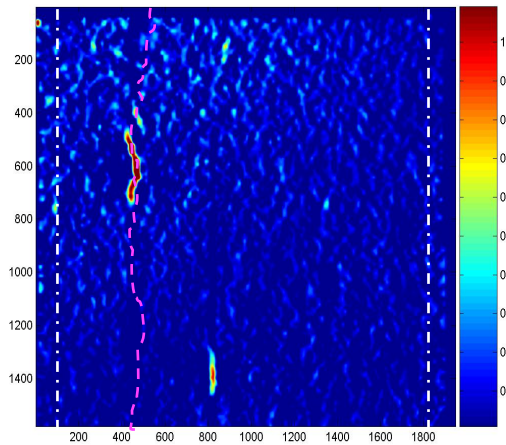
A 50mm lens was used to capture the whole surface of the sample, so enlarged images of small areas are blurred

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Damage Nucleation before Fracture

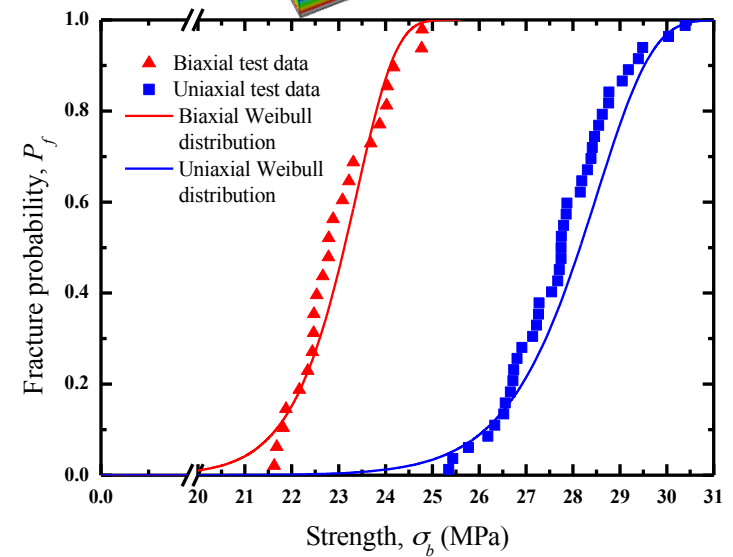
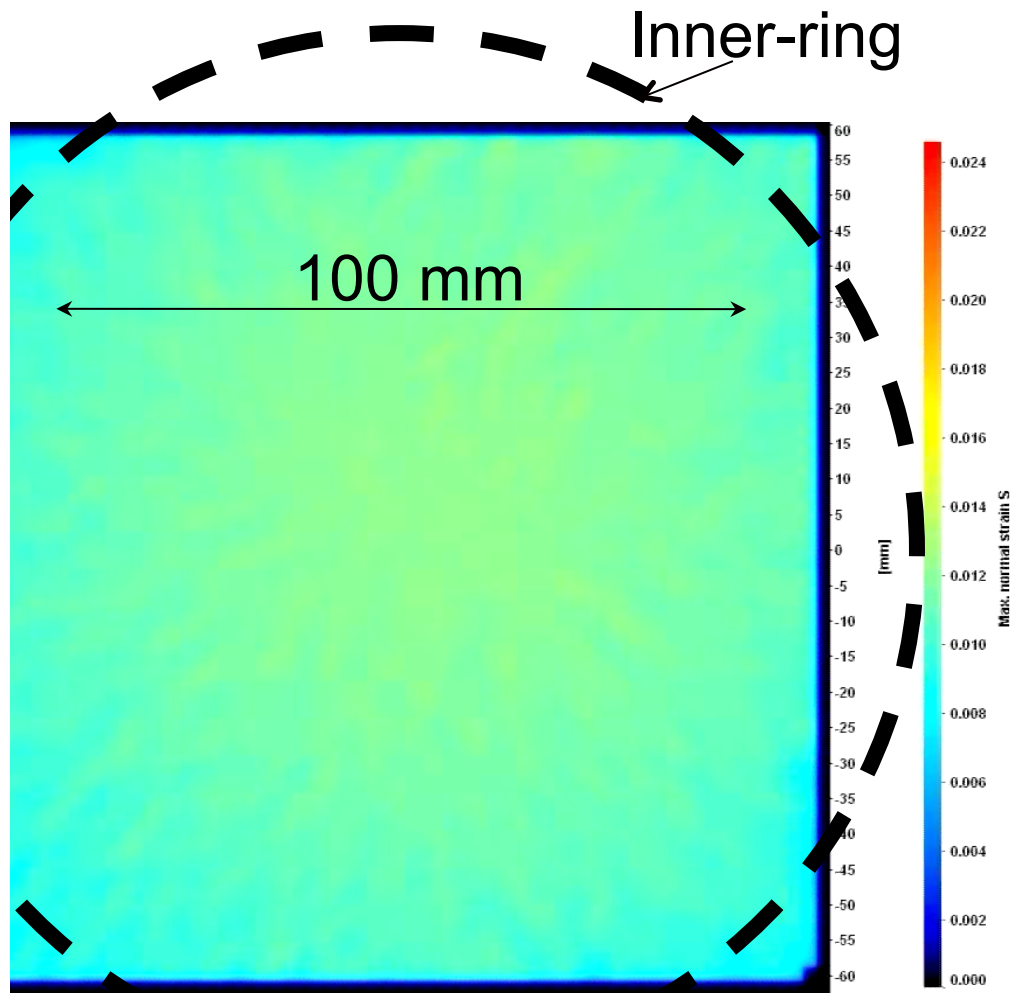
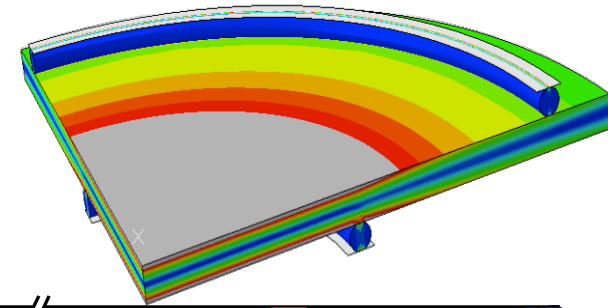
Failure path

Inner Roller



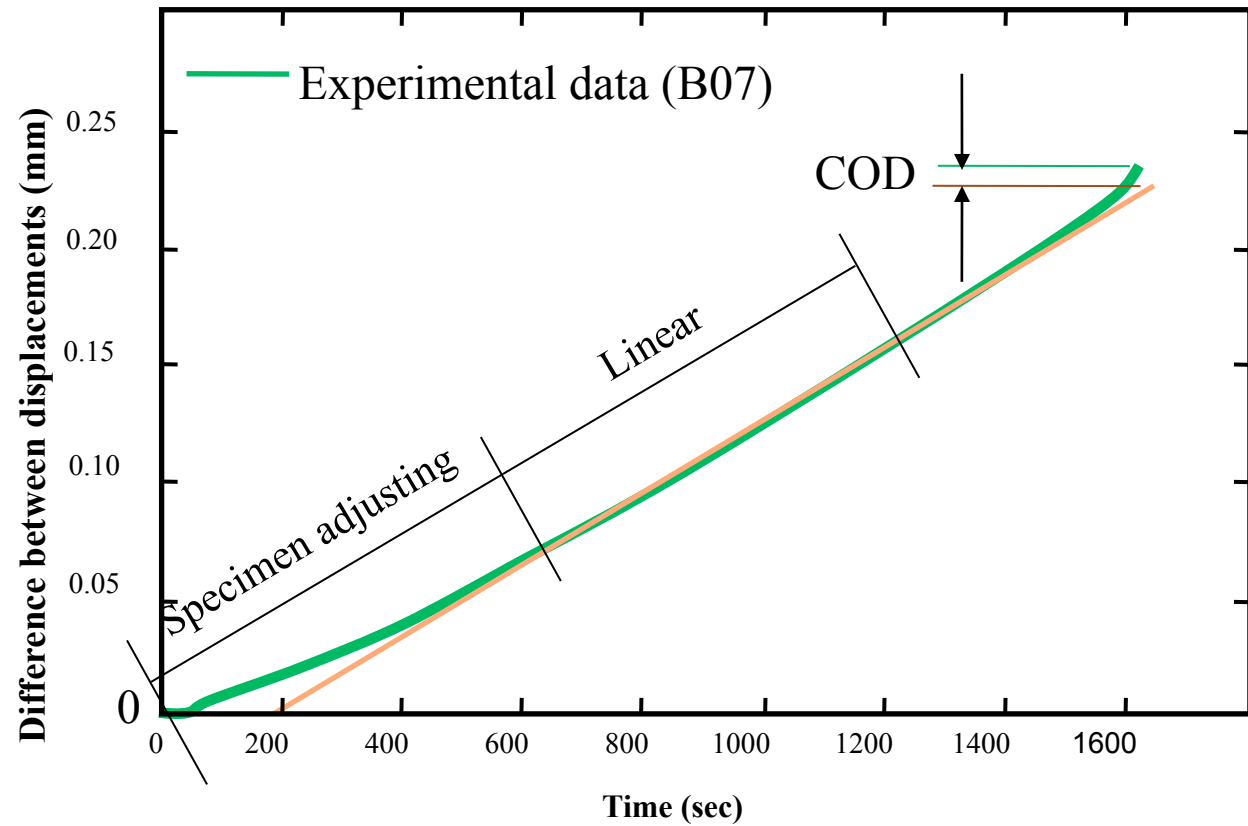
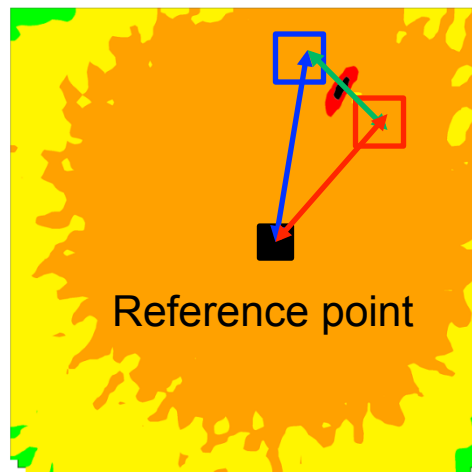
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Ring on Ring Biaxial Fracture



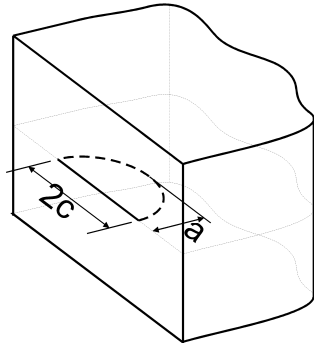
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Crack Opening Displacements



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

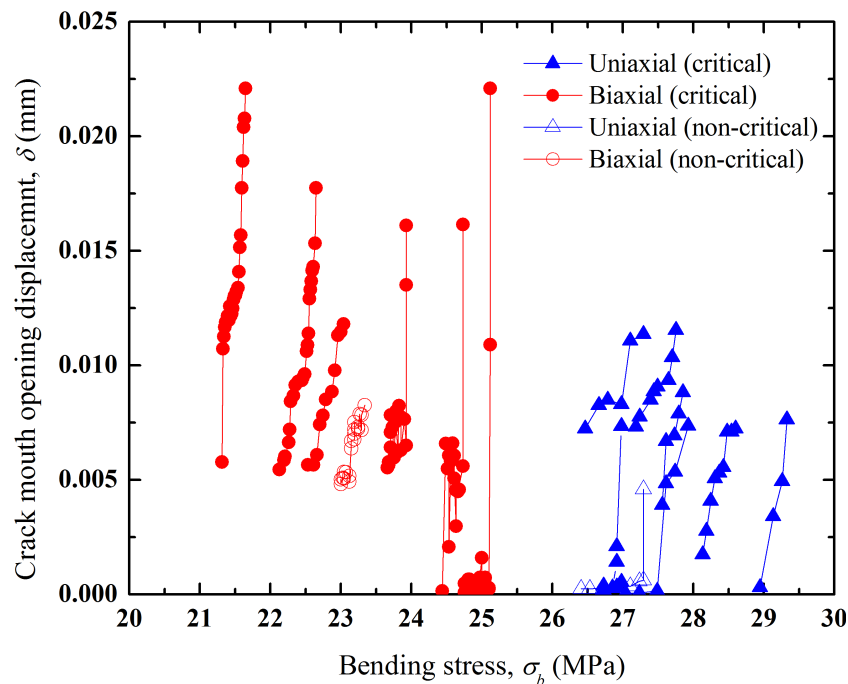
# Crack Opening and Size



$$r = \frac{\delta}{\sigma_b} = S \frac{4(1-\nu^2)}{E \int_0^{\pi/2} \sqrt{1-k^2 \cos \psi} d\psi} a \times$$

$$r \propto a$$

$$\left[ 1 + \frac{2a}{t} \frac{k^2 \int_0^{\pi/2} \sqrt{1-k^2 \cos \psi} d\psi}{(1+k^2) \int_0^{\pi/2} \sqrt{1-k^2 \cos \psi} d\psi - (1-k^2) \int_0^{\pi/2} \frac{1}{\sqrt{1-k^2 \cos \psi}} d\psi} \right]$$

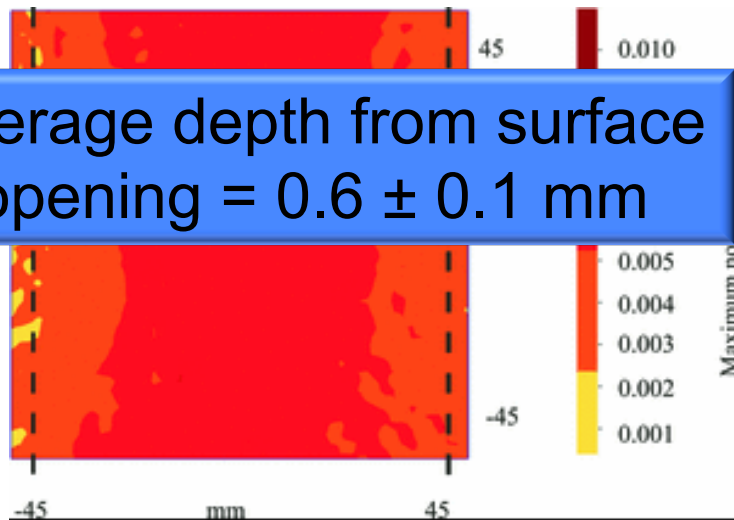


- Crack depth may be estimated from the elastic crack opening
- Defects open more under biaxial load than under uniaxial load

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

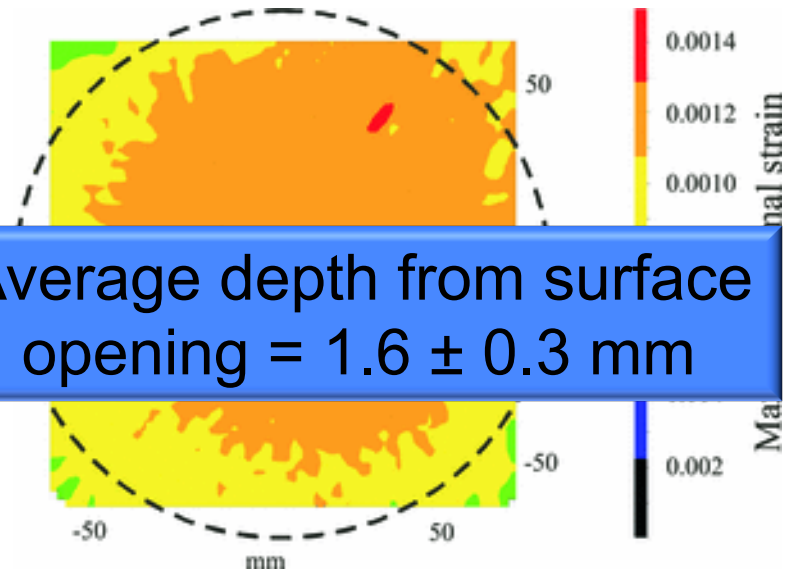
# Defect Size

Average depth from surface opening =  $0.6 \pm 0.1$  mm



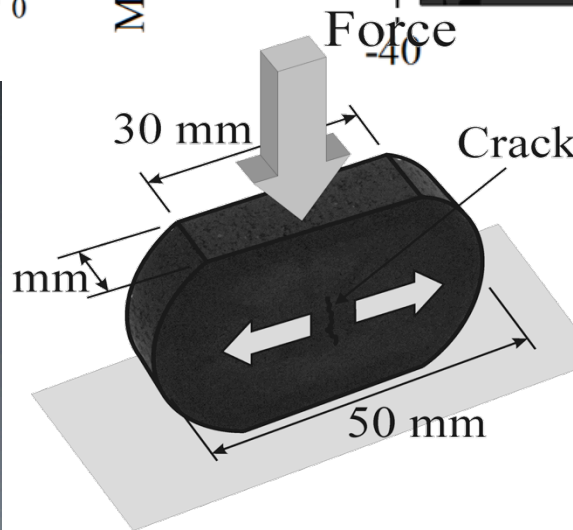
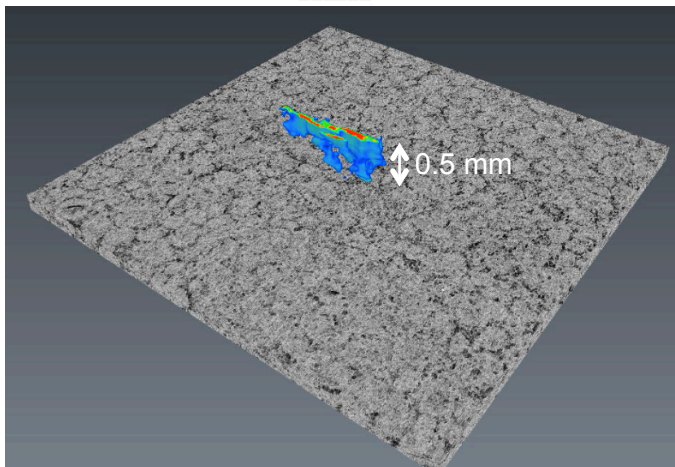
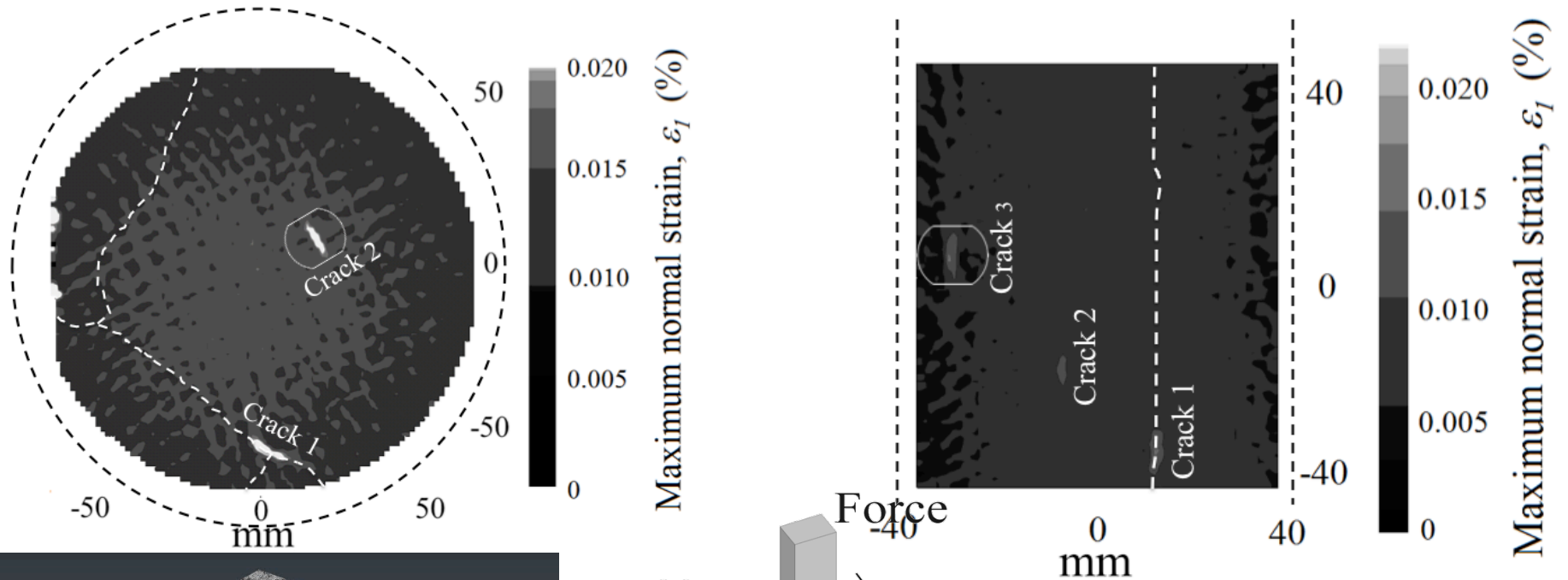
This can't be right, as it's the same microstructure...

Average depth from surface opening =  $1.6 \pm 0.3$  mm



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Defect Size

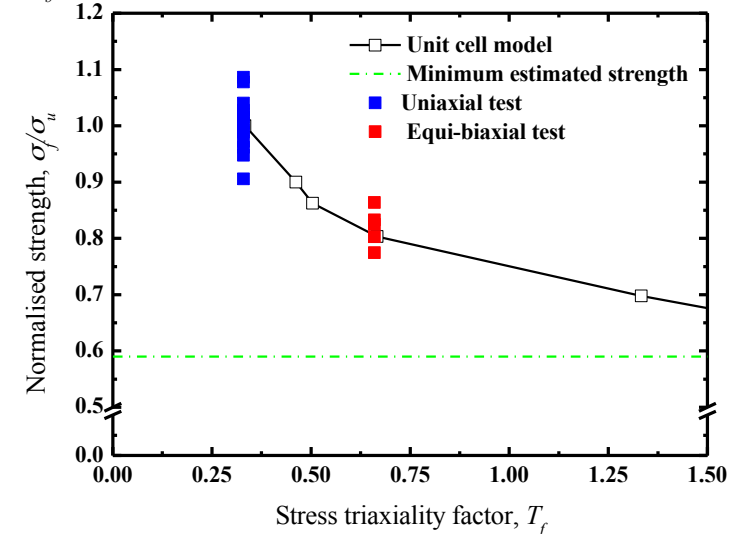
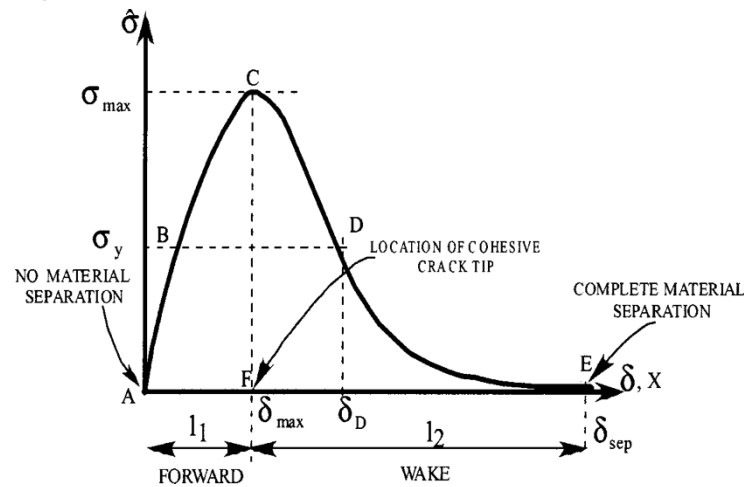
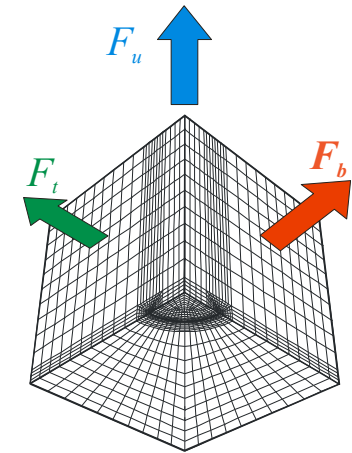
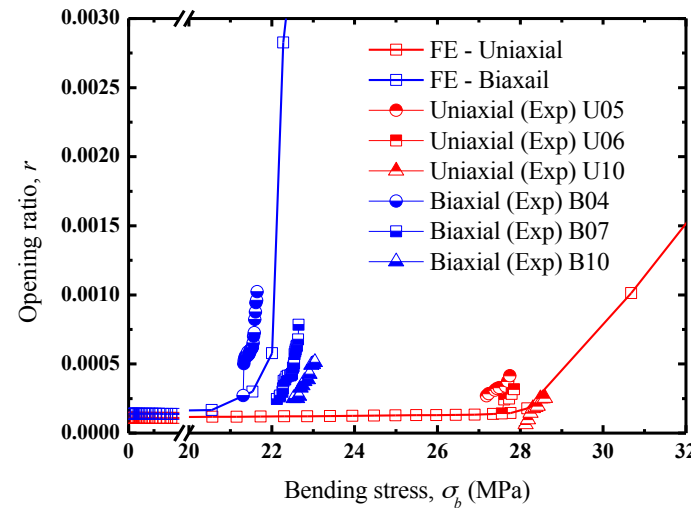



Defect depth  
~0.5 mm for both uniaxial  
and biaxial stress

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Modelling of Short Cracks

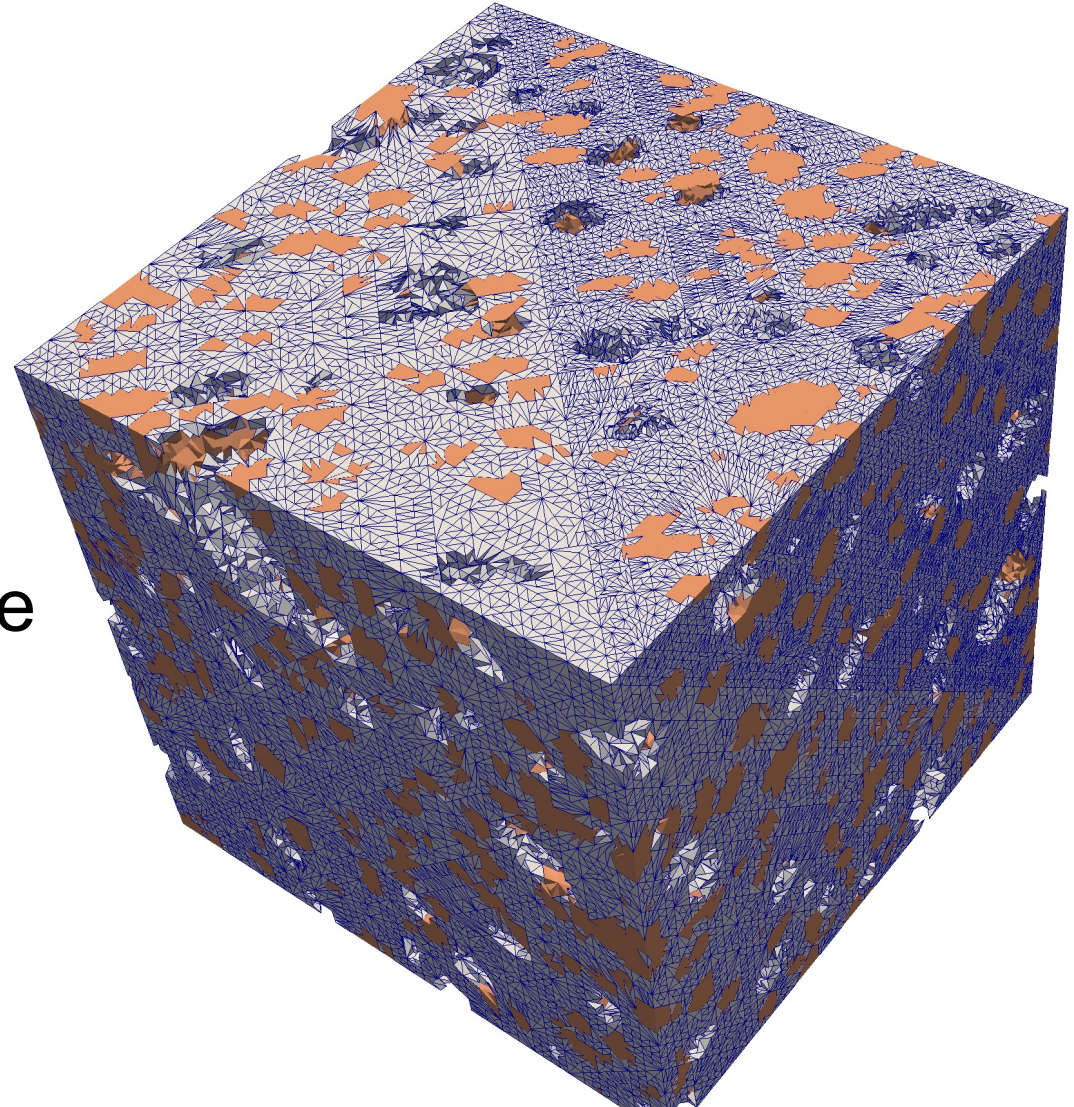
- Parameters calibrated using uniaxial test
- Effect of stress state on strength and opening ratio behaviour are in good agreement with experiment




 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Current Perspectives

- Cellular-Automata  
Finite Element  
modelling of damage  
propagation
- Multi-scale modelling  
of quasi-brittle fracture
- EPSRC project
  - “QUBE”
  - Oxford/Bristol/  
Manchester



 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# In-situ 3D Fracture Studies

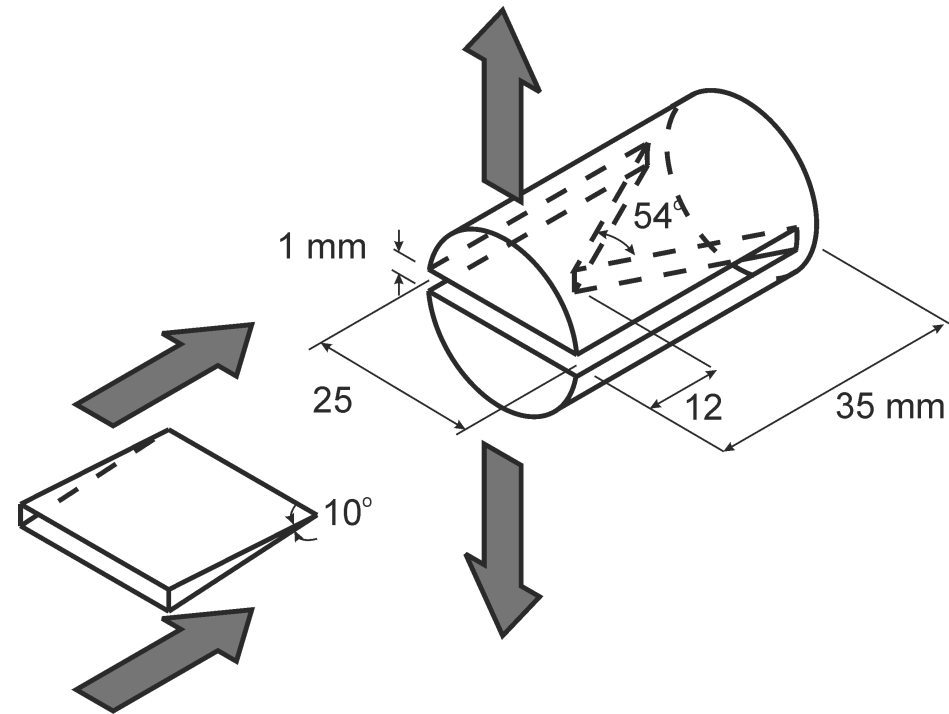


- Observation of the fracture process zone within a test specimen
- 3D measurement of parameters of a propagating stable crack

# Stable Crack Propagation

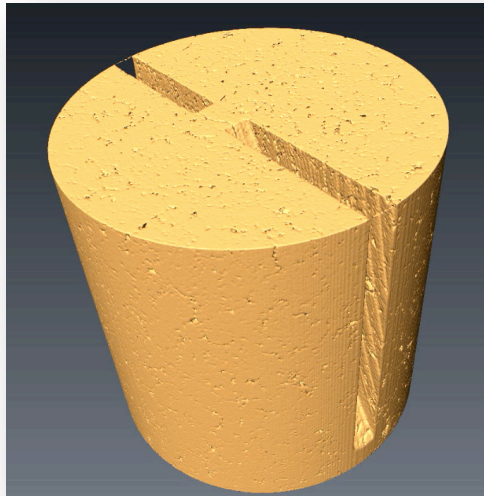
- Experiment objectives
  - Stable crack growth, observed in 3D
  - Specimen suitable for X-ray tomography
  - Measurement of crack opening and fracture process zone

- Short Chevron Notch Specimen



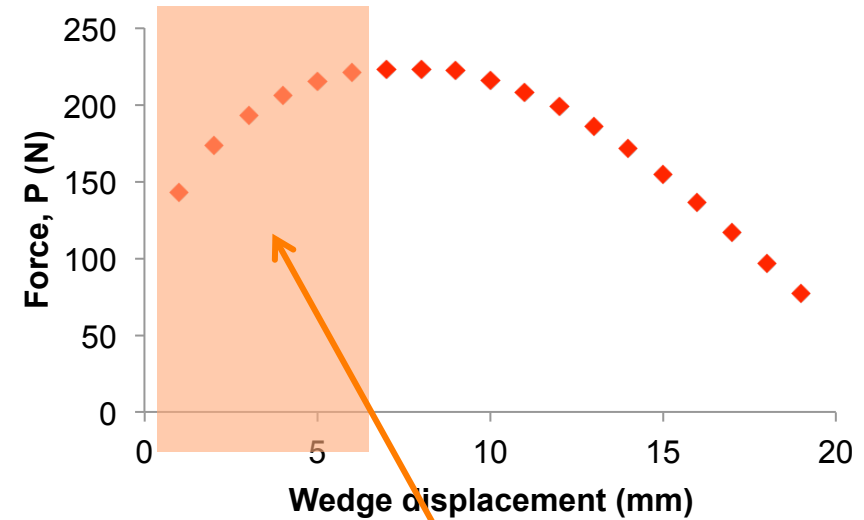
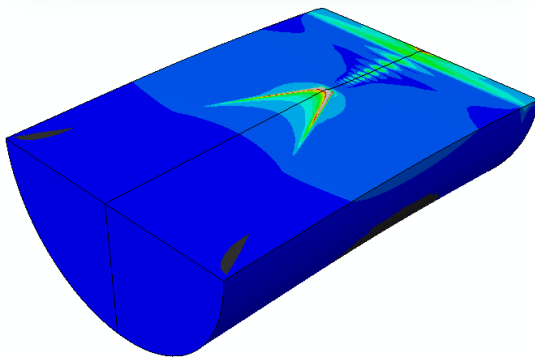
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Short Rod Chevron Specimen



S, Max. Principal  
(Avg: 75%)

+	1.733e+02
+	2.600e+01
+	2.527e+01
+	2.333e+01
+	2.100e+01
+	1.867e+01
+	1.633e+01
+	1.400e+01
+	1.167e+01
+	9.333e+00
+	7.000e+00
+	4.667e+00
+	2.333e+00
+	0.000e+00
-	3.076e+00

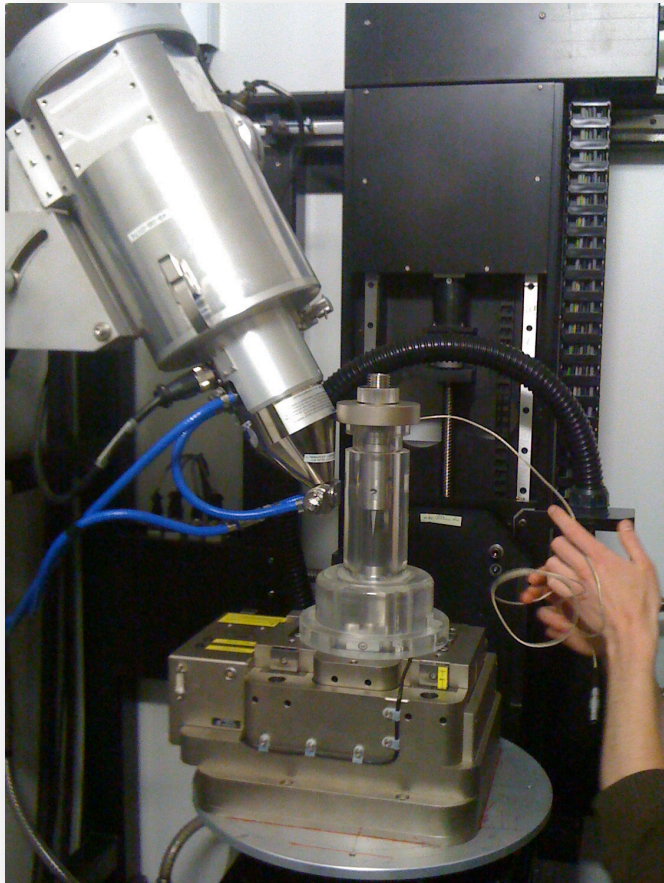


Stable crack growth region  
 $K=K_{1C}$

Finite element simulation of the fracture of chevron notch specimen

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

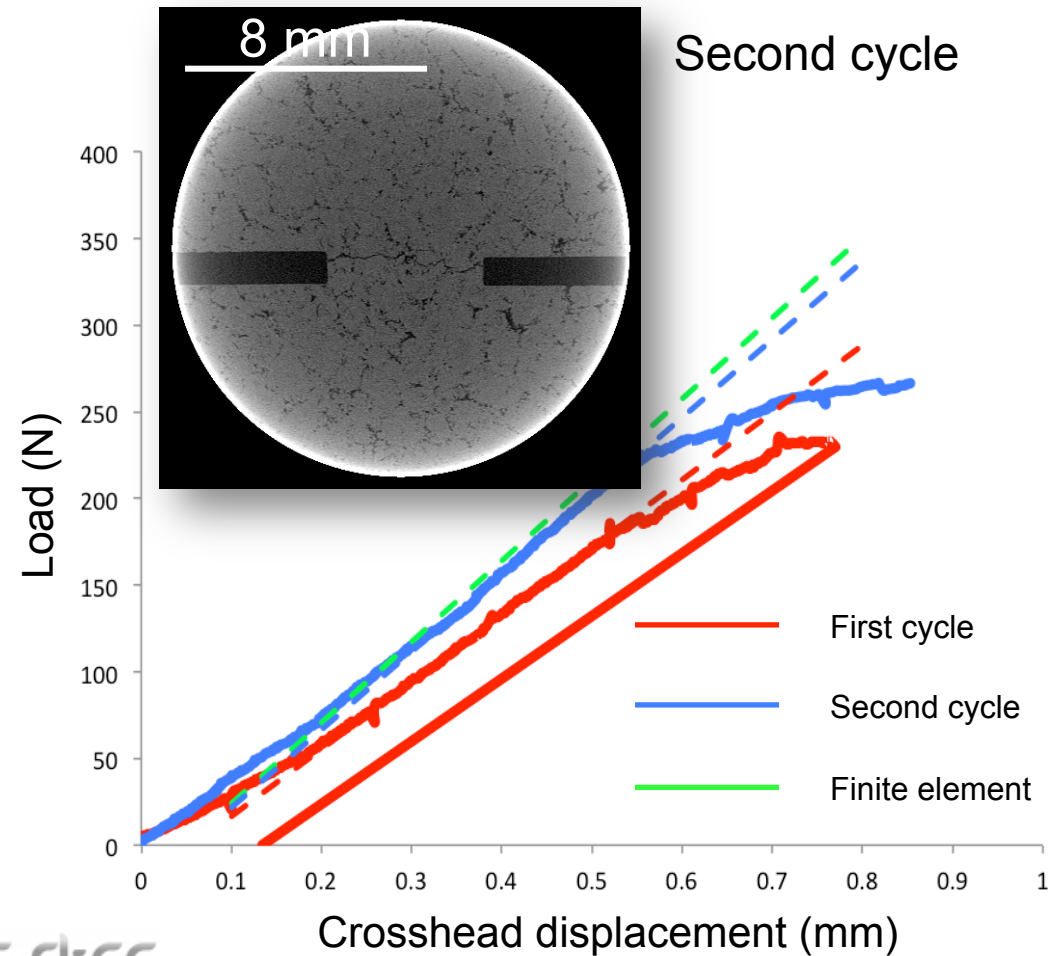
# In-Situ Fracture with X-CT



8  $\mu\text{m}$  resolution

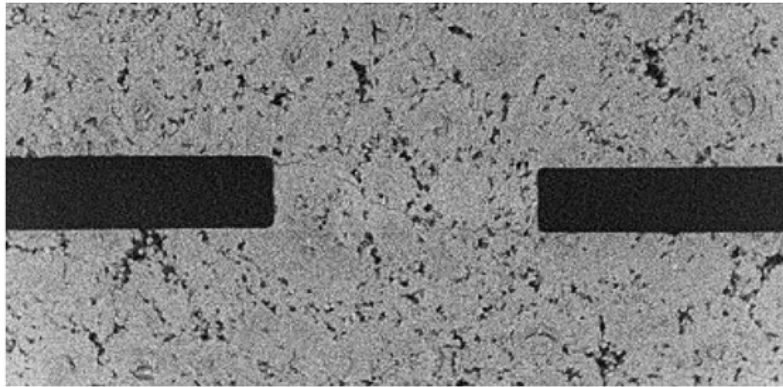
**MANCHESTER**  
1824

The University of Manchester

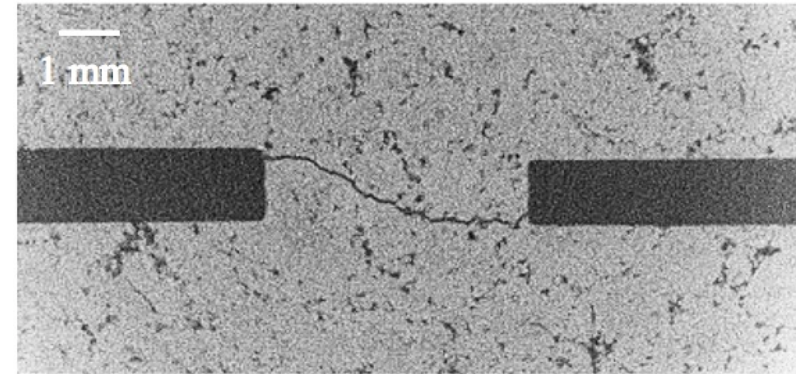


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

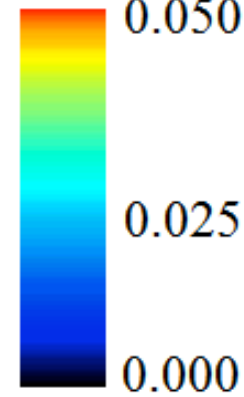
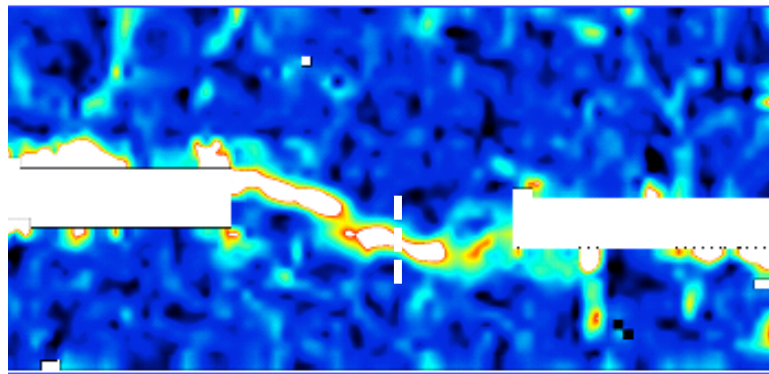
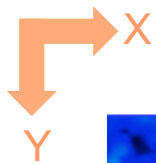
# Digital Volume Correlation



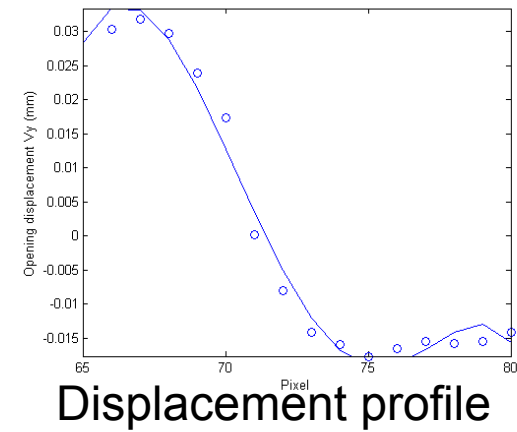
Unloaded




Loaded



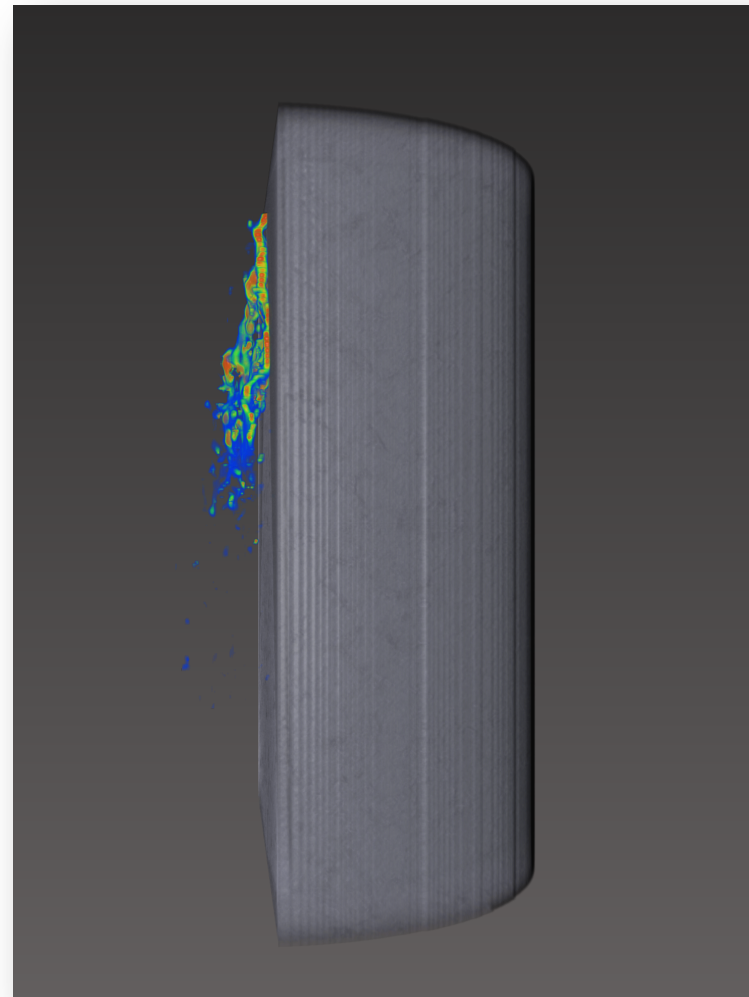
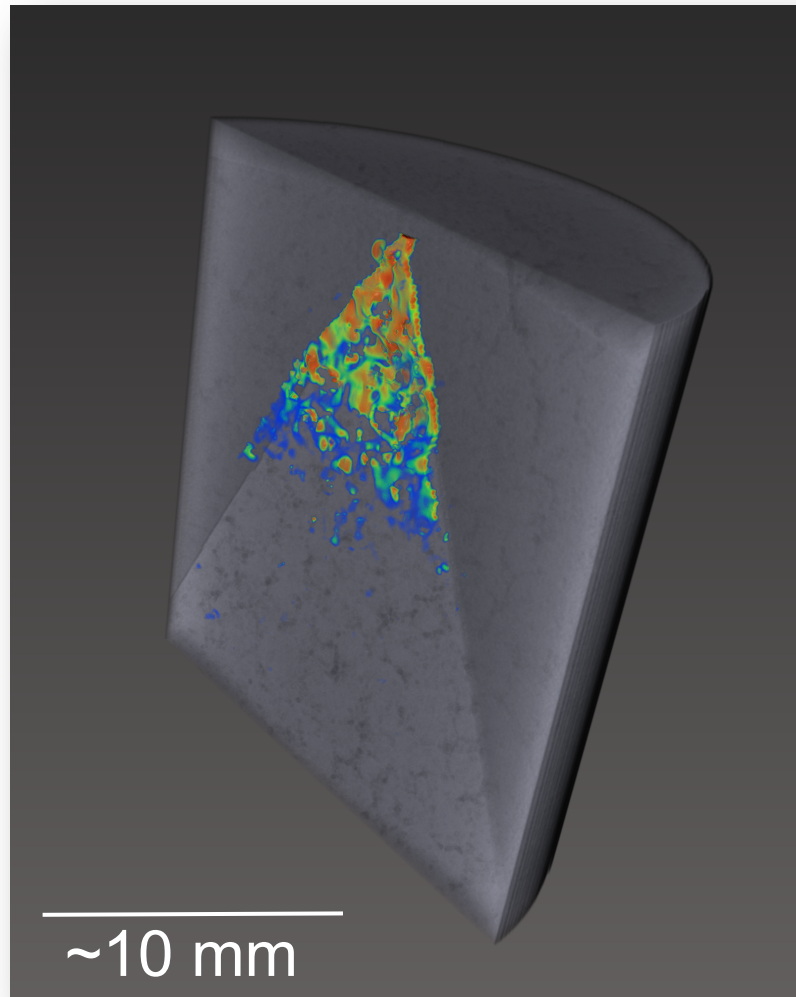
Maximum normal strain,  
 $\epsilon_1$  (%)



~3 mm below notch tip

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

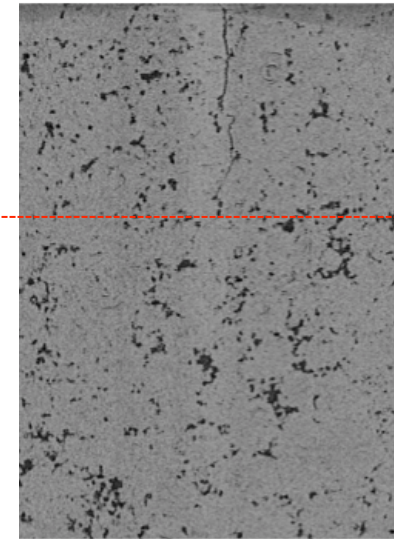
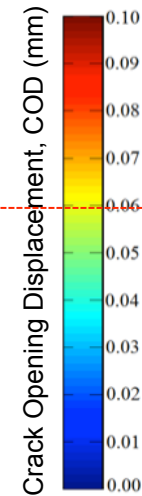
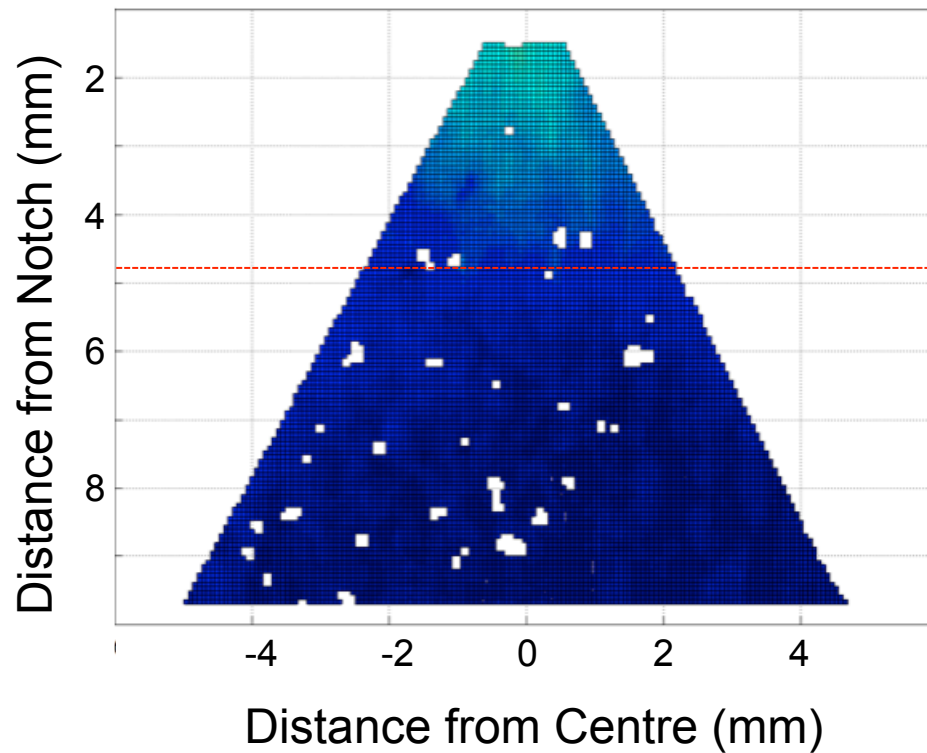
# Strain Visualisation



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Crack Opening Data

Load cycle 1



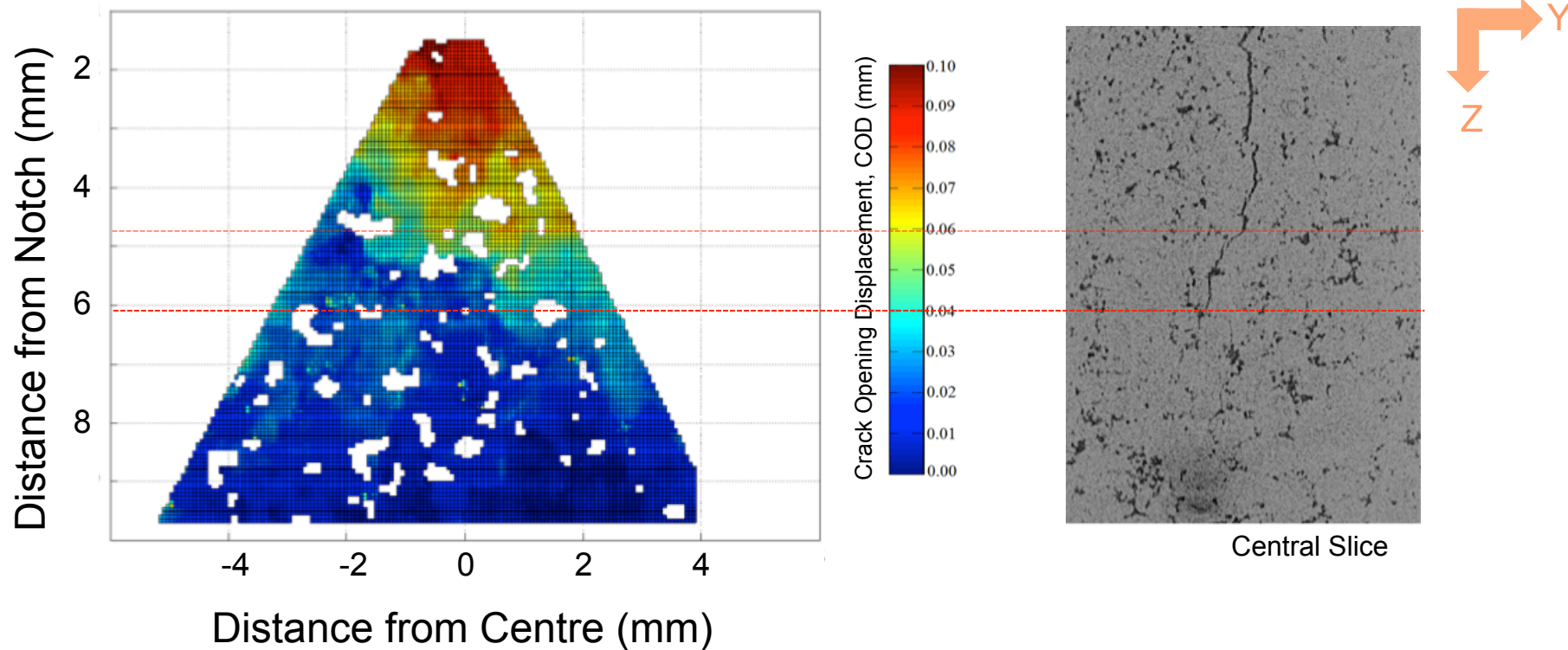
Central Slice

*White areas: DVC noise too high for automated measurement*


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Crack Opening Data

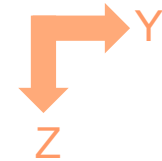
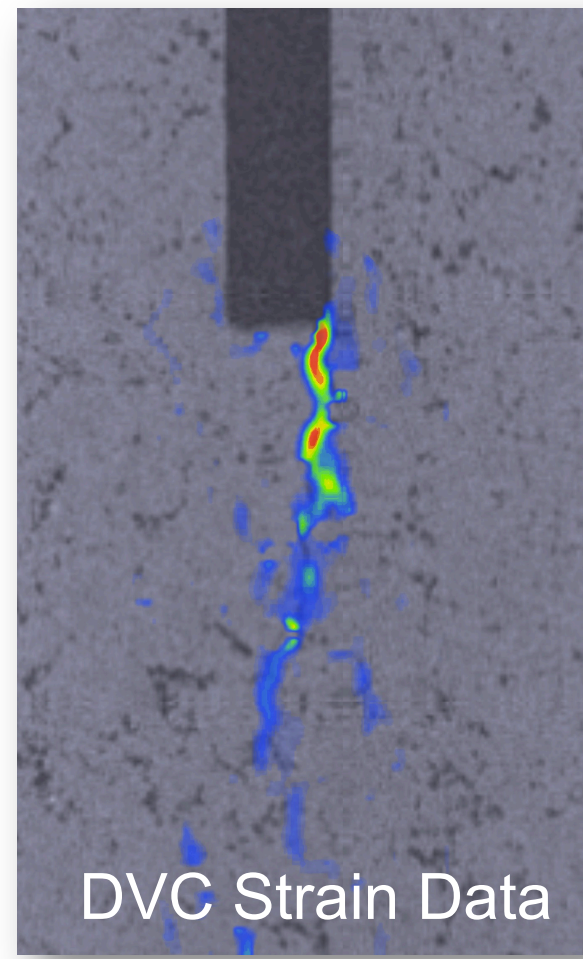
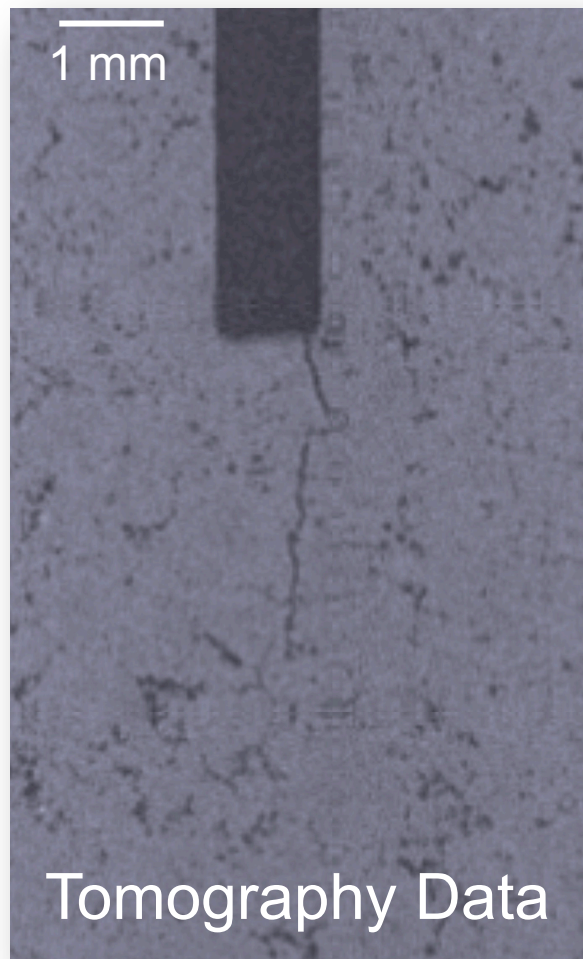
Load cycle 2



Crack opening in response to load can be mapped

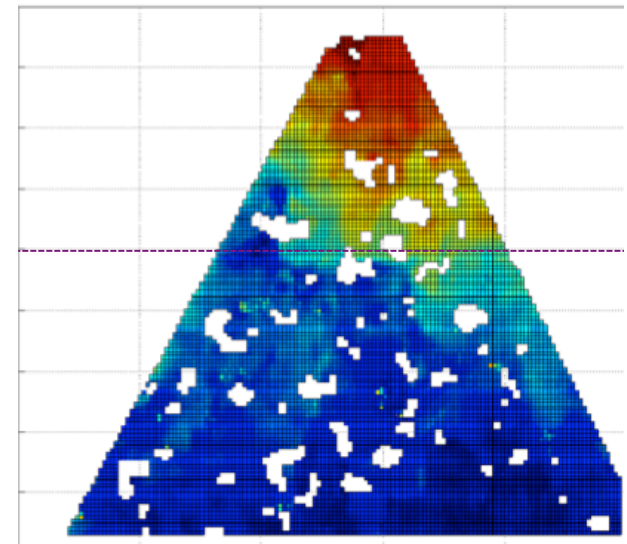
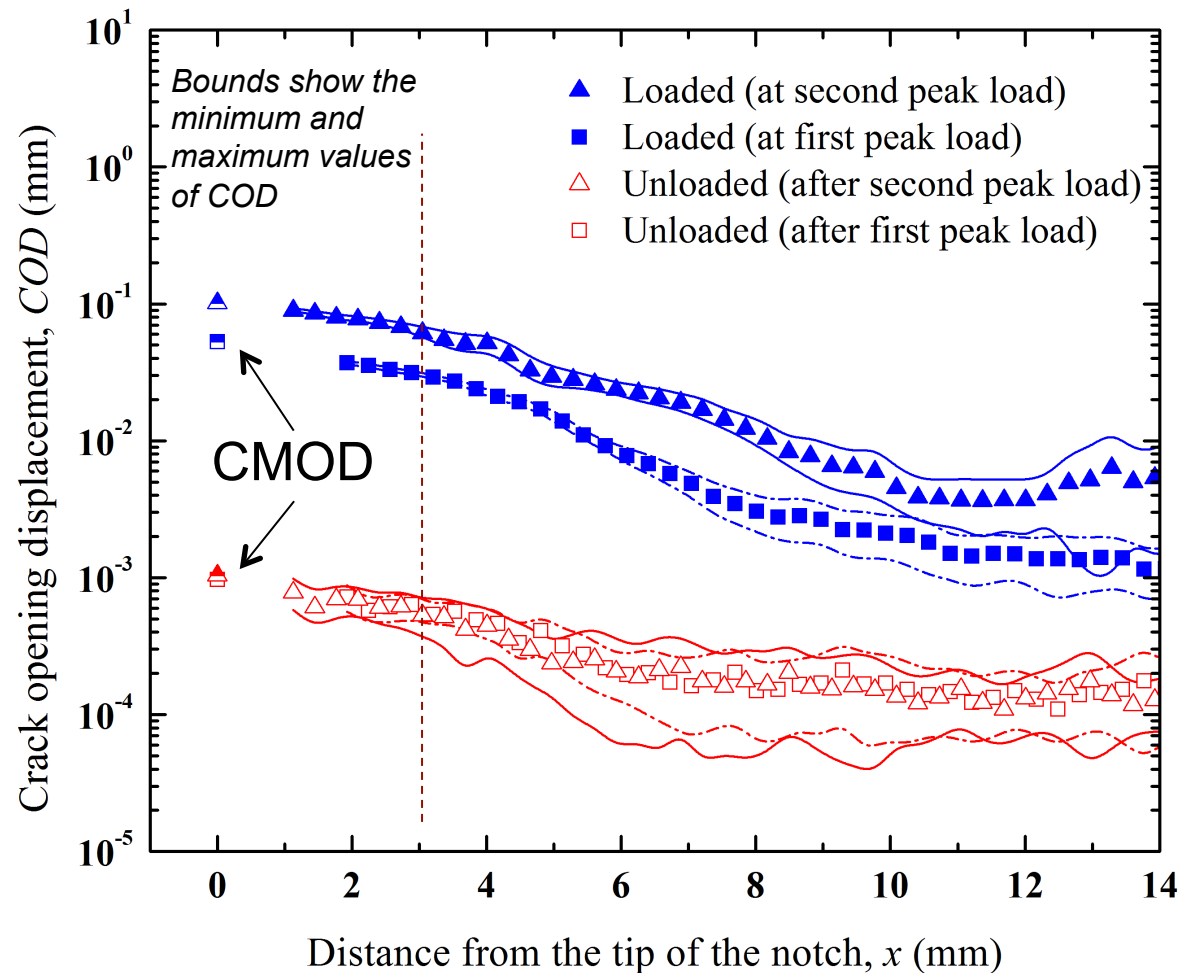
 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Strain Visualisation



The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Crack Opening Profiles

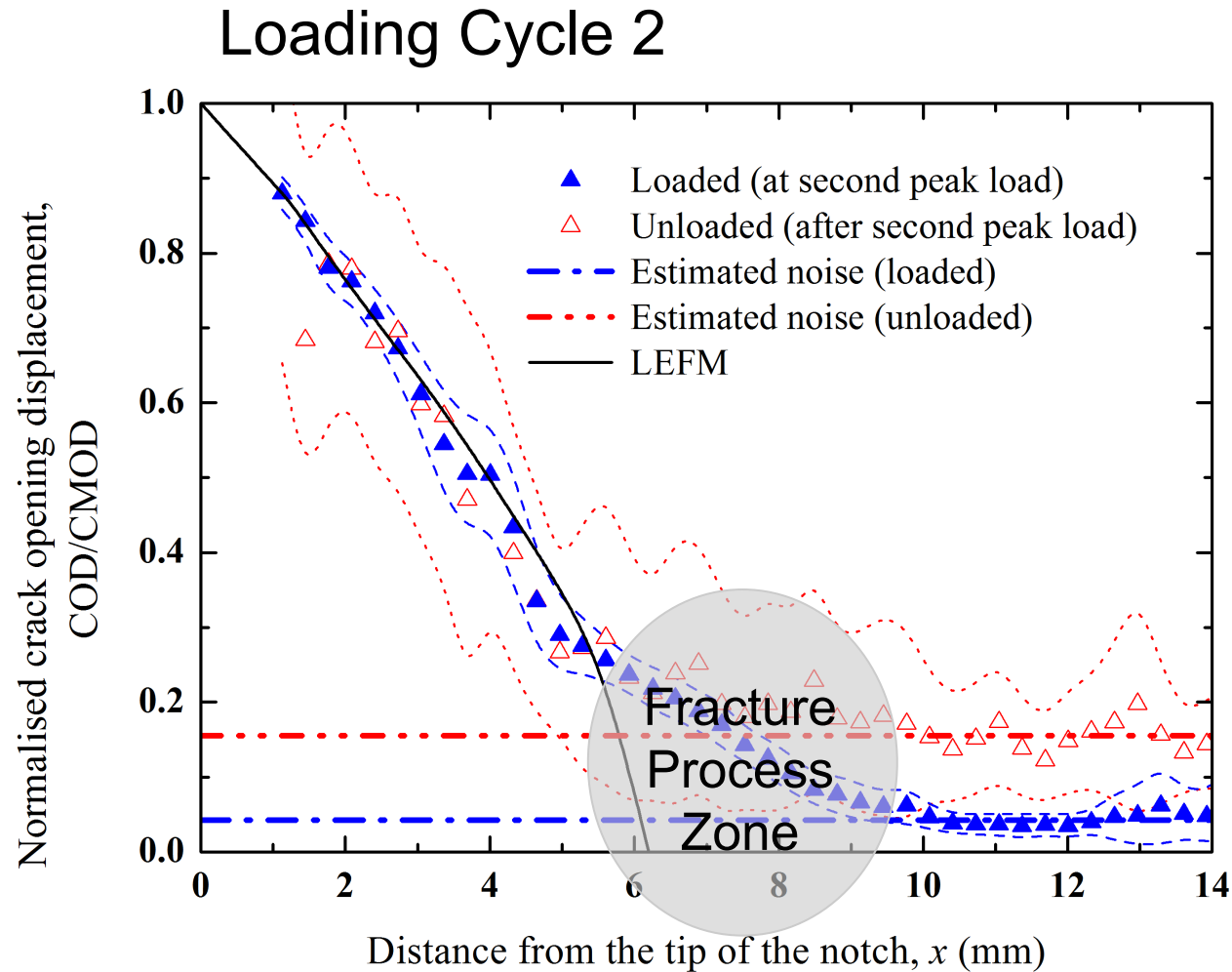


No residual displacements measurable when crack wake removed

CMOD – Crack Mouth Opening Displacement (extrapolated)


The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Crack Opening Profile




Elastic opening of loaded and unloaded crack is consistent with a nominal elastic crack tip

Significant displacements ahead of elastic crack tip when loaded

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.


# Research Summary

- Computed X-ray tomography and Digital Volume Correlation can be used to map displacements and observe cracks within a test specimen
- A fracture process zone is observed in long cracks, and is indicated for short cracks
  - Damaged (microcracked) zone with reduced elastic modulus
- Data will be used to tune cohesive zone/ microstructure sensitive model for graphite fracture
- Research program aims to design small-scale test specimens to monitor notch sensitivity of aging graphite components

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Conclusions

- Ageing (and life-extension) of nuclear plant is managed through knowledge
  - Reducing uncertainty in data and models improves confidence
  - This may support life extension
- Monitoring of material properties in ageing plant is essential
  - It must be planned for in new build of Gen III+, Gen IV and Fusion reactors

 The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Acknowledgements

- Mahmoud Mostafavi
  - EDF Energy
  - University of Manchester
    - X-ray Imaging Facility
  - Diamond Light Source
  - Oxford Martin School
- (The opinions expressed are mine!)*

