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Graphite Research

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- Why?
  - Core of AGRs; irradiation damage during operation leads to weight loss, change in dimensions & properties, stress and cracking
  - Life-limiting component of reactors
    - See recent (BBC, Times) and upcoming news items
- Current research activity
  - Funded by industry (EDF), regulator (ONR), EPSRC, TSB, EU
  - Plant life extension (PLEX) and future systems
    - Fundamentals of irradiation damage
    - Irradiation creep (mitigating stress development)
    - Strength and fracture
    - Waste treatment

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Irradiation damage

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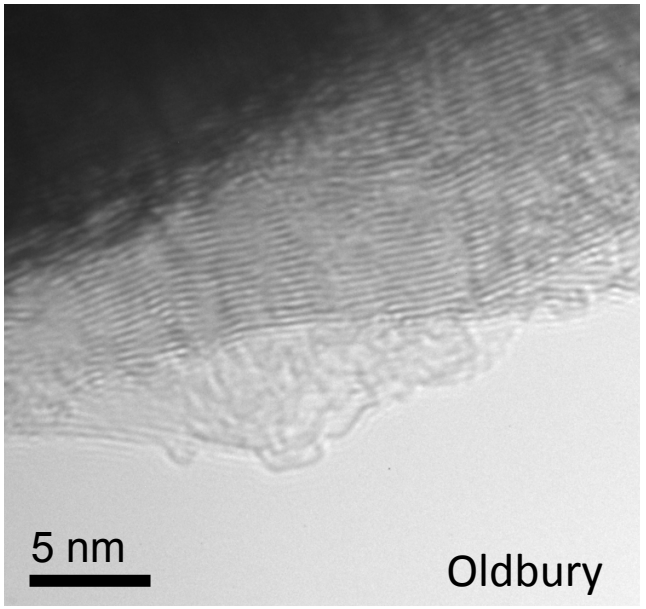
- FunGraph (EPSRC)
  - ***Fundamentals of Current and Future Uses of Nuclear Graphite***
  - Consortium of Huddersfield, Leeds, Manchester, Nottingham, Salford, **Surrey** universities

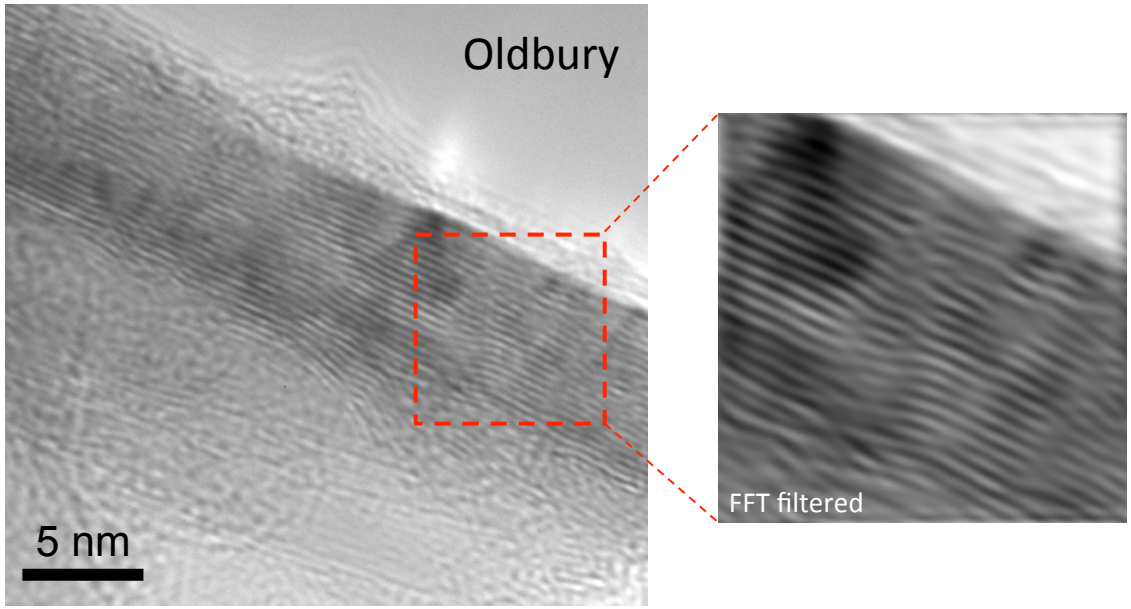
- Mechanistic understanding of irradiation effects
  - Ab initio; kinetic Monte Carlo; dislocation models of defects
  - Electron microscopy
    - Model (thick graphene) and irradiated material
    - Evolution of damage i*n situ*
  - Neutron and synchrotron x-ray studies
    - Structural changes; crack and void closure; effects of loading

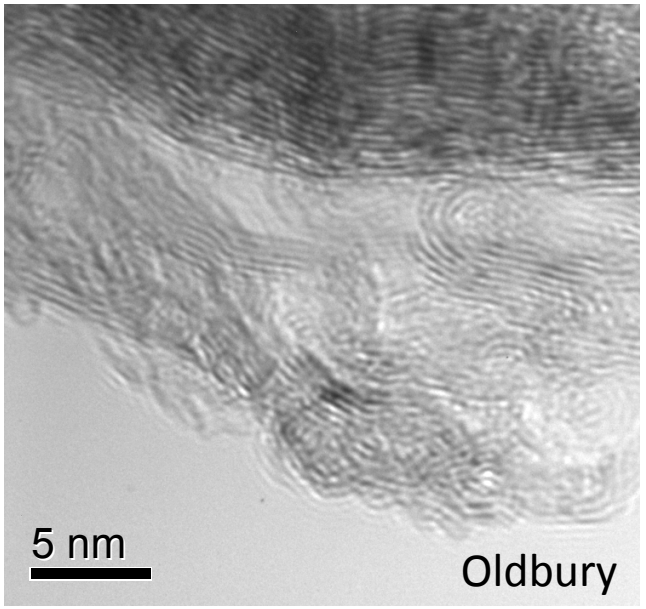
Range of model and irradiated materials

Neutron irradiated samples

- Manchester's samples
  - Oldbury (PGA 5dpa)
  - BEPO channel 16 (PGA)
- 80 kV

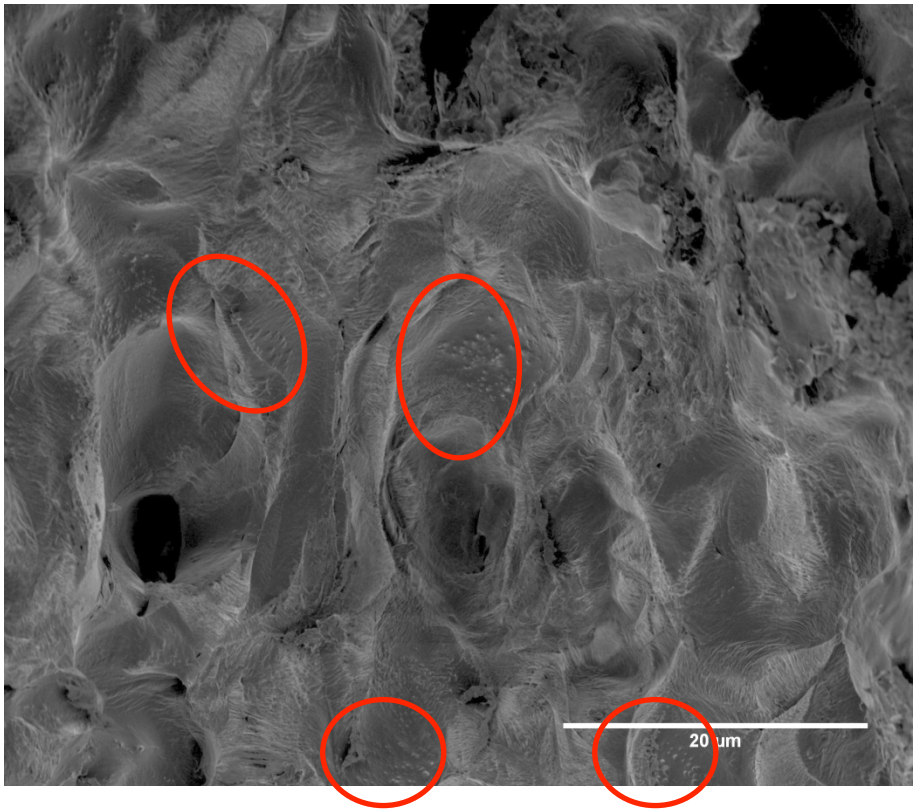




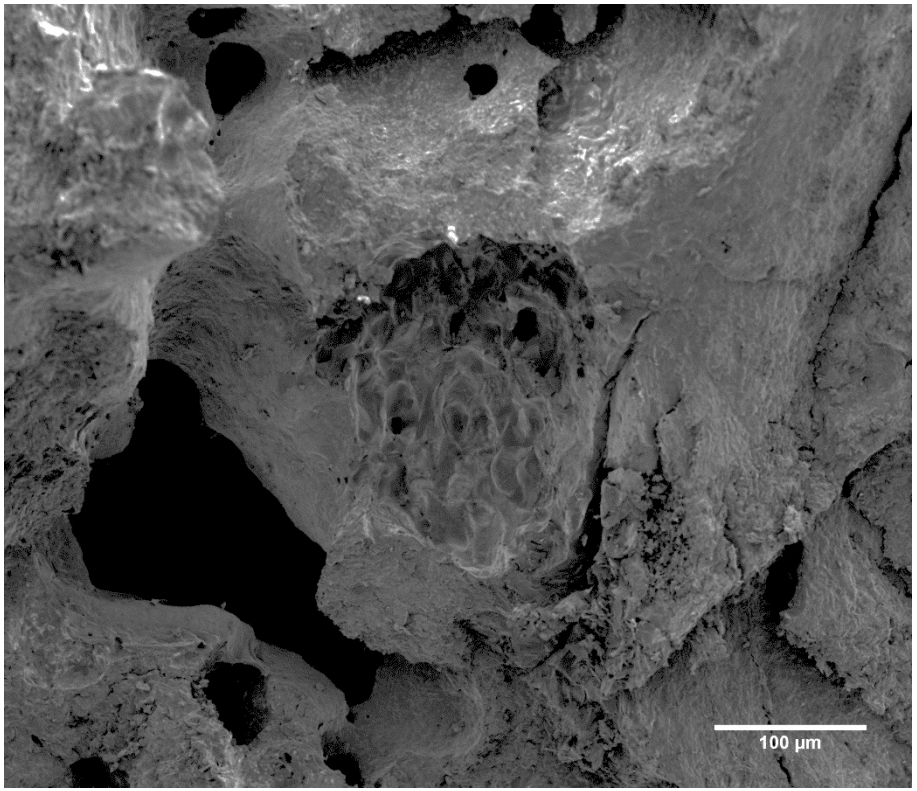


Microstructure: Irradiated graphite

Irradiated AGR Near surface
120E20 EDND



Irradiated AGR Near surface
120E20 EDND

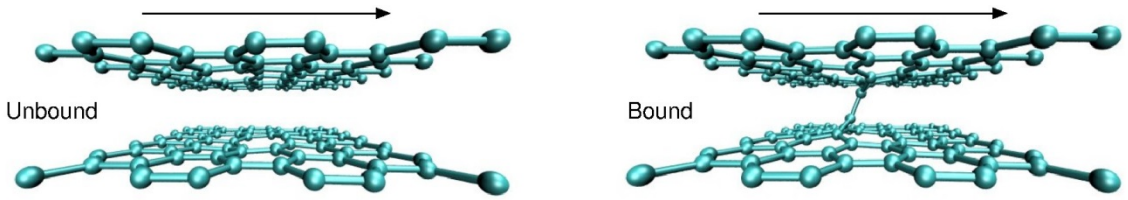


Imaged at Central Labs, NNL

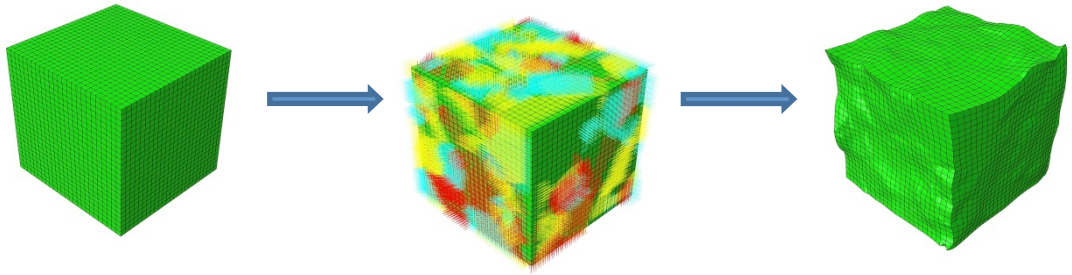
Irradiation Creep

- TSB-funded, EDF-lead
  - ***Influence of Irradiation Creep on Plant Life Optimisation***
  - Manchester and Surrey universities
  - NRG, Fraser-Nash, AMEC

- Mechanistic understanding of irradiation creep
  - Defect structures and mobility under load
    - Configuration; energies of formation
  - Microstructural changes
    - Role of interfaces/boundaries
  - Stress relaxation



Unbound and bound configurations of the $V^{2,2}_{bb}$ interlayer di-vacancy.

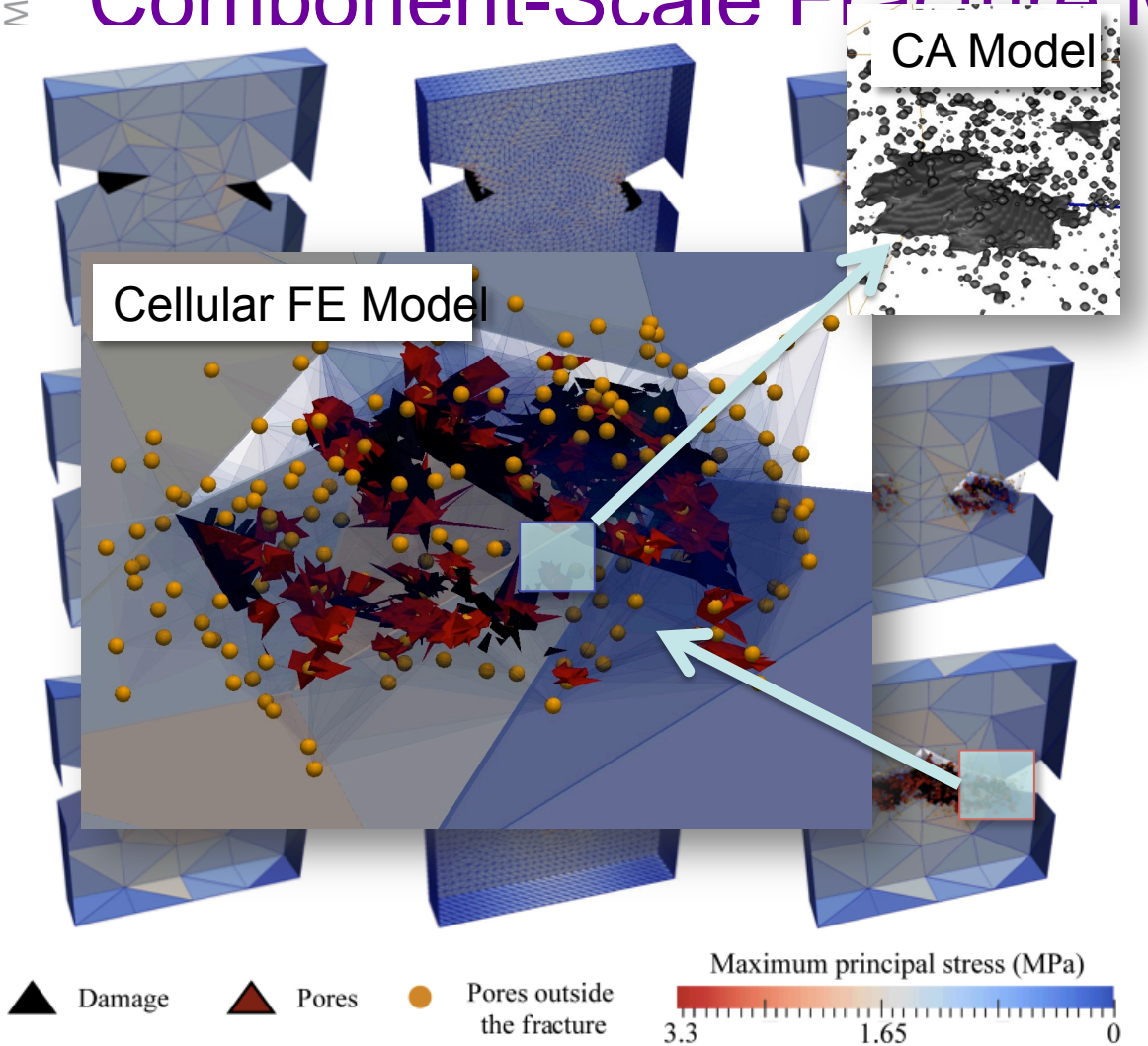


Microstructure-based FE models for irradiation creep

Strength and Fracture

- QUBE (EPSRC)
  - Oxford, Bristol and Manchester universities

Microstructure-Sensitive Component-Scale Fracture Modelling



Cellular FE model: Meshfree linking of microstructure-dependent heterogeneous model and coarse FE component model

The CA model may be used as microstructure dependent input, providing properties of coarser "cells" in the Cellular FE model

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AGR BCN

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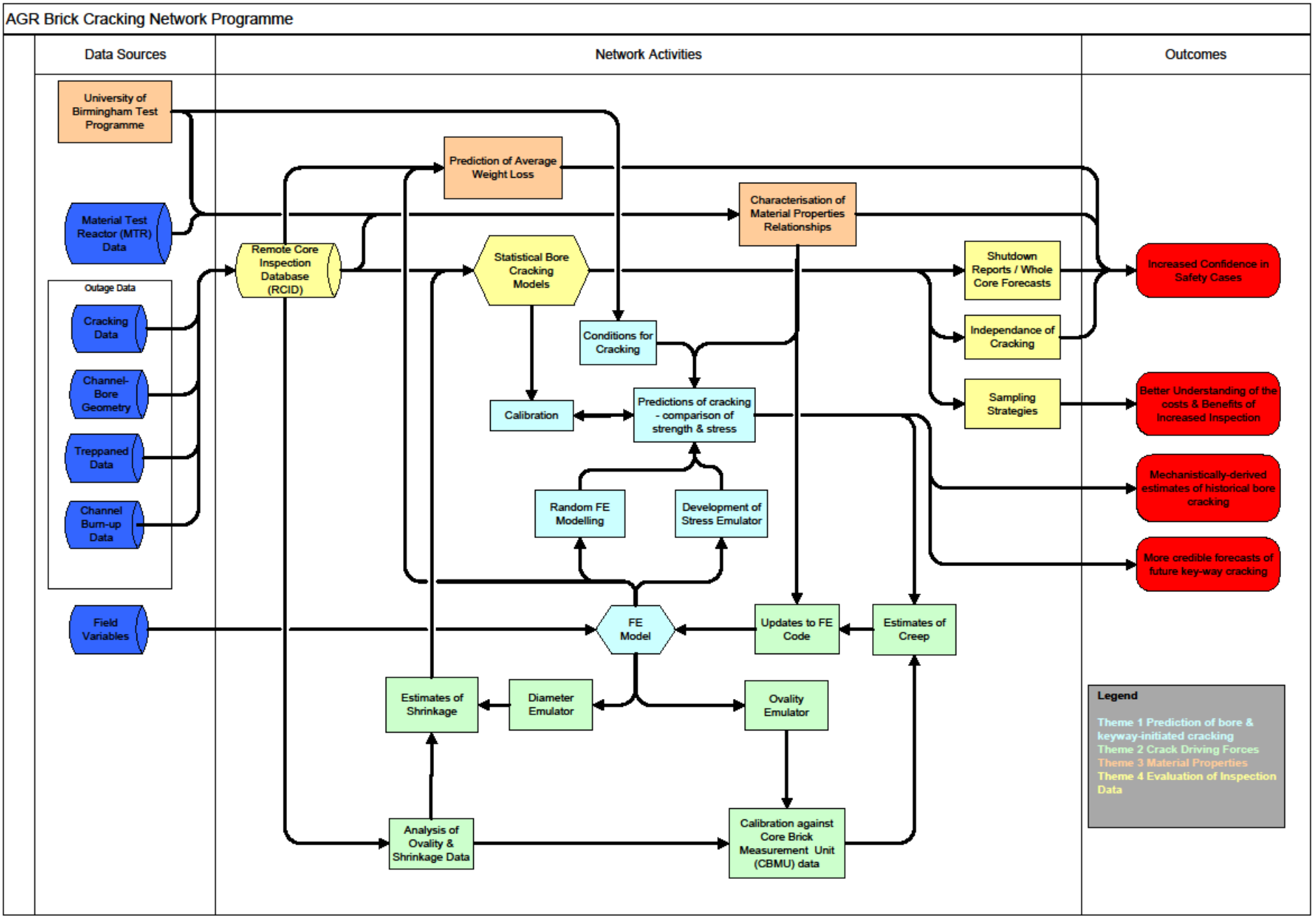
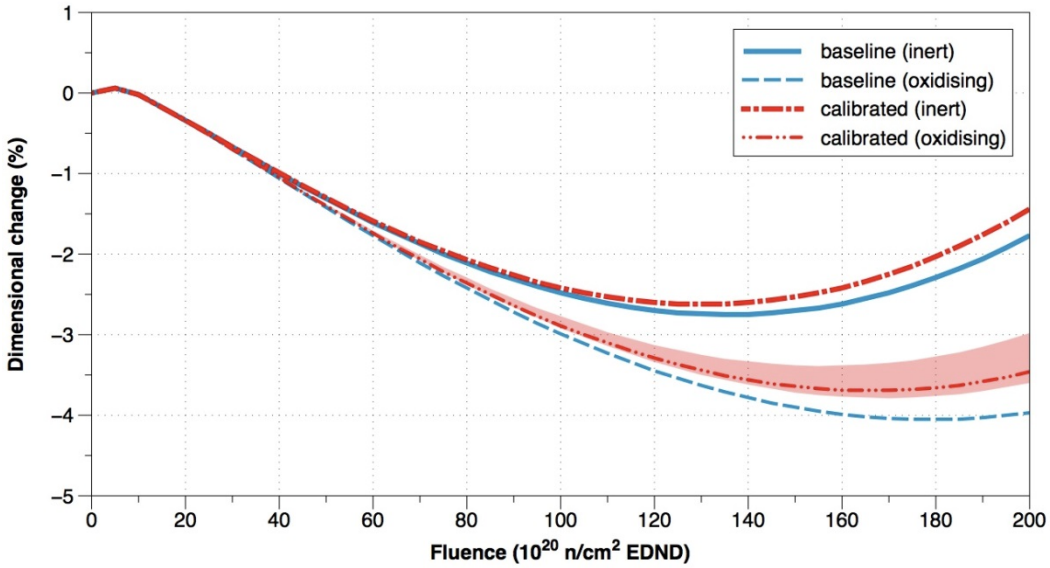
- HSE(NII) established the AGR Brick Cracking Network (AGR BCN) in 2008 to:
  - develop an improved understanding of cracking observed in AGR graphite bricks and develop a predictive capability
  - secure, maintain and develop sources of independent advice
  - ensure NII is well informed on key technical issues and therefore able to make sound regulatory decisions
- AGR BCN is a tripartite programme
  - The University of Birmingham, The University of Manchester, Health & Safety Laboratory
- Two aspects under investigation
  - crack driving force parameters (HSL & UoM)
  - materials resistance parameters (UoB & HSL)


AGR Brick Cracking Network Programme
Data Sources
Network Activities
Outcomes
University of Birmingham Test Programme
Material Test Reactor (MTR) Data
Outage Data
Cracking Data
Channel-Bore Geometry
Treppaned Data
Channel Burn-up Data
Field Variables
Remote Core Inspection Database (RCID)
Prediction of Average Weight Loss
Characterisation of Material Properties Relationships
Statistical Bore Cracking Models
Conditions for Cracking
Calibration
Predictions of cracking - comparison of strength & stress
Random FE Modelling
Development of Stress Emulator
FE Model
Updates to FE Code
Estimates of Creep
Estimates of Shrinkage
Diameter Emulator
Ovality Emulator
Analysis of Ovality & Shrinkage Data
Calibration against Core Brick Measurement Unit (CBMU) data
Shutdown Reports / Whole Core Forecasts
Independance of Cracking
Sampling Strategies
Increased Confidence in Safety Cases
Better Understanding of the costs & Benefits of Increased Inspection
Mechanistically-derived estimates of historical bore cracking
More credible forecasts of future key-way cracking
Legend
Theme 1 Prediction of bore & keyway-initiated cracking
Theme 2 Crack Driving Forces
Theme 3 Material Properties
Theme 4 Evaluation of Inspection Data

Introduction

- Emulator approach
  - applied successfully for dimensional change behaviour
    - inspection data
    - constitutive equations
  - calibrated dimensional changes
    - inert similar to baseline
    - reduced effect of oxidation



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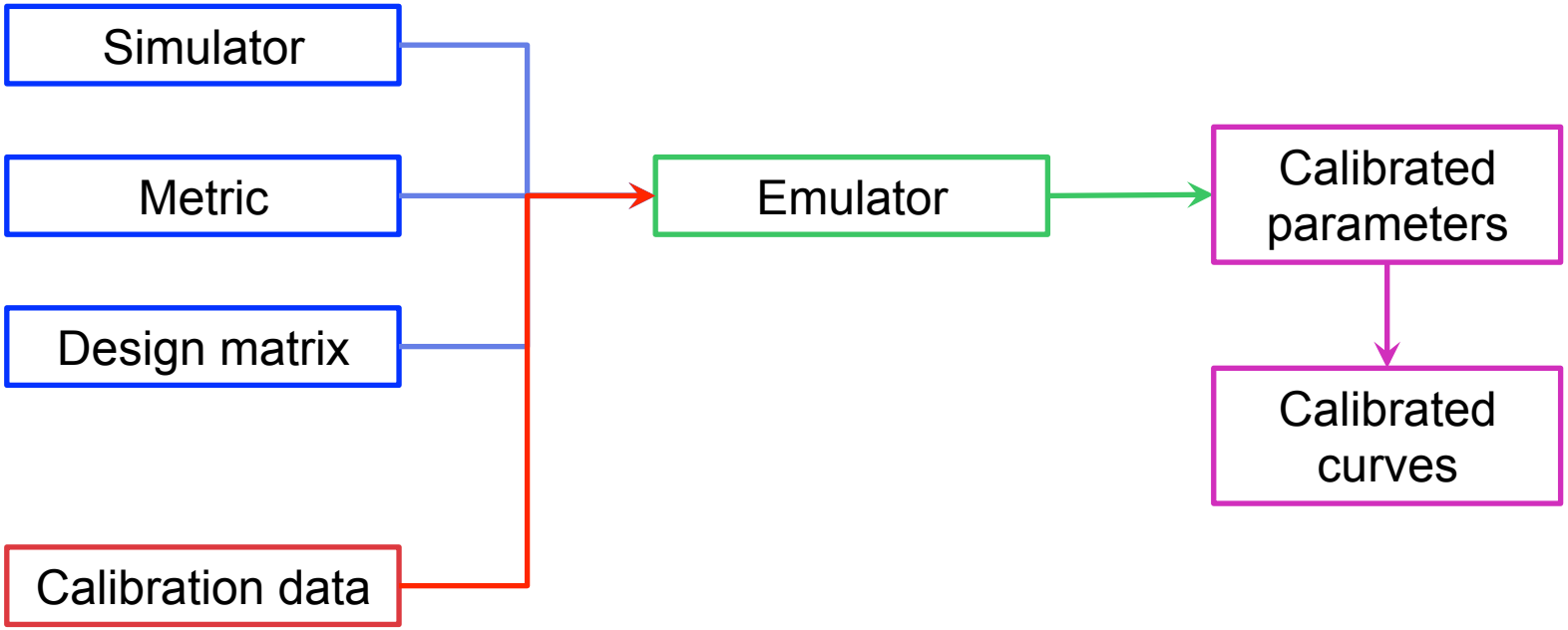
Modelling approach



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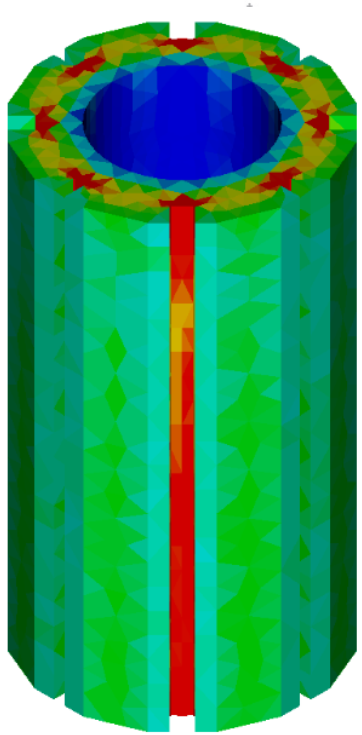
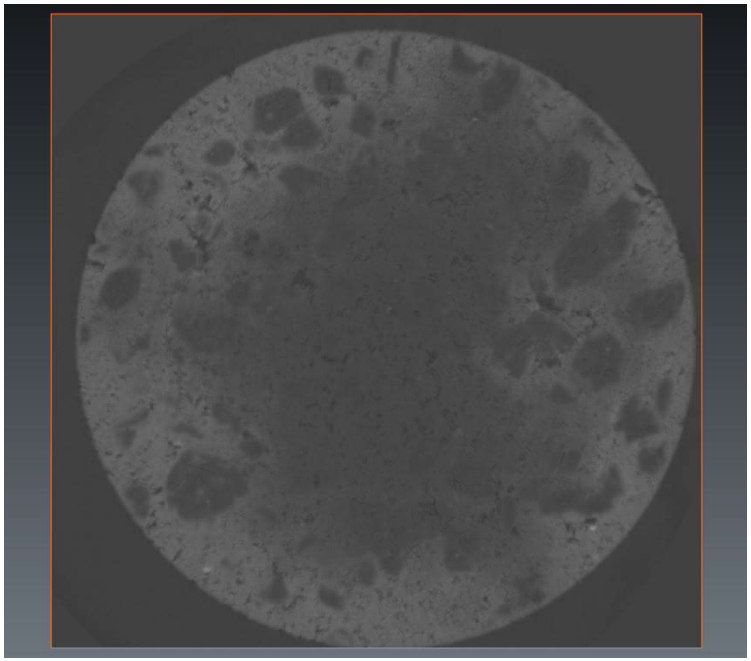
Strength and Fracture



- Two TSB projects; both EDF-lead
  - ***Fracture of Graphite Fuel Bricks***
    - University of Manchester, EDF NG, EDF R&D
- Modelling crack propagation in fuel bricks
  - XFEM, energy release rates
  - Comparison with experiment
- Statistical models of core normal and seismic behaviour
- Mimic irradiation damage by bromination
  - No external driving forces for crack growth (cf in service)
  - Criteria for crack initiation as function of local microstructure

Strength and Fracture



Tomographic image of brominated grapite

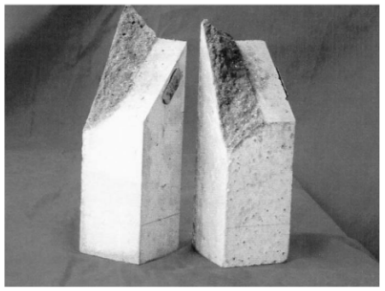
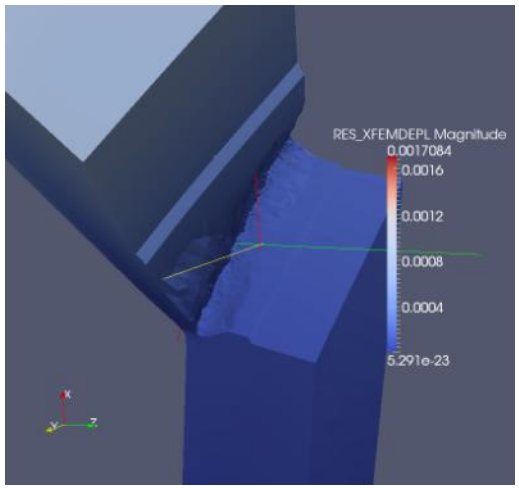
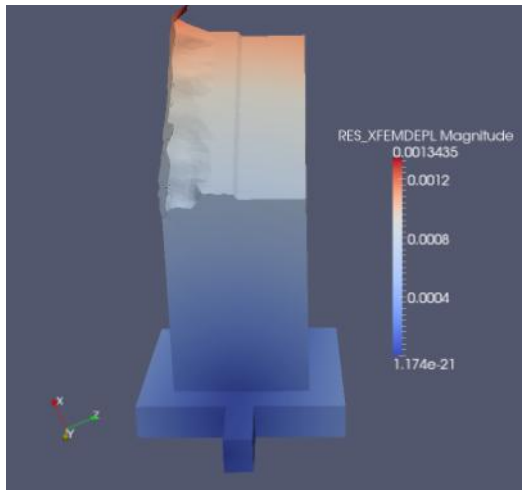


Plate 5 Prismatic torsion specimen after failure (After Brokenshire 1995)





Comparison of crack paths with prediction

Strength and Fracture

- ***Influence of Creep and Geometry on Strength of Irradiated Graphite Components***
  - University of Manchester, EDF NG

- Valid fracture data on irradiated material
  - Large trepanned specimens at reactor end–of-life
    - Ex-Oldbury
  - effects of notch geometries on properties
- Crack initiation and propagation
- Comparison with AGR installed sets
- Thermal creep as basis for irradiation creep
- Effects of creep on mechanical/fracture behaviour