Failure from Notches in Virgin and Irradiated Graphite: Insights on Onset of Keyway Root Cracking

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Outline

• Deformation of virgin and irradiated graphite
  • Reversible processes and energy loss

• Crack growth in virgin and irradiated graphite
  • In situ tomographic studies
  • Toughness determination

• Notch strengthening in virgin and irradiated graphite
  • Feature tests
  • Keyway Root Crack initiation

• Effect of Keyway geometry on brick failure

• Conclusions

• Acknowledgements
Background

• At present, the single most important life-limiting factor for AGRs currently in service across the UK is irradiation damage-induced cracking, which could jeopardise the structural integrity and the safe operation of the graphite reactor core.

• However, it is argued that the reactor is capable of functioning safely in late-life with finite amounts of brick cracking.

Fig 1: Schematic of the stress reversal experienced by graphite reactor bricks during lifetime and the potential for cracks to form as a result (from: Crump, T. et al., 2017, Nucl Eng Des)
Graphite Core Lifetime Strategy

Prediction with deterministic approach

Uncertainty in onset

Uncertainty in the tolerable limit of degradation (weight loss or brick cracking)

Conservative estimate of lifetime

Best estimate of lifetime

Conservative estimate

Best estimate

Best estimate

Uncertainty in the rate of increase of degradation

Time

Degradation

Courtesy J Reed
Deformation of virgin and irradiated graphite
Deformation of Virgin and Irradiated Graphite

- Unirradiated
  - non-linear
  - permanent set
  - different in tension and compression
  - much stronger in compression
- Pinning on irradiation causes
  - Significant increase in $E$
  - $E$ becomes almost linear
  - Deformation is recoverable
- Secondary increase attributed to structure tightening
- Final fall off due to degeneration
- Reduced by oxidation
Deformation of Un- and Irradiated Graphite

Non-linear, irreversible deformation does non-recoverable work
- dissipates/consumes energy
- possibility of constrained deformation > apparent strengthening

Brocklehurst, 1977
• Graphite is stronger in bend than tension
• Stronger in compression than bend
• Irradiated strength follows same trend as modulus
  • Increase
  • Secondary increase
  • Rapid decrease and disintegration
Notch Strengthening and KWRC Initiation
**INTRODUCTION**

- Graphite component fracture is predicted when the component is subjected to stresses that exceed the graphite strength.

- Both stress and strength change over time due to irradiation and radiolytic oxidation.

![Schematic of graphite component stress and strength during reactor life](image)
Graphite fuel bricks are subject to tensile stress at the bore and compression stress at the keyways early in the reactor life due to dose gradient across brick.

This stress state is reversed later in the reactor life, leading to tensile stresses at the keyway.
INTRODUCTION

- The **sharp corners** of the keyway act as **stress raisers**.

Fuel brick cross-section  

Typical keyway
• Need to scale from measurements of properties of small specimens to components

• Feature tests of slices of fuel bricks are carried out to determine the **unirradiated** strength at the keyway root.

Schematic of a feature test: Designed to give pure bending moment at keys
The obtained keyway root strength, using FE analysis, from these tests is considerably higher than the virgin strength obtained from bending specimens, due to notch strengthening.

For example, virgin strengths of HPB/HNB graphite are 25.2/24.7 MPa respectively. After FE analysis of feature test results, the feature strengths are 39.5/38.8 MPa. (Jones and Beesley, SERCO/E.005155/003 (2011))

**ASSUMPTION:** These apparent gains in strength of features measured on virgin graphite are retained after irradiation.
• Due to irradiation, the stress-strain behaviour of graphite becomes more linear.

Change in the stress strain behaviour of graphite due to fast neutron irradiation (Brocklehurst, 1977)
Notch Effects

Variation in stress across specimen ligament

Parts of ligament attempt to strain differently

Unable to do so by surrounding material

Constrained deformation
Notch Strengthening

Known that material type gives rise to differing notch behaviour

Specifically the extent of **plastic** deformation available

Plastic deformation constrained by surrounding elastic strain field

Increased load needed to generate flow thereby increased strength

No such mechanism available to brittle, elastic materials
• The notch strengthening effect in irradiated graphite may therefore be different from the unirradiated strengthening factor.
  • No constraint effect from plastic deformation

• Notch strengthening of irradiated vs unirradiated graphite can be assessed through experimental results obtained for plain and notched beams made of irradiated and virgin graphite.
INTRODUCTION

• Results for the **irradiated notch strengthening factors** are **presented** here based on data obtained through an Innovate-UK project.

• Data for **unirradiated** specimen of sizes similar to the irradiated small specimens are provided by M. Jordan (Oxford University/NNL). However, the notch dimensions and loading configuration are different.
• Specimens are from **AGR HPB R3 & R4** installed sets.

• The notches are **U-shaped** and shallow.

• The notch dimensions compared to the specimen sizes are not representative of the ratio of the brick to keyway root dimensions.

• **Two different sizes** (~ 8 per type) were tested under **three-point bending** conditions.

• The **plain and notched** specimens are **paired** (cut from the same installed sample).
Notch Strengthening of Irradiated Graphite

Large Beams

$\sim (8*8*38\text{mm})$, support span 30mm

notch radius $\sim 2\text{mm}$

notch depth $\sim 2\text{mm}$
Notch Strengthening of Irradiated Graphite

Small Beams

~ (6*6*18mm), support span: 15mm

notch radius ~2mm

notch depth ~1.5mm
Notch Strengthening of Irradiated Graphite

- The samples were modelled using **finite elements**.

- **Similar meshes** were used for all the samples.

- **Notch strengthening factor (NSF)** of each pair of specimens is defined as the **maximum stress of the notched sample divided by the maximum stress of the sister plain beam sample**.
Notch Strengthening of Irradiated Graphite

- **Large samples** average NSF = 1.40
- **Small samples** average NSF = 1.41
Notch Strengthening of Virgin Graphite

• Specimens are from graphite produced by UCAR for the Heysham 2/Torness reactors.
• **Four-point bending** tests (~14 per type) of plain, notched and deep notched beams.
• 6*6*19mm, load span 5.3mm, support span 16mm, notch radius=1, Notch depths=1mm and 3mm.
Notch Strengthening of Virgin Graphite

• Shallow Notch average NSF = 1.9

• Deep Notch average NSF = 1.85
OBSERVATIONS

• The NSFs of “small” and “large” irradiated samples are almost the same for the specimens tested. This may be due to the fact that the dimensions of the cross-sections and notches of large and small samples are very similar, mainly the specimens lengths changed between the large and small samples.

• The values of the NSFs from the samples presented are not necessarily representative of the keyway root NSFs as the ratio of the dimensions of the samples are different from those of an AGR fuel brick.

• Ideally the virgin samples should be of the same size and source of the irradiated samples and tested under similar loading conditions (Further work may be needed).
CONCLUSIONS

• The notched strengthening factor of virgin graphite appears to be considerably larger than that for irradiated graphite, keeping in mind the caveats mentioned throughout the presentation.
• potential for stress redistribution by creep
• In this analysis, as an indication, strength should be scaled by 1.4/1.9, for example

• The cause for the difference between virgin and irradiated notch strengthening factors likely due to the more linear nature of the stress-strain curve of irradiated graphite.
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Conclusions

- This main conclusion could have consequences regarding how the irradiated strength of the keyway root of fuel bricks is estimated.

Onset of KWRC potentially brought forward by ~ 4 fpy
Summary

• Demonstrated the effect of irradiation on notch strengthening of keyway features
• More work needs to be undertaken to be more certain of consequences
  • Same geometry, loading conditions
  • Future work under BCN contract
• Potential for more complete understanding of onset of KWRC
  • Safer operation of AGR
Acknowledgements

The authors would like to acknowledge the contributions of other University of Manchester staff and project collaborators, as well as thank our project sponsors:

- **Diamond**: Andrew Bodey, Shashidhara Marathe, David Eastwood, Kaz Wanelik, Christoph Rau
- **NNL**: Nassia Tzelpi, Jon Bradley, Matthew Jordan, Sam Wilkinson
- **InnovateUK**
ACKNOWLEDGEMENT

Mo Treifi would like to thank the Office for Nuclear Regulation for financial support. The views expressed in this presentation are those of the authors and do not necessarily represent those of the Office for Nuclear Regulation.