GRAPHITE ACTIVITIES AT NRG

Research and qualification overview

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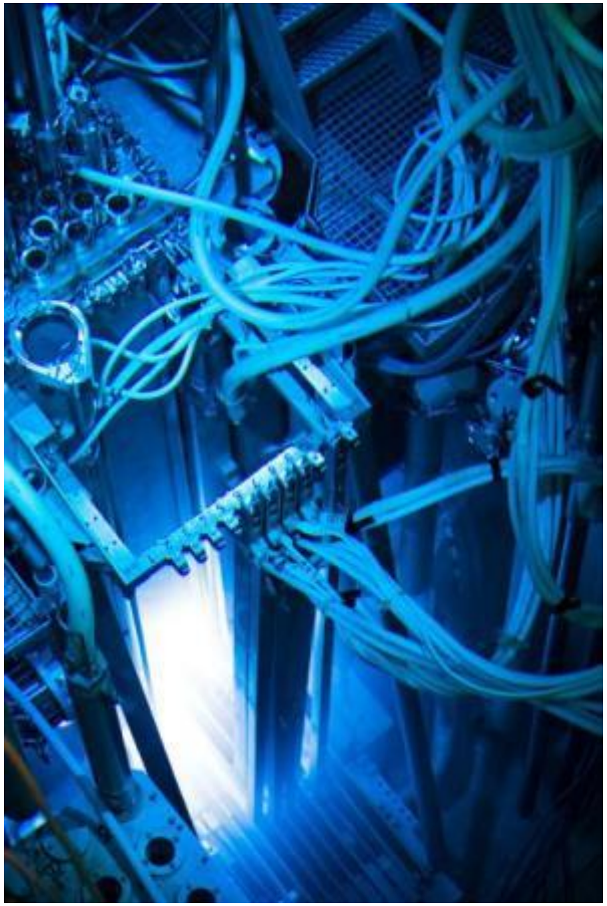
Washington, 12 December 2019

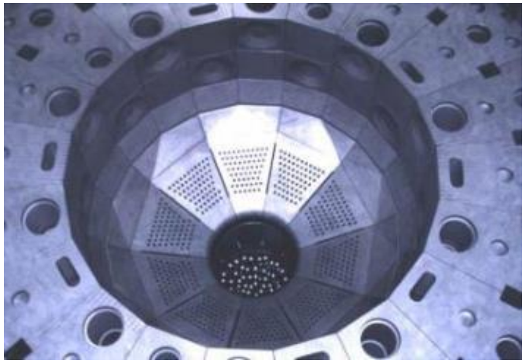
OVERVIEW

- Graphite research and qualification activities at NRG
- Graphite irradiation program for Advanced Gas-Cooled Reactors

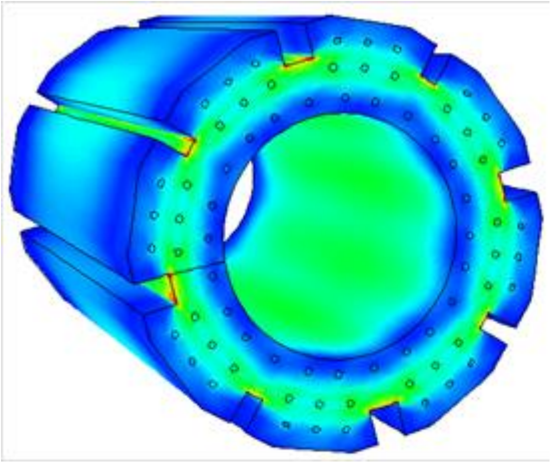


GRAPHITE IS LIFE-LIMITING

- Graphite in nuclear reactors
  - Moderator
  - Core structural integrity
  - **Life-limiting component**
  - Impact on economics
- Neutron-damage to graphite
  - Changes in material properties increase stresses
  - Increased stresses lead to graphite failure
  - Moment of failure depends on graphite material properties
- High quality graphite irradiation data needed for graphite selection, design and safety cases



GRAPHITE IRRADIATION BEHAVIOUR



- Volume change
  - Induces stresses in graphite components
- Length change in AG and WG direction
  - Induces anisotropy
  - Induces stresses in graphite components
- Coefficient of Thermal Expansion
  - Induces stresses in graphite components
- Young’s Modulus
  - Response of graphite to load and deformation
- Irradiation creep
  - Deformation and stress relief of graphite under irradiation and load
- Strength
  - Determination of failure under load/stress
- Stress build-up leads to graphite component failure
- **How and when > requires accurate data**

GRAPHITE PROGRAMS AT NRG

- Research for GenIV reactors (2001-2015)
  - Study of modern graphite grades for High Temperature Reactors
  - Work conducted within European Framework programs

Archer
Advanced Reactor for Cogeneration of Heat & Electricity-R&D

- EDF Energy AGR life time extension (from 2006)
  - BLACKSTONE: irradiation of AGR graphite under oxidising conditions
  - ACCENT: irradiation creep irradiation

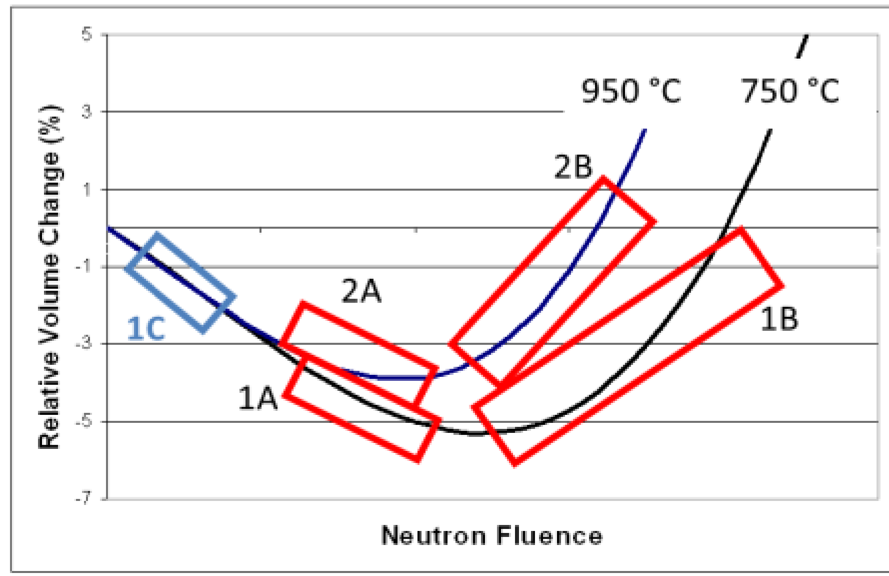
edf ENERGY

- Irradiations for current graphite suppliers and reactor developers

- Graphite irradiation as part of MSR program

HTR GRAPHITE IRRADIATION AT NRG

- 5 “INNOGRAPH” irradiations
- Modern-day HTR graphite candidates
- European framework programs (HTR-M, RAPHAEL, ARCHER)
- Low, medium, and high dose ranges to cover graphite behaviour beyond cross-over
- Re-load of active “A”-phase samples in “B”-phase for time-efficient acquisition high dose data



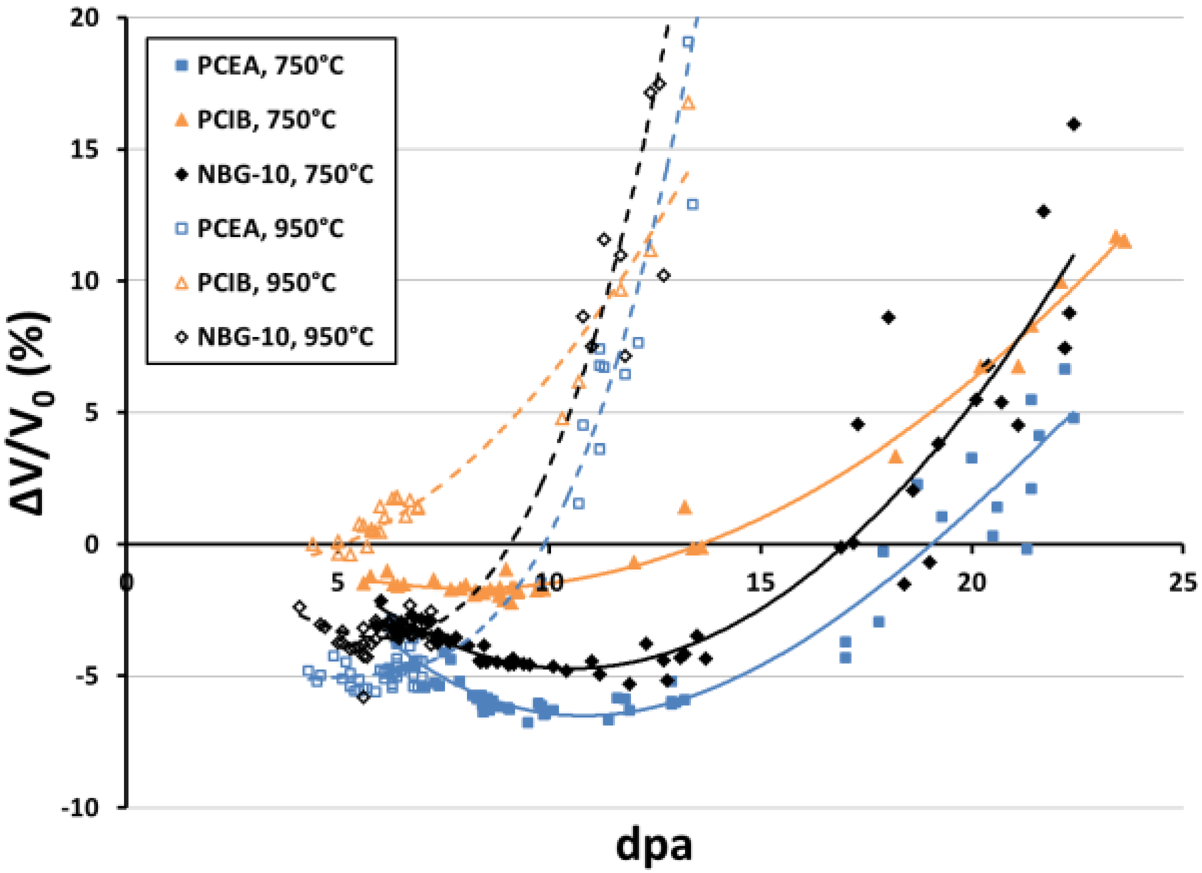
Schematic of INNOGRAPH irradiation campaign

2001-2006 HTR-M High Temperature Reactor - Materials

2006-2011 RAPHAEL

2011-2015 Archer Advanced Reactor for Cogeneration of Heat & Electricity-R&D

DIMENSIONAL CHANGE AND IRRADIATION TEMPERATURE



Heijna et al., Comparison of irradiation behaviour of HTR graphite grades, Journal of Nuclear Materials 492:148 · May 2017

USE OF MTR DATA

Irradiation

- Application of graphite within reactor core can be limited by the range and accuracy with which the material is characterised in an MTR program, e.g.:
  - Temperature
  - Dose
  - Stress
  - Specimen environment (inert / oxidising etc.)
- Control of these parameters is performed by design and operation of the irradiation facility, in order to:
  - Meet target irradiation conditions
  - Minimise deviations, drift and uncertainties
- There is no qualitative or quantitative specification in international standards on the accuracy and method by which the irradiation conditions (e.g. temperature, stress) should be obtained

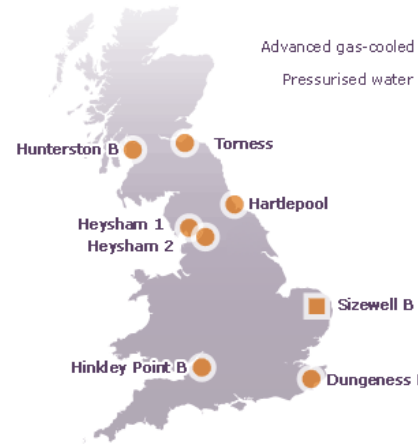
Material characterisation

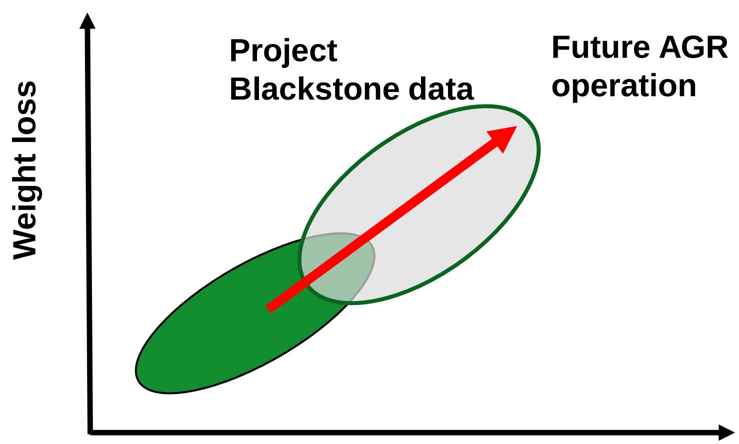
- Measurements are typically performed on small sized specimens, which may require additional validation efforts

LIFETIME EXTENSION AGR REACTORS

Supporting long life of Advanced Gas Cooled Reactors

- EDF Energy operates Advanced Gas Cooled Reactors, supplying ~ 20% of electricity in the United Kingdom
- Graphite cores age with time due to neutron damage and radiolytic oxidation
- Accelerated ageing tests to determine graphite properties ahead of actual AGR core structures





BLACKSTONE INTRODUCTION

Aim >

- Collect material property data in advance of the operating AGR stations, specifically at high dose and weight loss
    - Demonstrate lack of cliff-edge at end of generation conditions

Approach >

- Irradiate specimens High Flux Reactor (HFR) in Petten using accelerated conditions relative to the AGRs
- Use source material from operating AGRs

Key succes factors >

- Representative irradiation conditions
    - Generating similar graphite property evolution in AGR and HFR
- Accurate measurements on small specimens
- Ensuring quality for application of data in reactor safety cases

BLACKSTONE PROJECT FLOWCHART

Samples drilled from AGR reactor core and shipped to NRG Petten

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Machining of specimens from extracted discs in hot cell laboratories (HCL)

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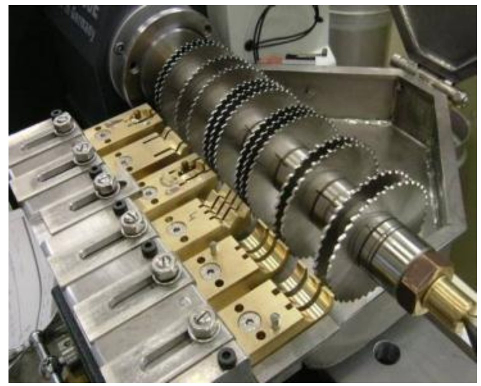
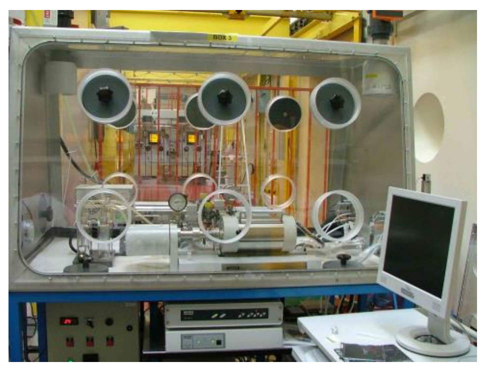
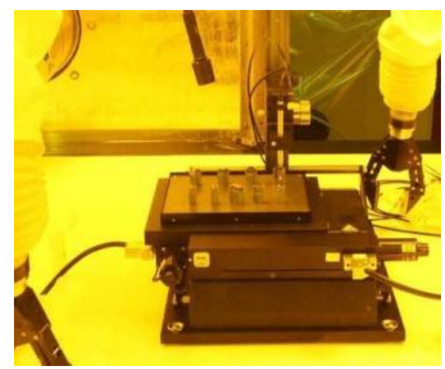
Characterisation of radioactive graphite specimens in hot cell laboratories







BLACKSTONE PROJECT FLOWCHART

Blackstone capsules are assembled in hot cell laboratories

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Blackstone capsules are loaded into the HFR and connected to a dedicated gas handling system that controls graphite oxidation

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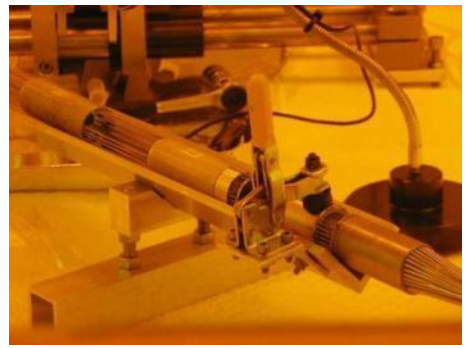
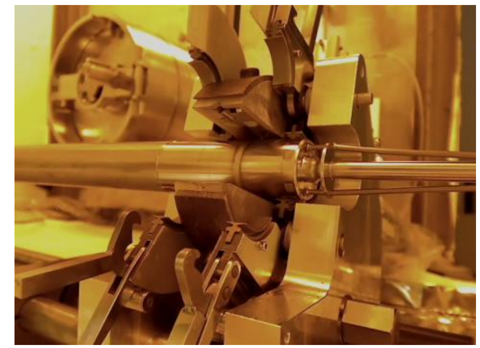
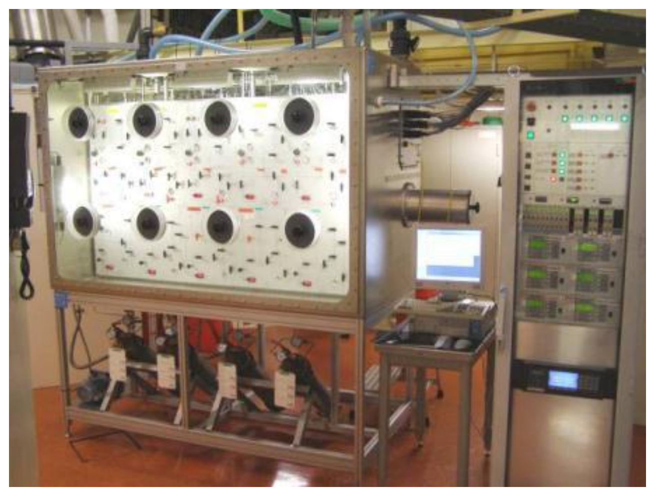
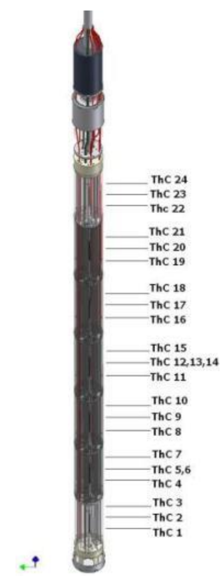
After irradiation the capsules are dismantled, and post-irradiation characterisation on the specimens is carried out



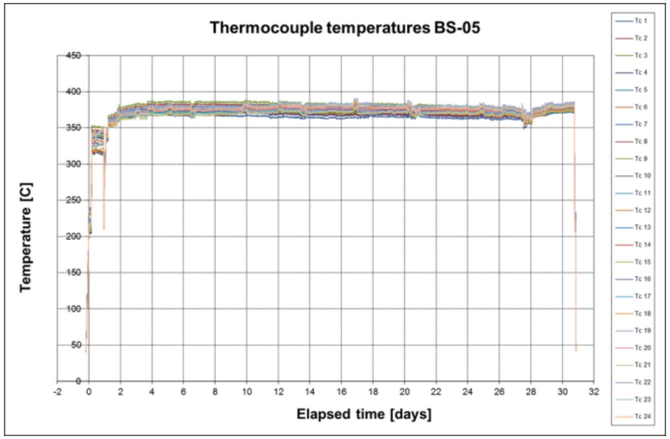


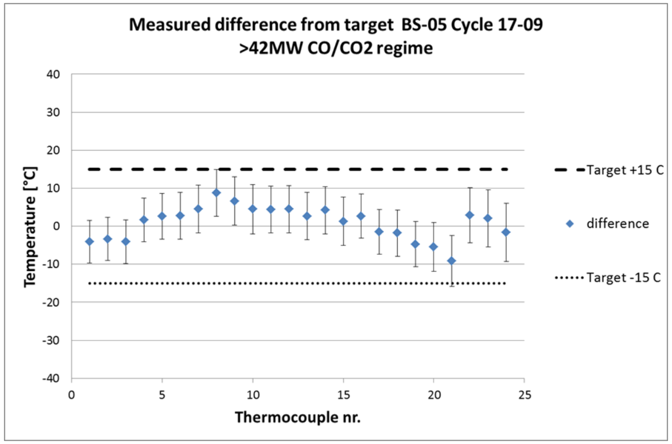




REPRESENTATIVE IRRADIATION CONDITIONS (1/2)

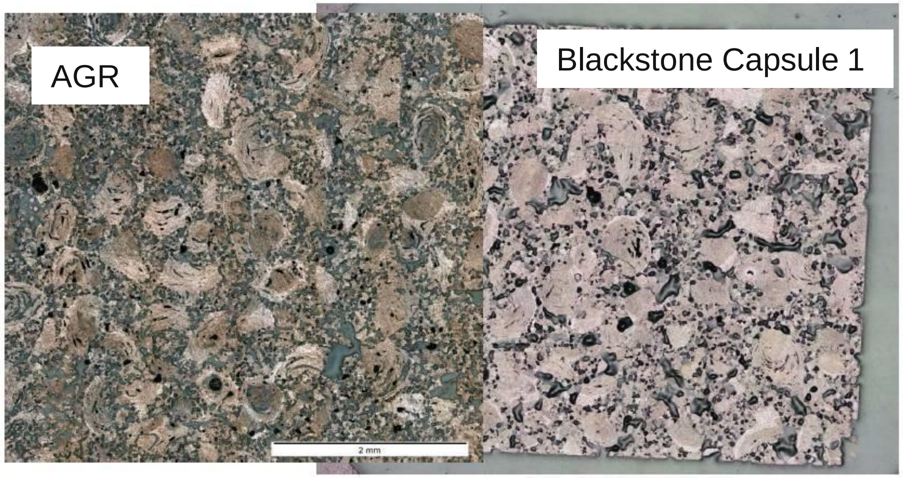
- Temperature
  - Validated thermomechanical models using MCNP input, using true dimensions of specimens and capsule materials
  - Online temperature measurement and control
  - Temperatures were well controlled, generally within ±20°C of target with minimal drift
- Dose
  - MNCP models using predicted and acual core loadings
  - Validation of model predictions by measurement of neutron activation monitor sets
- Environment: weight loss / oxidation control
  - Weight loss controlled by monitoring chromatography on the capsule outlet and adjusting the inhibitors (mainly CO, CH4, C2H6)
  - Final weight loss calculated for each specimen using the starting weight loss and measured mass



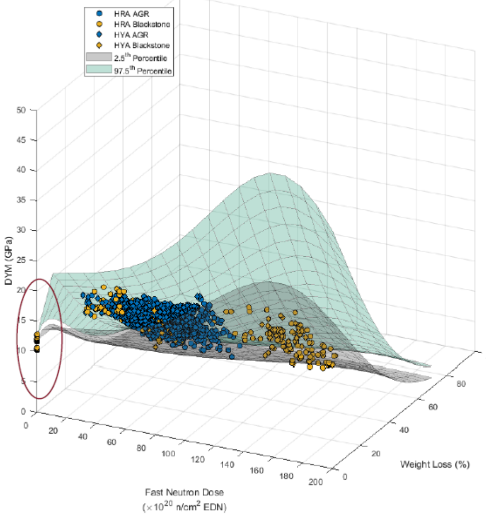


REPRESENTATIVE IRRADIATION CONDITIONS (2/2)

- Microstructural characterisation to demonstrate similarity (or otherwise) of aging mechanisms
  - ➢ The AGR and Blackstone microscopy images have been compared and are broadly similar



- Data analysis to demonstrate consistency and tie in with AGR data
  - ➢ The measurements from the different Blackstone capsules and oxidation rates have been compared and are broadly consistent.
  - ➢ The Blackstone measurements have been compared to the AGR inspection and monitoring data and are of similar magnitude



VALIDATION OF MEASUREMENTS

- Comparison with international (ASTM) standards
- Investigation of the influence of non-conformities with standards
- Perform measurements on standard materials with known properties
- Perform measurements on similar materials (thermally oxidised specimens with comparable weight losses)
- Show repeatability of test method
- Prove independence of operator / experimental conditions and specimen size
- Round Robins (ASTM, NNL, NPL, ORNL, ECN)
- Independent review of work procedures (e.g. NPL)
- Tie-in with inspection data from AGRs
- Historical MTR data

CONCLUSIONS

- Graphite research and qualification activities at NRG, supporting
  - High Temperature Reactors
  - Advanced Gas-cooled Reactors
  - Molten Salt Reactors
- Recent graphite irradiations at NRG are well controlled and have successfully supplied data for:
  - Analysis of modern graphite grades for HTR application
  - Life time extension of AGR reactors
- Apply lessons learned on control of irradiation conditions and validation of measurements in support of development of new reactor types and graphite qualification