



GRAPHITE ACTIVITIES AT NRG

Research and qualification overview

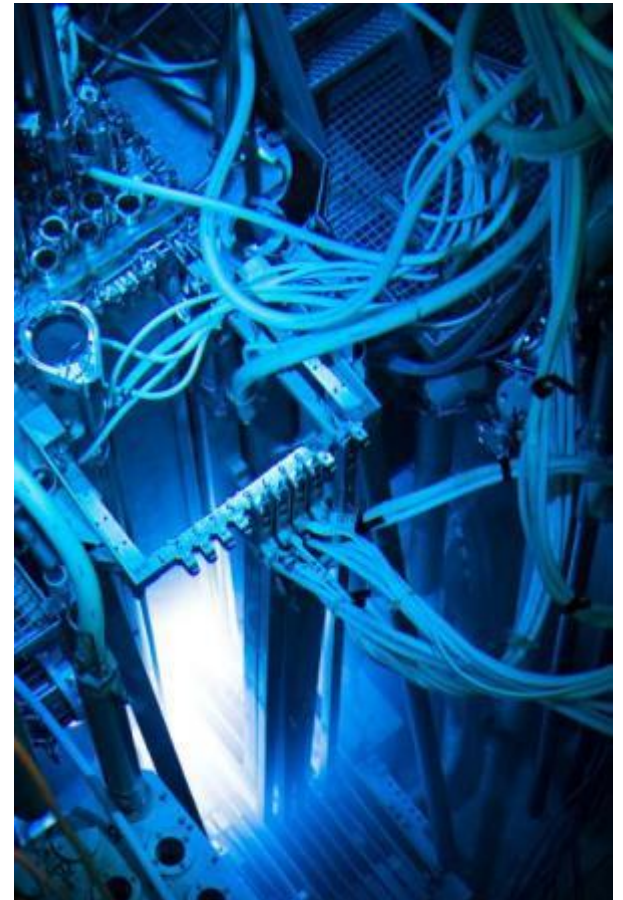
T.O. van Staveren

Washington, 12 December 2019



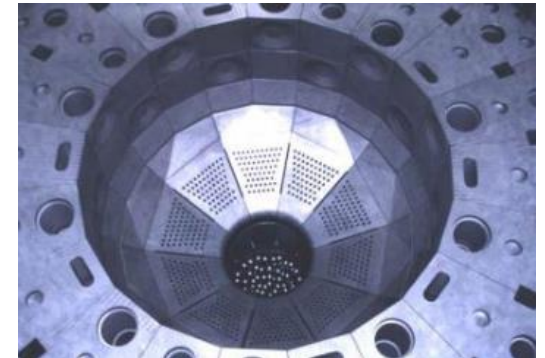
OVERVIEW

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



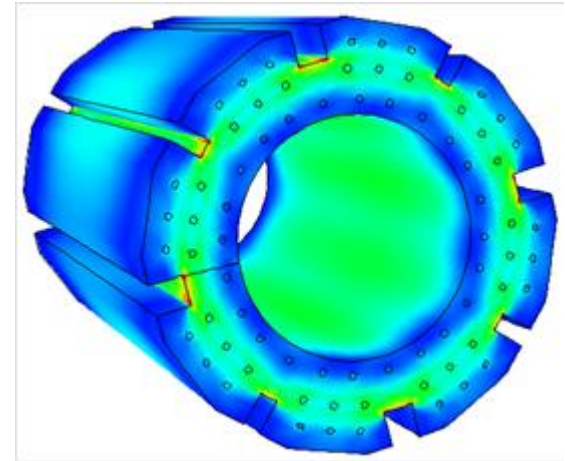
GRAPHITE IS LIFE-LIMITING

- 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**



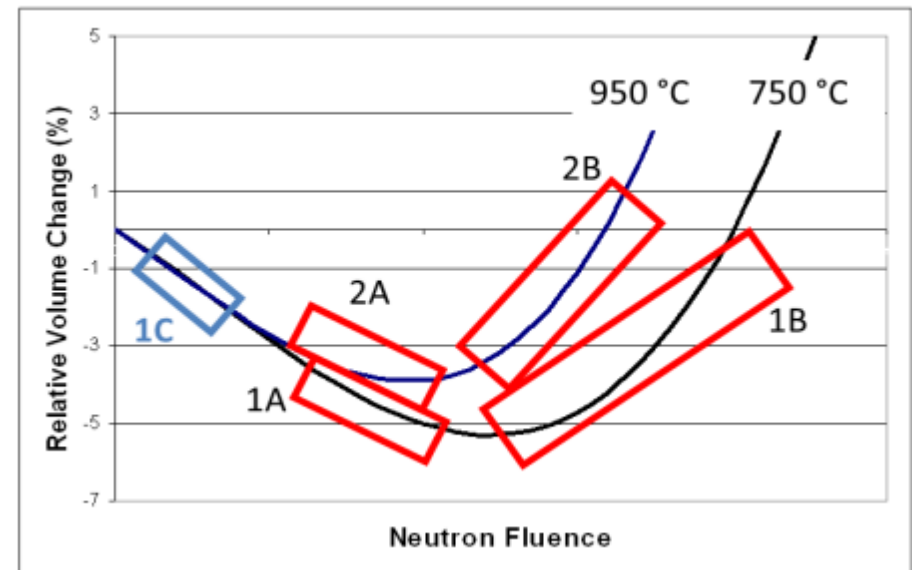
GRAPHITE PROGRAMS AT NRG

- Research for GenIV reactors (2001-2015)
 - Study of modern graphite grades for High Temperature Reactors
 - Work conducted within European Framework programs
- EDF Energy AGR life time extension (from 2006)
 - BLACKSTONE: irradiation of AGR graphite under oxidising conditions
 - ACCENT: irradiation creep irradiation
- 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



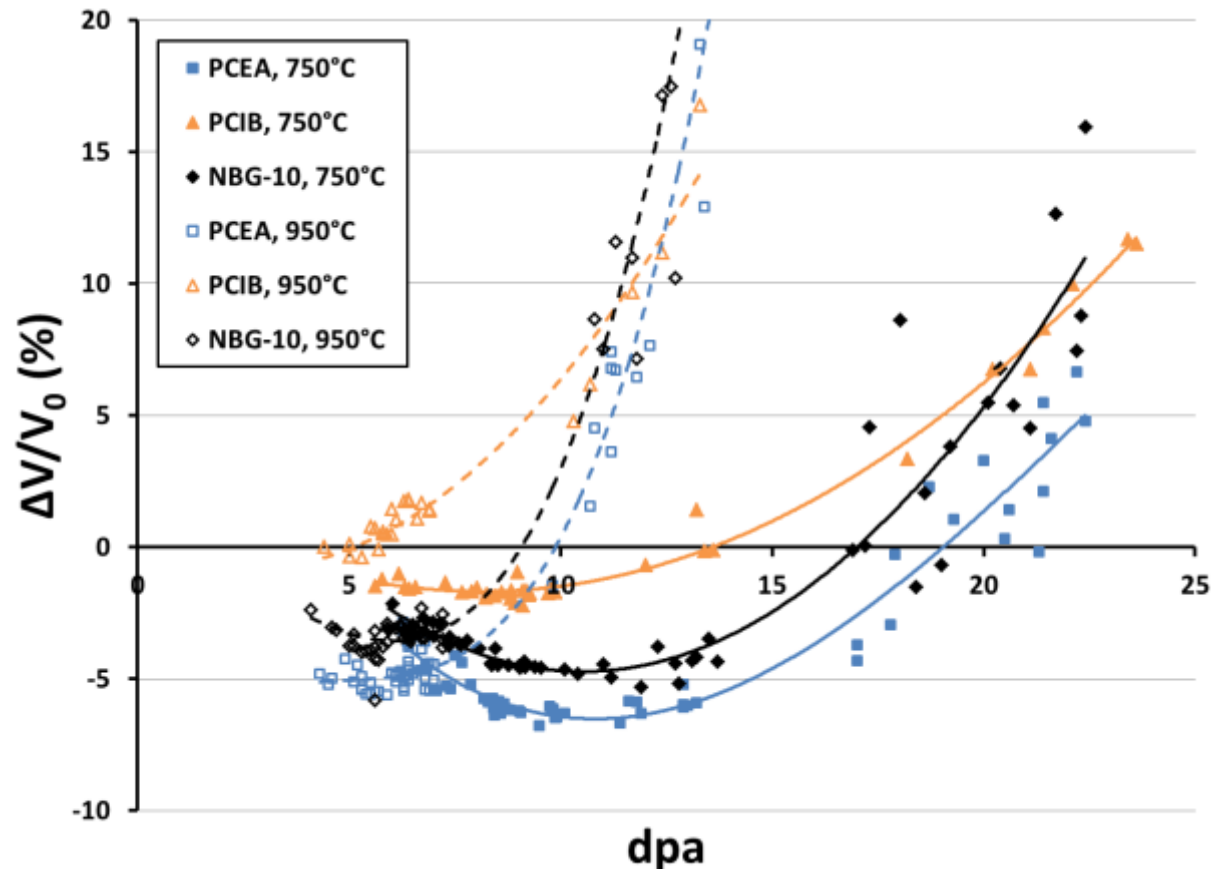
2006-2011



2011-2015



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

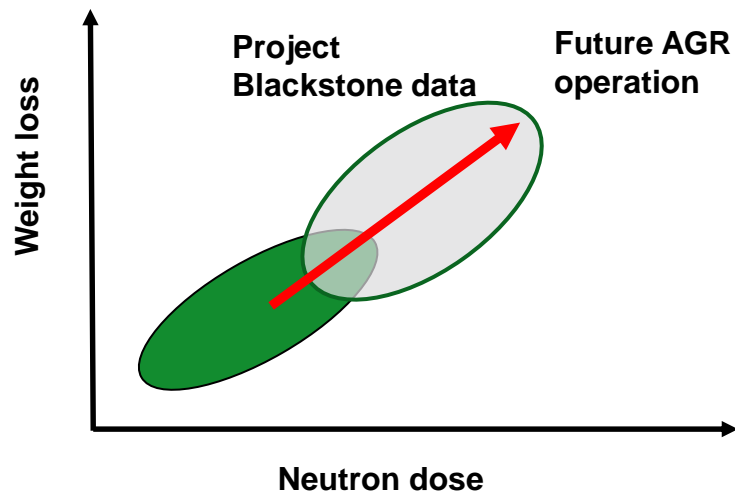
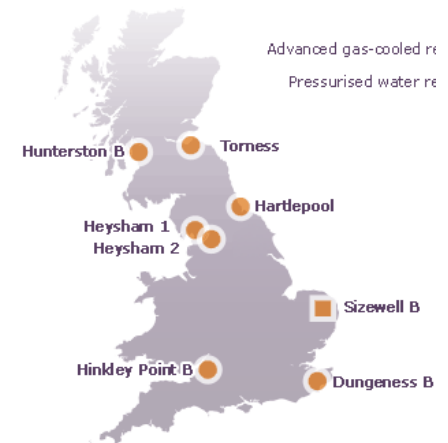
Material characterisation

- 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

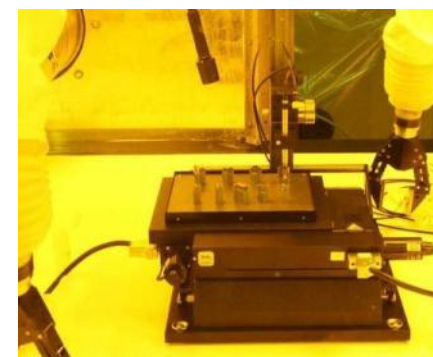
Samples drilled from AGR reactor core and shipped to NRG Petten



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

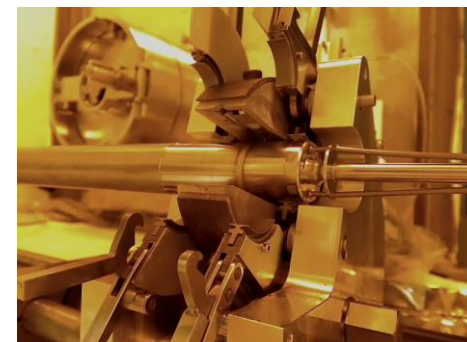
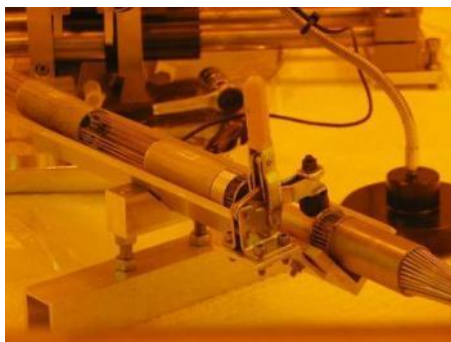


Characterisation of radioactive graphite specimens in hot cell laboratories

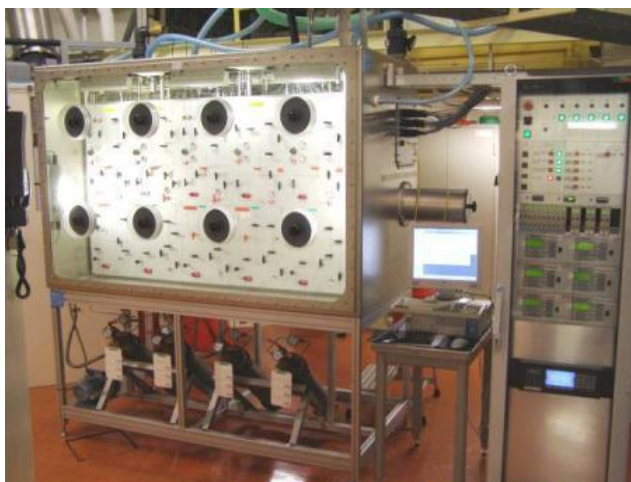


BLACKSTONE PROJECT FLOWCHART

Blackstone capsules are assembled in hot cell laboratories



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

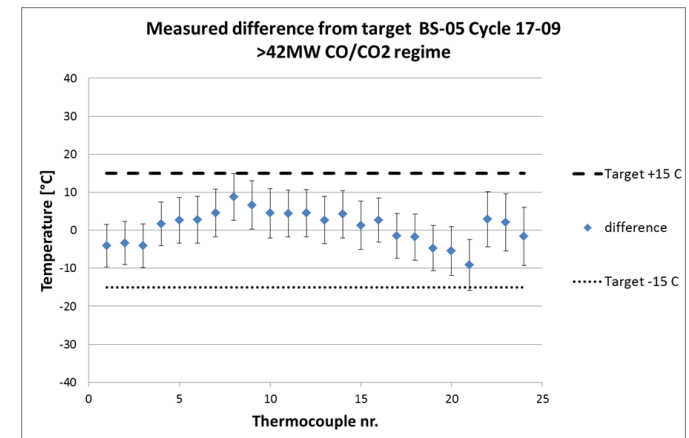
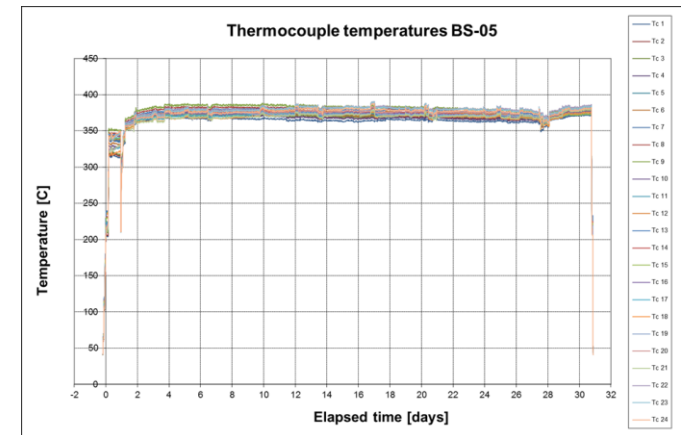


After irradiation the capsules are dismantled, and post-irradiation characterisation on the specimens is carried out



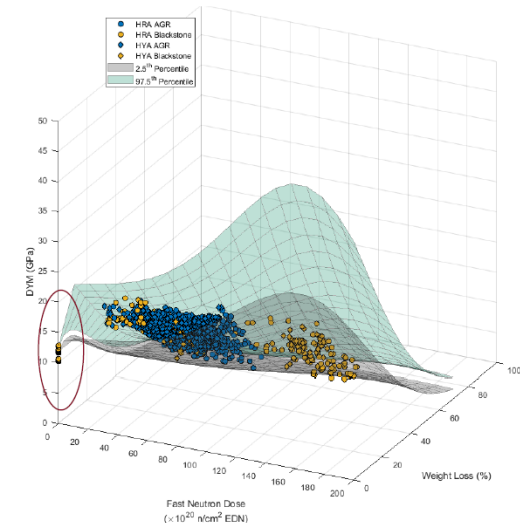
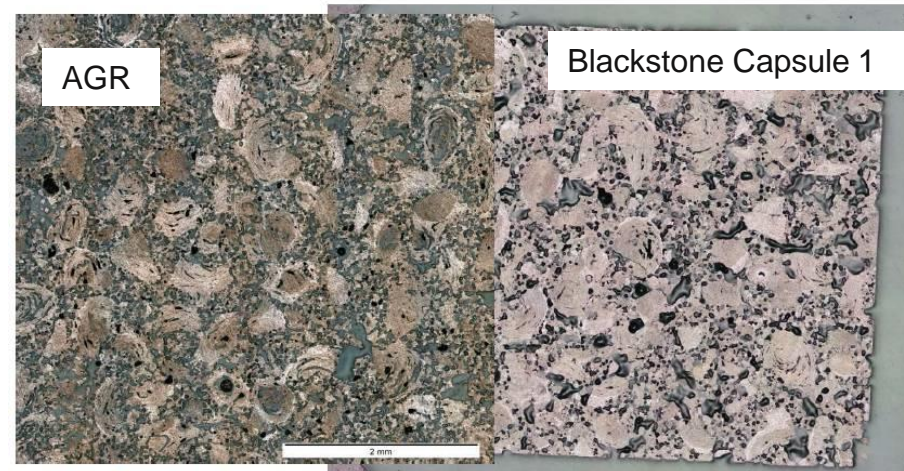
REPRESENTATIVE IRRADIATION CONDITIONS (1/2)

- 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 $\pm 20^\circ\text{C}$ of target with minimal drift
- Dose
 - MNCP models using predicted and actual 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