**Institution:** University of Manchester

**Unit of Assessment:** UoA12b Mechanical, Aerospace and Manufacturing Engineering

**Title of case study:** UK Reactors Safety and Life Extension

## 1. Summary of the impact

About 18% of UK electric supply is provided by 14 graphite-moderated Advanced Gas-cooled Reactors (AGRs) and 1 Pressurised Water Reactor (PWR). The AGRs are graphite-moderated, generic in design and the nuclear regulator is concerned that a common safety related fault could lead to immediately shutdown of all AGRs. The development of novel techniques at Manchester has allowed the continued operation helping the operators to establish an expected seven-year life extensions for all AGRs. For the plant operators this represents a potential income of £2.5bn per annum, avoid 30m tonnes $CO_2$ pa and generate supply chain income within the UK of £650m pa and create or protect 2000 jobs.

## 2. Underpinning research

Key members of the research team have included:

Barry Marsden (2001-date, Professor of Nuclear Graphite Technology)

Paul Mummery (2000-date, Senior Lecturer '04, Reader '08, Professor '12)

James Marrow (1996-2011, Senior Lecturer '03, Reader '07-11,)

Alex Fok (2001-06, Lecturer '01, to '06)

Graham Hall (2001-date, EngD '01, PDRA '03, Lecturer '11)

Abbie Jones (2006-date, PDRA '06, Lecturer '11)

Derek Tsang (2002-date, PDRA '02, Research Fellow '11)

Tony Wickham (2010-date, Honorary Visiting Professor '10)

Ernie Eason (2010-date, Honorary Visiting Professor '10)

In addition there are/have been around 25 EngD/PhD students and 12 PDRAs.

The key insights from the research relate to the development of a fundamental understanding of the changes in microstructure and behaviour of graphite on irradiation. This has determined that, as far as changes to irradiated graphite properties are concerned, there are no "cliff edges" to properties such as strength and modulus for the next few years that would be of concern. Key findings that support this conclusion are:

a) X-ray microtomography combined with strain mapping techniques (such as digital image correlation and Raman spectroscopy), providing novel insights on defect structures, crack growth, and damage development [2, 4].

b) High resolution transmission electron microscopy (TEM), providing an understanding of defects and their development under irradiation and temperature [3, 5].

c) Predictive models of failure of core elements in a reactor using multi-scale models of irradiated graphite behaviour under normal operation and seismic loading [1, 2].

d) Novel material statistical models of core behaviour using pattern recognition and data mining validated from historic material test reactor graphite data and recent data from samples trepanned from the Magnox and AGR graphite cores [6].

A spin off from this project has been international recognition of the group as a centre of expertise in nuclear graphite technology, participating in “Generation IV” programmes with the USA, France, China, Japan, South Africa and South Korea. For example ten papers are being presented by the NGRG at the INGSM-14 in Seattle this year (2013).

**3. References to the research**

The research has been published in the leading journals in the area namely the Journal of Nuclear Materials and Carbon. In November 2011 the University of Manchester Dalton Nuclear Institute was granted a Queen’s Anniversary Prize to which the activities described made a significant contribution [B]

**Key Publications**


[1] Tsang, K-L, and Marsden, B. 2008 "Constitutive material model for the prediction of stresses in irradiated anisotropic graphite components." Journal of Nuclear Materials 381 (1-2), 129-136. eScholarID:1e543 | DOI: 10.1016/j.jnucmat.2008.07.025

[2] Berre C, Fok A S, Marsden B J, Babout L, Hodgkins A, Marrow T J, Mummery P M. 2006. "Numerical modelling of the effects of porosity changes on the mechanical properties of nuclear graphite". Journal of Nuclear Materials 352 (1-3), 1-5. DOI: 10.1016/j.jnucmat.2006.02.037

[3] Jones, AN, GN Hall, M Joyce, A Hodgkins, K Wen, TJ Marrow, and BJ Marsden. 2008 "Microstructural characterisation of nuclear grade graphite." Journal of Nuclear Materials 381 (1-2) 152-157. Journal article eScholarID: 147053 | DOI: 10.1016/j.jnucmat.2008.07.038.


**Other Relevant Publications**


[4] Babout, L, Marrow, T.J., Marsden, B.J., and Mummery, P.M. 2008. “Three-dimensional characterization and thermal property modelling of thermally oxidized nuclear graphite”, Acta Materialia 56, 4242-4254 DOI: 10.1016/j.actamat.2008.04.045

[5] Wen K, Marsden B J, Marrow T J. 2008. "The microstructure of nuclear graphite binders". Carbon 46 (1), 62-71. January. DOI: 10.1016/j.carbon.2007.10.025

[6] Eason E D, Hall G N, Marsden B J, Heys G B. 2008. "Development of a Young’s modulus model for Gilsocarbon graphites irradiated in inert environments". Journal of Nuclear Materials 381 (1-2), pp 145-151. October. DOI: 10.1016/j.jnucmat.2008.07.036


**4. Details of the impact**

**Context**

The fourteen AGR and the one Magnox reactors produce about 18% [A] of the UK electricity. The graphite cores of these reactors provide channels for fuel cooling and control rod entry. During reactor operation irradiation damage and radiolytic oxidation changes the dimensions and properties of the approximately 1700 tonnes of graphite components that make up a single typical graphite reactor core. These changes can challenge the structural integrity of the core. However, the irradiated graphite database for these reactors is incomplete and the mechanisms driving the structural and property changes are not well understood. Therefore, the reactor licensees are required to make safety cases for continued operation of reactors every three

years.

**Pathways to Impact**

The Office for Nuclear Regulation (ONR) encouraged the establishment of the Nuclear Graphite Research Group (NGRG) in 2001 to supply independent research and advice on the structural integrity of nuclear graphite reactor core components. The ONR also encouraged and enabled the NGRG to gear up their funding by obtaining research funding in other related areas from industry, the EU and EPSRC.

The codes, data, and statistical models developed by NGRG are made available and have been adopted by the licensees operating nuclear power reactors. In addition, the NGRG has made available the experimental techniques and medium-scale facilities to industry. This has informed the licensees' research output and experimental planning for life extension.

The ONR seeks independent advice and research from the NGRG at the University of Manchester to enable them to assess the graphite core safety cases.

NGRG's reputation has enabled it to become as a major partner within international sponsored programmes on the development of inherently safe High Temperature Gas-cooled Reactor technology and the development of methodologies for dealing with the ~200,000 tonnes of irradiated nuclear graphite waste which exists worldwide.

**Reach and Significance of the Impact**

During the impact period NGRG has produced 25 reports for the HSE, IAEA and others [C]; 15 GTAC technical reports for ONR [D], published papers in leading journals, and attended and made presentations at both national and international conferences and meetings, including IAEA co-ordinated research programmes (see above). Members of the NGRG also attended over forty official licensee/ONR meetings [E] to offer advice and critical input.

Significant advances in computational power have enabled development of sophisticated numerical models and data analysis techniques for single components through to whole cores [1, 2, 6]. This is key to interrogating safety cases for reactors as experimental data on whole components and reactors under operating conditions through life is impossible to obtain:

The advice given by the NGRG ensured that Oldbury continued safe operation for 44 years, until 2012. "Both of the site's reactors were scheduled to close at the end of 2008, and since that time the site has generated an additional 7 terawatt hours (TWh) of electricity, worth an estimated £300 million to the taxpayer. The extra generation has also saved around six million tonnes of carbon from being released into the atmosphere." (Oldbury News 21.10.2011)

On current figures, the operating value of a reactor is approximately £0.5m per day. Therefore, to extend the life of the operating fleet has a value of approximately £2.5bn per year to the licensees [F]. This clearly has a significant impact in reduced electricity prices. EDF have identified the benefits to UK plc of plant life extension of the nuclear generation fleet [G]. This includes

- Avoiding 30 million tonnes of $CO_2$ every year which over the 7 year life extension is equivalent to removing all cars from UK roads for 5 years
- Annual spend in the supply chain of £650m pa of which 90% is in the UK
- Partnership with specialist suppliers employing 2000 staff on average and 6000 at the peak of the extension programme

Having provided the data on which the life of the Oldbury power station was extended, the

decision that safety considerations now determined that the station should cease operation was taken in consultation with the NGRG [H], hence minimising the risk of accidents and associated economic and societal consequences.

On the decommissioning side the NGRG is a major partner in the EU CARBOWASTE FP-7 programme involving 28 partners from the EU and elsewhere. This is a £12m programme set up to investigate methods and provide international recommendations for dealing with irradiated graphite waste. The value associated with reducing the designation of graphite waste from Intermediate Level to Low Level is significant [I].

The impact of the research is such that the ONR has established a Chair, Lectureship and Research Fellowship at the University of Manchester.

**5. Sources to corroborate the impact**

A. Spreadsheet of Fuel used in electricity generation annually showing the level of nuclear generation is about 18% from https://www.gov.uk/government/publications/electricity-section-5-energy-trends
B. Submission for Dalton Queen's Award detailing the role of the NGRG in this award
C. NGRG Report Register List of reports prepared by the NGRG
D. GTAC report Summary List of the reports prepared for GTAC with those in the impact period highlighted
E. List of ONR meetings Extract from the diary of Prof Marsden showing the ONR meetings attended.
F. Calculation of the annual value of nuclear generation to licensees.
G. Slide provided by EDF of the benefits to UK plc of nuclear fleet extension
H. Letter from ONR on independent advice and input to Oldbury closure.
I. EU Carbowaste Programme http://www.carbowaste.eu/home.html. Carbowaste website detailing the programme and strategy of this EU FP7 project.