Institution: University of Sussex

Unit of Assessment: UoA 08 Chemistry

Title of case study: Extending nuclear reactor life by research into radiation damage in graphite

1. Summary of the impact

This research underpins assessments of nuclear reactor longevity and safety and has contributed to EDF's project to extend the life of nuclear reactors by 100+ reactor-years. So far this project has achieved 48 years or nearly £9bn in benefit. The Sussex contribution is accruing value to the UK economy of an estimated £100M at today's prices, with about £40M of that achieved already. Graphite in nuclear reactors is susceptible to neutron damage, and accurate estimations of the rate of graphite damage in reactors are critical to safety and to predicting reactor lifespan. Research from Sussex has developed models for graphite damage that now underpin one component (of six independent components) of the safety assessments conducted by the nuclear industry for Advanced Gas-cooled Reactors. The research demonstrated that a previous model employed for this purpose was invalid, and developed alternative models that have been adopted by the nuclear industry.

2. Underpinning research

The safe provision of electrical power is critical to the social and economic infrastructure of the UK and worldwide. It is an ambition of EDF Energy Nuclear Generation (EDF-E-NG), formally British Energy, to achieve an extra 100 reactor-years from existing Advanced Gas-cooled Nuclear Reactors, which equates to £60 billion of additional power output at today's retail prices. Whereas a design life of 25 years invoked very conservative models of graphite behaviour and lifespan following neutron damage in nuclear reactors, the safety assessment for plant extension requires a more precise model that must be supported by new experiments for the neutron doses experienced in the extended lifetime. Such a model has emerged, in part, from the research programme on nuclear graphite at Sussex.

Radiation damage changes the shape and size of the crystallites that comprise graphite, a process known as dimensional change, which in turn degrades the mechanical properties of the graphite. The primary focus is on neutron damage, such as atomic displacement damage in which neutrons collide with atoms in the graphite lattice, both creating a 'vacancy' (a 'point defect') and displacing an atom into another position. Some of the displaced atoms find another vacancy to fill. However, those that do not, come to rest in non-ideal locations; that is, not along the symmetrical lines of the lattice. Because these atoms, known as interstitial atoms, are not in the ideal location they have an energy (Wigner energy) associated with them. When large amounts of interstitial atoms have accumulated they pose a risk of releasing all of their energy suddenly, creating a temperature spike. Sudden unplanned increases in temperature can present a large risk for certain types of nuclear reactors with low operating temperatures and were the indirect cause of the Windscale fire in 1957, the worst nuclear incident in British history.

The existing consensus for radiation damage considers the aggregation of interstitial atoms into discs/sheets of new graphite (graphene) between existing layers, and the aggregation of vacancies into lines, making a slot in the graphite. The Sussex nuclear graphite programme started with discovering in 1997 that the interstitial atoms bonded neighbouring layers together covalently (this is the so-called 'spiro'-structure). A whole class of cross-linking defects between graphite layers were found [See Section 3, R1]. It became apparent from research in Sussex that the assumed extreme mobility of interstitial atoms was incorrect and longstanding theories of dimensional change were incomplete [R2]. Archival research confirmed quantitative inadequacies in the theory and so a new theory was proposed, by Heggie and colleagues, with the most important component being reported in 2007 [R2]. The new theory does not rely on the movement of vacancies and interstitial atoms and on the formation of new graphite sheets, but argues that 'basal slip' is promoted by neutron collisions, resulting in buckling and folding of existing graphite layers [R6]. This theory is supported experimentally, and has been refined by Heggie and co-workers with improved simulations and diffractograms [R3 and R2]. In the context of the science of radiation damage, this is a paradigm shift, and the description of buckling and folding in layered materials such as graphite is new and fundamental.

Key researcher: Malcolm Heggie at Sussex 1/1/96 to 30/9/2012.

3. References to the research

R1 Telling, R.H., El-Barbary, A., Ewels, C.P. and Heggie, M.I. (2003) 'Wigner defects bridge the graphite gap', Nature Materials, 2(5): 333-337. http://www.nature.com/nmat/journal/v2/n5/full/nmat876.html

R2 Heggie, M.I., Suarez-Martinez, I., Savini, G., Haffenden, G.L. and Campanera, J.M. (2010) 'Radiation damage in graphite – a new model' in Proc. IAEA Consultancy, Solutions for Graphite Waste: A Contribution to the Accelerated Decommissioning of Graphite-Moderated Nuclear Reactors, IAEA-TECDOC-1647, Manchester UK, 39-46. http://www.pub.iaea.org/MTCD/publications/PDF/TE_1647_CD/PDF/TECDOC_1647.pdf

R3 Heggie, M.I., Suarez-Martinez, I., Davidson, C. and Haffenden, G. (2011) 'Buckle, ruck and tuck: a proposed new model for the response of graphite to neutron irradiation', Journal of Nuclear Materials, 413(3): 150-155. http://dx.doi.org/10.1016/j.jnucmat.2011.04.015

R4 Latham, C.D, Heggie, M.I., Gámez, J.A., Suárez-Martínez, I., Ewels, C.P. and Briddon, P.R. (2008) 'The di-interstitial in graphite', Journal of Physics: Condensed Matter, 20(39) 395220 doi: 10.1088/0953-8984/20/39/395220

R5 Haffenden G. and Heggie, M. (2010) 'Using First Principles Calculations to Estimate Thermal Properties of Graphite and its Defects', in Neighbour, G. (ed.) Securing the Safe Performance of Graphite Reactor Cores. RSC Publishing 185-192. ISBN 978-1-84755-913-5

R6 Heggie, M.I. (2010) 'Carbon in Moderation', Vega Science Trust. http://www.vega.org.uk/video/programme/316

Research grants underpinning, and/or resulting from, underpinning research:

- EPSRC £1.4M *Fundamentals of current and future uses of nuclear graphite*: EP/I003312/1 (15/09/2010 to 14/03/2014, now extended to 14/9/14)
- EPSRC *The Elementary Carbon project* (EP/G062943/1, 2009-2010)
- TSB Developing the Nuclear Supply Chain: *The influence of Graphite Irradiation on Plant Life Optimisation*

Outputs R1, R3 and R4 best indicate the quality of the underpinning research.

Outputs can be supplied by the University on request.

4. Details of the impact

Research by Heggie at Sussex has impacted significantly on generation and interpretation, by the nuclear industry, of Materials Test Reactor data, used to assess reactor lifetime. In particular, Heggie's research has influenced the Core Component Condition Assessment (CCCA); the CCCA is a key component of the safety assessment that comprises elaborate modelling of reactors, including a module (UMAT) that describes the material properties of the graphite moderator as a function of temperature, coolant composition, neutron dose, and applied stresses. The UMAT module relies on constitutive equations that employ the concept of equivalent temperature (Paper 28). However, the Sussex model has demonstrated this concept is inappropriate for reactor graphite temperatures, and contributed to a decision by the nuclear industry to revise it. Without this demonstration, there was a danger that the £22M Materials Test Reactor programme (Blackstone project) would have produced data less relevant to reactor operation.

More importantly, in light of the Sussex model, Paper 28 (which employed the equivalent temperature concept) has been replaced by EDF with a new paper ('P28') that uses a new graphite behaviour model (B++) that does not invoke the equivalent temperature concept. See for example DAO/JIEC/162/AGR/11 J. Smith and B.C. Davies May 2012 and other Graphite Core Committee papers. [C1]

'Paper 28' separated 'dimensional change' and 'irradiation creep' – the first being a strain that depended on neutron dose and the second being the response of graphite components to applied stresses while under irradiation. The Sussex model attributes the bulk of dimensional change to basal slip, however, a process inherently related to irradiation creep. The implication of this model is that, rather than being two separate physical processes, irradiation creep is best described as dimensional change occurring under applied stresses. The new behaviour model for the core, being one of the 20 or so potentially life-limiting factors, has allowed an extra 48 total reactor-years, so far, of planned life [C1].

Calculations to quantify the impact of the Sussex contribution, are based on reference data from the submission by EDF to the Technology Strategy Board for a project on irradiation creep, which was successful in being funded. These calculations are supported by EDF [C1]. The total plant life extension project (PLEX) provides for an extra nine years of life for 14 reactors. At £0.5M per day, per reactor, this equates to £23bn at today's prices. Approximately two thirds of this contributes to the UK economy through the nuclear supply chain (i.e. £15bn). Aside from the direct economic effects, there are also, of course, effects on the UK's carbon dioxide emissions, fossil fuel reduction, and energy deficit.

An alternative calculation is based on the present annual contribution to UK GDP of the industry, of about £3.3bn, which gives a potential £30bn over nine years at today's prices. So PLEX is worth £15bn–£30bn to the UK economy at today's prices.

An understanding of irradiation creep is estimated as contributing (£500M), i.e. 1/30th of the £15bn. An understanding of creep is not possible without understanding underlying dimensional change and the Sussex work has provided a foundation for understanding dimensional change, which is conservatively 10-20 per cent of the solution [C1]. This gives an impact of the order of £100M at today's prices, with £40M having accrued already and a further £60M over the rest of the period.

Undoubtedly, there remains a difference between what might be possible with engineering solutions and what would be acceptable to the nuclear regulator. Increasing the fundamental understanding helps the industry to maximise its use of engineering solutions to reactor life extension.

The EPSRC, in its review of the impact of Chemistry, concludes: 'the work at the University of Sussex on graphite as a moderator in AGRs is contributing to the better definition of reactor longevity and safety. If the fourteen UK operating AGRs closed unnecessarily early, by perhaps one year, it could lead to losses running into billions of pounds, threaten the UK's carbon dioxide emission targets (linked to reducing fossil fuel dependency) and widen the nation's energy deficit'. [C2]

The importance of Heggie's work in this respect is illustrated by regular invitations for dialogue with EDF Energy Nuclear Generation (EDF-E-NG), by Heggie's invited position on the Graphite Core Committee that has advised EDF-E-NG since 2007, and by Heggie's invitation onto the International Atomic Energy Agency (IAEA) Collaborative Research Programme on Irradiation

Creep in Graphite [C3]. The understanding of graphite damage is also relevant to the material's use in the design and development of generation IV reactors.

5. Sources to corroborate the impact

C1 Group Head, Graphite Core Project Team, EDF Energy.

C2 RSC/EPSRC (2010) *Economic Benefits of Chemistry Research to the UK* pp76-77 http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ChemistryImpact.pdf

C3 Gas-Cooled Reactors Technology, Nuclear Power Technology Development Section, Division of Nuclear Power, Department of Nuclear Energy, International Atomic Energy Agency.

C4 Nuclear Inspector, Office for Nuclear Regulation.
Can endorse the general impact of the research and the importance of graphite core as being the most probable life limiting factor for AGR

C5 Poulter, L. *(2012). The role of graphite in nuclear power stations*.
http://news.hse.gov.uk/onr/2012/10/onr-regulates-graphite-in-nuclear-reactors/
This explains why it's vital to monitor the continued use of graphite, as reactors reach the end of their planned operation.