Institution: University of Bristol

Unit of Assessment: 9 - Physics

Title of case study: Bristol research helps extend life of nuclear power stations, with major financial and environmental benefits

1. Summary of the impact

Researchers at the University of Bristol's Interface Analysis Centre played a key role in making it possible to extend the life of two nuclear power stations. Their insights into how the microstructure of reactor-core graphite degrades during service and how the material fractures enabled Magnox Ltd to construct a convincing safety case for Oldbury nuclear power station to operate for an extra four years and Wylfa power station to run for an additional four to six years. In terms of the value of the electricity generated, these extensions are worth some £5 billion. In addition, the longer lifespan of these low-carbon power sources means that less energy has to be generated from other, high-carbon sources, with the environmental benefit of an overall reduction in CO_2 emissions.

2. Underpinning research

Background

Graphite bricks are used as a moderator for Magnox and advanced gas-cooled nuclear reactors (AGRs). The graphite is polygranular, porous and quasi-brittle (i.e., the material remains brittle but behaves in a non-linear fashion prior to macroscopic failure).

During service, the graphite reactor core is subject to an environment of neutron irradiation and hot CO_2 gas which changes the microstructure and the mechanical and physical properties of the graphite. The mass-loss and associated decrease in strength is monitored by periodically removing surveillance specimens installed at commencement of operation and samples trepanned from fuel and interstitial channel bricks. These provide material on which to undertake a range of measurements including porosity (weight loss) and mechanical properties. However, it is important to be able to understand the mechanisms that lead to these changes in order to maintain safe operation for the whole of the reactor's service life, which in the case of the Oldbury and Wylfa Magnox power stations is more than 40 years rather than 25 years as originally intended.

To provide improved understanding of the mechanisms leading to the observed changes in the properties of pile grade A (PGA) graphite used for Oldbury and Wylfa, Magnox Ltd placed a series of research contracts with the University of Bristol between 2005 and 2011.

The research

The aim was to investigate the mechanisms leading to changes in (i) the microstructure and (ii) the deformation and fracture characteristics. A range of novel, state-of-the-art experimental techniques were employed and developed to undertake this research.

In 2002, a new materials analysis technique – a focused ion beam (FIB) instrument – was introduced to the University of Bristol. This allowed the machining and imaging of materials on a nanometre scale. The technique was used here to provide high spatial resolution tomographic images of the virgin and irradiated PGA graphite for the first time. When combined with commercial software, it was possible to obtain 3-D representations of the underlying pore structure to a nanometre-scale resolution [1,2]. The size, shape and inter-connectivity of the pores was established, revealing that the overall porosity developing over service life was both irregular in shape and tortuous in morphology, and that the graphite assumed a skeletal structure when highly porous.

Deformation and fracture behaviour was considered at both the macro- and micro-scale. In general, at the macro-scale force-displacement traces showed pre-peak non-linearity and a post-peak progressive decrease in force [3,4]. Digital image correlation studies using flexural tests showed macro-crack initiation involving the formation of three- to five-millimetre-long process zones. Within such localised regions, micro-cracks initiate and grow as a precursor to the formation of macro-cracks. The latter propagate preferentially through the porous matrix, but are impeded and deflected by the filler particles [4]. Detail of the fracture mode was investigated at the micro-scale using a combination of FIB milling and imaging, which provided new insights into the underlying fracture mechanisms [5,6]. The research team found that a key stage in the overall cracking mechanism was the ability of the material to store elastic strain energy. Combined with micro-cracking, the elastic strain energy has to achieve a critical value to allow macro-crack formation, leading to failure of a component [6].

Key researchers

Dr. P. J. Heard, University of Bristol Research Fellow; appointed October 1993.
Dr. G. M. Hughes, University of Bristol Research Assistant; appointed December 2003; moved to Department of Materials, University of Oxford, February 2008.
Dr. S. Nakhodchi, University of Bristol Research Associate; appointed 2007; moved to K.N. Toosi University of Technology, Iran, 2012.
Prof. P. E. J. Flewitt, School of Physics, University of Bristol; appointed 1995.

3. References to the research

[1] Hughes, G.M. and Wootton, M.R. (2008), A preliminary examination of the pore structure of graphite using focussed ion beam microscopy, Magnox Electric Report, MEN/ESTD/GEN/REP/0060/07, Issue 1. Can be supplied upon request.
[2] Hughes, G.M., Heard, P.J. and Wootton, M.R. (2009), Examination of the pore structure of PGA using FIB and Amira 3-D reconstruction software, Magnox North Report, MEN/EWST/GEN/0001/09. Can be supplied upon request.
[3] *Nakhodchi, S., Smith. D.J. and Flewitt, P.E.J. (2013), The formation of fracture process zones in polygranular graphite as a precursor to fracture, *Journal of Materials Science*, **48**, 720-732. DOI: 10.1007/s10853-012-6785-4.
[4] Heard, P.J., Wootton, M.R., Moskovic, R. and Flewitt, P.E.J. (2010), Crack initiation and propagation in pile grade A (PGA) reactor core graphite under a range of loading conditions, *Journal of Nuclear Materials*, **401**, 71-77. DOI: 10.1016/j.jnucmat.2010.03.023.
[5] *Heard, P.J., Wootton, M.R., Moskovic, R. and Flewitt, P.E.J. (2011), Deformation and fracture of irradiated polygranular pile grade A reactor core graphite, *Journal of Nuclear Materials,* **418**, 223-232. DOI: 10.1016/j.jnucmat.2011.07.003.
[6] *Moskovic, R., Heard, P.J., Flewitt, P.E.J. and Wootton, M.R. (2013), Overview of strength, crack propagation and fracture of nuclear reactor moderator graphite, *Nuclear Engineering and Design*, accepted manuscript in press. DOI: 10.1016/j.nucengdes.2013.05.011.

Grants

[7] Flewitt, P.E.J., Smith, D. and Heard, P.J. (2012-2015) *"QUasi-Brittle fracture: a 3D Experimentally-validated approach, 'QUBE'"*, EPSRC EP/J019801/1, £532,854.
[8] Humphries, P.N., Bond, G., Scott, T.B., Heard, P.J., Cooke, D.J. and Eccles, H. (2011-2015). *"The Post-Disposal Behaviour of C-14 and Irradiated Graphite. 'C14-BIG'"*, EPSRC EP/I036354/1, £728,414.
[9] Fox, N., Flewitt, P.E.J., Heard P.J., Scott, T.B., Allan, N. and Cryan M.J. (2012-2016). *"Beta-enhanced thermionic energy converters and nuclear batteries employing nanostructured diamond electrodes",* EPSRC EP/K030302/01, £951,947.

4. Details of the impact

As part of the research described above, the University of Bristol was asked in 2007 to undertake a study of the micro- and nano-scale structure of the nuclear graphite used in Magnox power stations. At that time, the Oldbury station was due to cease generation in 2008, and Wylfa in 2010. As detailed in the letter of support from Magnox [a], there was a concern that the graphite bricks within the core of the reactor could fracture, which might lead to an alteration in the coolant gas flow path within the bricks, local hotspots and possibly melting of the fuel. It was acknowledged that the reactor core was a life-limiting factor for both the Oldbury and the Wylfa reactors. Further studies were commissioned from Bristol by Magnox between 2007 and 2011. Confidential reports were returned to Magnox, and some of the work was published in the open literature to give the work an independently reviewed pedigree.

Bristol's research improved the understanding of the degradation and fracture mechanisms of the graphite. It showed that the material is unlikely to undergo a sudden catastrophic failure, and that instead it behaves in a "quasi-brittle" way, in which failure is more graceful and preceded by a more gradual deformation. The novel use of FIB combined with small-scale mechanical testing to investigate this material at Bristol was listed as a highlight in the Health and Safety Commission Nuclear Safety Advisory Committee Review Group, dated 2 October 2007 [b].

As a result of this and other work, a safety case was constructed by Magnox and a decision taken to extend the closure point of the Oldbury power station from 2008 to 2012. The lifespan of the Wylfa power station, which had been scheduled to cease operation in 2010, was also extended, with one reactor closed in 2012 and the other operating until at least 2014.

The safety cases for the operation of nuclear power stations are incremental, in that the lifetime of each station is continually reassessed. End-of-life is delayed as long as it is deemed safe to do so. At each stage, the nuclear authorities require evidence to support the case for lifetime extension. The safety cases are reviewed by the Office for Nuclear Regulation (ONR), an agency of the Health and Safety Executive that oversees the process and grants consent for continued operation. In addition, Periodic Safety Reviews (PSRs) must be carried out by the licensee of a nuclear power plant. These provide the opportunity to undertake a comprehensive review of plant safety, including operational history, ageing factors and the advancement of safety standards.

A recent ONR Project Assessment Report [c] referred to the lifetime extension for the Oldbury nuclear power station, stating: "In support of the graphite safety case and continued operation the licensee also carried out a programme of work associated with the material properties of the graphite moderator ….". The work referred to includes that carried out at Bristol, and as stated in the Magnox letter of support [a], "The research undertaken by the University of Bristol contributed to the necessary improved understanding of how the microstructure of reactor core graphite degrades during service and how such changes modify the associated deformation and fracture… This information, when combined with our other research programmes and detailed assessments, was used to support the arguments in the Safety Cases and provided confidence to the Regulator that Magnox was making every effort and indeed was successful in understanding holistically how this complex material (PGA graphite) performs in service. Indeed it allowed Oldbury to achieve 45 years' operation and one reactor at Wylfa continues to operate."

The value of this life extension can be estimated by considering that operation of a 500-megawatt power station turbine/generator unit (roughly the size of Oldbury) for four years generates revenue of approximately £1.7 billion for the electricity produced. Hence life extension of four years for Oldbury and Wylfa corresponds to approximately £5 billion. Additionally, since nuclear is a low-carbon energy source, considerable benefits to the environment are realised by life extension of the nuclear fleet. For example, a coal-fired power station of the same output as the combined Oldbury and Wylfa power stations operated for four years would emit approximately 60,000,000 tonnes of CO_2. The Bristol research has therefore played a significant role in helping the UK meet its CO_2 reduction targets.

Current work at Bristol is directed at understanding the behaviour of the graphite used in AGR reactor cores, as well as possible routes for decommissioning [7,8,9].

5. Sources to corroborate the impact

[a] Technical Manager, Engineering Function, Magnox Ltd.
Provided a letter of support to corroborate the assertion that the research at Bristol was significant and important in furthering the understanding of PGA graphite, and that this work was used to support the safety case that allowed a lifetime extension.

[b] Health & Safety Executive, www.hse.gov.uk/aboutus/meetings/iacs/nusac/021007/p04.pdf.
Highlighted Bristol's FIB work to map pore interconnectivity in graphite and measure pore sizes, as part of the Magnox safety-related research programme.

[c] ONR-D1-OBA-PAR-11-025, www.hse.gov.uk/nuclear/pars/2011/oldbury-6.pdf.
Gives details of the extension of the Oldbury power station from 31 December 2008 to the end of December 2012 (Introduction) and details of supporting work on the graphite safety case (section 3.3).