Institution: University of Bristol		
Unit of Assessment: 9) Physics		
Title of case study: Bristol's materials research is keeping the UK's fleet of nuclear power stations safe and operating		
Period when the underpinning research was undertaken: 2014 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Peter M Heard	Research Fellow	08/1993 - present
Tomas L Martin	Lecturer	02/2017 - present
Dong Liu	Research Fellow (Honorary) / Lecturer	11/2012 - present
Alexander D Warren	Research Fellow	04/2015 - present
Charles Younes	Research Fellow	1990 - 02/2018
Peter EJ Flewitt	Professor (Honorary)	1995 - present
Period when the claimed impact occurred: 2015 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

University of Bristol (UoB) research has provided essential knowledge that underpins the safety cases made to the Office for Nuclear Regulation for extensions to the operating lifetime of EDF's fleet of advanced gas cooled reactors (AGRs). Prolonged exposure to radiation and extreme thermal environments damages reactor materials and can jeopardise the structural integrity of nuclear power plants. UoB researchers have employed cutting-edge instrumentation and novel analysis techniques to study the degradation of ex-service materials taken from AGRs. This has yielded transformational insights and critical benchmarking to ensure experiments and modelling within EDF Energy's research programme are representative and appropriate for describing the ageing behaviour of materials inside their AGRs. UoB research has also greatly informed the industry standard R5 procedure for assessing structural integrity of materials under extreme conditions. Consequently, UoB research has been instrumental in keeping the UK's fleet of AGRs, which contribute 14% of the UK's energy supply, operational.

2. Underpinning research

The integrity of a large engineering-scale component frequently depends on changes to its nano-scale structure. A mechanistic understanding of the effects of high temperatures, high stresses and environmental degradation can be developed by using a combination of experimental and computational techniques that provide data across multiple length and timescales. Adopting such an approach, UoB physicists working within the School of Physics Interface Analysis Centre (IAC) and the South West Nuclear Hub, have greatly improved the fundamental understanding of degradation processes for two central components of AGRs: Boiler Plant Steels [1-4] and Core Graphite [5, 6]. The structural integrity of these components constitutes a limiting factor for the lifetime of an AGR power plant as they cannot be replaced.

i) Boiler Plant Steels: The boiler plant in an AGR is a series of metal headers and pipework, whose purpose is to transfer energy from the hot pressurised CO_2 coolant in the reactor to the steam circuit which generates power in the turbine. Metals in the boiler plant experience high temperatures and stresses as well as chemical ingress of the CO_2 coolant, which can lead to component cracking. For over a decade, UoB has been performing research in collaboration with, and funded by, EDF Energy through GBP3.5M of industrial contracts and GBP600,000 of UKRI grants to characterise steel and graphite material specimens. The collaboration was motivated by UoB's 30 years of experience working with industry to solve real world materials problems using cutting-edge instrumentation, novel analysis techniques and wide-ranging expertise. They are the only partner of EDF who study via microscopy ex-service and radioactive specimens taken from decommissioned AGR plants.

UoB researchers have deployed a novel combination of advanced characterisation techniques (including electron backscatter diffraction, magnetic force microscopy and high-speed atomic force microscopy) to study the microstructural changes that arise in-service through thermal ageing [1] and creep [2], which affect the structural integrity of the Type-316H steel alloy used in boiler plants. Creep is a major factor affecting the strength of boiler plant steels, and the work showed how creep initiates via the preferential formation of creep cavities in the vicinity of localised ferrite phases, as pictured in Figure 1(a) [2]. Analysis of the evolution of the microstructure of the steel tubing material in the boiler when exposed to the CO_2 coolant [3] revealed that more carbide phase grew within the steel with increasing exposure to CO_2 (Figure 1(b)). Such carbide growth degrades and weakens the steel because it removes elements from the metal that protect it from the breakaway oxidation that causes structural failure [3]. Characterisation of the structure of ex-service boiler steels also demonstrated that the steel phase chemistry at cracks is significantly different in ex-service reactor material than in specimens tested in air or non-pressurised CO_2 [4]. This demonstrates unequivocally that to accurately predict the aging behaviour of boiler plant steel components, it is essential to study ex-service specimens. This is made possible by UoB's unique ability to characterise radioactive samples.

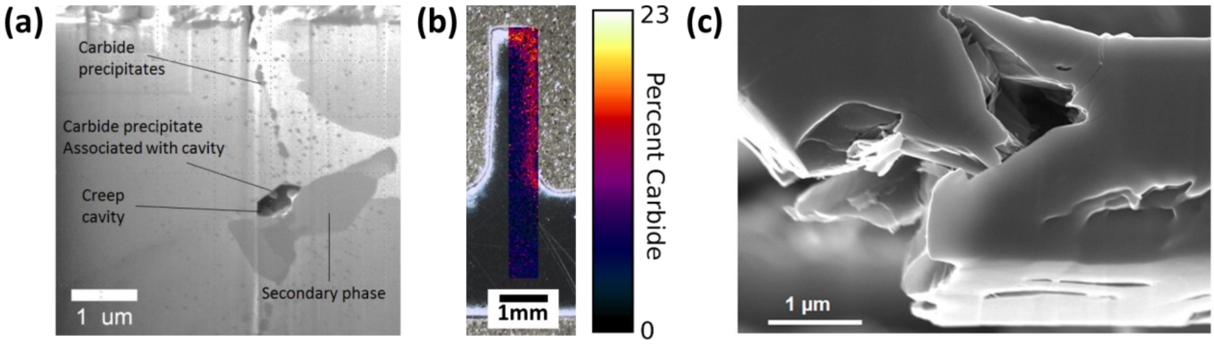

Figure 1: *Microscopy on reactor materials undertaken at UoB. (a) Focused ion beam cross-section showing secondary phase ferrite and carbide precipitates associated with creep cavities in a 316H boiler steel alloy [2] (b) HS-AFM mapping of carbide fraction data across an entire boiler fin [3] (c) Complex fracture behaviour of a microcantilever of nuclear-grade graphite [5].*

ii) Core Graphite: Graphite bricks are employed in the reactor core of AGRs both as a neutron moderator and for structural support. The microstructure and physical properties of the graphite evolve over the service lifetime due to radiation damage and oxidation by CO_2 coolant gas. Specifically, the graphite increases its porosity and slowly weakens, resulting in deformation of the bricks. Ongoing funding through the EDF High Temperature Centre, along with over GBP1 million funding from EPSRC, has supported the development of a novel in-situ micro-mechanical testing method using focused ion beam techniques, which allows real-time viewing of deformation and fracture (Figure 1(c)) [5]. UoB researchers have used a combination of X-ray diffraction and electron microscopy on both reactor-exposed and laboratory specimens simulating reactor conditions. This work has enabled a comprehensive characterisation of the changes in the mechanical properties of core graphite that arise due to both irradiation and oxidation. A key finding was a differing response between the filler particles (which are added to the bricks in manufacture to improve structural stability), which became stiffer under irradiation in an oxidising environment, and the matrix, which remained unchanged [5]. Experimental data were used to develop a detailed computer simulation model, which showed that increasing irradiation levels result in a progressive decrease in elastic modulus and tensile strength of the graphite [6]. The combination of computer modelling and materials characterisation used by UoB provides a much more robust estimate of graphite degradation mechanisms than either approach alone and represents the state-of-the-art in terms of efforts to understand and predict the aging properties of core graphite in AGRs.

3. References to the research

1. B Chen, JN Hu, **PEJ Flewitt**, ACF Cocks, RA Ainsworth, DJ Smith, DW Dean, F Scenini. (2015). Effect of thermal ageing on creep and oxidation behaviour of Type 316H stainless steel, *Materials at High Temperatures,* 32, 592-606 DOI:10.1179/1878641315Y.0000000005
2. **AD Warren**, IJ Griffiths, RL Harniman, **PEJ Flewitt** and TB Scott. (2015). The role of ferrite in Type 316H austenitic stainless steels on the susceptibility to creep cavitation, *Materials Science and Engineering: A*, 635m 59-69. DOI:10.1016/j.msea.2015.03.048
3. C Liu, **PJ Heard**, OD Payton, L Picco, **PEJ Flewitt.** (2019). A comparison of two high spatial resolution imaging techniques for determining carbide precipitate type and size in ferritic 9Cr-1Mo steel, *Ultramicroscopy*, 205, 13-19. DOI:10.1016/j.ultramic.2019.06.005
4. **AD Warren, PJ Heard, PEJ Flewitt, TL Martin.** (2020). The role of replicated service atmosphere on deformation and fracture behaviour of carburised AISI Type 316H steel, *Key Engineering Materials,* 827, 318-323. DOI:10.4028/www.scientific.net/KEM.827.318
5. **D Liu** and **PEJ Flewitt.** (2017). Deformation and fracture of carbonaceous materials using in situ micro-mechanical testing, *Carbon,* 114, 261-274. DOI:10.1016/j.carbon.2016.11.084
6. B Šavija, GE Smith, **PJ Heard**, E Sarakinou, JE Darnbrough, KR Hallam, E Schlangen, **PEJ Flewitt.** (2018). Modelling deformation and fracture of Gilsocarbon graphite subject to service environments, *Journal of Nuclear Materials*, 499, 18-28. DOI:10.1016/j.jnucmat.2017.10.076

These references have accrued significant citations, including from international groups.

4. Details of the impact

The EDF Energy's fleet of nuclear power stations contribute 8.7GW to UK electricity generation and are a key source of low CO_2 electricity for the UK. Fourteen reactors totalling 7.5GW of generation (14% of overall UK capacity) are Advanced Gas-cooled Reactors (AGR), all of which were originally scheduled to cease operation within the next decade. With new nuclear reactors such as EDF's Hinkley Point C not scheduled to come online until the mid-2020s, and with an ongoing programme to close the UK's remaining coal-fuelled power plants by 2025 in order to combat climate change, there is a considerable risk that the UK electricity grid will be unable to cope with demand. The issues were detailed in a 2013, Royal Academy of Engineering report which concluded that '*in the near term the focus must be on maintaining sufficient existing plant'.*

To ensure the security of the UK's electricity supply, EDF has, for the past fifteen years, been investigating whether the operational lifetime of their AGR fleet can be safely extended. Since 2008, EDF Energy has added an average of over eight years to the expected closure date of the AGR fleet; without these extensions, four stations (eight reactors) would have closed, depriving the UK of much needed low carbon electricity [A]. Continued operation of the AGR fleet has a direct benefit to the UK economy by reducing the costs of replacement generation and meeting CO_2 emission targets. Each reactor powers approximately 1 million homes and generates over GBP1 million worth of electricity per day. If all the AGR plants achieve the required 40-year operating life, it will equate to savings of many tens of billions of pounds. Operating lifetime extensions to date correspond to around GBP40 billion of additional electricity generated.

Contribution to the safety cases for the extension of operation of AGRs

The approval process for extending the operating period of AGRs requires the development and submission of detailed and robust safety cases to the UK Office for Nuclear Regulation (ONR). Cases are individual and bespoke to each reactor, for example, in 2018, the ONR agreed to the extension of the operating period of Hunterston B Reactor 3 [B]. The availability of reliable scientific evidence is critical for the validity of such safety cases. UoB's research has made an essential contribution:

“The Interface Analysis Centre (IAC) at the University of Bristol has the unique capacity to analyse ex-service material from reactor extraction and surveillance schemes. This capability is essential to provide accurate information about the microstructure and degradation behaviour of reactor components and benchmark against simulated experiments performed elsewhere as part of the programme. ***Without the information on in-service material behaviour provided by Bristol, it would have not been possible to develop the understanding required to underwrite the safety cases on boiler plant steels.****”* - EDF CTO Chemistry & CO_2 Oxidation Group and CTO Assessment Technology Group [C].

UoB research has enabled the study of radioactive samples using state-of-the-art microscopy [1-4] which has allowed the analyses of boiler steel materials taken directly from AGR plants through the multi-million-pound oxidation monitoring scheme (OMS) [D] and Boiler Lifetime Inspection and Monitoring Program (BLIMP) [E]. These analyses of ex-service materials combined with in-situ surveillance analysis [5] and computer simulation studies [6] of reactor core graphite have led to transformational new insights into how reactor materials age and become damaged in AGR plants. This new understanding allows, in turn, considerably more accurate and reliable predictions of structural integrity than had previously been possible. UoB results have provided crucial input into EDF Energy’s R&D programmes on oxidation and carburisation [F] and creep, the outputs of which serve to validate arguments in the safety cases submitted to ONR for safe continued operation of AGRs. Consequently, UoB research provides an essential element of EDF Energy’s safety case for lifetime extension of the entire AGR fleet, including, for example, the 2018 extension of Hunterston B Reactor 3 [A].

UoB analysis of oxidation [2] and carburisation [4] (as part of the Innovate UK programmes ENVISINC and ENCAMP) revealed that degradation due to carburisation occurs in the Type-316H steel components used at the top of the AGR boiler [G]. This finding was not anticipated prior to the UoB study and has subsequently become a major part of EDF’s research programme [H] and considerations for lifetime extension [C]. Additionally, this research [4] demonstrated the existence of important differences in crack chemistry between specimens exposed to real reactor conditions and those where reactor pressure CO_2 was not present. This latter finding has justified the construction of a new GBP300,000 high temperature gas stress rig at Jacobs (ENCAMP project) which enables laboratory simulations of real reactor conditions. The significance of UoB’s contribution to the science underpinning lifetime extension cases was recognised by the 2018 Academic Innovator award to the South West Nuclear Hub by The Engineer magazine.

Beyond materials investigations, the UoB team provide expert scientific advice on nuclear materials to EDF as well as key professional and governmental bodies. Professor Flewitt, Dr Martin and Dr Warren contributed research and expertise to EDF Energy via the Bristol-EDF High Temperature Centre research programme. Regarding the importance of the IAC’s advice, EDF stated: “*The research work performed by the University of Bristol over the last few years has proved extremely useful information for the company in terms of the investigation of specific plant components and furthering our understanding of the detailed degradation mechanisms of the graphite core in AGRs. This work has strengthened our strategic partnership between EDF Energy and UoB, designed to help solve some of our technical challenges for AGR plant life extension. We consider that the IAC’s work as being* ***extremely valuable*** *for the company and the research performed by Bristol feeds directly to help* ***underwrite the safety cases for lifetime extension*** *made by EDF Energy to the Office of Nuclear Regulation.”* – EDF CTO on graphite [I].

Bristol’s contribution to the R5 procedure — Setting industry technical standards

Bristol’s research on nuclear materials has impact beyond lifetime extension for AGRs. The R5 procedure is an industry-developed standard that is maintained by EDF for structural integrity assessments of components at high temperature where creep is a relevant failure mechanism, such as the steels in an AGR. This procedure is recognised by the ONR and the International Atomic Energy Agency (IAEA) as reflecting the latest understanding of materials behaviour at high temperature. R5 is also utilised by other UK and international industries, such as the UK Atomic Energy Agency (UKAEA) and Rolls Royce, whose fusion reactors and aerospace engines experience similar high temperature and stress regimes [J].

UoB research on the microstructure of boiler plant steels [2,3] feeds directly into the R5 assessment procedure. The R5 procedure contains engineering predictions of plant life based on understanding of degradation mechanisms and relies on direct evidence of material behaviour from characterisation performed by UoB such as that reported in Refs. [2] and [3]. Specifically, electron backscatter diffraction of boiler plant material was used to inform finite element crystal plasticity modelling that input directly into the R5 procedure on primary creep regeneration and repriming. UoB analysis of ex-service materials has been used to compare the effects of high temperatures and stresses on real specimens to what is predicted by R5 procedures, which has improved the reliability of the standards.

Whilst UoB research in this area is currently focused on the needs of AGR lifetime extension, the insights from the research into high temperature materials degradation will also inform future developments in high temperature generation IV fission reactors, fusion energy and aerospace. EDF have stated that: *"We see the IAC's work as being extremely valuable for the company and the research performed by Bristol feeds directly into development of the R5 procedures and the safety case for lifetime extension made by EDF Energy to the Office of Nuclear Regulation."* - EDF CTO Chemistry & CO_2 Oxidation Group and CTO Assessment Technology Group [C].

In summary, the UK is committed to greatly reducing CO_2 emissions and is commissioning a range of new low-carbon sources of electricity. While this capability is being developed, UoB's vital contributions to the safety cases for lifetime extensions of the existing AGR fleet play a key role in underpinning the UK's energy strategy for the coming decade.

5. Sources to corroborate the impact

[A] EDF Energy (2020). Nuclear Lifetime Management

[B] ONR (2019). The Purpose, Scope and Content of Safety Cases

[C] EDF Energy (2021). Corroborating statement - CTO Chemistry & CO_2 Oxidation Group and CTO Structural Integrity

[D] **AD Warren**, KR Hallam, **PJ Heard, C Liu, PG Martin**, JA Nicholson, **CM Younes**. (2018). Metallurgical analysis of oxidation monitoring scheme (OMS) samples from HRA R1 2014, University of Bristol Interface Analysis Report KRH/IAC/06/16/C01/1872 (confidential)

[E] **AD Warren, PJ Heard,** A. el Turke. (2018). Metallurgical Analysis of Boiler Lifetime Inspection and Monitoring Program (BLIMP) Samples from HYA R2 2016, University of Bristol Interface Analysis Report ADW/IAC/09/18/C03/1927 (confidential)

[F] JE Darnbrough, KR Hallam, **PEJ Flewitt.** (2017). Graphite X-ray diffraction data analysis phase 1. Confidential report prepared for EDF Energy Nuclear Generation Ltd. (confidential)

[G] **CM Younes**. (2015). Oxidation and Carburisation of Type 316 Stainless Steels in AGR Environments. Report prepared for EDF Energy as part of the ENVISINC Innovate UK program, CMY/IAC/15/C04. (confidential)

[H] Shin *et al.* (2017). Oxidation behaviour of steels in advanced gas cooled reactors, *Materials at High Temperatures,* 35, 1-3, 30-38. DOI:10.1080/09603409.2017.1389114

[I] EDF Energy (2020). Corroborating statement – Chief Graphite Engineer

[J] Nuclear Structural Integrity Probabilistic Working Group (2019). Nuclear Structural Integrity Probabilistic Working Principles (produced by Rolls Royce, EDF Energy, Wood, NNL, UKAEA, TWI, University of Bristol and Imperial College London)