Institution: The University of Manchester		
Unit of Assessment: 12 (Engineering)		
Title of case study: Manchester's independent graphite research for the Office for Nuclear Regulation has been instrumental in improving the safety, security and reliability of the UK's nuclear industry.		
Period when the underpinning research was undertaken: 2001 – 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:**
Abbie Jones	Professor	2006 – present
Paul Mummery	Professor	2002 – present
Barry Marsden	Professor (Emeritus)	2001 – 2019
Graham Hall	Senior Lecturer	2003 – present
Alex Theodosiou	Lecturer	2013 – present
Muhammad Fahad	PDRF	2012 – 2020
Tatiana Grebennikova	PDRA	2019 – present
Rahul Nair	PDRA	2019 – present
Wu Wen	PDRA	2019 – present
Period when the claimed impact occurred: August 2013 – July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research conducted by the Nuclear Graphite Research Group (NGRG) at the University of Manchester (UoM) has been instrumental in addressing the problem of safe continued operation of the UK's ageing advanced gas-cooled, graphite-moderated (AGR) nuclear reactors. Analysis developed and conducted by the NGRG has enabled the Office for Nuclear Regulation (ONR) to robustly challenge the position of the licensee and ensure nuclear safety to enable the continued operation of AGRs for **up to an additional 10 years**. Independent modelling of graphite core degradation using software developed at Manchester (ManUMAT) combined with novel statistically-based models and experimental validation has enabled the structural analysis of graphite reactors to be translated into environmental and economic impacts, specifically:

- Extending the operational lifetime of nuclear reactors resulting in direct economic impacts of **GBP1,500,000,000 *per annum*,** generating supply chain income within the UK of **GBP650,000,000 *per annum*** and underpinning **2,000 jobs**.
- **Avoidance of more than 42 million tonnes CO_2** emissions (>17 million *per annum*, *vs* combined cycle gas turbines) **through the provision of ~7.7 GW net of low carbon emission electricity**, which corresponds to the equivalent of **~50 million cars** taken off-road per year.
- Research by NGRG on the life extension has indirectly led to saving up to **GBP745,000,000** in excise from the Climate Change Levy in the UK.
- Capability **growth** and **transfer of essential skills** to the nuclear sector, leading to **>GBP2,000,000** external funding investment in the prevention of AGR core degradation.

2. Underpinning research

The predominant life-limiting factor affecting the UK's nuclear power production is the ageing and degradation of the irreplaceable graphite core, which provides channels for fuel cooling and control rod entry. During reactor operation, irradiation damage and radiolytic oxidation changes the dimensions and properties of the ~1,700 tonnes of graphite components that make up a single typical graphite reactor core. This damage evolution can challenge the structural integrity of the core. UoM's NGRG has pioneered novel approaches to nuclear graphite technology to establish microstructural change/irradiation property relationships, through assessing the structural integrity of reactor graphite components and understanding the age development process. **These have allowed the investigation of mechanisms of graphite behaviour that were previously impossible or impractical to conduct.** This has enabled interpolation of existing databases and prediction of the combined effects of irradiation and radiolytic oxidation on the lifetime behaviour of bricks in AGRs. **The key findings that support this impact are:**

1. The closure of porosity and possible reorientation of crystals can have a significant effect on the response of the material to irradiation, oxidation and stress. Sheets of graphite crystallites form twisted structures that can deform, and recover, to a certain extent, under load. Significant swelling and load-deformation can be accommodated by porosity, which extends in size from the nanoscale to the microscale, published as novel NGRG research findings **[1]**.
2. The inspection data from operating reactors combined with finite element models (a simulator) and Bayesian statistical models (an emulator) was used to calibrate the dimensional changes in graphite and the effect of oxidation enabling the better prediction of core ageing and lifetime of AGR reactors **[2]**.
3. UoM's novel bending strength model has demonstrated the ability to predict trepanned validation data (extracted reactor samples) that were randomly selected in advance and not used in model fitting. The new model accurately predicts the trend of tensile strength in oxidised and annealed Material Testing Reactor (MTR) data **[3,4]**.
4. Although there is a wealth of data, knowledge, and experience on the design and operation of graphite-moderated reactors, we demonstrated that there is a need for existing plants to extrapolate beyond current data and to predict the behaviour of new graphite grades operating for longer lifetimes at higher temperatures **[5]**. This extrapolation will be crucial for future graphite-moderated reactors used in, for example, the hydrogen economy.
5. A difference in dynamic Young's modulus was identified between the edge and the interior of the billet. This variability may affect predictions of graphite ageing because the material response is going to be more complicated and variable than is accounted for in previous models **[6]**.

3. References to the research

The world-leading quality of NGRG's research activity was recognised in the awards of the highly prestigious Queen's Anniversary Prizes for Higher and Further Education in 2011 for Nuclear Engineering and 2013 for X-ray Imaging. The research described in papers **[3]** and **[4]** made a significant contribution to the award of these prizes.

1. B. J. Marsden, M. Haverty, W. Bodel, G. N. Hall, A. N. Jones, P. M. Mummery, M. Treifi, "Dimensional change, irradiation creep and thermal/mechanical property changes in nuclear graphite", *International Materials Reviews*, **2016**, 61(3), 155-182, DOI: 10.1080/09506608.2015.1136460
2. K. McNally, G. Hall, E. Tan, B. J. Marsden, N. Warren, "Calibration of dimensional change in finite element models using AGR moderator brick measurements", *Journal of Nuclear Materials*, **2014**, 451(1–3), 179–188, DOI: 10.1016/j.jnucmat.2014.03.015
3. E. D. Eason, G. N. Hall, B. J. Marsden, G. B. Heys, "Models of bending strength for Gilsocarbon graphites irradiated in inert and oxidising environments," *Journal of Nuclear Materials*, **2013**, 436(1-3), 208–216. DOI: 10.1016/j.jnucmat.2012.06.034
4. E. D. Eason, G. N. Hall, B. J. Marsden, G. B. Heys, "Models of coefficient of thermal expansion (CTE) for Gilsocarbon graphites irradiated in inert and oxidising environments," *Journal of Nuclear Materials*, **2013**, 436(1-3), 191–200. DOI: 10.1016/j.jnucmat.2012.08.022
5. B. J. Marsden, G. N. Hall, A. N. Jones "Graphite in Gas-Cooled Reactors, Reference Module in Materials Science and Materials Engineering, Elsevier, **2020** DOI: 10.1016/B978-0-12-803581-8.00729-3
6. J. D. Arregui-Mena, W. Bodel, R. N. Worth, L. Margetts, P. M. Mummery, "Spatial variability in the mechanical properties of Gilsocarbon", *Carbon*, **2016**, 110, 497-517, DOI: 10.1016/j.carbon.2016.09.051

Over the years 2014–2020, the research described in this case study was supported by grants totalling GBP9,200,000, including funding from the ONR of GBP6,800,000, and pathways that enabled GBP2,400,000 of additional funding.

Awards of particular note include:

- "Provision of a Research team to Support ONR in Graphite Structural Integrity", ONR, 12/2016 – 09/2022, GBP2,100,000, PI: A. Jones
- "Regulatory Support in Analysis of Irradiated Graphite Brick Cracking and Weight Loss", ONR, 1/2020– 1/2024, GBP733,000, PI: G. Hall

- “Graphite Technology Advisory Committee (GTAC)”. ONR, 01/2018 – 12/2022, GBP1,100,000, PI: A. Jones
- “ONR independent Advice and Research”, ONR, 08/2011 – 08/2016, GBP1,100,000, PI: P. Mummery
- “Brick Cracking Network”, ONR, 09/2015 –09/2019, GBP702,000, PI: G. Hall
- “Influence of creep and geometry on strength of irradiated graphite components”, Innovate UK/EPSRC, 04/2015 – 04/2018, GBP586,000, PI: P. Mummery

4. Details of the impact

Context

Around 20% of UK electrical power is generated by 14 graphite-moderated AGRs owned by EDF Energy Nuclear Generation Limited (EDF NGL), with licences to operate issued by the ONR. All these AGRs are between 30 and 42 years old, well beyond their design life of ~25 years. EDF NGL has identified the **life-limiting factor** of these reactors is the condition of the **irreplaceable graphite core**, which provides structural integrity for the fuel and neutron moderation. This condition determines the end of life generation date. To extend operation beyond the reactors approved operation time, the licensee (EDF NGL) is required to submit an extensive safety case to the ONR. To be agreed by the Regulator, the safety case should demonstrate that the graphite core meets fundamental nuclear safety requirements in both standard and fault conditions during any proposed period of life extension. Previously, data and modelling from the MTR was used as a primary source of corroborative evidence. With the limited experimental data available for the further life extension and the age of the graphite core now well beyond original MTR data, EDF NGL has based the recent safety cases on prediction models. Research insights provided by UoM’s independent research and verification (*e.g.* **[1–6]**) has underpinned ONR’s assessment of EDF NGL’s modelling. This helped to prove the safety case for extending the operation of EDF’s AGRs for **up to an additional 10 years**.

Pathway to impact

Since 2001, the NGRG has provided the independent advice to ONR on multiple aspects of graphite core degradation, such as core weight loss, brick cracking, oxidation lifetime behaviour and other aspects of structural integrity of all 14 existing AGRs. This advice was delivered through formal technical reports, publications **[1–6]** and presentations available directly to government bodies and the public **[A]**.

Additionally, with continuous involvement of the Graphite Technology Advisory Committee (GTAC) and Brick Cracking Network (BCN), NGRG members supplied peer reviewed independent research data and analysis of the structural integrity of graphite components *via* reports and during formal meetings **[A]**, **[1–6].**

NGRG has developed the independent software (ManUMAT) and several statistically-based models on structural analysis of graphite material. Using finite element modelling in conjunction with advanced pattern recognition modelling techniques, the assessment studies on the AGR core behaviour, specifically focusing on the predictions associated with extended lifetime, were validated against trepanned reactor data provided by EDF NGL and reported in **[3–6]**.

UoM’s NGRG has pioneered novel approaches to nuclear graphite research by developing a dedicated suite of radiologically supervised laboratories on the UoM campus for the experimental investigation of non-irradiated, irradiated, and oxidised graphite. Using these laboratories, the NGRG was able to characterise nuclear graphite microstructurally (X-ray tomography, spectroscopy, microscopy), isotopically (*e.g.* β & γ), measure irradiated graphite properties (*e.g.* dynamic Young’s modulus *via* ultrasonic and resonance techniques), and further evaluate the evolution in graphite behaviour using thermal oxidation and thermal creep rigs **[B]**, **[1, 2]**.

Furthermore, NGRG has created a bespoke nuclear graphite technology course for Continuing Professional Development (CPD) aimed at building professional capability and graphite knowledge within the nuclear sector. The course was delivered in 2009, 2010, 2012, 2014 and 2019 with attendance of over 120 delegates in total including EDF, ONR, National Nuclear Laboratory (NNL) and numerous nuclear supply chain companies.

Reach and significance of the impact

Extending the operating lifetime of AGR reactors addresses concerns about the approaching energy supply gap, continues to support local economies and jobs, and helps meet the UK's legally binding carbon emission reduction targets.

The significance of NGRG's contribution towards the extension of lifetime operation of advanced nuclear graphite reactors was evidenced by the ONR's Principal Inspector for Graphite Structural Integrity, who states that, "*The ONRs judgements, on the adequacy of EDF Energy NGL's safety justifications for the graphite cores of the UK's Advanced Gas-cooled Reactors, have repeatedly been informed by the independent research conducted by the University of Manchester's NGRG"* **[C]**. Additionally, they elaborate that, "*NGRG research and advice has directly contributed to the improved understanding of the science that underpins safe operation of the UK's Advanced Gas-cooled Reactors. This has had the direct benefit of enabling the ONR to consent to further operation of EDF Energy NGL's oldest reactors at Hinkley Point B and Hunterston B,* ***securing up to 5% of the UK power consumption and capable of supplying electricity to approximately 3.5 million UK homes****"* **[C]**.

The significance of NGRG's contributions was also highlighted by EDF's Chief Graphite Engineer, who stated that, *"Understanding a complex material like graphite as a moderator in a nuclear core involves a blend of science and engineering as well as the consequence on nuclear safety. University of Manchester has a unique role in bringing excellent multi-discipline scientific expertise to address these issues. Their involvement naturally leads to significant impact in their role in supporting safe nuclear generation in the UK"* **[D]**. Additionally they stated, "*The University of Manchester's NGRG have independently developed models to predict the interaction of graphite components in AGR cores under normal operating conditions, and provided challenges to our models and understanding of graphite behaviour leading to more robust safety case arguments and providing more confidence of the predictions of the future state of the graphite core*" **[D]**.

NGRG's research has provided additional benefits for other experts working in nuclear safety regulation. For example, the UK Health and Safety Executive (HSE)'s Principal Statistician stated that, "*the NGRG research has enabled the significant advances in computational power resulting in the development of sophisticated numerical models and data analysis techniques. Their significant contribution in the field of the structural integrity of irradiated graphite components has led directly to greater confidence in predictions of the degradation and failure of core elements in UK Advanced Gas-cooled Reactors (AGRs)*" **[E]**.

Economic benefit of AGR lifetime extension

The economic impacts that reactor lifetime extension has supported for both the UK economy and EDF were characterised by EDF's Chief Graphite Engineer, who states "*NGRG research indirectly influenced a slowing down of the increase in electricity prices in the UK. With the daily operation value of a reactor being* ***~£300k****, the approved life extensions of AGRs results in estimated* ***~£108m*** *per reactor for every additional year of operation. Continued operation of nuclear reactors results in direct economic impacts of* ***£1.5bn per annum,*** *generating supply chain income within the UK of* ***£650m per annum.*** *This profit covers aspects such as use of the grid and contribution to decarbonising the UK's electricity supplies and maintains low-carbon tariffs to the public"* **[D]**.

EDF also highlighted the significant time and financial resources they have invested in the reactor lifetime extension programme, noting that, "*EDF NGL invested over 1000 person-years into the research and invested* ***over £125m****, including over* ***£4.2m in joint NGRG/EDF Innovate UK funding****, in the research to ensure the support for the safety case of Hunterston B reactor and other stations*" **[D]**. Additionally, EDF emphasise the beneficial impact of reactor lifetime extension on high-skilled employment, highlighting that, "*the extended operation of these reactors, made possible by NGRG addressing the need of the independent assessment, guaranteed the employment of staff of around* ***700 positions per reactor*** *(around 500 full-time jobs and around 200 contracts) rising to 6,000 positions during the peak of the extension programme*" **[D]**.

Environmental benefit of AGR lifetime extension

As well as significant economic and employment impacts, the continued operation of EDF's AGRs has been beneficial to the environment by abrogating greenhouse gas emissions associated with energy generation, helping the UK meet its legally binding carbon emission reduction targets. EDF's Chief Graphite Engineer elaborates on the scale of these avoided emissions: "*By providing a crucial independent assessment of the failure of core elements using sophisticated numerical models and data analysis, the NGRG research has generated an indirect impact on the reduction in CO_2 emissions. More than **17m tonnes** of CO_2 emissions are saved over every year of AGRs operation, which corresponds more than **7.5m cars** taken off-road in UK for a year. **~42m tonnes of CO_2 emissions** have already been saved by July 2020 while the overall approval of life-extension for up to 10 years is expected to lead to the savings of more than **116m** tonnes of CO_2 emissions, equivalent to taking more than **50m cars** off the road for a year, helping the UK to meet the CO_2 targets*" **[D]**. EDF also highlighted that reactor lifetime extension has also saved them a significant amount of money as part of the Climate Change Levy, highlighting that "*the research by NGRG on the life extension has also indirectly led to saving up to **£745m** in excise from the Climate Change Levy in the UK, which was set by the government of £18 per tonne of CO_2*" **[D]**.

Building industry capacity of nuclear engineers and transfer of essential skills

The NGRG research has significantly contributed to the capability growth and transfer of essential skills to the nuclear sector. The Chair of the ONR's Graphite Technical Advisory Group (GTAC) has highlighted that "*a range of new analytical characterisation techniques, developed by NGRG, has been at the forefront of the nuclear graphite community worldwide. These advanced characterisation techniques have been used to investigate graphite behaviour and have led to greater insight into the in-service performance of current graphite reactor core systems. They have also: underpinned the use of mechanistically based models to predict future in-reactor performance; have enabled further advice on the safe operation of AGRs to be made with confidence; and have contributed to regulatory decisions which have extended the life of AGRs within the UK"* **[B]**. Additionally, they highlight "*the unique academic contribution that the NGRG have made, and continue to make, in this area of Graphite Structural Integrity for the benefit of "UK plc". REF impact statements are supported naturally by open literature publications, but in addition it is also important to recognise the significant number of quality research reports which you produce directly for ONR (and that are too sensitive to publish openly). These have also underpinned important regulatory decisions."*

The ONR has also had the benefit of skills transfer from NGRG to the nuclear sector. As the ONR's Principal Inspector for Nuclear Safety says, "*The NGRG staff development approach has benefitted the capability at the ONR through the employment of two ex-NGRG researchers, thus increasing the ONR internal capability and increasing the effectiveness of the ONRs challenge of EDF Energy NGL"* **[C]**.

NGRG's research activities have also provided a pipeline of expert scientists to benefit the nuclear industry. NNL, which is the UK Government's industrial nuclear research body, has highlighted how it has benefitted from experts trained by NGRG, stating that, "*NNL has grown the graphite core team through the employment of NGRG doctoral students and research associates, which has led to NNL developing further graphite capability and raising awareness, leading to > £2 M of income (including Innovate UK joint with NGRG, Henry Royce Institute and Nuclear Users Facility) and reinvestments by NNL into the continued graphite research".* Additionally, they highlight "*The Manchester NGRG is the first port of call internationally for all nuclear graphite topics"* **[F]**.

5. Sources to corroborate the impact

[A] List of reports, including: (1) NGRG Report Register; (2) GTAC Report Summary List; (3) ONR - BCN reports; (4) Publications.

[B] Letter of corroboration from the Chair of the Office for Nuclear Regulation's Graphite Technical Advisory Committee, dated 18 August 2020.

[C] Letter of corroboration from the Principal Inspector – Nuclear Safety at the Office for Nuclear Regulation, dated 23 June 2020.

[D] Letter of corroboration from the Chief Graphite Engineer at EDF Graphite Branch, Design Authority for Nuclear Generation, dated 25 June 2020.

[E] Letter of corroboration from a Principal Statistician at the HSE's Science and Research Centre, received 29 July 2020

[F] Statement of corroboration from a Laboratory Fellow – Graphite Technology and PIE at National Nuclear Laboratory, dated 21 June 2020.