Institution: University of Bristol		
Unit of Assessment: 12) General Engineering		
Title of case study: Award-winning earthquake experiments underpin GBP4bn safe life extension of the UK's fleet of Advanced Gas-cooled Reactor nuclear power stations		
Period when the underpinning research was undertaken: 2013 - 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:**
Colin A Taylor	Professor of Earthquake Engineering	08/1983 - 09/2019
Adam J Crewe	Reader in Earthquake Engineering	11/1992 - present
Period when the claimed impact occurred: 2016 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Over GBP4 billion of low carbon electricity generation was directly underpinned by the University of Bristol's award-winning earthquake shaking table experiments on an innovative ¼-scale model of a cracked Advanced Gas-cooled Reactor (AGR) graphite core. Without this research, the UK's 14 AGRs (contributing 14% of the UK's electricity supply) would not be operating beyond the onset of cracking in their graphite cores. The research enabled EDF to present successful seismic safety cases to the Office for Nuclear Regulation, resulting in safe-life extensions of the 8 oldest reactors, from 2016 to 2022. Atkins improved and validated their modelling capability upon which the safety cases depend. EDF's improved safe-life projection of the AGR fleet aids planning of the UK's electricity security and renewal. International industry and public awareness were raised through three prestigious industry awards and a stand at the 2019 Royal Society Summer Science Exhibition.

2. Underpinning research

Advanced Gas-cooled Reactors (AGRs) are unique to the UK. Radiation-driven ageing leads to a loss of mass, geometric distortions, and cracks in the reactor core's graphite lattice bricks. The cores of the 14 reactors (Fig. 1) in the UK's seven-station AGR fleet are gradually cracking in accordance with anticipated mechanisms. For continued operation, EDF must demonstrate that this cracking does not affect the safe shutdown of a reactor following an earthquake. The unique research challenge was to create and shake a meaningful physical model of an AGR's aged graphite core (Fig. 2) to validate the computational methodology (known as GCORE) that is used to assess the seismic safety of a reactor when subjected to a 1-in-10,000-year UK earthquake (equivalent to about a Magnitude 6.2 event). The GCORE numerical model is developed and run by EDF's consulting engineers, Atkins, who were partners in the validation research alongside EDF.

A reactor core consists of a 3D array of thousands of graphite moderator bricks loosely interconnected through a graphite keying system that constrains relative motion between bricks, whilst allowing small movements due to thermal and nuclear radiation effects (Fig. 3a and b). Vertical columns of hollow, 16-sided, lattice bricks accommodate the nuclear fuel rods. The interstices between the lattice bricks are filled by columns of smaller hollow rectangular bricks, which accommodate the control rods. The lattice and interstitial bricks are loosely connected through thin rectangular graphite keys that are free to move in the vertical keyway slots machined into the lattice bricks. The keying system allows the c40,000-component graphite array to expand and contract uniformly in all directions.

Cracks mainly emanate from the lattice brick keyways. Bricks usually crack vertically into two, three or four segments (Fig. 4). Others develop single vertical cracks. Cracking increases the dynamic flexibility of the graphite core, which affects its seismic response. Crucially, excessive distortions of the interstitial columns might prevent insertion of the control rods needed to shut down the reactor. This is a truly complex, non-linear structural dynamics problem, with the principal non-linear mechanisms being the rocking, impact, and contact dynamics between the graphite components.

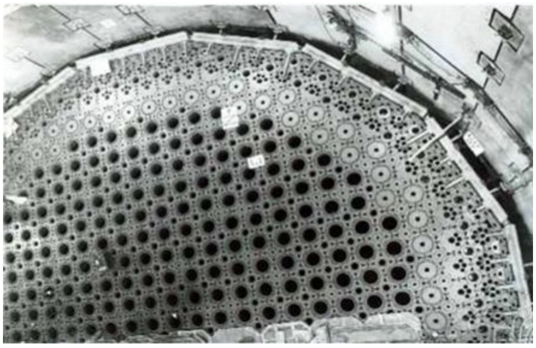

Fig.1 Real graphite core

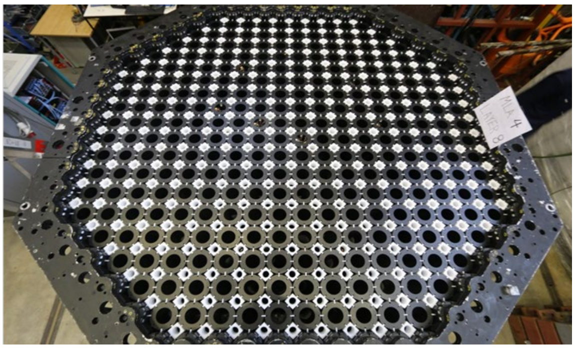

Fig.2 ¼-scale model core

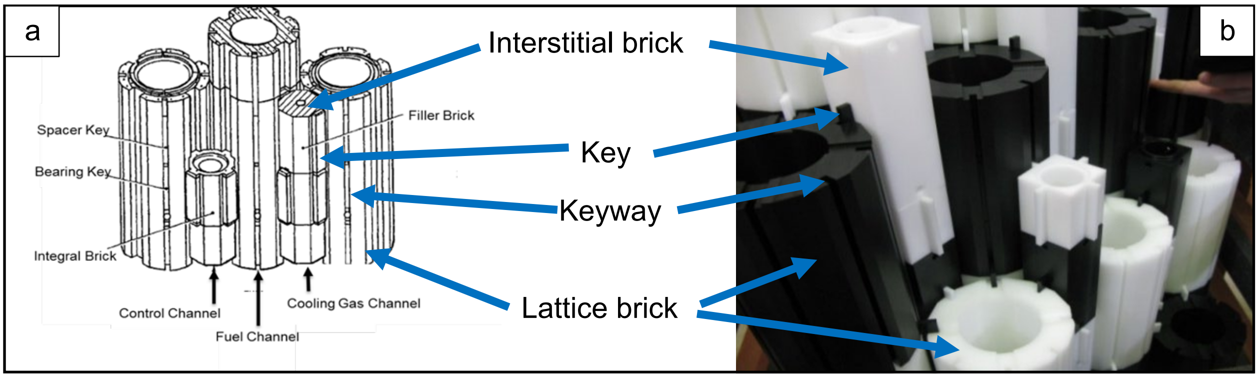

Fig.3 Reactor core arrangement: a) Real core, b) ¼-scale model core

Fig.4 Cracked fuel bricks

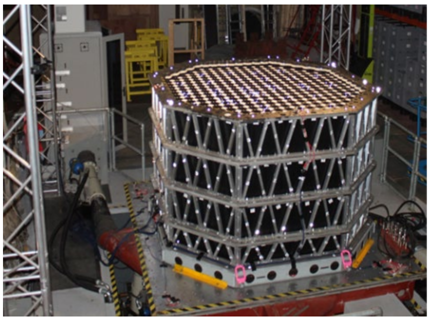

Fig.5 Model on shaking table

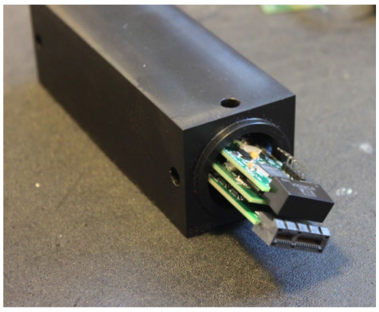

Fig.6 32-channel module

Physical testing of a real core is impossible. Physical scale modelling was the only alternative empirical validation approach [1]. The University's 7-year, GBP6.95 million research programme [i] developed an innovative, complex, high precision, ¼-scale physical model of a representative AGR graphite core assembly that could accommodate a wide range of structurally degraded core configurations. The model was made from Acetal plastic and was shaken on the six-axis EPSRC Earthquake Simulator (shaking table) in the University's engineering laboratories (Fig. 5).

The bespoke physical model contained over 40,000 components and 3,200 sensors in a package measuring approximately 2.5 x 2.5 x 2.0m and weighing 8t. The rig development involved integration of high precision structural engineering and manufacturing, innovative electronic sensor development, and cutting-edge data analysis and experimental techniques [2, 3]. Fig. 6 shows a typical, miniaturised, 32-channel sensor conditioning and data acquisition package (equivalent to three conventional 19-inch-wide electronics racks) designed to fit inside the model bricks. Twelve model cores were shaken with hundreds of simulated earthquakes, producing c20 TB of data that revealed important insights into an aged graphite core's non-linear seismic behaviour and integrity [4].

3. References to the research

[1] The development of a physical model of an Advanced Gas Cooled Reactor core: Outline of the feasibility study, Dihoru L, Oddbjornsson O, Kloukinas P, Dietz M, Horseman T, Voyagaki E, **Crewe AJ, Taylor CA.** & Steer AG. 2017, In: *Nuclear Engineering and Design.* 323, 269-279. DOI:10.1016/j.nucengdes.2017.01.012

[2] A Computer Vision Approach for Dynamic Tracking of Components in a Nuclear Reactor Core Model, Dihoru L, **Crewe AJ,** Horseman T, Dietz M, Oddbjornsson O, Kloukinas P, Voyagaki E. & **Taylor CA.** 2019, In: *Nuclear Engineering and Design*. 344, 1-14. DOI:10.1016/j.nucengdes.2019.01.017

[3] Neural networks for displacement analysis in an advanced gas cooled reactor core model, Dihoru L, Dietz M, Horseman T, Kloukinas P, Oddbjornsson O, Voyagaki E, **Crewe AJ.** & **Taylor CA.** 2018, In: *Nuclear Engineering and Design.* 332, 252-266. DOI:10.1016/j.nucengdes.2018.03.039

[4] Earthquake response of a multiblock nuclear reactor graphite core: Experimental model *vs* simulations, Voyagaki E, Kloukinas P, Dietz M, Dihoru L, Horseman T, Oddbjornsson O, **Crewe AJ, Taylor CA.** & Steer A. 2018, In: *Earthquake Engineering and Structural Dynamics.* 47(13), 2601-2626. DOI:10.1002/eqe.3100

Funding Information:

[i] Six EDF-funded research contracts to the University of Bristol from 2014 - 2020, totalling GBP6.95 million (excl VAT).

4. Details of the impact

Safe lifetime extension for UK AGRs:

EDF determines whether a plant is safe to operate; its safety case must prove this to the Office for Nuclear Regulation (ONR) to gain a licence instrument that permits operation of a reactor. EDF's safety case must prove that sufficient control rods can be inserted to shut down a reactor safely after a 1-in-10,000-year seismic event, otherwise ONR will not issue a licence instrument and the reactor will have to close permanently, as repair or improvement of the graphite core are impossible [A].

Data from the University of Bristol physical model [4] were used by EDF and Atkins to validate the GCORE numerical modelling methodology. Significant improvements to the numerical models were identified, covering issues such as damping, friction and the structural actions of particular keys and cracked brick patterns. Convergence between the numerical and physical models was greatly improved to the point where the ONR accepted the evidence from them [B]. Hunterston B Reactor 4 gained the latest ONR re-start approval in September 2020 [B].

The Chief Technical Officer of EDF described the principal impacts as follows [A]:

> "*The reliable and justified operation of the UK's fleet of Advanced Gas Cooled Reactors (AGR) depends upon the physical plant condition and the maintenance of a valid safety case. The graphite core ages and degrades due to the fast neutron irradiation and radiolytic oxidation. Graphite cores cannot be repaired or replaced, therefore understanding these changes, and their consequences, is important to setting the safe operational life of the graphite cores, which are expected to be a life limiting feature of the current fleet of AGRs.*
>
> *The University of Bristol and EDF have been partners on the Graphite Seismic Validation experiment since 2013. Analysis shows that the graphite cores are very tolerant to widespread cracking of the bricks. However, there was no experimental evidence available and, hence, the requirement to build, shake and analyse a scale model of the graphite core…*
>
> *…The experiments devised and completed by the team at the University have been providing rigorous, highly innovative, and original validation of the computational models built to underwrite the seismic qualification of the AGR fleet. The University assembled a multi-disciplinary team to work on the programme since not only did it require the right seismic physics to scale the behaviour of the full AGR core to the ¼-scale model, it required the*

development and use of novel techniques, involving specially designed miniaturised data acquisition hardware, to capture and process the many thousands of transducer signals needed to provide measures of the brick displacements during the excitations.

The experiment showed that the computer models over-predicted the movements of the model bricks and enabled the reasons to be identified. This experiment successfully showed that the computer models of the AGR cores are conservative and that the predicted safety margins are appropriate to support continued operation.

Without this research the UKs fleet of 14 AGRs would not be operating past the onset of keyway root cracking in the graphite core. Hunterston and Hinkley Point B would have shut in 2018 and Hartlepool and Heysham 1 reactors would be likely to shut in 2021. The research has directly supported over GBP4 billion (13TWd) of generation [to July 2020]. This is up to 14% of the UK's electricity supply at any given time, and directly supports thousands of jobs in the UK, Europe, and the wider international supply chain.

The experiment has been an excellent ambassador for the University of Bristol and EDF. Tours of the University laboratory have been regularly conducted to engage stakeholders ranging from the student body, members of the public, the Office for Nuclear Regulation and all levels of EDF staff from across Europe. The experiment has supported one EDF-funded PhD and multiple undergraduate projects. The experiment was deemed suitably original to be presented at the Royal Society Summer Science Exhibition in 2019…

…The experiment would not have been as successful without the commitment and professionalism of the team at the University of Bristol, EDF are very grateful and proud of the team's achievements."

Informing future UK electricity security and EDF's commercial strategy:

In the UK, EDF currently has 9008 MW of low carbon nuclear generation capacity (including Sizewell B), and 3332 MW of coal and gas fired generation (West Burton A & B). Given the improved understanding of the AGR fleet's seismic integrity that the research has established, EDF's expected AGR station extended closure dates are now as follows [C]:

AGR station	Generating capacity (MW)	Generation started	Originally scheduled closure	Expected closure after extension
Heysham 1	1155	1983	2014	2024
Hartlepool	1185	1983	2014	2024
Hunterston B	965	1976	2016	2022
Hinkley Point B	965	1976	2016	2022
Dungeness B	1120	1983	2018	2028
Heysham 2	1230	1988	2023	2030
Torness	1190	1988	2023	2030
Total	*7810*			

Confidence in the above closure dates is crucial for EDF's long-term business and financial planning. It is also crucial for planning the security and renewal of the UK's future low-carbon electricity supply capacity, noting that the UK's gross electricity capacity margin is c20-30% (7% derated) [D] and the AGRs contribute up to 14% of the UK's current generating capacity [A] (Sizewell B, not an AGR, adds a further c4%[1]).

Capacity building for consultant R&D:

Atkins, a global consultancy, are EDF's consulting engineers responsible for developing and running the GCORE numerical model of the seismic response of AGRs. Atkins benefitted from their partnership with the University of Bristol in several ways [E]:

- A strengthened relationship with EDF due to the validation of GCORE.
- The experimental validation robustly substantiated the modelling technique, which Atkins can in future apply to model dynamic simulation problems efficiently in a range of other

[1] https://www.ofgem.gov.uk/publications-and-updates/infographic-energy-security

situations, improving model fidelity and offering significantly better computational performance and efficiency.
- The opportunity to collaborate with the University of Bristol also gave the Atkins team insight into state-of-the-art seismic testing, which widens the range of options they are able to consider for other seismic analyses.
- Development opportunities for more than 10 engineers since 2015, building technical capability in areas such as seismic analysis, data processing and programming.
- Valuable practical experience for early career engineers through supporting testing campaigns and laboratory-based work.

Industry and Public Engagement Impacts:

The project successfully raised the awareness of wider industry and the general public (particularly young people) of the nature and importance of the AGR seismic safety assessment challenge, and of the rigour, inventiveness, broader applications and career opportunities in the world leading, multidisciplinary, research and engineering that underpins the solution.

In addition to the EDF Innovation Team of the Year prize 2014, the project won two prestigious national industry awards: the ICE SW Region Showcase Award 2017 [F], and The Engineer: Collaborate to Innovate Academic Innovator Award 2018 [G], both generating international publicity.

The project was selected for the Royal Society's 2019 Summer Science Exhibition [H]. The project's 'The Great Bristol Shake Off' stand included interactive learning exhibits culminating in a game for visitors to show what they had learned about earthquake engineering by designing and building their own version of a nuclear power station building and then shaking it to destruction using a mini shaking table. The exhibition was attended by 12,653 students, teachers, members of the public, science and industry leaders, and national politicians [H]. The stand led to online news articles on the Institution of Mechanical Engineers [I] and Geographical Magazine [J] websites, and it generated much positive audience feedback [H], e.g.:
- "*Best: application! Are UK nuclear reactors safe? Knowing that work is being done to ensure safety of UK population*."
- "*Earthquake simulator is impressive and illustrates how the technology developed for the project works. Building your own pieces of architecture makes it more interactive. The touch screen contains lots of information*."
- "*The earthquake simulator was a highlight, the objectives of the project were clearly explained and related to daily life (energy source)*."
- "*Jim from their team was excellent at explaining both the pure science and the industry application. Their "earthquake" experiments were excellent hooks which gave some foundational knowledge for understanding their nuclear reactor project*."
- "*Long engaging conversation with academic on their research. Showed how building can be safeguarded. What is involved in the numerical model – machine learning*."
- "*Everything worked and the game was well thought-out and attracted a lot of attention*."

5. Sources to corroborate the impact

[A] EDF (2020). Corroborating Statement – Chief Technical Officer.
[B] i) ONR (2019, 2020). Hunterston B return to service safety cases. ONR Assessment reports ONR-OFD-AR-19-007, Revision 1, August 2019, *paragraph 151, page 39,* and ii) ONR-OFD-PAR-20-012, Revision 0, September 2020, *paragraphs 20 & 21, pages 12-13.*
[C] EDF Nuclear lifetime management (accessed 23/10/2020).
[D] Royal Academy of Engineering (Oct 2013). GB electricity capacity margin.
[E] Atkins (2020). Corroborating Statement – GCORE Validation Workstream Lead.
[F] ICE SW (2017) Showcase Award 2017 Certificate.
[G] The Engineer (2018). 2018 Winners (accessed 28/10/2020).
[H] Royal Society – Summer Science Exhibition 2019: Individual Exhibitor Feedback.
[I] IMechE news article (2019). 'Shaking table' research protects UK from earthquake-triggered nuclear disaster (accessed 28/10/2020).
[J] Geographical (2019). Are nuclear reactors at risk from earthquakes? (accessed 28/10/2020).