Institution: University of Glasgow (UofG)

Unit of Assessment: UoA12 – General Engineering

Title of case study: Advanced engineering analysis for safe operation and life extension of nuclear power stations

Period when the underpinning research was undertaken: 2011–present

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:
Prof Chris Pearce	Professor of Computational Mechanics	1997–present
Dr Łukasz Kaczmarczyk	Senior Lecturer, Infrastructure and Environment	2009–present

Period when the claimed impact occurred: 2016–present

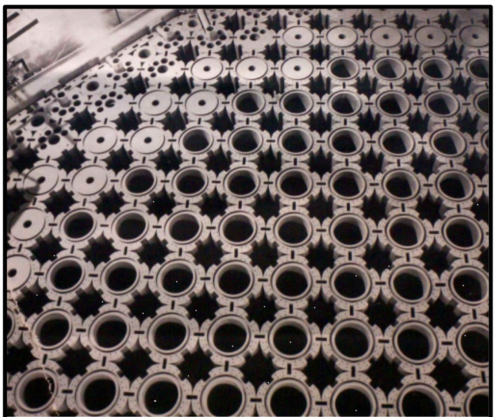
Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

UofG engineering research has developed analysis software and provided the accompanying technical support for predicting and assessing critical, life-limiting structural integrity issues for civil nuclear reactors in the UK. These have assisted the operator, EDF, in assessing the ongoing safe operation of ageing nuclear power stations and have supported nuclear safety cases for the continued and future operation of stations. As more reactors approach their end of life, this research has helped to identify future issues and influenced plans for inspections. This work has contributed to both securing the UK's baseload electricity supply (currently ~17% from nuclear) and achieving the UK's low-carbon energy targets.

2. Underpinning research

Context: Nuclear power provides ~17% of UK electricity. Seven out of the eight civil nuclear power stations in the UK are the Advanced Gas-cooled Reactor (AGR) design, each with two reactors. Each reactor core is 10m high with a diameter of 10m contained within a concrete pressure vessel. A reactor comprises ~3,000 cylindrical graphite bricks that are connected and stacked vertically into 250 channels. Uranium fuel is inserted into these channels.

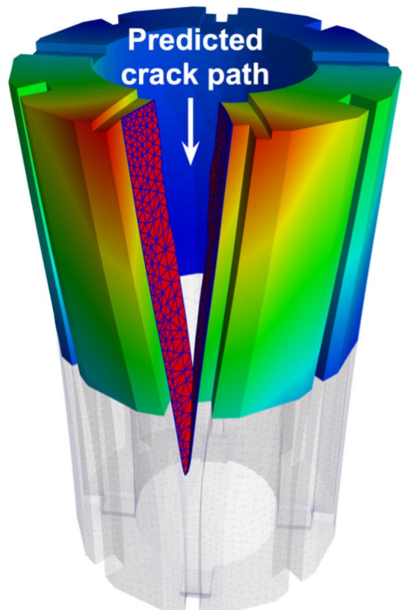


Graphite bricks in AGR reactor core

The core provides structural integrity for housing the fuel and acts as the neutron moderator. In the reactor's aggressive environment, the graphite undergoes neutron damage, compromising reactor structural integrity. Assessment and prediction of integrity are critical to safety and planning reactor lifespan. The condition of the graphite reactor core is the major life-limiting factor for nuclear power stations. Routine inspections of the oldest AGR cores have shown significant cracks in the graphite bricks. Numerical models give EDF the ability to predict if these cracks are life-limiting.

EDF have commissioned several research projects since 2011 at UofG (PI: Pearce) and supported two EPSRC Impact Acceleration Account projects, to develop a new predictive modelling capability. In 2016, Pearce was awarded the Royal Academy of Engineering/EDF Energy Research Chair in Computational Mechanics to continue this work.

Research: Brittle crack propagation is an inherently unstable and highly nonlinear process that continues to be the subject of significant scientific attention despite decades of study. Pearce and Kaczmarczyk established a new methodology and computational framework for simulating this phenomenon in the complex environment of a nuclear reactor. The research exploits *Configurational Mechanics* to describe crack propagation mathematically [3.1, 3.2]. This led to theoretical advances and new numerical methods that were integrated into MoFEM – an open-source finite element analysis software [3.3], developed by Pearce and Kaczmarczyk, that incorporates many of the latest advances in scientific computing.



Computational modelling of cracking in graphite brick

The implementation in MoFEM enables the continuous advancement of crack fronts to be simulated objectively, without influence from the underlying finite element mesh – i.e. without the need for mesh enrichment, mesh splitting or changes to mesh connectivity. The implicit nature of the analyses, requiring several new algorithmic developments, ensures a robust modelling framework in which numerical errors are closely controlled. This has delivered a modelling capability unmatched by other software packages investigated by EDF, that have failed to provide reliable, realistic, accurate predictions of crack propagation and paths.

The primary driver for crack propagation in the reactor core is the complex internal stress state resulting from long-term exposure of the bricks to the reactor's aggressive environment. When one brick cracks and deforms, additional cracks occur in adjacent bricks. This can lead to intersecting cracks and fragments that impair reactor control. Therefore, Pearce and Kaczmarczyk extended their formulation to capture internal stress-driven crack propagation and brick-to-brick contact [3.4].

MoFEM has been extensively tested and validated by UofG and EDF (using partners EDF R&D and Jacobs) against standard benchmarks; available literature; experiments commissioned by EDF for this purpose; and routine reactor inspections.

Whilst being subject to continuous development for research purposes, MoFEM is also simultaneously in use as a robust industrial tool.

3. References to the research

3.1. Kaczmarczyk, Ł., Mousavi Nezhad, M. & Pearce, C. (2014) Three-dimensional brittle fracture: configurational-force-driven crack propagation. International Journal for Numerical Methods in Engineering, 97(7), pp. 531–550; doi:10.1002/nme.4603 *

3.2. Kaczmarczyk, Ł., Ullah, Z. & Pearce, C. J. (2017) Energy consistent framework for continuously evolving 3D crack propagation. Computer Methods in Applied Mechanics and Engineering, 324, pp. 54–73; doi:10.1016/j.cma.2017.06.001 *

3.3. Kaczmarczyk, Ł., Ullah, Z., Lewandowski, K., Meng, X., Zhou, X.Y., Athanasiadis, I., Nguyen, H., Chalons-Mouriesse, C.A., Richardson, E., Miur, E., Shvarts, A., Wakeni, M. &

Pearce, C.J. (2020) MoFEM: An open source, parallel finite element library. Journal of Open Source Software, 5(45), p.1441. (doi:10.21105/joss.01441)

3.4. Athanasiadis1, I., Kaczmarczyk, L., Ullah, Z., & Pearce, C. J. (2019). Mortar contact formulation for hierarchical basis functions using smooth active set strategy. Paper presented at UK Association for Computational Mechanics Conference, London, UK.

4. Details of the impact

The UK's electricity supply is generated by a mixture of nuclear, renewables and fossil fuels. The UK government is committed to the continued use of nuclear power, alongside renewable generation and Carbon Capture and Storage, as an important contributor to the nation's low-carbon energy mix. All of these technologies are important in tackling climate change and diversifying supply, contributing to the UK's energy security and growth. UofG research has allowed EDF to extend the operation of its fleet of nuclear power stations [5.1], supporting the security of the UK's electricity supply, with economic and social impact.

Enhanced operational safety through improved analysis and interpretation of reactor core condition

Although EDF have long predicted the onset of cracking in Advanced Gas-cooled Reactors (AGRs), MoFEM represents a key enabling technology that lets EDF fully interpret observed crack paths and predict future crack paths with increased confidence [5.1]. Since the aggressive environment of reactor cores cannot be replicated experimentally, EDF relies on such predictive modelling. As a direct consequence of UofG research, EDF now have a more reliable, safe method of predicting failure modes, leading to increased safety for the public and EDF's plants.

Over several years, EDF has investigated the ability of other leading computational analysis tools to simulate the onset and propagation of graphite brick cracks. These have all failed to provide reliable, realistic, accurate predictions of crack propagation and paths [5.1]. In 2017, after several years of development, testing and validation, MoFEM was identified by EDF as the primary analysis tool for computer modelling of the development of cracks in graphite bricks [5.1]. MoFEM is the only analysis software able to accurately model existing cracks in a real core environment and to predict future scenarios [5.1]. In 2018, routine inspection of Hunterston B AGR indicated increased graphite brick cracking [5.2], which led to the acceleration of MoFEM's development.

The combination of UofG expertise and MoFEM have supported **nuclear safety cases** [5.1, 5.3] for the continued and future operation of nuclear power plants. Specifically:

- **Hunterston B** – predictions of crack shapes and understanding of graphite fragments (resulting from intersecting cracks) contributed to the safety case that enabled both reactors at Hunterston B to be restarted [5.1].
- **Hartlepool and Heysham 1** – predictions of crack shapes and assessment of the potential for crack arrest in graphite bricks, validated by limited inspections, underpinned the safety case for the future state of the reactor cores, thereby enabling future plant operation [5.1, 5.3].

EDF and Jacobs have already decided to work with UofG and to use MoFEM to assess future challenges (including Heysham 2 and Torness) where *"the ability to model crack propagation in irradiated graphite with a complex geometry and complex contact loading would pose an insurmountable challenge to other tools"* [5.1].

Improving Business Performance

EDF operates all 8 of the UK's nuclear power plants, including 7 ageing AGRs. Inspection of these AGRs confirmed the presence of new keyway root cracks in the reactor core and identified that these were occurring at a higher rate than predicted [5.2]. This led to the decision to keep a number of reactors offline, followed by a short-term return to service. These offline periods and uncertainty about long-term operation of the AGR fleet have significant financial consequences for EDF.

EDF saves millions of pounds for every week of shutdown that is avoided [5.1]. UofG has supported EDF in restarting and continued operation of power stations [5.1] and enabled EDF to predict future behaviour [5.1, 5.3], enabling challenges to be addressed while predicting lifespan and developing mitigating actions long before structural integrity is compromised. This represents a major financial saving to EDF and contributes to long-term stability for the business and its sub-contractors. To give context, a 2016 report by Oxford Economics [5.4] showed that the nuclear sector contributed GBP6.4 billion to the UK economy, employing 66,000 people directly and 154,600 indirectly.

UofG has delivered the industrialisation of MoFEM, critical to its uptake and use by EDF and Jacobs. As is crucial for professional software, a continuous integration system is used for code development, version control and testing. Working with EDF R&D, MoFEM has been extensively tested and validated [5.1]. MoFEM has been integrated with EDF's own engineering analysis software (Code_Aster) and implemented into the workflow of Jacobs [5.3]. UofG lead weekly technical meetings for engineers in Jacobs and EDF R&D on using MoFEM to model crack propagation in reactor cores.

5. Sources to corroborate the impact [all supplied in PDF]

5.1. Testimonial: Graphite Chief Engineer, EDF Nuclear Generation.

5.2. Public statement by EDF Energy on cracking of the Hunterston B reactor core.

5.3. Testimonial: Consultant Engineer and Technical Director, Jacobs.

5.4. Oxford Economics 2016 Nuclear Activity Report for the Nuclear Industries Association.