

## PROJECT ACCENT: GRAPHITE IRRADIATION-INDUCED CREEP IN A MATERIALS TEST REACTOR

M. BROOKING<sup>1</sup>, J. REED<sup>2</sup>, M. DAVIES<sup>3</sup>

<sup>1</sup> Energy, Atkins. The Hub, Bristol – United Kingdom

<sup>2</sup> EDF Energy. Barnwood, Gloucester – United Kingdom

<sup>3</sup> Independent consultant – MARAD. United Kingdom

### ABSTRACT

Graphite core degradation of an Advanced Gas-cooled Reactor (AGR) in the form of brick cracking is one of the life limiting features of AGRs in the UK. Understanding of the phenomenon of graphite irradiation-induced creep (or stress modified dimensional change) is an important factor in the determination of the onset and rate of brick cracking. To date there has been a lack of data that would enable prediction to end of life conditions.

In response to this, as part of the plant life extension programme, EDF Energy has undertaken a unique programme of experimentation using bespoke technologies to produce AGR lifetime graphite creep data. The experiments take both un-irradiated and irradiated graphite through a series of carefully controlled irradiation conditions. The results from these experiments will help inform the irradiation creep models and provide understanding to support the AGR graphite safety cases.

This paper will provide an overview of the Project, experimental programme, design and progress to date.

## 1 Introduction to Project ACCENT, the Creep Experiment

In order to be able to answer the question of what happens to nuclear reactor graphite beyond the original design life of an Advance Gas-cooled Reactor (AGR), EDF Energy identified the need to undertake a programme of experimental work to increase the understanding of graphite behaviour at temperature and high dose. As part of this programme an experiment was identified that would combine both neutron irradiation at the right temperature and simultaneous stressing of the graphite sample, in order to evaluate the impact on the graphite structure. This is a technically complex and challenging experiment.

The experiments have been shared between two suppliers of irradiation facilities, one in The Netherlands (Nuclear Research and consultancy Group, NRG) and the other in the USA (Oakridge National Laboratories, ORNL). Atkins provides the technical management of the Project (comprising engagement with suppliers, design of the experiments, running of the experiments and initial analysis of data) for EDF Energy. In-house experience comes from EDF Energy and an independent technical expert, providing the technical knowledge and understanding. This Project is unique as the core project team working on behalf of EDF Energy originates from outside of the company, demonstrating the high level of trust that has been forged between the parties.

This paper provides:

- Brief overview of the Project, including experimental programme and design;
- Discussion of the challenges faced by the Project
- Project phases and progress; and
- Conclusion elaborating on the aims of the Project.

## 2 Background

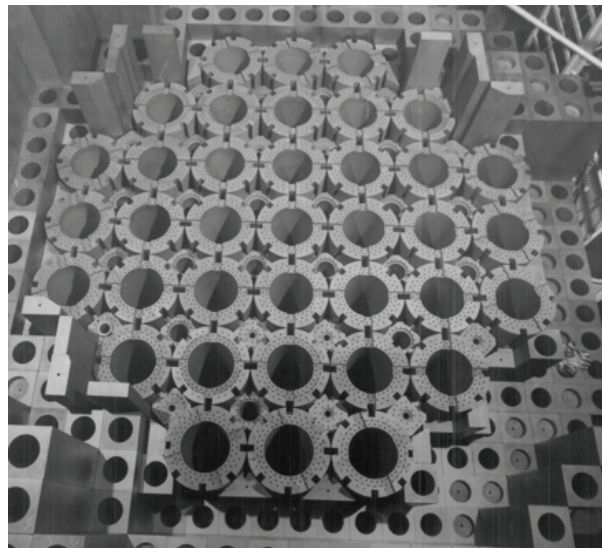
EDF Energy operate 14 AGRs (Figure 1) at 7 sites in the UK<sup>(1)</sup>, and the current declared lifetimes for the fleet of AGRs range from 2023 to 2028<sup>(2)</sup>. Extending the period of operation of each AGR beyond initially proposed lifetimes not only has financial benefits, but is strategically important in maintaining the contribution of nuclear generated electricity pending the introduction of the 'New Build' nuclear capacity. Safe lifetime extension of the AGRs has been increased by years (dependant on additional factors not discussed in this paper).



(Courtesy of EDF Energy)

Figure 1. EDF Energy AGR (Hinkley Point B)

The graphite core (Figure 2) plays an essential role in the safe operation of an AGR by ensuring unimpeded movement of fuel and control rods under all operating and fault conditions. In order to ensure safe operation the structural integrity and dimensional stability of the graphite bricks comprising the reactor core must be assessed, understood and maintained. It must be remembered that the graphite core is critical to the operating lifetime of the AGR, as it cannot be replaced or repaired.



(Courtesy of EDF Energy)

Figure 2. Scaled model, representative of AGR graphite core

The graphite core is made up of a large number of graphite bricks. Each graphite brick is subject to both internal and external stresses. Specifically it is the internal stress, consisting of **shrinkage** and **thermal** stress, which is important to understanding the changes within the graphite bricks. To calculate stress and component strength, knowledge of the following is required:

- Dimensional change;
- Coefficient of thermal expansion (CTE);
- Elastic modulus;
- Graphite strength; and
- Graphite irradiation-induced creep (or stress modified dimensional change).

To extend the database for future conditions, information continues to be collected in the current Materials Test Reactor (MTR) programme with NRG (Project Blackstone)<sup>(3)</sup> on all properties except irradiation-induced creep. Project ACCENT is providing further data on irradiation-induced creep. Sufficient evidence of this physical property means evidence of the relaxation of the internal stresses within the graphite brick. This data is being used to demonstrate continued operation and life extension of the AGRs can be safely undertaken.

It has been known for a long time that data on irradiation-induced creep is required, but historically this would have involved a large, high risk irradiation programme with a prohibitive cost. Previously such measurements have never been attempted on graphite samples at such high weight loss. However, a new capability has been developed to allow a limited number of samples to be irradiated at lower cost and at much less risk. This has allowed the modular approach to be proposed, which forms a key part of this Project.

Due to the complex nature of the experiment and the importance of the data to the safety case, EDF Energy chose to carry out a focused programme of research at two irradiation facilities. An international alliance with NRG (Holland) and ORNL (USA) was established. NRG and ORNL each provided their plant and facilities to undertake the irradiation of nuclear graphite and the associated handling, preparation and measurement of the graphite slices and samples.

- **NRG** – operator of the HFR (High Flux Reactor) in Petten, Holland. Uses a bespoke module technology that allows a number of modules to be loaded into a capsule and irradiated.
- **ORNL** – having HFIR (High Flux Isotope Reactor) in Tennessee, USA. Has developed a “rabbit” technology that allows for a “rabbit” (a capsule containing samples) to be pushed in and out of the reactor as desired.

### 3 Experiment

This challenging experiment is using bespoke technology and both virgin (un-irradiated) and irradiated AGR graphite. The results are helping to better understand graphite irradiation-induced creep (or stress modified dimensional change) properties and therefore more accurately determine lifetime and safe operating envelopes of the AGRs.

The strategy adopted by the Project is to produce data on irradiation creep for high weight loss irradiated samples up to AGR lifetime dose. A range of starting conditions has been used to provide additional properties information.

As currently defined, Project ACCENT will have taken 5 years to complete. However, since a modular approach with repeat irradiations has been adopted, data important to safety cases has been generated after 2 years.

Project ACCENT is currently split into three main phases. An overview of the relationship between the Phases is described in Section 5. Phases 1 and 2 of the Project are comprised of the following key activities:

- **Source material** – The majority of graphite samples (Figure 3) irradiated in Project ACCENT are active, having a history in both AGRs and Project Blackstone. Virgin samples are also used.



(Courtesy of EDF Energy)

Figure 3. Machined graphite sample (pre-radiolytically oxidised)

- **Machining and pre-characterisation** – The irradiated samples come from Project Blackstone, having been machined from either broken beams or cuboid samples. The un-irradiated (virgin) specimens have been machined from stock material. Once machined, each sample is subjected to a suite of non-destructive measurements to quantify and record the condition of the samples prior to irradiation, the 'pre-characterisation' or Pre-IE. The measurements made during both pre-characterisation and post-irradiation examination (PIE) are as follows:
  - Visual examination and photography;
  - Mass and dimensions;
  - Dynamic Young's modulus (DYM);
  - Coefficient of thermal expansion (CTE);
  - Thermal diffusivity;
  - Electrical resistivity;
  - X-ray diffraction;
  - X-ray diffraction pole figures; and
  - Digital tomography.
- **Irradiation capsule design** – Sample pairs are loaded into modules (NRG) or rabbits (ORNL). The sample pairs are in close proximity within the module or rabbit ensuring they both see the same experimental conditions. One sample is simultaneously subject to a load via a pressurised bellows and the other sample is unloaded and acts as a control. The desired irradiation temperature is achieved by designed gas gaps within the module or rabbit.
- **Irradiation** – The samples are irradiated within the reactor at NRG or ORNL in an inert environment. The effect of oxidation is investigated by using pre-irradiated, pre-radiolytically oxidised samples. Both of the MTRs operate in a series of cycles, each lasting roughly 30 days. Modules or rabbits can be removed from the reactors at the end of each cycle. A 'cycle report' is produced for each cycle detailing the conditions experienced during that period of irradiation, which includes temperatures and irradiation doses. This allows updated predictions concerning the evolution of the samples during irradiation and comparison against predicted and measured experiment parameters.
- **Post-irradiation examination (PIE)** – Each sample is subjected to a series of non-destructive measurements after irradiation and removal from the module, mirroring those conducted during pre-characterisation. Data from this testing will be analysed and compared with the pre-characterisation results to quantify the irradiation induced changes to the graphite creep properties.
- **Irradiation anneal** – Following the exposure of the samples to irradiation and stress, selected samples will be irradiated again, this time without stress. This will aid understanding of the stress recovery properties of graphite.
- **Storage or disposal** – Following PIE, microscopy or destructive strength testing, a decision will be made as to whether the samples should be sent for disposal or stored for future reference.

## **4 Challenges and Solutions**

Drawing on the good work established under Project Blackstone, we have continued to develop the means of dealing with the challenges that such a Project presents. Project Blackstone provided a solid foundation with many of the processes adopted in other projects, Project ACCENT included, and it is worth sharing them. This section summarises some of the key challenges and solutions.

### **4.1 Dedicated project management team**

Dealing with a multi-million pound Project of such complexity, for this duration, requires careful planning and control. It has been necessary to strike the right balance between providing the right level of technical information needed by EDF Energy for the safety cases, without gold-plating the experiment for the sake of science. In order to achieve this we have utilised an integrated, international team lead by Atkins on behalf of EDF Energy.

### **4.2 Overseas working**

Working between different sites brings challenges, whilst working overseas and with different languages brings even more. For example challenges associated with culture, language (both conversational and technical) and technical preconceptions, which need to be overcome to produce an effective project team. It is important to nurture and develop the project team to enable co-operative working between all organisations. Most importantly a technical respect has to be established between all parties. We sought to establish a solid working structure for the Project, enabling each member to understand their roles and to give their best to the experiment.

### **4.3 Unique experiment**

Bespoke design of a simultaneous irradiation and stressed sample module or rabbit has required specialised capsule design. This required a strong level of peer review prior to carrying out the experiment. Following each set of irradiations a number of ways to evaluate the experiment were developed to allow the success criteria to be measured.

### **4.4 Measurement techniques**

There has been the development of handling techniques and measurement techniques of small, friable, sometimes active, unique graphite samples both inside glove boxes and hot cells. It has been necessary to develop new and specific procedures and operator training, to be able to carry out the delicate handling procedures necessary, in order to gather the information we need from the samples.

### **4.5 Delivery and timescales**

The delivery of the data from the experiment to the safety case community is critical, and central to the success of the Project. The extension of the graphite database needs to be accepted and endorsed by independent parties. There are time constraints to ensure provision of information in sufficient time so that the safety cases can be written and approved, to allow for continued safe operation of the reactors. We have in place a programme to deal with and manage these expectations and ensure delivery on time.

## 4.6 Stakeholder engagement

Stakeholder engagement sits at the centre of the way in which the Project has been established. Engagement and management of expectations is necessary at each step of the Project, both for internal and external stakeholders. We implemented a stakeholder engagement plan to make sure that we address this. For example, from EDF Energy there are the technical and financial considerations. There has been regular independent peer review of what has been undertaken and will be done in the future built into the Project programme.

## 5 Project Phases

The Project has been broken down into three distinct phases, which are described in the following section, and in Figure 4.

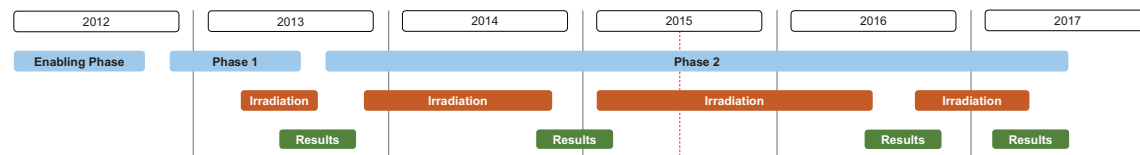


Figure 4. Project Phases and Progress

### 5.1 Enabling Phase

Following a round of optioneering, the Enabling Phase successfully achieved the following:

- Formally engage and contract with both NRG and ORNL;
- Agreement of the scope of work, structure of deliverables, milestones, stage payments, communications plan, timescales, reporting and quality requirements;
- Finalise the export licence arrangements;
- Provide an independent peer review of experiment; and
- Undertake an Invitation to Tender with both suppliers.

### 5.2 Phase 1

Following the Enabling Phase undertaken during 2012, the Project moved to the first of two experimental phases, the following key elements have also successfully been completed:

- Physical shipment of non-irradiated graphite to ORNL, USA;
- Proving of both the module and rabbit technology by providing initial data to confirm feasibility and PIE quality;
- Gathering confidence in ability to deliver to time, cost and quality;
- Completion of 'round-robin' Pre-IE exercise to prove comparable measurement capability at both supplier facilities; and
- Conducting first irradiation cycle and PIE of first experiment at both supplier facilities.

The hard work in Phase 1 paid off with encouraging results reported. Initial results confirmed that irradiation-induced creep with the graphite samples can be measured. This successful outcome allowed us to move forward with Phase 2 of the Project.

### 5.3 Phase 2

Phase 2 has built on what has been achieved in Phase 1, and the following activities are underway and continuing:

- Providing data to substantiate graphite core and brick models;
- Supporting lifetime safety case claims;
- Completing the full suite of irradiation experiments; and
- Completing all subsequent PIE on test specimens from all the experiments.

## 6 Benefits

Ultimately the graphite irradiation-induced creep experimental programme has been designed to provide stressed material data which, with an improved graphite creep model, will:

- Give evidence for a safety case to show that the irradiation-induced creep process behaves as expected (an element of this is the relaxation of the stresses within the graphite bricks);
- Allow better judgement of the appropriate inspection burden to be applied; and
- Improve the value of the inspection programme.

This Project supports the realisation of the full lifetime ambition of the AGRs by improving the understanding of graphite under irradiation and load, and ensuring that the stations continue to operate within safe parameters. This is strategically important as it helps to maintain the contribution of nuclear generated electricity pending the introduction of the 'New Build' nuclear capacity.

## 7 References

- (1) EDF Energy, 2015. *EDF Energy Power Stations* [online]. Available from: <http://www.edfenergy.com/energy> [last accessed 28<sup>th</sup> May 2015].
- (2) EDF Energy, 2015. *EDF Energy announces 10 more years for Dungeness B* [online news article]. Available from: <http://www.edfenergy.com/news/edf-energy-announces-10-more-years-dungeness-b> [last accessed 28<sup>th</sup> May 2015].
- (3) Brooking, M., 2012. *Project Blackstone: Graphite Irradiation in a Materials Test Reactor*. In: *ENC 2012: The European Forum to discuss Nuclear Technology Issues, Opportunities & Challenges* (Transactions: Plant Operations) 9 -12 December 2012, Manchester, United Kingdom. Brussels, Belgium: European Nuclear Society (ISBN 978-92-95064-14-0), pp. 77-84.