Institution: University of Strathclyde

Unit of Assessment: 13

Title of case study: Improved monitoring of graphite cores supports the safety case for life extension of nuclear power stations

1. Summary of the impact (indicative maximum 100 words)

Deployment of robust diagnostic techniques developed at the University of Strathclyde has improved the analysis of reactor core data and has directly supported the Safety Case for continued and extended operation of the Advanced Gas-cooled Reactor nuclear power stations in the UK. The new diagnostic techniques have been used on a daily basis since 16/5/2008 (BETA) and 5/3/2009 (IMAPS) in four power stations: 1) providing improved support and confirmation of the manual assessment of reactor core data by graphite engineers; 2) informing and advising power station personnel making strategic decisions on channels requiring inspection during statutory outages, and 3) providing evidence and increased confidence for the monitoring stage of station Safety Cases.

2. Underpinning research (indicative maximum 500 words)

Context: The UK relies on nuclear power for nearly 20% of its electricity. Seven out of the eight civil nuclear power stations in the UK are of the 2nd Generation Advanced Gas-cooled Reactor (AGR) design. The initial design lifetimes of some of the stations has now passed and there is a desire to keep operating these stations. For the Office for Nuclear Regulation to grant extensions to the licenses to operate them, the operator (EDF Energy) is required to submit a safety case. This safety case is a collection of documents detailing why it is safe to continue operating the stations, and the monitoring and inspection regimes to back these claims up. The major life-limiting factor on these stations is the condition of the graphite core, which provides structural integrity for housing the uranium fuel and acts as the neutron moderator. Inspection of the reactor core during routine outages every 2-3 years, provides information relating to the health of the core, and forms one aspect of the safety case. Manual analysis of condition monitoring data, gathered during routine operation, supplements the detailed inspection information and forms another leg of the safety case. Manual analysis of this data is time consuming, requires specialist expert knowledge and can suffer from variations in human judgment between experts. EDF Energy recognised that as their stations age there is a requirement to analyse an ever increasing volume of condition monitoring data, and that manually analysing this data would become more and more costly in terms of time to undertake the analysis and the level of expertise required. Therefore, development and deployment of robust, automated analysis techniques to assess this condition monitoring data was required.

Key Findings: To address these challenges, research into identification and benchmarking of normal reactor behaviour through data mining of historical data was undertaken, leading to the creation of statistical anomaly detection algorithms. In addition, knowledge elicitation and modelling of domain expertise relating to the analysis of fuel grab load trace data resulted in a prototype knowledge-based system for graphite brick crack detection [1]. A key challenge was to ensure that the results of these automated analysis techniques were suitably robust and auditable for use within nuclear facilities. Further research enhanced the analysis through the application of novel feature identification algorithms derived from advances in the Artificial Intelligence and the machine learning community; these algorithms were applied to the automatic detection of important artefacts in Fuel Grab Load Trace (FGLT) data, a primary indicator of core distortion [2]. Subsequent funding focussed on taking these prototype systems and deploying them as robust, industrial strength systems, accessible via EDF Energy’s company intranet. Use of the systems by EDF energy graphite core engineers allowed significant volumes of operational data to be gathered and analysed, which opened up new research challenges in developing techniques for trending and characterising this data [3]. Additional challenges addressed at this point involved developing a framework to fuse together condition monitoring data arising from multiple different data sources to provide core-wide condition monitoring [4].

The outcome of the novel research was the development, implementation and adoption of two production grade systems, BETA and IMAPS, for the storage and automated analysis of reactor core condition monitoring data [5]. Both systems have had their 3rd major version release onto the

EDF Energy company intranet, demonstrating the path from novel analysis techniques, to prototype demonstrator, to robust deployed systems providing beneficial decision support to the continued operation of the nuclear power stations in the UK.

Key Researchers at Strathclyde: This research was undertaken by the following staff in the Department of Electronic and Electrical Engineering :

- Prof Stephen McArthur – appointed 1993. Director of Centre and Academic/Research Leader of Intelligent Systems Team. Prof McArthur has been involved continuously since EDF Energy related research commenced in Nov 1998 to present.
- Dr Graeme West – appointed 2001. Research Fellow in the Intelligent Systems Team; involved with EDF Energy funded research since October 2002 to present.
- Dr Gordon Jahn – Research Fellow on this project from 2003 -2011. Dr Jahn left the project at the end April 2011.

3. References to the research (indicative maximum of six references)

References 1, 2 and 4 best exemplify the quality of the body of research. Reference 2 is part of the REF2014 submission

1. West, G. M., Jahn, G. J., McArthur, S. D. J., McDonald, J. R. & Reed, J. “Data mining reactor fuel grab load trace data to support nuclear core condition monitoring”, IEEE Transactions on Nuclear Science, 2006, 53, p. 1494-1503. DOI: 10.1109/TNS.2006.874725
2. Stephen, B., West, G. M., Galloway, S. J., McArthur, S. D. J, McDonald, J. R. & Towle, D. “The use of hidden Markov models for anomaly detection in nuclear core condition monitoring”, IEEE Transactions on Nuclear Science, 2009, 56, p. 453-461. DOI: 10.1109/TNS.2008.2011904
3. West, G. M., McArthur, S. D. J. & Towle, D. “Knowledge-directed characterization of nuclear power plant reactor core parameters”, Nuclear Engineering and Design, 2011, 241, 9, p. 4013-4025. DOI: 10.1016/j.nucengdes.2011.08.013
4. Wallace, C. J., West, G. M., McArthur, S. D. J & Towle, D. “Distributed Data and Information Fusion For Nuclear Reactor Condition Monitoring, IEEE Transactions on Nuclear Science, 2012, 59, 1, p 182-189. http://xplqa30.ieee.org/stamp/stamp.jsp?tp=&arnumber=6123182 .
5. West, G. M., McArthur, S. D. J., & Towle, D., "Industrial implementation of intelligent system techniques for nuclear power plant condition monitoring", Expert Systems with Applications, 2012, 39, 8., p. 7432-7440 DOI: http://dx.doi.org/10.1016/j.eswa.2012.01.107

Other evidence for quality of research

This research was funded by EDF Energy through the EDF Energy Strategic Alliance with the University of Strathclyde, and by EPSRC through the Nuclear EngD programme. 7 grants with a total value of over £1.4M were awarded by EDF Energy since 2002, including:

1. S. McArthur, G. West, G. Jahn, “Automated Intelligent Analysis Techniques for Graphite Core Condition Monitoring”, Funded by EDF Energy Ref: 080307, Value £339,622, Dates 1/4/2008 - 31/8/2011
2. S. McArthur, G. West, G. Jahn, “Graphite Core Diagnostic and Prognostic Techniques” Funded by EDF Energy Ref: 115275, Value £430,885, Dates 16/8/2011 - 30/9/2014

4. Details of the impact (indicative maximum 750 words)

Process/events from research to impact

EDF Energy first commissioned research into the use of intelligent analysis techniques applied to condition monitoring data gathered from their fleet of Advanced Gas-cooled Reactor (AGR) stations in September 2003. Research into suitable algorithms led to their deployment, first as prototype stand-alone systems (7/7/2005 for BETA and 7/9/2007 for IMAPS), then to full industrial strength systems on the EDF intranet (16/5/2008 for BETA and 5/3/2009 for IMAPS).

Types of impact

Enhanced operational safety through improved analysis of reactor core condition:

The immediate beneficiaries are engineers involved in monitoring the AGR stations, and EDF

Energy, the operator of all the AGR stations in the UK. The BETA system has been used by engineers in the EDF Energy Graphite Core Project Team on a daily basis to provide an automated assessment of every refuelling event undertaken at Hunterston B and Hinkley Point B power stations since the first release of the software in May 2008. An improved version of the software was deployed in May 2013. The results of the assessment are fed into the relevant Monitoring Assessment Panel (MAP) meeting. The MAP meetings are held quarterly at each participating station where a panel of engineers make decisions as to whether any operational action is required, based on all condition monitoring evidence gathered since the last MAP. As of May 2013, the BETA system at EDF Energy contained information on 2549 refuelling events dating back to November 2003. "*The graphite cores are the life-limiting component in our AGR stations and as they age, the need for high quality information about their health increases. The BETA system supports the monitoring functions within the graphite core project team … by driving towards their objective of an average of 9 years lifetime extension for each power station*" [Source 1 Group Head - Existing Nuclear, EDF Energy].

The IMAPS system is used to support the MAP meetings at the oldest four participating stations (oldest in terms of the cumulative irradiation to which the reactor core has been exposed). As the remaining stations age, there will be the need to instigate MAP meetings at them, and the IMAPS system has been designed to accommodate this. The system allows any monitoring observation to be stored, whether that be a possible cracked brick identified through Fuel Grab Load Trace (FGLT) analysis or a control rod which appears to have impeded movement. The IMAPS software meets rigorous requirements set out by EDF, based on the Programmable Electronic Systems (PES) guidelines, in terms of the quality and management of the lifecycle of the data stored within the system. The IMAPS system was deployed on 5th March 2009 with improved versions of the software deployed in November 2011 and May 2013. As of May 2013, the IMAPS system contains 19,873 reactor core observations and has supported 64 station MAP meetings. The Nuclear Safety Group Head at Hinckley B notes that "*The IMAPS system is an integral part of our MAP process and provides us with an effective tool for managing all the observations discussed during each meeting. It is also a one stop shop for the data relating to findings for any fuel or control rod channel. It is used at MAP meetings to look at channels history and supports decision making in regard to future strategy for inspections or study* " [Source 2 MAP Chair, Hinkley Point B Power Station].

Improving Business Performance within EDF: Analysis of condition monitoring data is used to offset some of the current and future need for an increased number of inspections required during an outage (as a guide, each day an AGR reactor is on outage equates to approximately £0.5M in lost revenue). IMAPS has changed working practice within EDF Energy as it is now the recognized repository for storage of all condition monitoring observations made at the MAP meetings, and is stated in the formal Departmental Instruction documentation for each station involved. Furthermore, IMAPS has become the first point of call for the graphite core project team whenever an issue arises with a fuel channel, as it contains the most up-to-date verified information relating to the condition of the channel, along with useful historical information. "*The IMAPS system is consistently used to view the history of a fuel channel as the principal data is displayed immediately with links to more detailed information in our document management system. In addition, IMAPS is used to assist in the selection of channels for inspection during an outage*" [Source 3 Monitoring Team Leader EDF].

The systems have proved extremely beneficial to EDF Energy as they provide a rapid and auditable manner of assessing Fuel Grab Load Trace data. Further, the systems provide a means of managing and trending large volumes of condition monitoring data, which provides supporting evidence to the claims that the reactors are currently healthy, thus supporting the safety case for continued operation. "*The BETA and IMAPS systems directly support the analysis of our core condition monitoring data which feeds into the monitoring leg of our safety case for continued and future station operation*" [Source 4].

Reducing the risk to energy supply by extending lifetime of nuclear power stations: Another impact is on the energy supply available to UK consumers, via the Department of Energy and

Climate Change's policy on "Maintaining UK energy security." In the wider societal context, keeping the existing nuclear power plants generating, and extending their operational lifetimes, providing it is safe to do so, is of great significance to the UK. Civil nuclear power generation plays a substantial role in the UK's current energy mix, by providing low carbon, base load generation. In 2012, 63.9TWh of electricity was supplied by nuclear power in the UK, which is equivalent to 18.5% of all electricity supplied, and the AGR stations supplied over 83% of this electricity.

In December 2007, the oldest power stations Hunterston B and Hinkley Point B were granted 5-year operational extensions to 2016, and a further 7-year extension to these stations was announced on 4th December 2012. In 2010, both Heysham 1 and Hartlepool were granted 5-year operational extensions to 2019, and it is likely that the case will be made for further extensions in the future for these newer stations. Dungeness B, Torness and Heysham 2 are newer still and the likelihood is that similar extensions will be sought. Without the existing nuclear generation portfolio, the UK would be facing a significant gap of about 19% of total demand in its energy supply, and though new stations are planned, these are not due to come online for at least another 8-10 years. Furthermore, the upcoming energy crisis that the UK risks facing was highlighted by Ofgem, which stated on 27th June 2013, that *"electricity supplies are set to tighten faster than previously expected in the middle of this decade"* [Source 6]. Extended operation of the existing nuclear power plants mitigates some of this risk to supply, without which the country would be facing the increased possibility of the lights going out. The likelihood of this occurring is part of the current public energy debate, but what is clear is that extended operation is beneficial to security of supply.

Influence on international planning: Though the algorithms are specific to the AGR design of reactors, the wider international community benefits from the lessons learned from deploying such systems for lifetime extension. Dr West was a member of the International Atomic Energy Agency (IAEA) co-ordinated research program entitled: "*Advanced Surveillance, Diagnostics, and Prognostics Techniques used for Health Monitoring of Systems, Structures and Components in Nuclear Power Plants"* which focussed on the latest developments in techniques to support continued and extended operation of nuclear power plants worldwide [Source 5]. Dr West's input was also provided to the U.S. Department of Energy sponsored "invitation only" workshop to solicit input from nuclear power experts to support research planning for the Light Water Reactor Sustainability (LWRS) program [Source 6]. The goal of the workshop was to supplement the US Department of the Environment's understanding of research needs to close the technology, economic, implementation, and regulatory gaps for the economically justifiable integration of advanced on-line monitoring (OLM) technologies into the aging fleet of nuclear power plants.

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. Statement from Group Head - Existing Nuclear, EDF Energy - corroborates the claims made about the systems' use within EDF Energy
2. Statement from Nuclear Safety Group Head & MAP Chair, Hinkley Point B Power Station, EDF Energy corroborates the use of the IMAPS system
3. Statement from Inspection and Monitoring Team Leader, Graphite Core Project team, EDF Energy, corroborates the claims that BETA and IMAPS are in regular use within EDF Energy and are used to support core condition monitoring
4. Statement from Safety Case Lead, Graphite Core Project Team, EDF Energy - corroborates the claims made relating to the contribution towards the safety cases
5. http://www.iaea.org/NuclearPower/Engineering/CRP/asdpt-hm/index.html Summary of the IAEA CRP on Advanced Surveillance, Diagnostics, and Prognostics Techniques used for Health Monitoring of Systems, Structures, and Components in Nuclear Power Plants
6. https://www.ofgem.gov.uk/ofgem-publications/76215/27june2013.pdf
7. http://smr.inl.gov/Document.ashx?path=DOCS%2FReading+Room%2FIRISINLREPORT4680344.pdf Report from the Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies, Idaho National Laboratory, June 2010 INL/EXT-10-19500