Institution: University of Strathclyde		
Unit of Assessment: B12 Engineering		
Title of case study: Improving operational availability and revenue through enhanced management and life extension of nuclear power stations		
Period when the underpinning research was undertaken: 2002 - 2018		
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:**
Stephen McArthur	Professor	01/04/1993 – present
Graeme West	Reader	01/07/2001 – present
Paul Murray	Senior Lecturer	01/04/2012 – present
Chris Wallace	Researcher; KE Fellow	17/10/2011-22/11/2013; 07/08/2017 – present
Matthew Revie	Professor	01/10/2007 – present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Analytic software applications developed at the University of Strathclyde for the nuclear industry provide robust data interpretation and decision support regarding the health, condition and remaining lifetime of nuclear reactor cores, related plant and equipment. These support systems have been implemented and used by EDF (UK) and Bruce Power (Canada), and are critical tools in securing the supply of low carbon energy for the UK and Canadian economy and consumers. As a result of these advances, the nuclear industry has benefited from:

- Enhanced safety cases for the Office for Nuclear Regulation in the UK, leading to the extension to planned operational lifetime of nuclear power stations
- Accelerated plant availability and return to service following planned outages at nuclear power stations, providing significant time and cost savings
- Improved management of nuclear facilities through the application of AI and data science
- New revenue streams for the nuclear supply chain.

2. Underpinning research

The nuclear industry, globally, faces challenges of continued and extended operation of reactors, plant and equipment that was constructed and commissioned over 40 years ago. Instrumentation and control systems have been modernised, and there is now the opportunity to modernise the associated analysis process so that the latest advances in Artificial Intelligence (AI), data analytics and decision support technologies can be leveraged. However, significant challenges are present with the application of such techniques in a heavily regulated, risk averse industry. Research at Strathclyde has developed fundamental advances in AI-based analytics that address the challenges and operating requirements within the nuclear industry. The research has extended to demonstrator software and prototype industrial implementations that evidence that the data science methods, AI methodologies and analytic techniques can be effectively and safely deployed in a nuclear context to provide actionable information.

Automated intelligent analysis: Fuel Grab Load Trace (FGLT) data is gathered by EDF during routine refuelling operations for safety purposes. Our research allows this data to be reused to derive the condition of the graphite reactor core. In 2006 West and McArthur [**R1**] pioneered the use of automated intelligent analysis techniques to provide a method for automatically determining the presence of cracks in the core from the FGLT data. This was enhanced in 2009 through the application of Hidden Markov Models [**R2**] and in 2014 combined with operational data to demonstrate the feasibility of estimating the fuel channel bore from the FGLT data from a single power station [**R3**].

Distributed data analysis: From 2005, research was undertaken into the application of multi-agent systems to provide distributed data analysis across a range of monitoring data sources, ranging from control rod positions, thermal to neutron power ratios, FGLT data and thermocouples [**R4**]. A pioneering approach in the field, this demonstrated the suitability of a multi-agent approach to graphite core monitoring, combining models derived from laboratory experimentation with current operational plant data to infer an underlying measure of health.

Continuous imaging: Inspection of AGR cores requires the use of specialist radiation hardened camera equipment. The captured video is of low resolution by modern standards and the fuel channel surface being inspected is largely grey and featureless. Current state-of-the-art approaches for feature detection and matching do not perform adequately in this application so a novel approach to detecting and matching points in low feature space by leveraging a-priori knowledge of the camera pose and position was published by West and Murray in 2015 [**R5**]. This addressed a number of technical challenges and allowed engineers to view the entire surface of an AGR fuel channel as a single continuous image for the first time.

Ultrasonic pressure tube data analysis: From 2014, research was undertaken to translate approaches applied to the UK's AGR design to the Canadian Deuterium Uranium (CANDU) heavy-water reactor design [**R3**]. Key contributions of this work were enhanced analysis of ultrasonic pressure tube data through capture, representation and deployment of machine coded human expertise. Research and development of a suite of analytics tools has also enabled the acceleration of their monitoring and prognostics activities, and led to improved fault detection, prognostic health monitoring and outage forecasting for critical plant items including primary heat transport pumps, primary coolant loops, and fuelling machines.

Probabilistic predictive algorithms: Advances in the elicitation of structured expert judgement has led to improved predictive and diagnostic models, which can then be applied to industrial applications and integrated with other analytical techniques in mixed-method prediction. Such expert-judgement mixed-method techniques offer improved probabilistic modelling to deliver advice that optimises operational and maintenance decision making [**R6**].

3. References to the research (Strathclyde-affiliated authors in **bold**)

R1 **G.M. West**, **G.J. Jahn**, **S.D.J. McArthur**, **J.R. McDonald,** J. Reed (2006) Data mining reactor fuel grab load trace data to support nuclear core condition monitoring, *IEEE Transactions on Nuclear Science*, 53(3): 1494-1503 https://doi.org/10.1109/TNS.2006.874725

R2 **B. Stephen**, **G.M. West**, **S. Galloway**, **S.D.J. McArthur**, **J.R. McDonald**, D. Towle (2009) The use of Hidden Markov Models for anomaly detection in nuclear core condition monitoring, *IEEE Transactions on Nuclear Science*, 56(2): 453-461 https://doi.org/10.1109/TNS.2008.2011904 [REF2 in 2014]

R3 **G.M. West**, **C.J. Wallace**, **S.D.J. McArthur** (2014) Combining models of behaviour with operational data to provide enhanced condition monitoring of AGR Cores, *Nuclear Engineering and Design,* 272: 11-18 https://doi.org/10.1016/j.nucengdes.2013.12.067

R4 **C.J. Wallace**, **G.M. West**, **S.D.J McArthur**, D. Towle (2012) Distributed data and information fusion for nuclear reactor condition monitoring, *IEEE Transactions on Nuclear Science*, 59(1): 182-189 https://doi.org/10.1109/TNS.2011.2176959

R5 **P. Murray**, **G.M. West**, **S. Marshall**, **S.D.J. McArthur** (2016) Automated in-core image generation from video to aid visual inspection of nuclear power plant cores, *Nuclear Engineering and Design*, 300: 57-66 https://doi.org/10.1016/j.nucengdes.2015.11.037 [REF2]

R6 **M. Revie**, **T. J. Bedford**, **L. A. Walls** (2011) Supporting reliability decisions during defense procurement using a Bayes linear methodology, *IEEE Transactions on Engineering Management*, 58(4): 662-673 https://doi.org/10.1109/TEM.2011.2131655 [REF2 in 2014]

Notes on the quality of research: All outputs are peer reviewed articles in leading journals for researchers making key advances in the use of AI and data science for nuclear and other operations. The research was supported by competitively won EPSRC research funding (e.g. McArthur et al, Prosperity Partnership: Delivering Enhanced Through-Life Nuclear Asset Management, 1/09/17-31/08/22, GBP2,160,697); 3 Nuclear Engineering Doctorate studentships totalling GBP300,000; and industrial research funding from EDF Energy from 2001-20 (GBP3,500,000), Bruce Power, Babcock International and Doosan Babcock (GBP3,000,000).

4. Details of the impact

Strathclyde's research into distributed intelligence and advanced analytics has helped to secure low-carbon energy supply in the UK and Canada by extending the operation of nuclear power stations through efficient and effective safety monitoring. This has been achieved through the development of a range of innovative software tools (ASIST [**R5**], iMAPS [**R4**], BETA [**R1**, **R2**, **R3**], ADAPT) which have advanced the collection and automated analysis of monitoring and inspection data to provide timely and accurate insights into reactor health and condition. As illustrated with examples below, these tools have sustained and improved operations across the UK's Advanced Gas-cooled Reactor (AGR) nuclear power plants. These were opened between 1976 and 1988, and have either passed or are reaching the end of their design lifespan. Impact in operational advances has also been evidenced at the Bruce Power Generating Station (BPGS) in Canada, the world's largest operational nuclear site with 8 CANDU heavy-water reactors generating approximately 30% of Ontario's electricity. Commercialisation of the prototype tools into fully supported commercial software systems has also created significant new revenue streams for supply chain companies.

1. Enhanced safety monitoring to satisfy regulatory requirements

Implementation of the iMAPS system [**R4**] has enabled routine monitoring information to be leveraged to provide additional evidence for continued operation of nuclear power stations in the UK. As confirmed by EDF Energy's Graphite Branch Technical Lead: *'The data gathered using the software fed directly into the monitoring leg of the safety case to the Office for Nuclear Regulation. Since August 2013 the iMAPS system has supported every single Monitoring and Assessment Panel (MAP) meeting held quarterly by EDF at all 7 AGR stations (95 meetings as of the November 2020)'*. The BETA system [**R1**, **R2**, **R3**] (now industrially supported as the LoTAS system) automatically assesses FGLT data and *'has been used to support the assessment during outages at Hinkley Point B and Hunterston B power stations. These happen every 18 months per reactor (2 per station), so approximately 14 inspection campaigns have been supported since August 2013'* [**S1**].

2. Accelerated return to service following outages, creating time and cost savings

The ASIST tool [**R5**], first deployed in 2014, provided EDF with a *'step change in the way it assesses its inspection data'* [**S1**]. The previous approach required up to one day of an experienced engineer assembling an image of a crack from frames manually captured from the video feed. ASIST allowed this to occur automatically within 30 minutes of inspection, allowing the station to return to service much sooner. The engineering consultancy, Jacobs, uses the ASIST software, as the main contract partner responsible for supporting EDF with their programme of graphite inspections. According to Jacobs' Technical Director for Technology and Consulting: *'The ASIST software has revolutionised the manner in which Jacobs analyses in-core video inspection footage…leading to significant time saved on analysis, and providing a more holistic view of the fuel channels than previously possible. Since deployment of the software in May 2014, the ASIST software has been utilised to support the assessment of over 850 fuel channel inspections, from all seven AGR stations in the UK'* [**S2**]. The time savings from implementation of ASIST has also freed up experienced personnel to focus on the analysis rather than laborious creation of meaningful data. EDF Energy acknowledges: *'ASIST has resulted in time and resource savings for both EDF and Jacobs…The time savings EDF make on initial analysis may result in faster* *return to service in some cases. For each reactor that is returned to service half a day quicker, GBP250,000 of additional revenue is achieved, so ASIST has the potential to increase revenue on the order of GBP1,000,000 each year'* [**S1**]. A further example of the effectiveness of the software is demonstrated during the extended outage in 2018 of Hunterston Reactor R4, where the discovery of a new type of brick cracking led to a requirement for an increased inspection campaign and a new safety case to return the reactor to service. According to Jacobs, this *'led to a significant increase in the volume of inspection footage to be assessed'* and *'without the ASIST software, processing all the inspections in a timely manner would have been extremely challenging'* [**S2**]. The images produced by the ASIST software have become the standard presentation format for this data. For instance, the industry regulator ONR used an image produced by Strathclyde's software to illustrate the new type of crack (known as a keyway root crack) in its 2019 report granting permission to restart reactor 4 after a year offline [**S3**: p.12, Fig.3]. This demonstrates the ability to use modern AI and analytics tools in the safety-critical and highly regulated nuclear industry.

At Bruce Power in Canada, the ADAPT software is showing similar benefits. This automates the interpretation of ultrasonic inspections carried out on the pressure tubes within their reactors. A translation plan has been formed, with the underpinning data management and software support framework activities required for full industrial deployment of ADAPT into existing workflows having been initiated. According to Bruce Power's Chief Engineer: *'This research has confirmed the viability of such an approach and has led to the development of a translation plan and the identification of further areas of related research with the intention to implement the resulting system as soon as possible'* [**S4**]. In addition, garter springs (spacers) are used to separate the pressure tube and the calandria tube. The location of these spacers is critical to safe operation, however, limited time is available during each maintenance outage to verify the location of the spacers and any required movement. Analysis and modelling of data from historical outages fused with engineering judgement [**R6**] provided the Outage and Maintenance Services (OMS) team at Bruce Power with a structured framework to select the most effective approach to move challenging spacers. An interactive decision support system was developed that supported the OMS team in developing and delivering their Spacer Location and Repositioning (SLAR) programme strategy within each outage, by understanding where difficulties may arise and interrogating the expected effectiveness of alternative tool settings. A web-based app was deployed with an interactive decision support system, combining three different modelling approaches to provide: an analysis tool summarising historical data on SLAR operations, a rule-based system combining empirical data and engineering knowledge on repositioning difficulties and mitigating actions, and a data-based predictive model to understand the expected effectiveness of a SLAR operation. As outlined by the Chief Engineer: *'The tool provides the outage team with the most probable route to success when they encounter garter springs that are difficult to move and has, as such, minimised the amount of time required to make the required moves'* [**S4**].

3. Improved management of nuclear facilities through the application of AI and data science

In 2018, Strathclyde University led and delivered a strategic analysis of the improved use of data sources and AI to improve operations, efficiency and revenue at the Bruce Power facility in Canada. Through discussions with 7 technical groups, 15 prioritised areas where AI could offer immediate value were specified. Following from this, through continued engagement with Strathclyde and funding a full-time Knowledge Exchange Fellow from Strathclyde to deliver AI analyses and prototypes, they have created a Continuous Online Monitoring programme and built a Monitoring and Diagnostics Centre to showcase and evaluate their new AI-driven operations. They have engaged the equivalent of 4 developers to deliver a number of applications. As confirmed by Bruce Power's Chief Engineer: *'This has resulted in AI analyses and prototypes being delivered that are now being evaluated and showcased as part of our new AI-driven* *operations. It is fair to say that the research undertaken at Strathclyde, along with the AI review it undertook with our technical teams, has directly led to the investment in and creation of our Monitoring and Diagnostics Centre. This will change how we use data to improve our operations'* [**S4**]. Our research in data science and analytics is also supporting the location of fuel bundle defects, providing Bruce Power's Fuel and Physics team with supporting evidence and increased confidence in the selection of channels scheduled for refuelling. It has *'automated the extraction and analysis of complex technical information from fuelling machine logs, which has reduced the time spent extracting and processing data … enabling them to focus on combining information from a range of sources in order to identify efficiency savings during refuelling, enhance decision making and improve fault detection'* [**S4**].

4. Created new revenue streams for start-ups and supply chains

As a direct result of research collaboration with EDF, Strathclyde's Advanced Nuclear Research Centre (ANRC) was formed in 2016 to accelerate innovations in through-life nuclear plant lifetime. By the end of July 2020, this had grown into a GBP19,600,000 portfolio of activity with 14 international companies, including Babcock International, Bruce Power (Canada), Doosan Babcock and EDF. The focus of ANRC is on translating innovations into commercial solutions across a wide range of nuclear facilities. The success of the prototype systems (ASIST, BETA and iMAPS) led to their industrialisation as fully supported software systems, leading to revenue streams for the supply chain. Bellrock Technology Ltd is a University of Strathclyde spin-out company, formed in 2012 and with a product that accelerates the deployment of data and AI solutions. It now provides the software product and platform upon which the BETA (since 2016, now called LoTAS) and iMAPS (since 2018) solutions are deployed. Bellrock's Chief Executive Officer notes: *'Our work with EDF has built upon the excellent research prototypes and early industry implementations created by the University, and has led to a continual revenue stream from EDF since 2016. They now license our Lumen® product as part of a multi-year agreement'* [**S5**]. Jacobs also generates income from their support partnership with EDF [**S2**]. Furthermore, since 2019 Cavendish Nuclear Ltd, a wholly-owned subsidiary of Babcock International Group, has *'made good progress in establishing its commercial presence in Canada…[as] a direct result of involvement with the Advanced Nuclear Research Centre, which provided: key and well-connected stakeholders leading to better understanding of the market; development of strong in-country partnerships formed through ANRC partner businesses; identification of prospective innovative opportunities; and, the ability to leverage joint projects to increase presence via conferences and events'* [**S6**].

5. Sources to corroborate the impact

S1 Factual statement from Technical Lead, Graphite Branch, DA, EDF Energy Nuclear Generation Ltd, dated 16 November 2020.

S2 Factual statement from Technical Director, Technology and Consulting, Jacobs, dated 3 November 2020.

S3 Office for Nuclear Regulation, Agreement to NP/SC 7785 Hunterston B Power Station – Return to Service safety case for Reactor 4 following core inspection results in 2018, Project Assessment Report ONR-OFD-PAR-19-004, August 2019. http://www.onr.org.uk/pars/2019/hunterston-b-19-004.pdf

S4 Factual statement from Chief Engineer, Senior Vice President, Engineering, Bruce Power LP, dated 11 November 2020.

S5 Factual statement from Chief Executive Officer, Bellrock Technology Ltd, dated 13 November 2020.

S6 Factual statement from Business Director Canada, Cavendish Nuclear, dated 9 November 2020.