Institution: The Open University

Unit of Assessment: B13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Life extensions of nuclear power plant

1. Summary of the impact

The lifetimes of Hartlepool and Heysham I nuclear power stations have been extended from 2011 to 2019 as a direct result of our research into the development and application of new measurement techniques for the accurate determination of residual stresses. These life extensions are contributing to the health of the UK economy, maintaining jobs, ensuring security of electricity supply, and deferring the need for decommissioning and replacement of two nuclear power stations at a cost of several billion pounds each. The electricity generated during the life extension period has a market value of over £8 billion. New numerical modelling methods, underpinned by our measurements, are now used by the nuclear industry in life assessment procedures.

2. Underpinning research

Since the 1990s The Open University (OU) has led research into the determination of spatially varying residual stresses in welded components. Over the past 15 years it has developed and applied novel techniques to study welded structures for the nuclear power generation industry.

1998–2001: Edwards (Senior Lecturer / Reader) worked closely with Nuclear Electric, within the EU-funded thematic network TRAINSS (contract BRRT-CT97-5043**)**, on measuring residual stresses in weld repairs [3.1] using neutron diffraction.

1999–2001: Edwards (Reader) led the £3.5m consortium to design and construct ENGIN-X [3.2], the dedicated materials engineering beamline at the UK's ISIS neutron source.

2001–present: Edwards (Reader / Professor), **Fitzpatrick** (Senior Lecturer / Reader / Professor), and **Bouchard** (Professor, joined the OU 2008) initiate and participate in the NeT European consortium for the standardisation and validation of residual stress measurement and modelling in power plant welds [3.3, 3.4].

2004–08: Edwards (Professor, left OU 2011) and **James** (Research Fellow, appointed to permanent position 2006) delivered the British Energy Boiler Spines Research Programme contract (£0.5m). The work characterised spatially resolved material properties and studied residual stresses in ten welded benchmark and nuclear component mock-ups [3.4]. These measurements were used to validate improved numerical methods for simulating welding residual stresses [3.5] and revealed, for the first time, the nature of residual stress concentrations in multi-pass weld repairs and the dominant effect of weld capping passes.

2006–08: Fitzpatrick (Reader) researched residual stress generation in welds for light water reactor applications for the Japanese Nuclear Energy Safety Organization.

2010–13: James (Research Fellow) extended this research to the characterisation of residual stresses in dissimilar-metal welds using the ISIS and SNS neutron facilities. The joints were made by AREVA for the European pressurised water reactor using new welding procedures designed to mitigate the risk of stress corrosion cracking.

2009–12: James (Research Fellow) undertook measurements on the Australian OPAL research reactor where delayed hydride cracking had been identified as the cause of a leaking reactor reflector vessel [3.6].

3. References to the research

3.1 **Journal article**. Bouchard, P. J., George, D., Santisteban, J. R., Bruno, G., Dutta, A., Edwards, L., Kingston, E. and Smith, D. J. (2005) 'Measurement of the residual stresses in a stainless steel pipe girth weld containing long and short repairs', *International Journal of Pressure Vessels and Piping*, vol. 82, no. 4, pp. 299–310, DOI: 10.1016/j.ijpvp.2004.08.008

3.2 **Journal article**. Santisteban, J. R., Daymond, M. R., James, J. A. and Edwards, L. (2006) 'ENGIN-X: A third generation neutron strain scanner', *J. Appl. Cryst.*, vol. 39, pp. 812–825, DOI: 10.1107/S0021889806042245

3.3 **Journal article**. Turski, M. and Edwards, L. (2009) 'Residual stress measurement of a 316L stainless steel bead-on-plate specimen utilising the contour method', *Int. J. Pres. Ves. & Piping*, vol. 86, pp. 126–131, DOI: 10.1016/j.ijpvp.2008.11.020

3.4 **Journal article**. Pratihar, S., Turski, M., Edwards, L. and Bouchard, P.J. (2009) 'Neutron diffraction residual stress measurements in a 316L stainless steel bead-on-plate weld specimen', *International Journal of Pressure Vessels and Piping*, Vol. 86, pp.13-19. DOI: 10.1016/j.ijpvp.2008.11.010

3.5 **Journal article**. Smith, M. C., Bouchard, P. J., Turski, M., Edwards, L. and Dennis, R. J. (2012) 'Accurate prediction of residual stress in stainless steel welds', *Computational Materials Science*, vol. 54, pp. 312–328, DOI: 10.1016/j.commatsci.2011.10.024

3.6 **Journal article**. Muránsky, O., Holden, T. M., Kirstein, O., James, J. A., Paradowska, A. M. and Edwards, L. (2013) 'Evaluation of residual stresses in electron-beam welded Zr2.5Nb0.9Hf Zircadyne flange mock-up of a reflector vessel beam tube flange', *Journal of Nuclear Materials*, vol. 438, nos 1–3, pp. 154–162, DOI: 10.1016/j.jnucmat.2013.02.045
Listed in REF2.

4. Details of the impact

The Head of Research and Development, EDF Energy, writes: '*We have a fifteen-year long relationship with the OU and consider its expertise in combining small scale and large scale residual stress measurement techniques, together with analytical modelling techniques, to be unique.*' [5.1].

The OU and Nuclear Electric measured residual stresses in a weld repair [5.2], using neutron diffraction, following a steam leak at Hunterston power station in 1997. This led to an OU/British Energy research training partnership (within the EU-funded thematic network TRAINSS, 1998–2001) involving neutron diffraction measurements of residual stress in long and short weld repairs [3.1]. These were the first measurements of their kind and revealed the surprisingly severe nature of residual stress fields associated with repairs which, most importantly, demonstrated that the simplified 2-D finite element predictions of stresses at weld repairs routinely used by British Energy to support safety cases for repairs were not conservative. '*This resulted in a multi-million pound program of weld modelling development and validation at British Energy (2001–10) to underwrite safety cases for repaired AGR* [Advanced Gas-Cooled Reactor] *weldments prone to reheat cracking*' [5.1]. The UK AGRs operate at coolant temperatures significantly higher (over 600˚C) than the water-cooled reactors used elsewhere in the world where temperatures are below 350˚C: this is a demanding operating regime for ageing plant susceptible to creep degradation (for example reheat cracking and creep crack growth) in the presence of residual stresses.

In 2004 British Energy funded our 'Boiler Spines Residual Stress Measurement Programme', a five-year research project to quantify residual stresses using neutron diffraction and the contour method, and measure spatially resolved weld properties using digital image correlation, on carefully designed benchmark welds and mock-ups of complex nuclear plant welds. This work has had a direct impact on life-extensions of nuclear plant in the UK [5.3]. Our results were used by British Energy to develop and validate the use of more realistic heat source and material hardening models in weld residual stress simulations [3.5], to characterise the nature of residual stress concentrations at weld repairs [5.4] and to validate predicted creep relaxation of residual stresses.

The outcomes of this research have mitigated uncertainty associated with the development of reheat cracking: '*The new understanding of weld repairs and refined life analysis methods, underpinned by the OU measurements, has allowed the lives of Hartlepool and Heysham 1 AGR power stations to be extended to 300,000 hours, rather than the previous restriction of 175,000 hours caused by uncertainty about creep damage to weld repairs in the main boiler support structures. The previous restriction would have required the reactors to close early. With each reactor generating around £700k of electricity per day, these life extensions represent a major contribution to the UK economy, on jobs and on security of electricity supply. It also deferred the need for decommissioning and replacement of two nuclear power stations at a cost of several billion pounds each*' [5.1]. In aggregate the economic impact of lifetime extensions for the Hartlepool and Heysham 1 twin-reactor power stations, from 2011 to 2019, amounts to electricity generation worth over £8 billion.

The application and impact of our research has continued through characterising residual stresses in dissimilar metal welds for pressurized water reactors in Japan and France, and on a critical component in a reactor in Australia that was rendered barely usable due to a water leak, until a repair was justified. '*Our collaborative measurements with the Open University team to validate the FEA* [finite element analysis] *model of the reflector leak was a critical input to the process that identified the successful reactor repair method. The OPAL reactor provides neutrons to both undertake neutron beam science and the production of radio pharmaceuticals for Australia. If the reactor had not been repaired then the economic impact would run to many millions of* [Australian] *dollars per annum*.' [5.5].

Finally, new numerical modelling methods, underpinned by our measurements, are now widely used by the regulated nuclear industry in life assessment procedures for pressurised water reactor plant. The weld modelling technology validated by our measurements has been captured in the R6 Failure Assessment Procedure [5.6], transferred by EDF Energy to the Australian Nuclear Science and Technology Organisation, and applied to the pressuriser surge nozzle of Sizewell B Power Station to justify relaxation of the inspection interval, '*saving the station £1m per annum in lost electricity generation*' [5.1].

5. Sources to corroborate the impact

5.1 'Impact of OU research on nuclear power plant operations', Letter from Head of Research and Development, EDF Energy, dated 2 July 2013.

5.2 Edwards, L., Bouchard, P. J., Dutta, M., Wang, D. Q., Santisteban, J. R., Hiller, S., Fitzpatrick, M. E. (2005) 'Direct measurement of the residual stresses near a 'boat-shaped' repair in a 20 mm thick stainless steel tube butt weld', *International Journal of Pressure Vessels and Piping*, vol. 82, no. 4, pp. 288–298, DOI: 10.1016/j.ijpvp.2004.08.007

5.3 Science and Technology Facilities Council (2012) *Neutron Scattering: Materials research for modern life*, STFC Media Services [online] http://www.isis.stfc.ac.uk/news-and-events/news/2012/impact-of-neutron-scattering-brochure13478.pdf

5.4 Bouchard, P.J. (2009) *Hartlepool and Heysham 1 Power Stations – Current understanding of boiler spine weld repairs residual stress concentration effects*, Report E/REP/BBGB/0023/AGR/07, British Energy Generation Limited.

5.5 Head, Institute of Materials Engineering, Australian Nuclear Science and Technology Organisation, Australia.

5.6 EDF Energy Ltd (2012) *R6 Revision 4: Assessment of the integrity of structures containing defects*, Sections III.15 and V.5, 2012, EDF Energy Ltd: Gloucester, UK [online] http://www.r-desk.co.uk/r6-procedure