HIGH TEMPERATURE ISSUES IN ADVANCED GAS COOLED REACTORS (AGR)

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This paper outlines, by way of an example, some of the materials degradation issues associated with the operational experience gained from the fleet of **A**dvanced **G**as cooled **R**eactors operating in the UK, typically referred to as the AGRs. The aim is to highlight where industrial focused research and development programmes have provided support for safe and reliable plant operation, through in-depth technical understanding, and the importance of continued developments in support of plant lifetime extension ambitions, where it is safe and economic to do so. The example relates to the high temperature structural integrity of components associated with the main boilers – one of the potentially life limiting features of the AGRs. It is concluded that the tools and techniques developed and deployed to address the challenges faced have helped to maintain the high end skills and knowledge which are necessary to support current operations, plant life extensions and will support potential future high temperature reactor designs.

ADVANCED GAS GOOLED REACTORS

From the late 1960s through to the late 1980s there were 14 AGRs constructed at 7 sites across the UK. There are, essentially, four design types, but all are high temperature, carbon dioxide (CO_2) gas cooled – graphite moderated – nuclear reactors. The AGRs are the only high temperature civil nuclear power stations in operation worldwide and the knowledge and expertise needed to mitigate these challenges both today and during the plants' lifetime are also unique to the UK. It is acknowledged that some of the potential future Generation IV reactor designs are also of a high temperature gas cooled design.

This paper provides a schematic overview of the AGRs with a focus on the materials degradation issues associated with the challenging operational environment to which some components are subjected. The focus is on the components internal to the reactor as they present challenges related to accessibility and typically they cannot be replaced, which makes understanding their structural integrity particularly important from a lifetime

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perspective. Due to the unique high temperature operational challenges of the AGRs the example provided is for one of the reactor internal metallic components associated with the irreplaceable boiler structures, noting that some of the boiler components can and have been replaced in some cases.

A schematic of an AGR reactor is shown in Figure 1, which identifies some of the important AGR features including; the fuel and fuel channels; the boilers and superheater locations; the graphite core moderator; the surrounding concrete pressure vessel and the CO_2 gas circulators. The secondary steam circuit including the turbine and conventional electrical generation equipment and cooling water circuit are also illustrated, but are not considered further in this paper. The nuclear core is surrounded by the concrete pressure vessel and it is the structures and components within this that are difficult to access and replace. Therefore their integrity is important for safe operation of the nuclear plant and for the potential life limiting nature of these components. This is important as there is an ambition to extend the operational life of the AGRs where it is safe and economic to do so, and builds on previous successes in plant lifetime extension. For example, although the stations which began operations in the mid-1970s had a design life of 30 years, they are now projected to operate until 2023. Other life extensions are also planned across the AGRs. This places an importance on the structural integrity developments conducted today to support safety cases to achieve this, and in particular for the structural integrity of the irreplaceable systems which operate at high temperature.

AGR MATERIAL DEGRADATION ISSUES

Figure 1 also highlights some the materials degradation challenges. In terms of metals, there are a large number of both ferritic (e.g. ½CMV) and austenitic steel weldments (e.g 300 series stainless steels), where many of the austenitic weldments are in the as-welded condition (i.e. not stress relieved). Of particular importance is where components operate within the creep regime. For example, the boilers which transfer heat within the CO_2 gas internally in the reactor to the secondary circuit (water/steam) can be subjected to operational temperatures up to 650°C. Hence, some of these components operate within the creep regime. Also due to normal reactor operation and cycles of start-up/shut down the interaction of creep and fatigue is important. Finally, because of the AGR operational environment, CO_2 oxidation, steam corrosion, thermal ageing, and the impact of irradiation embrittlement on some reactor internal components, are additional degradation mechanisms which need to be considered.

As noted above creep is a significant degradation mechanism and has challenged the AGRs in the past. An example is provided in the next section. Fundamental understanding of past issues is important so that the potential threat to other reactor components can be addressed. The procedures for assessing lifetime of high temperature components have been developed under an industrial focused research and development programme since the early 1990s [1]. The procedure contains 4 main sections covering the assessment of creep and creep-fatigue for initially defect free components; creep and creep-fatigue crack growth for components containing defects; and assessment routes for dissimilar metal welds and similar (ferritic) weldments.

The next section provides an example of how developments of the assessment methods and understanding of material performance have been used to address a high temperature structural integrity issue.

EXAMPLE OF A HIGH TEMPERATURE INTEGRITY ISSUE

SUPERHEATER TAILPIPES AND BIFURCATIONS

Since the mid 1980s to early 1990s a small number of leaks related to pintle weld and bifurcation locations had been observed and managed. Figure 2 provides some details of the super heater at the top of the boilers and indicates the location of interest for these inspections. The material is a 316 stainless steel with high carbon content (316H). Around 2006 there was an increase in the number of reported defects from boiler inspections. This was in part due to improvements in inspection detection capability and technology but also pointed to an ongoing degradation of plant at power due to creep mechanisms. The outcome for plant operations was to down rate the power and hence lower temperatures to ameliorate creep mechanisms in conjunction with more rigorous inspection schedules and some component repairs and replacements. Figure 2 shows the replacement design of tailpipes fitted to some of the affected boilers. These tailpipes have additional flexibility loops and welds on these replacement tailpipes have not cracked. In addition to work on the reactor itself, defects were assessed such that the creep-fatigue crack growth rates maintained a crack depth which remained below the critical defect size [1 and 2]. This places significant demands on the structural integrity assessment of defects and the associated input materials data to underwrite the safety case and support lifetime ambitions.

To develop improved understanding of the issue, detailed metallurgical investigation of some of the observed defects were carried out. This confirmed a creep dominated creep-fatigue growth mechanism, see Figure 3. The R5 procedure [1] was used as the basis to perform the high temperature structural integrity assessment. In summary this required the following; characterisation of the operational loads as primary or secondary; idealisation of the defect location, orientation and shape and then an assessment of creep and fatigue crack growth. The latter require estimation of stress intensity factors for both primary and secondary stresses and calculation of the creep and fatigue crack growth parameters, C^* and ΔK, respectively [1]. Detailed finite element analyses of the fabrication and in-service loading of the structure was carried out to this end, e.g., Ref. [3].

Of key importance to the assessment methodology are the requirements on engineering materials data needed to obtain appropriately conservative assessments. For high temperature assessments the data demands are great; ranging from elastic modulus (E) because secondary stress relaxation depends on E; the relevant tensile stress-strain curve because the transient creep parameter C(t) for creep prior to steady state growth is dependent on plastic strain; creep crack growth parameters; creep ductility for assessment of ligament failure and proximity to tertiary creep effects; fatigue crack growth parameters, and creep strain rates. It is well known that creep data are very scattered and correlations / anti correlations exist between some material parameters. Hence combinations of bounding properties, not using the worst for all cases, are important to achieving an appropriately conservative prediction. Guidance is provided in reference [1]. The main point to note is that high temperature structural integrity assessments are involved in terms of knowledge and understanding, are complex and place significant demands on the engineering materials data requirements. Advances in both methodology for assessments and understanding of materials performance have enabled significant challenges to be safely overcome and provide ongoing support to AGR lifetime. Putting all these ingredients together (the structural analyses, the materials performance issues, and the capability of the in-reactor inspections) has led to a good understanding of the development of the defects, e.g., Ref.[4].

However, the assessment outlined above concentrated on the crack growth, as defects were already present. The formation of these defects in service could not be explained on the basis of a creep-fatigue mechanism employing R5, Ref.[1]. This points to a potential short fall in the defect free assessment methodology or the absence of appropriate consideration of another material degradation mechanism. To address this, an investigation was carried out to improve understanding of the impact of the AGR CO_2 environment. This involved examination of both ex-service bifurcation material and material samples from the AGR CO_2 oxidation surveillance scheme. For example, Figure 4 shows a through thickness hardness survey of an AGR surveillance sample indicating an increased surface hardness layer to approximately 300μm at the external surface, where the material grain size is larger, and is similar to observations on the ex-service material. Note that the internal surface, with a smaller grain size, exhibited no increase in hardening. This is considered to be linked to the difference in oxidation behavior for the different grain sizes. The difference in grain size relates to the manufacturing route (*i.e.* a tube extrusion process). The sample was exposed to CO_2 gas for 50khrs (about 6 years) at 560°C.

Different metallographic examination techniques and tools (*e.g.* etching, microscope / SEM and sample break open) were used and have identified carburization in the surface grains and sub-surface grain boundary carbide formation with subsequent oxidation to a depth of around 300 μm. Similar effects were observed on ex-service bifurcations, as illustrated in Figure 5, which shows the fracture surface from a sample taken near the outside surface of an ex-service bifurcation. The figure clearly indicates a brittle fracture zone at the outside CO_2 facing surface and more ductile fracture in the reminder of the section thickness. This CO_2 affected surface layer has the potential to adversely impact the local material creep ductility in particular – reducing the components' resistance to crack initiation by creep and creep-fatigue mechanisms. Hence the importance of the methodology for conducting crack growth calculations in this instance and the input material data needs to support the current safety case and any lifetime extensions.

Finally, in parallel with developments related to inspection and repair strategies, further work on high temperature structural integrity assessment is ongoing including, investigation of the impact of the AGR CO_2 environment, residual stress modelling techniques, methodologies for assessing combined loading effects on crack growth, continued improvements in creep damage modelling and understanding of material behaviour at high temperature.

CONCLUSIONS

Nuclear plant that operates at high temperatures within the creep range present particularly challenging structural integrity issues. The experience gained by EDF Energy in developing strategies for addressing and managing these issues has allowed knowledge and expertise to be built up and captured within the high temperature assessment procedures. Work in this area related to commercial operation of high temperature nuclear reactors is unique to the UK. This has enabled the development of a UK based set of expertise to address high temperature structural integrity issues in support of current operations, lifetime extensions and could be adapted for potential future high temperature reactor designs.

ACKNOWLEDGEMENTS

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REFERENCE LIST

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FIGURES

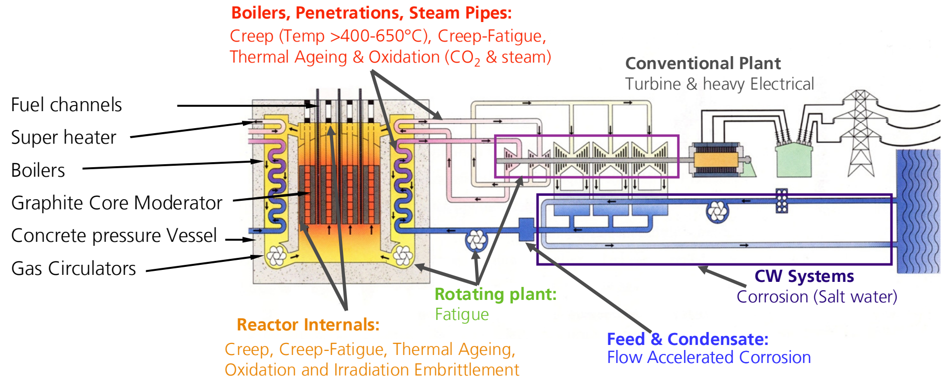

FIGURE: 1 – Schematic of an AGR and material degradation mechanisms.

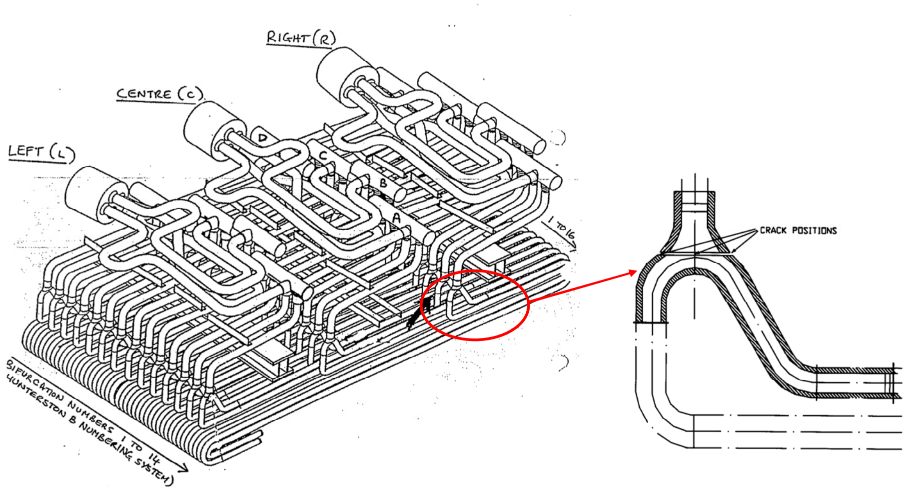

FIGURE: 2 – Detail of superheater bifurcations and location of interest (316H stainless steel).

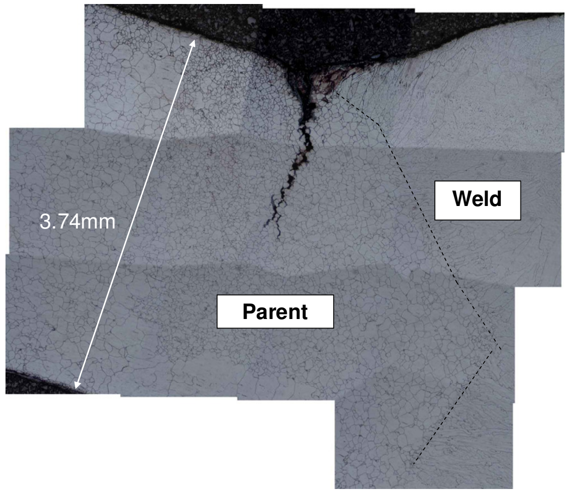

FIGURE: 3 – Superheater bifurcations metallographic evidence of creep dominated (intergranular) creep-fatigue cracking.

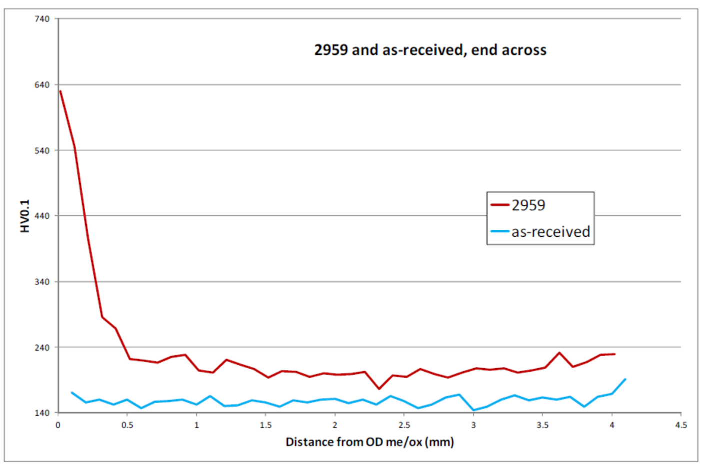

FIGURE: 4 – Through thickness hardness survey of AGR surveillance samples indicating increased surface hardness layer to approximately 300 μm (50khrs at 560°C).

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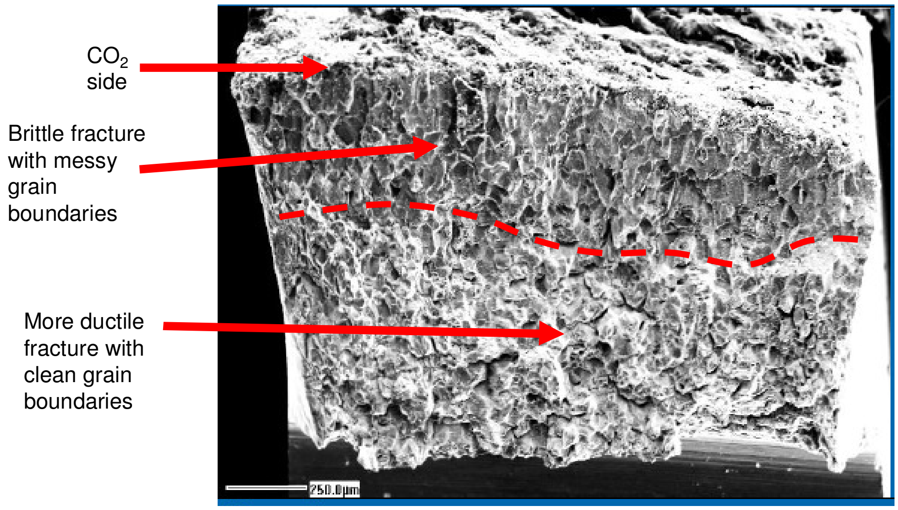

FIGURE: 5 – Examination on fracture surface of a sample taken near the outside surface of an ex-service bifurcation.