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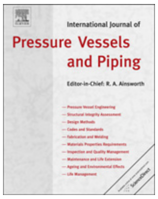

Application of probabilistic modelling to the lifetime management of nuclear boilers in the creep regime: Part 1

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ABSTRACT

Monte Carlo probabilistic simulation has been applied to a large population of nominally identical components in an AGR boiler operating in the creep regime. The components have a history of defectiveness. The R5 procedure is used to calculate creep-fatigue crack growth rates within a probabilistic programme. The inspection process is also modelled probabilistically. The overall result is a 'prediction' of past inspection results which can be used to tune the parameters of the model. The model then makes genuine predictions of the required level of remediations in future overhauls by predicting the inspection results. The probabilistic treatment of both the structural calculations and the inspection process jointly has been shown to assist in clarifying the interpretation of the inspections and ascertaining the true state of the plant.

1. Introduction

Some of the UK's Advanced Gas Cooled (AGR) reactors are already operating beyond their original design lifetime, and all the AGRs may be expected to do so in due course. At full power the reactor coolant gas temperature is around 650 °C as it enters the boilers. Consequently, creep is a potentially life limiting mechanism for some boiler components. The accurate prediction of creep lives is hampered by the large scatter in creep material properties. For the purposes of underwriting nuclear safety, bounding material properties are assumed in conservative assessment methodologies. The degree of conservatism in such safety related assessments can be such that, whilst entirely appropriate for ensuring safety, they give no realistic picture of plant lifetimes.

In common with boilers in conventional power plant, AGR boiler surfaces consist of large numbers of very similar tubes and associated features. This lends itself naturally to a probabilistic treatment. The failure of small numbers of tubes is tolerable from the nuclear safety perspective. Indeed the occasional occurrence of steam leaks is anticipated and managed by repairs, replacements or by plugging tubes. This need have no commercial or safety implications so long as the rate of leaks and the number of tubes requiring remediation remains small. One of the purposes of a probabilistic treatment is to predict future leak and remediation rates, and hence the likely commercial impact and the degree of challenge to the safety envelope. Two cases may be distinguished depending upon the availability of inspection evidence,

[1] Extensive in-service inspection evidence exists and there is a history of cracking as well as some steam leaks;
[2] Little or no in-service inspection evidence exists and hence the potential defectiveness is unknown other than indirectly from a few steam leaks.

Case [1] is considered in this paper. The focus in this case is on the probabilistic modelling of creep-fatigue crack growth and the probabilistic modelling of the inspection process. Modelling the combination of these two factors statistically is unusual, though crucial to the outcome in this case.

It is intended that subsequent work will treat case [2] for which the focus will be the probabilistic modelling of either creep rupture or creep-fatigue crack initiation (possibly followed by crack growth). There is also, of course, the case where there is in-service inspection evidence but with no history of cracking. However this more benign case is unlikely to merit detailed probabilistic modelling and hence is not considered further.

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2. Component modelled

The boilers in question here are of serpentine design. The features with a known history of cracking are bifurcations in the main (superheater) boiler. These bifurcations lie at the top (the hotter end) of the boiler. They bring together the steam flows from the two tubes which comprise a single platen into a single outlet pipe, see Fig. 1. In this design the swaged end of the outlet pipe is connected to the bend at the top of the platen via an oval shaped saddle weld. The boiler platen tubes are nominally 38 mm OD and 4 mm wall thickness. On both sides of the bifurcation the parent material is 316H stainless steel. The saddle weld is a two-pass TIG weld with compatible consumable. There are twelve boiler units per reactor, and 44 bifurcations per boiler unit, making 528 bifurcations per reactor.

Cracks have been found in the HAZ on the platen side of this saddle weld. They have been discovered centred on any of the four cardinal points shown in Fig. 1, though the 0° crotch position is most common. Cracks can occur centred on one, two, three or all four of the cardinal points, but never coalesce. The analysis and inspection results presented in this paper refer exclusively to the 0° crotch location. Eddy current inspection is used, the results of which are expressed as percentage full-scale deflection (%FSD). One of the key features of the probabilistic simulations is to incorporate the substantial uncertainty in the conversion of %FSD to crack depth. This aspect is particularly important in the present application because of the difficulty of carrying out the inspections inside a reactor, in hot conditions with difficult access, and due to the defects being shallow.

Metallurgical examinations confirm that the crack growth mechanism is creep dominated. The mechanism which initiated the cracks, however, is less clear – partly because the initiation site has long since been consumed by oxidation. Following an increase in the incidence of reported defects in 2006 the operating temperature was reduced to ameliorate further creep degradation, specifically crack growth. At full power the bifurcations operated at typically 503–525 °C. At reduced power the bifurcation temperature does not exceed 480 °C and is typically 470 °C.

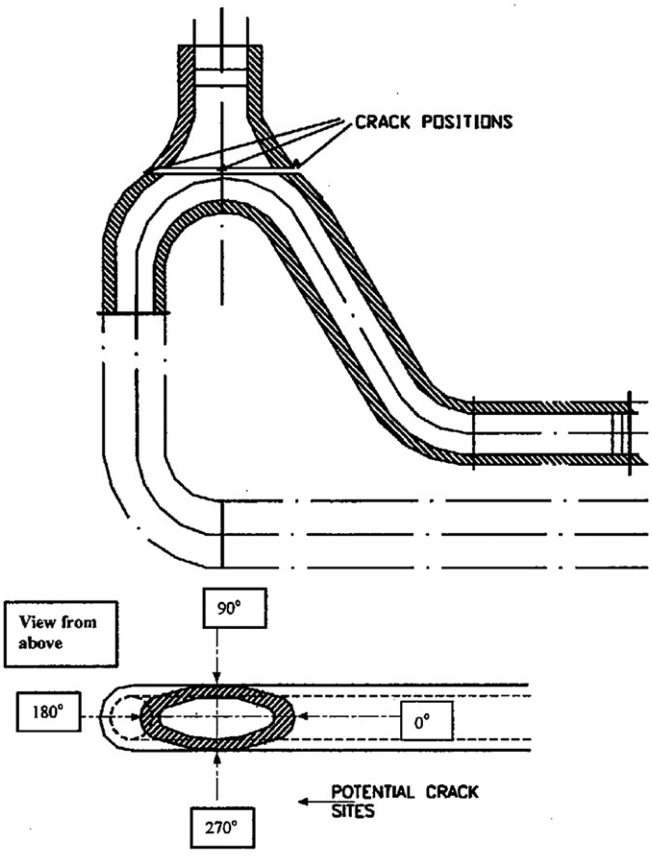

Fig. 1. Bifurcation geometry and potential crack positions.

3. Crack growth calculations

At the heart of the probabilistic simulation is a deterministic calculation of creep-fatigue crack growth. This employs volume 4/5 of EDF Energy's R5 procedure, Ref. [1]. The bifurcations have been subject to detailed finite element analyses, e.g., Ref. [2], from which the stresses used in this paper have been extracted.

Operating steam pressure at full power is ~160 barg, whereas the reactor coolant CO_2 pressure is ~40 barg, so the differential pressure is ~120 bar. The oval geometry of the branch weld results in stresses due to pressure which are substantially larger than those of the nominal tubing. In addition, the tailpipes, which convey the steam out of the reactor from the bifurcation outlets, are subject to large system loads due to boiler thermal expansions. The combination of these two sources of stress creates an onerous condition which is probably one of the main causes of the cracking observed. (The incidence of cracking is correlated with system loading which varies across the different bifurcations in a given boiler unit). Welding residual stresses are negligible due to solution heat treatment during fabrication. However, proof testing can induce residual stresses and this was taken into account.

The fatigue contribution to crack growth is dominated by the reactor start-up/shutdown cycles. The assessments treated long shutdowns to cold conditions separately from shorter shutdowns under 'hot standby' conditions, since the latter involve much reduced system stress ranges. Reactor shutdowns can involve transient steam pressure peaks and the resulting enhanced stress ranges were included in the fatigue assessments.

The methodology involves calculating the elastic stress intensity factor (SIF) for assumed semi-elliptic cracks on the outer surface, aligned with the HAZ, characteristic of the observed defects. The calculation of fatigue crack growth is based on the SIF range via a Paris law. Creep crack growth rate is calculated using $\dot{a} = AC(t)^q$ where the creep fracture parameter $C(t)$ is estimated using the R5 procedure, Ref. [1] and the coefficients A and q are fitted to laboratory test data. The parameter $C(t)$ involves the SIF, the reference stress and the creep strain rate at the reference stress, amongst other factors. The use of $C(t)$ rather than C^* is to permit incorporation of secondary stresses (see Ref. [1] for details).

Crack growth is calculated at the deepest point of the semi-elliptic profile. The surface crack length, $2c$, is assumed to be related to the fractional crack depth, a/w, in a manner derived from measured crack sizes on components removed from the reactors. Hence the aspect ratio $2c/a$ is taken as 25 for very shallow defects, reducing linearly as a function of crack depth to 10 for $a/w \geq 0.63$.

4. Monte Carlo probabilistic simulation methodology

The Monte Carlo method involves randomly sampling the distributed input variables many times so as to build a statistical picture of the output quantities, see for example Ref. [3]. The method has a very wide range of applicability, engineering applications being only one. The method is particularly appropriate when there are a large number of independent variables which can influence the outcome. The Monte Carlo method is being used increasingly in structural integrity applications. Examples include: applications to the analysis of creep data or the development of