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APPLICATION OF PROBABILISTIC ASSESSMENTS TO THE LIFETIME MANAGEMENT OF NUCLEAR BOILERS IN THE CREEP REGIME

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ABSTRACT

Deterministic structural assessments in the creep regime are subject to large uncertainties due to the intrinsic scatter in creep data and the sensitivity of creep to both temperature and stress, parameters which may also be very uncertain in plant applications. Where bounding assumptions provide a clear assurance of structural integrity, traditional deterministic approaches may be perfectly adequate. Where this is not the case, the engineer may have difficulty determining whether the lack of a deterministic margin is indicative of a real threat to the plant or simply an artefact of multiple conservatisms. This can be addressed by a probabilistic assessment which will quantify the degree of threat. Moreover, bounding deterministic assessments are of little utility in cases where individual components have already failed, for example in boilers where small numbers of tube leaks are to be expected over plant life. The objective in such cases is not avoidance of any failures, but managing the failure rate within tolerable limits. This requires a probabilistic treatment. Monte Carlo probabilistic assessments based on the R5 procedure have been carried out for a number of AGR boiler features. These are used here to illustrate the methodology and also to emphasise the benefits of the probabilistic approach. These include identifying which factors dominate the failure probability, an issue upon which deterministic assessment may be misleading. The probabilistic approach provides a better quantitative guide to the commercial threat than traditional deterministic methodologies based on bounding data.

INTRODUCTION

The upper sections of the boilers in Advanced Gas-Cooled Reactors (AGRs) operate in the creep temperature regime. Creep has been the cause of a number of instances of cracking in AGRs. Most AGRs are now past their original design life and as the plant ages further the potential for creep problems to arise is under constant review within the industry. Assessment predictions in the creep regime are subject to great uncertainty due to the intrinsically scattered nature of creep data, and the sensitivity of creep to uncertainties in temperature and stress. This makes creep assessments particularly suited to a probabilistic approach and this is particularly the case for boiler surfaces which tend to consist of large numbers of nominally identical features (boiler tubes and associated assemblies). Several probabilistic creep assessments of AGR boiler surface components have been completed in the last few years. The examples reviewed briefly below relate to the so-called bifurcation features near the top of the main superheater boilers (the designs differing in different AGRs).

The first application was to features which had suffered extensive cracking in service, leading to small steam leaks into the reactor in some cases. Probabilistic Monte Carlo modelling was used to rationalise the observed rate of degradation. This involved a probabilistic treatment of the prediction of creep-fatigue crack growth based on the methodology of Volume 4/5 of EDF Energy’s R5 procedure, Dean *et al* (2007). It also involved a probabilistic modelling of the in-reactor non-destructive testing procedures. This work has been described in Holt and Bradford (2012). One of the key features of this work was the recognition that inspection results are subject to significant uncertainty, just as are structural assessments. The history of crack growth in these components was found to align well with the predictions of the combined Monte Carlo simulations. In particular, the small incidence of steam leaks was found to be consistent with the general crack development, i.e., the leaking components formed part of the same statistical population as the others. A particularly important finding was that a sudden increase in the reported incidence of cracking in 2006 was attributable to a change in the inspection procedure rather than a sudden increase in the true level of defectiveness of the plant. The practical measure taken to manage the rate of degradation was to reduced operating temperatures (and hence power), thus reducing creep rates by about a factor of ten. Despite assessments indicating that the rate of degradation should then be virtually negligible, routine inspections continued to indicate a need for a certain residual level of remediation. The probabilistic model successfully predicted this and showed that it was due primarily, not to true deterioration, but to the performance of the inspection technique (i.e., either undefective features which were falsely identified as defective by the inspection, or true defects that were missed by the previous inspections). Overall, the probabilistic modelling provided a far sounder picture of the state of the plant than had been possible without it.

The second application was to features with no known cracks but which are subject to various mechanisms of in-service thinning. In addition some of the components have had a history of partial steam flow restrictions which can cause an elevation of their operating temperature, potentially raising the rate of creep life usage. The R5 procedure, Dean *et al* (2007), was again used within a probabilistic program, on this occasion to calculate the expected frequency of both creep rupture and creep-fatigue crack initiation. This work has been described in Bradford and Holt (2013). The probabilistic approach was shown to provide a better quantitative guide to the commercial threat posed by metal losses and flow restrictions than traditional deterministic methodologies based on bounding data. In particular, probabilistic assessments identified that the most significant factors in determining rupture and crack initiation probabilities were the stresses, the material creep properties and their correlations, and aspects of the assessment methodology. In contrast, deterministic assessments had resulted in a considerable focus of attention on restricted tubes, whereas the probabilistic treatment revealed that restrictions are much less dominant in their structural effect. The numerical preponderance of unrestricted tubes means that they dominate the rupture and crack initiation probabilities, despite the occurrence of a flow restriction increasing the probabilities for individual tubes. This puts the threat posed by partial flow restrictions into a perspective which is missed by deterministic assessment.

The present paper concerns an attempt to understand the service initiation of cracks in the same components and reactors as considered in Holt and Bradford (2012). Cracking is known to be very widespread in these items, but deterministic assessments have failed to provide an explanation for the cracking in terms of creep-fatigue. Various observations indicated that the reactor coolant environment was playing a role in degrading material properties and enhancing the likelihood of cracking. The probabilistic technique has been used, together with R5 Volume 2/3, Dean *et al* (2007), to investigate whether an environmental effect is indeed required to explain the observed incidence of cracking, and if so to quantify the degrading effect of the environment.

DETERMINISTIC R5 VOLUME 2/3 ASSESSMENT

A probabilistic assessment using a Monte Carlo technique consists of carrying out many deterministic assessments for differing values of the distributed parameters. In this case the deterministic core consists of an R5 Volume 2/3 creep-fatigue crack initiation assessment. The essence of the R5 Volume 2/3 method consists of constructing the relevant stress-strain hysteresis cycle, which for the present application is illustrated schematically by Figure 1. The plant experiences many different types of operational cycles which generate different stress-strain hysteresis cycles. In practice these must be idealised in some way to render the problem tractable.

The major plant conditions are cold shutdown (CSD), normal steady operation at full power (NO), reactor trip / reactor shutdown (T), and hot standby (HSB). Hence, possible major reactor cycles are, for example, CSD-NO-T-HSB or HSB-NO-T-HSB or HSB-NO-T-CSD. These differ principally because temperatures remain fairly high during HSB but reduce to nominally 'cold' conditions during CSD, hence the stress range associated with the latter are larger than for the former. On the other hand, HSB cycles are more common. Moreover, the minimum temperature during HSB varies widely and is treated here as a distributed variable. Attention is confined here to the first 30 years operation of the reactors, prior to being down-rated to ameliorate the creep rate. The number of cycles assumed for assessment of the four relevant reactors are given in Table 1. A single deterministic assessment therefore consists of up to 385 plant cycles, all different and all requiring a hysteresis cycle to be constructed.

The R5 Volume 2/3 assessment involves calculating the damage associated with each cycle, and adding this damage over successive cycles. The damage per cycle consists of the linear sum of a creep damage and a fatigue damage. Without giving the full details, the creep damage is essentially the creep strain accumulated during the creep dwell (CE in Figure 1) divided by an appropriate creep ductility (which will, in general, depend upon stress state, strain rate and temperature). The fatigue damage is estimated from endurance data at the strain range calculated from the hysteresis cycle (AG or GJ in Figure 1), with corrections being applied for size effects. Calculation of these damage terms requires knowledge of many parameters, most of them taken as distributed in the probabilistic assessment.

In addition to randomly distributed variables, some parameters have a known variation from component to component. Thus there are 528 of these components per reactor, arranged as 44 in each of 12 boiler units. The system stressing varies considerably across the 44 items in any one boiler unit, in the manner illustrated by Figure 2. (Note that the system stress does not include the pressure stress). Similarly, there are known differences between the four relevant reactors in terms of historic average operating temperatures and average creep dwell times (see Table 1). Such systematic features were also built into the Monte Carlo code.

Assessment concentrated on the most onerous location on the feature, where most (but not all) cracks had been found. The percentage of items discovered to be cracked in each reactor are given in Table 1. These percentages are the targets which the probabilistic simulation is attempting to reproduce.

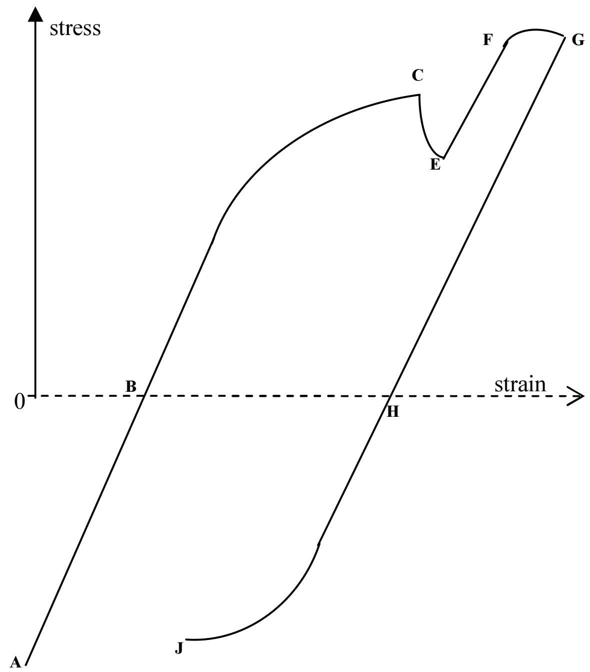

Figure 1. Idealised hysteresis cycle (schematic only). For CSD-NO-T-HSB cycle: A = cold shutdown, C = end of start-up = start of operating dwell, E = end of operating creep dwell, G = trip transient peak stress, J = hot standby. For HSB-NO-T-HSB cycle: A = hot standby, J = hot standby. For HSB-NO-T-CSD Cycle: A = hot standby, J = cold shutdown

Table 1: Number of major reactor cycles assessed

Reactor	Number of CSD Cycles (N_{CSD})	Number of HSB cycles per CSD cycle (N_{HSB})	Hence total number of cycles assessed over 30 years	Average Dwell Time (Hours)	Reactor Mean Creep Temperature °C	Percentage of reactor population reported cracked by 30 years
1	18	13	252	822	528	7%
2	33	8	297	690	522	10%
3	35	10	385	542	507	24%
4	26	10	286	672	513	14%

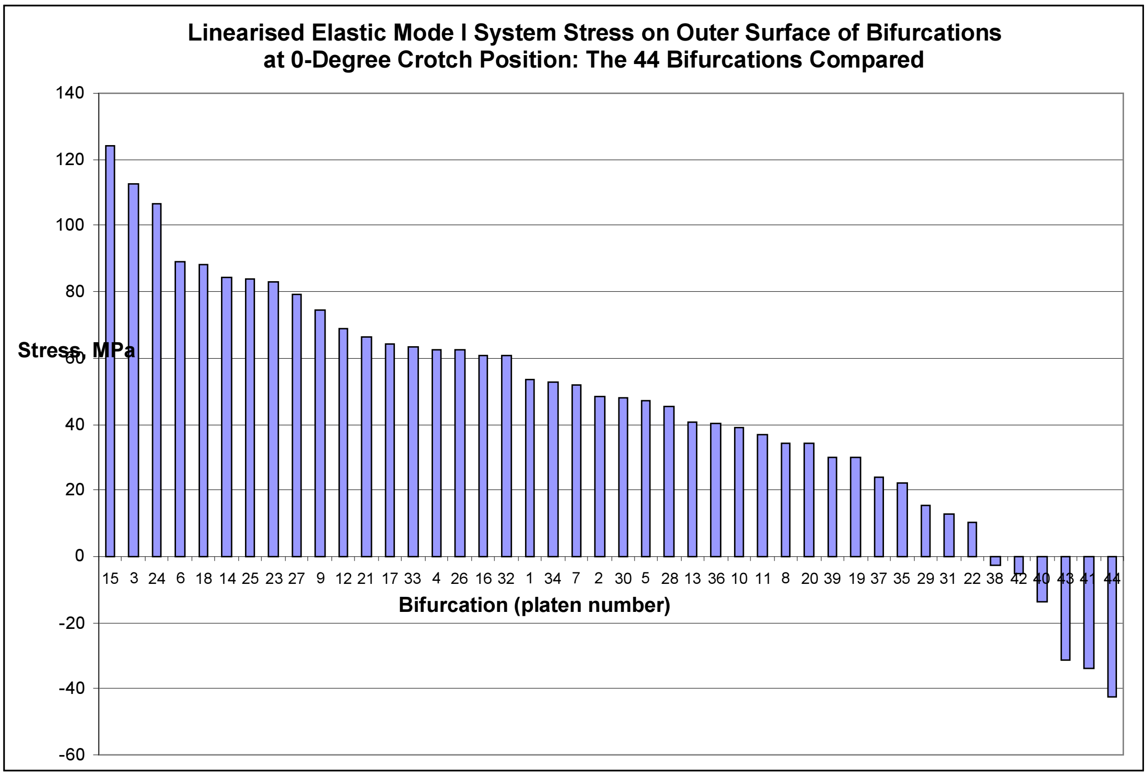

Figure 2. Linearised elastic mode I system stress variations across a boiler unit

SURFACE CARBURISATION

Long term operation of the grade 316H stainless steel at high temperatures in the pressurised reactor carbon-dioxide leads to both oxidation of the surface of the steel and carburisation to depths of perhaps 0.5mm or so. The carburisation causes substantial hardening of the affected near-surface material, with resulting reductions in both fatigue endurance and creep ductility. The methodology adopted here for the creep-fatigue crack initiation assessment of the thin hardened surface layer is simply to carry out an R5 Volume 2/3 assessment ignoring the hardened layer *other than* in respect of the creep ductility and the fatigue endurance. Research work underway within EDF Energy is aimed at quantifying the degradation of these creep and fatigue properties by carburisation, but has not yet reached a conclusion.

In the present work the approach adopted was to determine the fatigue endurance and creep ductility which must be assumed for the carburised layer in order to reproduce the observed incidence of cracking. So the non-carburised fatigue endurance was factored down by a factor, f, taken to be a lognormally distributed variable. Both the mean and the standard deviation of $\log_{10} f$ were regarded as tuneable parameters, the objective being to best reproduce the observed incidence of cracking. Similarly, a lognormal distribution of uniaxial creep ductility is assumed for the carburised surface, the desired mean and standard deviation of $\log_{10} \varepsilon_{f,uni}$ being tuneable. (NB: ductility is assumed in %).

LATIN HYPERCUBE MONTE CARLO SIMULATION

The Monte Carlo method involves randomly sampling the distributed input variables many times, carrying out a deterministic assessment for every trial. Latin hypercube sampling was used in this case, see for example Kroese *et al* (2011). This is an efficient simulation technique which permits a large number of distributed variables to be addressed. Each variable can take one of a finite number of values each of which represents a range of values (a 'bin'). All bins are of equal probability. The Latin hypercube algorithm ensures that all bins of all variables are sampled in the minimum number of trials (though not, of course, in all possible combinations). Moreover, because all bins are of equal probability it follows that all trials are of equal probability, thus ensuring that all trials are of equal weight in the simulation.

The estimated probability that a crack initiates in a given component is then simply the ratio of the number of trials which crack (i.e., produce a damage of unity) divided by the total number of trials for that component. Alternatively, for the simulation of a population of components, the frequency of cracks initiating is estimated by the ratio of the total number of crack initiations divided by the total number of simulations, each of which covers the whole population of components.

One of the strengths of the Monte Carlo / Latin hypercube approach is that it can handle very large numbers of distributed variables with ease and without excessive computation times. To-date our probabilistic simulations have involved in excess of 40 distributed variables in some cases. The assessment reported here used 14 random variables.

THE DISTRIBUTED VARIABLES

The following 14 variables have been taken as distributed: pressure stress (normal distribution), system stress (normal distribution), thickness (normal distribution), operating temperature (normal distribution), uniaxial creep ductility (lognormal distribution), parent substrate fatigue endurance (lognormal distribution), carburised surface fatigue endurance reduction factor, f (lognormal distribution), elastic follow-up factor (truncated normal distribution), creep strain rate (lognormal distribution), factor on relaxation rate (truncated lognormal distribution), weld strain enhancement factor (truncated lognormal distribution), 0.2% proof stress (lognormal distribution), Ramberg-Osgood cyclic stress-strain A parameter (lognormal distribution), Young's modulus (normal distribution). Correlations between variables can be of crucial importance in probabilistic assessments. However, no correlations were assumed in this application.

The following variables have been treated as deterministic: weld toe stress concentration factor, pressures under each relevant condition, metal loss, numbers of cycles of each type, dwell times, multiaxial stress state adjustment to creep ductility, shakedown factor (K_S) and the Ramberg-Osgood cyclic stress-strain β parameter.

CODING, NUMBERS OF TRIALS, RUN TIMES AND CONVERGENCE

All coding was done in Visual Basic within Excel using standard office desktop PCs. The reactor was assumed characterised by a single boiler unit of 44 features. Runs generally consisted of 1000 trials of each of the 44 features in turn, i.e., 44,000 trials per run, each trial involving the numerical construction of the hysteresis cycle for each of the 385 cycles over life individually. The run time on a standard desktop PC (core i5-2400 quad core processor at 3.1GHz) was 62 minutes for 44,000 trials (whole reactor simulation), or 0.085 seconds per trial of 385 cycles (0.22 ms per R5 cycle assessment).

It is important to confirm that a sufficient number of trials has been used in a given run to obtain convergence of the predicted probability of cracking. This can be done in two ways. The first is to monitor in real time how the estimate of cracking probability develops whilst the simulation is running. An example of this is shown as Figure 3. Note that this relates to the simulation of just one item, using 1000 trials. Figure 3 clearly indicates convergence, the cracking probability varying by only a fraction of a percent over the last two-thirds of the run.

The second method is to re-run a simulation with unchanged inputs. This was done for a single bifurcation and indicated that the standard deviation of the resulting cracking probability was ~0.7% (of its mean) over 1000 trials. However, using 1000 trials for each of the 44 bifurcations in a boiler unit, as was done for the production runs, will result in a standard deviation of the reactor-averaged cracking probability which is a factor $1/\sqrt{44}$ less, i.e., ~0.1% (of its mean). This demonstrates convergence, not accuracy.

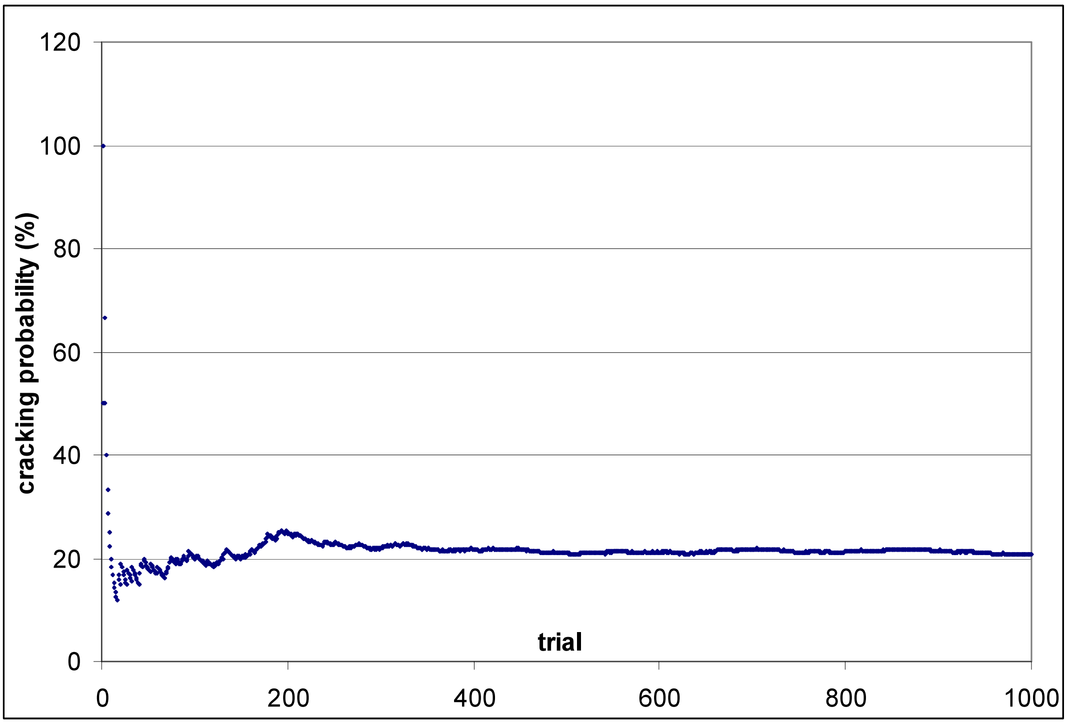

Figure 3. Illustration of convergence of cracking probability (for a single component)

RESULTS

Runs were carried out for each of the reactors with no allowance for carburisation, i.e., using nominal substrate creep ductility and fatigue endurance distributions. The reactor-average cracking probability by year 30 was ~1%. This falls well short of the observed incidence of cracks, of up to 24% (Table 1).

Hence, the incidence of cracking cannot be explained based on a creep-fatigue mechanism with nominal material properties.

To obtain agreement with the plant incidence of cracking there are four tuneable parameters: the median values of the creep ductility and the fatigue endurance reduction factor, f, and their standard deviations. Considering firstly the worst reactor (reactor 3), with 24% of items cracked, Figure 4 shows combinations of these parameters for which the Monte Carlo simulation reproduced close to a 24% incidence of cracking, the standard deviation in $\log_{10} \varepsilon_{f,uni}(\%)$ being assumed to be 0.3 in all cases. For example, the 24% incidence of cracking is reproduced for a median ductility of 1%, a ductility at the 1-sigma level of 0.5%, and a value of f at the 1-sigma level of ~0.005 for a wide range of median values for f. (Here the 1-sigma level refers to the mean minus one standard deviation).

Figure 5 displays combinations of the parameters which reproduce the incidence of cracking for the least affected reactor (reactor 1) with a 7% incidence of cracking. These combinations fix the standard deviation in $\log_{10} f$ at 0.35. For example, the target 7% cracking incidence is reproduced by the probabilistic simulation for a median ductility of 1.57% and a ductility of 1% at the 1-sigma level, with a value of f at the 1-sigma level of ~0.2.

It was not possible to obtain agreement with the cracking incidence across all reactors using a compatible set of parameters. In fact, for the same set of input assumptions the predicted incidence of cracking is similar for all reactors, in contrast to the observed incidence which varies between 7% and 24%. The greater incidence of cracking in some reactors is therefore more likely to be due to the speed or severity of formation of the carburised layer, perhaps due to temperature differences or reactor coolant chemistry differences or simply differing material susceptibility.

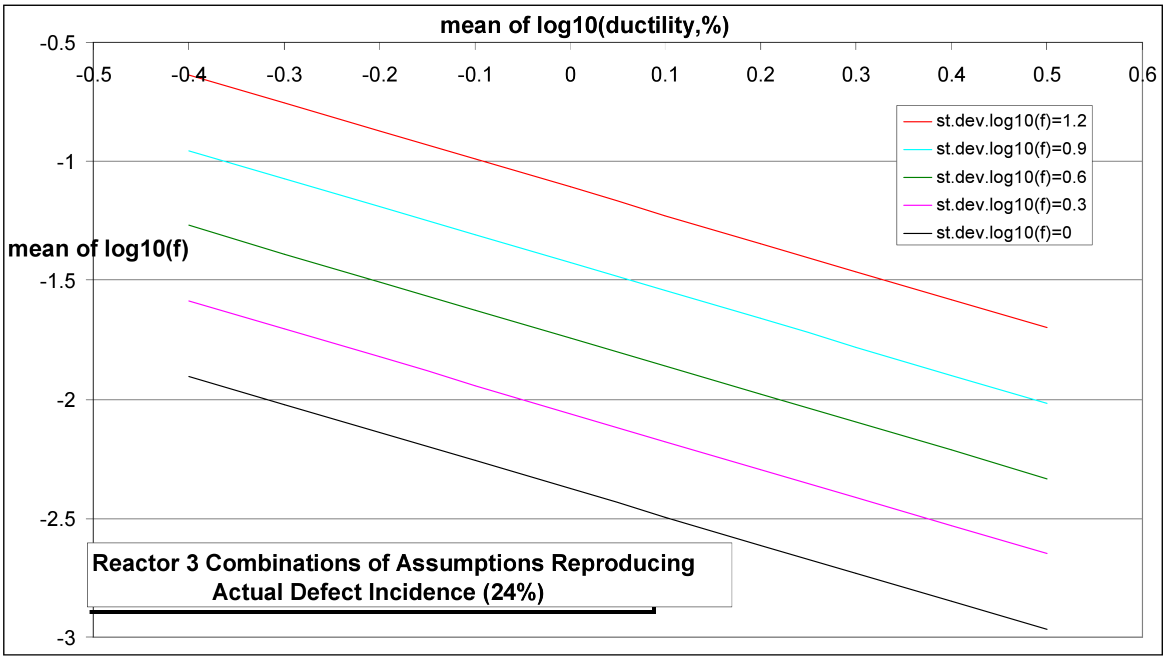

Figure 4. Combinations of mean ductility and mean and standard deviation of the fatigue endurance factor, *f*, which predict a defect incidence of 24% for reactor 3 assuming a standard deviation in $\log_{10} \varepsilon_{f,uni}(\%)$ of 0.3

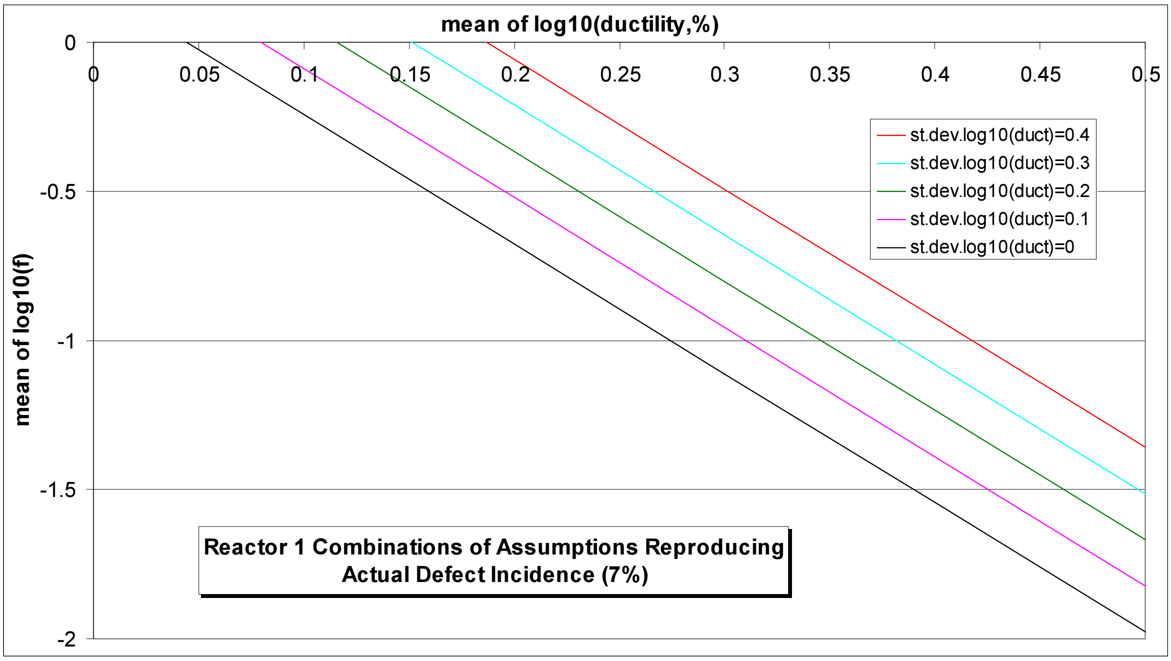

Figure 5. Combinations of mean and standard deviation of the ductility and the mean of the fatigue endurance factor, *f*, which predict a defect incidence of 7% for reactor 1 assuming standard deviation in $\log_{10} f$ of 0.35

CONCLUSIONS

Probabilistic analysis provides insight into plant behaviour that is not apparent, even obscured, in deterministic assessments. In the present application the probabilistic treatment provides a quantitative refutation of the possibility that the observed incidence of cracking might be attributable to creep-fatigue of nominal material. It therefore helps consolidate the hypothesis that the carburisation due to the reactor coolant plays an essential role in the formation of the cracks. Moreover, the probabilistic model quantifies the degree of degradation in creep ductility and/or fatigue endurance required to explain the incidence of cracking. Ongoing materials testing of material with a carburised surface will shortly permit the accuracy of these estimates to be examined.

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