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FLAW ASSESSMENT PROCEDURE FOR HIGH TEMPERATURE REACTOR COMPONENTS

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ABSTRACT

An interim high-temperature flaw assessment procedure is described. This is a result of a collaborative effort between Electric Power Research Institute in the USA, Central Research Institute of Electric Power Industry in Japan, and Nuclear Electric plc in the UK. The procedure addresses preexisting defects subject to creep-fatigue loading conditions. Laws employed to calculate the crack growth per cycle are defined in terms of fracture mechanics parameters and constants related to the component material. The crack growth laws may be integrated to calculate the remaining life of a component or to predict the amount of crack extension in a given period. Fatigue and creep crack growth per cycle are calculated separately, and the total crack extension is taken as the simple sum of the two contributions. An interaction between the two propagation modes is accounted for in the material properties in the separate calculations. In producing the procedure, limitations of the approach have been identified. Some of these limitations are to be addressed in an extension of the current collaborative program.

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1. INTRODUCTION

The Electric Power Research Institute (EPRI) in the USA, the Central Research Institute of Electric Power Industry (CRIEPI) in Japan, and the former Central Electricity Generating Board (CEGB) in the UK have been conducting collaborative studies in the field of liquid metal reactor development. The joint studies focus on several areas of research, among them the high-temperature flaw assessment procedure for reactor components. An interim high-temperature flaw assessment guide presented below is the result of a two-year collaboration. The guide is based on the findings described in the joint EPRI/CRIEPI/CEGB state-of-the-art survey [1], interim and final reports [2,3], and on a developing high temperature assessment procedure known as R5 [4,5].

The procedure addresses preexisting defects subject to creep-fatigue conditions. The crack growth per cycle is calculated using laws defined in terms of fracture mechanics parameters and material constants. The fracture mechanics parameters are determined from the operational history, crack size, structural geometry and high-temperature material deformation characteristics. The crack growth laws may be integrated between initial and final defect depths to calculate the remaining life of a component, or over a given number of cycles to predict the amount of crack extension in that period. The cyclic (fatigue) and creep crack growth per cycle are calculated separately, the total crack extension being a simple sum of the two contributions. However, it is recognized that there may be an interaction between the two propagation modes and this is accounted for in the material properties used in the separate calculations.

Some limitations of the approach are identified in the sections describing specific calculations which are required in order to apply the procedure. Some of these limitations are to be addressed in Phase II of the collaborative program, commencing in July 1990 and spanning 24 months.

2. PROCEDURE

Outlined below are the steps to be followed when performing a creep-fatigue crack growth assessment. The steps refer to sections

where detailed guidance is provided concerning the required calculations or materials data.

- Step 1 Determine the temperature and stress histories at the defective section, allowing where necessary for the influence of the defect on overall structural response (Sections 3.1, 3.3.1).
- Step 2 Specify the initial defect size, a_0 , and estimate, if possible, the permissible final defect size, a_f . The latter is the maximum crack depth that the structure can safely tolerate under service and overload conditions (Section 3.2).
- Step 3 Calculate the effective fatigue J-integral range as a function of crack size taking due account of the influence of the defect on the overall structural response (Section 3.3).
- Step 4 Calculate the creep parameter, C^* , as a function of crack size and time during hold period taking due account of the influence of the defect on structural response and the possible effects of this and cyclic loading on the material deformation behavior (Section 3.4).
- Step 5 Experimentally measure or otherwise obtain the cyclic crack growth law (Section 3.5).
- Step 6 Experimentally measure or otherwise obtain the creep crack growth law (Section 3.6).
- Step 7 Linearly sum the two laws to obtain the total crack growth per cycle and hence obtain either:
- (i) the remaining life by integrating the total crack growth per cycle between the initial defect size, a_0 , and the permissible final defect size, a_f (section 3.7); or
 - (ii) the amount of crack extension that occurs from an initial crack size a_0 in a given number of cycles (Section 3.7).

- Step 8 Perform a sensitivity analysis with respect to the input data to identify the life limiting aspects of the assessment. Where the calculated remaining life or the calculated crack extension is unacceptable, it may be possible to re-appraise the input data taking due account of their influence on the overall assessment (Section 3.8).
- Step 9 Report the results of the assessment and provide information on the analysis methods and materials data used in all aspects of the analysis.

3. SUPPORTING CALCULATIONS

3.1 STRESS ANALYSIS

To properly define the loading conditions on the defective region, the complete load history of the component needs to be broken down into well-defined cyclic events. Each different service cycle will have an associated cyclic load, load during the hold period, and a characteristic temperature history. The actual loading history is thus reduced to the application of a definite number of different service cycles.

The most complete stress analysis would involve inelastic calculations for the defective component performed for a number of cycles with allowances for increases in crack size due to both cyclic and creep contributions. Such an approach, however, may be impractical for complex components. The present procedure recommends simplified methods of stress analysis. For components subject to many cycles limitation of creep-fatigue damage requires that plastic strain ranges, plastic strains and creep strains are all small. Consequently, components reach a steady cyclic state in which behavior of most of the material is essentially elastic, with localized regions experiencing plastic cycling. In such cases the shakedown method may be used [5]. The shakedown method employs the results of an elastic analysis. Once the elastic stress analysis is performed, a residual stress is added to the elastic stress history to produce a steady cyclic stress history, the value of which at the defective section is used in the present procedure. It should be noted that for the shakedown approach to apply, at least 80% of any

structural section must form a continuous ligament over which shakedown is satisfied [5].

3.2 SPECIFICATION of DEFECT SIZES

3.2.1 Initial Defect Size a_0 The initial defect size may be defined in a number of ways:

- (i) the maximum size that can elude detection at the design/manufacturing stage as set by inspection standards;
- (ii) the size of a defect found in service;
- (iii) a size based on experience in fabricating a particular type of component;
- (iv) the maximum size of defect that could be present and yet not have caused failure during a proof test;
- (v) a defect created at an initially non-defective surface by creep-fatigue mechanisms. This may be estimated using a modified creep-fatigue endurance, defined as the number of cycles necessary to produce a defect of a particular size, rather than the number of cycles required to cause total failure of a test specimen [4].

Flaws discovered in practice will have an irregular shape. In order to perform the calculations outlined in Sections 3.3 and 3.4, it is necessary to characterize the flaw by a circumscribing curve. The ASME Boiler and Pressure Vessel Code, Section XI [6] and the British Standards Institution Published Document 6493 [7] provide guidelines for flaw characterization. Generally, a surface defect is characterized as a semi-ellipse and a buried defect as an ellipse.

3.2.2 Permissible Final Defect Size a_f The maximum permissible defect is the defect that can be present in the structure during service and overload conditions without causing failure. Where creep is negligible, the value of a_f is controlled by fast fracture or short-term ductile failure. In this case predictions can be made using the R6 procedure [8]. In other cases the permissible defect size may be controlled by creep rupture of the remaining ligament ahead of the crack, as calculated by continuum damage mechanics. The reference stress techniques based on the stresses occurring during the hold time may be used to assess this failure mode.

3.3 CALCULATION of EFFECTIVE FATIGUE J-INTEGRAL RANGE

The crack growth per cycle under rapid loading is well correlated with an effective fatigue J-integral range, ΔJ_{eff} . For application to components it is necessary to calculate ΔJ_{eff} from the service stresses as a function of crack size ranging from a_0 to a_f . This can be accomplished by a number of methods, some of which are presented below.

3.3.1 Elastic Response. For the elastic approach to be applicable, the uncracked body stresses must remain elastic, and the crack must be sufficiently small so that the remaining ligament can sustain the elastically calculated loads by an essentially elastic response. For deep cracks, or when the elastically calculated stresses in the uncracked body exceed the yield stress, substantial plasticity may be obtained in the ligament. In this case the elastic approach is inadequate and alternative estimates of ΔJ_{eff} must be adopted.

In the elastic approach, the total stress intensity factor range is calculated as the difference between maximum and minimum values. Code and handbook solutions, and weight function methods may be used to calculate the stress intensity factor from the uncracked body stresses. In addition, finite element methods can be employed.

To derive the effective fatigue J-integral range, the total stress intensity factor range must first be modified to account for crack closure which significantly influences the fatigue crack growth per cycle. Crack closure is influenced by the stress ratio, the maximum stress intensity factor in the cycle (i. e. plasticity), and by the amount of creep strain occurring in hold periods [9]. A simplified conservative estimate of closure may be defined in terms of only the stress ratio. This gives an effective stress intensity factor range, ΔK_{eff} as:

$$\Delta K_{eff} = q_0 \Delta K, \quad (1)$$

where q_0 is the total load range for which a crack is judged to be open and this is calculated in terms of the stress ratio, R :

$$R = K_{min}/K_{max} \quad (2)$$

One conservative estimate for q_0 is [2]

$$\begin{aligned} q_0 &= 0.5, & -2.5 > R \\ q_0 &= 1 + R/5, & 0 > R \geq -2.5 \\ q_0 &= 1, & R > 0 \end{aligned} \quad (3)$$

Once ΔK_{eff} is evaluated, the effective J-integral range, ΔJ_{eff} , is simply

$$\Delta J_{\text{eff}} = (\Delta K_{\text{eff}})^2 / E' \quad (4)$$

where Young's modulus $E' = E$ in plane stress and $E' = E/(1-\nu^2)$ in plane strain, and ν is the Poisson's ratio.

It should be noted, that even when response is elastic, compliance changes due to the presence of a crack may affect structural behavior and cause the cracked body stress resultants to differ significantly from those of the uncracked body. Examples of such behavior may be found in [10].

3.3.2 Representation of Cyclic Deformation Behavior. If an inelastic approach is adopted to derive ΔJ_{eff} , it is necessary to have a representation of the cyclic stress-strain behavior of the material. The Ramberg-Osgood equation can be employed to relate the stress range $\Delta\sigma$ to the total strain range $\Delta\epsilon$

$$\Delta\epsilon = \Delta\sigma/E + \alpha(\Delta\sigma)^m \quad (5)$$

where α and m are temperature-dependent material constants. This equation defines the locus of the ranges of stress and strain. For the approximate methods described below, it is adequate to describe only this locus. However, if a detailed analysis approach were adopted then a description of the loading path for a particular strain range would be needed. The loading path (ϵ', σ) with the origin defined at the point of zero stress on the tensile-going part of the hysteresis loop may also be described by a Ramberg-Osgood equation

$$\epsilon'(\sigma) = \sigma/E + \alpha(2\sigma)^m \quad (6)$$

where ϵ' is the tensile-going strain. In general the constants α and m in equations (5) and (6) must differ in order to accurately describe both the locus of the ranges of stress and strain and the loading path.

3.3.3 GE/EPRI Method for Estimating ΔJ_{eff} Fully plastic solutions for typical specimen geometries are presented in a non-dimensional form in the GE/EPRI handbook [11,12]. When the cyclic stress-strain properties are represented by the Ramberg-Osgood equation, these solutions can be employed to estimate the fatigue J-integral range, ΔJ_f as:

$$\Delta J_f = \Delta J_e + \Delta J_p \quad (7)$$

$$\Delta J_e = (\Delta K)^2/E' \quad (8)$$

$$\Delta J_p = \alpha c(a/w)h_1(a/w,m)(\Delta P\sigma_0/P_0)^{m+1} \quad (9)$$

Here ΔJ_e and ΔJ_p are contributions due to elastic and plastic deformation, w is section width, c is a geometrical parameter often equal to the remaining ligament, h_1 is the non-dimensional fully plastic solution for J obtained by interpolation of values in [11,12] for a particular geometry, and P_0 is a normalized load proportional to stress σ_0 . It should be noted that the stress σ_0 is not one of the constants in the Ramberg-Osgood equation (5) and that the value of σ_0 does not affect the estimate in equation (9). Equation (7) does not include an allowance for crack closure but a reasonable estimate may be given by

$$\Delta J_{eff} = q_0^2 \Delta J_f \quad (10)$$

Especially for displacement-controlled loading, equation (10) is consistent with equation (4) in the elastic limit ($\Delta J_p \ll \Delta J_e$) when $R < 0$. For stress-controlled cycling, ratcheting may reduce the amount of closure and in such circumstance it is conservative to set $\Delta J_{eff} = \Delta J_f$.

3.3.4 Reference Stress Method for Estimating ΔJ_{eff} The reference stress method may be used to estimate inelastic deformation of structures from the results of elastic analysis and the limit load [13]. The estimate of fatigue J-integral range, ΔJ_f , is

obtained by analogy with reference stress J-estimation methods [14] as

$$\Delta J_f = \Delta \sigma_{ref} \Delta \epsilon_{ref} R' \quad (11)$$

where

$$R' = (\Delta K / \Delta \sigma_{ref})^2 \quad (12)$$

$$\Delta \sigma_{ref} = \sigma_Y \Delta P / P_L(a/w, \sigma_Y) \quad (13)$$

Here P_L is the limit load for the cracked geometry (tabulated solutions are given in [15]), and $\Delta \epsilon_{ref}$ is the strain range corresponding to $\Delta \sigma_{ref}$ on the material cyclic stress-strain curve. The cyclic stress-strain curve in this case is given by

$$\Delta \epsilon_{ref} = \Delta \sigma_{ref} / E + \alpha (\Delta \sigma_{ref})^m \quad (14)$$

In general equation (11) does not rely on material behavior being represented by the Ramberg-Osgood relation or on the availability of fully-plastic solutions. Equation (11) does not allow for crack closure, however, the modification of equation (10) and the following discussion can then be used to define the effective fatigue J-integral range.

3.3.5 Limitations of the Approach for Estimating ΔJ_{eff}

The approximate methods described above rely on solutions developed primarily for mechanical loading. These approaches can be followed where the results of the stress analysis can be represented by equivalent mechanical loads.

For pure secondary thermal loading ΔJ_f may be estimated from the results of an elastic analysis as

$$\Delta J_f = \Delta K^2 / E' \quad (15)$$

For elastic-thermal stresses well in excess of the yield stress, equation (15) can significantly overpredict ΔJ_f . An improved estimate can be obtained by using results of an elastic-plastic analysis of the uncracked body according to the method presented in [16].

When a mechanical load is combined with the cyclic thermal loading, it is necessary to include plasticity more explicitly. Techniques for use with the GE/EPRI scheme and the reference stress approach are given in [17] and [18], respectively.

Extensive plasticity complicates the overall structural response and may lead to ratcheting. The treatment of crack closure under creep-fatigue loading conditions is likewise complicated by extensive plasticity and is still under development.

3.4 CALCULATION of CREEP PARAMETER C^*

During the hold periods in creep-fatigue cycles, crack growth rates have been successfully correlated with the creep integral C^* . For application to components, it is necessary to calculate C^* from the service stresses as a function of crack size for defects in the range a_0 to a_f . In addition, it is necessary to mathematically represent the creep deformation behavior of material. Representation of creep deformation behavior and a number of methods for estimating C^* are described below.

3.4.1 Material Creep Deformation Behavior. In creep-fatigue cycles creep deformation may occur at essentially constant strain during hold periods. Stress relaxation under such conditions may be described by:

$$\dot{\epsilon} = 2A' \sinh [(\sigma - \sigma_i)/B'\sigma_0] \quad (16)$$

where σ_0 is the stress at the start of the hold period, A' and B' are temperature dependent material constants, and σ_i is an internal or back stress such that $\dot{\epsilon} = 0$ for $\sigma \leq \sigma_i$. Equation (16) permits the stress history, and hence the creep strain rate, to be established under stress relaxation conditions. For cycles in which creep deformation occurs at essentially constant stress during hold periods, conventional creep strain equations (e. g. Blackburn type) can be used. These equations may also be relevant to stress relaxation under creep-fatigue loading but validation and the necessary material constants should be obtained from tests on material in the cycled condition.

3.4.2 GE/EPRI Method for Estimating C^* Under Constant Load. By analogy with the fully plastic solutions used to evaluate ΔJ_I , C^* for steady-state creep conditions can be estimated by

$$C^* = A c(a/w) h_1(a/w, n) (P \sigma_0 / P_0)^{n+1} \quad (17)$$

where A and n are material constants in the creep law

$$\dot{\epsilon} = A \sigma^n \quad (18),$$

and P is the load level during the hold period. When creep behavior deviates from the power law, the reference stress method described below may be used.

3.4.3 Reference Stress Method for Estimating C^* Under Constant Load. By analogy with the reference stress J-estimation techniques (see Section 3.3.4), C^* during the hold period is estimated from

$$C^* = \sigma_{ref} \dot{\epsilon}_{ref} R' \quad (19)$$

The reference stress is defined as

$$\sigma_{ref} = P \sigma_Y / P_L(a/w, \sigma_Y) \quad (20)$$

where P is the load during the hold period. The length parameter R' may be estimated from:

$$R' = K^2 / \sigma_{ref}^2 \quad (21)$$

3.4.4 Estimating C^* Under Constant Displacement. Under constant displacement conditions, the total displacement rate, composed of elastic and creep contributions, is zero during hold periods:

$$\dot{\Delta} = \dot{\Delta}_{el} + \dot{\Delta}_{cr} = 0 \quad (22)$$

The influence of change in crack length is usually of little practical importance for component assessments where crack growth is

small. Consequently, the elastic displacement rate can be represented as:

$$\dot{\Delta}_{el} \approx (\dot{P}/P) \Delta_{el} \quad (23)$$

The creep displacement rate is composed of contributions due to the crack and to the uncracked-body:

$$\dot{\Delta}_{cr} = \dot{\Delta}_{cr}^c + \dot{\Delta}_{cr}^{uc} \quad (24)$$

Equations (22-24) allow the load to be represented as a function of time and the load drop rate to be determined. The value of C^* is then determined using the methods described in Sections 3.4.2 and 3.4.3 with the instantaneous load. Within the reference stress method the load drop rate can be expressed in terms of change in the reference stress:

$$\dot{\sigma}_{ref} = -E \dot{\epsilon}_{ref} / Z \quad (25)$$

where Z is the elastic follow-up factor. The factor Z is composed of the follow-up factor for the uncracked component and a contribution from the cracked component reflecting differences between elastic and creep compliances.

It is conservative to use the value of load or reference stress at the start of the hold period in equations (17) or (19) for estimating C^* , since the amount of stress relaxation is often small. However, changes in $\dot{\epsilon}_{ref}$, the creep strain rate corresponding to σ_{ref} , are more significant and need to be considered. For displacement controlled loading $\dot{\epsilon}_{ref}$ can be obtained directly from stress relaxation data.

3.4.5 Transient Effects. Transient effects occur due to adjustment of the crack-tip stress field from the elastic-plastic distribution at the end of the cyclic load change to a steady-state creep distribution [19]. Methods for treating these transient effects based on detailed numerical analyses are described in [2,3]. However, for displacement-controlled cycling, the reduction in C^* during hold periods is rapid and experimental evidence suggests that the approach described above adequately describes observed behavior [20].

3.4.6 Limitations of the Approach. Although a method for treating elastic follow-up for displacement-controlled loading has been described in Section 3.4.4, evaluation of the follow-up factor for cracked components is complex. Further numerical and experimental evidence is needed to confirm the suggested approach.

The approximate methods presented above employ solutions developed primarily for mechanical loading. Further numerical and experimental validation is needed where thermal and thermo-mechanical loadings are concerned.

3.5 CYCLIC CRACK GROWTH LAW

The crack growth per cycle due to cyclic load changes may be represented as

$$(da/dN)_f = C (\Delta J_{eff})^I \quad (26)$$

where C and I are material constants, dependent on temperature, and on the previous hold time and its position in the cycle. Data are presented in this form in [1-3], or in terms of ΔK_{eff} related to ΔJ_{eff} by equation (4). In generating test data, the maximum value of J in a cycle should be insufficient to cause ductile crack extension. The portion of a cycle for which the crack is open can be obtained experimentally by, for example, observing the point on the tension-going part of the load-displacement hysteresis loops at which the specimen compliance changes. The value of ΔJ_{eff} can then be obtained from the corresponding area under the load-displacement record [3].

A limitation of the above approach is that any hold-time dependence of the constants in equation (26) needs to be determined experimentally. Thus a number of creep-fatigue crack growth tests need to be performed for a range of hold times, and creep crack growth during these hold periods needs to be subtracted from the total crack growth. The influence of the hold time is found to be significant in materials with low creep ductility (e.g. some austenitic weld metals) but less pronounced in materials with high creep ductility such as austenitic base steels. A method for predicting the creep damage and its influence on the cyclic crack growth is needed. Alternatively, a unified approach for describing the total crack growth per cycle in terms of parameters which can be readily calculated could be developed in the longer term.

3.6 CREEP CRACK GROWTH LAW

Although standards for obtaining creep crack growth data are still in the development stage, methods are reasonably established [5] and results can be described by

$$\dot{a} = AC^{*q} \quad (27)$$

where $\dot{a}$ is the creep crack growth rate, C^* is obtained from experimental load and displacement measurements in a similar manner to obtaining ΔJ_{eff} , and A and q are experimentally determined material constants. The crack extension per cycle is obtained by integration of equation (27) as

$$(da/dN)_c = \int_0^{t_h} AC^{*q} dt \quad (28)$$

3.7 INTEGRATION OF GROWTH LAWS

The total crack growth per cycle (da/dN) is defined as

$$da/dN = (da/dN)_f + (da/dN)_c \quad (29)$$

This must be determined for each cycle type, accounting for the dependence of da/dN on crack size, a , and on hold time, t_h . The hold period affects $(da/dN)_c$ through the direct integration of the creep crack growth rate, and $(da/dN)_f$, through the possible dependence of the constants C and l on t_h . Crack size affects ΔJ_{eff} and C^* and hence affects both $(da/dN)_f$ and $(da/dN)_c$.

3.7.1 Remaining Life. The number of cycles required for the crack to grow from the initial to the final size can be obtained from:

$$a_f - a_0 = \sum_{i=1}^{N_g} (da/dN)_i \quad (30)$$

where $(da/dN)_i$ is evaluated for the crack size and hold time, t_h^i , for the i 'th load cycle. The remaining life (i.e. time required for the crack to grow from the initial to the final size) then is estimated as

$$t_g = \sum_{i=1}^{N_g} t_h^i \quad (31)$$

3.7.2 Crack Extension. The crack extension, a_e , during N_0 operating cycles is

$$a_e = \sum_{i=1}^{N_0} (da/dN)_i \quad (32)$$

Note, however, that crack size should not exceed a_f .

3.8 SENSITIVITY ANALYSIS

The procedure presented here does not contain margins or reserve factors, although small conservatisms are introduced by some of the approximate approaches. Confidence in an assessment is obtained by using lower and upper bound materials data as appropriate and by introducing a measure of conservatism in the analytical calculations. Additional confidence should then be gained by assessing the sensitivity of the predicted life to variations in the input parameters. Sensitivity analysis should examine effects of assumptions made with regard to loading conditions; extrapolation of materials data to service conditions; the nature, size and shape of the flaw; and calculational inputs. In addition, uncertainties due to the limitations of this procedure may be examined with the sensitivity analysis. Confidence in an assessment is gained when it is possible to demonstrate that small changes in input parameters do not dramatically change the remaining life or crack extension; and when realistic variations in the input parameters still lead to a demonstration of safe margins.

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