STP-NU-039

CREEP AND CREEP-FATIGUE CRACK GROWTH AT STRUCTURAL DISCONTINUITIES AND WELDS

ASME STANDARDS TECHNOLOGY, LLC

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Prepared by:

F. W. Brust

G. M. Wilkowski

P. Krishnaswamy

K. Wichman

Engineering Mechanics Corporation of Columbus (Emc^2)

ASME STANDARDS TECHNOLOGY, LLC

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ASME Standards Technology, LLC
Three Park Avenue, New York, NY 10016-5990

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FOREWORD

This document is the result of work resulting from Cooperative Agreement DE-FC07-05ID14712 between the U.S. Department of Energy (DOE) and ASME Standards Technology, LLC (ASME ST-LLC) for the Generation IV (Gen IV) Reactor Materials Project. The objective of the project is to provide technical information necessary to update and expand appropriate ASME materials, construction and design codes for application in future Gen IV nuclear reactor systems that operate at elevated temperatures. The scope of work is divided into specific areas that are tied to the Generation IV Reactors Integrated Materials Technology Program Plan. This report is the result of work performed under Task 8 titled "Creep and Creep-Fatigue Crack Growth at Structural Discontinuities and Welds."

ASME ST-LLC has introduced the results of the project into the ASME volunteer standards committees developing new code rules for Generation IV nuclear reactors. The project deliverables are expected to become vital references for the committees and serve as important technical bases for new rules. These new rules will be developed under ASME's voluntary consensus process, which requires balance of interest, openness, consensus and due process. Through the course of the project, ASME ST-LLC has involved key stakeholders from industry and government to help ensure that the technical direction of the research supports the anticipated codes and standards needs. This directed approach and early stakeholder involvement is expected to result in consensus building that will ultimately expedite the standards development process as well as commercialization of the technology.

ASME has been involved in nuclear codes and standards since 1956. The Society created Section III of the Boiler and Pressure Vessel Code, which addresses nuclear reactor technology, in 1963. ASME Standards promote safety, reliability and component interchangeability in mechanical systems.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a professional not-for-profit organization with more than 127,000 members promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit www.asme.org for more information.

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EXECUTIVE SUMMARY

The subsection ASME NH high temperature design procedure does not admit crack-like defects into the structural components. The US NRC identified the lack of treatment of crack growth within NH as a limitation of the code and thus this effort was undertaken. This effort is broken into two parts. Part I involved examining all high temperature creep-fatigue crack growth codes being used today and from these, the objective was to choose a methodology that is appropriate for possible implementation within NH. The second part of this task is to develop design rules for possible implementation within NH. This second part is a challenge since all codes require step-by-step analysis procedures to be undertaken in order to assess the crack growth and life of the component. Simple rules for design do not exist in any code at present. The codes examined in this effort included R5, RCC-MR (A16), BS 7910, API 579, and ATK (and some lesser known codes).

There are several reasons that the capability for assessing cracks in high temperature nuclear components is desirable. These include:

- Some components that are part of GEN IV reactors may have geometries that have sharp corners – which are essentially cracks. Design of these components within the traditional ASME NH procedure is quite challenging. It is natural to ensure adequate life design by modeling these features as cracks within a creep-fatigue crack growth procedure.
- Workmanship flaws in welds sometimes occur and are accepted in some ASME code sections. It can be convenient to consider these as flaws when making a design life assessment.
- Non-destructive Evaluation (NDE) and inspection methods after fabrication are limited in the size of the crack or flaw that can be detected. It is often convenient to perform a life assessment using a flaw of a size that represents the maximum size that can elude detection.
- Flaws that are observed using in-service detection methods often need to be addressed as plants age. Shutdown inspection intervals can only be designed using creep and creep-fatigue crack growth techniques.
- The use of crack growth procedures can aid in examining the seriousness of creep damage in structural components. How cracks grow can be used to assess margins on components and lead to further safe operation.

After examining the pros and cons of all these methods, the R5 code was chosen as the most up-to-date and validated high temperature creep and creep fatigue code currently used in the world at present. R5 is considered the leader because the code: (i) has well established and validated rules, (ii) has a team of experts continually improving and updating it, (iii) has software that can be used by designers, (iv) extensive validation in many parts with available data from BE resources as well as input from Imperial college's database, and (v) was specifically developed for use in nuclear plants.

R5 was specifically developed for use in gas cooled nuclear reactors which operate in the UK and much of the experience is based on materials and temperatures which are experienced in these reactors. If the next generation advanced reactors to be built in the US use these same materials within the same temperature ranges as these reactors, then R5 may be appropriate for consideration of direct implementation within ASME code NH or Section XI. However, until more verification and validation of these creep/fatigue crack growth rules for the specific materials and temperatures to be used in the GEN IV reactors is complete, ASME should consider delaying this implementation. With this in mind, it is this authors opinion that R5 methods are the best available for code use today.

The focus of this work was to examine the literature for creep and creep-fatigue crack growth procedures that are well established in codes in other countries and choose a procedure to consider

implementation into ASME NH. It is very important to recognize that all creep and creep fatigue crack growth procedures that are part of high temperature design codes are related and very similar. This effort made no attempt to develop a new creep-fatigue crack growth predictive methodology. Rather examination of current procedures was the only goal. The uncertainties in the R5 crack growth methods and recommendations for more work are summarized here also.

Finally, it is important to recognize that R5 was developed as an "assessment" procedure. A high temperature assessment procedure is used to assess or determine the effect of cracks on safety and performance of high temperature components. As such, it is not really used for design.

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1 INTRODUCTION

The GEN IV reactor concepts require structural components to operate at high temperatures in a regime where creep damage may occur and cracks may grow. The U.S. Nuclear Regulatory Commission (NRC) has identified the lack of a quantitative methodology for evaluating creep and creep crack growth as a shortcoming of the ASME Subsection NH (Class 1 Components in Elevated Temperature Service) standard [1]. The development of elastic-plastic fracture mechanics methods and the concepts of leak-before-break (LBB) were led by the needs of the nuclear industry. These crack assessment methods are now well established and used routinely in PWR and BWR plant extension applications and new designs. Quantitative creep and creep-fatigue crack growth assessment procedures are now needed for these GEN IV developments.

The subsection ASME NH high temperature design procedure does not admit crack-like defects into the structural components. In fact, design codes generally consider defect free structures while assessment codes address flaws and their treatment. Therefore, from a code design perspective, the need for creep and creep-fatigue crack growth procedures within NH is not warranted. However, there are several reasons that the capability for assessing cracks in high temperature nuclear components is desirable. These include:

- Some components that are part of GEN IV reactors may have geometries that have sharp corners – which are essentially cracks. For instance, some of the heat exchanger designs consist of micro-process technology, which are diffusion bonded sheets with hole patterns strategically placed so as to make thousands of small passages and features. Due to the fabrication procedure, the features have sharp corners. Design of these components within the traditional ASME NH procedure is quite challenging. It is natural to ensure adequate life design by modeling these features as cracks within a creep-fatigue crack growth procedure.
- Workmanship flaws in welds sometimes occur. It can be convenient to consider these as flaws when making a design life assessment.
- Non-destructive Evaluation (NDE) and inspection methods after fabrication are limited in the size of the crack or flaw that can be detected. In fact, it can be said that every nuclear component has crack like defects of some size that cannot be detected due to limitations in NDE technology. It is often convenient to perform a life assessment using a flaw of a size that represents the maximum size that can elude detection.
- Flaws that are observed using in-service detection methods often need to be addressed as plants age. Shutdown inspection intervals can only be designed using creep and creep-fatigue crack growth techniques. While NH is meant to be a design procedure rather than a service assessment procedure, methods for crack growth analysis can be useful.
- The use of crack growth procedures can aid in examining the seriousness of creep damage in structural components. How cracks grow can be used to determine the ultimate or limit load of a component and margins on safety.

The focus of this work was to examine the literature for creep and creep-fatigue crack growth procedures that are well established in codes in other countries and choose a procedure to consider implementation into ASME NH. The currently established engineering methods for predicting creep and creep fatigue crack growth at discontinuities and welded components was thoroughly reviewed. For the most part, these procedures were developed in Europe and have been implemented into European codes. *It is very important to recognize that all creep and creep fatigue crack growth procedures that are part of high temperature design codes are related and very similar.* The differences, which are pointed out later, are mainly in how to estimate the appropriate creep crack growth parameters. As such, the choice of the procedure to implement within ASME NH is made based on applicability to nuclear components, validation databases, ongoing support for the methods, maturity of the procedures, and options for computer codes to apply the methods, among others.

These procedures examined in this effort include:

- British R5. The R5 standard [2], which was an extension of the low temperature crack assessment procedure R6, is the oldest and most established code procedure available. The procedures were developed in the 1980s in response to the need for high temperature crack assessment of UK reactor designs which operate at higher temperatures compared with the U.S. PWR and BWR designs. R5 also has a crack initiation procedure, called Time Dependent Failure Assessment Diagram (TPFAD approach) also since crack initiation can be important for minimal fatigue conditions.
- The French RCC-MR (A-16) procedure [3]. This method, which is quite similar in concept to the R5 method and appears to have followed the philosophy of R5 from the beginning, has seen extensive development in the 1990s. The main difference compared to R5 is the methods used to estimate the reference stress methods used.
- API 579 approach. The API fitness for service (FFS) standard provides guidance for conducting FFS assessments using methods specifically prepared for equipment in the refining and petrochemical industry, although they are used in other industries as well [4]. The specific approach for creep and creep-fatigue crack growth has recently been implemented and a computer code has been developed for FFS assessment for both time-dependent and time-independent crack growth. The methods again are similar to the other approaches.
- BS-7910 code. The BS-7910 code, which is an advanced creep-fatigue crack growth assessment approach [5] similar to R5 and A16 (in fact, many portions come from the R5 code), provides assessment and remaining life estimation procedure that can be used at the design stage and for in service situations.
- The German KTA method. KTA does not appear as well established as R5 or A16 as a creep-fatigue crack growth assessment code. The 2-criterion method regards crack initiation as the most important factor in life assessment and does not deal with the crack growth regime [6]. The flat-bottom-hole approach (FBH) represents a crack detection and characterization method. The approaches used in Germany follow along the lines the R5 and A16 approaches, and are not discussed further here. It is important to note that crack incubation time can take up to 70% of the life, especially under conditions where fatigue is not important.
- Several other code approaches exist in other countries, many of which are summarized and compared in [7], also are available. However, these approaches either follow R5 or A16 or do not consider crack growth explicitly.

Damage based methods used in some industries such as the Omega Method can be quite valuable for creep-fatigue life assessment as well. The creep-crack code procedures discussed above are related to each other. Most currently established methods use variations of K, C* (C_t) and reference stress, all of which will be discussed. An engineering approach based on these parameters is natural since estimates are based on extensions of methods and solution handbooks on well-established elastic-plastic fracture. Hence, new users of the NH crack growth code that are familiar with elastic-plastic methods should adjust rather quickly. It is anticipated that a step-by-step procedure will be recommended for code implementation.

2 CREEP AND CREEP-FATIGUE CRACK GROWTH FUNDAMENTALS AND ENGINEERING METHODS

Damage nucleation usually begins with the development of small voids. These voids begin to grow via both diffusion mechanisms along the grain boundaries and with dislocation creep within the grains. At high stresses as occur near a material discontinuity or crack tip, a particle/matrix de-cohesion process with rupture could be predominant. Voids eventually link-up to produce micro-cracks and then macro-cracks. The treatment of crack growth, which eventually leads to component failure, is the purpose of this effort. These issues have been studied for more than 30 years and engineering methods for predicting creep crack growth now exist. Implementation of established crack growth methods is the purpose of this effort. However, before proceeding it is important to point out that more work is needed to reduce the conservatism in the current engineering methods of life prediction. Moreover, it is not clear that the current creep/fatigue crack growth procedures will perform adequately under GEN IV conditions and materials. While the engineering methods that have emerged to predict creep-fatigue crack growth lives are generally accepted it is important to point out that these methods are not appealing from a theoretical standpoint due to the assumptions made. The research needs needed to improve these methods will be discussed at the end of this report. This is especially true when trying to extend the well established R5 rules to conditions where experience and/or validation has not been made yet.

2.1 High Temperature Damage Progression and Crack Growth: Theoretical Considerations

Damage nucleation, growth, damage link-up, crack growth and breakage are the typical progression of failure for components that operate at high temperature. Damage nucleation begins with the nucleation of a cavity at a size-scale at the higher end of nano-scale level (~50 to 500 nm, depending on the material) as shown in Figure 1, below.

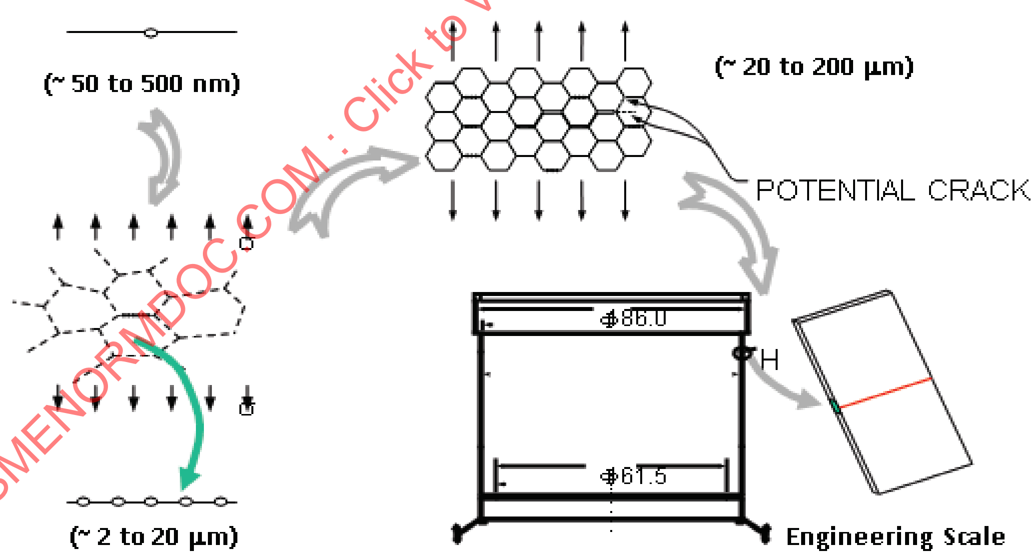


Figure 1 - Scales of Creep Damage Development and Failure

Early in the process, such nucleation and growth phenomenon is explained by diffusion of atomic flux from the cavities to the grain boundaries, along with grain boundary sliding (to a lesser extent)[1]. As time proceeds, nonlinear viscous flow (creep) occurs, and, depending on the local stress state, eventually overrides the diffusion growth process, especially as the neighboring voids approach each other. This is fortunate since engineering creep crack growth methods that exist today can only deal with nonlinear viscous flow type crack growth. This is also one reason that crack nucleation is very difficult to predict, as discussed later. As voids link, micro-cracks develop, link-up, and lead to a macro-crack.

Depending on the operating conditions, the macro-crack can slowly grow during component operation, or fail quickly. The growth of this crack during high temperature cyclic load conditions is considered here.

Much of the general theoretical discussion provided above, along with limitations of current engineering approaches, was obtained through a long grant by the authors (1990 through 2003).[2] Many summary and technical papers were developed describing this work, which focused on creep-fatigue crack growth (both modeling and testing) under cyclic loading, weld modeling, high temperature cyclic constitutive modeling and development of diffusion creep models (References [8] – [32] and many references sited therein). ***Deficiencies in the current engineering methods recommended here for possible implementation into NH, along with suggestions for further development work required to improve the present engineering creep-fatigue crack growth methods, are presented at the end of this report.*** Despite the limitations, we recognize that conservatisms in the current engineering methods existing today are due to these unknowns. The methods considered are the best available today. Unfortunately, it is has not been established that the current code based methods are conservative for GEN IV conditions yet. Until enough data and validation is available for GEN IV conditions, current creep fatigue crack growth rules should be used only if an experimental validation program is undertaken.

2.2 Currently Established Engineering Methods for Creep Fatigue Crack Growth

The engineering methods for predicting creep and creep fatigue crack growth are essentially an extension of engineering approaches which are used to predict elastic-plastic fracture. The methods are based on the concept that crack growth can be characterized by the strength of the asymptotic crack tip field. Creep crack growth rates can be correlated with the stress intensity factor (K), the C*-Integral and the reference stress (used in R5) among other approaches. The forms of the creep crack growth laws typically are power-law relationships between crack growth rates and these parameters. Crack growth rates can correlate with K when creep is confined very locally to the crack tip; with C* when the creep zone is larger during secondary creep; and with C_t (or C(t)) when creep transients occur at the crack tip (C* and C_t are related); and with reference stress (which can also be related to C*). While reference stress methods are often used to estimate creep/fatigue crack growth parameters within the current code approaches, there is some evidence that these methods are not accurate for all

[1] Practical engineering methods to account for diffusion based creep damage development and crack growth are in their infancy. Classical grain boundary cavitations' only can be predicted properly in an engineering assessment.

[2] Department of Energy, Office of Basic Energy Sciences, DOE Grant No. DE-FG02-90ER14135 entitled, *An Investigation of the Effects of History Dependent Damage In Time Dependent Fracture Mechanics,* PI, F. W. Brust.

crack shapes. This is the topic of research at present. However, finite element methods can always be used to obtain the crack growth parameters – although this may not always be practical. Most creep crack growth procedures used in worldwide codes are related to each other.

The C*-integral is the creep analogue of the elastic-plastic J-Integral which is used extensively to predict elastic-plastic fracture. For this reason, C*/C(t) approach is a natural parameter to use in ASME NH code procedures. The U.S. NRC and utilities have developed a very large database of solutions used to estimate the J-integral for through-wall and surface cracks in pipe, plate, vessels and other nuclear power plant components. Once the creep material constants in the form of power-law fits of creep data are available, these estimation schemes can be used directly to obtain C* and provide predictions of creep crack growth. Moreover, most commercial finite element codes permit the easy calculation of both C* and C_t, so obtaining this parameter for a creep-fatigue crack growth prediction for cases where compiled solutions are not available is not difficult. It is our view that extension of the J-integral based methods for incorporation into NH based on C* is natural since NRC, contractors and utilities are well versed in these methods and, furthermore, J-based solutions are also in the ASME Boiler and Pressure Vessel code (e.g., Section XI flaw evaluation procedures).

2.3 Creep Fatigue Crack Growth Methods for NH Code

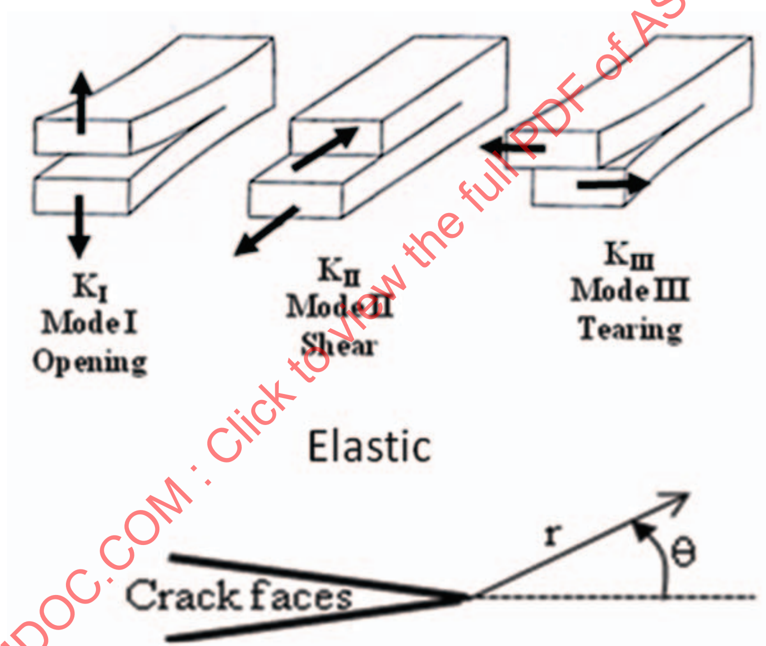
For conditions where time-dependent deformation does not occur, fatigue crack growth rates can be correlated with K using the Paris law, the Forman equation (including mean stress effects) and many other fatigue laws. When creep deformation can occur at the crack tip, the fatigue crack growth rates are strongly affected. Hold times at load increase crack growth rates. A higher mean stress will increase crack growth rates, which can be important in and near welds or high-constraint cracks. The NH code has conservative procedures for combining the damage caused by fatigue and creep in un-cracked structures. For crack-growth predictions, the separation of creep and fatigue crack growth damage is also the accepted procedure with well established engineering rules within R5 for materials where validation results are available. We anticipate that rules of this form will serve as the basis of the new NH rules if and when they can be accepted for GEN IV conditions. It turns out that low-frequency creep conditions permit crack growth correlation with C*, and high-frequency fatigue correlates with ΔK. In the transition regime, the current rules must be shown to be adequate for code use. However, the precise implementation into ASME code NH or other division should be delayed until validation is made for GEN IV materials. Alternatively, R5 rules should only be permitted for materials and conditions where validation has been made. These conditions are mainly those experienced within the gas cooled reactors within UK. For low cycle fatigue, where there is non-negligible plasticity at the crack tip during reloading, the cyclic J-integral parameter may be more appropriate. Despite theoretical concerns with Dowling ΔJ based low cycle fatigue crack growth predictions, it has performed reasonably well in engineering predictions.

3 FRACTURE MECHANICS BASIS FOR ENGINEERING CREEP-FATIGUE METHODS

The engineering creep/fatigue crack growth methods depend on both elastic and creep fracture mechanics parameters. These parameters are summarized in this section.

3.1 Elastic Fracture Considerations

Fracture mechanics began in the 1920s with the famous A. E. Griffith study of glass fracture. Griffith pondered the question as to why glass does not have the theoretical strength of the molecular bond and concluded that "cracking" was the cause. George Irwin is the father of modern fracture mechanics with his definition of the stress intensity factor needed for his famous studies of naval fractures in the 1950s and 1960s. Irwin identified three "modes" of fracture which are illustrated in Figure 2. Mode I type fracture is the opening mode defined by stresses which directly open the crack faces in the direction of the applied load. Modes II and III are shear modes with Mode III representing the "tearing" type analogous to ripping a sheet of paper. All three modes of fracture are possible at the same time – however mode I type fracture often dominates. *In fact, all engineering creep crack growth methods available today require that Mode I crack growth dominates.*



$$\sigma = K_I \left[f(\theta) / \sqrt{2\pi r} \right] \qquad (1)$$

Figure 2 - Elastic Crack Tip Fields

Irwin applied the elasticity procedures of Westergaard to write the asymptotic solution of the crack tip stress fields as (for Mode I type fracture) as seen in Figure 2, equation 1. Equation (1) then provides the stress field for every point (r, θ) near the crack tip. The figure inserted above equation (1) illustrates the geometric definitions and "r" represents the radial distance from the crack tip and "θ" represents the angular distance around the crack for the radial coordinate system centered at the crack tip[3]. f(θ) is a known function of sine and cosine functions. K_I is called the stress intensity factor (mode one hence the designation "I") since, if one knows its value (K_I units are psi-in$^{1/2}$, Mpa-m$^{1/2}$ etc.), then one can determine if the crack will be stable or grow. *If K_I =$\boldsymbol{K_c}$ then the crack grows, where $\boldsymbol{K_c}$ is obtained from tests on fracture specimen in the laboratory*. K_I depends on crack size, crack shape, material parameters and loading conditions. Tables of K are available in all of the code methods, including R5 and A16. Alternatively, one can always calculate K using finite element methods for the geometry and load condition of interest. One can write similar equations for the other modes of fracture with the same conclusion: if one knows the stress intensity factor(s), then one knows if the crack will grow or not.

When time independent plasticity dominates near the crack tip, i.e., when the plastic zone at the crack tip is not embedded within the elastic crack tip fields, a nonlinear parameter called the J-integral is used to characterize fracture. As for the elastic case, J represents the strength of the asymptotic crack tip fields for a for a power law hardening material where the crack experiences proportional loading (replace C* in equation (3) of Figure 4 by "J"). For this case, the crack grows when $J = J_{IC}$, where J_{IC} is the measured fracture toughness. J-tearing theory applies for small amount of crack growth as well. The commercial nuclear industry in the U.S. (and in many other countries) bases crack growth assessment and leak before break rules on J-Theory. In practice, especially in the nuclear industry, J-tearing theory is applied far beyond its theoretical basis into crack growth ranges and non-proportional load ranges that greatly violate the strict theoretical limits with success. The main reason it is accepted far beyond its theoretical limits is that extensive fracture test data in many geometries (specimens, pipe, vessels, elbows, etc.) and in many nuclear materials validates its use as a conservative predictive tool. This will be discussed later as well with regard to creep/fatigue fracture methods since the currently used methods violate the theory as well.

3.2 Fatigue Crack Growth

Fatigue of metals became a concern in the early 1950s when the British de Havilland Comet, the world's first commercial jet aircraft, experienced catastrophic service failures that were identified as metal fatigue. Structures are now designed to prevent fatigue failures throughout their expected life. There are two general philosophies of fatigue design, stress based and fracture mechanics based design.

Stress Based Fatigue Design. The standard ASME NH procedure for the fatigue portion of life in high temperature design is based on developing an "S-N" or Goodman curve type of approach. "S" represents the cyclic stress range of a structural part and "N" represents the number of cyclic loads to failure. This is combined with creep damage and interaction in NH using the well known and validated procedures in [1].

Fracture Mechanics Based Fatigue Design. Another type of fatigue weld design philosophy is based on fracture mechanics. Paris and colleagues in the early 1960s observed that fatigue life can be correlated with the stress intensity as

$$\Delta a/\Delta N = C(\Delta K)^n \qquad (2)$$

Here (Δa/ΔN) represents the amount of crack growth, Δa that occurs for every load cycle, ΔN. The sigmoidal curve plotted in Figure 3 in log scale mode illustrates this. From a laboratory cyclic fatigue

[3] Note that this equation implies that the stress near a crack tip is infinite since "r" is in the denominator. This is of course not possible. Actually, plasticity near the crack tip reduces the stress to a physically realistic value but is still characterized by the stress intensity factor.

test of a cracked specimen, one can plot the amount of crack growth per cycle versus the range of stress intensity factor, ΔK. This curve may be divided into three regions. At low stress intensities, Region A, cracking behavior is associated with a threshold value, below which the crack does not grow. In the mid-region, Region B, the curve is essentially linear. Finally, in Region C, crack growth rates are high and little fatigue life is expected. Most of the current applications of LEFM (linear elastic fracture mechanics) concepts to describe crack growth behavior are associated with Region B. In this region the slope of the log **Δa/ΔN** versus log **ΔK** curve is approximately linear and lies roughly between 10^{-6} and 10^{-3} in/cycle, depending on the material. In equation (2), C and n are constants with n usually between 3 and 4.

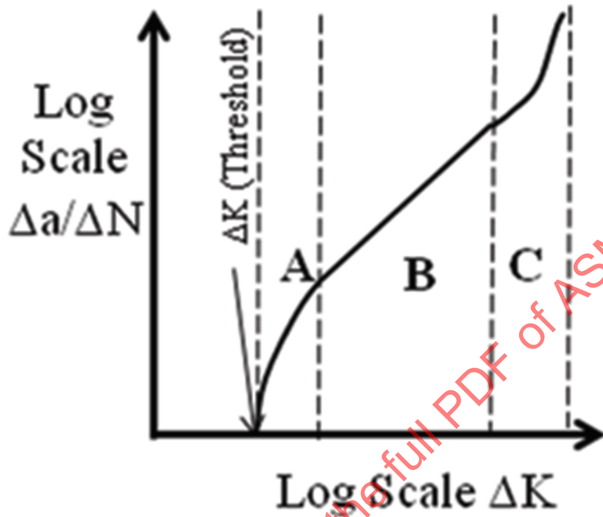


Figure 3 - Fatigue Crack Growth Relationship

In using the fracture mechanics based philosophy to fatigue design, one models fatigue crack growth using equation (2) and failure is predicted when $K = K_c$, or when $J = J_c$ if plasticity is important. The fracture mechanics approach to fatigue life is used in industries which use a "damage tolerant" approach to life design. A damage tolerant approach recognizes the fact that cracks are present in the structure and ensures that the crack will not grow to failure within the design life of the structures with a safety factor applied. This method is often used for aerospace and other high fidelity design applications where non-destructive evaluation methods (such as ultrasonic methods) are used to measure and monitor crack growth during the life of the structure.

All of the creep-fatigue crack growth methodologies are based on interaction between the creep and cyclic crack growth. The fatigue relationship is obtained by testing at the temperature of interest. It is seen that the fracture mechanics and NH design approaches are analogous to each other.

3.3 Creep Crack Growth

Referring to Figure 4, for a power law type creep law, a creep zone will develop at the crack tip ("blue" zone in Figure 4) and grow with time even under constant load. During early times, or for low loading conditions, the creep zone may be small. For this case, the creep crack growth rates can be correlated with the stress intensity factor of Section 3.1.

$$\sigma_{ij} = \left(\frac{C^*}{r}\right)^{\frac{1}{n+1}} f_{ij}(\theta, n) \qquad (3)$$

$$C^* = \int_{\Gamma}\left[\dot{W}\,\mathrm{d}y - T_i\left(\frac{\partial \dot{u}_i}{\partial x}\right)\mathrm{d}s\right] \qquad (4)$$

$$C(t) = \int_{\Gamma\to 0}\left[\dot{W}\,\mathrm{d}y - T_i\left(\frac{\partial \dot{u}_i}{\partial x}\right)\mathrm{d}s\right] \qquad (5)$$

$$\dot{W} = \int_0^{\dot{\varepsilon}^c} \sigma \,\mathrm{d}\dot{\varepsilon}^c$$

$\dot{W}$ is strain energy rate density

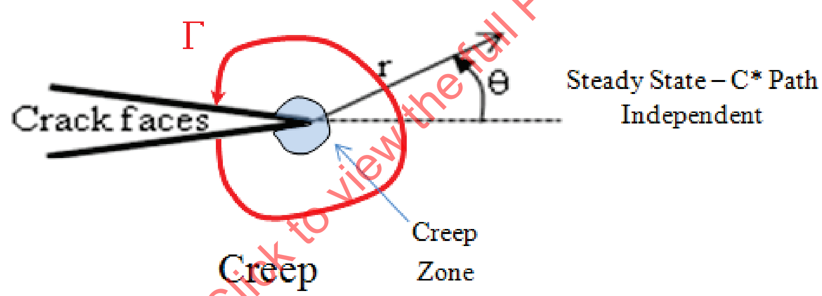


Figure 4 - Asymptotic Creep Crack Tip Fields

For steady state creep, where the creep zone is large and dominates the deformation, the asymptotic crack tip field can be written as the HRR field [33], [34] shown in equation (3) in Figure 4. Using the crack tip coordinate system shown in the illustration at the bottom of Figure 4, it is seen that the asymptotic stress field depends only on "r" (the distance from the crack tip), "n" (the power law exponent on stress for the simple power creep law), other geometric parameters, and C*. Analogous to the discussion of the stress intensity factor, here the strength of the asymptotic field depends only on C*. If one can calculate C*, then the crack tip severity can be determined. For large scale creep and steady state conditions, C* can be calculated as a line integral, as seen in equation (4). In Equation 4, C* is evaluated as a path independent integral along a path, Γ, which circles the crack tip as seen in the bottom illustration in Figure 4. Here "x" is in the direction of crack growth, "y" is perpendicular to this, T_i and u_i are tractions and displacements (i = 1; x, i = 2; y) calculated along Γ, and W is strain energy rate density, also defined in Figure 4. In practice, C* can be easily estimated or calculated using numerical methods. In practice, C* values are tabulated for many types of geometries for the engineering crack growth methods such as R5 and A16. Indeed, due the direct correlation between the HRR field for elastic-plastic fracture and creep fracture, any estimation technique or tabulation of the J-integral (used for elastic-plastic fracture) can be used directly to estimate C*. The last 20 years have seen many estimation methods and tabulations of J for nuclear type components (pipe, vessels, elbows, nozzles, etc.). Therefore, in practice, C* is not difficult to obtain without using numerical methods.

For regions where non-steady creep persist, the C(t) parameter shown in equation (5) of Figure 1 is used. This is identical to C*, except that the path, Γ, is calculated in the limit as the size goes to zero. As with C* estimation, C(t) (or C_t) can be easily estimated using reference stress techniques, which are discussed later with regard to the R5 approach.

Therefore, the creep and creep-fatigue crack growth rates are calculated using these parameters. As with NH, interaction between fatigue and creep crack growth can be included. It is important to note that the engineering creep crack growth predictive methods are also valid for creep laws that are general, although the asymptotic interpretation of meaning is obscured. It is also claimed in the crack growth procedures that the methods are also applicable to creep laws that do not experience any secondary creep. Again for this case, the theoretical interpretation is lacking. Moreover, we are not certain that this is generally true. As will be summarized later, more work is needed to study this phenomenon. This is important since some new high temperature materials may not experience secondary creep for all temperatures.

4 REVIEW AND SUMMARY OF CURRENT ENGINEERING METHODS

The currently established code-based engineering methods for predicting creep and creep fatigue crack growth at discontinuities and welded components was thoroughly reviewed. All established creep-crack code procedures are related to each other and so the choice of method is difficult. The main difference is how crack initiation is treated. As summarized in the last section, all currently established methods use variations of K, C* (C_t) and reference stress as previously discussed to make creep and creep/fatigue crack growth predictions. The procedures used for elastic-plastic fracture analysis are much more established and have clearer differences in them compared with creep fracture so such a choice would be more difficult. An engineering approach based on the above parameters is natural since estimates are based on extensions of methods and solution handbooks on well-established elastic-plastic fracture. Hence, new users of the NH crack growth code that are familiar with elastic-plastic methods such as those in Section XI should adjust rather quickly. Some of the issues that were addressed in this code implementation study include the following.

- Rules for determination of creep-fatigue crack growth interaction must be incorporated.
- The ductility exhaustion method for estimating creep crack damage for multi-axial stress states and discontinuities other than cracks should be considered.
- Creep–fatigue crack initiation in initially defect free components and the growth of flaws by creep and creep–fatigue mechanisms.
- Possible shakedown effects for structural assessment and relaxation of residual stresses.
- Creep crack initiation time should be considered since, for some cracked structures, the time to incubation can be a large portion of the crack growth life. Neglecting crack initiation is conservative. For conditions where fatigue loading is important, neglecting crack initiation is warranted since initiation predictive methods under combined creep/fatigue are not considered to be always conservative.
- Multi-axial stress effects, tri-axial stress effects and crack constraint effects (plane stress and between conditions).
- The treatment of the effects of crack closure during creep-fatigue growth.
- For treatment of weld residual stresses, it is noted that weld residual stresses play a major role in some current issues of corrosion in nuclear plants. It is well known that creep cracks can nucleate from relaxation of weld residual stresses alone.
- Incorporate rules for inclusion of plasticity effects in combination with creep under some circumstances.
- Consider the effects of diffusion creep issues. It turns out that none of the engineering methods account for this effect adequately. Moreover, including a diffusion creep component is a considerable challenge for engineering assessments due to its complexity.
- Established procedures for testing and obtaining material parameters must be clear. This includes obtaining creep constants, creep crack growth laws, fatigue laws and interactions.

Material properties need to include elastic properties, elastic-plastic properties, tensile creep rate curves and crack growth material parameters. Properties for many nuclear materials such as stainless steels and Cr-Mo steels are available in the literature. Some material data is available for IN 617 and 230 in the literature and there is much proprietary data for these materials (especially for IN 617), some of which may be available. Plans for incorporating material data into the creep crack growth portion of NH will be developed and outlined.

4.1 Overview of Engineering Creep Methods

Five different methods for creep-fatigue crack growth assessment were briefly summarized in Section 1, the introduction. These were R5, A16, API 579, BS 7910 and KTA. Here we provide a little more detailed description of R5, A16 and API579. The KTA method is very basic, has not been fully developed and is mainly concerned with crack initiation (although for some structures which experience no or little fatigue, crack initiation times dominate life). BS 7910 is very similar to R5–in fact many parts of the standard were taken directly from R5.

4.1.1 R5 Approach

The R5 approach [2] was developed specifically for use in nuclear and fossil fueled power plants in the UK by British Energy. British Energy pioneered the development of a code approach for handling creep-fatigue crack growth in high temperature structures. Indeed, the theoretical development of the method is summarized in the book by Webster and Ainsworth, two of the main R5 code developers [35].

The basic ingredients required for an assessment are: (i) the operating conditions; (ii) the nature of the defects; (iii) materials data; and (iv) structural calculations to correlate materials data tests with the behavior of complex structures. This information may be used to assess whether a defect of a given size will grow to an unacceptable size in a given service life under a given loading history. A step-by-step procedure (discussed in the next section) is written in a form which addresses assessments of this type. Detailed methods for following each step are provided with further background information on materials data and structural calculations being included in Appendices. Worked examples illustrating application of the procedure are given in Appendices as well. The procedure represents the current state of the art. The status of the procedures and areas where care needs to be exercised in implementation are also discussed. This includes a list of changes from previous issues of R5.

The procedure can readily be adapted to consider assessments of various types, perhaps for a sensitivity analysis:

- The loadings which give a life equal to a given service life.
- The initial flaw size which will just grow to the maximum acceptable size in a given service life (and hence the margin for a given flaw size).
- The combinations of materials properties, geometry and loadings for which crack tip behavior has a negligible effect on lifetime.

A separate procedure in R5 also assesses whether or not a small, defined crack extension will occur in the required service life. This is the new time dependent failure assessment diagram (TPFAD) approach, which can be used to predict crack initiation. The procedure uses a failure assessment diagram approach similar to that in R6, which has long been used in UK for elastic-plastic fracture. Another procedure uses the calculation of a stress at a small distance ahead of the crack tip, the σ_d approach, which is also part of A16 [3], to assess whether significant crack extension occurs in the required service life (crack initiation). If the predicted crack growth in service is unacceptable, then there is a choice of

- removing some of the uncertainties in the input data,
- using an alternative assessment procedure, or
- taking remedial measures.

One alternative assessment procedure is to rely on inspection to limit failures to statistically acceptable numbers. The approach is only acceptable when inspection is relatively easy and when there are large numbers of similar components which can be sampled. Another possible alternative approach is given where the probability of failure can be determined. This relies on knowledge of the probability distribution functions of the variable input parameters, such as creep crack growth rate and creep strain behavior.

Two different methods of calculating creep-fatigue crack growth are given in this procedure. The method to be applied depends on both the defect size and the type and severity of the applied loading. In Method I, cyclic and creep crack growth rates are calculated separately and the total rate of crack extension taken as the simple sum of the two rates. For cycles in which strict shakedown is achieved, and significant thermal shock loading is absent, it is adequate to base the fatigue assessment on the elastically calculated stress intensity factor range, ΔK. For certain cases in which the loading is more severe and cyclic plastic deformation occurs, the value of ΔK needs to be modified to take account of plasticity by means of the parameter ΔJ. Creep crack growth during the dwell is determined from the C^* parameter. In Method II, the defect is required to be sufficiently small to be embedded in a cyclic plastic zone, as for example for severe thermal cycling; the structure satisfies global shakedown as defined. A crack growth rate law is derived by combining the creep damage occurring during a dwell with a high strain fatigue crack growth law. This avoids the complication of having to define fracture mechanics parameters such as ΔJ or C^*. The high strain fatigue law can also be derived from continuous cycling endurance data corresponding to the initiation of a crack of a specific size in the defect-free structure. The approach assumes that creep influences the cyclic contribution to crack growth and that no explicit calculation of creep crack growth is then required. Guidance on the choice of appropriate method for calculating crack growth is given in this procedure. The basic deterministic procedures of R5 require an end-of-life margin to be determined but do not otherwise contain margins or reserve factors. Confidence in the assessment is obtained by the use of 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 sensitivity of predicted life to variations of input parameters.

The R5 method is presented in a binder which details each step of a creep/fatigue life prediction. The procedure is obtained from British Energy for an original fee and yearly updates can be obtained for a much smaller yearly fee. A computer code can be obtained from British Energy which aids in R5 analyses. Limited material data is available in R5 so often the user must obtain his own data from tests or obtain it from the literature.

4.1.2 RCC-MR (A16)

The French A16 procedure is quite similar to R5 and in fact some of the procedures were taken directly from R5. The main difference is the way crack initiation is determined and the choice of the reference stress. A16 has detailed and complete procedures for determining the reference stress. As discussed later, the reference stress is a key ingredient in the estimation procedures. This procedure is also considered state of the art. Many of the specific differences between R5 and A16 can be seen in the recent summary work of S. Marie et al. [43], which spell out a number of stress intensity factor solutions and reference stress procedures. With the purchase of British Energy by the French utility Electricite De France (now called EDF Group), the merger of R5 with A16 is quite possible.

4.1.3 API-579 Approach

As with ASME, the API construction code does not provide rules to evaluate a component containing a flaw or damage that results from operation or after initial commissioning. Fitness-for-service (FFS) assessments in the petroleum industry are quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component containing a flaw or damage. API 579 was originally developed to evaluate flaws and damage associated with in-service operation.

While API 579 FFS procedures were not originally intended to evaluate fabrication flaws (or “design” flaws), these procedures have been used for this purpose by many Owner-Users of petroleum manufacturing and transportation products. The API fitness for service standard provides guidance for conducting FFS assessments using methods specifically prepared for equipment in the refining and petrochemical industry. As with many codes, three levels of assessment are possible, with higher level assessments (level 3) being the least conservative but requiring an expert engineer. API 579 requires a remaining life assessment to be made for the damaged component and this forms the basis for in-service inspection intervals. As with many assessment codes, API 579 includes a step-by-step method with 8 steps for making a creep/fatigue crack analysis. The types of damage covered by API 579 include metal loss, corrosion and blistering, weld misalignment, assessment of crack-like flaws, including those operating in the creep regime of concern here.

A level 3 expert assessment permits the use of alternative FFS procedures including R-5, R-6, BS-7910, EPRI J- and C*-integral approaches and other methods. As with other creep-fatigue fracture assessment codes such as R5, API 579 has appendices which provide stress intensity factor solutions and reference stress solutions that are necessary to perform a creep crack growth assessment. The methods in API 579 for creep-fatigue crack growth assessment are rather newly implemented. These procedures could be used here but the methods are more suited for equipment used in the refining and petrochemical industries. R5 was specifically developed for use in the nuclear field.

4.2 Choice of Code Creep Crack Growth Procedure

All of the procedures were carefully examined by studying copies of the code and from a series of references. Moreover, direct discussion with some of the developers was made. With R5, face-to-face meetings with Kamran Nikbin of Imperial College in London (and some of his colleagues), as well as e-mail discussions with R. Ainsworth of British Energy were made. In particular, Nikbin has made direct comparison of R5 with all of the other approaches. Both men have been intimately involved with the development of R5 from the beginning in the 1980s. Discussions with C. Faidy of EDF Group regarding A16 and E. Keim (German code) were made as well. Faidy has made it clear that since EDF (French utility where Faidy works) has acquired British Energy, there will likely be more interaction between R5 and A16 in the future. In essence, R5, A16, API 579 and BS 7910 all work well and could have been chosen. It was a difficult choice. The most appropriate code choice for possible implementation of creep fatigue crack growth procedures into ASME NH is R5 for the reasons discussed below.

R5 was chosen because the code: (i) has well established and validated rules, (ii) has a team of experts continually improving and updating it, (iii) has software that can be used by designers, (iv) extensive validation in many parts with available data from BE resources as well as input from Imperial college’s database. Some of the reasons for the choice of R5 are listed in the following bullets.

- A recent European project meeting called HIDA (High Temperature Defect Assessment) and also a follow on called FITNET concluded that R5 is likely to be most up-to-date and state-of-the-art code for high temperature crack growth assessment compared to any of the other code procedures for creep crack growth assessment.
- R5 has a team of experts who are continually improving and updating the code. This will continue into the foreseeable future.
- R5 is used daily in BE plant to assess the integrity of nuclear components and it was developed with full emphasis on nuclear applications. However, it is used worldwide in other industries as well.
- R5 properly deals with cracked components under the creep and creep/fatigue regimes.

- R5 has methods to estimate crack nucleation (TDFAD approach).
- Has an optional software system (R-code) which can be used to run the cracked high temperature code. This feature can make learning the code for new users simple. Moreover, a material data base exists in the code.
- R5 has been extensively validated in many nuclear components, including piping, reactor vessels and nozzles, steam generator components and valves.
- Material data is available data from BE resources as well as input from Imperial College's database. Nikbin and Ainsworth have agreed to provide some data and more data can be obtained for a fee.
- A draft A16 section used the R5 methodology to do exactly the same as R5 but only limited to the cases of interest in the French nuclear plant. It has its own database and reference stress solutions, and could be used as well. There may be some portions of A16 that may be appropriate to include in the NH implementation, especially limit load solutions.
- The German code is very basic and has not really been developed. It uses a two criteria method only relevant to crack initiation. However, for some components, initiation life can dominate.
- BS 7910 is essentially R5.
- API 579 has just recently introduced creep crack growth. Again, it uses features within the philosophy of R5. However, the API 579 procedure has material data and methods for estimating material constants if they are not available. API 579 could be an equally good choice for possible implementation into ASME. Moreover, since there is already a relationship between ASME and API 579, it would be natural to implement API 579 procedures. However, since it follows R5 for the most part, it seems more appropriate to use R5.
- The Japanese are interested in R5 but they follow ASME. They have some basic in-house methods which are not developed as codes as such.

Because the R5 approach (and all other approaches) are based on K, C* (and their transient counterpart components (C(t), C_t) and reference stress methods, the assumptions underlying the methods need further scrutiny, especially for needs in the Gen IV program. R5 limitations, issues, and need for further information are summarized later in this report. Before R5 procedures can be implemented into ASME NH we recommend further study and validation of the methods under Gen IV loading, temperature and material conditions.

4.3 U.S. Nuclear Regulatory Commission (NRC) Interface

As discussed in the introduction, a main goal of the Part I of this report is to assess the feasibility of addressing creep/fatigue crack growth at the design stage within NH, and at the service stage (perhaps within Section XI) as requested by NRC. As such, one task goal is to ensure that the NRC is having its needs met. This interaction with the NRC will continue. Some of the interface activities include the following activities.

- Ensure NRC agrees with approach.
- Estimates based on extensions of methods and solution handbooks used for well-established elastic-plastic fracture is natural. The NRC pioneered elastic-plastic fracture methods and implementation in the U.S. Since the creep crack growth methods are related to established elastic-plastic methods, new users should adjust rather quickly.

- Consider establishing the relationship between current flaw evaluation and Leak Before Break (LBB) procedures for elastic-plastic fracture to creep fracture (SRP 3.6.3, NUREGs). While this is not a direct ASME need or requirement, it is a key important issue of concern to the NRC, nuclear plant builder and utilities. For an LBB assessment, which is used to eliminate expensive plant equipment such as pipe whip restraint and jet impingement shields, well established procedures have been developed for elastic-plastic crack growth. For creep crack growth these procedures would be quite different. Some differences between elastic-plastic and creep fracture mechanics LBB concerns include crack instability calculations, leak rate methods through creep cracks, how to deal with an active degradation mechanism like creep (similar to the current with primary water stress corrosion cracking (PWSCC) in current PWR plants), among many other issues. Hence, while our efforts for ASME NH do not require LBB, keeping the issues in mind during NH implementation is an important issue for NRC.

5 THE R5 CREEP-FATIGUE CRACK GROWTH METHOD

The R5 procedure is an engineering approach to predict creep-fatigue crack growth in components which operate at high temperature. Here we provide a summary of the R5 approach, the material property needs and requirements and a short summary of the process. An example problem is provided in the next section. Some of the description below is part of the R5 code (presented with permission of BE, Inc.).

5.1 The R5 Method

The procedure of R5 [2] is concerned with estimating the remaining safe life of a structure which is subject to creep-fatigue loading and which contains a crack or a postulated crack (for design purposes). The ASME NH code procedure does not permit a crack to be in the structural component being designed. The question then is how can this procedure be implemented within NH even if it was considered appropriate? This question is being addressed with the 2nd part of this program entitled "ASME NH Code Implementation." Essentially, there are several reasons why a creep-fatigue creep crack growth assessment might be desirable. These include: (i) some GEN IV components may have unavoidable sharp corners (or crack like defects) from fabrication, (ii) workmanship flaws may be assumed, (iii) it may be desirable to perform a life assessment with an initial flaw size defined by the maximum size non-detectable flaw that can persist after inspection, (iv) address in service observed flaws, (v) determine crack growth failure mode, and (vi) determine the amount of crack growth over a given operating period.

For the R5 approach, only Mode I loading is considered; mixed modes are not taken into account. The procedure concentrates components which operate within the global creep shakedown limit. The cyclic modes of crack propagation which occur during load changes and crack growth during dwell periods due to creep mechanisms are considered. However, an indication of the approach for more extensive cyclic plastic deformation can also be accounted for. The R5 procedures were originally developed for austenitic and ferritic steels but they have been used in recent years for super alloy materials. Some potential Gen IV materials include In 617 and other nickel base alloys. Experimental and finite element validation for a range of these materials is given in the Appendices of the R5 documentation. Defects are assumed to be in homogeneous parent or weld metal or in non-homogeneous weldments.

Crack behavior under both load-controlled and combined load- and displacement-controlled stress systems is considered. Particular advice is given in an Appendix for the cases of displacement control due to a constant applied displacement and for thermal loads acting alone. R5 does not address leak-before-break procedures for pressurized components so that LBB considerations would have to be developed separately by NRC, if desired in the future. However, LBB arguments may be constructed using, as a basis, the failure assessment diagram procedure in an Appendix of R5.

Before proceeding it is important to point out that GEN IV applications are likely outside the validation range of R5 applications. Before R5 could be used with confidence within the ASME code framework, more validation is necessary for GEN IV applications. Section 6 will deal with this in more detail.

5.2 The R5 Step-by-Step Approach

Here a step-by-step procedure is set out whereby a component containing a known or postulated defect can be assessed under creep-fatigue loading. The general 13 step approach is provided in Figure 5. Both continuum damage accumulation and crack growth are addressed. The cases of insignificant creep and insignificant fatigue are included as special cases. The procedure may be applied to a component in the design stage, or where it has already experienced high temperature operation, as in an operating plant where damage has been observed or is postulated. In the case of addressing an aging nuclear component, advice is given on the effect of the time at which the defect is assumed to form. Continuum damage failure (creep rupture) of an un-cracked body may be considered as a special case by omitting the steps covering crack growth and cyclic loading. However, ASME NH already addresses this. The steps in the procedure are listed below with a description. Please refer to reference [2] for the complete details of the R5 method, where many examples are provided.

Step 1) Establish cause of cracking or expected cracking
- Define defect type, bounding size, incubation. Mode I required.

Step 2) Define service conditions
- Resolve loads into cycle blocks, desired service life (loads, temperatures, etc.)

Step 3) Define materials and properties
- cyclic, creep crack growth, temperatures: collect appropriate data

Step 4) Basic stress analysis (operating extremes)
- Shakedown assessment. If shakedown not established, inelastic analysis necessary.

Step 5) Check time independent stability
- Time independent fracture analysis (section XI type): failure predicted stop here

Step 6) Check significance of creep and fatigue
- Rules are checked to determine insignificance of creep or fatigue. Check if creep-fatigue interaction is important

Step 7) Calculate rupture life based on initial defect size
- Rupture life calculated based on cracked limit load stress. Ductility exhaustion methods may be needed

Step 8) Calculate crack incubation time
- Conservative to ignore this

Step 9) Calculate crack growth for the desired life time
- Integrate creep and fatigue crack growth expressions. Note both affect each other. Changes in reference stress during crack growth should be included.

Step 10) Recalculate rupture life for final crack size (Step 7)
- Continuum damage prediction after crack growth. Conservative to base this final crack size.

Step 11) Time independent stability check for final crack size
- This is actually performed during crack growth analysis in practice

Step 12) Assess significance of results
- R5 does not prescribe margins. ASME may require this.

Step 13) Report results
- Prescribe inspection intervals, etc.

Figure 5 - Draft Step by Step Procedure (13 Steps)

5.2.1 STEP 1 - Establish the Expected or Actual Cause of Cracking and Characterize Initial Defect

Establish the cause of the cracking to ensure that the procedures of this volume are applicable. The defect type, position and size should be identified. For a creep-fatigue design crack growth assessment, the expected crack size and location can be determined from the stress analysis where the highest stresses occur. The size would be the limit on the NDE confidence. For defects found in service, this process may require the advice of materials and non-destructive testing experts, particularly for the case of defects in weldments. Suitable sensitivity studies (Step 12) should be performed to address uncertainties. The detected defect should be characterized by a suitable bounding profile amenable to analysis. Defects which are not of simple Mode I type should be resolved into Mode I orientation.

5.2.2 STEP 2 - Define Service Conditions for the Component

Resolve the load history into cycle types suitable for analysis. This includes all design cycles or, for in-service assessment, the historical operation and the assumed future service conditions. The service life should be defined. For the case of a component which is defect-free at the start of high-temperature operation, an estimate of the time at which the defect formed (or the crack nucleation time) can be determined. It is conservative to neglect this time. Suitable sensitivity studies should be performed to address uncertainty in the time of defect formation.

5.2.3 STEP 3 - Collect Materials Data

The material data needs to be defined and collected. The details of the material data necessary will be discussed in the next section. Define the materials relevant to the assessed feature including, in the case of weldments, the weld metal and heat-affected zone structures. The material properties must be appropriate over temperature range and in the correct cyclically-conditioned state. The effects of thermal ageing may also need to be considered for some materials, especially cast stainless steel. In practice, the requirements are influenced by the outcome of the tests for significant creep or fatigue in Step 6 below. Time-independent material properties are required for the stability analyses performed in Steps 5 and 11. It should be noted in particular that fracture toughness properties are required for creep-damaged material, if available. If not available, they must be estimated from creep undamaged material. It is important to mention that some materials that may be used for GEN IV applications may not have been validated for R5 assessment yet. This will need to occur before R5 can be used in NH.

5.2.4 STEP 4 - Perform Basic Stress Analysis

Elastic stress analyses of the un-cracked feature should be performed for the extremes of the service cycles. In the case of cyclic loading, a shakedown assessment of the un-cracked feature should then be performed. The type of shakedown is quite similar to NH and could be performed using NH procedures. It should be determined if the feature does or does not satisfy strict or global shakedown.

In the case that shakedown cannot be demonstrated, it is necessary to justify the use of the methods of this volume using, for example, inelastic analysis methods, including finite element analysis. If shakedown is demonstrated, the crack depth should be such that the compliance of the structure is not significantly affected.

5.2.5 STEP 5 - Check Stability Under Time-Independent Loads

The cracked component must be checked to ensure time-independent mechanisms under fault or overload load conditions at the initial defect size does not occur. R5 suggests using R6 [36]. However, for ASME NH purposes and the U.S. NRC, this can be performed using Section XI procedures or a J-Tearing assessment. If failure occurs due to time independent effects alone at this step, then the assumptions in the analysis should be revisited and remedial design action taken. Only if sufficient margins can be justified is it permissible to continue to Step 6 to justify future service life or the design.

5.2.6 STEP 6 - Check Significance of Creep and Fatigue

The checks for insignificant creep should be made using ASME NH or R5 procedures. If creep is insignificant then the assessment becomes one of fatigue loading alone and Steps 7 and 10 below are omitted. Conversely, if fatigue is judged to be insignificant then the assessment becomes one of steady creep loading alone and further consideration of cyclic loading is not required. A further test determines if creep-fatigue interaction is significant. If it is not, simplified summation rules for combining creep and fatigue crack growth increments may be adopted (Step 9).

5.2.7 STEP 7 - Calculate Rupture Life based on the Initial Defect Size

The time to continuum damage failure (creep rupture) must be calculated based on the initial crack size from Step 1. If this is less than the required service life, it may not be necessary to perform crack growth calculations and the NH procedure alone suffices. The estimate of rupture life is based on a calculated limit load reference stress (discussed in the appendices) and, for predominately primary loading, the material's creep rupture data. For damage due to cyclic relaxation and due to the relaxation of welding residual stresses, ductility exhaustion methods are more appropriate. The particular requirements for defects in weldments are also addressed. For the case of short defects close to stress concentrations such as notch radii or weld toes, special considerations must be followed to ensure that the reference stress is conservatively calculated.

5.2.8 STEP 8 - Calculate Crack Nucleation or Incubation Time

Typically it takes some time for a crack in a nuclear component to begin growing. For some components, crack initiation may consume the bulk of the life and when crack growth commences, failure occurs quickly. The crack nucleation or incubation time is the time from the start of the of high-temperature operation to the start of crack growth. Depending on the cause of cracking, its location within a weldment and the type of loading, it may be possible to calculate a non-zero incubation time. *It is always conservative to ignore this period and assume that crack growth occurs on first loading*. The cause of cracking will influence the determination of an incubation time. For example, a naturally-occurring creep defect, such as some weld defects, may not experience an incubation period prior to macroscopic crack growth. There are several procedures for calculating crack incubation time within R5 including TDFAD and the two criteria approach (similar to A16).

5.2.9 STEP 9 - Calculate Crack Growth for the Desired Lifetime

The crack size at the end of the design period of operation is calculated, following the procedures of R5 based on K, C*, reference stress and the appropriate estimation schemes laid out. Finite element analysis can also be used. This is done by integrating the appropriate creep and fatigue crack growth expressions. This incremental process is simplified in some cases, depending on the outcomes of the significance creep and fatigue tests determined in Step 6. Changes in reference stress due to crack growth should be included in the calculations. Integration is required because all parameters (K, C*, C(t)) and reference stress change with time as the crack proceeds.

5.2.10 STEP 10 - Re-Calculate Rupture Life after Crack Growth

The time to continuum damage failure should be re-calculated taking into account the increased crack size from Step 9. Crack growth calculations should not be performed in practice beyond an acceptable rupture life. It is conservative to base the estimate of rupture life on the final crack size as this neglects slower accumulation of creep damage when the crack size is smaller during growth.

5.2.11 STEP 11 - Check Stability Under Time-Independent Loads after Crack Growth

In practice, this step is carried out in conjunction with the crack size calculations of Step 9. The crack growth calculations of that step should not be performed beyond a crack size at which failure by time-independent mechanisms is conceded at fault or overload load levels using the R6 procedure [36]. For ASME purposes, this assessment could be made using ASME section XI methods.

5.2.12 STEP 12 - Assess Significance of Results

The uncertainties in loads, material properties, defined crack location, etc., need to be assessed. Margins against failure are not prescribed in R5 and are left to the user to set. The sensitivity of the results of the preceding steps to realistic variations in loads, initial flaw size and location and material properties should be assessed as part of a sensitivity study. The various modeling assumptions made can also be revisited with a view to reducing conservative assumptions in the analysis if unacceptable margins are determined. If this still fails to result in an acceptable crack growth life, the options of new design, or, for service assessment, of reducing future service conditions, or repair or replacement of the defective components, should be considered. For NRC needs, this may require placing the procedure within a probabilistic framework.

An alternative to the quantitative assessment of margins using the deterministic approach of this section is to use probabilistic methods to directly determine failure probabilities. A procedure for doing this is set out in the appendices but requires estimates of the distributions of variable quantities.

5.2.13 STEP 13 - Report Results

The results of the assessment, including margins determined, and the details of the materials properties, flaw size, loads, stress analysis calculations, etc, used in the assessment should be comprehensively reported. This facilitates both verification of the particular assessment and repeatability in future assessments. Each of these steps is summarized in great detail within the large volume of material provided within R5. This includes some material data along with extensive examples of the use of the method. A simple example calculation of the procedure is provided in Section 6.

5.3 Comments on R5 Application for ASME

From the flow chart description and 13 step procedure described above, it must appear that there are a number of judgments, interpretations and supporting properties data required to sort through the various behavioral regimes and to make an eventual design assessment. For near term HTGR applications as described above, it is not possible to narrow down the options and simplify the procedure. To do so would make the assessments too conservative to be used as a practical design tool within NH. Also, the goal of Code design rules is to have requirements that can be implemented consistently such that the design assessment will not be dependent on the individual/organization doing the assessment. To ensure that the creep/fatigue assessment procedures are properly applied, organizations using the procedure must ensure that the staff is properly trained. The use of the procedure (and all other methods) requires an experienced user. Therefore, the R5 procedure may not be ready for generally applicable design rules within NH but may be more suitable to regulatory requirements and licensing review. This last point requires further discussion and cannot be answered at this point.

5.4 The R5 Material Data Requirements

The material requirements for R5 crack growth analyses are summarized here in this section. The material data testing requirements are well established in R5. In addition to the typical high temperature properties required for an ASME NH design life assessment, the following material data is needed.

- Creep rate material properties and the constitutive law. The constitutive law could be a classical law (power law) or other type of law depending on the material and temperature (including hyperbolic laws and even tertiary laws). Validation examples are provided in the next section.
- Creep crack growth constants are required to predict the creep crack growth portion of the analysis. Figure 6 provides an example of the creep crack growth data that is required. As seen in Figure 6, a compact tension specimen shown in the insert at the top is tested at temperature. The test can be done under applied load or displacement. The crack growth is monitored, along with the loads and displacements. From this, the crack growth rate can be plotted as a function of the C* integral, as seen in Figure 6. Since this plot is logarithmic, the relation between crack growth rates and C* is typically a power law. *It is very important to note that this data can be estimated using a simple procedure within R5 if creep crack growth data is not available. This estimate is based only on knowledge of the tensile creep properties and the estimates are made to be conservative.*
- Fatigue crack growth constants are needed as spelled out in R5. This data is obtained at the temperature of interest using one of a number of fracture specimens including the compact tension type specimen shown in Figure 6. Again, a power law relationship between crack growth per cycle and the change in stress intensity factor (ΔK) is generally obtained.
- Creep ductility properties along with elastic and elastic-plastic fracture properties at temperature.

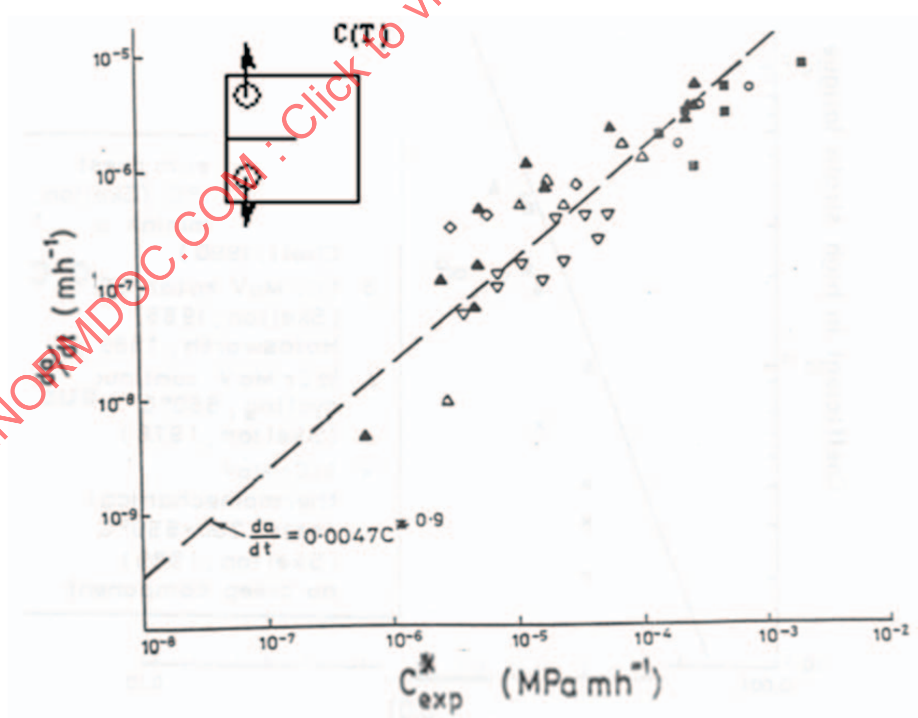


Figure 6 - Example of Creep Crack Growth Data

Many of the high temperature materials within NH are included in R5 and have been validated for creep-fatigue crack growth using the R5 approach. Figure 7 provides a comparison of materials that are supported within NH and those within R5. From Figure 7 it is seen that both NH and R5 support 2 1/4Cr-1Mo steels across nearly the same temperature ranges. For stainless steels, R5 has not been used much for temperatures higher than about 650 C while NH goes to 815C. However, R5 has been used for a larger variety of austenitic steels, including 347. BE says that R5 has been used outside this temperature range, but only on a spot basis, and it is not possible to document the specifics here. From the middle of Figure 7 it is seen that R5 has not been used for alloy 800H. As noted in Figure 7 though, it has been used for some other super alloys for a steel similar to IN 617. Also, 9Cr-1Mo-V steel has not been used, mainly since these steels are not used in any BE plants. Because of the success of R5 for other Cr-Mo steels, there is no reason to suspect that R5 cannot perform for this steel. At the bottom of Figure 7 some steels that have been supported by R5 are listed which are not supported within ASME NH.

NH:	**2 1/4Cr-1Mo steel (Grade 22 Class 1)** Stress intensity values to 1100F (575C) for 300,000 h .
R5:	**21/4 CrMoV, 1/2CrMoV and 1CrMoV** in the range 500-565C
NH:	**304H stainless steel** Stress intensity values to 1500F(815C) for 300,000 h.
NH:	**316H stainless steel** Stress intensity values to 1500F (815C) for 300,000 h.
R5:	**Various stainless steels and weldments (304, 316, 316H, 321, 347 weld, 316 weld)** in the range 525-650C
NH:	**Alloy 800H** Stress intensity values to 1400F (750C) for 300,000 h.
R5	**No Alloy 800 H.** However, BE has used R5 for super alloys up to 800C (similar to IN617)
NH:	**9Cr-1Mo-V steel (Grade 91)** Stress intensity values to 1200F (650C) for 300,000 h.
R5:	**No 9Cr-1Mo-V steel (Grade 91)**
R5:	CMn steels in the range 360-390C
R5:	**P22, P91 and some P92 ferritic steels**

Figure 7 - Comparison of Materials within NH and R5
BE has used R5 successfully outside these temperature ranges also – to lower and higher temperatures especially in austenitic steels

5.5 Summary of the R5 Material Data

Some of the material data required was summarized above. Sources for data are available in the literature. BE (Ainsworth) and Imperial College (Nikbin) can compile this data into a coherent library and this should be considered by ASME. The current sources for data needed for R5 assessments are:

- R66 (Materials Data Handbook for R5), BE, is not available in general since some of the data is proprietary. The data is from a number of sources. However, some of this data that is not proprietary could be made available by BE.
- BE is willing to supply some of the data that is in the public domain.
- Much is compiled in the R5-Code software, which can be licensed.
- API 579 has a fair amount of data.
- Some data for materials (including IN 617) is available from the German database.

In summary, a large database exists but much of it is proprietary. Methods exist for estimating crack growth law without the necessary data. This is convenient and provides conservative estimates of the properties. Finally, Nikbin (Imperial College) and Ainsworth (BE) will compile a data base of non-proprietary data for a fee. Material data required creep/fatigue crack growth assessments using R5 is not available for some GEN IV materials.

6 R5 VALIDATION AND EXAMPLE PROBLEMS

Here we provide some material that illustrates the validity of R5 along with an example which shows how to use it. First, an example problem is illustrated which shows the step-by-step procedure for applying the method for a cracked nuclear plant component (pipe). Here we leave out some of the details for brevity, but the full example problem can be found in Appendix A8 of [2]. Next we discuss some validation of the methods which address some of the concerns discussed earlier.

6.1 Example Problem - Surface Crack Pipe

Figure 8 illustrates a practical problem concerning the life estimate of a nuclear power plant component. The pipe is made of 316 stainless steel with an inner radius of 300 mm and thickness of 100 mm. This is a thick pipe of the type often welded to, and near, nozzles in nuclear plants. The pipe has a 3 mm deep, 360-degree crack in it. This size crack was chosen based on the limit of NDE capability at this particular plant. As seen in Figure 8, the pipe is to operate at 600 C. The design life is 1.5 million years with 500 equal cycles with 3000 hour dwell times. Figure 9a llustrates the elastic stresses that result from the internal pressure loading of 16 Mpa. It is seen that hoop and radial stresses vary from the pipe ID to OD while the axial stresses are constant at 20.57 Mpa. The pipe experiences a thermal gradient at temperature which produces tensile stresses on the pipe ID and compression at the OD (Figure 9b). The stresses in the pipe are initially zero and are zero at shutdown (which is the minimum of the load cycle). Therefore, the cause of cracking during service (creep-fatigue), geometries and load have been defined constituting completion of steps 1 and 2 of Figure 5.

The material properties are shown in Figure 10. At the top of Figure 10, the creep material law is listed. This law represents a combination of primary and secondary creep. The primary creep law is an exponential time hardening law while the secondary law is a classical Norton type creep law. All material parameters are shown in Figure 10 as well. In addition, the fatigue crack growth law is shown at the bottom of Figure 10, with the material constants listed for 316SS at 600 C. Note that the "effective" stress intensity factor range (ΔK_{eff}) is used. This accounts for a concept called crack closure in fracture mechanics based fatigue crack growth. Essentially, the crack will not grow when it is closed and methods for calculating the effective value of K are shown in R5. Finally, the bottom of Figure 10 lists the creep crack growth law used, also with material constants. These represent the materials required in step 3.

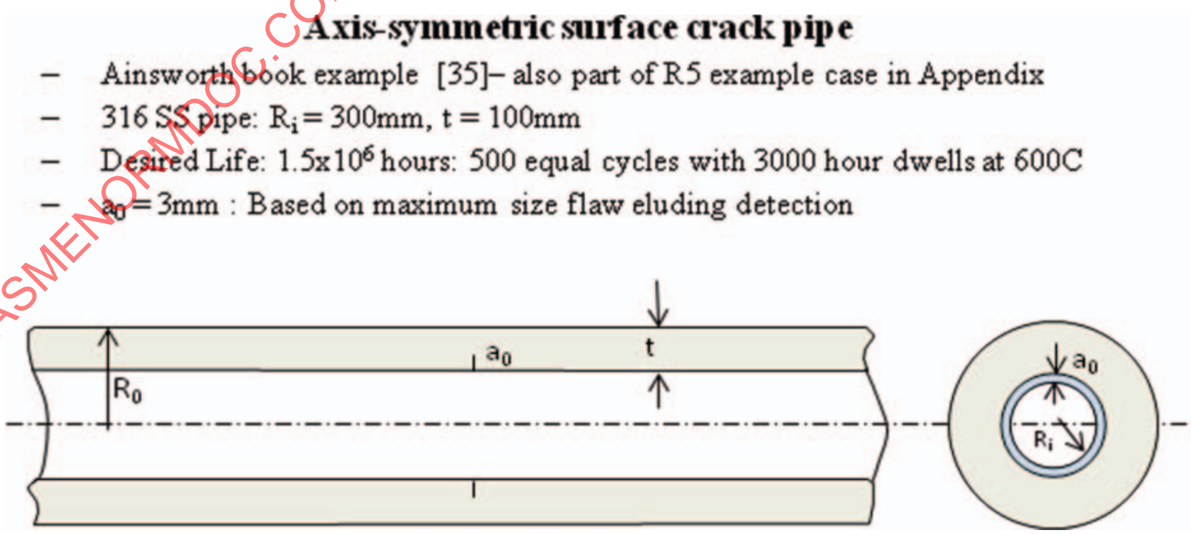


Figure 8 - R5 Example Problem – Surface Crack Pipe

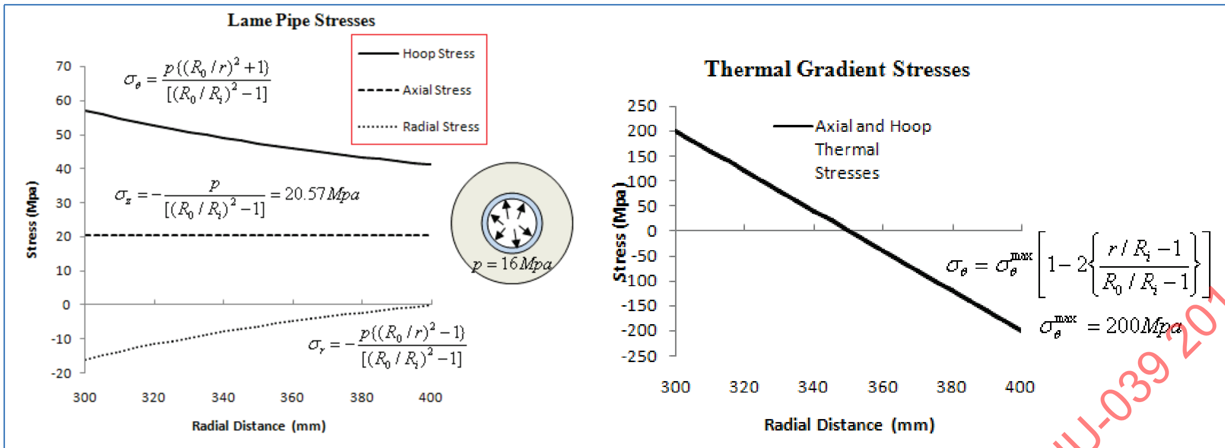


Figure 9a - Pipe Stresses due to Pressure **Figure 9b - Pipe Stresses due to Thermal Gradient**

Figure 9 - Pipe Stresses

Primary Creep Rate

$$\dot{\varepsilon}_c = \varepsilon_p r\mu t^{\mu-1}\exp(-rt^{\mu}) + \dot{\varepsilon}_s$$

$$\varepsilon_p = A'\sigma^{m(\theta)}\exp\{-P/(\theta+273)\}$$

$m(\theta) = \alpha - \gamma\theta$, where θ is temperature (C)

Secondary Creep Rate

$$\dot{\varepsilon}_s = B\sigma^n\exp\{-Q/(\theta+273)\}$$

Creep constitutive law

$r = 2.42\times10^{-2}$
$\mu = 0.64$
$A' = 1.632\times10^{35}$
$P = 9.292\times10^{4}$
$\alpha = 16.32$
$\gamma = 0.02044$
$B = 5.184\times10^{-6}$
$Q = 1.97\times10^{4}$
$n = 4$

$$\left[\frac{da}{dN}\right]_f = C\left[\Delta K_{eff}\right]^{\lambda}$$

$C = 2\times10^{-9}$ m/cycle
$\lambda = 3$ (316 SS at 600C)

Fatigue Law

$$\left[\frac{da}{dt}\right] = A\left[C^*\right]^q$$

A=.0197 ; q=0.89 (m/hr)

Creep Law

Figure 10 - Material Laws and Properties

Step 4 involves determining whether the structure is operating within the strict shakedown or global shakedown limit. The procedures used to assess shakedown are performed without consideration of fracture mechanics, and details are omitted here (see Appendix A8 of [2]). The R5 shakedown procedure is similar to the ASME NH procedure, and is not summarized here (see [2] for details). For this pipe structure, strict shakedown conditions are satisfied. The shakedown analysis is used to determine the re-distributed stresses caused by creep that are actually used for the crack growth analysis. The loads are low and the crack is small so the component easily passes the time independent fracture check in step 5. We are now ready to predict life using the fracture methods discussed earlier.

The parameters necessary for the crack growth and life prediction are the stress intensity factor, K, and C* (and the transient C(t)). C* is calculated using the reference stress and the stress intensity factor also. The stress intensity factors for this cracked pipe case can be determined from fracture mechanics handbooks. For complicated geometries, or for cases where K is not available, it can be easily determined from finite-element methods. For an axis-symmetric crack in a pipe, K is:

$$K = \{F_m \sigma_m + F_b \sigma_b\}\sqrt{\pi a}$$

$$C^* = \left[\frac{K}{E'}\right]^2 \frac{E\dot{\varepsilon}_c}{\sigma_{ref}}$$

Where F_m and F_b are functions of a/t (crack depth over thickness), and σ_m and σ_b represent the membrane and bending stresses, respectively. Since the crack depth changes with time, K changes throughout the crack growth phase of the analysis. The value of C* is calculated using the equation above where σ_{ref} is the reference stress and is the creep strain rate calculated at the reference stress value. Since the crack depth constantly changes, the reference stress and stress intensity factor constantly change throughout the analysis. As such, both the creep and fatigue portions of crack growth must be integrated (or summed) throughout the time life of the component. The reference stress is a simple well established function crack depth, thickness, pipe size and yield stress for a pipe containing an axis-symmetric crack, and is listed in the R5 code. For this case, at the initial crack depth, the initial reference stress is 80.1 Mpa and at shakedown, it is 57.6 Mpa. The reference stress values within R5 are being improved at present. It is always possible to perform finite element analyses to obtain K and C* (C(t)) but it is more convenient to use reference stress estimates if they can lead to conservative estimates. Conservative estimates of these parameters using the reference stress approach are not always guaranteed. This is the subject of improvements being implemented into R5 at present and is discussed in the next section.

The creep response for the constitutive law shown in Figure 10 is shown for two constant levels of stress (100 and 150 Mpa) in Figure 11. For the 3000 hour dwell times, it is seen that primary creep is expected to play an important rule. Hence, using the equations and material parameters in Figure 10 with the stresses defined earlier.

6.1.1 Crack Growth Calculation

The total crack growth per cycle is obtained by summing the cyclic and creep contributions. The crack extension over the design life of 1.5 million hours is calculated iteratively using a computer program. The main features of the procedure are as follows.

- Calculate the creep crack growth for the dwell period in the first cycle. The creep crack growth and strain rates are assumed constant over short time periods (a Newton scheme can also be used, but it is not necessary). The new crack depth and accumulated creep strain are then updated and new values of reference stress and creep strain rate are obtained using the creep law in Figure 10. The value of C* can then be obtained with K evaluated for the new crack depth, leading to a new value of crack growth rate.

- Calculate the cyclic crack growth for the first cycle and increment the crack depth by this amount.

- Repeat these calculations for subsequent cycles. This can automatically be performed with the R-code, although for this example, a simple FORTRAN code can be written.

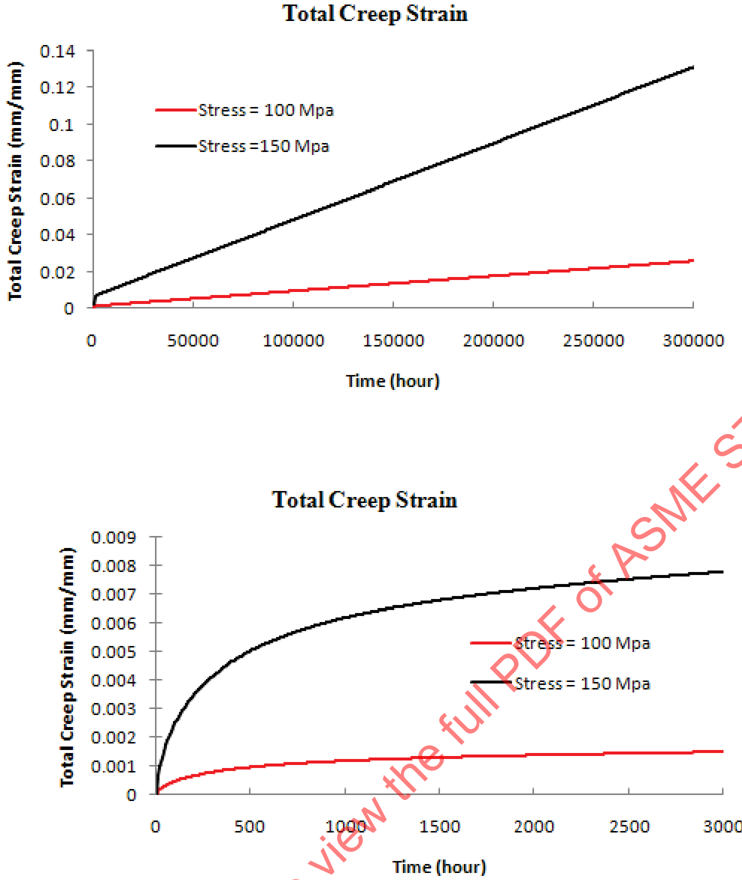


Figure 11 - Material Laws and Properties

The crack growth versus time is shown in Figure 12, which is taken from [2] (Figure A4.14 with permission of R5 authors). It is seen that this component is designed to handle the required lifetime in this example.

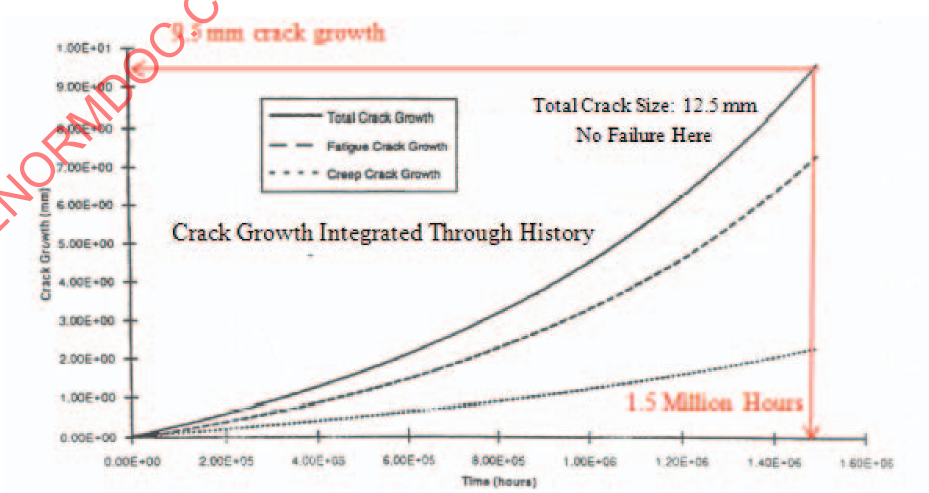


Figure 12 - Crack Growth versus Time

6.2 Theoretical Issues and Concerns with Engineering Creep Crack Growth Methods

The state-of-the-art engineering creep and creep-fatigue crack growth predictive methodologies are based on characterizing the crack growth rates using parameters (K, C*, C(t)) that measure, in theory, the strength of the asymptotic crack tip fields, as discussed in Section 3. There are a number of theoretical concerns regarding this approach. Perhaps the main concern is that the asymptotic crack tip fields can only be developed for simple creep constitutive laws (such as power law types). Moreover, the methods formally break down once crack growth occurs, non-proportional stressing occurs, and cyclic loads are experienced when a creep crack grows in service.

For a creep/fatigue crack growth predictive methodology to be valid, the measured values of the parameters (here C*, C(t)) must be related to crack growth events. Experiments on fracture specimen are performed by measuring far field parameters (load, load point displacement (or crack opening displacement) and crack size). These parameters are then properly integrated to obtain the crack characterizing parameters. A fundamental question that must be answered in any fracture mechanics based approach is whether these far field measurements can properly characterize the near crack field events. Traditionally with fracture mechanics, this characterization is made because the asymptotic crack tip fields, which characterize growth, can be related to far field measurements. For instance, with elastic-plastic fracture, far field events can be related to near crack tip field fracture events through the use of a path independent integral (J-integral). For creep crack growth, this relationship is only strictly valid for full scale creep for a stationary crack and for simplistic constitutive laws. When crack growth occurs, or more importantly, when both crack growth and cyclic loading occur, the asymptotic interpretation of the crack tip events to far field measurements, breaks down. *In fact, for cyclic loading of a stationary crack, the asymptotic crack tip fields depend strongly on the form of the constitutive law being used and these fields can change for each cycle of loading [15] and Appendix A!* This makes establishing the link between near field crack events, which drive crack growth and fracture, and far field events (where measurements are made to characterize material properties) quite challenging. Today, despite the fact that engineering creep/fatigue crack growth procedures based on R5 type methods have been used with success for years, controversy over the general nature of the methods persists. Indeed, while R5 has been established and validated for materials and operating conditions within BE plants, it is not certain whether these methods will carry over in a straightforward fashion to GEN IV conditions. Hence, even if R5 approaches were implemented within NH, validation under GEN IV conditions is necessary. This issue is discussed further in the next section.

More theoretically sound creep and creep-fatigue crack growth parameters have been proposed which are based on energy considerations. Atluri [37], [38] summarized quite general crack parameters for all types of nonlinear materials, including creep, which is based on energetic principles. Brust and Nakagaki [8], [9], [39] more recently summarized some of these parameters and discuss applications of the use of these parameters. These parameters represent "the energy deposited into a finite sized crack tip region (and crack growth wake region) per crack growth increment" [39]. Moreover, there remains controversy over the appropriate general nature of these energetic parameters. Even so, these methods are not amenable to simple engineering application approaches at present since calculation of the energetic crack parameters requires the use of numerical methods and fine meshes. Hence, since asymptotic approaches break down under cyclic creep crack growth conditions and energetic approaches are either not practical or controversial, the engineering methods of R5 need to be established with validated field experience when being used under conditions outside their range of validity. More details of these theoretical issues are discussed in Appendix A.

The engineering creep-fatigue methods used in all codes today, including R5, are used outside their range of validity. Despite this, the methods have shown to provide reasonable predictions of creep-fatigue life, albeit conservative, perhaps sometimes too conservative. Here we provide some discussion of the estimation of these parameters when used for creep constitutive laws and used under conditions outside the theoretical range of validity. Most of this summary comes from the R5 manual [2], Ainsworth's book [35], and a recent paper by Kim et al [40]. It is this author's belief that continued development of more fundamentally sound creep-fatigue life predictive methods must continue while we continue to use the engineering approaches in R5.

6.3 Validation and Creep Constitutive Laws

Essentially, the theory behind the R5 engineering method (and all other methods) is summarized in the book by Webster and Ainsworth [35] and it is based on earlier asymptotic solutions for creep emanating from an initially elastic field (or plastic HRR field) within a creeping zone (both primary, secondary and combined primary and secondary creep). Herman Riedel, in his classic treatise in 1987 [41], summarizes all of this. Riedel bases his work on earlier work when he was working with Rice, Bassani and colleagues work, etc. [44] – [55]. So a firm theoretical foundation based on the asymptotic interpretation of crack tip fields does exist and it is clear.

In practice though, these conditions are violated, often severely. The creep response very near the crack tip (high stresses) cannot be represented by power laws. Once the crack grows beyond a small amount, the asymptotic interpretation becomes unclear, and we can go on and on. As Hoffelner [56] points out, the linear life fraction rules used in NH today have no real basis. However, from an applications standpoint all these simplified rules and laws do a very good job for design provided you build in the necessary safety margins. The same can be said for R5. Nothing would ever be built if we kept waiting for the perfect theory. There are no perfect theories in the fracture field. The conservatisms built into the methods were done so with these issues in mind. They were then validated with mock-ups, and service experience over the years. As such, we must start with the R5 approach, see how well it performs for GEN IV conditions, and improve on these methods or develop new methods as required. We must keep in mind that, in practice, J-Tearing theory for elastic-plastic fracture is used far beyond its theoretical validity routinely, with success, and it can guarantee conservative results.

The original theoretical development of the R5 method required the constitutive theory to be of the power law type (Norton secondary creep, power primary creep). The classical treatise by Riedel [41] summarizes the theory and limitations. R5 was originally developed to be applicable for materials which are characterized by a more general creep law. Consider three different creep laws, as illustrated in Figure 13. The material constants are also presented there. The creep laws are quite different from each other. The Norton law is the classic law wherein many of the creep theories were developed from. The theta projection law is more of a secondary-tertiary creep law. The theta projection model constants in Figure 13 were developed for Cr-Mo-V steel at 565 C [42]. The RCC-MR law is a combination of primary and secondary creep. The RCC-MR material constants shown in Figure 13 are for 316 stainless steel at 565C [3]. The response of the three material models can be seen in Figure 14 where the vastly different response of the material laws can be easily seen.

As mentioned earlier, because the original theory for R5 (and all other engineering creep fracture laws) was based on power law creep laws, there is a question as to how accurate the estimation of the C* and C(t) parameters are within R5. Here this is addressed by showing comparison of the estimates of these parameters with finite element calculations. Such validation comparisons are provided in the R5 manual as well as reference [35]. Here we show some more recent validation examples developed in [40]. In [40] a number of different fracture specimens were considered for validation cases including center crack tension plate, compact tension specimen, single edge notch and axially cracked cylinder. In addition, and of direct relevance to nuclear components, both circumferentially through wall cracked and surface cracked pipe were considered. Many of the estimation scheme methods for C(t) compared quite well with the finite element predictions, although some were overly conservative. Here we briefly summarize the through-wall crack pipe validation case of [40]. Figure 15 shows the comparison of C(t) estimated using the procedure of R5 (called RSM or "reference stress method") with finite element predictions for RCC-MR and the theta projection laws. It is seen that using the reference stress method to estimate C(t) over the time history is actually non-conservative in that it under predicts. An enhanced reference stress method (ERSM) proposed in [40] is seen in Figure 15 to provide better estimates of C(t) throughout the time domain.

Norton Power Law (Stress in Mpa, time in hours)

$$\dot{\varepsilon}_s = A\sigma^n \quad A = 10^{-16}; n = 5$$

Theta Projection (Stress; Mpa, time; hours, T; Kelvin)

$$\varepsilon_c = \theta_1(1-\exp(-3600\theta_2 t)) + \theta_3(\exp(3600\theta_4 t - 1)$$

$$\log\theta_i = a_i + b_i T + c_i\sigma + d_i\sigma T; i = 1,4$$

$$a_1 = -8.736; b_1 = .004604; c_1 = -.04489; d_1 = 0.6814E-4$$

$$a_2 = -23.46; b_2 = .02225; c_2 = .02195; d_2 = -.1951E-4$$

$$a_3 = -1.869; b_3 = -.002034; c_3 = -.05497; d_3 = 0.799E-4$$

$$a_4 = -16.43; b_4 = .009149; c_4 = -.04723; d_4 = 0.719E-4$$

Primary-Secondary (RCC-MR)

$$\varepsilon_c = B\sigma^m t^p : t \le t_{fp}$$

$$\varepsilon_c = B\sigma^m t_{fp}^p + A\sigma^n(t - t_{fp}) : t \ge t_{fp}$$

$$B = 2.2243E-14; m = 4.3056; p = 0.44633$$

$$A = 1.7122E-25; n = 8.2; t_{fp} = 2.75366E19\sigma^{-7.0337}$$

Figure 13 - Creep Laws Tested

Reference stress methods to estimate creep fracture parameters (C*, C(t)) were developed to simplify the calculation procedure. This can avoid the need for finite element calculations. In general, the RSM estimation methods are meant to be conservative in the sense that they overestimate the actual value of the parameter. Webster and Ainsworth [35] and the R5 manual [2] provide many examples where the estimate of C(t) using reference stress methods are quite accurate and conservative. Figure 15 illustrates a counter example where the current reference stress methods may not be conservative.

One of the main differences between the R5 and A16 are the methods used to estimate reference stress. Reference [43] summarizes some of the new reference stress solutions developed for A16.

Wasmer, Nikbin and Webster [57] also show some examples where reference stress methods may not always be conservative in calculating creep fracture parameters. The R5 code is currently re-evaluating the RSM methods and improved formulae will be appearing in the code soon. However, it is always good to perform finite element calculations for some spot cases to verify the accuracy of RSM methods during an R5 assessment. In fact, if doubt exists, finite element solutions are recommended for calculating the creep/fatigue fracture parameters in order to ensure accuracy. Likewise, Samuelson et al show examples of application of R5 to creep crack growth in welds and conclude that "… determination of creep crack growth rates in welds based on the C* value only may result in uncertain estimates."[60] The weld mismatch effect can lead to uncertainties in R5 predictions. Therefore, while R5 is certainly the best code procedure available for creep/fatigue crack growth predictions, there is more validation work necessary, even for materials that are qualified for R5 assessment.

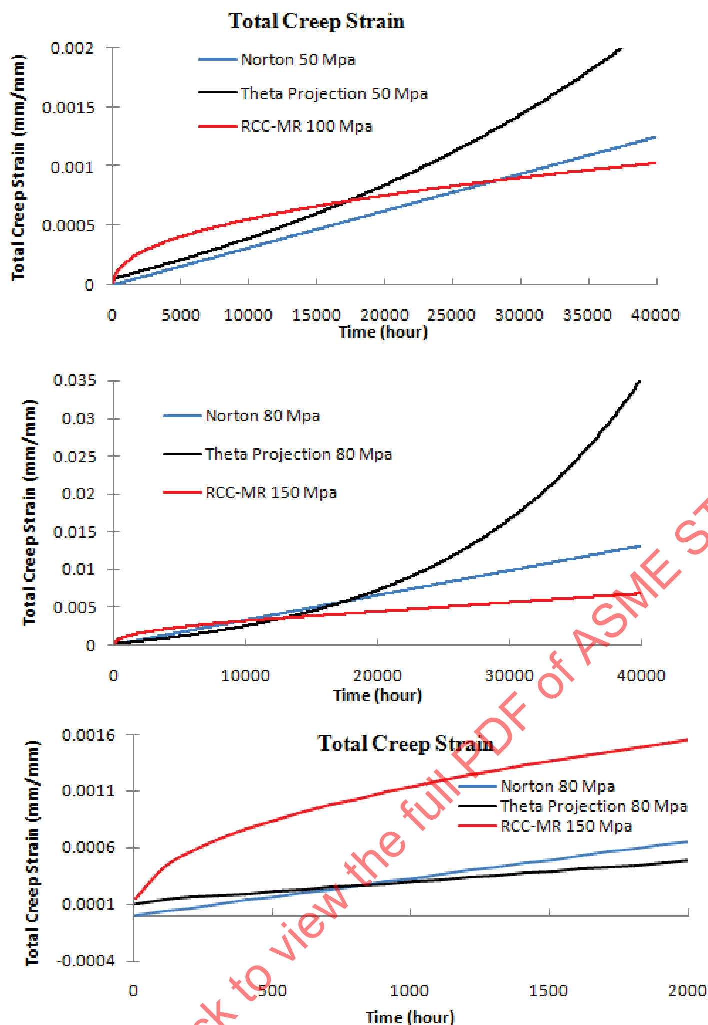


Figure 14 - Total Creep Strain Different Creep Laws

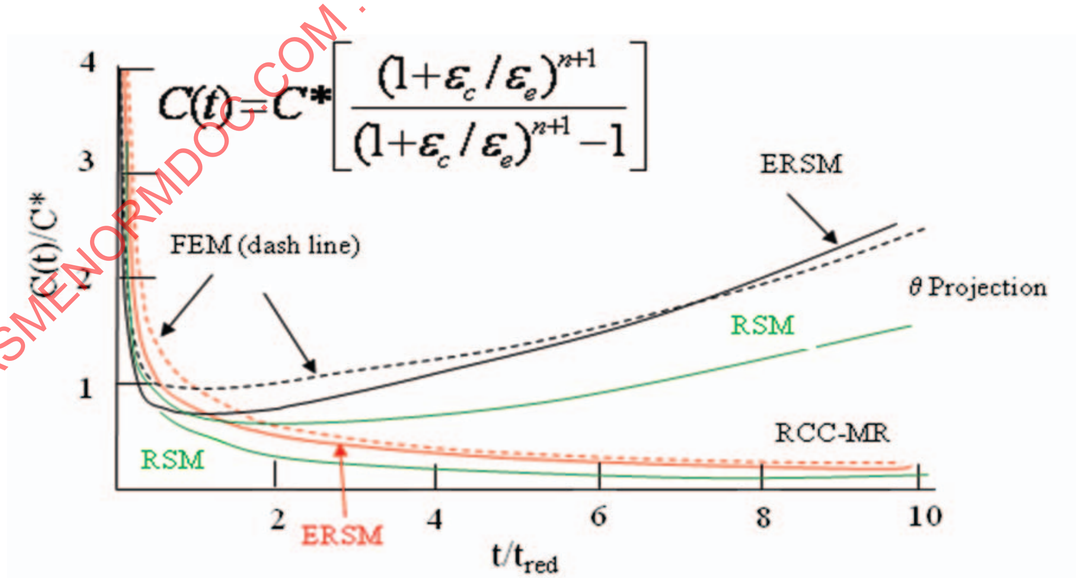


Figure 15 - Comparison of C(t) Estimates to FEM Predictions

7 DISCUSSION OF GEN IV AND R5

7.1 R5 as a Possible ASME NH Rule Set

The R5 creep/fatigue life cycle crack growth prediction code represents the state-of-the-art procedure for assessing the life of cracked components operating in the creep regime. The method has a theoretical foundation which is based on rather simple constitutive laws and, in practice, these assumptions are violated. This is not uncommon in the fracture mechanics field. J-tearing theory, which is used for predicting elastic-plastic fracture, likewise has a theoretical basis that is routinely violated in practice and is used far beyond its basis, with success. The success is possible by obtaining confidence in the procedures through validation with mock-up tests and service experience. Likewise, the success with R5 is based on a similar series of mock-up validations and service experience, mainly for the materials and operating conditions within British Energy HTGC reactors.

As such, the R5 procedure is a semi-empirical procedure (as is ASME NH) that needs qualification for materials and operating conditions that will be experienced in GEN IV. Certainly, the stainless steels and Cr-Mo steels are qualified for creep/fatigue crack growth assessment for a range of operating conditions in R5. We cannot recommend implementation of R5 procedures outside this range until further qualification for GEN IV materials is made. R5 is an assessment procedure rather than a design procedure in its present form. An assessment procedure attempts to accurately predict crack growth response while a design procedure involves built-in safety factors and conservatism. This is the case with all creep/fatigue crack growth procedures. Hence, if R5 were implemented to the high temperature design procedure of NH in the future, safety factors would have to be introduced.

Certainly there is ample data in the literature which supports the use of R5 outside the range of qualification. References [58], [59], [60] illustrate the use of this approach for nickel base alloys. The Petten database provides material constants for alloy 617 and 800H, and the method has been used to assess creep/fatigue lives in these materials. However, the method must be fully qualified for these materials and others that may be used in GEN IV applications—including ferritic vessel materials that may operate near the negligible creep range. For the near term, the gas outlet temperature for GEN IV has been reduced to 750–800 C which means that alloy 617 may not be required for hot gas exposed structures. In addition, the only potential code boundary exposed to the hot gas will be the primary to secondary hot gas heat transfer interface. And, even there, the safety consequences of minor leakage across the interface may not be consequential. On the other hand, the reactor pressure vessel (and crossover duct in some concepts) will normally operate at nominally 350C, either below the conventional creep threshold or in the “twilight zone” between the creep regime and the negligible creep regime. For the near term, the material(s) of choice are SA533/508. These components can also potentially see quite limited off-normal conditions roughly within the scope of Code Case 499, i. e. 800–1000 F. From that perspective, R5 procedure may have to be qualified for vessel materials as well.

Finally, the issue of crack initiation must be dealt with. There is ample recent work examining crack initiation under creep/fatigue conditions. References [61], [62] discuss recent efforts on accurately predicting initiation under creep conditions. The recent thesis by Davies [63] (out of Imperial college, advised by Nikbin) summarizes the recent work relevant to R5 future implementations. For some structures and operating conditions, crack initiation may dominate life. However, the predictive methods are not robust enough and fully qualified to be used under creep/fatigue conditions. While conservative, Ainsworth, the main author of R5 over the years, recommends neglecting this phase for R5 since it will be conservative. However, it may be too conservative for use as a design criteria within NH.

7.2 Theoretical Issues with R5 Needing Resolution

Sections 1, 2 and 3, briefly summarized some of the theoretical concerns with the C* based engineering methods for creep/fatigue crack growth prediction. While possibly controversial, Appendix A summarizes these concerns in detail through the use of experimental, analytical and numerical studies. For these reasons, and despite the fact that R5 is the best available code procedure in use today for creep/fatigue crack growth life prediction, it must be qualified for GEN IV applications since the application use will be outside the window of R5 qualification.

7.3 Concluding Remarks on the R5 Approach

Fracture mechanics methods have proven a valuable practical tool to predict life of structures which develop cracks. The aerospace industry has adopted a "damage tolerant" design approach which permits the presence of cracks. The structures are maintained by specifying sufficient inspection intervals so that a crack will not grow to a critical length between inspection intervals. Despite the fact that ASME does not permit cracks, they will be present and having a procedure for assessing them is important. Some of the statements below must be kept in mind as we consider R5 for possible implementation into NH in the future.

- A commitment to a fracture mechanics approach for components operating at high temperatures can only be on the basis of existing parameters (K, J, C*, C(t), TDFAD, 2-criteria concepts).
- Each of these concepts has clear limitations which we have to live with. Bear in mind also that for the currently used linear life fraction rule in NH, no real physical justification exists and that we are using static stress-strain curves for materials undergoing cyclic softening etc. Moreover, elastic-plastic fracture mechanics methods are used routinely far beyond their theoretical validity with success since the methods are suitably "qualified" from test data.
- There are some doubts about the existence of a secondary creep stage for nickel-based alloys, which may find their way into GEN IV structures. It may be acceptable to "interpret" a secondary creep phase into the creep curves. Investigations [56-59] on nickel base alloys demonstrated that different sample geometries (CT, SENT, SENB, DENT) gave very comparable results based on C*.
- The use of a reference stress for determination of C* (and C(t)) might bear some uncertainties as discussed earlier. Finite element calculations would be better and should be used for critical applications.
- When crack extension up to 0.5 mm is considered as crack initiation then it may be sufficient to consider only this phase (TDFAD or 2-criteria) for some components. This may be too conservative for design purposes. Moreover, neglecting the crack initiation phase will always be conservative.
- Creep-fatigue is certainly an ambitious field which still needs improvement and clarification. However, this is not only true for the fracture mechanics approach but is also true for the current design approach in NH.
- Negligible creep should probably also be re-visited with respect to crack growth (K-controlled crack growth may be applicable for some materials and service conditions).
- A clear definition of the requirements for a fracture mechanics treatment of safety issues in an HTGR has to be agreed upon within NH (or Section XI if these procedures belong there). Should fracture mechanics be used for design, for safety considerations or to set NDE and maintenance schedules?

In conclusion, in future HTGRs the influence of stress raisers like notches, production flaws, welding defects, developing cracks, etc. should be considered for safety and/or NDE purpose, a fracture mechanics concept (for creep, fatigue and creep-fatigue) is needed. It is certainly a valid approach to use the methods, procedures and data developed within the R5 for that purpose, certainly as a starting point until the procedures are qualified for GEN IV conditions. Whether either the complete R5 procedure or only parts of it should be used depends on the demands and NRC's requirements and concerns.

8 SUMMARY, CONCLUSION AND SUGGESTIONS FOR ADDITIONAL WORK

8.1 Summary

The subsection ASME NH high temperature design procedure does not admit crack-like defects into the structural components. The U.S. NRC identified the lack of treatment of crack growth within NH as a limitation of the code and thus this effort was undertaken. This effort is broken into two parts. Part 1, summarized here, involved examining all high temperature creep-fatigue crack growth codes being used today and from these, choose a methodology that is appropriate for possible implementation within NH. The second part of this task is to develop design rules for possible implementation within NH. This second part is a challenge since all codes require step-by-step analysis procedures to be undertaken in order to assess the crack growth and life of the component. Simple rules for design do not exist in any code at present. The codes examined in this effort included R5, RCC-MR (A16), BS 7910, API 579 and ATK (and some lesser-known codes).

After examining the pros and cons of all these methods, the R5 code was chosen for consideration. R5 was chosen because the code: (i) has well established and validated rules, (ii) has a team of experts continually improving and updating it, (iii) has software that can be used by designers, (iv) extensive validation in many parts with available data from BE resources as well as input from Imperial college's database, and (v) was specifically developed for use in nuclear plants. Further reasons for the choice of R5 are listed in Section 4.2.

There are several reasons that the capability for assessing cracks in high temperature nuclear components is desirable. These include:

- Some components that are part of GEN IV reactors may have geometries that have sharp corners—which are essentially cracks. Design of these components within the traditional ASME NH procedure is quite challenging. It is natural to ensure adequate life design by modeling these features as cracks within a creep-fatigue crack growth procedure. Figure 16 illustrates some types of components that may be part of GEN IV that fall into this category.
- Workmanship flaws in welds sometimes occur. It can be convenient to consider these as flaws when making a design life assessment.
- Non-destructive Evaluation (NDE) and inspection methods after fabrication are limited in the size of the crack or flaw that can be detected. It is often convenient to perform a life assessment using a flaw of a size that represents the maximum size that can elude detection.
- Flaws that are observed using in-service detection methods often need to be addressed as plants age. Shutdown inspection intervals can only be designed using creep and creep-fatigue crack growth techniques.
- The use of crack growth procedures can aid in examining the seriousness of creep damage in structural components. How cracks grow can be used to assess margins on components and lead to further safe operation.

The focus of this work was to examine the literature for creep and creep-fatigue crack growth procedures that are well established in codes in other countries and choose a procedure to consider implementation into ASME NH. It is very important to recognize that all creep and creep fatigue crack growth procedures that are part of high temperature design codes are related and very similar. This effort made no attempt to develop a new creep-fatigue crack growth predictive methodology. Rather, examination of current procedures was the only goal.

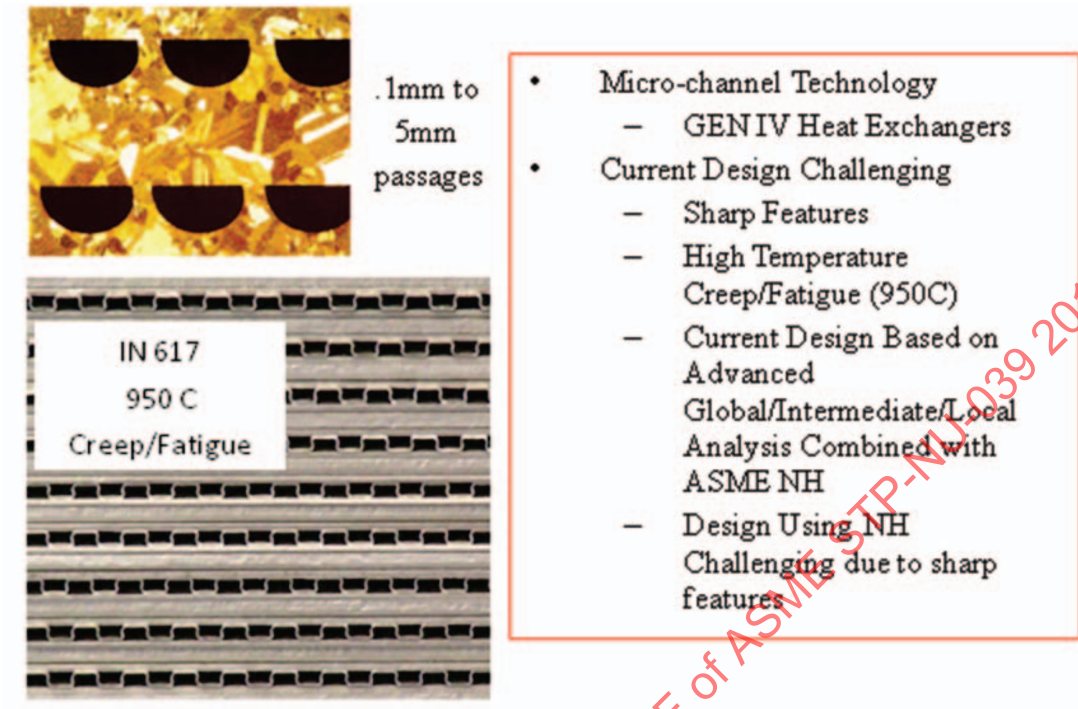


Figure 16 - Example of Possible GEN IV Type Heat Exchangers
These illustrations are from "Heat Exchangers for the Next Generation of Nuclear Reactors" by Li, Le Pierres and Dewson, Heatric Division of Meggitt (UK) Ltd., Proceedings of ICAPP '06, Reno, NV USA, June 4-8, 2006, Paper 6105

8.2 R5 Usage

Some details of R5 acquisition, training and use are listed here.

- R5 can be obtained for $1700 for 1-year and $300 for future yearly renewal. This includes support. The methods are also well established to the point where one can learn the procedures from open literature publication such as in [35].
- Material libraries are available in the code.
- Methods exist for estimating crack growth laws from only knowing tensile properties if data is not available.

Much data is available in the open literature.

- BE willing to supply some of the data that is in the public domain (might charge for compilation).
- Much is compiled in the R5-Code software, which can be licensed.
- Nikbin also has data—he will charge a fee to compile it. This may be worth consideration by DOE/ASME since this represents a small investment to obtain a large database.
- API 579 has some data that can be used.

8.3 Uncertainties in R5 and All Creep-Fatigue Crack Growth Methods

Creep-fatigue crack growth methods for design are now well established in Europe. In fact, many European countries ***require*** organizations to consider creep crack growth as part of the design process. While the methods in R5 are now well established and have been used on a daily basis for more than 15 years, there remain a number of modeling uncertainties which must be kept in mind when using the methods. These include the following, which also are true for every method examined in this report.

- Crack Nucleation. The methods for predicting the onset of crack growth from an assumed or existing flaw are not considered to be fully robust by this author. One can always neglect this process and the assessment will be conservative.
- Material Properties for the R5 often have inherent statistical scatter. While this is also the case for current NH material properties, this results in additional sources of uncertainty.
    - The creep constitutive relationship for high temperature crack life assessment can be complicated, especially for new very high temperature materials. While R5 claims to be useful for all material laws, this remains to be seen in general.
    - The creep crack growth relationship is obtained by plotting the creep crack growth parameter (C(t), C*) on log-log paper to obtain a power law relationship. There is often scatter in these results so a lower bound curve is often taken. Moreover, it is not certain that a power law relationship will persist for new materials.
    - The fatigue crack growth relationship is likewise fraught with the similar uncertainties discussed for creep crack growth.
    - The creep-fatigue crack growth interaction equations are also subject to material variability and uncertainty.
    - The performance of the methods for very high temperature performance and for new materials will need to be established.
- There are also uncertainties that persist within the modeling and estimation assumptions used.
    - The estimation of the reference stress which is required to estimate the parameters for an engineering assessment of crack growth are difficult to determine for complicated cracked components. This can lead to overly conservative estimates of life. While finite element analysis is always possible, this can make the crack life assessment time consuming.
    - The constraint at the growing crack tip can be difficult to determine. Moreover, the constraint can change as the crack grows. Figure 17 illustrates the elastic-plastic fracture toughness for different types of crack geometries and loadings. This same type of effect can affect the creep crack growth relationship and is a source of uncertainty.
    - Estimates of C(t) for complicated constitutive relationships using equations such as those shown in Figure 15 can be overly conservative.

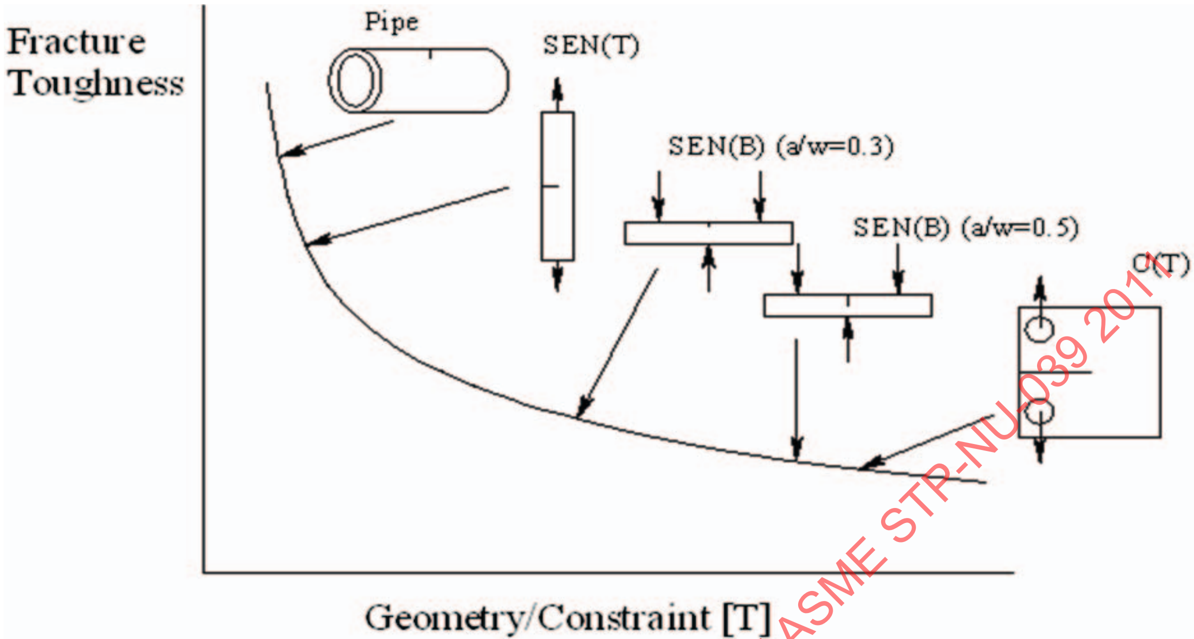


Figure 17 - The Effect of Constraint on Fracture Toughness

8.4 Recommendations Regarding Additional R&D Needs and Testing Requirements

Some additional research and development needs for creep and creep-fatigue crack growth modeling are listed in the following bullets.

- Material data tests required for new materials (e.g. IN617) and operating conditions for GEN IV.
- Reference Stress Approach Needs More Validation for complicated geometries. These include more work for:
    - High constraint crack geometries.
    - Complex Crack Geometries (e.g. nozzles, advanced heat exchangers, etc.).
    - Materials without secondary creep regime (or minimal regime). The methods appear to have difficulties for materials that do not attain a secondary creep regime. The estimation schemes (such as the equation in Figure 15) apparently require this despite claims made by the R5 developers. More work is clearly needed here.
    - Validity for transient creep conditions needs more work. The current estimation schemes are too conservative for cases where extensive transient creep crack growth occurs.
    - Validity for advanced constitutive laws required—R5 developed to work for materials which exhibit complex creep response. However, we have not seen extensive validation and generality for new material and higher temperature operation.
    - Assumptions tend to result in extensive conservatism—Should re-evaluate these.
    - Others areas of research needs will be developed during the part II effort.

- Finite element methods should be used for situations where the accuracy of reference stress method is in doubt.
- Enhancement and further development of theory is necessary for new materials and higher temperature cyclic application. As discussed in Sections 2, 7 and Appendix A, the theory underlying R5 (and all other methods) is quite old and is fraught with issues that need to be studied more thoroughly. This can lead to a more fundamentally sound theory which can enhance the method, reduce conservatism, remove some uncertainties, and lead to more confidence in life predictions.
- Engineering methods to predict diffusion creep are needed.

R5 should be qualified for materials and operating conditions of GEN IV before implementation into NH. In the meantime, R5 procedures (for Cr-Mo and stainless steels) where qualification within R5 has been made, can be recommended.

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APPENDIX A

INVESTIGATIONS OF HIGH TEMPERATURE DAMAGE AND CRACK GROWTH UNDER VARIABLE LOAD HISTORIES

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Also

International Journal of Solids and Structure, Vol. 32, No. 15, pp. 2191-2218, 1995.

Pergamon

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INVESTIGATIONS OF HIGH TEMPERATURE DEFORMATION AND CRACK GROWTH UNDER VARIABLE LOAD HISTORIES

F. W. BRUST

Battelle, 505 King Avenue, Columbus, Ohio 43201-2693, U.S.A.

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Abstract—Time dependent deformation and crack growth behavior under variable load conditions are investigated in this study. Experimental observations of load/unload effects in cracked creeping bodies are first discussed. Then a detailed analysis of a typical test result is presented. The potential of integral parameters, including the T^*-integral, to characterize this complex response, is shown.

1. INTRODUCTION

The demands for structural systems to perform reliably under severe operating conditions continue to increase. Time dependent deformation and corresponding damage development can be the limiting design feature for engineering structures that operate at high temperatures. This is true for both monolithic and composite materials. Time dependent degradation may also be a contributing factor to reducing life even at room temperatures and below [see, for instance, Brust and Leis (1992)].

Most of the studies of time dependent or creep crack growth have been concerned with simplified load conditions and constitutive relations. The methods developed by Riedel (1987) and extended into useful and practical engineering methods by Saxena (1991) are all based on simplified constitutive relations. Indeed, creep fracture parameters such as C^*, C_h^* (Riedel, 1987), C_t (Saxena, 1991), Q^* (Yokobori, 1984), $C(t)$ (Bassani, 1981), and others, are based on the assumptions of strain hardening primary creep law and/or Norton creep. Moreover, simple creep-fatigue engineering approaches rely on Miner's Rule, where the effects of creep crack growth and fatigue are considered separately for predictive purposes, as typified by Jaske's (1984) approach.

The approaches described above can provide useful engineering predictions of creep crack growth, especially under constant load conditions. However, for structural components that operate in a severe thermal environment, including thermal load-history effects in the analysis procedure is essential for accurate crack growth predictions. Indeed, the series of papers recently produced out of the AFWAL Materials Laboratory at Wright–Patterson Air Force Base [see Nicholas and Weerasooriya (1985, 1986) and the references therein] have clearly identified the importance of load history on crack growth behavior. This work, mainly applied to crack growth in the turbine disks of advanced military gas turbine engines made of IN100, consisted of a series of experiments and corresponding numerical analyses of this problem. The numerical analyses included more appropriate constitutive relations than the simple power law type theories discussed above. Useful design models to enable the Retirement for Cause philosophy to be used were developed for handling the creep/fatigue interactions for the turbine disk problem.

Kim *et al.* (1988, 1992) have been studying creep crack growth behavior under severe operating conditions as part of the NASA Hot Section Technology program. They have found that near field integral parameters have the ability to characterize creep crack growth under complex thermal mechanical loading conditions. The other simplified parameters discussed above could not characterize the behavior.

With the above comments in mind, this paper presents an investigation of the fundamental processes that develop in cracked bodies which experience history dependent loading. The paper begins by discussing some general considerations regarding cyclic creep and experimental observations of this process. A detailed analysis of one of the experiments is then described. As part of this discussion, the importance of proper constitutive laws on response, discussion of asymptotic approaches, and the ability of integral parameters to characterize the response is provided.

2. GENERAL CONSIDERATIONS

The phemonema of creep response under *stress reversals* may be explained as follows. If a uniaxial (metal) bar is heated to a temperature in the materials creep range and then loaded, the following response may be observed [see Gittus (1975) or Murakami and Ohno (1982) for instance]. As creep deformations advance, dislocations lose their mobility as they pile up at obstacles or owing to the formation of various networks, i.e. hardening is induced. These dislocations consist of two parts:

(i) a reversible part, which recovers mobility upon stress reversals; and
(ii) an irreversible part, which has formed irreversible networks.

When the stress in the bar is reversed from tension to compression, or from compression to tension, the reversible dislocations of type (i) remobilize in a direction directly opposite to those previously immobilized. This induces a significant creep strain rate, which may be attributed to material softening. With time, after the stress reversal, the (i) dislocations again become immobilized, and they again start to form irreversible dislocation networks.

If a structural component, or a portion of a component experiences stress reversals, significant creep strain rates are reintroduced. These strain rates cannot be neglected. Moreover, classical creep constitutive laws such as Norton's law or strain hardening laws do not account for this effect.

When a cracked component is loaded in the creep regime, creep strains accumulate from the crack tip outward. When the component is unloaded globally to zero load or even a net positive load, a region of compressive stresses *always* develops near the crack tip. That is, the tensile stresses in the crack tip region at the end of the load-hold period reverse sign upon unloading. This happens because of elastic stress recovery that occurs in the crack tip region where a localized creep zone has developed during the load-hold period. These compressive stresses cause large compressive creep strain rates in the crack tip region. Upon reloading, these compressive stresses that develop during the unload-hold period again reverse sign to tension. This again induces large tensile creep strains, which emanate outward from the crack tip region.

Thus, it is seen that cyclic loading in the creep regime in cracked bodies causes significant creep strain rate reversals, and corresponding increased crack tip strain development. The size of the zone of stress reversals depends on several factors, including load magnitude and amount of creep strain. Under severe conditions (which are increasingly being demanded of structural components), this effect is very important.

The next section describes some of the consequences of this stress reversal effect on the creep crack growth process. This is done by observing the response of creep crack growth specimens that are subjected to variable loads. The analysis sections will also show vivid examples of the above-described processes.

3. EXPERIMENTS OF VARIABLE LOAD CREEP

Before reporting the experimental observations, a description of the experimental procedure is provided.

3.1. *Experimental procedure*

All specimens are standard 1T compact tension specimens with a nominal thickness of 25.4 mm and width (W) of 50.8 mm, which were machined and fatigue precracked prior to testing. The specimens had approximately 20% side grooves machined into them to enforce straight crack growth. During the initial testing phase, one specimen experienced failure of one of the electric potential (EP) leads that measure crack growth rates, which led to incomplete crack growth data. Two separate EP leads were then used for all other tests.

For the variable load tests, the experimental technique is automated, with the load history programmed on an Instron Servohydraulic machine. This required development of a novel spring-loaded extensometer system. Data acquisition was triggered by load changes. This resulted in rapid data acquisition after load changes, and slower data acquisition during the load-hold periods, which is desired for testing the analysis results. Figure 1 provides a view of the test set-up.

3.2. *Experimental observations regarding variable load creep*

Experimental results on three 9 Cr–Mo tests that were subjected to three different load/unload sequences are described here. Tests have also been performed on 316 stainless steel at two different temperatures, with results indicating the same trends as are to be reported here. [Some of these results may be found in Brust *et al.* (1993) and Brust and Majumdar (1994), and other results will be reported soon.]

Let us first examine some of the general conclusions that can be made regarding history dependent loading in the time dependent deformation regime. Figure 2 illustrates a load versus time sequence that was applied to one of the 9 Cr–Mo compact tension specimens at 538°C. All were fatigue precracked prior to testing. As seen in Fig. 2a, an initial load period of 36 h was made to ensure the development of an initial creep zone in the specimen. The unload-hold times and subsequent reload times were continually decreased until about 90 h, after which 4-h hold periods and 1-h unload periods were maintained until the specimen failed. This assured a truly variable load history.

An enlargement of the displacement versus time history for this experiment between 325 and 365 h, after beginning the test, is illustrated in Fig. 2b. This specimen failed after about 400 h. Another specimen was loaded to the same load level and was identical in all other ways to the above-described specimen except for a slightly larger initial crack. However, this specimen was held for 320 h before unload/reload occurred, and only one cycle was applied. Figure 3 illustrates the displacement versus time history for this test. Note that this test failed at more than 600 h.

Several important general conclusions can be drawn from these results, as follows.

- During the unload-hold period, load-point displacement recovery occurs (Fig. 2b). This is due to the compressive stresses that develop at the crack tip during unload. This zone of compressive stresses near the crack tip can be quite large, as was verified through computational studies, even though the global load is never less than zero. The compressive stress zones will be illustrated later.
- After reload, the displacement rates increase as compared with the rates during the previous loading period. This is clearly seen in Figs 2b and 3. Note also that the displacement just after reloading is always smaller than the corresponding value just before unloading.
- Load history effects significantly decrease life as compared with the nearly constant load (only one unload) test, i.e. in this case the constant load test lasted nearly 1.5 times as long.

Further evidence of this behavior can be seen by observing the results of another test on 9 Cr–Mo steel, also at 538°C. However, the applied load was smaller than in the above tests, and the load sequence is as illustrated in Fig. 4a. As seen, the unload-hold times were only 5 min (as compared with the minimum hold time of 1 h in Fig. 2a). Figure 4b illustrates the load-point displacement response of this specimen before crack growth began. This was a long test, taking over 30 days, and crack growth began at about 192 h after the test began. Figure 4b shows that, as with Figs 2b and 3, the load-point displacement rates (i.e. slope of the curve) increase after an unload compared with the rates before unloading, even before crack growth begins. However, as seen in Fig. 4c, the change in displacements after an unload/load sequence becomes greater as time proceeds. This particular test has been completely analyzed, and the results will be presented later.

4. ANALYSIS RESULTS

This section will provide several types of analysis results that illustrate the effect of load history on time dependent crack growth and fracture. The first topic discussed involved observations of asymptotic fields that develop under cyclic creep. This is interesting, since most work to date and most practical approaches to the creep crack problem are based on asymptotic solutions using very simple constitutive relations. Here we compare some asymptotic solutions using several types of constitutive laws, including classical and more advanced creep models, which are capable of adequately predicting cyclic response under creep conditions. The second topic briefly examines some integral parameters that are being examined regarding their ability to characterize variable load creep crack growth. The final analysis topic presents the results of the third creep crack problem illustrated in Fig. 4. This test was analyzed throughout the entire 700 h test by using an appropriate constitutive law. The performance of the integral parameters, as well as comparisons with experimental data, is illustrated. Before this, a brief discussion of the computational tools used to develop these solutions is provided.

4.1. *Constitutive laws and finite element code*

The creep behavior of metals under a constant sustained load is classified into three phases: primary, secondary, and tertiary creep. In this work, which considers creep crack growth under variable loads, tertiary creep is not considered, since it occurs only in a small process region near the tip. The influence of the constitutive model used to represent time dependent materials on the stress and strain fields in the vicinity of a crack tip has been shown to be significant (Leung *et al.*, 1988), *even for constant sustained load*. As discussed in Section 2, upon stress reversal, a temporary increase in strain rate has been observed that was due to strain softening. Classical time or strain hardening (S-H) creep laws, upon which most of the current engineering approaches to predicting creep crack growth are based, are incapable of predicting these phenomena. The next section will clearly illustrate this. In the Inoue benchmark problems (Inoue *et al.*, 1991), a model developed by Murakami and Ohno (1982) and improved by Ohno *et al.* (1985) provided as good or better predictions of a complex load response in the creep regime than more than ten different models. The Murakami–Ohno (M–O) law has the advantage of having very simple material property requirements. The mathematical structure and the complicated effort required to obtain material properties for other recently proposed constitutive models render their use in numerical analyses of the creeping crack problem cumbersome.

The constitutive law used for most of the creep crack growth analyses presented here is based on the concept of a creep hardening surface (CHS) developed by Murakami and Ohno (1982, 1985). This model is quite convenient since the material property requirements consist of only the classical time hardening material constants (A, n, m), and the two Norton law constants [A_1, n_1; see eqn (1)].

For the general multi-axial case, the creep strain rate in this model is given by:

$$\dot{\epsilon}^c_{ij} = C(\sigma, q)S_{ij} = \tfrac{3}{2}m(A)^{1/m}(\sigma)^{(n-m)/m}(q)^{(m-1)/m}S_{ij} + \tfrac{3}{2}A_1(\sigma)^{n_1-1}S_{ij}, \quad (1)$$

where S_{ij} and σ are the deviatoric and equivalent stress, respectively. In eqn (1), q is given by:

$$q = p + \left(\frac{\epsilon^c_{ij} - \alpha_{ij}}{\sigma}\right)S_{ij}. \quad (2)$$

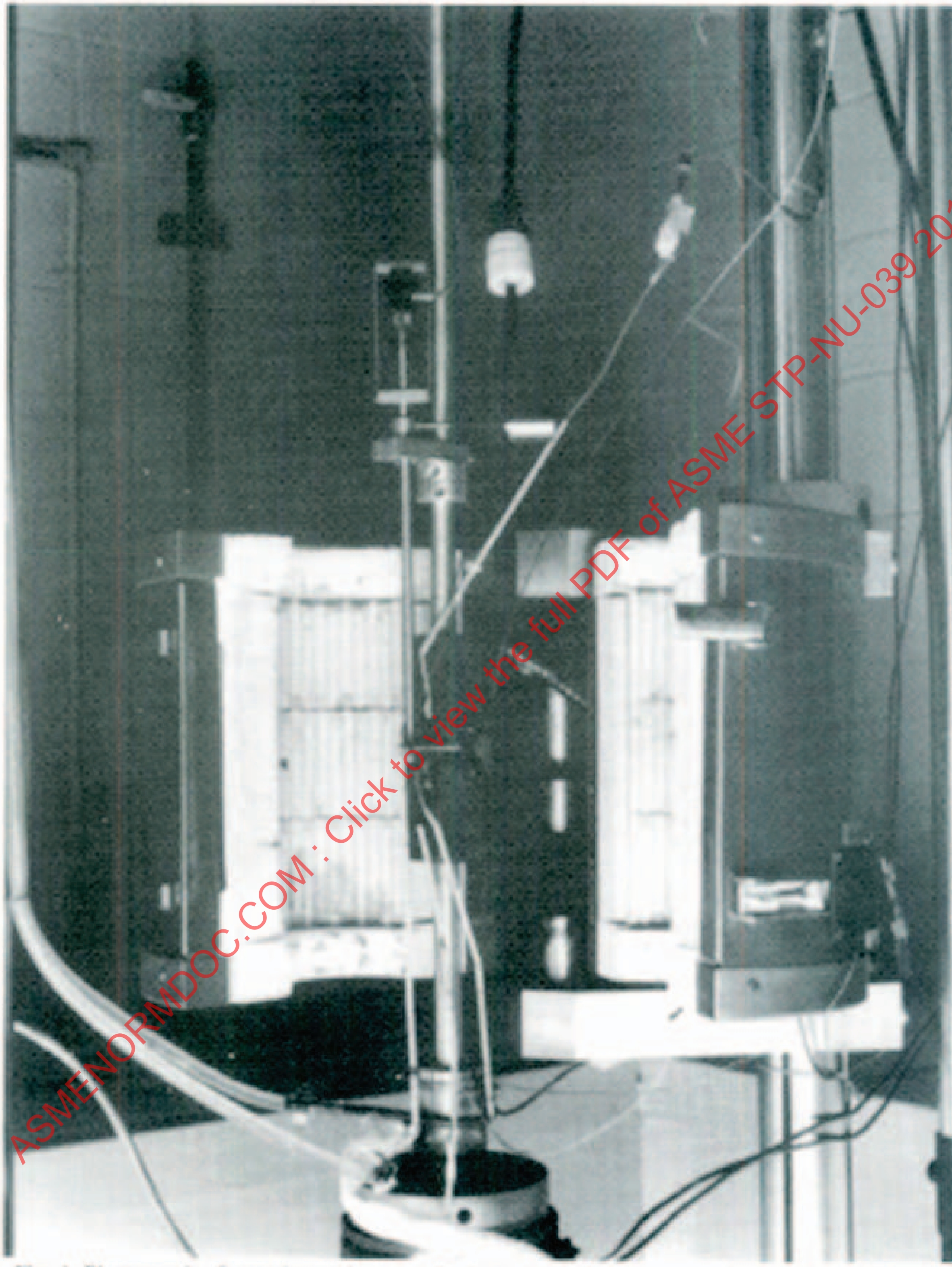

Fig. 1. Photograph of experimental set-up. An instrumented compact tension-specimen is shown here. The load pins go through the specimen. Note the spring-loaded extensometer entering the furnace from the top. This was used to measure crack opening displacements.

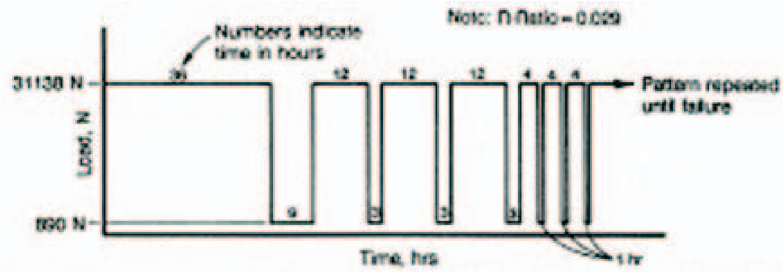

Fig. 2a. Load-time sequence applied to the first 9 Cr–Mo test. The initial crack size (a_0) was 26.75 mm, and $a_0/W = 0.527$.

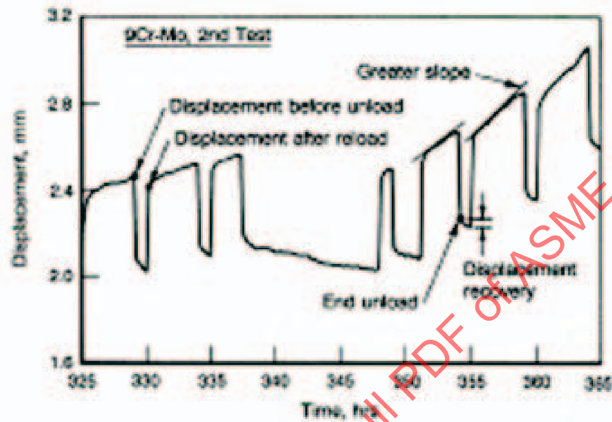

Fig. 2b. Displacement-time history for first 9 Cr–Mo test between 325 and 365 h.

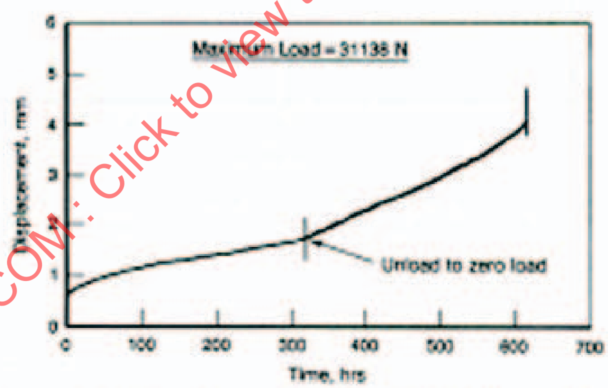

Fig. 3. Displacement-time history for second 9 Cr–Mo test. The load magnitude was identical to the load of Fig. 2a, but only one unload at time of about 320 h occurred. The initial crack size, a_0, was 27.23 mm with $a_0/W = 0.536$.

The evolution equations for the center of the yield surface α_{ij} and radius ρ are given by:

$$\dot{\alpha}_{ij} = \dot{\rho} = 0 \quad \text{if} \quad g < 0 \quad \text{or} \quad \frac{\partial g}{\partial \varepsilon_{ij}^c}\dot{\varepsilon}_{ij} \leq 0 \tag{3}$$

with

$$\dot{\alpha}_{ij} = \tfrac{1}{2}(\dot{\varepsilon}_{kl}\eta_{kl})\eta_{ij}; \quad \dot{\rho} = \frac{1}{\sqrt{6}}\dot{\varepsilon}_{ij}\eta_{ij} \quad \text{if} \quad g = 0 \quad \text{and} \quad \frac{\partial g}{\partial \varepsilon_{ij}^c}\dot{\varepsilon}_{ij} > 0. \tag{4}$$

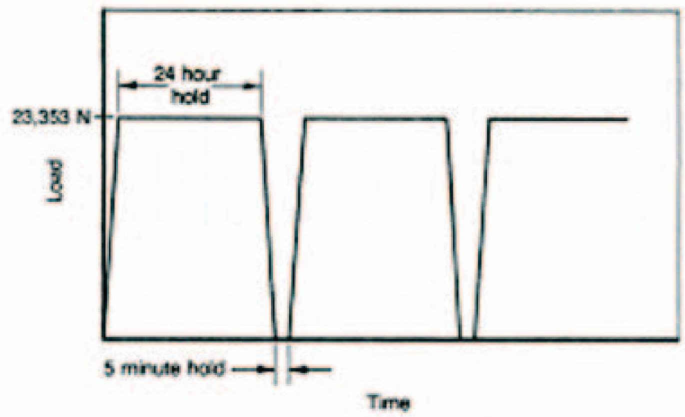

Fig. 4a. Load-time sequence for the third 9 Cr-Mo test.

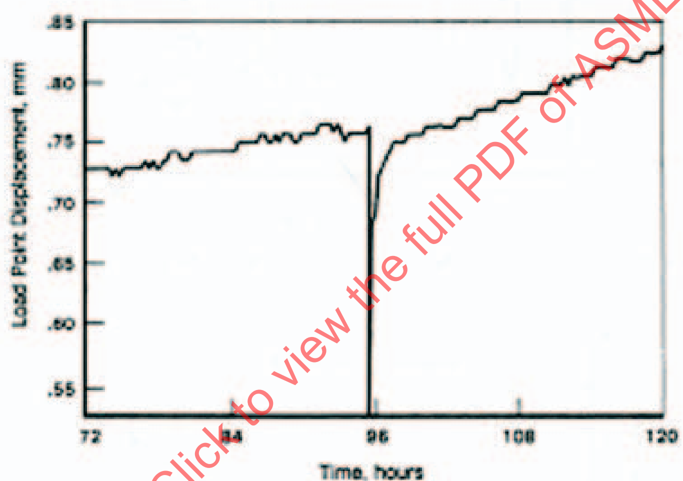

Fig. 4b. Load-point displacement versus time behavior between 72 and 120 h. Note in this specimen crack growth began at about 192 h (a_o = 23.75 mm).

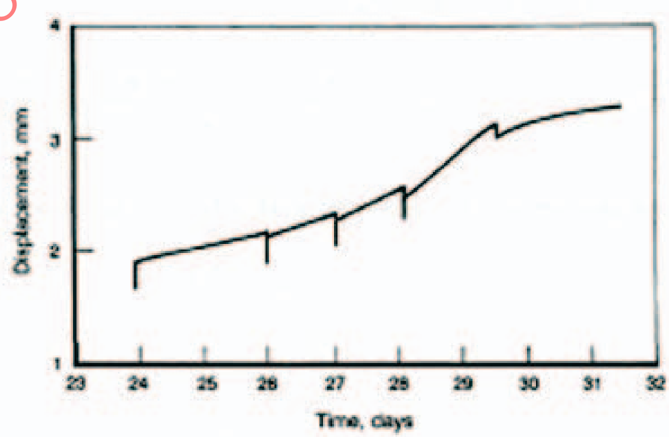

Fig. 4c. Displacement-time record for third test between the 24th and 30th days.

where η_{ij} is the outward normal vector to the CHS defined as

$$\eta_{ij} = \frac{\varepsilon^c_{ij} - \alpha_{ij}}{\{(\varepsilon^c_{kl} - \alpha_{kl}) - (\varepsilon^c_{kl} - \alpha_{kl})\}^{1/2}}. \tag{5}$$

The CHS is given as

$$g = \tfrac{3}{2}(\varepsilon^c_{ij} - \alpha_{ij})(\varepsilon^c_{ij} - \alpha_{ij}) - \rho^2 = 0 \text{ on CHS} \tag{6}$$

and

$$< 0 \text{ inside.}$$

The radius and center of the CHS therefore change only when the material state is on the CHS ($g = 0$) and remain the same when the state of creep strain is inside the CHS ($g < 0$).

From the evolution equations, it can be easily shown that q becomes $\bar{\varepsilon}_c$ (the equivalent creep strain) when stress reversals do not occur. Thus a principal advantage of this theory is that it coincides with classical creep constitutive laws when they apply. All material constants are therefore easily obtained from uniaxial creep data, which exist for most materials.

When a stress reversal occurs, q of eqn (2) becomes small, which renders the creep strain rates predicted in eqn (1) large. This accounts for large increases in creep strain rates observed experimentally during stress reversals [see Murakami and Ohno (1982, 1983) and Krishnaswamy *et al.* (1994)]. Classical laws upon which most creep fracture theories are based cannot account for this effect. Plasticity is included in this model by assuming that these strains occur over a very short time in evaluating the creep material constants.

A finite element (FE) algorithm using an implicit scheme has been developed for the Ohno and Murakami constitutive model and discussed by Krishnaswamy *et al.* (1993, 1994). The implicit method used here has the advantage of ensuring a convergent and stable solution for large time step sizes, unlike explicit integration schemes. The details of the algorithm have been omitted here and may be found in the cited references. Numerous comparisons using the implicit algorithm are compared with experimental data and with strain hardening theory and are also presented by Krishnaswamy *et al.* (1994) with good results.

The computational model for all analyses consisted of eight-noded isoparametric elements using plane stress or plane strain assumptions. Crack growth was modeled by using a node release technique whereby the nodal forces at both nodes in the particular element through which the crack is growing are released simultaneously over a period of time. The integral fracture parameters were calculated by using existing element shape functions and nodal averaged field quantities using a direct approach (i.e. a domain integral approach, which is convenient for three-dimensional problems, was *not* used). The analysis of the third experiment (Fig. 4) required a great deal of effort on a Cray computer system.

4.2. *Asymptotic observations*

Most practical methods for predicting the lives of cracked structural components that operate at temperatures at which creep occurs are based on a series of asymptotic solutions. These solutions were developed by using simple constitutive laws and are, for the most part, strictly valid for monotonic load-hold conditions [see Goldman and Hutchinson (1975), Riedel (1981), Riedel and Rice (1980), and the summaries provided by Riedel (1987)]. [Note that Riedel (1987) does provide an asymptotic solution for cyclic loading by using Norton's creep law, but the usefulness of this solution is unclear since Norton creep is inaccurate under cyclic load conditions.] Saxena and Han (1986) and Saxena (1991) (and many references cited therein) then developed engineering methods based on parameters that characterize the strength of these fields. In the following examples, we illustrate that the structures of these near tip fields change with time and load cycles, precluding the use of a single asymptotic strength parameter for cyclic load applications.

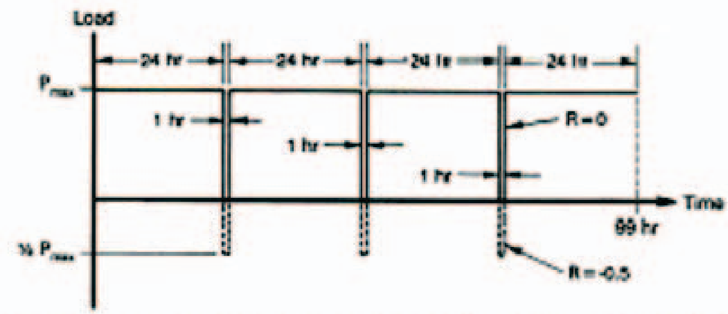

Fig. 5. Load spectra applied to asymptotic problem. Both $R = 0$ and $R = -0.5$ were considered. $P_{max} = 10$ kN for the 304 SS analysis, and $P_{max} = 23.353$ for the 9 Cr–Mo analysis.

Asymptotic solutions. The stress and strain fields near a crack tip are evaluated by using both the classical strain hardening creep law and the Murakami–Ohno (M–O) law [eqn (1)], the former of which is a special case of the M–O law. Cyclic loads are considered and the solutions are developed numerically by using the above-described finite element methodology. Only the first terms in eqn (1) are used since the primary creep term dominates during load changes.

Consider a standard compact tension specimen with crack length $a = 23.75$ mm and uncracked ligament length $c = 27.05$ mm. A finite element analysis of this specimen was performed by using creep properties of both 9 Cr–Mo Steel at 538°C and 304 stainless steel (SS) at 650°C. The applied load spectrum is shown in Fig. 5. Note from Fig. 5 that an $R = 0$ and an $R = -0.5$ spectrum were both used. This spectrum was applied up to 99 total hours. This means that the ends of the load-hold periods were 24, 49, 74, and 99 h while the *ends* of the unload-hold periods were 25, 50, and 75 h (four load and three unload periods). The material properties are:

$$A = 7.09 \times 10^{-17}, \quad n = 5.6, \quad m = 0.24 \quad (9\,\text{Cr–Mo})$$

$$A = 3.10 \times 10^{-19}, \quad n = 7.2, \quad m = 0.54 \quad (304\,\text{SS})$$

for stress in MPa and time in hours. These same constants are used for a strain hardening law and for the Murakami–Ohno cyclic creep law.

The symmetric finite element mesh was a focused mesh with ten rings of six-noded isoparametric triangular elements surrounding the crack tip and eight-noded elements elsewhere. The element size at the crack tip is about 0.00048 c, which is about two-and-one-half times more refined than the mesh used by Shih and German (1981) in their studies of HRR field dominance.

Figure 6(a) provides a plot of the shear creep strain rates just after two of the unload periods for the 304 SS with the $R = 0$ spectrum. This is a plot of $\dot{\varepsilon}_{r\theta}$ as a function of angle, θ, at a constant radius of 0.086 mm from the crack tip (standard crack tip polar co-ordinate definitions are used, with $\theta = 0$ ahead of the crack tip, and $\theta = \pi$ along the crack faces). This distance corresponds to about the seventh ring of elements away from the crack tip. Immediately afterwards the unloads occur at the first unload (time = 24+h) and third unload (time = 74+h), large stresses develop, which emanate from the crack tip. These stresses are relaxed with rather large creep strain rates. From Fig. 6(a), the maximum shear strain rates occur at an angle of about $\pi/2$, and it is clear that using a classical strain hardening creep law greatly underpredicts these strain rates. Figure 6(b) shows the shear creep strain rates at the end of the 1-h unload-hold period. Note that the position of maximum strain rate has shifted to about 1 radian. The strain rates have relaxed significantly; however, the rates from the Murakami–Ohno law are still higher than those of the classical law. All other components of creep strain rate exhibit a similar behavior at this location, and at all other locations.

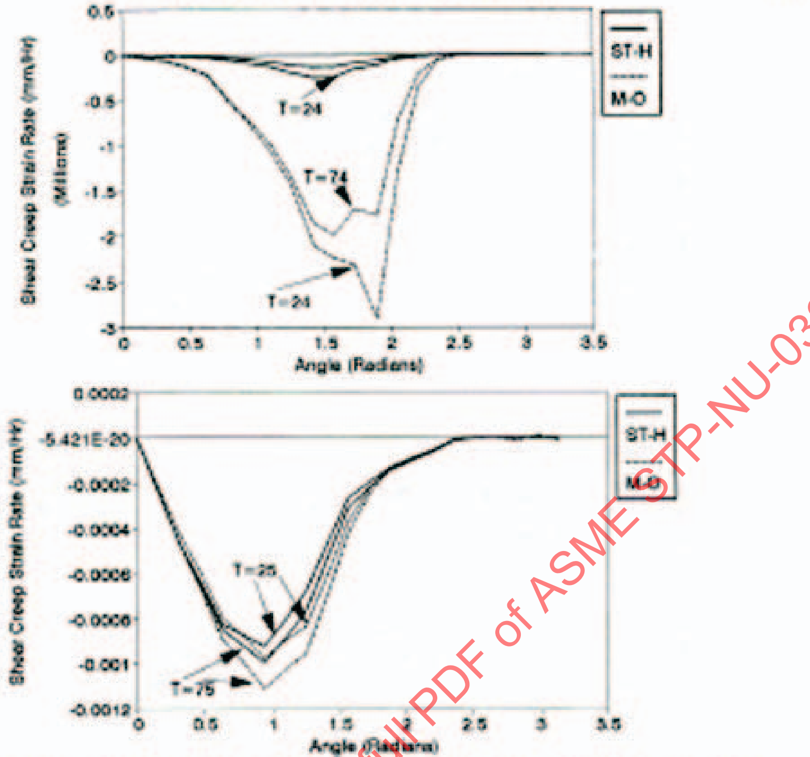

Fig. 6. Shear creep strain rates ($\dot{\varepsilon}_{r\theta}$) at a constant value of radius, 0.086 mm from the crack tip. (a) Just after the first and third unloads ($t = 24$, 74 h). (b) At the end of the hold times ($t = 25$, 75 h).

Figures 7(a)–7(c) show the θ component of stress at an angle of zero, also as a function of distance ahead of the crack tip. Figures 7(a)–7(c) show the stresses at the end of the hold times for 304 SS; $R = 0$, 304 SS; $R = -0.5$, and 9 Cr–Mo; $R = 0$ cases, respectively. Note that these plots show stresses versus log(r). The solutions for the Murakami–Ohno case, which has much better capability for modeling stress reversals, appear linear on these plots. Although certainly not proven here, it appears that the asymptotic fields behave as:

$$\sigma = C_1 \log(C_2 r). \tag{7}$$

In fact, this apparent logarithmic singularity appears to dominate over a very large distance, and, at least for these cases, does not change with cycle. On the other hand, the stress field when a strain hardening law is used appears to vary as a function of cycle number. Note also that the differences between the S–H and M–O solutions increase as the cycle number increases.

Figures 8a and 8b show the accumulated strains (ε_{θ} at $\theta = 0$) for the 9 Cr–Mo case, at the end of the unload-hold periods (times 25, 50, 75 h), and at the end of the load-hold periods (times 24, 49, 74 h), respectively. The differences between the S–H and M–O solutions increase as the number of cycles proceeds. Moreover, the strains at the end of the load-hold times are close, independent of the number of cycles for the S–H model. Note that these are the total accumulated creep strains, obtained by integrating the creep strain rates throughout the load history, as appropriate. An interesting observation can be made regarding the results of Figs 6–8. The stresses tend to be higher when a strain hardening law is used than when the Murakami–Ohno law is used, whereas the creep strains are lower. This can be explained as follows. During the load changes, the creep strain rates are greatly under-predicted by using a strain hardening law, whereas they are adequately predicted by using the Murakami–Ohno law. Because of this, the stresses do not relax after load path

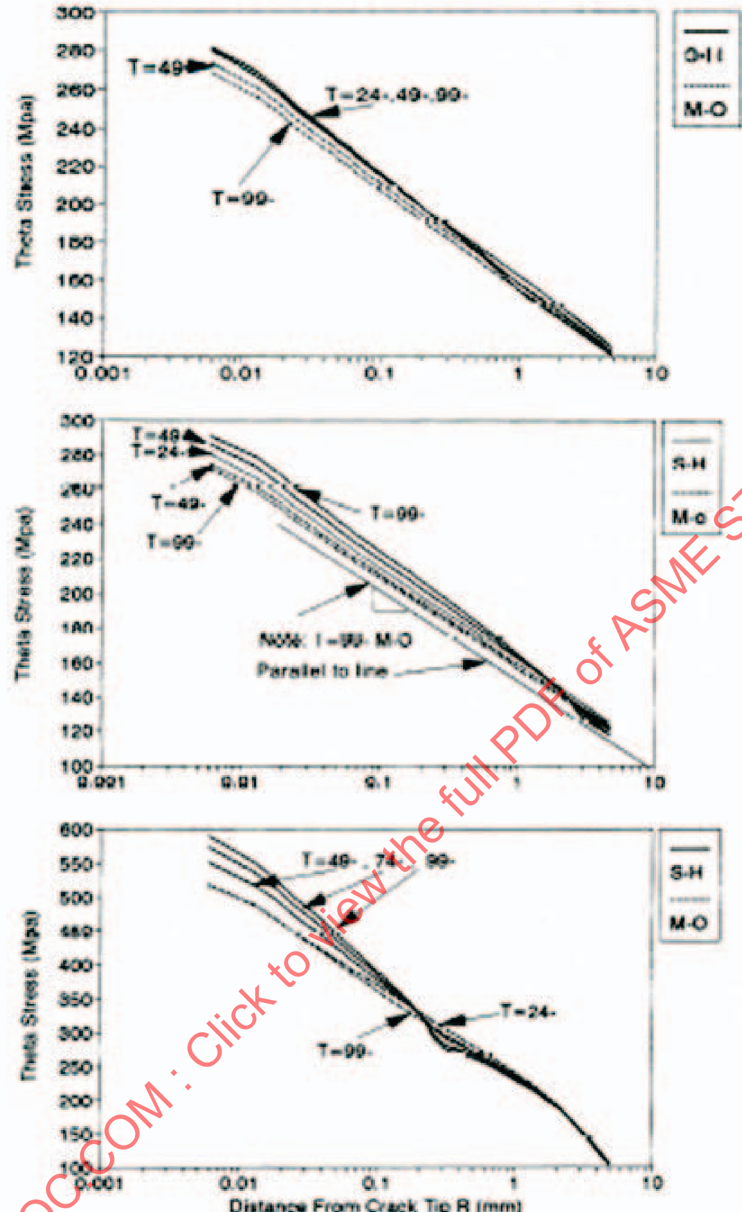

Fig. [illegible] (a) Stresses plotted as a function of distance from the crack tip for $\theta = 0$. Results are for times of 24, 49, and 99 h, i.e. after reload-hold sequences. (a) 304SS, $R = 0$ case. (b) 304SS, $R = -0.5$ case. (c) 9 Cr-Mo, $R = 0$ case.

changes as much as they should when a strain hardening law is used. At the same time, the corresponding creep strains do not accumulate as rapidly as they should when strain hardening theory is used.

Further comments are in order regarding Figs 7 and 8. It is well known [see Riedel (1981, 1987)] that the asymptotic stresses and strains are of $O\{[1/(n+1)]\}$ and $O\{(n/(n+1)\}$, respectively. When Figs 7 and 8 are plotted on a log-log scale, this means that the stresses and strains will plot as straight lines with a slope of $\{1/(n+1)\}$ and $\{n/(n+1)\}$, respectively. These slope values are indeed observed before unloading occurs, i.e. at time less than 24 h. At the end of the unload/reload sequences (times = 49, 74, 99 h), the stresses when a Murakami–Ohno creep law is used are not inconsistent with a slope of $\{1/(n+1)\}$