STP-NU-039

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

ASME STANDARDS
TECHNOLOGY, LLC

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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.