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GUIDELINES FOR EVALUATING FATIGUE ANALYSES INCORPORATING THE LIFE REDUCTION OF METAL COMPONENTS DUE TO THE EFFECTS OF THE LIGHT-WATER REACTOR ENVIRONMENT FOR NEW REACTORS

A. INTRODUCTION

In Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10, Part 50, of the *Code of Federal Regulations* (10 CFR Part 50), "Domestic Licensing of Production and Utilization Facilities" (Ref. 1), General Design Criterion (GDC) 1, "Quality Standards and Records," requires, in part, that structures, systems, and components that are important to safety shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety function performed. In addition, GDC 30, "Quality of Reactor Coolant Pressure Boundary," requires, in part, that components that are part of the reactor coolant pressure boundary shall be designed, fabricated, erected, and tested to the highest practical quality standards.

Augmenting those design criteria, 10 CFR 50.55a, "Codes and Standards," endorses the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Ref. 2) for design of safety-related systems and components. In particular, Section 50.55a(c), "Reactor Coolant Pressure Boundary," requires, in part, that components of the reactor coolant pressure boundary must meet the requirements for Class 1 components in Section III, "Rules for Construction of Nuclear Power Plant Components," of the ASME Code, except as provided in that section.

Specifically, the ASME Class 1 requirements contain provisions, including fatigue design curves, for determining a component's suitability for cyclic service. These fatigue design curves are based on strain-controlled tests performed on small polished specimens, at room temperature, in air environments. Thus, these curves do not address the impact of the reactor coolant system environment on the components of the reactor coolant pressure boundary.

This regulatory guide provides guidance for use in determining the acceptable fatigue life of ASME pressure boundary components, with consideration of the light-water reactor (LWR) environment. In so doing, this guide describes a method that the staff of the U.S. Nuclear Regulatory Commission (NRC) considers acceptable to support reviews of applications that the agency expects to receive for new nuclear reactor construction permits or operating licenses under 10 CFR Part 50; design certifications under 10 CFR Part 52, "Early Site Permits; Standard Design Certifications; and Combined Licenses for Nuclear Power Plants" (Ref. 3); and combined licenses under 10 CFR Part 52 that do not reference a standard design. Because of significant conservatism in quantifying other plant-related variables (such as cyclic behavior, including stress and loading rates) involved in cumulative fatigue life calculations, the design of the current fleet of reactors is satisfactory.

This regulatory guide contains information collections that are covered by the requirements of 10 CFR Parts 50 and 52, which the Office of Management and Budget (OMB) approved under OMB control numbers 3150-0011 and 3150-0151, respectively. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number.

B. DISCUSSION

The ASME Section III design curves (Ref. 2), developed in the late 1960s and early 1970s, are based on tests conducted in laboratory air environments at ambient temperatures. The original code developers applied a margin of 2 on strain and a margin of 20 on cyclic life to account for variations in materials, surface finish, data scatter, and environmental effects (including temperature differences between specimen test conditions and reactor operating experience). However, the developers lacked sufficient data to explicitly evaluate and account for the degradation attributable to exposure to aqueous coolants. More recent fatigue test data from the United States, Japan, and elsewhere show that the LWR environment can have a significant impact on the fatigue life of carbon and low-alloy steels, austenitic stainless steel, and nickel-chromium-iron (Ni-Cr-Fe) alloys.

The staff evaluated two distinct methods for incorporating LWR environmental effects into the fatigue analysis of ASME Class 1 components. The first method involves developing new fatigue curves that are applicable to LWR environments. Given that the fatigue life of ASME Class 1 components in LWR environments is a function of several parameters, this method necessitates the development of several fatigue curves to address potential parameter variations. Alternatively, a single *bounding* fatigue curve could be developed, but this approach might be overly conservative for most applications. The second method involves using an environmental correction factor (F_{en}) to account for LWR environments by correcting the fatigue usage calculated with the ASME "air" curves. This method affords the designer greater flexibility to calculate the appropriate impacts for specific environmental parameters.

The NRC staff has selected the F_{en} method as an acceptable method to properly incorporate the LWR environmental effects into fatigue analyses of ASME Class 1 components. The F_{en} method is presented in NUREG/CR-6909, "Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials" (Ref. 4). In particular, Appendix A to that report, "Incorporating Environmental Effects into Fatigue Evaluations," describes a method that the staff considers acceptable to incorporate the effects of reactor coolant environments on fatigue usage factor evaluations of metal components. In addition, NUREG/CR-6909 provides a comprehensive review of, and technical basis for, the method described in this regulatory guide, including analyses of each parameter affecting the fatigue evaluations. In developing the underlying models, researchers from Argonne National Laboratory (ANL) analyzed existing data to predict fatigue lives as a function of temperature, strain rate, dissolved oxygen level in water, and sulfur content of the steel. The resultant method postulates a strain threshold, below which environmental effects on fatigue life do not occur. By definition, F_{en} is the ratio of fatigue life of the component material in a room temperature air environment to its fatigue life in LWR coolant at operating temperature. To incorporate environmental effects into the fatigue evaluation, the fatigue usage is calculated using provisions set forth in Section III of the ASME Code, and the fatigue design curve is multiplied by the correction factor.

The staff also reviewed the nonconservatism of the current ASME Code design curve in respect to the existing fatigue data for austenitic stainless steels. Recent evaluations of stainless steel test data indicate that the ASME curve is inconsistent with the appropriate test materials and conduct of the fatigue test. Consequently, through this regulatory guide, the NRC staff endorses a new stainless steel air design curve. Section 5.1.8 of NUREG/CR-6909 (Ref. 4) provides a comprehensive review of, and technical basis for, that new design curve. The F_{en} defined for stainless steel in NUREG/CR-6909 should be used in conjunction with the new stainless steel air design curve when evaluating the fatigue usage of ASME Class 1 components.

In addition, the staff evaluated the incorporation of the F_{en} method in fatigue analyses for Ni-Cr-Fe alloys (e.g., Alloy 600 and 690) and welds. Section 6 of NUREG/CR-6909 (Ref. 4) discusses the technical basis for incorporating the environmental effects on nickel alloys and welds. In summary, fatigue evaluations for Ni-Cr-Fe alloys are based on the fatigue design curve for austenitic stainless steels. However, the existing fatigue data for Ni-Cr-Fe alloys and their welds are not consistent with the current ASME Code fatigue design curve for austenitic stainless steels. The data are either comparable or slightly conservative with the updated ANL model for austenitic stainless steels. Thus, the new fatigue design curve proposed for austenitic stainless steels adequately represents the fatigue behavior of Ni-Cr-Fe alloys and their welds. Therefore, the new design curve for austenitic stainless steels may also be used for Ni-Cr-Fe alloys and their welds, and the staff finds it acceptable to use the new austenitic stainless steels air design curve in Ni-Cr-Fe alloys environmental fatigue evaluations. Consequently, Section 6 of NUREG/CR-6909 presents the respective F_{en} equations to be used for Ni-Cr-Fe alloys and their welds.

Section 7 of NUREG/CR-6909 (Ref. 4) evaluates the ASME design curve margins. In conducting that evaluation, the researchers reviewed data available in the literature to assess the subfactors (excluding environment) that are necessary to account for the effects of various uncertainties and differences between actual components and laboratory test specimens. The researchers also performed statistical analyses using Monte Carlo simulations to develop fatigue design curves, using the "95/95 criterion." In other words, the curves should provide 95% confidence that the fatigue life of 95% of the population will be greater than that predicted by the design curves. The NRC deems this criterion acceptable because the fatigue design curves are based on crack initiation, rather than component failure and, therefore, additional margin exists between crack initiation and actual component failure.

The results of the Monte Carlo simulations indicate that for both carbon and low-alloy steels and austenitic stainless steels, the current ASME Code procedure of adjusting the mean test data by a factor of 20 for cyclic life is conservative compared to the 95/95 criterion. The results also indicate that a minimum factor of 12 for cyclic life of both carbon and low-alloy steels and austenitic stainless steels will satisfy the 95/95 criterion. Figures 9, 10, and 37 of NUREG/CR-6909 (Ref. 4) present the resultant new air design curves, using margins of 12 for cyclic life and 2 for stress, for carbon steel, low-alloy steel, and austenitic stainless steel, respectively. This regulatory guide uses these new air design curves; thus, an applicant that chooses to adopt the procedure discussed in this guide to determine the fatigue life of stainless steels should use these air design curves. However, the existing ASME air design curves for carbon and low-alloy steels may also be used with the procedure in this guide to determine the fatigue life of those materials, since their use will yield conservative results.

The NRC reviewed and found acceptable several methods for calculating F_{en}. Only the types of stress cycles or load set pairs that exceed strain threshold criteria for carbon and low-alloy steels, austenitic stainless steel, and Ni-Cr-Fe alloys need to be considered for F_{en} calculations. The evaluation options depend on the complexity of the analyzed transient condition and the detail of the evaluation. For example, in an evaluation in which the results of detailed transient analyses are available to determine the necessary parameters (strain rate, temperature, and others), the "modified rate approach" (presented and referenced in Section 4.2.14 of NUREG/CR-6909, Ref. 4) is an acceptable method for determining the F_{en} values. This method involves a strain-based integral for evaluating conditions for which temperature and strain rate change, resulting in the variation of F_{en} over time. This detailed approach calculates the F_{en} values based on the strain history for each load set in the fatigue analysis evaluation, considering the effects of strain rate and temperature variations for each incremental segment in the strain history. Such results may be used to reduce the conservatism in the calculated F_{en} values. For a simplified calculation yielding a more conservative result for a complex or poorly defined set of transients, the temperature is equal to the average temperature in the transient or segment. The calculated F_{en} values are then used to incorporate environmental effects into ASME fatigue usage factor evaluations.

C. REGULATORY POSITION

This section describes the methods that the staff considers acceptable for use in performing fatigue evaluations, considering the effects of LWR environments on carbon and low-alloy steels, austenitic stainless steels, and Ni-Cr-Fe alloys. Specifically, these methods include calculating the fatigue usage in air using ASME Code analysis procedures, and then employing the environmental correction factor (F_{en}), as described in NUREG/CR-6909 (Ref. 4). In particular, Appendix A to that report includes detailed descriptions and additional guidance concerning the overall method and all the required calculations.

1. Carbon and Low-Alloy Steels

The following procedure should be used to calculate the environmental fatigue usage of carbon and low-alloy steel components in LWR environments.

1.1 Fatigue Usage in Air

Calculate the fatigue usage in air using ASME Code analysis procedures and the fatigue air curves provided in NUREG/CR-6909, Appendix A, Figures A.1 and A.2 (updated ANL model curves).

1.2 Environmental Correction Factor (F_{en})

Calculate the environmental correction factor, F_{en}, using Equation A.2 of NUREG/CR-6909 for carbon steels, or Equation A.3 of NUREG/CR-6909 for low-alloy steels. Equations A.4 through A.7 of NUREG/CR-6909 should be used to calculate the parameters used in Equations A.2 and A.3. Equation A.8 of NUREG/CR-6909 defines the strain threshold.

1.3 Environmental Fatigue Usage

Calculate the environmental fatigue usage using Equation A.20 of NUREG/CR-6909.

2. Austenitic Stainless Steels

The following procedure should be used to calculate the environmental fatigue usage of austenitic stainless steel components in LWR environments.

2.1 Fatigue Usage in Air

Calculate the fatigue usage in air using ASME Code analysis procedures and the new stainless steel fatigue air curve provided in NUREG/CR-6909, Appendix A, Figure A.3 (proposed design curve).

2.2 Environmental Correction Factor (F_{en})

For all types of austenitic stainless steels (e.g., Types 304, 310, 316, 347, and 348), calculate F_{en} using Equation A.9 of NUREG/CR-6909. Equations A.10 through A.12 of NUREG/CR-6909 should be used to calculate the parameters used in Equation A.9. Equation A.13 of NUREG/CR-6909 defines the strain threshold.

2.3 Environmental Fatigue Usage

Calculate the environmental fatigue usage using Equation A.20 of NUREG/CR-6909.

3. Ni-Cr-Fe Alloys

The following procedure should be used to calculate the environmental fatigue usage for Ni-Cr-Fe alloy components in LWR environments (e.g., Alloy 600 and 690).

3.1 Fatigue Usage in Air

Calculate the fatigue usage in air using ASME Code analysis procedures and the new stainless steel fatigue air curve provided in NUREG/CR-6909, Appendix A, Figure A.3 (proposed design curve).

3.2 Environmental Correction Factor (Fen)

For all types of Ni-Cr-Fe alloys (e.g., Alloy 600 and 690), calculate F_{en} using Equation A.14 of NUREG/CR-6909. Equations A.15 through A.17 of NUREG/CR-6909 should be used to calculate the parameters used in Equation A.14. Equation A.18 of NUREG/CR-6909 defines the strain threshold.

3.3 Environmental Fatigue Usage

Calculate the environmental fatigue usage using Equation A.20 of NUREG/CR-6909.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide. This regulatory guide only applies to new plants, and no backfitting is intended or approved in connection with its issuance.

Except in those cases in which an applicant or licensee proposes or has previously established an acceptable alternative method for complying with specified portions of the NRC's regulations, the methods described in this guide will be used in evaluating submittals in connection with applications for construction permits, standard plant design certifications, operating licenses, early site permits, and combined licenses.

REGULATORY ANALYSIS / BACKFIT ANALYSIS

The regulatory analysis and backfit analysis for this regulatory guide are available in Draft Regulatory Guide DG-1144, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Environment in New Reactors" (Ref. 5). The NRC issued DG-1144 in July 2006 to solicit public comment on the draft of this Regulatory Guide 1.207.

REFERENCES

1. *U.S. Code of Federal Regulations,* Title 10, *Energy,* Part 50, "Domestic Licensing of Production and Utilization Facilities," U.S. Nuclear Regulatory Commission, Washington, DC.[1]

2. ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Power Plant Components," American Society of Mechanical Engineers, New York, NY, 1992.[2]

3. *U.S. Code of Federal Regulations,* Title 10, *Energy,* Part 52, "Early Site Permits; Standard Design Certifications; and Combined Licenses for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Washington, DC.[1]

4. NUREG/CR-6909, "Effect of LWR Coolant Environments on Fatigue Life of Reactor Materials" (Final Report), ANL-06/08, U.S. Nuclear Regulatory Commission, Washington, DC, February 2007.[3]

5. Draft Regulatory Guide DG-1144, "Guidelines for Evaluating Fatigue Analyses Incorporating the Life Reduction of Metal Components Due to the Effects of the Light-Water Reactor Environment for New Reactors," U.S. Nuclear Regulatory Commission, Washington, DC, July 2006.[4]

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[1] All NRC regulations listed herein are available electronically through the Electronic Reading Room on the NRC's public Web site, at http://www.nrc.gov/reading-rm/doc-collections/cfr/. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room at 11555 Rockville Pike, Rockville, Maryland; the PDR's mailing address is USNRC PDR, Washington, DC 20555; telephone (301) 415-4737 or (800) 397-4209; fax (301) 415-3548; email PDR@nrc.gov.

[2] Copies may be purchased from the American Society of Mechanical Engineers, Three Park Avenue, NewYork, NY 10016-5990; phone (212) 591-8500; fax (212) 591-8501; www.asme.org.

[3] Copies are available at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone 202-512-1800); or from the National Technical Information Service (NTIS) by writing NTIS at 5285 Port Royal Road, Springfield, Virginia 22161, online at http://www.ntis.gov, by telephone at (800) 553-NTIS (6847) or (703)605-6000, or by fax to (703) 605-6900. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room (PDR), which is located at 11555 Rockville Pike, Rockville, Maryland; the PDR's mailing address is USNRC PDR, Washington, DC 20555-0001. The PDR can also be reached by telephone at (301) 415-4737 or (800)397-4209, by fax at (301)415-3548, and by email to PDR@nrc.gov. NUREG/CR-6909 is also available through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html, under Accession #ML070660620.

[4] Draft Regulatory Guide DG-1144 is available electronically under Accession #ML060970173 in the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html. Copies are also available for inspection or copying for a fee from the NRC's Public Document Room (PDR), which is located at 11555 Rockville Pike, Rockville Maryland; the PDR's mailing address is USNRC PDR, Washington, DC 20555-0001. The PDR can also be reached by telephone at (301) 415-4737 or (800) 397-4209, by fax at (301) 415-3548, and by email to PDR@nrc.gov.