RAS H-295

PVRC'S POSITION ON ENVIRONMENTAL EFFECTS ON FATIGUE LIFE IN LWR APPLICATIONS

W. Alan Van Der Sluys

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FOREWORD

This report describes the activities of the PVRC Steering Committee on Cyclic Life and Environmental Effects (CLEE) and the PVRC Working Group S-N Data Analysis. This report presents the PVRC recommendations to the ASME Board on Nuclear Codes and Standards (BNCS) concerning needed modifications to the ASME fatigue analysis procedure. The proposed modifications will account for the effect of the environment on the fatigue properties of the pressure boundary materials. These recommendations are in response to the following request from the BNCS:

> *"BNCS Looks to PVRC to Obtain, Characterize, and Report in Sufficient Detail to ASME Such Data as May be Useful to ASME in its Evaluation of the Fatigue Curves of Sections IIII and XI"*

The PVRC Committee has worked closely with, and received comments from, investigators in Japan, Europe, and America and has reviewed essentially all public domain data. We are particularly appreciative of databases and analyses provided by those in Japan working on MITI projects and in America at the Argonne National Laboratory.

We believe we have been successful in guiding the experimental work and forging a consensus with regard to the key issues that were formerly much less than clear. Considering all well characterized, available data, PVRC has drawn the following major conclusions:

1. ASME Section III should adopt a procedure such as proposed in Section 7 of this report to apply an environmental correction factor, F_{en}, to life fractions calculated using the existing ASME S-N design curves when anticipated operating conditions are sufficiently severe that it is necessary to account for environmental effects.
2. ASME Section XI should adopt a procedure such as proposed in a draft code case in Section 7 of this report and apply the environmental correction factor, F_{en}, to life fractions calculated using the existing ASME S-N design curves when it is necessary to account for environmental effects.
3. The F_{en} models are shown to work well in predicting the effect of the coolant environments on the low cycle fatigue properties of stainless steel. The low cycle fatigue information on stainless steel in air, collected by the PVRC to perform the evaluation, does not appear to support the ASME mean data line for stainless steel, and more data are needed to adequately understand behavior.

The above conclusions are based on two principles:

1. The environmental correction factors can be determined using equations developed either by Argonne National Laboratory or by MITI's investigators in Japan. While these equations are somewhat different; in real situations, they are expected to give similar results, within the bounds of experimental error and operating uncertainties.

2. The factor of 20 on life, originally used in the development of the fatigue design curves to account for uncertainties, is adequate to account for reductions in fatigue life due to the environment under well controlled operating conditions. Under those conditions, provision for further reductions in fatigue life due to the environment is not essential.

The PVRC has reviewed the ASME Section III Fatigue Analysis procedure to determine what modifications are needed to take into account the effects of the coolant environment on the S-N fatigue properties. In performing this review, the PVRC evaluated the following areas:

1. The margins used in the development of the Section III procedure.
2. Laboratory data used in the development of the Section III procedure.
3. Laboratory fatigue data on smooth specimens in simulated reactor coolant environments.
4. Models to predict the S-N properties in Light Water Reactor (LWR) coolant environments of the pressure boundary materials.
5. Laboratory data on structural tests conducted in water environments.

This report is divided into 10 sections that describe in detail the development of the PVRC recommendations and present examples of the Code changes needed to implement the recommendations. The S-N fatigue data for carbon steel, low alloy steel, and stainless steels, collected by the PVRC are compared with the available S-N models. Both the models developed by Argonne National Laboratory and MITI are shown to adequately predict the S-N results in simulated LWR coolant environments.

The available data from laboratory specimens tested in simulated LWR coolant environments were used to evaluate expected reduction in life in plants. It was determined that the margins applied to laboratory data to develop the ASME Fatigue Design Curves need not be adjusted when certain operating thresholds are not exceeded. These thresholds identified by PVRC pertain to oxygen level, temperature, stain rate, etc. The PVRC developed thresholds, or more rigorous analysis without thresholds, can be used to determine the effect of the environment on specific components.

A limited amount of laboratory data exist on the effect of coolant flow rates on carbon and low alloy steels. These data show a reduction in the environmental effect with increasing flow rates. These flow rate effects need to be incorporated into the F_{en} models and the thresholds for carbon and low alloy steels. At this time no information exists as to the effect of flow rate on stainless steel.

Available data from the literature on the results of laboratory tests of structural components in water environments were evaluated using the proposed procedure. This evaluation supported the concept of a moderate reduction in fatigue life without applying the environmental correction factor, F_{en}, to the ASME Fatigue Design Curves.

In section 9, of this report a copy of the MITI Guidelines For Evaluating Fatigue Initiation Life Reduction in LWR Environments is reproduced. These guidelines recommend the use of the F_{en} factor to account for the effect of the environment but do not utilize the concept of thresholds to deal with moderate environmental effects.

CONTENTS

Acknowledgment

This report represents the culmination of ten years of activities within the PVRC. The author would like to acknowledge the help and contributions of a number of persons:

Throughout most of the ten years the work was preformed under the guidance of Sumio Yukawa. Without his guidance and contributions this report could not have been written.

Throughout this effort there has been continuous support from the following committees in Japan:

- Thermal and Nuclear Power Engineering Society (TENPES), EFD Project
- Japan Power Engineering and Inspection Corporation (JAPEIC), EFT project
- Japan Nuclear Energy Safety Organization (JNES)

These Japanese committees contributed much of the fatigue data collected by the PVRC as well as participated in the activities of the PVRC subcommittees. M Higuchi, Ishikawajima-Harima Heavy Industries Co. Ltd, attended many of the committee meetings, contributing in the discussions and keeping the PVRC informed as to activities in Japan.

In addition representatives from Hitachi, Mitsubishi Heavy Industries, Toshiba Corp, Tokyo Electric Power, Kansai Electric frequently attended meetings and contributed valuable test results.

Another major contributor to the committee activities was O. Chopra from Argonne National Laboratory. He attended most of the PVRC meetings, supplied significant data to the PVRC, and contributed in the discussions of the subcommittees.

EPRI contributed several figures from EPRI Report MRP-49.

PVRC's Position on Environmental Effects on Fatigue Life in LWR Applications

W. Alan Van Der Sluys[1]

1.0 Introduction

The rules and requirements provided in Section III of the ASME BOILER and PRESSURE VESSEL CODE has been widely used in the US and in other countries for the design, fabrication, and pressure integrity evaluation of the components for light water-cooled reactor (LWR) type of commercial nuclear power systems. Among its many features, Section III includes procedures for analyzing fatigue damage and the possibility of crack formation by fatigue as a result of pressure and temperature cycling during operation.

Beginning in the 1950's, design, fabrication, and construction activities related to nuclear power experienced a major increase and the ASME Code increased its scope and activities to keep pace with the increase. Emphasis on the "Design by Analysis" included additional effort on fatigue analysis with the formation of a Task Group for the determination of allowable fatigue stresses chaired by B.F Langer. The Task Group collected and analyzed the available fatigue test data and developed curves of allowable fatigue stresses as a function of number of imposed cycles.

The methodology utilized by the Langer Task Group to formulate Fatigue Design Curves (designated as Figs 1-9.0 in the Code) is described in Section 2 of this report. The work of the Langer Task Group was limited by the fact that the technology of fatigue testing in elevated temperature water at pressures and chemistries typical of LWR operating conditions was not well developed, which limited the available amount of fatigue test data for LWR coolant water environments. This limitation was recognized by the ASME in the 1974 and 1992 editions of the Code, wherein, Articles NB3120 and NB3121 entitled "SPECIAL CONSIDERATIONS," and "Corrosion" stated:

> "It should be noted that the tests on which the fatigue design curves (Figs I-9.0) are based did not include tests in the presence of corrosive environments which might accelerate fatigue failure."

Within a few years, results for fatigue tests conducted in water environments which simulated LWR coolant water became available in technical. Examples include:

D. Hale, S.A. Wilson, J.W. Kass, and E. Kiss "Low Cycle Fatigue of Commercial Piping Steels in a BWR Primary Water Environment," *Journal of Engineering Materials and Technology, Vol. 103, pp. 16–25 (1981)*

M. Higuchi and K. Iida, "Fatigue Strength Correction Factors for Carbon and Low-Alloy Steels in Oxygen—Containing High-Temperature Water," *Nuclear Engineering and Design, Vol. 129, pp. 293–306 (1991)*

O.K. Chopra, and W.J. Shack, "Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels," *NUREG 6717, ANL-0027 7 May 2001, U.S. Nuclear Regulatory Commission*

These results all indicated that LWR coolant water could have a significant detrimental effect on the fatigue life of metals utilized for the pressure boundary of LWR Nuclear systems.

1.1 BNCS Response and Request to PVRC

These results produced serious concerns within the ASME Board on Nuclear Codes and Standards (BNCS) regarding the structural integrity of Nuclear power plants and BNCS made the following request to PVRC to assist in resolving the concerns:

"BNCS Looks to PVRC to Obtain, Characterize, and Report in Sufficient Detail to ASME Such Data as May

[1]Consultant, Alliance, OH

be Useful to ASME in its Evaluation of the Fatigue Curves of Sections III and XI"

1.2 Proposed Environmental Factor Approach to Account for Environmental Effects in LWR Applications

In 1994–95, GE with EPRI support developed the environmental factor procedure for ASME Code-type Analysis of Environmental Effects in Fatigue Usage Evaluation. In Oct 1999, PVRC forwarded this procedure to the BNCS with a recommendation that the procedures be considered for Code application and implementation. The Procedure has been utilized for fatigue life evaluation in several License Submittals to the NRC. This report presents available data, models to predict the environmental factors and suggested Code Cases for Code implementation.

Starting in 1992, the Pressure Vessel Research Council (PVRC) has had a continuing activity concerned with the effect of the Light Water Reactor (LWR) coolant environment on the fatigue performance of the pressure boundary materials used in LWR applications. The activity has involved three main aspects of fatigue performance and applications. These are: (a) cyclic life under repeated stress and strain, the so-called S-N properties, (b) fatigue crack growth under repeated loading, and (c) evaluation of the design procedures and methodology used to assure performance and life of the structural components under anticipated cyclic duty. The primary focus of this paper concerns the effect of the LWR environment on the first aspect of fatigue performance, namely the S-N properties. The PVRC effort in this area has consisted of compiling and evaluating the available test data and assessing the various correlations of cyclic life and various mechanical and environmental parameters. The interim status and findings of this effort have been reported by Van Der Sluys and Yukawa [1-1, 1-2 and 1-3]. It may be noted that Hechmer [1-4] has presented a summary of the PVRC effort related to the design and evaluation aspects of fatigue performance.

1.3 Summaries of Programs External to PVRC

During the 1993–1995 period, the US Department of Energy (DOE) and the US Nuclear Regulatory Commission (NRC) initiated and supported several programs that evaluated and assessed the ASME Code design criterion for fatigue life performance of operating LWR nuclear power plants. In addition, the ASME Code adopted an enabling rule for reanalysis of usage factor calculations, and the Electric Power Research Institute (EPRI) supported development of an approach and procedures that could be implemented into the ASME Code to perform environmental effects analysis. The findings and/or ensuing actions from these activities included the following:

- A DOE supported study [1-5], examined the effect of applying an early version of a fatigue design curve that included an adjustment for LWR environmental effects on the calculated fatigue usage factor of representative ASME Class 1 components. As expected, the lower cyclic life of the adjusted curve increases the calculated usage factor. However, it was observed that in a number of instances, conservative and bounding values were utilized in the original usage factor calculations. Using more realistic values in the usage analysis could compensate for a significant portion of the environmental effect on usage factor.
- The NRC program, titled Fatigue Action Plan, included studies of a number of issues associated with the assessment of fatigue performance of structural components in a LWR environment. For example, it included a much broader and detailed study of situations noted in the DOE study mentioned above; these results are described by Ware et al. [1-6, 1-7]. Based in part on the results of the study, the NRC concluded that no major actions were needed by the NRC regarding environmental effects for currently operating LWR plants [1-8].
- In the 1996 Addenda to the ASME Code, Section XI added a new nonmandatory Appendix L titled Operating Plant Fatigue Assessment. In essence, the Appendix permits a re-evaluation of the original usage factor analysis to determine acceptability for continued service. Additionally, the Appendix also contains flaw tolerance based procedures and acceptance criteria to determine acceptability for continued service. An EPRI supported activity to develop procedures that could be used in conjunction with generally available data and information in existing ASME Code stress and fatigue analyses to account for LWR water environmental effects was completed in 1995 by Mehta and Gosselin [1-9, 1-10]. The approach and procedures have been reviewed and evaluated by the PVRC and determined to be a reasonable and workable approach for Code implementation. The detailed evaluation combined with some trial uses of the procedures has revealed areas where revisions and modifications are needed, and PVRC effort is being applied to this need. This development made full use of the results of the statistical modeling and analysis effort performed by the Argonne National Laboratory [1-11] and by Japanese investigators [1-12].
- In 2000 MITI Guidelines for Evaluating Fatigue Initiation Life Reduction in LWR Environments were issued by the Nuclear Power Safety Administration, Public Utilities Department, Agency of Natural Resources, and Energy Ministry of International Trade and Industry. These guidelines are presented in Section 9 of this report. These guidelines use F_{en} as a fatigue life correction factor in the same way as recommended by the PVRC. The equations for the calculation of

F_{en} give very similar results as F_{en} calculations developed by Argonne National Laboratory and used in the PVRC approach. Both sets of equations are presented in this report. The MITI approach differs from the PVRC approach in that it does not accept a moderate environmental effect which is discussed in sections 4 and 5 of this report.

- In 2001 EPRI published MRP-49 Materials Reliability Program (MRP) Evaluation of Fatigue Date Including Reactor Water Environmental Effects. This report recommends the use of the PVRC procedure in plant life extension evaluations. Many of the figures and some of the text in this PVRC report are the same as in this EPRI report.

1.4 Summary of PVRC Activities

This report recommends an approach which entails the use of a life reduction factor, F_{en}, for the cases when the characteristics of the transient being evaluated exceed a set of threshold conditions for the existence of an environmental effect on the fatigue life of the material. It has been shown that this approach will account for the environmental effects observed in laboratory studies. This approach is applicable because there is no observed effect of the environment on the fatigue limit of the material; thus, a factor of fatigue life alone will account for all observed effects. The laboratory studies have not shown an effect of the environment on the fatigue limit and the experience in Germany with oxygen water treatment in fossil boilers, that will be discussed later in this paper, has not observed such an effect.

The following sections of this report will present the technical bases for the life reduction factor approach. These sections will show the development of the threshold values for carbon, low alloy and stainless steel in the environment and present the models used to calculate the life reduction factors F_{en}.

This report will also describe the application of this procedure to the results from a number of laboratory tests programs in which structures were tested under fatigue loading conditions in water environments until failure. In these cases the recommended procedure is shown to work very well to predict the life of the structures.

References

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1-2. Van Der Sluys, W.A. and Yukawa, S., "Studies of PVRC Evaluation of LWR Coolant Environmental Effects on the S-N Fatigue Properties of Pressure Boundary Materials," in: *PVP-Vol. 306*, pp. 47–58, presented at ASME PVP 1995, Honolulu, HI, July 23–27, 1995.

1-3. Van Der Sluys, W.A. and Yukawa, S., "S-N Fatigue Properties of Pressure Boundary Materials in LWR Coolant Environments," in: *PVP-Vol. 374*, pp. 269–276, presented at ASME PVP 1998, San Diego, July 26–30, 1998.

1-4. Hechmer, J., "Evaluation Methods For Fatigue—A PVRC Project," in: *PVP-Vol. 374*, pp. 191–196, presented at ASME PVP 1998, San Diego, July 26–30, 1998.

1-5. Smith, J.K., Deardorff, A.F., and Nakos, J.T., "An Assessment of the Conservatisms In Fatigue Evaluation of ASME Class 1 Pressure Vessels and Piping," PVP-Vol. 286, ASME, 1994, pp. 19–29.

1-6. Ware, A.G., Morton, D.K., and Nitzel, M.E., "Application of Environmentally-Corrected Fatigue Curves To Nuclear Power Plant Components," PVP-Vol. 323, ASME, 1996, pp. 141–150.

1-7. Ware, A.G., Morton, D.K., and Nitzel, M.E., "Application of NUREG/CR-5999 Interim Fatigue Curves to Selected Nuclear Power Plant Components," NUREG/CR-6260, U.S. Nuclear Regulatory Commission, March 1995.

1-8. SECY-95-245, "Completion of the Fatigue Action Plan," James M. Taylor, Executive Director for Operations, U.S. Nuclear Regulatory Commission, Washington, DC, September 25, 1995.

1-9. Mehta, H.S. and Gosselin, S.R., "An Environmental Factor Approach to Account for Reactor Water Effects In Light Water Reactor Pressure Vessels and Piping Fatigue Evaluations," PVP-Vol. 323, ASME, 1996, pp. 171–185.

1-10. Mehta, H.S. and Gosselin, S.R., "An Environmental Factor Approach to Account for Reactor Water Effects in Light Water Reactor Pressure Vessels and Piping Fatigue Evaluations," EPRI Report No. 105759, Dec. 1995.

1-11. Meisler, J. and Chopra, O., "Statistical Analysis of Fatigue Strain-Life Data for Carbon and Low-Alloy Steels," PVP-Vol. 296, Risk and Safety Assessments: Where is the Balance? Book No. H00959-1995.

1-12. Nakao, G., Higuchi, M., Iida, K., and Asada, Y., "Effects of Temperature and Dissolved Oxygen Contents on Fatigue Lives of Carbon and Low Alloy Steels in LWR Water Environments," *Effects of the Environment on the Initiation of Crack Growth, ASTM STP 1298*, ASTM, 1997, pp. 232–245.

2.0 Summary of Technical Basis of Section III Fatigue Evaluation Procedure

The fatigue evaluation procedure in Section III of the ASME Boiler and Pressure Vessel Code was developed in the early 1960's. It was based on the Bureau of Ships Design Bases developed in the late 1950's. The S-N fatigue curves and a description of the technical basis for the curves for the BuShips Design Basis Ref 2-1. The following is taken from this reference and is the description of the procedure used to develop the S-N curves.

"This curve was constructed in the following manner:

(a) Available strain fatigue data for this general class of material were plotted in the form of total strain (elastic plus plastic) range versus cycles-to-failure. Machined specimens without notches that were tested at temperatures less than 600°F were considered. The mean curve for each material was drawn.

(b) A lower limit of the mean curves was drawn and then converted to a stress amplitude versus cycles-to-failure curve by multiplying the strain range by E/2, where E was taken as 26×10^6 psi.

(c) The design fatigue curve was then constructed by applying a factor of safety of either 2.0 on stress amplitude of a factor of 20 on cycles, whichever was more conservative at each point. The factor of 20 on life is the product of the following sub-factors:

a. Scatter of data (minimum to mean)	2.0
b. Size Effect	2.5
c. Surface finish, atmosphere, etc.	4.0

(d) The design fatigue curve stress amplitude for less than 100 cycles was taken as the value at 100 cycles."

This procedure is essentially the same as used in the development of the ASME curves as described in Ref. 2-2. The data and equations used in this development are described in the next section.

2.1 ASME Air Curve

In Reference [2-2] the ASME Sub-Task Group on Fatigue recommended to the ASME Boiler and Pressure Vessel Committee, Special Committee to Review Code Stress Basis that the formula given below be use in low cycle fatigue. Langer describes the application of this equation to 18-8 stainless steels in ref [2-3].

$$S = \frac{E}{4\sqrt{N}} \ln \frac{100}{100 - RA} + S_e$$

Where

S = elastic modulus × stain amplitude (psi)
E = elastic modulus (psi)
N = cycles-to-failure
RA = reduction of area in tensile test (percent)
S_e = endurance limit or fatigue strength at 10^7 cycles (psi)

The above formula was used to determine the low cycle fatigue curves for carbon steel, low alloy steel, and austenitic stainless steel. A best-fit curve obtained from the method of least squares, applied to the logarithms of the measured S and N values, using the above equation as a model. The room temperature modulus, E, was known in each case, and the computer code gave the best-fit value for RA and S_e. These values are shown on the curves reproduced from this report as Figures 2-1, 2-2, and 2-3.

These curves were then corrected for the maximum effect of mean stress using the formula below. This was derived from the Goodman diagram considering the change in the mean stress that is produced by yielding.

$$S' = S\left[\frac{S_u - S_Y}{S_U - S}\right] \text{ for } S < S_y$$

Where

S = value from curve
S' = adjusted S value
S_u = ultimate tensile strength
S_y = yield strength

The results from this correction for the mean stress are shown in the figures as dotted lines. It was felt that austenitic stainless steels due to their high endurance limit and low yield strength cannot sustain a mean stress at a cyclic strain level that would produce failure.

The best-fit lines, developed by Langer, appear to fit the data well. In these cases all of the results are from strain controlled experiments and the results are all in what is considered the low cycle region.

2.2 Margins

The last step in the development of the ASME S-N Fatigue Curve is the introduction of the margins of 20 on life and 2 on stress. These are the same margins as described earlier in this section. In Reference 2-4 W. Cooper describes this process as follows:

"The final step in the process was to shift the curves in recognition of the fact that laboratory data were to be applied to actual vessels. Reference [2-2] states that the 'design stress values were obtained from the best-fit curves by applying a factor of two on stress of a factor of twenty on cycles, whichever was more conservative at each point.' Unfortunately, these have been understood to be factors of safety, and nothing could be further from the truth. As stated in Reference [2-2] 'it is not to be expected that a vessel will actually operate safely for twenty times its specified life.'

The factor of twenty applied to cycles was developed to account for real effects. Reference [2-1] states

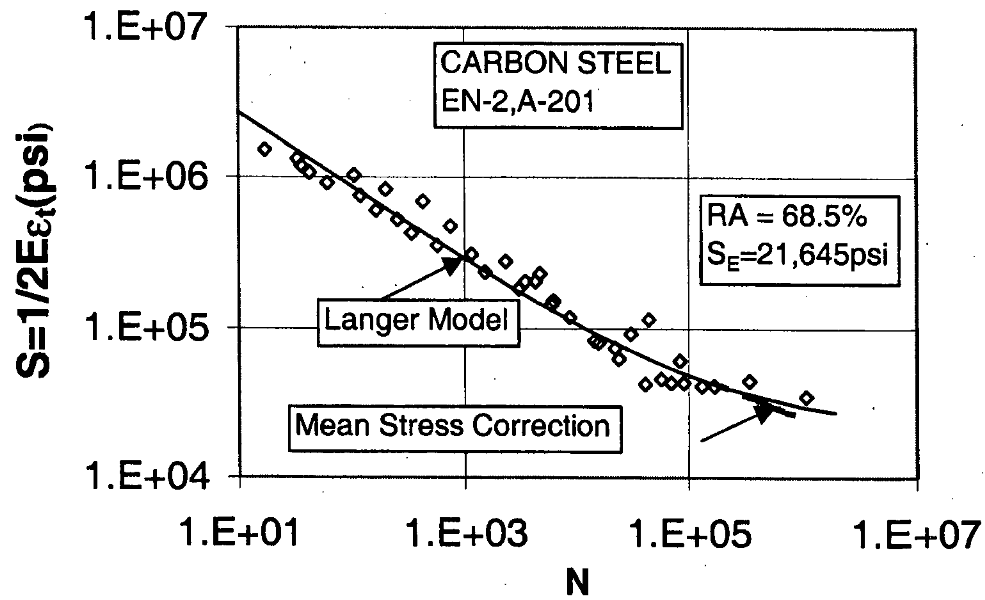

Fig. 2-1—ASME Mean Air Fatigue Curve for Carbon Steel

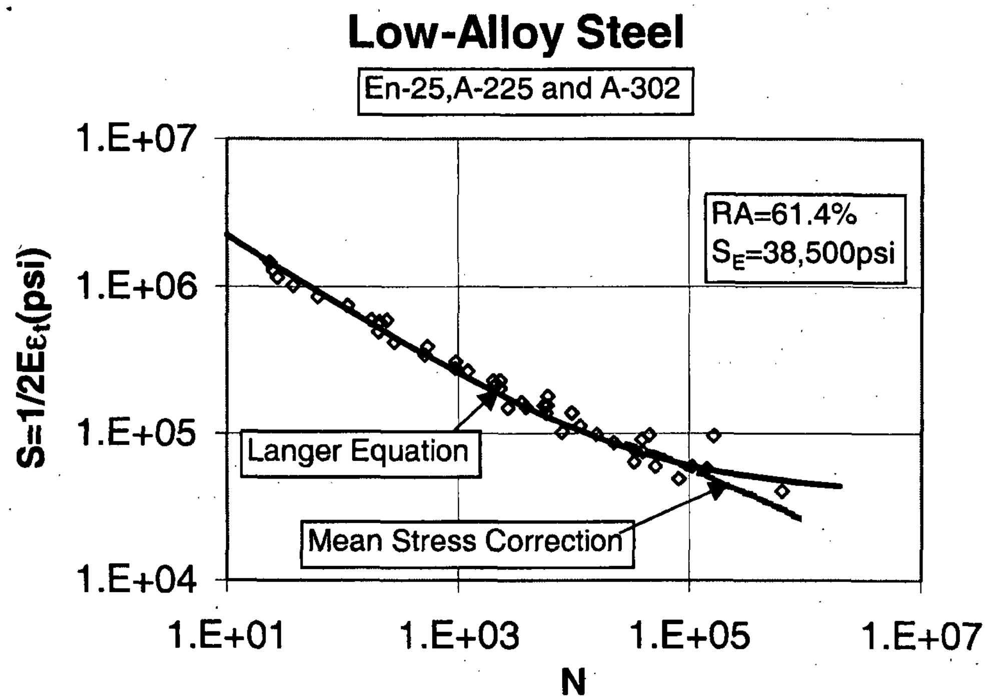

Fig. 2-2—ASME Mean Air Fatigue Curve for Low-Alloy Steel

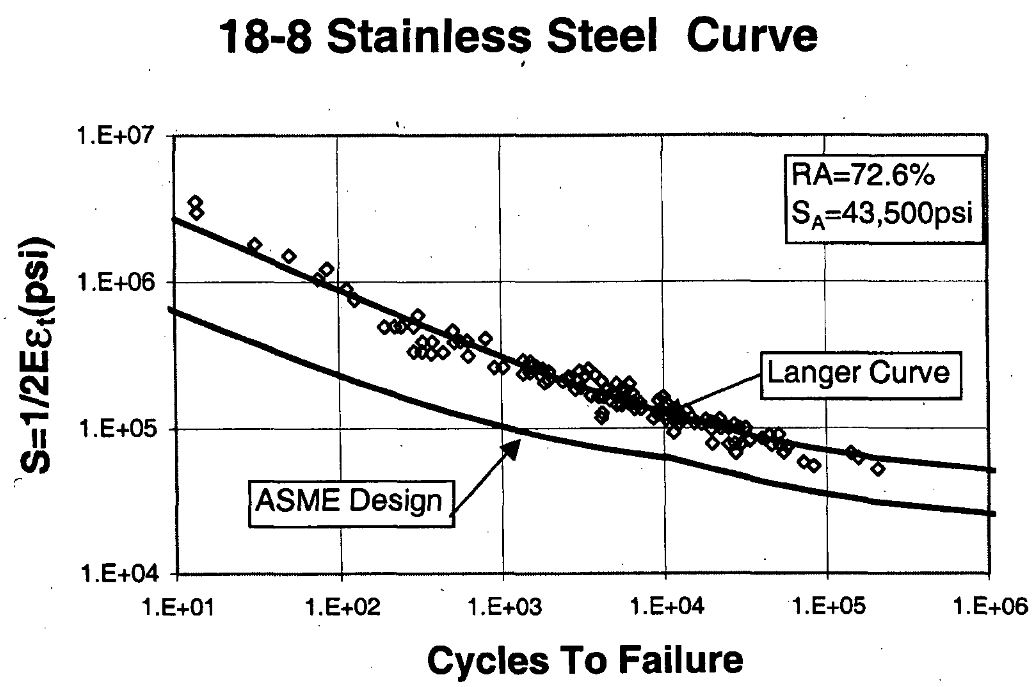

Fig. 2-3—ASME Mean Air Fatigue Curve for Stainless Steel Comparison of Margins

'The factor of 20 on life is the product of the following subfactors:

a.	*Scatter of data (minimum to mean)*	*2.0*
b.	*Size Effect*	*2.5*
c.	*Surface finish, atmosphere, etc.*	*4.0*

Two terms in the last line require definition. 'Atmosphere' was intended to reflect the effects of the industrial atmosphere in comparison with an air-conditioned lab, not the effects of a specific coolant. "Etc," simply indicates that we thought this factor was less than four, but rounded it to give the factor of 20.

A factor on the number of cycles has little effect at a high number of cycles, so a factor on stress was required at the higher number of cycles. It was found that at 10,000 cycles, approximately the border between low- and high-cycle fatigue, a factor of two on stress gave approximately the same result as a factor of twenty on cycles."

The subject of the appropriate margins to be applied to the mean of the fatigue data obtained in the laboratory on smooth cylindrical specimens tested in simulated reactor coolant environments is one of the most important issues to be resolved by the PVRC in order to develop an analysis procedure which takes into account the effect of the coolant environment on the fatigue life of the material.

2.3 References

2-1. "Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components (Pressurized, Water Cooled Systems)," dated 1 December 1958, with Addendum dated 27 February 1959.

2-2. "Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2," ASME International, New York, NY, 1969.

2-3. Langer, B.F., "Design of Pressure Vessels for Low-Cycle" ASME Journal of Basic Engineering, pp. 389–402, 1962.

2-4. Cooper, W.B., "The Initial Scope and Intent of the Section III Fatigue Design Procedure," Presented at PVRC Workshop on Cyclic Life and Environmental Effects in Nuclear Applications, Jan. 1992.

3.0 Early Tests and Results in Simulated Reactor Coolant Environments

It has been known for some time that under some test conditions the low cycle fatigue properties of carbon and low alloy steels in simulated reactor coolant environments could be reduced. The General Electric Company conducted two series of experiments that showed such effects [3-1, 3-2]. The first of these was conducted at the Dresden Reactor and involved cantilever bending specimens exposed to the reactor coolant.

In these experiments, a special facility was set up at the Dresden-1 Nuclear Power Station, Morris, Illinois. Primary water from the Dresden-1 test loop BWR system was piped to this special test loop and circulated at 10 gpm through three test vessels. A total of 35,535 loading cycles were applied to the fatigue specimens. Four materials were evaluated, Types 304 and 304L stainless steel, Inconel 600 and A-516 carbon steel. A summary of the results is as follows:

"The results of this work confirm the adequacy of the current ASME Section III fatigue design curves to account for the effect of a BWR primary water environment on the low cycle fatigue behavior of the four materials tested. Specifically:

1. *Fatigue performance of non-sensitized stainless steel, even with slight chemical or machined notches, is consistent with the ASME Code Mean Data Curve and far exceeds the Design Curve. Performance of 304L stainless steel is comparable.*
2. *There is a slight reduction in fatigue life associated with zero-tension loading in the Type-304 stainless steel in the BWR water environment and this can be accounted for by use of a mean stress correction.*
3. *Reduction in cyclic life can be expected for heavily sensitized welded stainless steel. This is due to the presence of stress corrosion cracking when such welds are subject to cycling with long times and stresses exceeding the yield level.*
4. *Based on an admittedly few data points, the low cycle fatigue performance of Inconel far exceeds the ASME Section III Fatigue Design Curve. However, significant amounts of intergranular cracking were observed in normally welded material.*
5. *Carbon steel material, whether welded or non-welded, displayed a reduction in fatigue performance in the BWR environment. This reduction appears to be related to the surface pitting. However, all data fall above the ASME Section III design curve and this material is fully adequate for field performance."*

These conclusions appear to be inconsistent with the later results presented in this report. The results from this program are, however, consistent with the results from latter programs. The loading strain rates of from 0.03 to 0.06 in/in/sec., used in the Dresden experiments, are not low enough for the fatigue lives to be less than the ASME design curves.

The second series of experiments were conducted on both cylindrical specimens under axial loading and butt welded pipe samples of carbon steel with internal pressure and axial loading [3-2]. These experiments were conducted in simulated BWR coolant with various dissolved oxygen contents. A substantial environment effect was observed in these experiments and a K_e environmental correction factor was suggested.

Experiments were conducted on SA333-Gr6 carbon steel pipe material in room temperature air, 550F air and simulated BWR coolant with various dissolved oxygen contents. In this study, a number of different specimen geometries was tested including butt-welded pipe specimens. The program resulted in a number of recommendations as to changes needed in the ASME Code fatigue analysis procedure and a K_e environmental correction factor. The results from the butt-welded pipe specimen tests from this program will be discussed in more detail in Section 9 of this report.

In 1991 Higuchi and Iida [3-3] proposed a fatigue life correction factor, F_{en}, for correcting the low cycle fatigue properties of carbon and low alloy steels for the effect of the LWR coolant environment. These results stimulated the current concern for the effect of the environment on the low cycle fatigue properties of the pressure boundary materials. A number of versions of the correction factor has evolved since this original proposal but the basic concept has not changed. This concept is that the effect of the environment on the low cycle fatigue properties of carbon and low alloy steel can be corrected for the effect of the environment by applying a correction to the fatigue life as determined from the ASME design curve. A correction is not needed on the strain amplitude.