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TECHNICAL INFORMATION FROM WORKSHOP ON CYCLIC LIFE AND ENVIRONMENTAL EFFECTS IN NUCLEAR APPLICATIONS

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CLEARWATER BEACH, FL
January 20-21, 1992

PVRC

Workshop on Cyclic Life and Environmental Effects in Nuclear Applications

Part I - Basis, Status, and Issues
Monday, Jan. 20, 1992

Presentation	Topic	Speaker
1	Basis and Intent of Section III Fatigue Design Curves	W. E. Cooper Teledyne
2	Development of Section XI Fatigue Crack Growth Curves and Their Relation to Crack Initiation	W. H. Bamford Westinghouse
3	Design Application of Section III Fatigue Analysis	W. J. O'Donnell AEA O'Donnell
4	Discussion of Margins in Sect. III and XI Curves and Implications for Flaw Evaluation, Life Extension, and Usage Factor Calculations	S, Yukawa
5	Service Experience for Fatigue Problems	S. H. Bush Review & Synthesis
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THE INITIAL SCOPE AND INTENT OF THE SECTION III FATIGUE DESIGN PROCEDURES

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INTRODUCTION

PVRC, at the request of the ASME Board on Nuclear Codes and Standards, is reexamining the fatigue curves of Sections III and XI with particular interest in environmental effects. The purpose of my presentation is to provide the background of the present Section III rules. Subsequent presentations, by others, provide similar presentations with respect to the present Section XI rules and experiences with the application of both Sections. This paper includes some of my thoughts relative to later topics in order to place them in context.

The viewpoint of each of the participants obviously biases their presentations. The viewpoint I have taken is that of one engineer who was involved in the original development of the rules, primarily in the period 1954-1963, as well as one who has been involved in the subsequent applications and in the review of some of the proposals for change. The developmental dates of these procedures obviously indicate the need for reexamination of our state of knowledge. However, I will caution against expanding the intent of the Section III procedures, which are for design, to the evaluation of operation.

HISTORICAL BACKGROUND

Prior to World War 2 the design of pressure vessels, and similar pressure-retaining components was primarily based on selecting the thickness such that the maximum design pressure-induced stress in simple geometries was less than one-fifth of the ultimate tensile strength, with simple rules guiding the design of more complicated regions. As a war emergency measure this nominal factor of safety of five was reduced to four, and based on the apparent success of this step the Codes were revised to adopt this lower nominal factor of safety and questions arose as to the practicality of further reductions in this factor. However ,as design technology including material behavior advanced, concerns were expressed as to the need to include consideration of additional failure modes in the design of some vessels.

Prepared for the Pressure Vessel Reearch Council (PVRC) Workshop on Environmental Effects on Fatigue Performance, Clearwater Beach, FL January 20, 1992.

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These two aspects resulted in the creation in 1955 of the Special Committee to Review Code Stress Basis (SCRCSB) which developed Section III, published in 1963, and Division 2 of Section VIII, published in 1968. The assignment of this group was to determine what was required to reduce the nominal factor of safety from four to three while recognizing that service and safety considerations vary.

Although the rules for all aspects of construction were tightened by the recommendations of the SCRCSB, the major conceptual change was in design, a change so significant that it was termed "Design by Analysis" to distinguish the approach from that previously followed, which was then identified as "Design by Rule."

The Design by Analysis approach had been initiated by a Naval Reactor reactor vessel program started in 1954, a program which also initiated the modification of the steel now used in reactor vessels and the application of brittle fracture prevention rules. The state of the Navy program was presented in Reference 1, a document which was used to supplement the Code for many commercial reactor vessels constructed prior to issuance of Section III. This was a joint effort of Code 551 of the U. S. Navy Bureau of Ships (J. L. Mershon), Bettis Atomic Power Laboratory (B. F. Langer), and the Knolls Atomic Power Laboratory (W. E. Cooper) reporting to Code 1500 of BuShips (P. R. Clark). Those developing and applying these procedures to naval and commercial vessels played a major role in the SCRCSB and in contemporary PVRC activities.

The basic intent of the Code was not to be changed by the actions of the SCRCSB, it was to continue to address the requirements for new construction while providing reasonable assurance of reliable operation. Therefore, the requirements were addressed primarily to the Manufacturer, although an important role was assigned to the Owner/User with respect to defining the operational conditions to be considered by the Manufacturer for purposes of construction (where "construction" is defined as encompassing materials, design, fabrication, examination, testing, inspection, and certification).

The means by which the Owner/User fulfilled the assigned responsibilities, and transmitted the required information to the Manufacturer, was by the preparation of a Design Specification. This concept was new, at least with respect to the detail which needed to be provided, and many of the Code participants were concerned as to whether or not the responsibilities would be fully recognized by the Owner/User, for Section III the organization holding the Construction Permit. Having moved to the USAEC, Mr. Mershon was particularly concerned about this aspect and arranged for the publication of Reference 2. Since it is my opinion that preparation of proper Design Specifications has been the weak-link in the application of Section III for almost three decades, this document certainly was not effective, but is referenced here because it discusses several aspects of the initial intent.

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TECHNICAL BACKGROUND

The Design by Analysis procedure includes a number of related considerations, and only those applicable to fatigue design are intended to be discussed here in any detail. However, it is important to recognize several of the ground rules which were imposed in the interests of obtaining a practical approach, because of precedents in what the Code did or did not address, or the limits of the then-existing technology.

The most significant of these was the need to permit the application of elastic stress analysis techniques, even though practically all of the criteria were developed based on consideration of elastic-plastic failure modes because material selection requirements were intended to assure ductile behavior. Of course it was intended that the gross behavior of the vessel remain elastic, but it was necessary to recognize, as had the Design by Rule procedures, that localized plastic deformation was not necessarily harmful. Therefore, the concept of the "hopper diagram," see Figure 1, was developed to provide an orderly method for progressing through the design procedure in a manner which would assure the reasonable validity of the next step in the procedure. For example, it was necessary to assure that shakedown occurred if an elastic stress analysis was to provide a stress amplitude which properly represented the plastic strain amplitude of interest in many fatigue evaluations. Alternative provisions permitted the use of elastic-plastic analyses with respect to most of the criteria, but these have received much less use than I would expect considering the subsequent development of elastic-plastic analysis capabilities. The presentation which follows will concentrate on the provisions applicable to elastic analysis.

The most significant of these limitations with respect to the present workshop was the fact that the Code was intended only to cover new construction. Consequently rules addressing environmental effects on material properties were prohibited, although as will be seen later the Owner/User was expected to address these effects. There were several reasons for this prohibition, the most important of which is that control of the environment is beyond the control of the Manufacturer. Other reasons included the inability of the user of process vessels to predict the service to which the vessel might eventually be used, or a reluctance to do so in order to protect proprietary processes.

FATIGUE DESIGN RULE DEVELOPMENT

Reference 3, or an earlier version published prior to issuance of Division 2, is the basic document defining the Design by Analysis concepts. With respect to fatigue design, the major advance of the 1950s was recognition of low-cycle fatigue as a strain-controlled phenomena and the development of test techniques defining the required properties. Figure 2 indicates the difference between stress- and strain-controlled tests, and particularly the effect of stress concentrations.

The fatigue data available at the time the rules were developed are summarized by Figures 9-10 of Reference 3, and the specific curve for reactor vessel materials is reproduced here as Figure 3. As is shown by the Coffin-Manson relationship, the curve may be closely defined by the equation:

$$S = \frac{E}{4(N)^{0.5}} \ln \frac{100}{100 - A} + B$$

where

S = strain amplitude times elastic modulus
E = elastic modulus
N = number of cycles to failure
A = percentage reduction of area in the tensile test
B = endurance limit,

As is shown by Figure 3, at the higher numbers of cycles there is another curve labeled "adjusted for mean stress." As explained in Reference 3, the SCRCSB was concerned as to the effects of mean stress on fatigue resistance and realized that there was no way that the correct mean stress, resulting from fabrication or from prior operation, could be computed. Therefore, the Langer interpretation of the Modified Goodman Diagram was used to include the worst possible effects of such mean stress on the fatigue resistance. This procedure lowers the fatigue curve at alternating stresses lower than the yield strength and is known to be conservative. As noted by Reference 3, a different procedure using the Peterson cubic relationship was used to account for this effect in higher strength bolting.

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 3 states that the "design stress values were obtained from the best-fit curves by applying a factor of two on stress or 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 3, "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 1 states "The factor of 20 on life is the product of the following sub-factors:

Scatter of data (minimum to mean)	2.0
Size effect	2.5
Surface finish, atmosphere, etc.	4.0"

Two terms in the last line require definition. "Atmosphere" was intended to reflect the effects of an 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 high numbers of cycles, so a factor on stress was required at the higher number of cycles. It was found that at about 10,000 cycles, an approximate 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. In the early years a single smooth design fatigue curve was drawn, enveloping the curves so obtained above and below the point where the mean stress became effective or where the two factors were applied. In later years our computer-minded associates did not use a smooth curve, but retained the break(s) in the design curve. Without any additional data or thinking, engineering has become a science. Ain't progress wonderful?

Reference 3 also includes the PVRC work used to confirm the fatigue design approach, summarized in Figure 4. The 36 inch diameter vessels tested by SwRI are of most significance, if the T-1 vessel which experienced a brittle fracture is excluded. The beginning of a horizontal arrow indicates the presence of a visible crack (about 3/16" long). At least one of these points lies just above the design curve, others lie a factor of about five above the design curve. A factor of three is a reasonable average, unless you believe in more than one significant figure. The minimum factor on the curve leading to a through-crack was also about three.

With respect to the effects of corrosion on fatigue resistance, the only possibly pertinent data when the curves were developed indicated the possibility of a significant decrease in fatigue resistance on the secondary side of fire-tube boilers. The original design fatigue curves contained a note that the fatigue curves do not consider the deleterious effect of unusually corrosive environments. The words "unusually corrosive" were probably a poor choice. The intent was to distinguish this from the normally expected corrosion effects in vessels which is accommodated by increasing the thickness by providing a corrosion allowance. That technique does not ameliorate corrosion fatigue. Instead, the intent was that this was an effect to be explicitly considered by the Design Specification as one of the items identified in a previous paragraph. This is one of the guidelines spelled out in Reference 2.

Finally, the fatigue design curves terminated at one million cycles. Continuation of the fatigue design curves to higher cycles with the correction for the worst possible effects of mean stress included could have been overly conservative. Because of that conservatism, the conservative values utilized in developing the best fit curves at high numbers of cycles, and the factor of two on stress, it was felt that use of the upper end value present on the curves was sufficient for conditions which could exist for a few million cycles. However, it was recognized that no rules were presented for very high numbers of cycles, and the original paragraph N-110 required that such conditions required separate consideration. As explained in Reference 2, this, along with corrosion and radiation effects, was one of the aspects to be addressed in the Design Specification.

INTENDED USAGE

The purpose of adding fatigue as one of the failure modes for which explicit design criteria were provided was to assure that the reduction of the nominal factor of safety from four to three did not result in a decrease in reliability if the vessel was expected to be subjected to cyclic operating conditions. It was intended to be a design consideration, not a necessarily valid measure of the eventual operational fatigue life of the vessel. The Manufacturer has no control over the way in which the vessel is operated.

The cyclic loading conditions in the Owner's Design Specification were intended to define the vessel which the Owner wished to purchase, and were not intended to represent a commitment on how the vessel was to be operated. Given those conditions, the Manufacturer would first apply the Code procedures to determine whether or not the vessel was exempted from the fatigue evaluation requirements. If not exempted, the only obligation of the Manufacturer was to show that the fatigue usage factor was less than unity - the Manufacturer had no obligation to establish the "exact" fatigue usage factor! In most cases, this evaluation was made by combining less severe cycles with more severe cycles, assuming step changes in temperature rather than ramp changes, and using conservative fatigue stress concentration factors. All of this was possible because the cyclic conditions defined for the vessels were seldom significant.

The intent with respect to the manner in which the cyclic operating conditions were to be defined was consistent with the process just described, as described in Reference 2. Simple groups of operating conditions were to be defined with, usually, simple ramp changes in temperature and pressure and defined steady-state conditions before and after the transient. Also, the definitions were to be presented in a manner which could be interpreted as full operating cycles.

This does not mean that the Owner was intended to be completely oblivious to the manner in which the vessel was really expected to be operated, only that the definitions should provide him useful information. For example, one would hope that if a particular transient occurred in operation the Owner would be able to show that the Design Specification included a cyclic event which was more severe than that actually experienced and that the Design (previously, Stress) Report verified that the vessel was not subjected to an unevaluated condition.

There are several reasons why the intent as described here was all that could be reasonably expected. The most important of these is that the entire Section III procedure is related to crack initiation and significant fatigue conditions in operation must consider both fatigue initiation and propagation and the subsequent failure mode which results from the presence of the crack. The additional factors which are important include the situations which the Code rules were not intended to address (corrosion and high-cycle vibratory loadings which were the assigned responsibility of the Owners) and operational conditions not anticipated by the Owner when the Design Specification was prepared (particularly thermal mixing types of problems).

ACTUAL USAGE

The actual usage of the Section III fatigue design procedures has seldom been consistent with the intent just stated. As stated earlier, the Design Specification has been the weak link in the system.

Some of the early vessel Design Specifications provided reasonably simple transients for evaluation, consistent with the intent, but even these seldom contained definitions which were logically interpretable as full cycles. For example, it was not uncommon to find many more cooldown to cold conditions defined than there were heatups from the cold condition. Such an error is not "fatal" but usually simply lead to the Manufacturer assuming the necessary additional number of half cycles required to balance the total, a conservative approach.

In more recent years we have experienced the age of the computer output plot. The system analyst provides a very detailed temperature transients, with lots of fancy variations in rate and ups and downs, almost anything but loop-the-loops. The engineer (lower case) preparing the design specification then includes this fancy curve as the transient to be analyzed and the Manufacturer applies relatively complex and overly expensive analysis techniques for evaluation. This is in large part another indication of the negative impact of our present so-called "Quality Assurance" procedures. Any "good" QA person can tell whether or not a fancy curve matches another, but practically none are capable of determining whether any deviation is meaningful. On the other hand, many computer-oriented engineers can't do the latter either.

Finally, we have the cycle counter, the individual who believes that a plant should be shut down when the number of cycles of a given transient equals the number of cycles defined for that transient in the Design Specification. It matters not that there was never any requirement that even the effects of the defined transients be accurately evaluated, only conservatively evaluated.

RECOMMENDATIONS

I strongly recommend that the initial intent of the design fatigue procedures of Section III be retained, or perhaps I should say be restored. The appropriate place for fatigue life evaluation is in Section XI, where cracks are identified whether or not they initiate from conditions defined in the Design Specification, the propagation of the crack is evaluated using fracture mechanics techniques, and the consequences of the crack to <u>future</u> operation is similarly evaluated. I am unaware of any fatigue crack occurring as the result of a condition defined in the Design Specification and found acceptable by the Manufacturer applying the Section III procedures when those procedures are applicable (no significant corrosion or high-cycle vibration).

I have previously discussed this issue in References 4 and 5 and can not do this justice at this time. I acknowledge that my present position is contrary to one expressed on page 66 of Reference 4, where I advocated doing more detailed analyses as part of initial construction, but attribute the change in position as getting smarter in the last 16 years, and also to seeing what the computer engineer and QA have done to the process.

This is not to say that I am resistant to change in the existing rules. Both References 4 and 5 identify the need to include LWR coolant corrosion effects, both stress corrosion and corrosion fatigue, in the design process. My present position on related matters is essentially that stated in Reference 5:

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The present design rules for pressure retaining equipment contain more comprehensive structural acceptance criteria than do the rules applicable to non-nuclear vessels and piping. Many of these additional acceptance criteria and the material properties used with these criteria are two [now, over three] decades old. Although some improvements based upon newer technology may be desirable, operating experience indicates that the safety and reliability concerns are the result of conditions not anticipated at the design stage and do not indicate basic faults in the criteria. Therefore, major efforts in the design area should be directed towards a more accurate representation of service experience in the preparation of Design Specifications, with lesser efforts on improvement in the criteria.

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