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Parametric Calculations of Fatigue Crack Growth in Piping

Prepared by F. A. Simonen, C. W. Goodrich

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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Parametric Calculations of Fatigue Crack Growth in Piping

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ABSTRACT

This report describes work performed at the Pacific Northwest Laboratory (PNL) for the U.S. Nuclear Regulatory Commission (NRC) as part of a research program titled "Integration of NDE Reliability and Fracture Mechanics." A major objective of this program is to provide data that can be used to formulate recommended revisions to ASME Section XI and regulatory requirements for inservice inspection of piping and pressure vessels.

This study presents calculations of the growth of piping flaws produced by fatigue. Flaw growth was predicted as a function of the initial flaw size, the level and number of stress cycles, the piping material, and environmental factors. The results indicate that the present flaw acceptance standards of ASME Section XI provide a relatively consistent set of allowable flaw sizes because the predicted life of flawed piping is relatively insensitive to pipe wall thickness, flaw aspect ratio, and piping material (ferritic versus austenitic). On the other hand, the results show that flaws that are acceptable under ASME Section XI can grow at unacceptable rates if the cyclic stresses are at the maximum level permitted by the design rules of ASME Section III. However, a review of the conservatisms inherent to the ASME code rules is presented to explain the low occurrence of piping fatigue failures in service. It is concluded that decreases in the allowable flaw sizes are not justified.

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This report describes work performed at the Pacific Northwest Laboratory (PNL) for the U.S. Nuclear Regulatory Commission (NRC) as part of a research program titled "Integration of NDE Reliability and Fracture Mechanics." A major objective of this program is to provide data that can be used to formulate recommended revisions to ASME Section XI and regulatory requirements for in-service inspection of piping and pressure vessels.

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EXECUTIVE SUMMARY

This report describes work performed at the Pacific Northwest Laboratory (PNL) for the U.S. Nuclear Regulatory Commission (NRC) as part of a research program, "Integration of NDE Reliability and Fracture Mechanics." A major objective of this program is to provide data that can be used to formulate recommended revisions to ASME Section XI and regulatory requirements for inservice inspection of piping and pressure vessels.

This study presents calculations of the growth of piping flaws produced by fatigue. Flaw growth was predicted as a function of the initial flaw size, the level and number of stress cycles, the piping material, and environmental factors. The results indicate that the present flaw acceptance standards of ASME Section XI provide a relatively consistent set of allowable flaw sizes because the predicted life of flawed piping is relatively insensitive to pipe wall thickness, flaw aspect ratio, and piping material (ferritic versus austenitic). On the other hand, the results show that flaws that are acceptable under ASME Section XI can grow at unacceptable rates if the cyclic stresses are at the maximum level permitted by the design rules of ASME Section III.

The flaw sizes of the ASME Section XI acceptance standards are based on fracture mechanics and toughness considerations. The standards take into account flaw detectability and concerns for consistency with other provisions of the ASME Code, but they do not explicitly consider service-induced flaw growth by fatigue or other growth mechanisms. The study presented here evaluates flaw growth in piping, taking into consideration the cyclic stresses permitted by the design rules of ASME Section III.

In the crack growth predictions of this report, the piping is first assumed to have circumferential flaws corresponding to ASME preservice inspection standards. Later calculations indicate the expected increase in piping life attainable by decreasing the initial flaw sizes below the acceptance standards. Calculations are also performed to study the sensitivity of predicted piping life to piping material, environment, mean stress or R ratio, end-of-life flaw size, flaw aspect ratio, and through-wall stress distributions ranging from uniform tension to pure bending.

Calculations indicate that the present ASME Section III rules and fatigue curves could allow piping designs that would not tolerate even very small flaws if the piping were subject to severe cyclic stress. The present fatigue curves in the code can be unconservative for piping with code-acceptable flaws. The worst case of unconservatism can be about a factor of 4 based on stress and about 40 based on life. The estimated degree of potential unconservatism is similar for piping of ferritic and austenitic steels. Initial flaw sizes must be less than about 0.010 inch to guarantee that the fatigue life implied by the Section III rules can be achieved.

The results of the crack growth predictions are examined in relation to the successful service experience with reactor piping, which contrasts with the pessimistic implications of the present crack growth predictions. Conservative assumptions in the calculations are identified regarding cyclic stresses, fatigue crack growth rate data, and initial flaw depths. Example calculations for PWR primary coolant piping are presented. These indicated that actual cyclic stresses for design transients are well below code allowable levels. The calculations also indicated that standards for flaw acceptance are conservative enough to avoid excessive, fatigue-caused growth of cracks in many specific piping systems.

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PARAMETRIC CALCULATIONS OF FATIGUE CRACK GROWTH IN PIPING

INTRODUCTION

This report describes calculations of fatigue crack growth in piping as part of a program, "Integration of NDE Reliability and Fracture Mechanics," sponsored by the U.S. Nuclear Regulatory Commission. This work was performed at the Pacific Northwest Laboratory, which is operated by Battelle Memorial Institute for the U.S. Department of Energy. Data generated in the program are intended to provide a basis to formulate revisions to ASME Section XI Boiler and Pressure Vessel Code and regulatory requirements needed to assure low failure probabilities. The primary objective has been to determine the reliability of ultrasonic in-service inspection (ISI) as performed on commercial, light water reactor primary systems. This report concerns a second objective, which is to determine the impact of NDE (nondestructive evaluation) unreliability on system safety and to determine the level of inspection reliability required to assure a suitably low failure probability.

A key factor in establishing requirements for inspection reliability is the size of the smallest flaw that must be detected. This size must be sufficiently small to ensure that subsequent growth in service does not result in a flaw that can compromise the integrity of the piping system. This report describes predictions of fatigue crack growth of flaws in piping as a function of initial flaw size, the level and number of cyclic stresses, and the material and environmental factors that govern flaw growth.

The results presented in this report are closely related to a recent NRC study (Ref. 1) that postulated flaws that were acceptable by Section XI of the ASME Code, and then estimated the flaw growth that could occur with the maximum level of cyclic stress permitted by Section III design rules (usage factor of 1.0). These results indicated that very small cracks can propagate to sizes that exceed code-specified limits. The results presented here serve to expand the scope of the calculations of Reference 1, and point out the implications of the results relative to NDE requirements.

Section XI of the ASME Code provides acceptance standards for flaws detected during the preservice and in-service examinations required by the code. Maccary documents the rationale and technical basis for these standards (Ref. 2), which specify the sizes of flaws that need not be repaired. One objective of the Section XI inspections is to assure that fabrication flaws are not growing in service. A second objective is to identify generic defects that may initiate in service so that augmented inspection and corrective measures can be applied to the remainder of the

system or to similar plants and systems. In general, the Section XI acceptance standards are consistent with the standards of Section III for fabrication flaws. As such, Section XI standards were developed in large measure to provide a basis to accept or reject fabrication flaws that are detected during preservice and inservice inspection.

As outlined in Reference 2, the flaw sizes of the Section XI standards are based on fracture mechanics and toughness considerations, taking into account flaw detectability and consistency with other provisions of the ASME Code. Acceptable flaw sizes are set to provide a factor of 3.0 against failure pressure based on critical flaw size and fracture toughness considerations. This factor corresponds to the traditional design safety factor of the code. The margin between the acceptance standards and critical flaw sizes does not, however, specifically provide a provision for service-induced flaw growth by fatigue or other growth mechanisms. As such, the technical basis for the acceptance standards does not explicitly address fatigue crack growth as is required, for example, by the Section XI Appendix A procedure for evaluation of flaws in vessels. Therefore, the possibility exists that a flaw meeting Section XI acceptance standards would be unacceptable if evaluated in detail by Appendix A procedures.

The calculations in this report evaluate flaw growth in piping in the context of the cyclic stresses permitted by ASME Section III design rules. The objective is to evaluate the consistency and level of conservatism of the present Section XI flaw acceptance standards and specified inspection intervals. The code rules will be evaluated in both an absolute sense (i.e., flaws do not grow to an unacceptable size) and in a relative sense (i.e., piping of various sizes, materials, and with code-acceptable flaws of various shapes have similar safety margins if subject to the same levels of cyclic stress).

In the base line fatigue life predictions, the piping is first assumed to have circumferential flaws corresponding to ASME preservice inspection standards. Later calculations show the expected increase in fatigue life attainable by decreasing the initial flaw sizes below the acceptance standards. Calculations are also performed to study the sensitivity of predicted piping life to piping material, environment, mean stress or R ratio, end-of-life flaw size, flaw aspect ratio, and through-wall stress distributions ranging from uniform tension to pure bending.

In a final and key section of this report, the results are reviewed in relation to successful service experience with reactor piping, which contrasts with the pessimistic implications of the present crack growth predictions. Conservative assumptions in the calculations are identified regarding cyclic stresses, fatigue crack growth rate data, and initial flaw depths. Example calculations for PWR primary coolant piping are presented. These show that actual cyclic stresses for design transients are well below code allowable levels, and that present flaw acceptance standards are conservative enough to avoid excessive crack growth caused by fatigue.

FRACTURE MECHANICS MODEL

This section of the report outlines the methods and assumptions used in the fatigue crack growth calculations.

CYCLIC STRESSES

All calculations were performed for a specific level of cyclic stress with this level being varied in a parametric fashion. No attempt was made in these parametric calculations to approximate "typical" spectra of cyclic stresses experienced by reactor piping. Such spectra would need to be considered on a case-by-case basis, as has been done on other, more detailed piping systems studies (Refs. 3, 4). The results from these studies have been reviewed. The predicted crack growth rates were found, in general, to be dominated by a single type of stress cycle from the spectrum. In particular, the cyclic stress excursion corresponding to heat-up/cool-down and pressurization/depressurization of the piping system was the major contributor to crack growth. For this situation, use of a single cyclic stress level is a good approximation.

THROUGH-WALL STRESS DISTRIBUTION

Essentially all of the calculations in this report assumed a uniform stress distribution through the pipe wall. This simplifying assumption is a reasonable approximation for piping. The axial stresses on piping girth welds are due primarily to internal pressure and bending moments from thermal expansion. For these loadings the stress gradients through the pipe wall are relatively small. Radial thermal gradients will give substantial through-wall stress gradients. However, results of sensitivity calculations reported below show that assuming a uniform stress equal to the peak surface stress value gives crack growth rates that are conservative but not excessively conservative. Furthermore, the results of the Lawrence Livermore Laboratory Load Combination Program (Ref. 5) indicate that radial thermal gradient stresses are not a major cause of crack growth in PWR primary coolant pipes.

POSTULATED FLAWS

All flaws were assumed to be circumferential surface cracks. Such flaws in circumferential welds are the primary focus of inservice inspection.

Most calculations were for a 360-degree circumferential flaw (aspect ratio $a/2b = 0.0$) with limited calculations for half-penny flaws (aspect ratio $a/2b = 0.5$) as a basis for comparison where a and $2b$ are the flaw depth and length, respectively. The 360-degree flaw gave the more conservative results since longer flaws have a greater crack-tip stress intensity factor for a given flaw depth. The 360-degree flaw was also convenient

because stress intensity factor solutions published by Buchalet and Bamford (Ref. 6) were available for both deep flaws and nonuniform through-wall stress distributions.

In calculations related to the Section XI acceptance standards, the predicted life of flawed piping was found to be insensitive to the factor of flaw aspect ratio. In the development of the acceptance standards as described by Maccary (Ref. 2), flaw depths were selected to systematically offset the effect of aspect ratio on crack tip stress intensity factor.

FLAW GROWTH MODEL

In all calculations cracks were assumed to grow in a self-similar manner, that is, with no change in aspect ratio. Crack growth was taken to be governed by linear elastic fracture mechanics using the following growth law:

$$\begin{aligned} da/dN &= f(\Delta K), \quad \Delta K \geq K_{th} \\ &= 0, \quad \Delta K < K_{th} \end{aligned} \quad (1)$$

a = flaw depth

N = number of stress cycles

$$\Delta K = K_{max} - K_{min}$$

K_{max} , K_{min} = maximum and minimum values of stress intensity factor in stress cycle

ΔK_{th} = threshold ΔK

The function f can be viewed as providing a generalization of the Paris-type fatigue crack growth law. In the calculations for ferritic steel this function was defined by the Section XI crack growth rate curve.

For austenitic steels, the present code does not specify a crack growth curve. Calculations were based on a fit of data compiled by the BCL Cold Leg Integrity Evaluation (Ref. 3). The curve fitting procedure was intended to be consistent with that used to derive the present code curve for ferritic steels.

The effect of R-ratio ($R = K_{min}/K_{max}$) is not directly addressed in the above crack growth law. However, sensitivity calculations as reported below were performed for both high and low values of R . It was recognized that the value of R is governed largely by the levels of residual and assembly stresses at the location of concern. In this study it was conservatively assumed that tensile residual and assembly stresses gave rise to high R-ratios.

The integration of the equation $da/dN = f(\Delta K)$ was performed numerically with the aid of a special Fortran computer program written for this purpose. For a simple power law crack growth equation (i.e., $da/dN = C \Delta K^n$) the integration can be performed in closed form as was done in NUREG-0726 (Ref. 1). For more complex crack growth curves as used in this study, the numerical integration proved to be convenient.

The simplest of integration schemes was used. Starting with the assumed initial flaw depth, the depth was advanced in a sequence of steps by about two percent in each step. The crack tip stress intensity factor and corresponding growth rate (in./cycle) were calculated for the flaw depth at the beginning of the step. The number of cycles to grow the crack and the small increment in depth were then calculated. The corresponding fatigue usage factor was also computed for this number of cycles at the assumed cyclic stress level. The process of incrementing the flaw depth continued until the specified end-of-life flaw depth was attained.

FIGURE 1. Rate Curves for Ferritic Steel (Revised ASME Section XI Fatigue Crack Growth)

FATIGUE CRACK GROWTH RATE DATA

This section describes the fatigue growth rates (da/dN versus ΔK) used in the crack growth predictions. The intent was to apply curves specified in ASME Section XI where possible. However, Section XI did not specify the threshold values of ΔK or the growth rates for austenitic steels which were required for the present calculations. To fill these gaps, results of recent NRC-sponsored research were used.

FERRITIC STEELS

The recent modification of the ASME Section XI fatigue crack growth curves as developed by Bamford (Ref. 7) was applied in the calculations for ferritic steel piping. These curves are shown in Figure 1. The curves describe crack growth rates in water environments (PWR reactor conditions) as well as air environments (for subsurface flaws). The effects of high mean stress ($R = K_{min}/K_{max} \geq 0.65$) are also indicated by Figure 1.

FIGURE 1. Revised ASME Section XI Fatigue Crack Growth Rate Curve for Ferritic Steel

Both environment and mean stress are significant factors that can produce differences of an order of magnitude in fatigue crack growth rates. The curve for a water environment with high mean stress was used for the base line calculations, and the lower growth rate curves were used later for sensitivity type calculations.

The threshold value of $2.6 \text{ ksi } \sqrt{\text{in.}}$ for ΔK was adopted for use with the ferritic steel water environment curve for $K_{\min}/K_{\max} \geq 0.65$. This was the value estimated in the Battelle-Columbus Cold Leg Integrity Evaluation (Ref. 3) on the basis of available crack growth data.

Threshold ΔK 's for the other crack growth rate curves of Figure 1 were estimated. The shift in ΔK_{th} was taken to be proportional to the shift in the particular crack growth rate curve relative to the reference (water environment, high mean stress) curve. The resulting estimated values were:

$$\Delta K_{th} = 3.9 \text{ ksi } \sqrt{\text{in.}}, \text{ water environment, } R \leq 0.25,$$

$$\Delta K_{th} = 5.3 \text{ ksi } \sqrt{\text{in.}}, \text{ air environment.}$$

AUSTENITIC STEELS

Since there are no fatigue crack growth curves in ASME Section XI for austenitic stainless steels, it was necessary to adopt a curve that was analogous to the Section XI ferritic steel curves. The present calculations used the fatigue crack growth rate data compiled by Battelle-Columbus in their Cold Leg Integrity Evaluation (Ref. 3). In recent work, Battelle-Columbus has revised their curve fit of the test data given in Reference 3 to arrive at the multilinear fit shown in Figure 2. This curve was intended to be an upper bound on the available test data and to be applicable to conditions of high mean stress (i.e., high R-ratio).

Following the BCL Cold Leg study, the threshold ΔK value of $2.4 \text{ ksi } \sqrt{\text{in.}}$ for stainless steel was used in the present calculations. This value is applicable to conditions of water environment and high R-ratio.

FIGURE 2. Fatigue Crack Growth Rate Curve and Data for Stainless Steels

RESULTS OF CALCULATIONS

This section describes the numerical results of the fatigue crack growth calculations.

FERRITIC PIPING WITH SECTION XI FLAWS

In all calculations it was assumed that a circumferential ID surface flaw was present at the beginning of life and that the flaw depth was defined by the preservice flaw acceptance standards of ASME Section XI. Two flaw shapes were considered, namely a full 360-degree circumferential flaw and a half-penny surface flaw.

The objective of the fatigue life calculations was to predict the number of cycles of a given stress that would grow the flaw to an unacceptable depth. The unacceptable flaw was taken here to be a one-fourth-wall ($t/4$) flaw. Calculations reported below for deeper end-of-life flaws show that the predicted fatigue life is relatively insensitive to the somewhat arbitrary $t/4$ end-of-life flaw depth. This insensitivity occurs because the component life is dominated by the slow crack growth rates that prevail when the flaw is at or near its small initial size.

In these initial calculations the most conservative crack growth rate curve (da/dN versus ΔK) of Figure 1 was used to reflect worst-case effects of high mean stress and water environment. It was also assumed that the state of stress was uniform through the pipe wall. Thus, the calculations were conservative since they did not consider any decrease in stress from maximum levels at the ID surface because of through-wall stress gradients.

Figures 3 and 4 show the predicted fatigue life of the flawed ferritic piping. The format of the presentation is that used for the ASME Section III fatigue design curves, and the dashed curve shows for reference the Section III ferritic steel design curve. (Note that $\Delta\sigma = 2 S_a$.) The Section III curve is based on smooth bar fatigue tests and hence reflects the number of stress cycles to both initiate a fatigue crack and grow the crack through the specimen cross section. As expected, this life is substantially greater than that predicted by fracture mechanics for the initially flawed piping.

In Figures 3 and 4 three pipe wall thicknesses ranging from 0.5 to 3.0 inch were considered. The initial flaw depths (a_i) are also indicated, and these depths were taken from the tables of acceptable preservice surface flaws for ferritic piping of ASME Section XI. For each level of cyclic stress (S_a) the fracture mechanics equations described above were integrated numerically to calculate the number of cycles to grow the flaw from the depth a_i to the assumed end-of-life flaw depth of $a_f = t/4$. A computer program was written to generate the tables of values which enabled the curves of Figures 3 and 4 to be plotted.

FIGURE 3. Predicted Life for Defected Ferritic Piping

FIGURE 4. Predicted Life for Section XI Half-Penny Surface Flaws

A number of trends are apparent from the predicted life curves. Clearly, even relatively small flaws considered acceptable by ASME Section XI substantially reduce the expected fatigue life from the life predicted by the Section III fatigue design curve. This indicates that situations may exist where flaws can grow at unacceptable rates if the Section III fatigue usage factor is high. The potential unconservatism suggested by Figures 3 and 4 is equivalent to as much as a factor of 4.0 on stress and a factor of 40 on life. In a concluding section to this report, a number of reasons are cited to explain why this potential unconservatism has not led to the occurrence of rapidly growing fatigue cracks in service.

The predicted life of the flawed pipe is somewhat dependent on wall thickness. At the lower levels of cyclic stress the thicker wall piping can sustain fewer fatigue cycles. However, the trend is reversed for higher cyclic stresses (S_a greater than about 10 ksi).

There is little difference between the trends for the long 360-degree ID surface circumferential flaws and the very short half-penny ID surface flaws. The Section XI acceptance standards are slightly more conservative for the half-penny flaws, with the predicted life being somewhat greater for the short half-penny flaws compared to the long 360-degree flaw.

EXAMPLE CALCULATION FOR PWR PRIMARY PIPING

The results shown in Figures 3 and 4 indicate that code-acceptable flaws can grow by fatigue at unacceptable rates in reactor piping. An example calculation is presented here to show that this potential problem does not in general apply to reactor piping. The calculations consider representative stresses in a particular PWR primary coolant loop for design transients, and the results show very low crack growth rates.

Table 1 lists a typical set of design transients and cyclic stresses used in Reference 3 to predict fatigue crack growth. The data are for a typical joint (165B/170TR) in the St. Lucie plant, and the crack growth predictions are for a long circumferential flaw in a weld.

Table 1 compares the number of design transients (n) with the number of cycles (N) required to grow an acceptable preservice flaw to a depth of $t/4$. The number of cycles (N) was read directly from Figure 3 using the curve for a piping with 3.0-inch wall thickness. The number of design transients (n) is in each case far less than the required number (N) to grow the flaw to the end-of-life flaw depth. Of the operating transients, the threshold for crack growth is exceeded only for the start-up/shut-down cycle. The worst abnormal transient is the operating basis earthquake (OBE), for which the number of cycles is about 10 percent of the number required to grow the flaw to the end-of-life depth. In this regard, the

TABLE 1. Example Crack Growth Calculation for PWR Primary Piping

	Transient	$\Delta\sigma_{axial}$ ksi	S_a ksi	n = Number of Transients	N = Allowable Cycles	n/N = Fraction of Life	
Operation Transients ↓	(a,b) Start-Up/Shut-Down	9.00	4.50	500	65,000	0.0077	
	(c,d) Plant Loading/Plant Unloading	1.83	0.91	15,000	∞	0.0	
	(e,f) Step Increase/Step Decrease	3.10	1.55	2,000	∞	0.0	
	(g) Reactor Trip & Recover at Start-Up	2.82	1.41	480	∞	0.0	$\sum n/N = 0.0077$ (Operation Transients)
Abnormal Transients ↓	(l) Loss of Flow and Abnormal Loss of Load	5.50	2.75	40	950,000	0.0000	
	(m) Loss of Secondary Pressure	20.38	10.19	5	4,200	0.0012	
	(h) Hydrotest to 3,125 psig 400°F	34.58	17.29	10	1,450	0.0069	
	(OBE) Earthquake (OBE)	30.60	15.3	200	1,900	0.1052	
	(SSE) Earthquake (SSE)	58.42	29.21	1	520	0.0019	
	(Vibration) Vibration	1.00	0.50	2.1×10^{10}	∞	0.0	$\sum n/N = 0.1152$ (Abnormal Transients)

NOTES:

1. St. Lucie cold leg stresses at Joint 165B/170TR with OD = 35.0 inch and 2.50 inch wall from reference 3.
2. Allowable cycles (N) is the number of cycles to grow a 360 degree circumferential flaw with depth equal to ASME preservice acceptance standard to a depth of $t/4$.
3. Crack growth rates for ferritic steel in PWR water environment with $R \geq 0.65$.

cyclic stress of $S_a = 15.3$ ksi appears to be unusually high compared to seismic stress levels for other plants reported in References 3 and 4. This perhaps indicates excessive conservatism in the seismic stress analysis for the St. Lucie plant.

This example calculation is believed to reflect the general situation for PWR primary coolant piping. The results indicate that the level and number of cyclic stresses from design transients are well below the limits specified by ASME Section III. The growth of small flaws over the design life of the plants, in these particular systems, is predicted to be very small.

AUSTENITIC PIPING WITH SECTION XI FLAWS

The set of results shown in Figures 5 and 6 pertain to flawed austenitic piping. The curves of Figure 5 show the predicted fatigue life of austenitic piping with 360-degree ID circumferential surface flaws and were generated in the same manner as the curves of Figure 3 for ferritic piping. The only difference in the calculations was that the fatigue crack growth rates for austenitic steel (from Figure 2) were used and the initial flaws were somewhat deeper, reflecting the more generous flaw acceptance standards of ASME Section XI for austenitic piping.

The trends and conclusions regarding the fatigue life of austenitic piping are the same as those for ferritic piping. Again, significant flaw growth can occur in piping with both Section XI preservice flaws and high fatigue usage as calculated by the Section III design rules. Again, the predicted life of flawed austenitic piping is somewhat dependent on pipe wall thickness.

In Figure 6, the predicted fatigue life curves for 3.0-inch-thick ferritic and austenitic piping are compared. The predicted curves for flawed ferritic and austenitic piping are remarkably similar. It is notable that the difference in predicted lives for the flawed piping for the two materials is less than the corresponding differences in the Section III fatigue design curves for the two materials, which are also shown in Figure 6. For flawed piping the effect of deeper Section XI allowable flaws for austenitic piping is offset by the slower fatigue crack growth rates for the austenitic versus ferritic steels.

Since the austenitic steel piping results reproduce the trends for the ferritic piping, subsequent sections of this report will focus on ferritic piping.

FIGURE 5. Predicted Life for Defected Austenitic Piping

FIGURE 6. Ferritic Versus Austenitic Piping Fatigue Life Predictions

VARIATION OF INITIAL FLAW DEPTH

All results presented here so far have assumed the presence of ID surface flaws of the depth permitted by the preservice acceptance standards of ASME Section XI. As such, the calculations for larger pipe wall thicknesses had deeper flaws. The predicted life of the flawed piping (for a given level of cyclic stress) was found to have some dependency on wall thickness. One desirable feature for flaw acceptance standards would be that the expected fatigue life of the flawed piping be independent of wall thickness. Therefore, a possible alternative to the present Section XI preservice acceptance standards was evaluated; the initial flaw depth was taken to be the same for all pipe wall thicknesses.

Figure 7 presents predicted fatigue lives for ferritic piping for wall thicknesses from 0.5 to 3.0 inch, with all pipe thicknesses having a common initial ID surface flaw depth of 0.100 inch. Since crack tip stress intensity factors are governed by the absolute magnitude of flaw depth (e.g., $\Delta K \sim \Delta\sigma \sqrt{a}$), the initial flaw growth rates (inches per cycle) were approximately the same for all pipe sizes. However, the fatigue life of the smaller piping would be somewhat less because the flaws have to grow through a thinner wall pipe.

FIGURE 7. Initial Flaw Depth Independent of Wall Thickness

Figure 7 shows some trends in the alternative standard for the allowable initial depth of preservice flaws. At low cyclic stress levels the alternate flaw depths give a relatively uniform life relative to pipe size. This would be an improvement over the present Section XI flaw sizes. However, at higher levels of cyclic stress the predicted lives become significantly more dependent on wall thickness than the lives for the flaw depths of the present Section XI standards, as indicated in Figure 3.

In conclusion, there does not appear to be a specific combination of initial flaw depths that will give a predicted fatigue life that is independent of wall thickness. However, there may be other justifications for revising the present Section XI flaw acceptance standards. For example, current data on NDE flaw detection capabilities as generated in the present research project could be used to revise the flaw acceptance standards.

EFFECT OF THROUGH-WALL STRESS GRADIENTS

All results presented in the previous subsection were based on a uniform distribution of stress through the pipe wall. This assumption may be overconservative for conditions of stress gradients where the stresses decay from the peak ID surface stress. The effect of a stress gradient is to reduce the crack tip stress intensity factor for the deeper flaws and hence to reduce the fatigue crack growth rates as the flaws grow away from the ID surface.

A related consideration is the sensitivity of predicted fatigue life to the assumed end-of-life flaw depth (assumed to be $t/4$). Calculations have been performed in which the final flaw depth was increased to $2/3t$.

Figure 8 shows the predicted lives for piping with through-wall stress distributions of both uniform tensile and pure bending, and also for piping with end-of-life flaw depths ranging from $a_f = t/4$ to $a_f = 2/3t$. All the curves of Figure 8 are for 2.0-inch-wall ferritic piping in a reactor water environment under high mean stress. The curves fall relatively close to each other, indicating that the stress gradient and the prescribed end-of-life flaw depth have a secondary effect on predicted fatigue life. Nevertheless, the predicted life is greater for bending stress ($\alpha = -1.0$) than for uniform tension ($\alpha = +1.0$). The predicted life also increases somewhat when the specified end-of-life flaw size is increased. However, both effects together increase the predicted life by a factor of less than three.

ENVIRONMENT AND MEAN STRESS

The ferritic steel fatigue crack growth rate curves of Figure 1 show significant acceleration in crack growth due to water environment (versus air) and high mean stress ($R > 0.65$). All results presented in Figures 5 through 8 were for worst-case conditions (water and $R > 0.65$). Calcula-

FIGURE 8. Effect of Bending Versus Uniform Tensile Stress

tions have also been performed for less severe conditions, and results are presented in Figure 9. These results apply to 2.0-inch-wall ferritic piping with an ASME Section XI preservice flaw ($a_i = 0.114$ inch).

Results shown in Figure 9 are for the three crack growth rate curves of Section XI for ferritic steels. Clearly environment and mean stress have a significant effect on the predicted life of the flawed piping. Nevertheless, the predicted life for even the least severe condition (air environment) is substantially less than the Section III design curve for unflawed material. The air environment curve would apply to buried fabrication flaws, and this curve lies substantially below the Section III fatigue design curve for unflawed material. In situations of high fatigue usage, the results shown in Figure 9 suggest that fabrication flaws of acceptable size could lead to premature service failures.

PARAMETRIC VARIATION OF FLAW DEPTH

The focus in the above discussion has been on the expected fatigue life of piping with ASME Section XI preservice flaws. Piping with such code-acceptable flaws have predicted lives much shorter than those predicted by the Section III fatigue design curves. The calculations described here were intended to determine the allowable flaw depths consistent with the life predictions of the Section III design curves.

FIGURE 9. Environment and Mean Stress Effect on Predicted Life

Figures 10 through 12 show predicted lives for ferritic piping with initial flaw depths ranging from very small flaws of 0.005 inch to deeper flaws approaching the code-acceptable standards. Figure 10 addresses the worst-case condition for fatigue crack growth (water environment and high R), and Figure 12 addresses the most favorable condition corresponding to the air environment curve of Figure 2. The intermediate case of Figure 11 corresponds to water environment with low mean stresses.

As indicated by Figure 10, under adverse conditions of environment and mean stress, piping with even very small flaws (e.g., 0.005 inch) will not achieve a predicted life equal to that of the Section III design curve. However, if the mean stress is low, the curves of Figure 11 indicate that the design can be achieved in the water environment, provided the initial flaw depths are very small (i.e., 0.005 inch). Only for the air environment is the Section III design curve conservative for very small flaws.

It is believed that a reduction of flaw sizes in the code acceptance standards is not a practical approach to assure that flawed piping will achieve the full design life for conditions of high cyclic stress (i.e., for a fatigue usage factor approaching the 1.0 design limit). As the results of the PNL inspection round robin show, the present code acceptance standards are at the very limits of flaw detectability (Refs. 8, 9). Reduction of the standards to the very small depths as suggested by the present calculations would not be meaningful. The present results do show a need to reconsider inspection requirements for piping locations where

FIGURE 10. Fatigue Life Versus Initial Flaw Depth - Water Environment and High Mean Stress

FIGURE 11. Fatigue Life Versus Initial Flaw Depth - Water Environment and Low Mean Stress

FIGURE 12. Fatigue Life Versus Initial Flaw Depth - Air Environment

high fatigue usage factors are predicted in the Section III stress analyses. Present Section XI rules require joints with usage factors of 0.4 or greater to be included in the sample of welds to be inspected. This 0.4 value of usage factor as a general rule is not conservative. In addition, locations of high levels of fatigue usage may require more frequent inspection than required by the existing code to ensure that excessive crack growth does not occur between inspections.

It should be restated that the calculations presented here assumed a uniform distribution of cyclic stress through the wall of the pipe. The calculations did not model typical weld joint geometries where highly localized stress concentrations are present. Such stress concentrations will affect the initiation and early stages of propagation of fatigue cracks. The intent in this report has been to model the later stage of flaw growth where average or mean stresses rather than peak stresses will govern fatigue crack propagation. In contrast Section III fatigue calculations may or may not include effects of local weld geometry stress concentrations through prescribed stress indices. Consequently, high values of computed fatigue usage factors may arise from elevated values of cyclic stress corresponding to application of stress indices to nominal stresses. The present calculations address the later stages of flaw growth for fabrication- or fatigue-initiated flaws. Therefore, high values of calculated fatigue usage could be a misleading measure of the potential for unacceptable flaw growth.

A point of interest is the rough correlation of the Section III fatigue design curves with the fracture mechanics predictions of fatigue life for very small flaw depths (in the 0.005-inch to 0.010-inch range). This type of correlation has been observed in experimental studies of the growth of very small flaws (Ref. 10). The observed fatigue behavior of unflawed specimens has been similar to specimens with very small flaws on the order of a few thousands of an inch. This apparent flaw size is viewed as characteristic of the material and can be rationalized as being typical of inclusion sizes. Such an explanation would be consistent with the bases for the Section III fatigue design curves (Ref. 11). These curves are based on data from smooth bars tested in an air environment and with safety factors of 2 on stress and 20 on life applied to the data. As seen in Figure 12, the applied safety factors are sufficient for the air environment to allow for flaws up to 0.020 inch. However, for the enhanced flaw growth rates in reactor water environments, the safety factors are insufficient to accommodate small flaws of 0.005 inch. Since even smooth specimens can behave as if such small flaws are present, the present Section III design curve may be unconservative for the water environments.

RECONCILIATION WITH SERVICE EXPERIENCE

The fatigue crack growth calculations have predicted that small flaws can grow rapidly in service even at cyclic stress levels that are well within the limits of ASME Section III fatigue design curves. This would imply that fatigue failures are a common occurrence. On the other hand, service experience indicates that fatigue failures rarely occur, and that such failures are often due to cyclic stresses that were not anticipated in design (Refs. 12, 13, 14). The discussion below proposes a number of factors that can reconcile the low occurrence of fatigue failures with the pessimistic predictions of the present calculations.

FATIGUE USAGE LESS THAN 1.0

In practice, calculated fatigue usage factors seldom approach the limiting value of 1.0 permitted by Section III design rules. Figure 13 shows the range of usage factors calculated from transient stress data cited in the BCL cold leg integrity evaluation (Ref. 3). The usage factors, in the case of PWR primary coolant piping, are several orders of magnitude below the allowable value of 1.0. In this situation, detailed fracture mechanics calculations do predict slow crack growth rates and low probabilities of failure (Refs. 3, 4) for PWR primary coolant piping. On the other hand, calculated usage factors in the range of 0.1 to 1.0 are reported occasionally for other sizes and classes of piping that have vital safety-related functions. Detailed flaw growth calculations are recommended for these other piping systems to determine the real significance of such high usage factors. Such calculations are in progress at PNL for a PWR pressurizer surge line, and the results will be described in a forthcoming report.

SMALLNESS OF FABRICATION FLAWS

Available data on the occurrence and size of initial flaws in welds are summarized in Reference 5. These flaw size distributions indicate that less than one weld in ten would have a flaw as large as permitted by the Section XI preservice standards. Such estimates are probably conservative since they are based on data on weld defects of all types; these are predominantly porosity, inclusions, etc., and are seldom inner-diameter, surface-connected cracks.

INSERVICE INSPECTION

ASME Section XI inspection rules require roughly four inspections during a 40-year design life. One can take credit for inspection in Figures 3 through 12 by shifting the predicted fatigue life curves for flawed piping to the right by a factor of four along the cycles-to-failure axis. This removes a significant part of the difference between the life predictions for flawed piping and the Section III design fatigue curve.

FIGURE 13. Calculated Fatigue Usage at Selected Locations in PWR Cold Leg Piping

The Section XI weld joint sampling plans require special attention to joints with fatigue usage factors of 0.4 or greater. Thus, the calculated fatigue usage between inspections may be as low as 0.1 (0.25 if the usage factor is 1.0). However, the expected life of flawed piping (e.g., Figure 3) under worst-case conditions is about a factor of 40 short of the Section III design curve. In principle, an inspection should be performed whenever the increase in fatigue usage between inspections reaches a level of 1/40 (0.025). With four inservice inspections this suggests a revised usage factor in Section XI of $4/40 = 0.10$. However, joints with a factor just below 0.10 may then just avoid mandatory inclusion in the weld joint sampling plan. A reduction of the specified usage factor to 0.025 would avoid this undesirable situation, but the present code requirement of four inspections would exceed the number needed for usage factors in the range of 0.025 to 0.10. However, for usage factors greater than 0.10, more than four inspections would be required to avoid an accumulated usage factor greater than 1/40th between inspections.

The above discussion and reference to the factor of 40 relative to life (or cycles) does not address high cycle fatigue ($>10^6$ cycles). In this range, fatigue life is governed by endurance limit and threshold ΔK considerations. High cycle fatigue failures might typically result from vibrational stresses. The factor of 40 difference between the predicted life of flawed piping and the Section III design curve no longer applies. The factor becomes essentially infinite. As a result, for high cycle fatigue there is little that can be achieved through decreasing the inspection interval. Rather, a reduction in fatigue failures can be better achieved through reductions in design stress levels and through increased attention to the measurement and control of unanticipated vibrational stresses.

CONSERVATIVE DESIGN CALCULATIONS

Stress analyses performed to meet the design rules of ASME Section III are performed conservatively. Thus, both the levels of cyclic stress and the number of postulated loading transients used in computing fatigue usage factors are likely to be overestimated. In addition, typical procedures for combining cyclic stresses in time and space use simplified but conservative assumptions as described in Reference 15. If stresses are found to exceed code limits, only then would more exact methods be applied. Thus, reported fatigue usage factors may on occasion approach the code limit of one. However, less conservative calculations may well show these factors to be significantly less than one.

STRESS INDICES

An additional level of conservatism is present in Section III fatigue evaluations of piping as a result of the stress indices. Section III specifies stress indices in Table NB-3681(a)-1 for use with equations NB-3650. These stress indices can be viewed as stress concentration factors

applied to nominal pressure and bending moment stresses to calculate peak stresses for fatigue evaluations. For butt welds the prescribed factor ranges from 1.8 to 3.5, depending on wall thickness and other factors. For flush-ground welds the factor is only 1.1.

The use of peak surface stresses to account for local stress concentrations is certainly appropriate for the prediction of the initiation and early growth of small fatigue cracks. However, the later stages of growth of these cracks will be governed primarily by the membrane and linear bending stresses on the pipe cross section rather than by the localized peak stresses. In the application of the Section III fatigue life curves (Figures 3 through 12) it must then be recognized that a factor of two or more may be applied to the nominal pipe wall stresses before use of the curves. Displacing the Section III curve downward by a factor of two removes much of the discrepancy with the fatigue life predictions based on fracture mechanics.

Weld joints that have high stress indices (i.e., two or greater) should have similar predicted fatigue lives when evaluated either by Section XI methods for flawed piping and/or by Section III design criteria. However, serious disagreement in predicted fatigue lives would remain for base metal or ground welds for which prescribed stress indices have values close to unity.

CRACK GROWTH RATE DATA

The more pessimistic predictions for the fatigue life of flawed piping were based on worst-case da/dN data that reflected the adverse effects of water environment and high mean stress. While such worst-case effects will not always be present, high mean stresses and water environment are, nevertheless, relevant conditions for reactor piping. Sources of high mean stresses can be welding residual stresses and stresses from fit-up of piping. Such stresses are likely to be present at many locations of potential cracking. Likewise, environmental conditions are likely to be variable and may on occasion reflect the worst-case conditions of the test data used in generating the Section XI da/dN curves for PWR water chemistry (Ref. 7).

It should be recognized that the Section XI da/dN curves were developed to give mean growth rates for the test conditions. The only implied "margin of safety" is provided by a 95 percent global confidence limit on the mean curve to allow for all future data obtained for the same material environment combinations. As such, isolated data points do fall above the existing curve, indicating that there is a possibility that crack growth could, on occasion, exceed the mean curve of the code. Furthermore, that data on which the curve is based does not, and could not, include all possible conditions and combinations of environment and stress cycling.

In particular, the cyclic rate (cycles per minute) of the laboratory tests were by necessity orders of magnitude faster than the cyclic rates that occur in service. Data are lacking to show whether the cyclic rates of the tests are conservative or unconservative relative to cyclic rates encountered in service.

In summary, the Section XI crack rate curves may on many occasions overestimate growth rates, but in general they will not be consistently overconservative.

SPECTRUM LOADING EFFECTS

The calculations here assumed that each flaw experienced a single level of cyclic stress, whereas in service a mix of high-and-low stress cycles are encountered. A simple addition of the individual contributions to crack growth from cycles of differing amplitudes may not lead to accurate predictions. Crack growth tests under variable-amplitude loads show that an occasional high-amplitude cycle will retard growth for subsequent lower-amplitude cycles. This effect is included in "retardation" models for predicting flaw growth (Ref. 16).

In piping analysis, the large-amplitude stress cycles from hydrotest and cold shutdown would be a likely source of the retardation effect. Crack growth from less severe operating transients would be depressed. In recent studies of crack growth in reactor piping (Refs. 3, 4), this retardation effect has been neglected to add conservatism to the calculations and because of uncertainties in predicting the extent of the effect. However, the crack growth in these studies was mainly due to the large stress excursions. In this situation, neglecting the retardation of growth during the lower-amplitude stress cycles would not have a major effect on predicted piping fatigue life. In summary, it is believed that spectrum loading effects will tend to reduce crack growth rates from those predicted in this report. This will be particularly true if piping life is governed by the lower-amplitude stress cycles (i.e., if failure is due to a large number of the low-amplitude cyclic stresses).

COMPARISON WITH RESULTS IN NUREG-0726

The trends and conclusions of the present calculations confirm and expand on results published earlier in Reference 1. The format of presentation has been different, and it is useful to present the results of the present analyses in the format of NUREG-0726.

Figure 14 shows allowable initial flaw depths that will ensure that fatigue growth does not result in flaws that exceed the Section XI inservice acceptance standards. These results are for ferritic steel with crack growth rates from Reference 7 for PWR water environment with high mean stress. The different curves are for different values of fatigue usage factor and, as in NUREG-0726, the predicted allowable flaw depths are a function of the alternating stress level. These curves for flaw depth do not show a clear rise to a single maximum flaw depth as those in NUREG-0726 because of the use of a different da/dN curve. The observed changes in slope in Figure 14 are due to the curvature and slope changes in both the Section III fatigue design curve and the Section XI da/dN curve.

The predictions here, as in NUREG-0726, show that with high fatigue usage factors (at or near 1.0), initial flaw depths must be on the order of a few thousands of an inch to prevent growth to the Section XI allowable flaw depths.

FIGURE 14. INITIAL SURFACE FLAW DEPTHS FOR GROWTH TO SECTION XI INSERVICE ACCEPTANCE STANDARDS FOR 3-D INCL. WALL CRACKS GROWING WITH CRACK GROWTH RATE OF REFERENCE 7 IN PWR WATER AT $R = 0.0$

FIGURE 14. Initial Surface Flaw Depth for Growth to Section XI Inservice Acceptance Standards for 3.0 Inch Wall Ferritic Piping With Circumferential Flaw of Aspect Ratio $a/\ell = 0.0$

SUMMARY AND CONCLUSIONS

Calculations have been performed to predict flaw growth in piping on a parametric basis. Piping size, initial flaw size, cyclic stress levels, and through-wall stress distributions have been varied as well as factors governing fatigue crack growth rate. The objective has been to evaluate the consistency of ASME Section XI flaw acceptance standards and inspection intervals from the viewpoint of subcritical flaw growth by fatigue. In the process of addressing the flaw acceptance standards of Section XI, a number of issues were also encountered relative to the fatigue design curves of ASME Section III. The discussion below addresses Section XI and Section III with distinctly separate conclusions. Nevertheless, a common issue is the apparent discrepancy between the cyclic stress levels permitted by the Section III design rules and the flaws considered acceptable by the inservice inspection rules of Section XI.

SECTION XI - INSPECTION REQUIREMENTS

The present flaw acceptance standards are based on a number of considerations, including minimum toughness requirements and flaw detection capabilities, which together were used to obtain a workable set of rules. The present standards were evaluated here from the additional standpoint of the predicted life of flawed piping in the presence of cyclic stress.

The present flaw acceptance standards appear to be internally consistent in that the predicted life of flawed, cyclically stressed piping is relatively independent of pipe wall thickness, flaw aspect ratio and material of construction. This means that for a given level of cyclic stress in service, calculations predict comparable lives for the range of materials, flaw shapes, and pipe sizes of interest.

The results of the round-robin inspection of flawed piping at PNL show that the present Section XI flaw acceptance standards are at or below present flaw detection capabilities (Refs. 8, 9). Therefore, reductions in the flaw sizes given in the standards are not recommended.

The results of the present calculations do, however, show that specific locations of high fatigue usage in piping may require increased inspection, particularly if more detailed fracture mechanics calculations predict high growth rates for small flaws. The increased inspection would require additional locations to be included in the weld inspection sampling plan and a decrease in the required inspection interval. Specifically, a reduction in the 0.4 value of usage factor for selecting joints for the inspection plan may be in order. In addition, a selective reduction in inspection intervals, based on calculated fatigue usage factors and/or fracture mechanics calculations, may be in order.

The present Section XI rules make little distinction between surface-connected cracks and the various less serious types of subsurface and noncracklike fabrication flaws detected in inspection. The present calculations and concerns are limited to cracklike flaws exposed to the reactor environment, and revisions to present Section XI rules should address only such flaws. The present Section XI rules for flaw acceptance and inspection intervals appear to be adequate for subsurface flaws.

A final recommendation is that in-depth fracture mechanics analyses should be performed for actual piping designs and operating conditions to establish the extent to which the potential concerns discussed here actually exist in specific systems. Such analyses have been performed for PWR primary coolant piping (Refs. 3, 4) for which cyclic stresses are sufficiently low so that predicted flaw growth rates are low. Such studies should be expanded to include other safety-related piping systems with higher levels of cyclic stress.

SECTION III DESIGN RULES

The present calculations show that the present ASME Section III rules and fatigue design curves could allow piping designs that would not tolerate even very small flaws if the piping were subject to severe cyclic stress. On the other hand, the low occurrence of fatigue failures in service does not suggest a need for major changes in the present rules. Evidently, the various conservatisms in Section III design rules offset any unconservatism of the fatigue design curves. Possible problems may be limited to specific situations of high fatigue usage where the offsetting conservatisms in stress calculations are minimal.

The calculations reported here indicate that the present fatigue design curves can be unconservative for piping with code-acceptable flaws. The worst case of unconservatism can be equivalent to a factor of about 4 on stress and a factor of about 40 on life. The estimated degree of potential unconservatism is similar for piping of ferritic and austenitic steels.

The present calculations show that initial flaw sizes must be less than about 0.010 inch to guarantee that the fatigue life implied by the Section III rules is to be achieved. However, it has been noted that the Section III design rules specify the use of stress indices to account for stress concentrations at welds. The use of appropriate stress indices may be essentially equivalent to assuming initial flaws such as those of the Section XI flaw acceptance standards. Thus, a preferred alternative to changing the fatigue design curve may be to modify the present stress indices used in calculating S_a in fatigue evaluation so as to conservatively reflect fabrication quality, material variability, surface finish, etc.

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