November 6, 2001

MEMORANDUM TO: Dr. John T. Larkins, Executive Director
Advisory Committee on Reactor Safeguards

FROM: Jack R. Strosnider, Director ***/ra/***
Division of Engineering
Office of Nuclear Reactor Regulation

SUBJECT: PRELIMINARY STAFF ASSESSMENT OF REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLE CRACKING

The Office of Nuclear Reactor Regulation staff issued Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," on August 3, 2001, in response to recent observations of this new cracking phenomena. In the Bulletin, the staff discussed a graded approach for inspecting reactor pressure vessel head penetration (VHP) nozzles based on an industry-developed model to rank the pressurized water reactor units based on their relative susceptibility to this cracking mechanism.

In parallel with our efforts to engage the licensees regarding their responses to the Bulletin and this issue in general, the staff has been assessing the various technical issues regarding circumferential cracking of VHP nozzles. The attached preliminary technical assessment documents the status of the staff's work to date. The preliminary technical assessment will be discussed in detail with the Advisory Committee on Reactor Safeguards (ACRS) at the meeting scheduled for November 9, 2001.

This assessment represents our best characterization of this issue at this time. The staff continues to engage the industry and gather additional information regarding VHP nozzle inspection results and the various technical aspects related to this cracking issue, and we will continue to update our assessment.

Attached are the nonproprietary and proprietary versions of the staff's technical assessment.

If you have any questions regarding this report or related issues, please contact Allen Hiser of my staff.

Attachments: As stated

cc w/attachment: See next page

CONTACT: Allen Hiser, EMCB/DE
(301) 415-1034

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U.S. NUCLEAR REGULATORY COMMISSION

PRELIMINARY STAFF TECHNICAL ASSESSMENT FOR PRESSURIZED WATER REACTOR VESSEL HEAD PENETRATION NOZZLES ASSOCIATED WITH NRC BULLETIN 2001-01, "CIRCUMFERENTIAL CRACKING OF REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLES"

NOVEMBER 2001

NON-PROPRIETARY VERSION

ATTACHMENT 1

CONTENTS PAGE FROM PROPRIETARY DOCUMENT

1.0 INTRODUCTION

From the experience at Oconee Nuclear Station Units 1 and 3 (ONS-1 and ONS-3), two distinct chronologies were identified as sources for circumferential cracking on the outside diameter (OD) of the control rod drive mechanism (CRDM) nozzles. In one case, an axial crack could initiate due to primary water stress corrosion cracking (PWSCC) and grow in the interface between the nozzle base material and the J-groove weld. This crack could progress along the interface until it reaches a location above the J-groove weld, producing a throughwall crack and resulting in leakage of primary coolant into the annulus between the nozzle and the reactor pressure vessel (RPV) head. At this location, the stress levels in the nozzle could produce a turning of the axial crack such that the crack could begin to propagate in a circumferential orientation along the profile of the weld.

In the second case, an axial crack in the nozzle or a crack in the J-groove weld could initiate and propagate to the point that a throughwall crack would permit leakage of primary coolant into the annulus between the nozzle and the RPV head. As leakage from this crack occurs, an environment conducive to the initiation of stress corrosion cracking (SCC) could be produced in the annulus. After some characteristic initiation time period, a crack or a series of cracks could initiate on the OD of the nozzle in the circumferential orientation along the J-groove weld profile at a region of high axial tensile stress on the nozzle. This crack or series of cracks could propagate in the nozzle in the same orientation along the J-groove weld profile. A series of cracks could ultimately link up to form a larger crack.

A comprehensive analysis of circumferential cracking in vessel head penetration (VHP) nozzles would require treatment of the following aspects of the issue:

a. the time to initiate a crack on the inside diameter (ID) of the nozzle or in the J-groove weld,

b. the crack growth rate (da/dt) for the nozzle base material or the J-groove weld in a primary water environment, and determination of the time for the crack to grow throughwall (allowing primary water leakage into the annulus),

c. the time to begin circumferential cracking on the OD of the nozzle, including the time to establish a conducive environment in the annulus and initiate independent circumferential crack(s), **or** the time for an axial crack to turn and begin propagating in the circumferential direction along the weld profile,

d. the crack growth rate (da/dt) for the circumferential crack on the nozzle OD in the annulus environment set-up by the leaking coolant, including consideration of whether this environment is static or time dependent, evaluation of the time for the crack to grow throughwall or propagate as a part-through wall crack, and determination of the time for the crack to grow to reach the critical flaw size, and

e. the critical flaw size, based on tensile overload of the remaining ligament of the nozzle, including consideration of safety margins such as the American Society of Mechanical Engineers (ASME) Code margin of three on pressure loads.

Included in this comprehensive analysis at various points could be definition of inspection activities that would be sufficient to effectively manage the cracking through detection, characterization and remediation of defects, and assessment of the impact of these inspection activities on the population of flaws in the nozzles.

This assessment provides a discussion of the state of knowledge for each of the above variables and a model that integrates the variables to support analysis of the VHP nozzle cracking phenomena. A few important points need to be made:

1) for some of the variables the existing data are sparse or in some cases nonexistent,

2) the data and models for assessing this phenomena are still under developmen,

3) this assessment represents the staff's best understanding of the technical aspects of the issue at this time, and

4) additional work needs to be done by the industry to provide a better technical understanding and basis to support a program for effective management of this degradation mechanism.

Section 2 of this assessment summarizes the existing data for crack initiation time in Alloy 600 base metal and Alloy 182 weld metal under primary water conditions (and in Alloy 600 base metal under postulated annulus environmental condition), Section 3 summarizes the available crack growth rate data for the materials and environments of interest, Section 4 describes the stress state in the penetration nozzles (including residual and operating stresses), and Section 5 describes the critical crack size for circumferential cracks, considering both failure of the nozzle and a safety margin of three on the pressure load.

2.1.1 Staff Conclusions

Based on the preceding discussion, the environment in the annulus is not expected to be highly aggressive, and thus the staff has used crack initiation times and crack growth rates associated with normal PWR reactor coolant chemistry in its assessment. However, it is important that annulus deposits from a leaking nozzle be obtained and analyzed to provide confirmation of the assumed annulus environment.

2.2.2 Staff Conclusions

The operating experience of leaking nozzles, based on data available as of November 1, 2001, appears to be well modeled by the Weibull analysis with b = 1.5. The operating experience appears to fit between the 5th percentile to the 95th percentile. Note that final results for two of the plants and the results of additional inspections will be used to update this analysis.

3.1 Staff Conclusions

The staff concludes that the crack growth rate data for PWSCC is a reasonable approximation for OD VHP nozzle cracking, based on the data and analyses in this section. The staff has concluded that the crack growth rate function values given in Table 3 are appropriate for use at 325°C (617°F).

4.4 Staff Conclusions

The preliminary results from SIA given in Section 4.2 are available only for angles from 175° to 300°. This solution was extended to a wider range of crack angles by matching the ORNL solution for the K due to internal pressure discussed in Section 4.3 at large crack angles where it can be assumed that the pressure loading dominates K. At small angles, extrapolation of the SIA results was fairly consistent with estimates by ORNL of a K of about 66 MPa$\sqrt{m}$ (60 ksi$\sqrt{in.}$) due to residual stresses for a crack angle of 90°. The stress intensity decreases to zero as the crack angle decreases to zero. The resulting estimate of K is slightly more conservative than the SIA results for the range over which finite element method (FEM) results are available as shown in Figure 15. These results will vary from nozzle to nozzle, but until more results are available, it is assumed that Figure 15 gives a reasonable, conservative representation of K.

5.1 Staff Conclusions

From the industry and NRC contractor calculations, the critical crack size for a safety margin of three on pressure is 270°, and for nozzle failure/ejection the critical crack size is 324°.

6.0 DETERMINISTIC ASSESSMENT

6.1 Introduction

Previous sections of this report provided evaluation of available information on crack initiation and crack growth rate data, stress analyses and models applicable to assessing the CRDM cracking phenomena. In this section deterministic analyses of the time to failure for varying initial circumferential crack size along with deterministic sensitivity studies, and evaluation of deterministic margins are provided. Section 8 of this report discusses how this information along with a plant's specific susceptibility to cracking and prior inspection history can be used to inform decisions regarding the appropriate timing of inspections.

6.2 Base Case

The ASME Code, as referenced in Title 10 of the Code of Federal Regulations (10 CFR) Part 50.55a, does not allow through wall leakage. The deepest cracks allowed by the ASME Code would not exceed 75 percent of the wall thickness either for axial or circumferential cracks. Cracks that are evaluated as acceptable must have factors of safety of three against failure under operating conditions. Thus, any leakage which indicates a throughwall flaw would not satisfy the requirements of either 10 CFR 50.55a or the ASME Code, and would violate technical specification requirements that preclude pressure boundary leakage. Although these requirements are intended to preclude throughwall cracking and leakage, the high ductility characteristic of VHP nozzle materials mean that significant margins against failure can still exist even in the case of throughwall circumferential cracks. Thus, the staff has performed an analysis to understand the deterministic margins associated with the VHP nozzle cracking mechanism.

The parameters associated with these deterministic analysis are the initial crack size, the crack growth rate for circumferential cracks, and the critical crack size. As discussed in Sections 3 and 5, there are sufficient data available to evaluate pertinent crack growth rates and critical crack size. However, the lack of sufficient data from inservice inspections and the large uncertainties associated with crack initiation evaluations lead to a limited ability to provide reliable estimates of initial crack size. Therefore, the approach taken in this section is to define a base case utilizing a specified crack growth rate to calculate the operating time prior to reaching the critical crack size corresponding to a factor of safety of three against failure, consistent with the intent of the ASME Code, and also the time to reach a critical crack size that result in nozzle failure and probable ejection. These evaluations are made with a variety of circumferential crack sizes. Sensitivity studies on assumed crack growth rate and a discussions of uncertainties in the deterministic assessment are also presented.

It is expected that these analyses will be refined and expanded in the future as additional relevant data become available.

6.2.1 Assumed Critical Flaw Size

As described in Section 5, the critical flaw size can be determined in two ways, as either that flaw size which satisfies a margin of three on design pressure (consistent with the requirements of Section XI of the ASME Code), or the flaw size at which structural failure of the VHP nozzle would occur under normal operating conditions, possibly leading to ejection of the nozzle. As described in Section 5, estimates of the critical flaw size with a safety margin of three on the design pressure range from 262° to 269° from calculations by NRC contractors to 273° from industry calculations, and the critical flaw size for nozzle failure/ejection is 324° from calculations by NRC contractors and 330° from industry calculations. Note that these calculations assume there is not a surface flaw in the same plane as the throughwall flaw. As described in Section 5, a surface flaw in the crack plane would reduce the critical throughwall crack length, and if the surface flaw has a constant depth of 90-percent of the thickness, it would be critical with no throughwall crack. The growth of a surface flaw to such a large depth and having a critical depth without a throughwall component of the flaw is unlikely, so that there should be some throughwall leakage prior to failure.

The flaw size determined using the margin of three on design pressure is used in the base case deterministic analysis. Traditionally, a safety margin is intended, in part, to compensate for uncertainties, such as material properties, unanticipated loadings, etc. This use comes with the additional knowledge that the actual failure of the VHP nozzle would be expected to occur at some time period after reaching that flaw size. The effectiveness of a factor of safety of three in accounting for the variability in parameters such as crack growth rate is discussed as part of the sensitivity studies.

For the base case deterministic evaluation, the staff has used a failure/ejection circumferential crack length of 324°, and a crack length of 270° for a margin of three on the design pressure.

6.2.2 Assumed Crack Growth Rate

As described in Section 3, there are no crack growth data for conditions, e.g., material and test conditions (environment and temperature), directly relevant to VHP nozzle cracking, partly owing to the fact that the environmental conditions in the annulus between the nozzle and the RPV head have not been verified through field experience. In Section 3, it is concluded that the observed crack growth rates in primary coolant water should be representative of the expected crack growth rates, and an analysis of the available data for these conditions is described in Section 3.

For the deterministic calculations, the crack growth rate was evaluated through simplified K-dependent calculations. The deterministic calculations use the Scott model. With the high degree of variability evident in the crack growth rate data, the deterministic evaluation used the crack growth rate parameter A based on a 95/50 statistical evaluation of the data. From Table 3 at an operating temperature of 325°C (617°F), the 95/50 A is 1.8×10^{-11}. However, A is strongly dependent on the operating temperature, and can be adjusted to different temperatures based on the Arrhenius relationship. From a review of the reported RPV head operating temperatures, the staff has used a temperature of 318°C (605°F) for the base case deterministic evaluation. At this temperature, the 95/50 A is determined to be 1.303×10^{-11}. Using the stress intensity results illustrated in Figure 15, the crack growth rate at 318°C (605°F) as a function of circumferential crack size is illustrated in Figure 18. From this figure, the crack growth rates range from 12.7 to almost 51 mm/yr (0.5 to 2 in./yr).

The base case deterministic evaluation determined the crack growth rate for an increment of growth as the average value of the crack growth rate for that increment of growth, e.g., the growth rate from 20° to 30° was determined by averaging the crack growth rate at 20° and 30°. The time for this increment of growth was then determined by dividing the increment of growth by this average crack growth rate for the increment.

Consideration of the crack growth rate at other conditions, including varying the operating temperature and using different statistical bounds to the data, is described in Section 6.3.

6.2.3 Assumed Initial Flaw Size

Definition of the initial flaw size is the single most difficult task of the deterministic analysis. The use of qualified visual examinations to monitor for leakage deposits is at best an indirect indication of the presence of cracking, and may provide no direct tie to the crack length in any degraded nozzle. In addition, follow-up examinations with volumetric examination methods to characterize only those nozzles with detectable leakage deposits, and perhaps a small additional sample of nozzles, do not provide complete data on the population of flaws in nozzles, in that determination of the flaw population for nozzles without detectable leakage are generally not performed.

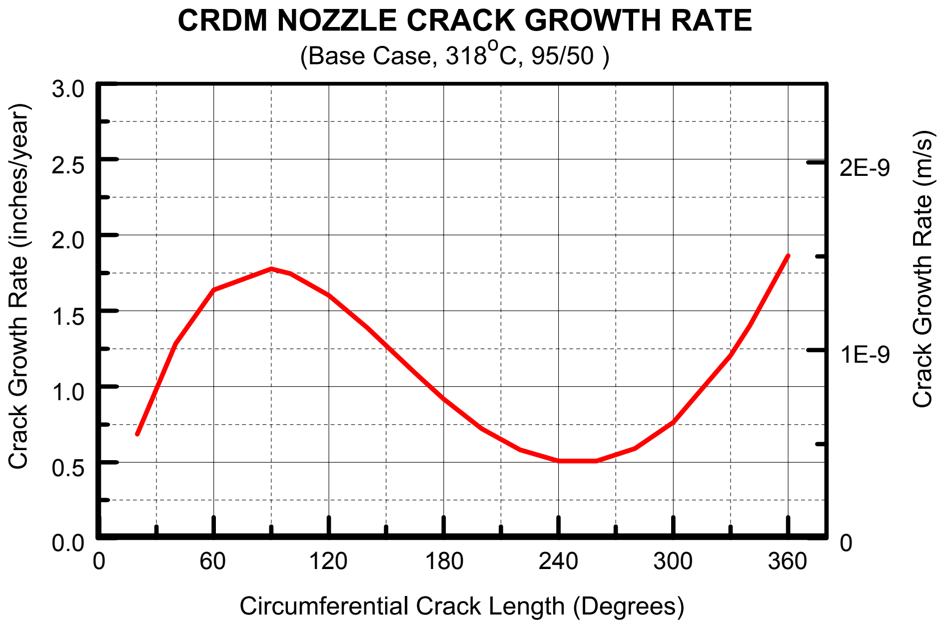

Figure 18 Variation of crack growth rate with circumferential crack length for the base case of 318°C (605°F) 95/50 curve.

That notwithstanding, the available data for OD circumferential flaws from examinations in the spring and fall 2001 outages are summarized in Table 4, based on the destructively measured crack lengths for two of the flaws and the ultrasonic (UT) measurements of the other three flaws. From these results there are a variety of sizes for the flaws that have been identified in CRDM nozzles. Based on these results it is possible to say that the largest flaw identified thus far is 165°. However, it should be noted that the only circumferential flaws for which the circumferential lengths has been verified destructively are the pair of 165° cracks at ONS-3, and one of these two flaws was significantly undersized by the UT measurements as 59°, an error by a factor of 2.8 or 106°. The flaw sizes for Crystal River Unit 3, the shorter of the flaws at ONS-3 and the single circumferential crack in ONS-2 are based only on UT measurements. It should be noted that the shorter flaw at ONS-3 was not identified by the UT examination until a third party review of the data, and hence it was not identified prior to the completion of repairs of the affected nozzle. In the other two cases, the cracks were removed by machining without any additional efforts to determine the actual extent of the cracking in the affected nozzles. Given prior experience with UT examination and the current state of qualification of UT inspections for these components, the actual sizes of these cracks is uncertain.

Table 4 Summary of OD Circumferential Flaws Identified in Spring and Fall 2001 Outages

Plant	Nozzle ID	Circumferential Crack Length	Throughwall Extent
Oconee Unit 3	50	165°	100%
Oconee Unit 3	56	165°	100%
Oconee Unit3	23	66° *	35% *
Oconee Unit 2	18	45° *	10% *
Crystal River Unit 3	32	90° *	50% *

* Crack dimensions estimated from UT data.

It should be noted that the purpose of NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," was to provide information regarding the extent and severity of cracking occurring in VHP nozzles. The assumption regarding the crack size remaining after a qualified visual examination represents the additional uncertainty that one has in the population of undetected flaws in the VHP nozzles, since the detection of no leakage deposits is not a direct indication of the absence of cracking in the VHP nozzles but only an indication that any cracking that is occurring has not resulted in a detectable leakage deposit on the RPV head.

Conversely, performance of surface or volumetric examinations of 100 percent of the VHP nozzles does provide an opportunity to directly sample the population of flaws that may be occurring in the VHP nozzles, within the detectability and reliability performance characteristics of the examination method. In such cases, the assumption of a smaller initial crack size remaining after examination can be more easily defined and defended based on the performance characteristics of the examination method.

Due to the lack of sufficient inspection data from plants and large uncertainties associated with time to crack initiation, the existing flaw sizes that could exist in plants is unknown. Therefore, the base case deterministic calculations focus on a determination of the operating times necessary to reach the 270° critical flaw size (at three times the design pressure) and the 324° critical flaw size (at nozzle failure/ejection). These operating times are determined as a function of the initial flaw size.

6.2.4 Base Case Results

The results of the analyses performed using the base case assumptions are provided in Figure 19. As illustrated in this figure, nozzle failure/ejection is predicted to occur about 12 months after the various sizes of flaws have reached the critical length at three times the design pressure. As an example, a 180° flaw would reach 270° in about 26 months and the 324° nozzle failure/ejection size in about 38 months.

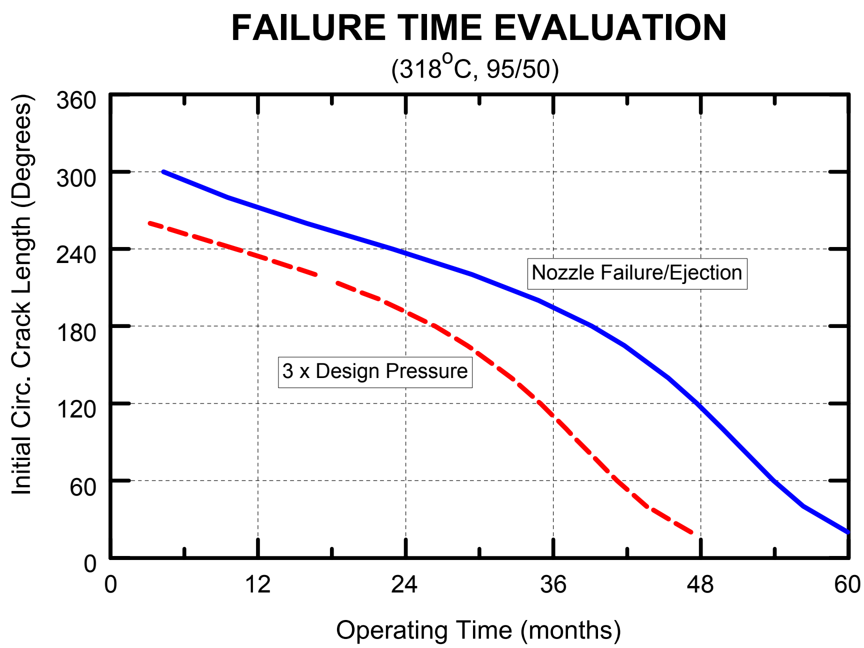

Figure 19 Variation of time to failure as a function of initial crack length, for the base case of 318°C (605°F), 95/50, crack growth rate.

Figure 20 presents the time to failure for a specific initial flaw size of 165°. This case would resemble the Oconee Unit 3 conditions when the two 165° circumferential flaws were identified in spring 2001. For this base case, the 165° flaw would grow to 270° in approximately 29 months, and to 324° in about 42 months. Note the non-linearity of the crack length curve as a function of operating time, reflective of the variations in crack growth size as a function of the crack size dependent applied stress intensity (K) level.

The evaluation presented in Figure 20 demonstrates the type of deterministic analysis that is normally performed with reliable information regarding the initial flaw size, and also supports the sensitivity studies discussed in the next section.

6.3 Uncertainties and Sensitivity Studies

In the absence of definitive data, the use of parametric values of crack growth rate can provide an understanding of the impact of various assumptions on the evaluation within the context of relevant values of the parameters. For the case of CRDM nozzle cracking, the effect of initial flaw size on the operating time to achieve the critical flaw sizes has been considered in Figure 19. Besides the initial crack size, another key parameter with a high level uncertainty is the crack growth rate.

At least three issues affect the selection of the crack growth rate: the environmental conditions, the operating temperature and the statistical basis for the selected crack growth rate. For OD circumferential cracking in CRDM nozzles, Section 2.1 concluded that PWSCC conditions are a reasonable approximation to the conditions thought to exist in the annulus between the nozzle and the RPV head, and as such crack growth data for PWSCC conditions are used in this

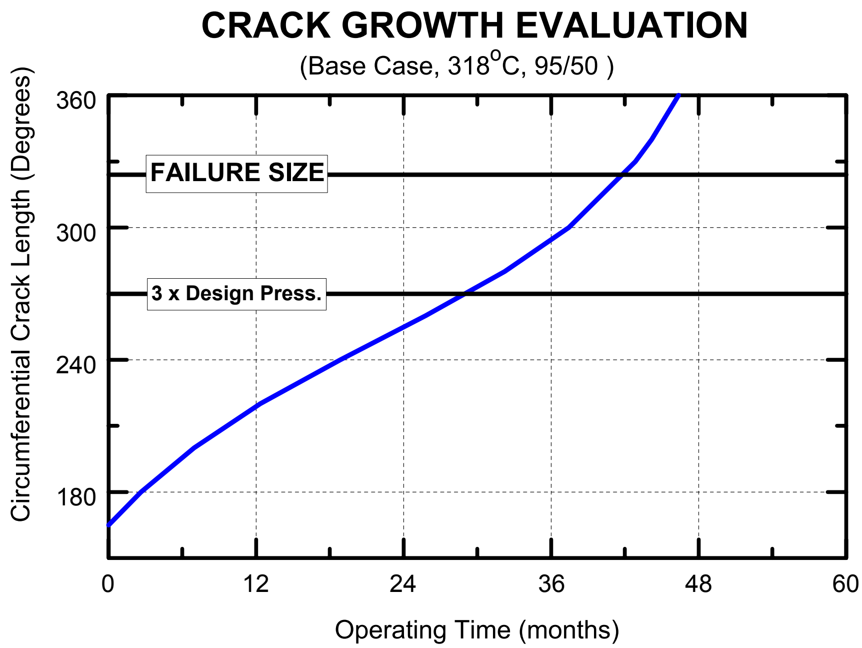

Figure 20 Evaluation of operating time to reach critical flaw sizes at three times design pressure and at nozzle failure/ejection after development of a 165° long circumferential through-wall flaw.

analysis. [As noted in Section 6.2.1, field confirmation of the annulus conditions should be pursued by the industry to eliminate any uncertainty regarding the annulus conditions.]

As described in Section 6.3, the effect of operating temperature on the crack growth rate can be assessed using an Arrhenius relation. For the case of CRDM nozzle conditions, MRP-48 (Ref. 33) indicates that RPV heads are operating in the temperature range from 286°C to 318°C (547°F to 605°F). The base case described in Section 6.2.2 used 318°C (605°F). In addition, the benchmark evaluations of the available crack growth data (see Section 3) have used 325°C (617°F). To illustrate the effects of operating temperature on the crack growth rate, the Arrhenius relation has been used to define the ratio of the A parameter from the Scott model at operating temperature with that at 325°C (617°F), as provided in Figure 21. Referencing from the base case of 318°C (605°F), reducing the operating temperature by 3°C (6°F), to 315°C (599°F), results in a reduction in the crack growth rate of 13 percent. Reducing the operating temperature to 286°C (547°F), the lowest CRDM nozzle operating temperature according to MRP-48 (Ref. 33), the crack growth rate reduces by 80 percent from the rate at 318°C (605°F).

In addition to the temperature at which the crack growth rate is evaluated, the statistical bound used to define the A parameter in the Scott model can also have an effect on the results. As indicated in Section 6.2.2, the base case used a 95/50 statistical evaluation of the data at 318°C (605°F). From Section 6.3, comparison of the 50/50 curve with the field measurements by EDF indicates that the 50/50 curve is less than the mean of the field measurements. One

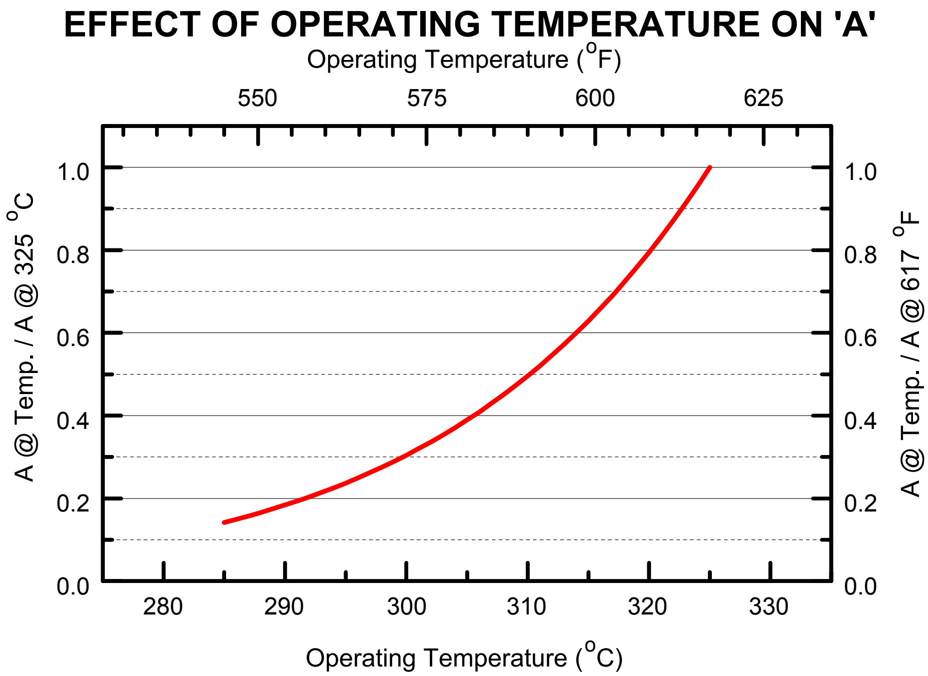

Figure 21 Lower operating temperature results in lower crack growth rates for VHP nozzle materials, within the operating temperature range of the nozzles.

hypothesis to explain this observation is that the heats exhibiting cracking in the field may be relatively higher in susceptibility to PWSCC than the overall population of heats that have been examined in the laboratory, such that the more susceptible materials would tend to crack earlier and more frequently than less susceptible heats, and would thus be disproportionately represented in the population of field data. With Figure 9 as a basis, an approximate mean to data for these "higher susceptibility heats" (that may result in cracking in the field) has been determined as the square root of the products of the 95/50 and 50/50 values for A from Table 3. This value of the "mean" A at 325°C (617°F), 7.47×10^{-12}, can then be adjusted for operating temperature conditions using the Arrhenius relation. The sensitivity to the statistical nature of the crack growth rate curve was evaluated using the 95/50 values, termed in the following figures as "B" for bounding, and these root product mean values, termed "M" in the following figures. The simultaneous effects of operating temperature and statistical nature of the curves are illustrated using 95/50 curves at 325°C (617°F), 318°C (605°F), and 315°C (599°F), along with mean values at 318°C (605°F) and 315°C (599°F).

Figure 22 illustrates the crack growth rates as a function of circumferential crack length for the five cases described above. Although there are reductions in crack growth rate related to decreases in operating temperature, there is a more significant decrease in rate in going from the 95/50 curves ('B' on the figure) to the mean curves ('M' on the figure). A comparison of these results with the crack growth rate used in a Framatome analysis (Ref. 34), a linearized rate of 10 mm/year (0.39 in./year), indicates that the Framatome rate is similar to the mean approximation to the crack growth rates for the higher susceptibility heats.

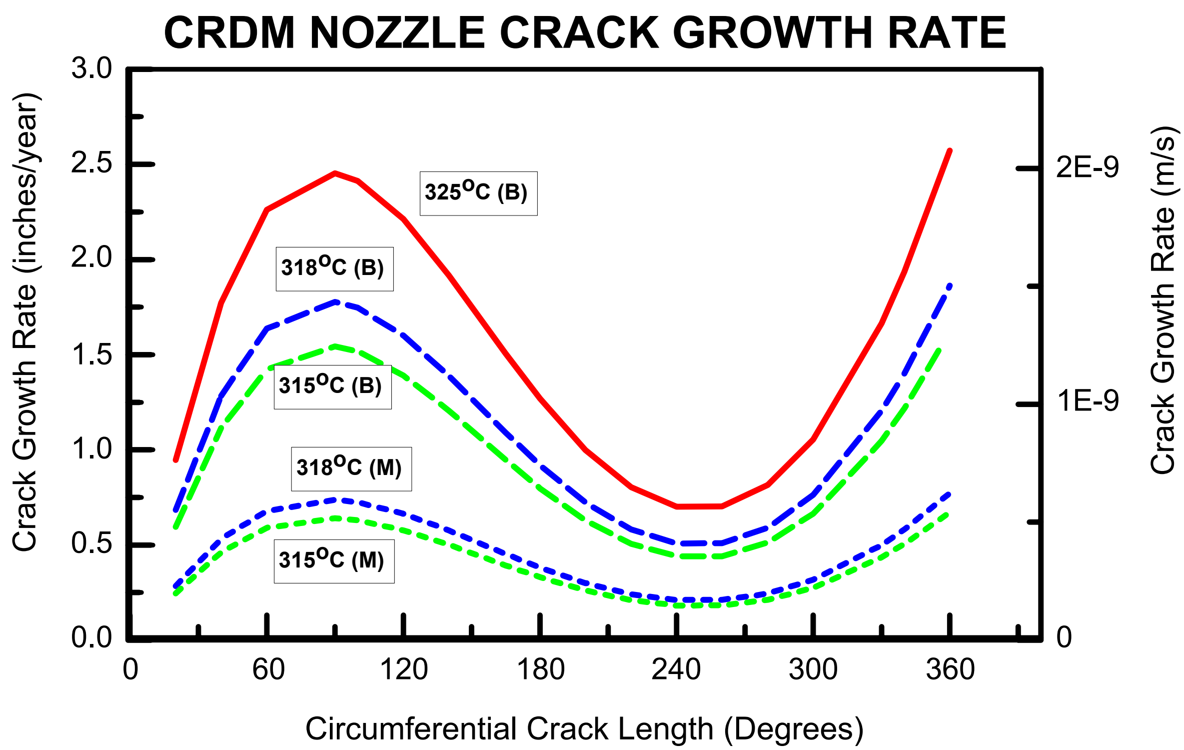

Figure 22 Variation of crack growth rates at several pertinent temperatures and using 95/50 ('B' on the curves) and mean values ('M' on the curves).

Translating these crack growth rates into an evaluation of the time to reach the critical flaw sizes from a 165° initial flaw, Figure 23 illustrates that reducing the temperature and using the 95/50 curves increases the time to reach the three times design pressure curve by up to 12 months and the time to reach the nozzle failure/ejection curve by up to 18 months. However, the most dramatic increase in time is for the mean curve evaluations, where the times to reach the critical flaw sizes increases by 3 to 4 years for the three times design pressure curve and more than 5 years for the nozzle failure/ejection curve.

Applying these crack growth rate curves to determining the time to reach the three times design pressure and the nozzle failure/ejection flaw sizes, the effects of using mean curves instead of the 95/50 curves are very large (Figs. 24 and 25, respectively). At all three temperatures, the 95/50 curves would project that a 60° initial flaw would reach 270° in 3 to 4 years. In contrast, the mean curves do not project reaching this flaw size until more than 8 years of operating time.

Added to these figures are curves for 318°C (605°F) using a 95/95 statistical bound. This curve does not have a high probability, but it does have a possibility of occurring for the VHP nozzles. In this case, the 95/95 curve projects growth of a very small starting flaw to a size that would result in nozzle failure/ejection within 24 months of initiation of the flaw.

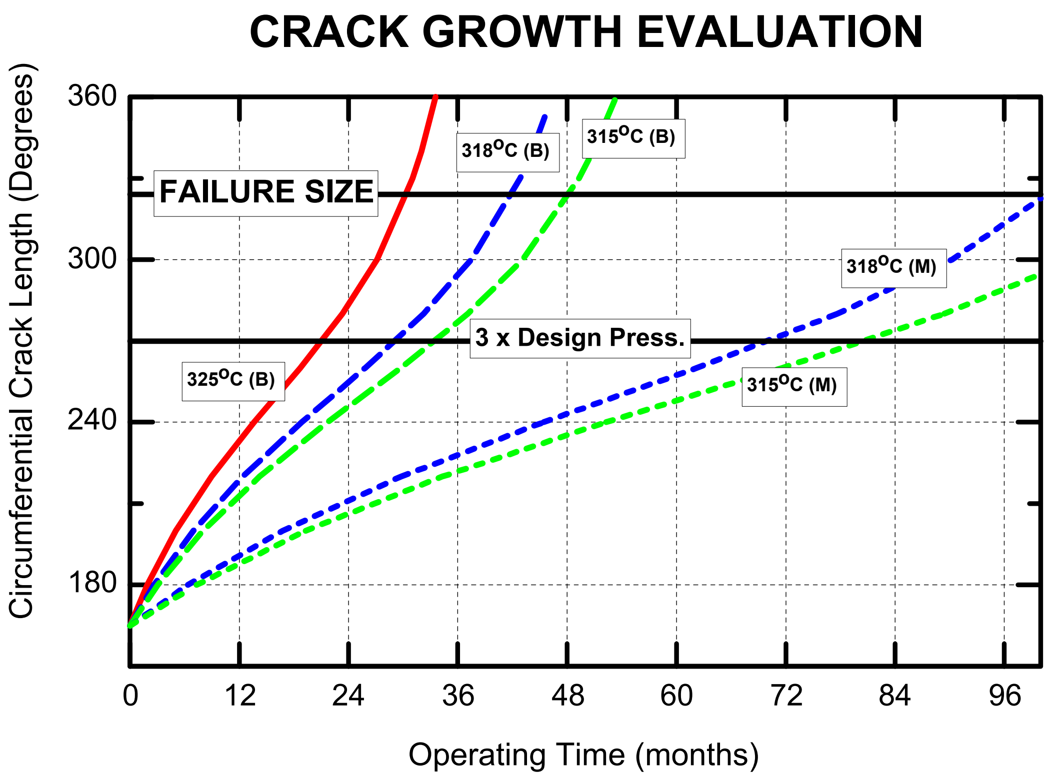

Figure 23 Crack growth analysis using various crack growth rate assumptions, from an initial flaw size of 165°. Although decreasing the temperature has some effect, the most dramatic increases in failure times occur with the mean crack growth curve instead of the 95/50 curve.

In some engineering analyses the approach is to use mean values of variables such as crack growth rate and then apply factors of safety, e.g,. three on pressure stresses, to account for uncertainties and variability in material properties. Figure 23 provides some interesting insights regarding the possible use of a mean value for crack growth rate and a factor of safety of three. First, as previously noted, the figure illustrates that the variability in crack growth rate is very large. The difference in predicted times to reach a 270° circumferential crack, corresponding to a factor of safety of three, is approximately 3.5 years. This has important implications regarding the effectiveness of an assumed factor of safety of three. For example, using the mean crack growth rate curve at 318°C with the "3 X Design Press" curve, would result in an acceptable operating time of approximately 6 years. However, if the crack being analyzed grew at the 95/50 growth rate for 318°C, the crack would reach the actual failure size in approximately 4.5

years. Thus, a larger factor of safety than three would need to be applied when utilizing the mean crack growth rates in order to account for the large variability in crack growth rate.

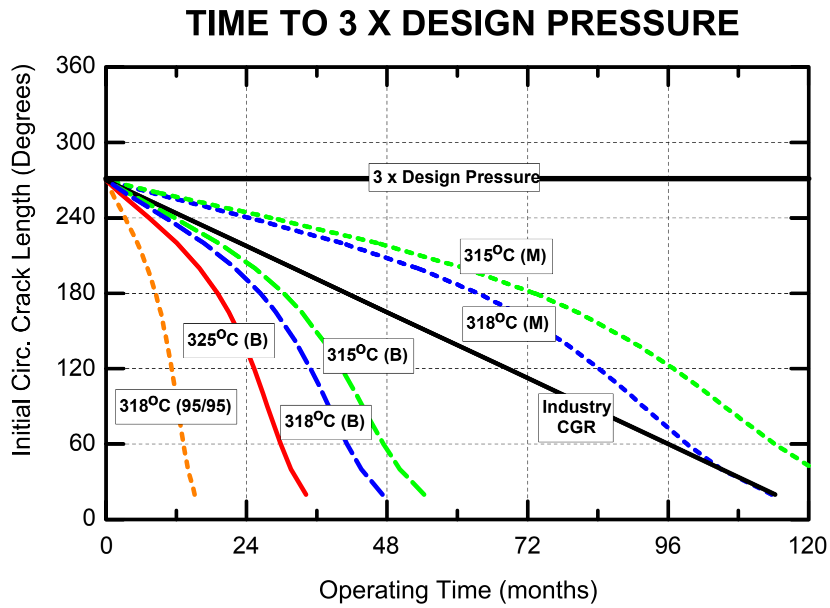

Figure 24 Comparison of time to reach the flaw size representing three times the design pressure, for a variety of crack growth rates and as a function of initial flaw size.

6.4 Conclusions From Deterministic Calculations

From the base case deterministic analysis, nozzles operated at temperatures no higher than 318°C (605°F) could have circumferential flaws grow from a very small size to a size that would not sustain a safety margin of three on the design pressure within about four years from the initiation of the flaw. Continued growth of this flaw for another 12 months would result in the flaw reaching a size that could result in a failure of the nozzle and nozzle ejection. These conclusions are based on a 95/50 crack growth curve. Using a mean curve for the high susceptibility materials would give operating times of 10 years or more from the initiation of cracking, whereas using a 95/95 crack growth rate curve would predict acceptable operating times of two years or less.

As indicated above, the variability in crack growth rates for Alloy 600 in PWSCC conditions is very large and results in significant differences in predicted times to failure based on various assumed statistical growth rate values. A traditional factor of safety of three on design pressure may not be sufficient to account for the large variability in growth rates for PWSCC in CRDM nozzles.

The growth rate of PWSCC cracks in CRDM nozzles is also very sensitive to the operating temperature of the component. As illustrated in Figures 24 and 25, the effect of decreasing the operating temperature by 3°C (5°F) can reduce the projected failure times by six months or more. The sensitivity of the crack growth rate to operating temperature indicates the need to confirm the RPV head operating conditions that are assumed for each plant.

7.0 PROBABILISTIC ASSESSMENT

Application of the results of the deterministic assessments described in Section 6.2 requires making important assumptions such as the sizes of flaws that could exist at various times in the life of a plant and appropriate statistical values to use for crack growth rates. Probabilistic assessments can provide valuable insights that can assist in making these assumptions and for effectively applying the results of the deterministic analyses. Assessments of particular interest include: 1) an assessment of the statistical distributions associated with the number and size of cracks expected at any time in the life of a plant, and 2) an assessment of the probabilities of failure associated with the various failure curves presented in Section 6.2.

One approach to the first assessment would be to model the entire cracking process from initiation of inside surface cracks in the J-groove weld or inside diameter of the VHP nozzle to development and growth of circumferential cracks. However, this approach requires a better understanding than currently exists of the complete cracking process, and additional data to support constructing such a model. An alternative approach is to assess the number and size of cracks based on in-service inspection data. The empirical approach appears more promising at this time than trying to construct a complete phenomenological model; however, it also has limitations, in this case the availability of reliable inspection data. The major challenge with the latter approach is acquiring sufficiently reliable data on the number and size of cracks found in service such that it is possible to determine the appropriate forms and parameters of statistical distributions to use. Acquiring reliable data on the size of cracks is limited because of the current state of qualification of volumetric examination methods with regard to sizing, and the high cost of destructive examinations to determine crack sizes. The staff has initiated work in this area and will continue to pursue these approaches as the industry and on-going research activities provide more data.

The assessment of the probabilities of failure associated with the various failure curves presented in Section 6.2 is more straight-forward since the only random variable involved is crack growth rate, and sufficient data exist for that variable to perform meaningful statistical analyses. The staff is currently developing an analysis to provide the failure probabilities associated with the failure curves developed in the deterministic analyses. Of course, these probabilities will be conditional on the initial flaw size.

Ultimately, analyses such as those described above need to provide frequencies of failure (rather than probabilities) that can be used with estimates of the conditional core damage probability in a decision-making process similar to that of Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis." It is important to continue to pursue these types of analyses in order to support development of the long term programs for managing VHP nozzle cracking.

8.0 INSPECTION TIMING

The results of the analyses presented in Section 6 are intended to help inform decisions regarding both the initial and subsequent timing of inspections. Several important assumptions are necessary to make such an assessment. This section provides a discussion of some of the key considerations involved in such evaluations.

In order to use the results presented in Section 6, one must first assess whether or not it is reasonable to assume that a circumferential crack exists in a VHP nozzle at a plant. NRC Bulletin 2001-01 assumed that there is a high likelihood that cracking could be occurring in plants exhibiting high susceptibility to PWSCC as evidenced by a susceptibility ranking of less than 5 EFPY from the ONS-3 condition. Results of inspections performed support this assumption. As of November 3, 2001, 8 of 9 high susceptibility plants (including one moderate susceptibility plant) that have performed inspections have detected cracking, and three of these plants had circumferential cracking. Therefore, it is reasonable to assume that some degree of circumferential cracking may exist in high susceptibility plants that have not performed inspections. Results from inspections planned at moderate susceptibility plants will provide data that can be used in the future to assess that category of plants.

High susceptibility plants that have performed effective inspections (e.g., qualified visual, surface or volumetric examinations of 100 percent of the VHP nozzles), and have affected repairs of leaking nozzles, should have a higher level of assurance that the cracking has not progressed to the point of throughwall cracking and development of circumferential cracks in the remaining unrepaired nozzles. However, it should be recognized that new circumferential cracks could develop in the next operating cycle.

Thus for high susceptibility plants that have performed inspections, Figures 23 through 25 can be used to determine the necessary inspection frequency. Of course, it must be decided what level of confidence on the crack growth model is appropriate. For example, utilizing the 95/50 curve for 318°C and assuming that any circumferential crack that may have been returned to service was small or that a circumferential crack just initiated when the plant was returned to power, Figure 24 would indicate that an inspection frequency of approximately 48 months, while the 95/95 curve would indicate an operating time of between inspection of less than 24 months. These curves can be used to assess what initial flaw size could grow to exceed the size that would meet the factor of safety of three on design pressure or grow to failure during the period of time between the last inspection and the proposed next inspection. It is expected that these types of evaluations, along with additional information regarding the reliability of various types of inspections, will be useful in developing long term inspection strategies.

For high susceptibility plants that have never performed an inspection, it is difficult to apply the results presented in Figures 23 through 25. Without some baseline inspection and absent reliable models to predict the time to crack initiation, there is little basis to assume a circumferential flaw size that could exist at a given point in time.

An important aspect of the evaluations described above is determining what level of confidence should be given to inspections. Expanding on the discussion in Bulletin 2001-01, the use of a qualified visual examination of 100 percent of the VHP nozzles represents the only “above-the-head” examination that is sufficient for detecting the existence of conditions that could lead to circumferential cracking of VHP nozzles. The qualified visual examination includes (1) a plant-specific analysis (using as-built dimensions or appropriate surrogates) which demonstrates that each nozzle has a leakage path that would permit deposits from throughwall nozzle cracking to become available on the RPV head for detection, and (2) implementation of a visual examination that is capable of detecting small boron deposits at the interface between the nozzle and the RPV head. This visual examination, sometimes called a “bare-metal visual examination,” requires access to the bare metal where the nozzle enters the RPV head, and the effectiveness of this visual examination must not be compromised by the presence of insulation, existing deposits on the RPV head, or other factors that could interfere with the detection of deposits indicative of primary coolant leakage from VHP nozzles.

Should the implementation of a qualified visual examination be impossible due to plant-specific considerations such as insulation configuration or pre-existing boric acid deposits that could mask the presence of deposits from VHP nozzle leaks, or an inability to provide the plant-specific analysis that would demonstrate leakage paths for each VHP nozzle, then implementation of “under-the-head” examination methods such as surface examinations (e.g., eddy current) or volumetric examinations (e.g., ultrasonic test) would provide reasonable assurance of the condition of the VHP nozzles for which the qualified visual examination cannot be performed.

The scope of inspections performed is also an important subject. The scope of inspections should include 100 percent of the nozzles and cover the entire surface or metal volume of interest. The surface of interest includes the “wetted surface” that comes into contact with the primary coolant during plant operation, including the nozzle inside diameter, the outside diameter below the J-groove weld, and the surface of the J-groove weld itself. This wetted surface examination is considered acceptable because it adequately addresses the first step of the multiple steps required to produce an OD circumferential crack above the J-groove weld, specifically the presence of leakage into the annulus via a throughwall crack. For a volumetric examination, the principal volume of interest is the OD of the nozzle above the J-groove weld, as a direct demonstration of the absence of such cracking.

For visual examinations completed by licensees prior to issuance of the Bulletin, the reliability of the visual examination as a qualified visual examination (as described above) can occur ex post facto with the successful demonstration of the presence of leakage paths in the nozzles using a plant-specific analysis. An inability to qualify the visual examination would place the plant in the same category as those plants that have not previously performed an examination of their VHP nozzles.

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