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Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555

SUBJECT: Responses to NRC Requests for Additional Information on Generic Letter 97-01

PROJECT NUMBER: 689

The NRC has issued PWR licensees requests for information (RAIs) on Generic Letter (GL) 97-01, *Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations*. The six groupings of RAIs are primarily categorized on the basis of PWR Owners Group membership and the model used by the licensee to assess head penetration crack initiation and growth. Due to the generic nature of the RAIs, the Alloy 600 Issues Task Group of the EPRI Materials Reliability Project chose to develop generic RAI responses for voluntary use by licensees. These generic responses are provided to the NRC staff because licensees may reference portions of the enclosures in their RAI responses.

The Alloy 600 Issue Task Group developed the generic responses with input from the PWR Owners Groups and EPRI. Efforts were made to use consistent responses when common RAI questions were asked. The content of the seven enclosures attached are:

Enclosure 1: The industry histogram that summarizes the predictive model results and identifies which plants have or will inspect their head penetrations

Enclosure 2: Responses to generic questions that apply to all PWR licensees (All six groupings of the RAIs contain generic questions or a question that applies to all PWR licensees. Since the generic questions were not always asked using the same text, the RAI generic questions have been paraphrased.)

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Enclosure 3: The responses for the RAI questions applicable to the Babcock and Wilcox Owners Group (B&WOG) members

Enclosure 4: The responses for the RAI questions applicable to the Combustion Engineering Owners Group (CEOG) members

Enclosure 5: The responses for the RAI questions applicable to the Westinghouse Owners Group (WOG) members

Enclosure 6: A discussion of the EPRI predictive model developed by Dominion Engineering, Inc.

Enclosure 7: A discussion of the Westinghouse predictive model

If you have questions, please contact Kurt Cozens at (202) 739-8085 or koc@nei.org.

Sincerely,

David J. Modeen

KOC/edb
Enclosures

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HISTOGRAM
OF
RPV HEAD NOZZLE ASSESSMENTS
AND
PLANT INSPECTION PLANS

HISTOGRAM OF RPV HEAD NOZZLE ASSESSMENTS AND PLANT INSPECTION PLANS

1.1 Introduction

The purpose of this document is to present a histogram (Figure 1) which compiles the PWR reactor pressure vessel (RPV) head penetration cracking assessments for all operating domestic PWRs (Combustion Engineering, Babcock & Wilcox, and Westinghouse designs). The histogram groups all plants into three categories representing the amount of time remaining (in effective full power years (EFPYs) from January 1, 1997) until the plants are calculated to have the same probability of having a crack at the allowable depth as DC Cook 2 had at the time the 6.8 millimeter deep crack was discovered in 1994. The three categories are 1) less than 5 EFPYs, 2) 5–15 EFPYs, and 3) more than 15 EFPYs.

1.2 Development of Histogram Based on Comparison to DC Cook 2

PWR RPV head penetrations were analyzed using models developed by the Electric Power Research Institute (EPRI) (see Enclosure 6) and by the Westinghouse Electric Company (see Enclosure 7). Both of these are probabilistic models which use the Monte Carlo method to handle uncertainties.

The histogram in Figure 1 is based on the cumulative probability of at least one penetration in the head of each plant having a crack at the allowable depth, typically 75% through-wall (see NRC Safety Evaluation Report addressed to NUMARC dated November 19, 1993). The analysis results are reported as the time (in EFPYs of operation from January 1, 1997) for each subject plant to reach a reference probability level. This reference probability was established using the results of the DC Cook Unit 2 inspection in 1994 and calculations made for DC Cook Unit 2 using the same methodology as for the subject plant. It is the probability that a 75% through-wall crack existed at DC Cook 2 at the time of its inspection. This probability is somewhat lower than that for the actual observed crack depth of 6.8 millimeters (43% through-wall), as illustrated in Figure 2.

By grouping the plants based on their relative probability of experiencing a flaw at the allowable depth, the results of both the EPRI and Westinghouse models were normalized and presented in the same histogram. The results plotted in Figure 1 show:

- Seven plants calculated to have the same probability of having a crack at the allowable depth as DC Cook 2 in less than 5 EFPYs after January 1, 1997.

- Sixteen plants calculated to have the same probability of having a crack at the allowable depth as DC Cook 2 in 5 to 15 EFPYs after January 1, 1997.

- Forty-six plants calculated to have the same probability of having a crack at the allowable depth as DC Cook 2 in more than 15 EFPYs after January 1, 1997.

The plant names in each of the three histogram categories are provided in Table 1 in alphabetical order within each category and separated by inspection status.

1.3 Discussion of Plant Assessments and Inspection Status

To date, six domestic plants have inspected some or all of the nozzles. These are DC Cook 2, North Anna 1, Oconee 2, Millstone 2, Point Beach 1, and Palisades. As reflected in the first row of Table 1, these six plants include plants in each of the three different histogram categories. DC Cook 2, North Anna 1, and Oconee 2 are in the group with highest calculated susceptibility, Millstone 2 and Point Beach 1 are in the group with intermediate calculated susceptibility, and Palisades is in the group of plants with lowest calculated susceptibility.

There are four other plants in the group with highest calculated susceptibility. These are Farley 2, Oconee 1, Oconee 3, and Surry 1. Farley 2 has plans to perform inspections. The remaining three plants in the highest susceptibility group are characterized by the licensee as "sister" plants to similar plants owned by the same licensee which have already inspected: Oconee 1 and Oconee 3 are lower calculated susceptibility "sister" plants to Oconee 2, while Surry 1 is a lower calculated susceptibility "sister" plant to North Anna 1. Consequently, all plants in the highest susceptibility group have inspected, have plans to inspect, or are lower susceptibility "sister" plants to units which have already inspected.

Four additional plants, which are in the intermediate susceptibility group, have planned inspections: Crystal River 3, Diablo Canyon 2, Ginna, and San Onofre 3. These inspections will provide additional assessment of the predictive models. Table 2 summarizes the above information.

Table 2. Summary of Plant Assessments and Inspection Status

Status	Assessment Groups		
	< 5 EFPYs	5–15 EFPYs	> 15 EFPYs
Inspected	3	2	1
Plans to Inspect	1	4	0
Sister Plants to Lead Units	3	--	--
Remaining Plants	0	10	45
Totals	7	16	46

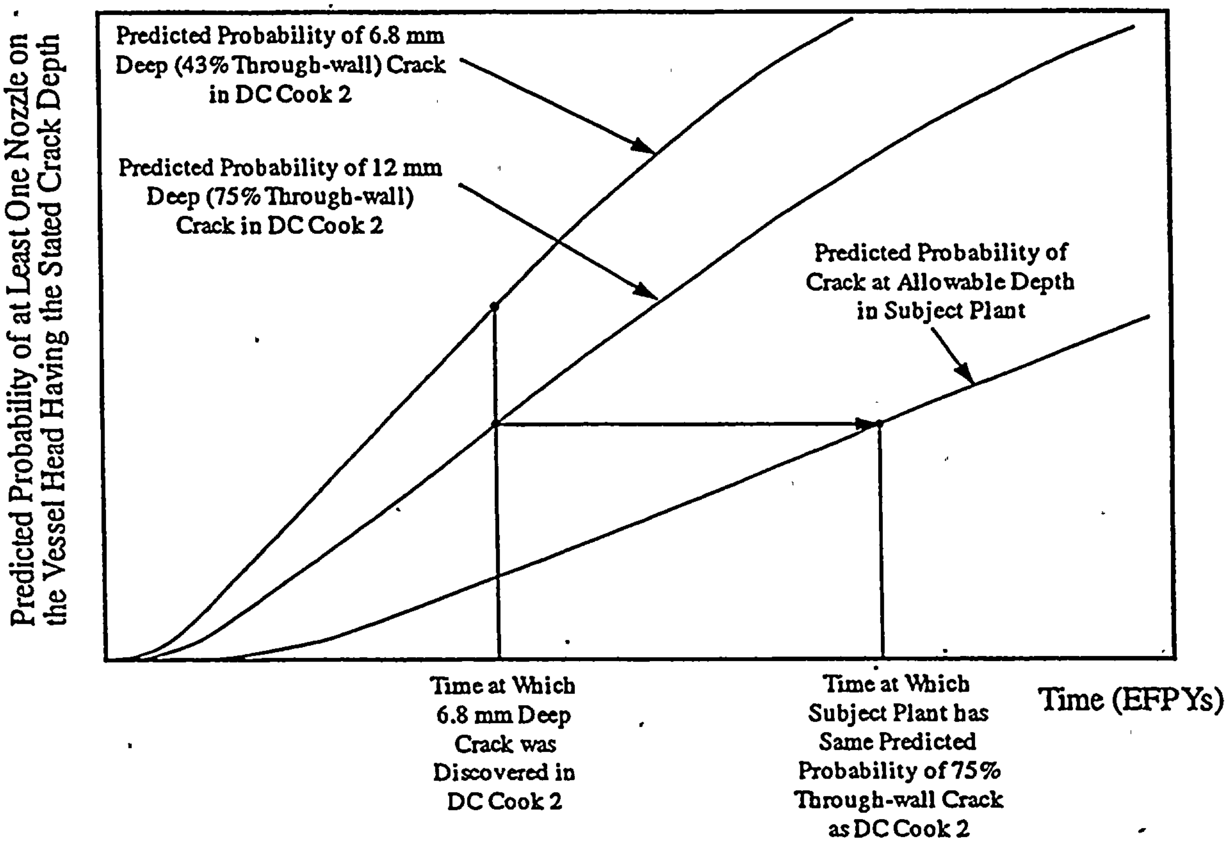

Figure 2. Method Used to Normalize Model Assessments

Table 1. Identification of Plants in Industry Histogram for RPV Head Nozzle PWSCC

Status	Assessment Groups*		
	< 5 EFPYs	5–15 EFPYs	> 15 EFPYs
Plants That Have Already Performed Inspections	DC Cook 2 North Anna 1 Oconee 2	Millstone 2 Point Beach 1	Palisades
Plants That Have Announced Plans to Inspect	Farley 2	Crystal River 3 Diablo Canyon 2 Ginna San Onofre 3	
Sister Plants to Lead Units That Have Already Inspected	Oconee 1 Oconee 3 Surry 1		
Remaining Plants		Beaver Valley 1 Beaver Valley 2 DC Cook 1 Davis Besse North Anna 2 Robinson 2 Salem 1 Surry 2 Turkey Point 4 Waterford 3	ANO 1 ANO 2 Braidwood 1 Braidwood 2 Byron 1 Byron 2 Callaway Calvert Cliffs 1 Calvert Cliffs 2 Catawba 1 Catawba 2 Comanche Peak 1 Comanche Peak 2 Diablo Canyon 1 Farley 1 Fort Calhoun Indian Point 2 Indian Point 3 Kewaunee McGuire 1 McGuire 2 Millstone 3 Palo Verde 1 Palo Verde 2 Palo Verde 3 Point Beach 2 Prairie Island 1 Prairie Island 2 Salem 2 San Onofre 2 Seabrook Sequoyah 1 Sequoyah 2 Shearon Harris South Texas 1 South Texas 2 St. Lucie 1 St. Lucie 2 Summer TMI 1 Turkey Point 3 Vogtle 1 Vogtle 2 Watts Bar 1 Wolf Creek

*Effective Full Power Years (EFPYs) from 1/1/97 until probability of having a crack at the allowable depth matches DC Cook 2 probability of one 75% through-wall crack at time of its 1994 inspection.

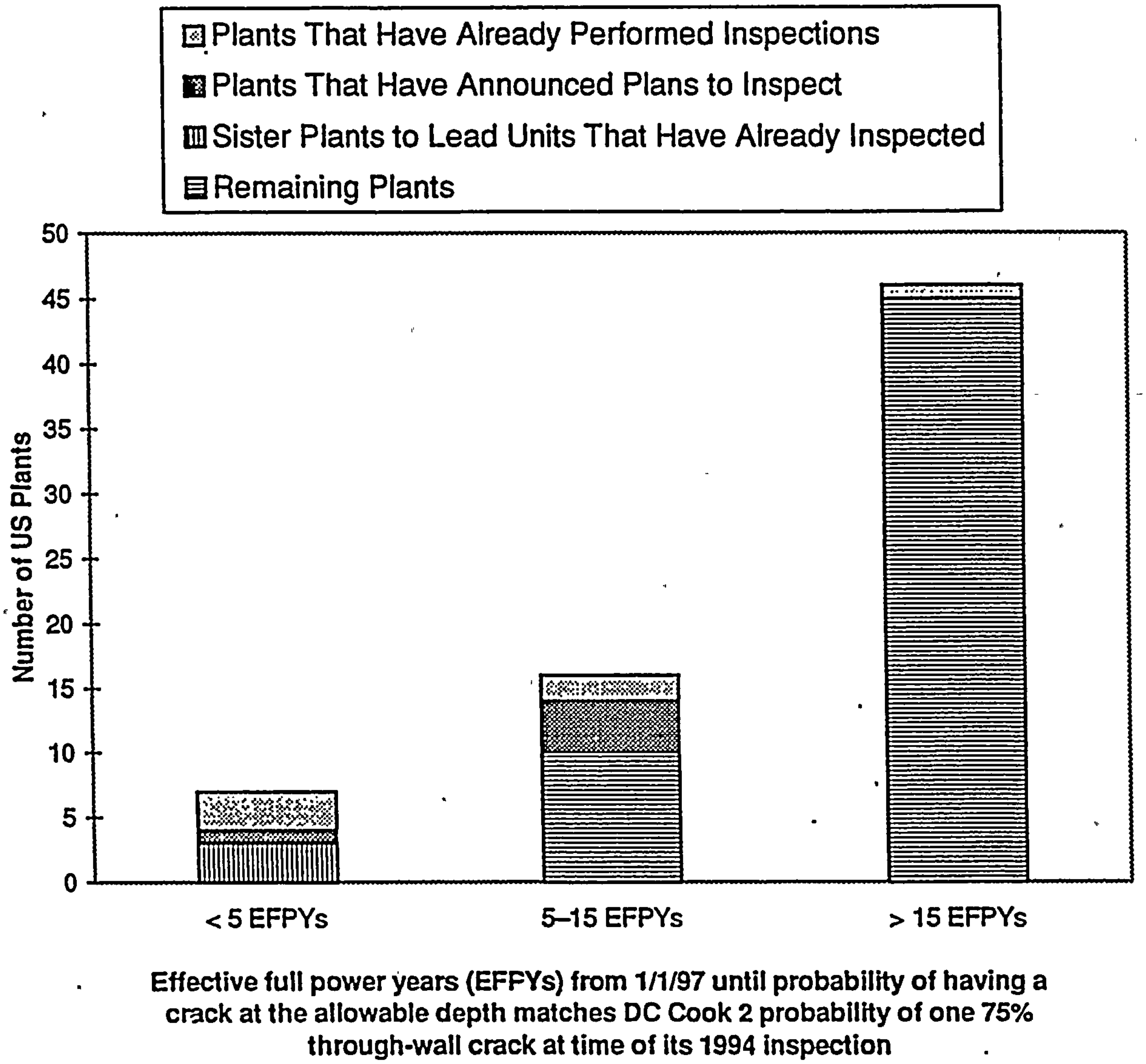

Figure 1. Industry Histogram for RPV Head Nozzle PWSCC

1.4 Summary

The above results can be summarized as follows:

- Six plants have inspected to date, including plants calculated to be in each of the three categories.

- There are seven plants in the group with highest calculated susceptibility. All seven of these plants have inspected, plan to inspect, or are "sister" plants to other lead units with higher computed susceptibility that have already inspected.

- A total of five plants plan to inspect over the next four years.

As additional inspection results become available, the industry Materials Reliability Project (MRP) will evaluate the results and take the necessary action to manage the issue.

RESPONSES TO GENERIC NRC REQUESTS FOR ADDITIONAL INFORMATION

This enclosure provides responses to the questions that are common to the six forms of NRC Generic Letter 97-01 Requests for Additional Information (RAIs). Descriptions of the EPRI and Westinghouse models are contained in Enclosures 6 and 7, respectively.

The RAI questions have been paraphrased to streamline and standardize the responses. The NRC has verbally agreed that these paraphrased questions are consistent with the original wording and may be used by licensees in their RAI responses. The order of the questions may be different than the order received by individual licensees.

QUESTION 1. "Describe how the variability in the product forms, material specifications, and heat treatments used to fabricate each CRDM/CEDM penetration are addressed in the crack initiation and growth models."

EPRI MODEL

RESPONSE 1.a. The EPRI model time-to-crack-initiation predictions for a subject plant are based on the results of inspections at plants which most closely resemble the subject plant in terms of material product form, material specification, material supplier, material heat treatment, and vessel head fabricator. This approach avoids the need for major corrections to reflect differences in material PWSCC susceptibility. Minor variations from nozzle to nozzle are accounted for statistically through the Weibull slope parameter and by applying a triangular distribution to the reference time to 10% probability of cracking. At the present time, EPRI considers that sufficient laboratory or field inspection data are not available to more precisely define the effect of product form, material specification, and heat treatment on the crack initiation rates. If proven correlations become available in the future, they will be included in the EPRI model. All EPRI model crack growth predictions are based on application of a log-triangular distribution to the available laboratory and field data corrected for temperature and stress intensity.

WESTINGHOUSE MODEL

RESPONSE 1.b. Since the Westinghouse probabilistic analysis models are mechanistically based, uncertainties are provided to directly account for the variability in such fabrication related input parameters as nozzle wall thickness, material grain boundary carbide coverage and monotonic yield strength. The Westinghouse mechanistic model also accounts for the variability in indirect fabrication related effects, such as the variation in surface roughness on crack initiation and the variation in the actual weld size on the local stress, where there is insufficient information to describe the causes and effects in a statistically

Enclosure 2

RESPONSES TO GENERIC NRC REQUESTS FOR ADDITIONAL INFORMATION

significant manner. Specifically, the model input also includes the observed uncertainties on the coefficients used to calculate residual stress, initiation time and crack growth rate.

QUESTION 2. *"Describe how the crack initiation and growth models for assessing postulated flaws in the nozzles were benchmarked, and list and discuss the standards that the models were benchmarked against."*

EPRI MODEL

RESPONSE 2.a. Benchmarking for crack initiation is performed using a *reference nozzle* concept. After each plant inspection is completed, the vessel head and nozzles are analyzed using the EPRI model to determine the time to 10% probability of cracking for a *reference nozzle* with a surface hoop stress level of 60 ksi and an operating temperature of 600°F which results in a 50% cumulative probability of the observed inspection results when corrections for differences in stress and temperature between the *reference nozzle* and the nozzles in the inspected plant are included. This information is then evaluated relative to the results of inspections for other plants to establish a time to 10% probability of crack initiation for each different group of nozzle materials.

Crack growth is benchmarked using reported crack growth rates obtained from controlled laboratory tests and field inspections corrected for differences in temperature and crack tip stress intensity. Please refer to the EPRI methodology description (Enclosure 6) for additional information on how the EPRI model is benchmarked.

WESTINGHOUSE MODEL

RESPONSE 2.b. The Westinghouse models and software used for the probabilistic analysis of reactor vessel head penetration nozzles were developed using the structural reliability and risk assessment (SRRA) methodology. The application of this SRRA methodology to piping risk-informed ISI was extensively benchmarked against hand calculations, available failure data and alternative calculations as described in WCAP-14572, Revision 1, Supplement 1 (October 1997). NRC is currently planning to issue a SER accepting this application of SRRA by the end of 1998.

As described in Table 4-2 of WCAP-14901 (July 1997), the SRRA probabilities for Alloy 600 PWSCC compare very well with inspection observations at four plants, where sufficient information existed to perform calculations for the worst head penetration nozzle at the time they were first inspected. While two of the plants (D. C. Cook 2 and Ringhals 2) with relatively high calculated probabilities had observed flaw indications, two other plants with lower calculated probabilities (Almaraz 1 and North Anna 1) did not. The initial WOG probabilistic model was revised as a result of the North Anna 1 inspection observations and an independent peer review by Alloy 600 PWSCC specialists (Jim Begley and Brian Woodman) at APTECH Engineering in the spring of 1997.

__*QUESTION 3*__. *"Provide additional information regarding how the model will be refined to allow the input of plant-specific inspection data into the model's analysis methodology."*

EPRI MODEL

__RESPONSE 3.a__. Plant-specific inspection data are factored into the EPRI model predictions in two ways:

1. As each plant inspection is completed, the vessel head and nozzles are analyzed using the EPRI model to determine the time to 10% probability of cracking for a *reference nozzle* with a surface hoop stress level of 60 ksi and an operating temperature of 600°F which results in a 50% cumulative probability of the observed inspection results. These data are updated periodically and provided to users of the EPRI model software. If an inspection indicates a significant change in *reference nozzle* conditions, users are notified.

2. Once a plant has performed an inspection, the results of the plant-specific inspection, along with the results for other plants in the same nozzle material group, are used to establish a plant-specific reference for future predictions.

WESTINGHOUSE MODEL

__RESPONSE 3.b__. There are two kinds of variations that are considered in the Westinghouse probabilistic analysis: random and systematic. The random variation is that due to localized material variability and other effects with insufficient information available to completely characterize them. This could include the effect of the variation in surface roughness on crack initiation and the variation in the actual weld size on the local stress. For these types of uncertainties, a Bayesian updating process has been developed by Westinghouse that could be used to combine the prior distribution on time to failure, which gives the initial calculated probability of failure with time, with the observations from the inspection. The updated posterior distribution that is generated in this manner can then be used to generate an updated estimate of the probability of failure with time for each penetration that was inspected.

The systematic or mechanistic type variations, such as the time to crack initiation being inversely proportional to the stress to the 4th power, are included directly in the Westinghouse probabilistic model. If the observations from an inspection would differ significantly from what was calculated, then the basic model would need to be revised. This in fact has already occurred based upon the observations from the North Anna Unit 1 inspections. The revised model now provides calculated probabilities that are consistent with the current inspection observations (see previous response to question 1b).

QUESTION 4. *"Provide the latest model susceptibility ranking of your plant based on the model analysis results, including the basis for establishing the ranking of your plant relative to the ranking of other plants in your owners group analyzed using your model."*

EPRI AND WESTINGHOUSE MODELS

RESPONSE 4. For industry planning purposes, plants have been grouped into three categories based on the predicted time to reach the allowable flaw depth limit. These results are provided in the industry histogram provided as Enclosure 1:

QUESTION 5. *"Table 1-2 in WCAP-14901 provides a summary of the key tasks in the WEC vessel head penetration nozzle assessment program. The table indicates that tasks for 1) evaluation of mitigation methods, 2) crack growth data and testing, and 3) crack initiation characterization studies are still in progress. In light of the fact that the predictive models appear dependent in part on crack initiation and growth estimates, provide your best estimate of when these tasks will be completed, and describe how these activities relate to and will be used to update the susceptibility assessments at your plant."*

EPRI AND WESTINGHOUSE MODELS

RESPONSE 5. The programs on crack growth testing and crack initiation have been essentially completed, and the program on mitigation is now underway and targeted for completion in mid-2000. These programs have thus far served to confirm the assumptions used in the original safety evaluations and models. As additional information becomes available from the referenced testing, the models will be reviewed and updated as necessary. No major changes are anticipated.

Enclosure 3

B&WOG Responses
To
NRC Requests for Additional Information

B&WOG RESPONSES TO NRC REQUESTS FOR ADDITIONAL INFORMATION

The B&W Owners Group (B&WOG) developed a cooperative, integrated program in response to the Nuclear Regulatory Commission (NRC) Generic Letter 97-01 titled "Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations." This program is documented in the B&WOG Topical Report, BAW-2301, dated July 1997 (reference 1). The NRC subsequently issued to member utilities of the B&WOG requests for additional information (RAIs), which are summarized in reference 2, and the responses are provided below.

Questions and Responses Applicable to All B&WOG Member Utilities

Q1. Provide a description of how the various product forms, material specifications, and heat treatments used to fabricate each CRDM penetration nozzle at the B&WOG member utilities are handled in the CIRSE model.

The basic B&WOG response to this question is provided in Response 1.a of Enclosure 2. For clarification, the Electric Power Research Institute (EPRI) CHECWORKS™ Reactor Pressure Vessel Head Nozzle Module (RHNM) model described in Enclosure 2 is an industry adaptation of the original CIRSE model software and uses the same inputs and assumptions as the CIRSE model cited in reference 1. A more detailed description of the EPRI model, than that provided in Appendix B of reference 1 for the CIRSE model, is provided in Section 3 of Enclosure 6.

The EPRI modeling approach, which is used by the B&WOG, predicts time to crack initiation for a particular plant based on the results of inspections at plant(s) that most closely resemble the particular plant in terms of material product form, material specification, material supplier, material heat treatment, and vessel head fabricator. For the B&WOG, the reference plant is currently Oconee Unit 2. As additional inspections are performed, these data will be incorporated into the reference plant(s) analysis (e.g., Crystal River Unit 3).

As stated in Section 2.2.1 of the B&WOG Generic Letter 97-01 response (reference 1), all of the existing 483 CRDM nozzles at the operating B&WOG plants were fabricated from the same product form (i.e., hot-finished seamless tubing) and from only 13 individual heats, which comprise 17 heat treatment lots, of Alloy 600 material. The Alloy 600 materials were either supplied by the Babcock & Wilcox Tubular Products Division (B&W-TPD) or by the International Nickel Company, Inc. Huntington Alloys Product Division (INCO). B&W-TPD manufactured 11 of the 13 heats of material (472 of the 483 CRDM nozzles), and B&W fabricated and installed all 483 CRDM nozzles. Therefore, relatively consistent material properties, such as microstructure, mechanical properties, material chemical composition, and as-fabricated surface finish were maintained for the CRDM nozzles installed at B&WOG plants. Also, only 11 CRDM nozzles were fabricated from the two heats of material supplied by the other material supplier (INCO). However, the differences in yield strength among the 17 heat treatment lots are used as input to the EPRI model to ascertain the inside surface hoop stress for each CRDM nozzle.

Obviously, there are heat-to-heat material variations in the B&W-design plants, as shown in Table 1 of reference 1. The triangular distributions and statistical treatment used in the EPRI model software were judged to be adequate for development of the B&WOG integrated inspection plan. When additional laboratory test and field inspection data become available, they will be evaluated and incorporated into the EPRI long-range planning model, as appropriate.

Q2. Provide any additional information, if available, regarding how the model will be refined to allow the input of plant-specific inspection data into the model's analysis methodology.

The basic B&WOG response to this question is provided in Response 3.a of Enclosure 2. In this manner, plant-specific inspection data applicable to the B&WOG (e.g., the Oconee Unit 2 re-inspection results and the Crystal River Unit 3 inspection results) is then factored into the model predictions.

These results, in addition to other planned U.S. industry inspections, worldwide industry experience, and economic factors, will be used to evaluate the time frame and need for future B&WOG plant inspections.

Additional details are provided in Section 3 of Enclosure 6.

Q3. Describe how FTI's crack initiation and crack growth models for assessing postulated flaws in vessel head penetration nozzles were benchmarked, and provide a listing and discussion of the standards the models were benchmarked against.

The B&WOG response to this question is provided in Response 2.a of Enclosure 2. Framatome Technologies, Incorporated (FTI) uses the EPRI crack initiation and crack growth models for assessing postulated flaws in vessel head penetration nozzles at B&WOG member plants.

Additional details are provided in Section 3 of Enclosure 6.

Q4. Provide the latest CIRSE model susceptibility rankings of B&W designed facilities based on the CIRSE model analysis results compiled from the analyses of the CRDM and instrumentation nozzles at the facilities.

The basic B&WOG response to this question is provided in Response 4 of Enclosure 2.

Since there are only two B&WOG plants (Oconee Unit 1 and Three Mile Island Unit 1) that each have eight thermocouple nozzles, the thermocouple nozzles have been evaluated independently and are addressed in the response to B&WOG member utility RAI question 5 below.

Questions and Responses Applicable to Duke Power Company for Oconee Units 1, 2, and 3 and GPU Nuclear, Incorporated for Three Mile Island Unit 1

Q5. Compare the overall susceptibility rankings of the thermocouple nozzles at ONS-1 and TMI-1 to that of the plants with the most susceptibly ranked CRDM penetration nozzles. Based on this assessment, indicate whether the thermocouple nozzles at ONS-1 and TMI-1 will be inspected during the year 2001 refueling outage. If it is determined that the thermocouple nozzles will not be inspected, provide the basis for omitting the inspections of the thermocouple nozzles in the year 2001.

As mentioned in reference 1, the RV head thermocouple nozzles (ONS-1 and TMI-1 only) are included in the integrated B&WOG inspection program. When the Generic Letter response was prepared in 1997, preliminary results of stress analysis indicated that these vessel head penetrations potentially ranked among the higher susceptibility nozzles at the B&WOG plants. Based on those preliminary results, inspections of the thermocouple nozzles were tentatively scheduled for 2001 at both ONS-1 and TMI-1.

Since that time, additional analytical evaluations have been performed, and it has been concluded that the thermocouple nozzles are still ranked among the higher susceptibility nozzles for the reactor vessel head nozzle population (e.g., ONS-2 and CR-3). However, the predicted integrated probability of at least one nozzle cracking of the eight thermocouple nozzles at ONS-1 is less than that predicted for the high susceptibility CRDM nozzles at ONS-2 and CR-3. For the thermocouple nozzles at TMI-1, the integrated probability of cracking is notably less. In addition, the following items provide further justification for concluding that the thermocouple nozzles are not of significant concern in the short term:

1. The thermocouple nozzles are attached to the reactor vessel head using a partial penetration weld. The predominant mode of cracking with this type of weld has been shown, both by finite element analysis and PWSCC experience, to be axially oriented. Circumferential cracking has occasionally been observed to initiate on the surface of some nozzles (e.g., pressurizer nozzles) and shown not to propagate beyond a very shallow depth.

2. The thermocouple nozzles are not shrunk fit into the reactor vessel head penetration prior to welding, and therefore a diametrical gap (approximately 5 mils) exists between the thermocouple nozzle and the reactor vessel head

penetration. Therefore, should any amount of leakage occur, it would be readily observable.

3. No known reaming or grinding operations were performed before welding, which would increase the PWSCC susceptibility of the thermocouple nozzles.

Therefore, it is concluded that no safety concern exists with the thermocouple nozzles.

Preliminary inspection plan activities are underway by Duke Power Company to inspect the thermocouple nozzles on the reactor vessel head of ONS-1; however, this inspection is planned for the end-of-cycle 20 outage in the spring of 2002, as there currently is no outage scheduled in 2001. Since TMI-1 has significantly less operating time than ONS-1, GPU Nuclear, Incorporated has decided to evaluate the thermocouple nozzle inspection results from ONS-1 before scheduling an inspection.

Questions and Responses Applicable to GPU Nuclear, Incorporated for Three Mile Island Unit 1

Q6. Given that the TMI-1 facility experienced an extended intrusion of thiosulfate ions into the TMI-1 RCS, and since the degradation of Alloy 600 steam generator tubes at TMI-1 has in part been attributed to this event, justify why the Alloy 600 CRDM penetration nozzles at TMI-1 are not being scheduled for volumetric inspection in the near term.

Response will be submitted directly by GPU Nuclear.

References

1. "B&WOG Integrated Response to Generic Letter 97-01: 'Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations'," BAW-2301, July 1997, available from Framatome Technologies, Inc., Lynchburg, Va.

2. "Request for Additional Information Regarding the Generic Responses from the Pressurized Water Reactor (PWR) Owners Groups to Generic Letter (GL) 97-01, 'Degradation of CRDM/CEDM Nozzles and Other Vessel Closure Head Penetrations'," Memorandum from J.F. Harold through S.S. Bajwa to NRR Project Directors, August 11, 1998, available in the Nuclear Regulatory Commission Public Document Room, Washington, D.C.

Enclosure 4

CEOG RESPONSES TO NRC REQUESTS FOR ADDITIONAL INFORMATION

CEOG RESPONSES TO NRC REQUESTS FOR ADDITIONAL INFORMATION

The Combustion Engineering Owners Group (CEOG) provided a generic response (CE NPSD-1085, "CEOG Response to NRC Generic Letter 97-01, Degradation of CEDM Nozzle and Other Vessel Closure Penetrations", July 1997) to NRC Generic Letter 97-01.

The NRC subsequently issued to CEOG members requests for additional information (RAIs) on the CEOG methodology for determining the susceptibility of vessel head nozzles to PWSCC. The RAIs noted that the NRC had informal information indicating that the CEOG had decided to change the methodology for evaluation of vessel head penetration susceptibility to PWSCC from the model described in detail in CE NPSD-1085 to a new EPRI model. The CEOG has decided that the most appropriate manner to respond to the RAIs is through an integrated response, as suggested by the NRC. The CEOG responses to the RAIs addressed to its member utilities are as follows (questions are paraphrased):

Question 1. *Specify whether the ABB-CE PITM model or the EPRI model is being endorsed for the assessment of CEOG plants.*

<u>Response</u>

The CEOG now endorses the use of the EPRI model for the assessment of PWSCC in Alloy 600 reactor vessel head penetrations. The use of this model and the results generated from its application supersede those of the probabilistic inspection timing model (PITM) described in CE NPSD-1085.

CE NPSD-1085, in responding to GL 97-01, noted that the PITM was used in selecting which CEOG plants to inspect and the timing associated with the inspections. The PITM was developed in 1993 to evaluate the susceptibility to PWSCC of all CEDM and ICI nozzles in all CEOG plants. The PITM addressed crack initiation and crack propagation to determine the time for a crack to grow to a detectable size and to propagate completely through wall. The PITM used

(a) a two parameter Weibull model to predict time-to-crack initiation for individual nozzles with estimates for the scale and shape parameters being derived from operating experience with small diameter Alloy 600 nozzles in CE plants.

(b) a power law fracture mechanics model for crack propagation.

(c) Monte Carlo simulation to calculate the risks of cracks or leaks for all nozzles in a specific head considering uncertainties in the input parameters and varying susceptibilities of nozzles to PWSCC.

After issuance of CE NPSD-1085, the CEOG compared the PITM with newer industry models and determined that the PITM needed to be upgraded or replaced with a newer model. The CEOG contracted EPRI to provide a new model which is described in Enclosure 6. This is the PWSCC susceptibility model that the CEOG is now endorsing and was the model used to develop the CEOG input to the industry histogram that is being submitted to the NRC along with this document.

The EPRI model general characteristics are the same as those of the CE PITM model described above - i.e., it uses

(a) a two parameter Weibull distribution to predict time to initiation.

(b) a power law fracture mechanics relationship to predict crack growth.

(c) a Monte Carlo analysis to calculate the integrated risk of cracks for an entire nozzle population considering the uncertainties in input parameters and varying PWSCC susceptibility of individual nozzles.

Unlike the CE model, the EPRI model permits utilities to evaluate the risk of cracking and the costs for a number of alternative strategies to address the cracking issue. Aside from an economic modeling capability, the EPRI model includes many enhancements not available in the PITM. Some of these include:

- use of Weibull distributions of head nozzle cracking data from "reference plants", which have performed inspections, to predict time to cracking in plants which have not inspected.

- improved estimates of head nozzle temperatures, obtained from a recent study to define the temperature of each CEOG plant.

- improved estimates of nozzle ID surface stresses for all CEDM and ICI nozzles based on 57 finite element analyses as compared to four FEA in the PITM.

- crack growth relationship supported by data from several laboratory test programs, including the EPRI program, and data from several plants in France.

- a correction to account for product form (bar forgings versus pipe) and fabrication practice, using the reference plant approach.

- predictions for other nozzles, such as the small diameter head vent nozzles in CEOG plants.
- improved bench marking of the model
- capability to incorporate plant specific inspection data
- flexibility to easily incorporate additional correction factors (such as for material microstructures, water chemistry effects, additional fabrication effects, etc. if appropriate correlations for these effects are developed) into the predictions.

Question 2. *Indicate how the model being endorsed relates to the CEOG integrated program and whether the model is consistent with Topical Report CE NPSD-1085.*

<u>Response</u>

The EPRI model is being used by the CEOG as part of the integrated inspection program and it supports the previous selection of CEOG plants for head nozzle inspections.

CE NPSD-1085 indicated that the plants with the highest susceptibility to PWSCC based on PITM predictions, were Millstone-2, San Onofre-3 and Palisades. These plants had the fewest EFPH to predicted nozzle through-wall cracking of all CEOG plants. CE NPSD-1085 indicated that these plants had inspected their head nozzles (Palisades, a partial inspection) or were planning to inspect at the next refueling outage. Millstone-2 did complete an inspection of all CEDM and ICI nozzles in August 1997 and San Onofre-3 has an inspection of all head nozzles planned for the next refueling outage (Spring, 1999).

When the 14 CEOG plants were re-analyzed in 1998 with the EPRI model, the top four plants in susceptibility to PWSCC from the prior analysis remained the top four plants. Three of these (Millstone-2, San Onofre-3 and Waterford-3) fall into Category 2 (5 to 15 EFPY from 1/1/97 to reach Section XI depths) of the industry histogram and the fourth (Palisades) falls into Category 3 (greater than 15 EFPY to reach Section XI depth). Thus, the results from the new model are consistent with the prior model results as described in CE NPSD-1085 and support the selection of plants for inspection as described in that document. In summary, the EPRI model supports the previously announced CEOG integrated inspection program.

Additional inspections beyond those described in CE NPSD-1085 are not currently scheduled. The CEOG number utilities will monitor reactor vessel inspections at CEOG plants and at other domestic PWRs and use results from these inspections to evaluate the need for future inspections of additional plants or re-inspections of plants that have already inspected. The EPRI model will be a tool in these evaluations.

Question 3. *Describe how the variability in the product form, material specifications, and heat treatment are addressed in the models.*

Response

The CEOG response to the question on PWSCC model treatment of variability in product forms, specifications and heat treatments is provided by the Response 1.a to Question 1 of Enclosure 2.

Question 4. *Describe how the crack initiation and growth models were benchmarked.*

Response

The CEOG response to the question on bench marking of the PWSCC initiation and growth model is provided by the Response 2.a to Question 2 of Enclosure 2.

Question 5. *Provide additional information regarding how each model will be refined to consider inspection data.*

Response

The CEOG response to the question on PWSCC model refinement to include plant specific inspection data is provided by the Response 3.a to Question 3 of Enclosure 2.

Question 6. *Provide the latest model susceptibility rankings, including the basis for comparing plants within each group.*

Response

The CEOG response to the question on the latest model susceptibility rankings for the CEOG plants is included in the response to Question 4 of Enclosure 2.

WOG RESPONSES
TO
NRC REQUESTS FOR ADDITIONAL INFORMATION

WOG RESPONSES TO NRC REQUESTS FOR ADDITIONAL INFORMATION

I. Responses to Generic RAI Questions

This section provides responses to questions in the NRC Generic Letter 97-01 Requests for Additional Information. These include responses to four generic questions posed to all plants and one question regarding the effect of ongoing laboratory tests posed to the WOG plants: This section also includes responses to owners group specific questions related to plant ranking, thermocouple nozzles, thiosulphate intrusions, etc. Additional supporting technical information regarding each of the models is presented in Enclosures 6 and 7 of this submittal, depending on the model used.

Q1. *"Describe how the variability in the product forms, material specifications, and heat treatments used to fabricate each CRDM/CEDM penetration are addressed in the crack initiation and growth models."*

R1. See Enclosure 2 Response to Question 1.

Q2. *"Describe how the crack initiation and growth models for assessing postulated flaws in the nozzles were benchmarked, and list and discuss the standards that the models were benchmarked against."*

R2. See Enclosure 2 Response to Question 2.

Q3. *"Provide additional information regarding how the model will be refined to allow the input of plant-specific inspection data into the model's analysis methodology."*

R3. See Enclosure 2 Response to Question 3.

Q4. *"Provide the latest model susceptibility ranking of your plant based on the model analysis results, including the basis for establishing the ranking of your plant relative to the ranking of other plants in your owners group analyzed using your model."*

R4. See Enclosure 2 Response to Question 4.

Q5. *"Table 1-2 in WCAP-14901 provides a summary of the key tasks in the WEC vessel head penetration nozzle assessment program. The table indicates that tasks for 1) evaluation of mitigation methods, 2) crack growth data and testing, and 3) crack initiation characterization studies are still in progress. In light of the fact that the predictive models appear* *dependent in part on crack initiation and growth estimates, provide your best estimate of when these tasks will be completed, and describe how these activities relate to and will be used to update the susceptibility assessments at your plant."*

R5. See Enclosure 2 Response to Question 5.

II. Responses to RAI Questions Specific to WOG Member Plants

Westinghouse Owners Group members each made separate submittals in response to Generic Letter 97-01. Some of the utilities used the Westinghouse methodology, and others chose to use the EPRI methodology. Those who used the Westinghouse methodology either submitted or referred to WCAP 14901 to describe the methodology.

The requests for additional information which have been issued for the Westinghouse plants fell into two categories: those that apply to all plants, and those that apply to Westinghouse plants only. The generic questions have been answered separately; this section contains the answers to the those questions which apply to the Westinghouse plants.

Q1. *In the NEI letters of January 29, 1998 (Ref. 1), and April 1, 1998 (Ref. 2), NEI indicated that inspection plans have been developed for the VHP nozzles at the Farley Unit 2 plant in the year 2002, and the Diablo Canyon Unit 2 plant in the year 2001, respectively. The staff has noted that although you have endorsed the probabilistic susceptibility model described in WCAP-14901, Revision 0, other WOG member licensees have endorsed a probabilistic susceptibility model developed by an alternate vendor of choice. The WOG's proposal to inspect the VHP nozzles at the Farley Unit 2 and Diablo Canyon Unit 2 plants appears to be based on a composite assessment of the VHP nozzles at all WOG member plants. Verify that such a composite ranking assessment has been applied to the evaluation of VHP nozzles at your plant(s). If composite ranking of the VHP nozzles at WOG member plants have been obtained from the composite results of the two models, justify why application of the probabilistic susceptibility model described in WCAP-14901, Revision 0, would yield the same comparable rankings of the VHP nozzle for your plant(s) as would application of the alternate probabilistic model used by the WOG member plants not subscribing to WCAP-14901, Revision 0. Comment on the susceptibility rankings of the VHP nozzles at your plant(s) relative to the susceptibility rankings of the VHP nozzles at the Farley Unit 2 and Diablo Canyon Unit 2 plants.*

R1. The announcement of inspection plans by individual WOG plants is the result of each individual plant's economic situation, along with their future operational plans. The individual plant results are all compared in the histogram in Enclosure 1. An individual plant's category in the histogram is one of the many considerations which must be evaluated in making inspection decisions.

Q2. Some WOG members have chosen to evaluate the vessel head penetrations for their facilities according to a probabilistic methodology that was developed by another vendor of choice. WEC and WOG did not provide a description of the crack initiation and growth susceptibility model used for the assessment of WEC vessel head penetration (VHP) nozzles in plants endorsing WCAP-14902, Revision 0. Provide a description of the crack initiation and growth susceptibility model used for assessment of the VHP nozzles at your plant(s).

R2. The WOG members which chose not to use the Westinghouse model all used the EPRI model, whose methodology is described in Enclosure 6.

DESCRIPTION OF THE EPRI RPV HEAD NOZZLE PWSCC PREDICTIVE MODEL

(BASED UPON EPRI TR-103198-P8)

DESCRIPTION OF THE EPRI RPV HEAD NOZZLE PWSCC PREDICTIVE MODEL

Table of Contents

Section 1

Introduction

The purpose of this document is to describe the EPRI (Electric Power Research Institute) RPV (Reactor Pressure Vessel) head nozzle PWSCC (Primary Water Stress Corrosion Cracking) predictive model and to provide information supplemental to the responses to generic requests for additional information (located in Enclosure 2 elsewhere within this industry submittal).

The model described in this report was originally developed by Dominion Engineering, Inc., for several individual utilities and was known as the CRDM Nozzle PWSCC Inspection and Repair Strategic Evaluation (CIRSE) program. This model was later adopted by the B&W Owners Group and partially formed the basis for the B&WOG head nozzle inspection plan.

In 1997, the CIRSE model was selected by EPRI to be included in the EPRI CHECWORKS™ suite of software under the name RPV Head Nozzle Module (RHNM). The EPRI RHNM model is an extension of the previous CIRSE model using the same basic input and modeling assumptions. The model was extended to Combustion Engineering Owners Group plants in early 1998. This EPRI model has been used to provide input to the integrated industry histogram for the B&W Owners Group, the Combustion Engineering Owners Group, and 14 individual Westinghouse plants. All histogram assessments reported for the RHNM/CIRSE model were generated using a single, consistent basis. The completed software package, including strategic planning features, will be issued by EPRI to its member utilities in December 1998.

Section 2

Summary EPRI Model Description

The EPRI RHNM model assists utilities in managing the RPV Alloy 600 head nozzle PWSCC issue through prediction of crack initiation and growth. The fundamental methodology and modeling assumptions of the model are as follows:

- The EPRI model uses a Weibull distribution of RPV head nozzle cracking data for reference plants which have performed inspections in order to predict the time to crack initiation for subject plants which have not performed inspections. The crack initiation predictions include the capability to correct for differences in temperature, stress, materials, and fabrication practices between the subject and reference plants. A key factor in this approach is the selection of reference plants for the predictions which are as similar as possible to each subject plant with regard to materials and fabrication methods. This eliminates the need to make large corrections for significant differences in materials and fabrication variables.

- The EPRI model uses a power-law stress intensity equation to predict crack growth. This equation is based on results of field inspections and controlled laboratory tests corrected for differences in temperature and crack tip stress intensity.

- The EPRI model uses the Monte Carlo analysis method to calculate the integrated risk of cracks for the entire nozzle population on a vessel head taking into account uncertainties in input parameters and varying PWSCC susceptibilities among individual nozzles.

- The EPRI model allows utilities to evaluate the risk of cracking and cost for a number of alternative strategic plans to address this issue.

A more detailed description of the EPRI model follows in Section 3 of this document.

Responses relative to the EPRI model to questions in the NRC Generic Letter 97-01 Requests for Additional Information are located in Enclosure 2. These include responses to four generic questions posed to all plants and one question regarding the effect of ongoing laboratory tests posed to the WOG plants.

Section 3

Methodology and Modeling Assumptions

The following outlines the methodology and modeling assumptions of the EPRI RHNM model.

3.1 Monte Carlo Method

The model uses the Monte Carlo method of analysis. This method was selected since prediction of PWSCC must be treated as a statistical process, and it is desirable to assess the effect of a significant number of variables and alternative strategic plans.

The time to crack initiation, crack growth rate, and many other variables are defined by distributions of values rather than by singular values in order to reflect uncertainties. The Monte Carlo method allows each input parameter to have distributed values and provides a framework which allows calculations required for the risk assessment and economic analyses to be performed in a straightforward manner.

The Monte Carlo method establishes input values for each Monte Carlo trial by random sampling of the distributions for each variable being considered. While most random samples fall near the mean value of a given parameter, small percentages of the samples are extracted near the upper and lower bounds of the distribution.

The model analysis uses 12 distributed variables which are listed in Table 3-1. These variables include the time to 10% probability of cracking for the reference conditions, the Weibull slope, the stress level in the nozzles, the crack growth rate under standard conditions, etc.

The predictions of cracking for each scenario being evaluated are saved for each Monte Carlo trial so that they can be sorted or counted to produce cumulative output distributions. Sufficient trials are run so that each input distribution is well sampled. When a sufficient number of trials are chosen for the Monte Carlo method, successive runs of the same case, using a different set of random numbers, will yield essentially the same results.

Because the Monte Carlo method is a statistical approach, the output results are also in the form of statistical distributions. The EPRI model reports median, lower bound, and upper bound values from the output distributions. For example, one of the bounds can be set to produce the input data to the industry histogram, i.e., the probability of DC Cook 2 having had a 75% through-wall crack at the time that inspections were performed.

3.2 Crack Initiation Predictions

The EPRI model predicts the time when a nozzle develops a crack and the maximum crack depth within a nozzle as a function of time by combining crack initiation and crack growth models. This section discusses the model for time to crack initiation, and Section 3.3 describes the model for crack growth.

3.2.1 Statistical Model for Crack Initiation

The model predicts the time to crack initiation for a subject plant based on statistical results from inspections performed at plants with similar materials, materials processing methods, and fabrication methods. This avoids the need to make major corrections for differences in material processing, microstructure, and fabrication methods. However, corrections are made for differences in operating temperature and nozzle stresses, which can be quantified.

For example, the time to crack initiation in a plant with Huntington Alloys extruded nozzle material would be based on the results of inspections at other similarly constructed plants with similar Huntington Alloys material. These predictions would not be based on inspection results at EdF plants, which have forged nozzles and machined tapers or counterbores on the nozzle inside diameter.

3.2.2 Weibull Distribution to Describe Time to Crack Initiation

The EPRI model uses a two-parameter Weibull distribution to calculate the probability of crack initiation as a function of time:

$$F(t)=1-e^{-\left(\frac{t}{\theta}\right)^{b}} \quad \text{(eq. 3-1)}$$

where:

F	=	the probability of a particular nozzle cracking by time t
t	=	degradation time (operating time corrected for temperature variations)
θ	=	"characteristic time" to 63.2% probability of cracking
b	=	Weibull "slope" which represents scatter

The two-parameter Weibull distribution is an industry standard approach for this type of phenomenon and is frequently used to predict PWSCC in steam generator tubing [3.1]. Rather than using θ, the model uses a corresponding quantity, the time to 10% probability of a nozzle cracking $t_{10\%}$. A typical Weibull distribution is shown in Figure 3-1.

3.2.3 Relative Susceptibility Factor

Because the time to crack initiation is a function of material susceptibility (microstructure), amount of cold work during machining, surface stress, operating temperature, water chemistry environment, etc., the time to 10% probability of nozzle cracking for any reference plant must be corrected to account for differences in these variables between the subject plant and the reference plant. This is accomplished using a Relative Susceptibility Factor (*RSF*) which relates the PWSCC susceptibility of a subject nozzle to that of a *reference nozzle* (see Section 3.6 for a discussion of how the time to 10% probability of crack initiation is determined for *reference nozzles*):

$$t_{10\%} = \frac{t_{10\%,ref}}{RSF} \qquad \text{(eq. 3-2)}$$

$$RSF = \left(\frac{f_{chem}}{f_{chem,ref}}\right)\left(\frac{f_{fab}}{f_{fab,ref}}\right)\left(\frac{f_{mat}}{f_{mat,ref}}\right)\left(\frac{s_{sur}}{s_{sur,ref}}\right)^{x} \exp\left[-\frac{Q_i}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right] \qquad \text{(eq. 3-3)}$$

where:

$t_{10\%}$	=	time to 10% probability of crack initiation (used to calculate probability F in eq. 3-1)
RSF	=	relative susceptibility factor for scaling $t_{10\%}$
f_{chem}	=	water chemistry factor (constant for all nozzles in a unit)
f_{fab}	=	nozzle fabrication factor (to account for undesirable surface conditions caused during fabrication)
f_{mat}	=	material factor (constant for all nozzles of a given heat)
s_{sur}	=	maximum inside surface hoop stress
x	=	stress exponent
Q_i	=	activation energy for crack initiation (kcal/mole)
R	=	gas constant = 1.103×10^{-3} kcal/mole·°R
T	=	absolute nozzle operating temperature (°R)

<u>Note</u>: the "ref" subscripts denote the reference plant values

3.2.4 Corrections for Differences in Material PWSCC Susceptibility

Differences in material susceptibility are addressed by selecting a reference Weibull distribution from an inspected plant which has nozzles produced by the same supplier at about the same point in time and using the same material processing and fabrication parameters as the subject plant. This avoids the need to make large adjustments for differences in materials (e.g., chemical composition, microstructure, etc.) and fabrication practices. Accordingly, the material and fabrication factors for the subject and reference nozzles are currently taken as 1.00. If future plant operating experience and laboratory testing confirm the need for different material and fabrication factors, then these factors can be directly input into the EPRI model.

3.2.5 Corrections for Differences in Operating Temperature

It is known that temperature is a key variable which affects time to crack initiation and crack growth. For example, many steam generators have significant amounts of cracking at expansion transitions on the hot leg side but essentially no cracking of identical transitions on the cold leg side. Similarly, several plants have experienced PWSCC of Alloy 600 instrument nozzles in hot leg piping without having any reported PWSCC in essentially identical nozzles in cold leg piping.

The difference in operating temperature between the subject and reference plants is taken into account by an activation energy model. Experimental and field data suggest that the thermal activation energy for crack initiation is in the range of 44–53 kcal/mole [3.2]. A recent summary paper by Staehle [3.3] suggests 50 kcal/mole. A nominal value of 50 kcal/mole has been used for the EPRI model calculations.

In many cases, plants have operated at essentially a constant hot leg temperature over the plant life such that the effective PWSCC degradation time can be taken as the actual plant running time in effective full power years (EFPYs). However, if a unit has operated for extended periods at different hot leg temperatures, then the effective full power years must be corrected for these temperature changes. For these cases, the model assumes the current operating temperature, and the EFPYs are adjusted as necessary to reflect the temperature changes.

3.2.6 Corrections for Differences in Nozzle Stresses

It is known that inside surface stress (residual plus operating) is a key variable in establishing time to crack initiation. This has been demonstrated by researchers [3.4, 3.5, 3.6, and 3.7] and confirmed by several field observations:

- cracking tends to occur first in outer row nozzles which typically have the highest calculated stresses,

- cracking has been axial and located on the uphill and downhill sides of the nozzles as predicted by stress analyses, and

- cracking has tended to occur most rapidly in nozzles with large welds.

EPRI has performed elastic-plastic finite element stress analyses of a wide range of CRDM, CEDM, and ICI (in-core instrumentation) nozzles using identical modeling assumptions with parametric-type material yield strength and geometry inputs [3.8]. The analysis of each nozzle geometry has been performed for several different material yield strengths.

The EPRI RHNM model corrects for differences in stresses between the subject and reference nozzles in the following manner.

- For cases where there are a limited number of nozzles of each basic configuration (e.g., ICI nozzles in Combustion Engineering plants), the EPRI model uses the finite element analysis results for the particular nozzle design and weld geometry in the analysis. The software interpolates results for intermediate yield strengths not explicitly analyzed.

- For cases where there are many similar but not identical nozzles designs (e.g., CRDM nozzles in Westinghouse plants), the EPRI model uses algorithms based on the results of the finite element analysis work on representative nozzles which predict the peak nozzle inside surface hoop stresses as a function of key variables such as nozzle yield strength, incidence angle in the vessel head, weld size, weld distribution (geometry), etc.

Differences in predicted stress level between a subject nozzle and the *reference nozzle* are accounted for by taking the ratio of stresses between the subject and reference nozzles to a power with the mean value of four. This exponent is based on the work reported by van Rooyen, Yonezawa, and Seman [3.5, 3.6, and 3.7].

3.2.7 Corrections for Differences in Fabrication Methods

The EPRI model is based on using reference plants for PWSCC predictions which are as similar to the subject plant as possible. This includes having been fabricated by the same vendor at approximately the same point in time. Accordingly, the fabrication factors for the subject and reference nozzles are currently taken as 1.00. As mentioned previously, if future plant operating experience and laboratory testing confirm the need for different material and fabrication factors, then these factors can be directly input into the model.

3.2.8 Corrections for Differences in Plant Water Chemistry

At present, the industry consensus is that there is no significant effect of primary water chemistry on Alloy 600 PWSCC within normal industry allowable water chemistry limits. Therefore, normal variations in water chemistry between the subject plant and the reference plant(s) do not affect PWSCC susceptibility significantly, and the water chemistry factors for the subject and reference nozzles are taken as 1.00.

3.2.9 Final Crack Initiation Model

The following equation is used to establish the Weibull distribution of time to 10% probability of crack initiation in a subject nozzle. The key factor $t_{10\%,ref}$ represents the *reference nozzle* for plants with the same basic material and fabrication parameters.

$$t_{10\%} = \frac{t_{10\%,ref}}{\left(\frac{s_{sur}}{s_{sur,ref}}\right)^{x} \exp\left[-\frac{Q_i}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]} \qquad \text{(eq. 3-4)}$$

3.3 Crack Growth Predictions

The EPRI model predicts crack growth using the power-law fracture mechanics model which has become the accepted industry standard for RPV head nozzle PWSCC [3.9].

3.3.1 Power-Law Fracture Mechanics Crack Growth Model

The power-law fracture mechanics crack growth model is given by the following expression:

$$\dot{a} = A(K - K_{th})^{n} \qquad \text{(eq. 3-5)}$$

where:

$\dot{a}$ = rate of crack depth increase (m/s)

A = growth rate constant (amplitude) (m, s, MPa)

K = nozzle maximum stress intensity (MPa$\sqrt{m}$)

= $1.1 s_{mid}\sqrt{\pi a}$

where:

a = crack depth

s_{mid} = mid-wall hoop stress

K_{th} = stress intensity threshold

n = power-law exponent

The effect of temperature on crack growth is considered by scaling the growth rate constant A using an activation energy model:

$$A = A_{ref} \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{g,ref}}\right)\right] \quad \text{(eq. 3-6)}$$

where:

A_{ref} = reference value of A selected based on field and laboratory experience

Q_g = activation energy for growth (kcal/mole)

R = gas constant = 1.103×10^{-3} kcal/mole·°R

T = absolute nozzle operating temperature (°R)

$T_{g,ref}$ = reference temperature used to normalize field and laboratory experience

3.3.2 Reference Temperature for Plotting Crack Growth Rates

Since the crack growth rate is a function of the material temperature, laboratory and field crack growth rate data must be plotted at a common reference temperature for comparison purposes. For purposes of the EPRI model, the reference temperature has been taken as 325°C (617°F). This temperature is widely used for crack growth rate tests.

The most recent activation energy for crack growth in Alloy 600 materials in primary water environments reported by EPRI is 32.4 kcal/mole [3.10]. The nominal activation energy value used for the EPRI model is Q = 33 kcal/mole.

3.3.3 Modified Peter Scott Growth Equation

Early in the evaluation of cracking in Alloy 600 nozzles, Peter Scott of Framatome proposed an equation for crack growth based on laboratory tests conducted on steam generator tubing specimens [3.11]. The crack growth rates measured for the steam generator tubing specimens were later corrected to account for cold working of the specimens in preparation for the tests. The Scott model has been used by several organizations performing crack growth analyses. The most recent modified form of Scott's equation at 325°C [3.10] is:

$$\dot{a} = 2.23 \times 10^{-12} (K - 9)^{1.16} \quad \text{m/s (where } K \text{ is in MPa}\sqrt{\text{m}}\text{)} \quad \text{(eq. 3-7)}$$

A more recent paper by Amzallag and Scott [3.12] reports the crack growth model at 323°C to be:

$$\dot{a} = 5.6\times10^{-12}(K-9)^{1.16} \quad \text{m/s (where } K \text{ is in MPa}\sqrt{\text{m}}\text{)} \qquad \text{(eq. 3-8)}$$

This is about twice the amplitude reported in EPRI TR-109136 [3.10]. Both of these curves are plotted in Figure 3-2.

3.3.4 Threshold Stress Intensity

The Scott curve is computed using a threshold stress intensity of 9 MPa$\sqrt{\text{m}}$. However, it is known that cracks which initiate and grow through the cold worked region must eventually propagate into the base material. Assuming a 0.004 inch (0.1 mm) cold worked surface layer and a 30 ksi (207 MPa) stress in the base metal below the cold worked region, the threshold stress intensity for the crack to propagate would have to be as low as

$$\begin{aligned} K_{th} &= 1.1\sigma\sqrt{\pi a} \\ &= 1.1(207\,\text{MPa})\sqrt{\pi(0.0001\,\text{m})} \qquad \text{(eq. 3-9)} \\ &= 4.0\,\text{MPa}\sqrt{\text{m}} \end{aligned}$$

The EPRI model uses an assumed stress threshold of 4 MPa$\sqrt{\text{m}}$. As shown in Figure 3-2, this has the effect of producing a more conservative crack growth rate for lower stress intensities relative to the modified Scott curve.

3.3.5 Laboratory Crack Growth Rate Measurements

Tests have been performed by several laboratories to determine crack growth rates in Alloy 600 materials as a function of crack tip stress intensity. The results of these tests, corrected to 325°C, are plotted in Figure 3-2. The tests included are the following:

- Westinghouse laboratory tests [3.10]
- EdF laboratory tests [3.13]
- CIEMAT laboratory tests [3.14]

3.3.6 Field Crack Growth Rate Measurements

Results of field inspections have also been used to determine crack growth rates. This has involved 1) measurements of crack growth based on repeat inspections and 2) estimation of crack growth based on a predicted time to crack initiation and the growth rate required to achieve the final measured crack depth.

EdF has reported on repeat inspections of a number of cracked nozzles [3.12]. The temperature corrected results of the repeat measurements on hot head plants are plotted in Figure 3-2. These data show four points at or below and two points somewhat above the modified Scott curve (eq. 3-7). There were also several cracks in hot head plants which did not grow from one cycle to the next. These points were conservatively not plotted in the figure.

During refueling outage 9, nozzle no. 75 in the DC Cook 2 plant was found to have three flaws. The deepest flaw was reported to have a depth of 6.8 mm (0.268 inches) [3.15]. During refueling outage 10, the deepest flaw in nozzle no. 75 was inspected and reported to have grown to 7.3 mm (0.287 inches) depth. The crack growth rate for the deep crack in the DC Cook nozzle was estimated two ways.

- First, the measured crack growth between the two inspections was plotted relative to the crack tip stress intensity computed using the same model as for other EPRI model calculations. As shown in Figure 3-2, the resultant crack growth is well below the other data. While the depth was reported to have increased by 0.5 mm, it should be noted that this increase is within the typical inspection accuracy and might actually have been a little higher or lower.

- Second, it was assumed that the crack initiated at 6.0 EFPYs and grew to the measured 6.8 mm at outage 9. The crack growth curve, corrected for temperature differences, which would produce this assumed growth is also plotted in Figure 3-2. This growth is much higher than the measured growth rate between outages 9 and 10 suggesting that the rate of growth has decreased rather than increased with crack depth.

Cracks were discovered in several Ringhals 2 nozzles during an inspection in 1992. Cracks in nozzles located above the bottom of the weld were removed while cracks below the bottom of the weld were left in place. The cracks left in place were inspected in 1993 and again in 1994. Vattenfall has reported that there was no significant increase in the size of the flaws left in place [3.16].

3.3.7 *High Reported Crack Growth Rates in EdF Cold Head Plants*

The major reported exception to the activation energy model discussed in the preceding paragraphs is the rapid crack growth rate measured in EdF cold head plants. Amzallag, et al., have reported that there is essentially no difference in the measured crack growth rate between nozzles in cold head plants at 290°C (554°F) and hot head plants at 315°C (599°F) [3.12]. The activation energy model would suggest a factor of 3.5 times lower crack growth rate at the cold head temperature using an activation energy $Q = 33$ kcal/mole.

The cause of the significantly different crack growth behavior reported for materials in the EdF cold head plants is not known at present. Possible sources of the difference could include materials processing method (forging at low material temperatures without subsequent annealing) or uncertainty of the actual nozzle operating temperature in plants with small bypass holes through the internals flange. Because the reported behavior of these materials is inconsistent with other laboratory and field experience, including EdF's own crack growth testing, and because the EPRI model does not address EdF plants, the crack growth measurements for the EdF cold head plants are not plotted in Figure 3-2 or included in the subsequent evaluation.

3.3.8 *Curve Fitting to Laboratory and Field Data*

The scatter in the data in Figure 3-2 clearly suggests that crack growth should be considered to be a statistical process with a distribution of reference values. Figure 3-3 shows the empirical distribution of power-law constants *A* (thin line) for the 36 data points in Figure 3-2. (The DC Cook 2 reinspection point is an outlier and is conservatively excluded.)

A log-triangular distribution (see paragraph 3.5.3 below) with lower bound *a*, upper bound *b*, and mode (nominal) value *c*

$$A \sim \exp\{\text{triang}[\ln(a), \ln(b), \ln(c)]\} \qquad \text{(eq. 3-10)}$$

was fitted to the empirical distribution such that the two distributions had equivalent bounds and intersected at a cumulative fraction of 0.500 (median). The log-triangular distribution shown in Figure 3-3 fits the data well and is implemented in the model. A plain triangular distribution was found to fit the data poorly.

Figure 3-2 shows the median, upper bound, and lower bound crack growth rate curves based on the set of reference data. Note that the upper bound growth curve is conservative with respect to the EPRI-reported modified Scott curve, eq. 3-7, and essentially identical to the "upper bound" curve reported in Scott's most recent paper, eq. 3-8. The figure also shows crack growth rates of 1 and 3 mm/year for reference purposes.

3.4 Effect of Previous Inspections on Predictions

The continuity of the Weibull curve and the Monte Carlo analysis always results in a small but finite probability of early cracking which will be inconsistent with the absence of observed leakage during the standard Generic Letter 88-05 required leak detection walkdowns or with the absence of observed cracking during past NDE inspections of nozzle inside surfaces. Therefore, after the crack initiation and crack growth predictions are integrated on a statistical basis for each nozzle, the predictions are modified ("truncated") as necessary to be consistent with the results of past leak detection walkdowns and NDE inspections of individual nozzles such that

- there are no predicted leaks at the most recent outage where visual inspections of the head did not show a leak, and
- there are no predicted cracks at the most recent outage where nondestructive examinations of the nozzle inside surfaces showed that no cracks existed.

"Truncation" lowers the predicted probability of cracking and leakage for the few cycles following the "truncation" inspection because the predictions must have continuity with respect to time. Because through-wall cracking below the bottom of the J-groove weld does not result in leakage, the statistical "truncation" for leak detection walkdowns only affects above-the-weld cracking. On the other hand, NDE inspections may verify the absence of cracking above or below the J-groove weld. The EPRI model provides inspection result inputs on a nozzle-by-nozzle basis for the two regions.

Truncation has a very small impact on predictions of time to cracking at the probability level used for the industry histogram.

3.5 Distributed Parameters

The EPRI model treats many of the variables as statistically distributed parameters to capture the effect of uncertainties. For example, the reference time to 10% probability of cracking is allowed to vary within a defined range because the reference time to cracking data available today are sparse. Similarly, there is some amount of uncertainty in the inside surface hoop stress.

Table 3-1 gives a list of the model inputs which are treated as statistically distributed parameters. The sampling frequency heading in Table 3-1 indicates how often the distributed parameters are sampled. The appropriate frequency is generally once at the start of each Monte Carlo trial. However, crack growth curves vary from nozzle to nozzle, so sampling for A_{ref} is performed for each nozzle (above and below the weld) and trial.

3.5.1 Weibull Distributions for Crack Initiation Above and Below the Weld

Field experience has shown that cracking tends to initiate either above the J-groove weld or below the J-groove weld. Cracks located below the bottom of the J-groove weld are not as significant as cracks located above the J-groove weld since they cannot result in leaks or loss of structural margin even if they grow through-wall. Accordingly, the EPRI model statistically samples two initiation times for each nozzle, one for the region above the bottom of the J-groove weld and one for the region below the bottom of the J-groove weld. The Weibull sampling and relative susceptibility factor calculations are performed independently for each region in each nozzle. The EPRI model input to the industry histogram is based on the predictions for the region above the bottom of the J-groove weld.

3.5.2 Triangular Distribution for Most Other Distributed Parameters

Table 3-1 shows that most of the distributed inputs are assumed to have triangular distributions. The triangular distribution is the preferred distribution when the available data do not justify a more elaborate choice. A variable with a triangular distribution can take on any value between a lower bound (a) and an upper bound (b). A third parameter (c) defines the mode of the distribution (value for which the density function is maximum). The mode can take on any value between a and b. The three parameters are chosen based on available industry and field data, controlled laboratory tests, and engineering judgment. A variable x has a triangular statistical distribution if its cumulative distribution function $F(x)$ has the form

$$F(x)=\begin{cases}0 & \text{if } x<a \\ \dfrac{(x-a)^2}{(b-a)(c-a)} & \text{if } a\le x\le c \\ 1-\dfrac{(b-x)^2}{(b-a)(b-c)} & \text{if } c<x\le b \\ 1 & \text{if } b<x\end{cases} \qquad \text{(eq. 3-11)}$$

and is written $x \sim \text{triang}(a,b,c)$.

3.5.3 Log-Triangular Distribution for Crack Growth Rate

The only exceptions to the Weibull and triangular distributions are the crack growth rate constant A_{ref} and exponent n. Because A_{ref} may vary over more than an order of magnitude, a log-triangular distribution was chosen. The log-triangular distribution is calculated from the triangular distribution as $x \sim \exp\{\text{triang}[\ln(a), \ln(b), \ln(c)]\}$.

Currently, not enough data exist to support a distribution for n, and Scott's recommended value of 1.16 is taken as the unique value.

3.6 Predictive Model Calibration

A key aspect of the EPRI model development was establishing a method to calibrate the analytical model with the results of inspections performed on actual reactor vessel heads. The calibration procedure consists of the following main steps:

1. A *reference nozzle* was established for each unique combination of material supplier and fabricator. The *reference nozzle* is assumed to have a 60.0 ksi inside surface hoop stress and to operate at 600°F.

2. Trial and error analyses were performed for each plant which has already performed inspections to determine the time to 10% probability of crack initiation for the *reference nozzle* which would produce a 50% cumulative probability (best estimate) of the observed inspection results (number of cracked nozzles and crack depth) in the reference plant at the time the inspection was performed. These calculations are based on the Weibull curve for the *reference nozzle* with corrections for differences in inside surface stress level and operating temperature between the *reference nozzle* and the reference plant being evaluated.

3. If the inspection did not show any cracks, then it was conservatively assumed that a crack initiated in a single nozzle immediately after the inspection.

4. If the reference inspected plant has nozzle materials of different types, such as extruded SB-167 ICI nozzles and rolled SB-166 CEDM nozzles, then each material group is evaluated separately.

For each subject plant to be evaluated, the EPRI model selects the *reference nozzle* for the previously inspected plant which is most similar in terms of material supplier and fabricator. If several similar plants have been inspected, the model uses the available information to establish upper bound, lower bound, and nominal reference values. If no plant with similar nozzle materials has been inspected, then an estimated time to 10% probability of cracking is established based on knowledge of the material being considered relative to materials at plants which have inspected and engineering judgment.

3.7 Risk Assessment

An important objective of modeling PWSCC in RPV head nozzles is to determine the risk of various depths of cracking at future refueling outages. The probability of cracking versus time is calculated statistically by the EPRI model as the ratio of the number of Monte Carlo trials with at least one cracked nozzle of a given depth at a particular refueling outage to the total number of trials run. As previously noted, the EPRI model performs crack initiation and growth calculations for locations above the bottom of the J-groove weld, which could lead to a leak, and below the bottom of the J-groove weld, which would not lead to a leak. The model risk assessment includes results for both regions.

3.8 Note on Model Quality Assurance

The models and software for the probabilistic analysis of reactor vessel head penetration nozzles were developed, verified, validated, and controlled in accordance with the Production Grade standards of the EPRI "Software Development Standards," EPRI TR-105061. Analysis work to compute operating stresses in nozzles, including the effects of welding residual stresses, were performed using the same computer software code and program listing, which Dominion Engineering, Inc., uses for nuclear safety related work performed to requirements of 10CFR50, Appendix B. The DEI 10CFR50, Appendix B, QA program is accepted by nuclear utilities through audits by NUPIC.

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Table 3-1. EPRI Model Distributed Inputs

Distributed Inputs	Units	Assumed Distribution	Sampling Frequency
Nozzle Inputs			
Nozzle Temperature	°F	Triangular	Trial
Nozzle Stress Tolerance	% from NOM	Triangular	Trial
Crack Initiation Reference			
Reference Time to 10%	EFPY	Triangular	Trial
Weibull Slope	–	Triangular	Trial
Activation Energy (Initiation)	kcal/mole	Triangular	Trial
Stress Exponent	–	Triangular	Trial
Crack Initiation Susceptibility Factors			
Water Chemistry Factor	–	Triangular	Trial
Material Factors Tolerance	% from NOM	Triangular	Trial
Fabrication Factors Tolerance	% from NOM	Triangular	Trial
Crack Growth Reference			
Reference Growth Curve Constant	m, s, MPa	Log-Triangular	Nozzle[2]
Reference Growth Curve Exponent[1]	–	Dependent	Nozzle[2]
Activation Energy (Growth)	kcal/mole	Triangular	Trial

NOTES:

[1]The reference growth curve exponent values are assigned based on the sampled growth curve constant value.

[2]Sampled independently for the above and below the bottom of the weld regions for each Monte Carlo trial.

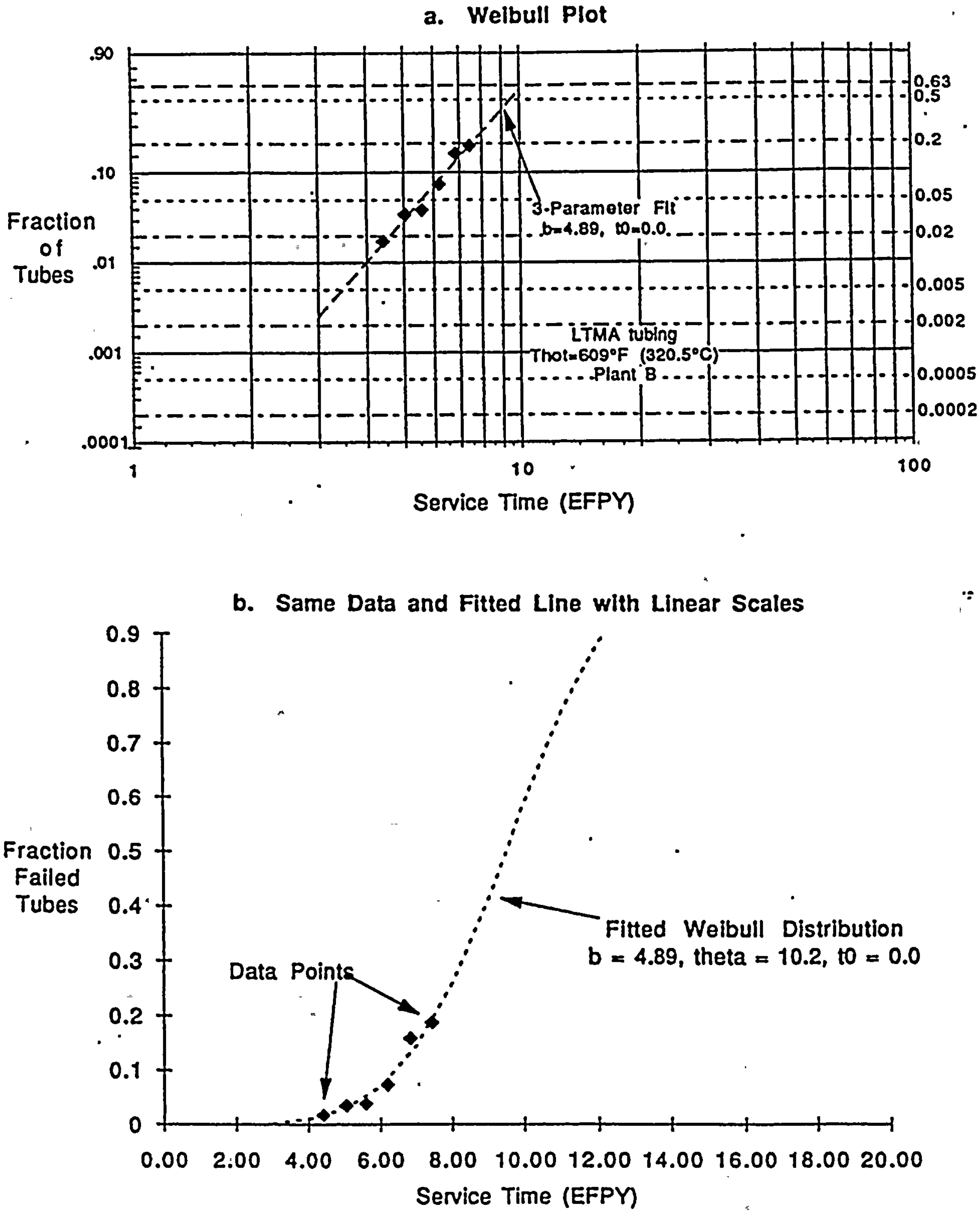

Figure 3-1. Typical Weibull Distribution

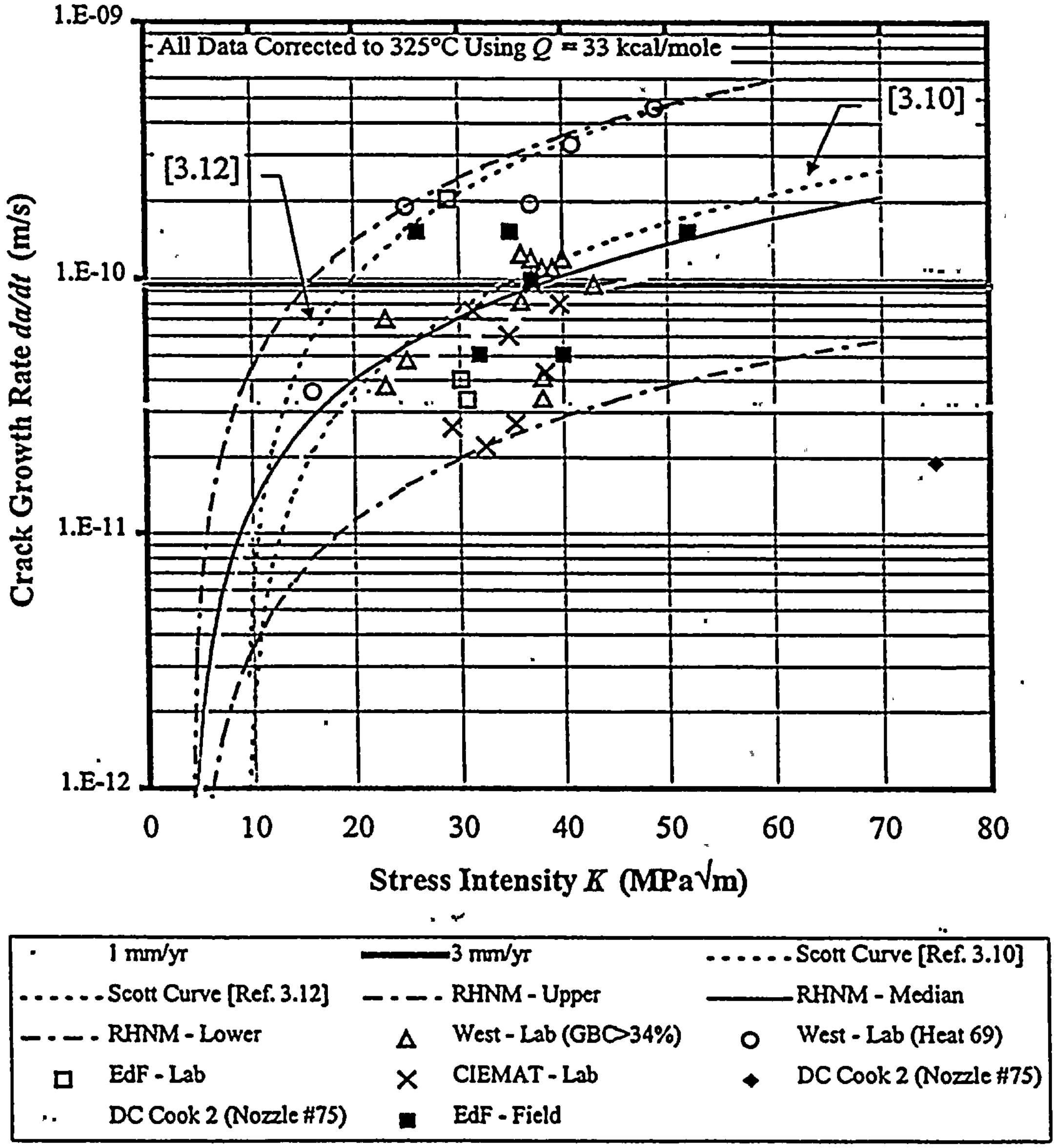

Figure 3-2. Summary of Field and Laboratory Crack Growth Rate Data

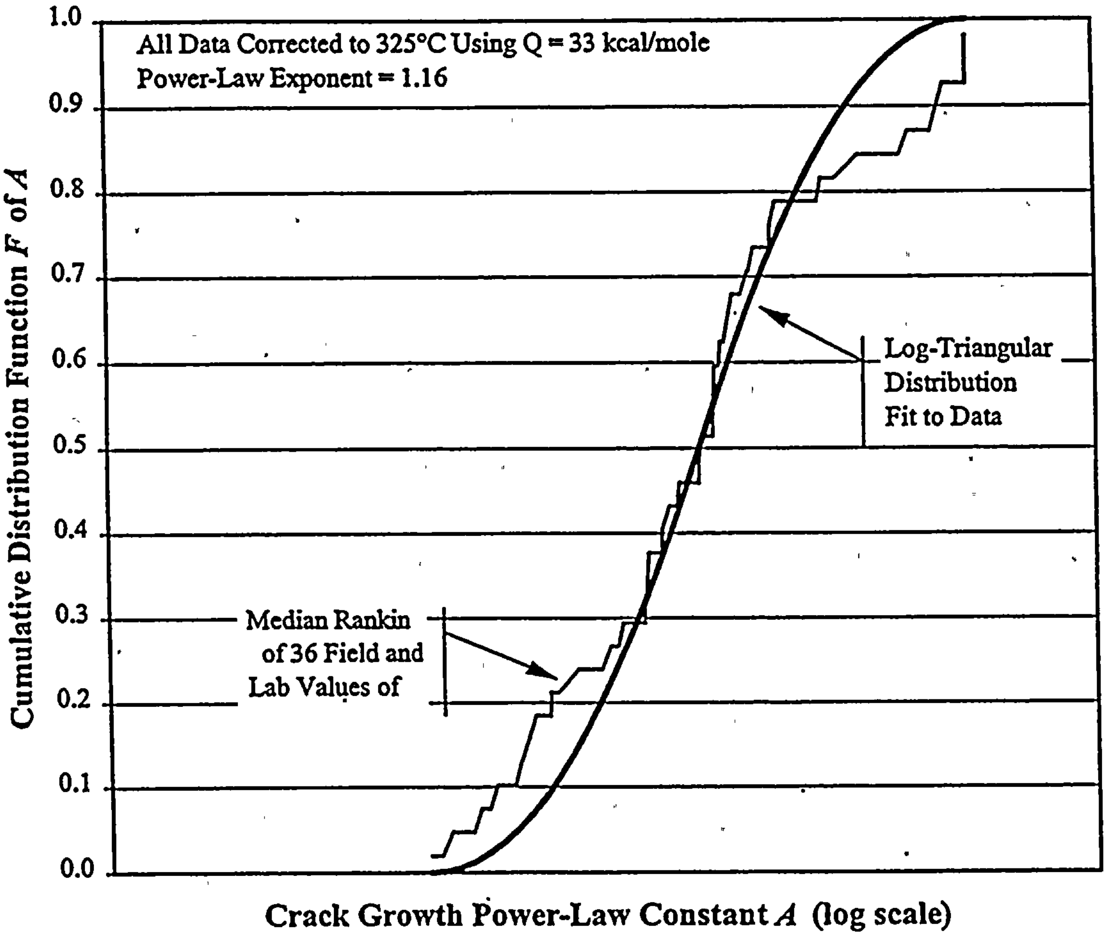

Figure 3-3. Statistical Distribution of Crack Growth Rate Power-Law Constant

METHODOLOGY FOR EVALUATION OF REACTOR VESSEL CLOSURE HEAD PENETRATION INTEGRITY FOR THE WESTINGHOUSE OWNERS GROUP

(BASED UPON WCAP-14901)

METHODOLOGY FOR EVALUATION OF REACTOR VESSEL CLOSURE HEAD PENETRATION INTEGRITY FOR THE WESTINGHOUSE OWNERS GROUP

1.0 Westinghouse Crack Initiation Model Development and Crack Initiation Testing

1.1 Crack Initiation Model

Westinghouse advanced an Alloy 600 PWSCC initiation model for primary components in Pressurized Water Reactors [10]. Briefly, the model incorporates three contributing factors for the prediction of crack initiation time; namely, material condition, stress, and temperature. These are discussed below.

Material Condition and Microstructure

As reported by several authors [17, 18, 19, 20, and 21], the Alloy 600 microstructure is a function of the thermomechanical history of the material heat as well as its carbon content. Alloy 600 material heats subjected to mill annealing at low temperatures exhibit a fine grained microstructure with heavy transgranular carbide precipitation and little or no carbides precipitate on the grain boundaries. Such a microstructure is reported to be more susceptible to PWSCC. On the other hand, a high temperature mill-anneal (>1000°C) tends to put more carbon into solution, increases grain size, produces grain boundary chromium carbide precipitation and renders the material more resistant to PWSCC. Norring, et al. [22], did not find a correlation between the total content of carbon and the crack initiation time, but they observed good correlation between the amount of grain boundary carbides and crack initiation time. The fact that grain boundary precipitation is beneficial to PWSCC has been reported by many researchers [23]. Norring, et al., [22], showed that the crack initiation time varied directly (linearly) with grain boundary carbides. Their data suggested that when the grain boundary carbide coverage is increased by a factor of 3, the crack initiation time also increased by a similar factor (from 4,000 hours to 12,000 hours). Bandy and Van Rooyen [24], pointed out that in addition to grain boundary carbide coverage, other features relating to processing history variables such as carbon concentration gradients, substructural features, grain size distribution, cold work, intragranular carbide distribution and the grain boundary segregates all play an important role in the cracking behavior of the Alloy 600 material.

When considering the influence of microstructure on the PWSCC susceptibility for the purpose of the current evaluation, to enable comparison of heats fabricated at different vendor shops, the thermomechanical processing history effect is separated from the grain boundary carbide coverage effects. In general, the influence of the grain boundary carbides is known and the coverage (G) can be easily measured directly from the microstructure. The influence of other structural features due to processing history cannot be assessed directly. These processing effects are represented in the current treatment by a single parameter (A) characteristic of the fabrication shop (vendor). This approach provides a means of comparing the PWSCC susceptibilities of Alloy 600 material heats from different vendor shops although they may contain similar grain boundary carbide contents.

Influence of Stress

Steady state tensile stress in the component, either due to residual and/or applied loads, has a strong influence on the PWSCC.

Bandy and Van Rooyen [24], reported that the time to failure varied inversely as the fourth power of applied stress in both annealed and cold-worked specimens. They also reported data to support that cold work reduces the resistance to PWSCC. The effective stress at a given Alloy 600 location is a function of the fabrication steps and their sequence, the yield stress of the material, and the service stress. In general, the local residual stresses resulting from fabrication can play a more significant role than the service stresses themselves.

Temperature Effects

Several investigators [17, 24], examined the role of temperature on PWSCC. It is well established from these results that the crack initiation time decreases exponentially with temperature and that they are related through an Arrhenius equation expressed as a function of the activation energy of the process. The experimental results confirm that Alloy 600 PWSCC is a thermally activated process and the activation energy for the process varies approximately between 50 to 55 kcal per mole. An activation energy value of 55 kcal/mole is consistently applied throughout the current assessments, for crack initiation. A different value, 32.4, applies for crack growth as was discussed in Section 2 of WCAP-14901.

1.2 The Westinghouse Crack Initiation Model

Consistent with tche contributing factors discussed above, the crack initiation time (t_i) or the rate of crack initiation ($1/t_i$) is proportional:

$$1/t_i \propto (\text{Stress})^n$$

$$\propto e^{-Q/RT}$$

$$\propto \text{inverse of the grain boundary carbide coverage factor, } (1/G)$$

so that $1/t_i \propto \dfrac{\sigma^n e^{-Q/RT}}{G}$.

Since the nature of the vendor thermomechanical processing is also a significant contributing factor, one can say that for a given fabrication process

$$1/t_i = A\frac{\sigma^n e^{-Q/RT}}{G} \qquad (1\text{-}1)$$

The proportionality constant "*A*" can be chosen to represent the processing conditions representative of a given manufacturing process or manufacturer, and could include parameters such as yield strength as part of the expression.

"*A*" can be assessed for a given heat by substituting the parameters of a service component with a known cracking history for the heat of material. "*A*" will then represent the processing condition (or the vendor) by the definition we have just established.

The parameters in the above rate equation (1-1) are described below:

A is a constant, relating to the processing, and fabrication conditions of the material

G is the grain boundary carbide coverage factor

F is the effective tensile stress (resulting from applied and residual stresses)

n is the stress exponent having a value ranging from 3.5 to 4.5 for Alloy 600 in primary water

Q is the activation energy for the crack initiation process and has an approximate value of 55 kcal/mole

R is the gas constant (1.987 cal/mole degrees K)

T is the absolute temperature in degrees K, and

t_i is the time to initiate cracking.

2.0 Technical Description of Probabilistic Models

To calculate the probability of failure of the Alloy 600 vessel head penetration as a function of operating time *t*, $Pr(t \leq t_f)$, structural reliability models were used with Monte-Carlo simulation methods. This section describes these structural reliability models and their basis for the primary failure mode of crack initiation and growth due to primary water stress corrosion cracking (PWSCC). The models used for the evaluation of head penetration nozzles are based upon the probabilistic and economic decision tools developed previously for the Westinghouse Owners Group (WOG). The capabilities of this software have already been verified in the following ways:

1. Calculated stresses compare well with measured stresses,
2. Crack growth rates agree with measured field data.

Recent improvements have also been made to the model in order to maximize its use for individual plant predictions. The changes include the following:

1. The model accepts measured microstructure (replication) and also has the capability to ignore its effects, if desired.
2. The relationship of initiation time to material microstructural effects and yield strength has been improved to more closely match the observations from the recent inspection at North Anna Unit 1.
3. Statistically based Bayesian updating of probabilities due to initial inspection results has been added (e.g. the lack of any indications at any given plant).
4. The uncertainty on crack growth rate after initiation has been updated to reflect the findings observed in the recent Westinghouse test data and the recent in-reactor measurement data to be published by EdF [16] (see Figure 4-2 of WCAP-14901).
5. All models have been independently reviewed by APTECH Engineering (Begley and Woodman)[25], and an improved model was developed for the effect of monotonic yield strength on time to initiation.
6. A wide range (both high and low values) of calculated probabilities are consistent with actual plant observations as discussed below.

The most important parameter for estimating the failure probability is the time to failure, t_f in hours. It is defined as follows:

$$t_f = t_i + (a_f - a_0)/(da/dt) \qquad (2\text{-}1)$$

where:

t_i	=	time to initiation in hours,
a_f	=	failure crack depth in inches,
a_0	=	crack depth at initiation in inches and
da/dt	=	crack growth rate in inch/hour.

In equation (2-1), both the crack depths at failure and initiation may be specified as a fraction of the penetration wall thickness, (w). The failure depth a_f depends upon the failure mode being calculated. Since the failure mode of concern is axial cracks in the penetration that are deeper than the structural limit of 75% of the penetration wall thickness (w), it would be specified as:

$$a_f = 0.75w \qquad (2\text{-}2)$$

The time to PWSCC crack initiation, t_i in hours, is consistent with the previous equation (1-1) by Rao [3] and is defined by:

$$t_i = \frac{C_1 + (1 + C_2 P_{GBC})}{\sigma^{n_1} S_y^{n_2}} \exp\left(\frac{Q_1}{RT}\right) \qquad (2\text{-}3)$$

where:

C_1	=	a log-normal distribution on the initiation coefficient, which was based upon the data of Hall and others [26] for forged Alloy 600 pressurizer nozzles, with only the uncertainty based upon the data of Gold and others [27],
C_2	=	coefficient for the effect of grain boundary carbide coverage, which is based upon the data of Norting and others [22],
σ	=	the maximum residual and operating stress level derived from the detailed elastic-plastic finite-element analysis from the WOG study of Ball and others [28] as shown in Figure 2-1, with its normally distributed uncertainty being derived from the variation in ovality from Duran and others [29] (see Figure 2-3), which is a trigonometric function of the penetration diameter and setup angle (local angle between the head and longitudinal axis of penetration).
S_y	=	yield strength of the penetration material,

n_1, n_2 = exponents on stress and yield strength, respectively ($n_1 = 4, n_2 = 2.5$)

Q_1 = the activation energy for crack initiation, which is normally distributed,

R = universal gas constant, and

T = the penetration absolute temperature, which is uniformly distributed based upon the calculated variation of the nominal head operating temperature.

Equation 2-3 is equivalent to the initiation equation by Rao [3], where $G/A = C_1 + (1 + C_2 P_{GBC})/S_y^{n_2}$.

Either data from field replication [30] or the correlation model by Rao [31] can be used to determine the percent grain boundary carbide coverage, P_{GBC} in equation (2-3). The model [31] is a statistical correlation of measured values with the following materials certification parameters:

- Carbon content,
- Nickel content,
- Manganese content,
- Ultimate tensile strength and
- Yield strength.

The uncertainty on this model applies equally well to both the predicted and measured values.

The hours at temperature per operating cycle, which is normally distributed, is used to check if crack initiation has occurred. Once the crack has initiated, it is assumed to have a depth of a_0 and its growth rate, *da/dt*, is calculated by the Peter Scott model, which matches the latest Westinghouse and EdF data and the previous data given in the WOG report on the industry Alloy 600 PWSCC growth rate testing results [32]. The crack growth model is:

$$\frac{da}{dt} = C_3 (K_I - K_{TH})^{1.16} \exp\left(\frac{Q_2}{RT}\right) \qquad (2\text{-}4)$$

where:

C_3 = a log-normally distributed crack growth rate coefficient,

K_I = the stress intensity factor conservatively calculated assuming a constant stress through the penetration wall for an axial flaw at the inside surface with a length 6 times its depth using the following form of the Raju and Newman equations [33]:

$$K_I = 0.982 + 1.006(a/w)^2 \sigma(\pi a)^{0.5} \qquad (2\text{-}5)$$

Q_2 = activation energy for PWSCC crack growth, which is also normally distributed, and

K_{TH} = threshold stress intensity factor for crack growth

The probability of failure of the Alloy 600 vessel head penetration as a function of operating time *t*, $Pr(t \leq t_f)$, is calculated directly for each set of input values using Monte-Carlo simulation. Monte Carlo simulation is an analytical method that provides a histogram of failures with time in a given number of trials (simulated life tests). The area under the simulated histogram increases with time due to PWSCC. The ratio of this area to the total number of trials is approximately equal to the probability of failure at any given time. In each trial, the values of the specified set of random variables is selected according to the specified distribution. A mechanistic analysis is performed using these values to calculate if the penetration will fail at any time during its lifetime (e.g. 60 years). This process is repeated many times (e.g. 6000) until a sufficient number of failures is achieved (e.g. 10 per year) to define a meaningful histogram, which is an approximation of the lower tail of the true statistical distribution in time to failure. The shape of the distribution depends upon the input median values and specified distributions of the random variables. It is not forced to be an assumed type of distribution (e.g. Weibull) as is done for other non-mechanistic probabilistic methods. For the worst penetration in one plant, the mean time to failure was greater than 160 years but its uncertainty was so large that the normalized area under the histogram (estimated probability) at 60 years was 8 percent.

To apply the Monte Carlo simulation method for vessel head penetration nozzle (VHPN) failure, the existing PROF (probability of failure) object library in the Westinghouse Structural Reliability and Risk Assessment (SRRA) software system was combined with the PWSCC structural reliability models described previously. This system provides standard input and output, including plotting, and probabilistic analysis capabilities (e.g. random number generation, importance sampling). The result was program VHPNPROF for calculation of head penetration failure probability with time.

As reported previously [34], the Westinghouse SRRA Software System has been verified by hand calculation for simple models and alternative methods for more complex models. Recently the application of this same Westinghouse SRRA methodology to the WOG sponsored pilot program for piping risk based inspection has been extensively reviewed and verified by the ASME Research Task Force on RBI Guidelines [35] and other independent NRC contractors. Table 2-1 provides a summary of the wide range of parameters that were considered in this comprehensive benchmarking study that compared the Westinghouse calculated probabilities from the analysis (labeled SRRA) with those from the pc-PRAISE program [36]. The comparison of calculated probabilities after 40 years of operation is excellent for both small and large leaks and full breaks, including those reduced due to taking credit for leak detection.

In addition, the VHPNPROF Program calculated probabilities of getting a given crack depth due to PWSCC were compared for four plants where sufficient head penetration information and inspection results were available. The four plants are identified in Table 2-2 along with the values of the key input parameters and calculated failure probabilities. Table 2-2 also shows the agreement between the latest available inspection results and VHPNPROF predicted failure trends due to PWSCC.

The models and software used for the probabilistic analysis of reactor vessel head penetration nozzles were developed, verified, validated and controlled in accordance with the Westinghouse Quality Management System, which has been audited per ISO-9001 requirements and accepted by NRC as meeting the requirements of 10CFR50, Appendix B. The input to and output from the software were also documented, verified and controlled in accordance with the same quality management system.

TABLE 2-1

PARAMETERS USED FOR THE pc PRAISE BENCHMARKING STUDY

Type of Parameter	Low Value	High Value
Pipe Material	Ferritic	Stainless Steel
Pipe Geometry	6.625" O.D. 0.562" Wall	29.0" O.D. 2.5" Wall
Failure Modes	Small Leak, Through-Wall Crack	Full Break, Unstable Fracture
Last Pass Weld Inspection	No X-Ray	Radiographic
Pressure Loading	1000 psi	2235 psi
Low-Cycle Loading	25 ksi Range 10 cycles/year	50 ksi Range 20 cycles/year
High-Cycle* Loading	1 ksi Range 0.1 cycles/min.	20 ksi Range 1.0 cycles/sec.
Design Limiting Stress	15 ksi	30 ksi
Disabling Leak Rate	50 gpm	500 gpm
Detectable Leak Rate	None	3 gpm

* Note: Mechanical Vibration (low value of stress range and high value of frequency) for small pipe, Thermal Fatigue (high value of stress range and low value of frequency) for large pipe.

TABLE 2-2

COMPARISON OF VHPNPROF CALCULATED PROBABILITIES WITH PLANT OBSERVATIONS

Parameters	Almaraz 1	D. C. Cook 2	Ringhals 2	North Anna 1
Hours of Operation	85,400	87,000	108,400	91,000
Setup Angle (°)	42.6	50.5	38.6	*
Temperature (°F)	604.3	598.5	605.6	600.0
Yield Strength (ksi)	37.5	58	51.2	51.2
Grain Boundary Carbides (%)	57.0	44.3	3.0	2.0
Flaw Depth/Wall	0.10	0.43	0.25	0.10
Initiation Probability	1.1%	41.4%	37.6%	15.3%
Failure Probability**	1.1%	38.1%	34.6%	15.3%
Penetrations With Reported Indications from ISI	0	1	3 (2 with scratches)	0

* Calculations performed at an equivalent setup angle for the 2nd highest stress location that could be inspected.

** Defined here as the probability of reaching the specified flaw depth for the individual penetration.

3.0 References

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