Westinghouse Non-Proprietary Class 3

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Development of a Technical Basis for the Inspection Interval of the H. B. Robinson Reactor Vessel Head Penetrations

Westinghouse

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Development of a Technical Basis for the Inspection Interval of the H. B. Robinson Reactor Vessel Head Penetrations

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EXECUTIVE SUMMARY

This report documents the development of a technical basis for changing the inspection interval for the H. B. Robinson 2 reactor vessel head penetrations. The plant performed a bare metal visual (BMV) inspection in the spring 2001, and again in October 2002. Also in October 2002, the plant performed an inspection of the 69 CRDM tubes and also of the J-groove welds by eddy current testing (ECT). In addition, ultrasonic tests (UT) of 17 of these CRDM tubes were also performed. No reportable PWSCC cracks or leaks were detected in any of the inspections.

H. B. Robinson's effective degradation years (EDY) put the plant well into the "High Susceptibility" range for primary water stress corrosion (PWSCC) in the head penetrations. NRC Inspection requirements for High Susceptibility plants include 100% BMV and UT/ECT of base material and welds at every refueling outage.

The Plant's next scheduled refueling outage is April 2004. Since no indications of cracking were detected in the October 2002 inspections, plant management is requesting a deferral of the next under-the-head inspection until fall 2005, when it is tentatively planning to replace the reactor vessel head. This deferred request is supported by a number of complementary evaluations which have been documented in this report.

The technical basis consists of the following key points:

- Two successful bare metal visual exams
- Successful inspection experience for heads of similar manufacture, and for H. B. Robinson in particular
- A statistical analysis which substantiates the effects of manufacturing differences
- A deterministic structural integrity evaluation, revealing that a leak is unlikely to occur as a result of the interval extension
- A probabilistic and risk evaluation concluding that the change in core damage frequency as a result of the interval extension would be insignificant, as defined by Regulatory Guide 1.174.

Historical inspection experience for reactor vessel heads fabricated by Combustion Engineering has been excellent, with few cracks found in any of these units heads. Adding to this the fact that the tubes were produced at Huntington Alloys, the service experience has been extraordinarily good.

A statistical analysis has been completed that confirms that other factors besides time and temperature are affecting the cracking behavior of head penetrations. Thus, using only time and temperature leads to substantially overestimating the likelihood of cracking in plants with H. B. Robinson – like attributes.

A deterministic structural integrity evaluation has been carried out to provide conservative estimates of time to leak as well as time to failure of a tube. Consideration of a range of postulated flaws, both axial and circumferential, led to calculated times to leakage of at least 3.8 years. The time to failure was dominated by the potential for a circumferential flaw to grow around the tube, which was at least 27 years. Therefore, it may be seen that extending the inspection interval from 18 months to 36 months will not even lead to a leak.

Building on the deterministic evaluation, a probabilistic analysis was performed, to support a risk-informed basis for extending the interval. The results showed that there was a very small probability of generating a leak over the 36 month period of interest. The risk-informed assessment concluded that the change in core damage frequency from such an extension would be below 10^{-6} per reactor year, which qualified as negligible using the guidelines of Regulatory Guide 1.174.

Taken together, these complimentary approaches all lead to the conclusion that extension of the NDE inspection interval from 18 months to three years will not result in any measurable impact to the operational safety of the H. B. Robinson reactor vessel head.

1 INTRODUCTION

This report documents the development of a technical basis for changing the inspection interval for the H. B. Robinson 2 reactor vessel head penetrations. The plant performed a bare metal visual (BMV) inspection in the spring 2001, and again in October 2002. Also in October 2002, the plant performed an inspection of the 69 CRDM tubes and also of the J-groove welds by eddy current testing (ECT). In addition, ultrasonic tests (UT) of 17 of these CRDM tubes were also performed. No reportable cracks or leaks were detected in any of the inspections.

H. B. Robinson's currently calculated effective degradation years (EDY) exceeds 20 EDY and this places the plant well into the "High Susceptibility" range for primary water stress corrosion cracking (PWSCC) in the head penetrations as defined in the February 11, 2003 Order issued by the Nuclear Regulatory Commission (NRC). Inspection requirements for High Susceptibility plants include 100% BMV and UT/ECT of base material and welds at every refueling outage.

The Plant's next scheduled refueling outage is in April 2004. Since no indications of cracking were detected in the October 2002 inspections, plant management is considering requesting a delay of the next under-the-head inspection until fall 2005, when it is tentatively planning to replace the reactor vessel head. To support such a decision, and to define a defendable inspection interval for this head, the Plant retained Westinghouse to perform the following tasks:

(Section 2) Historical Inspection Experience. Historical experience, for H. B. Robinson and its sister plants made at CE Chattanooga has been excellent. With the exceptions of Millstone 2 and, recently, St. Lucie 2,[1] there has been no CRDM nozzle or J-groove weld cracking reported at any of these plants. This task traces the history of the problem and organizes existing inspection data on the head penetration and J-groove weld inspection experience for heads as a function of the head manufacturer, NSSS designer, and material source and in a manner supportive of the evaluation of inspection interval extension.

(Section 3) Statistical Analysis of Differential Susceptibility. A statistical analysis is performed using the historical data compiled in Section 2 to test the hypothesis that factors other than time and temperature could be meaningful differentiators in determining plant susceptibility to PWSCC.

(Section 4) Deterministic Structural Integrity. Deterministic treatment of crack propagation shows a long period of time is needed to have a flaw grow throughwall (i.e., leak), and a longer time to cause a failure. This information is available for both axial and circumferential flaw orientations, as a flaw evaluation handbook has already been developed for the H. B. Robinson plant. This task assembles the key results and develops deterministic arguments to support the evaluation of extended inspection interval.

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1 While St. Lucie 2 does have a CE fabricated head, its penetration materials are from Standard Steel, which did not supply any of the H. B. Robinson head penetrations.

(Section 5) Risk and Probabilistic Evaluation. This task provides a probabilistic analysis to support a risk-informed basis for delaying future inspections until fall 2005 or spring 2007. This analysis uses a probabilistic model derived from extreme value theory, with values for inputs (initiating and critical sizes and crack growth rates) taken from Section 4. The results are a projected probability of leak and, for circumferential cracks, a probability of reaching a critical size. The incremental change in core damage frequency (CDF) associated with extending the inspection interval can be calculated based on (a) the calculated probability of a flaw becoming a leak before the target year, (b) the likelihood of a safety-related following event (rod ejection), and the conditional core damage probability. The resulting calculated incremental change in CDF is then compared to a threshold incremental change in CDF specified in RG 1.174 to ascertain whether one important condition of a "risk-informed" basis for extending the inspection interval exists.

(Section 6) Fabrication Methods. In this task, the method of fabrication of the reactor vessel head for H. B. Robinson is documented. The corresponding methods used by other fabricators are also documented, for comparison, based on available information. In addition to fabrication techniques, material properties for the penetration tubes used for Robinson is documented and compared to those material properties used by others based on publicly available data. This section includes consideration of the overall fabrication process and sequence for the RPV closure head.

Note that there are several locations in this report where proprietary information has been identified and bracketed. For each of the bracketed locations, the reason for the proprietary classification is given, using a standardized system. The proprietary brackets are labeled with three different letters to provide this information and the explanation for each letter is given below:

a. The information reveals the distinguishing aspects of a process or component, structure, tool, method, etc., and the prevention of its use by Westinghouse's competitors, without license from Westinghouse, gives Westinghouse a competitive economic advantage.

c. The information, if used by a competitor, would reduce the competitor's expenditure of resources or improve the competitor's advantage in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.

e. The information reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

2 HISTORICAL INSPECTION EXPERIENCE

In September of 1991, leakage was reported from the reactor vessel CRDM head penetration region of a French plant, Bugey Unit 3. Bugey 3 is a 920 megawatt three-loop Pressurized Water Reactor (PWR) plant which had just completed its tenth fuel cycle. The leak occurred during a post ten year hydrotest conducted at a pressure of approximately 3000 psi (204 bar) and a temperature of 194°F (90°C). The leak was detected by metal microphones located on the top and bottom heads, and the leak rate was estimated to be approximately 0.7 liter/hour (~0.003 GPM). The location of the leak was subsequently established on a peripheral penetration with an active control rod (H-14), as seen in Figure 2-1.

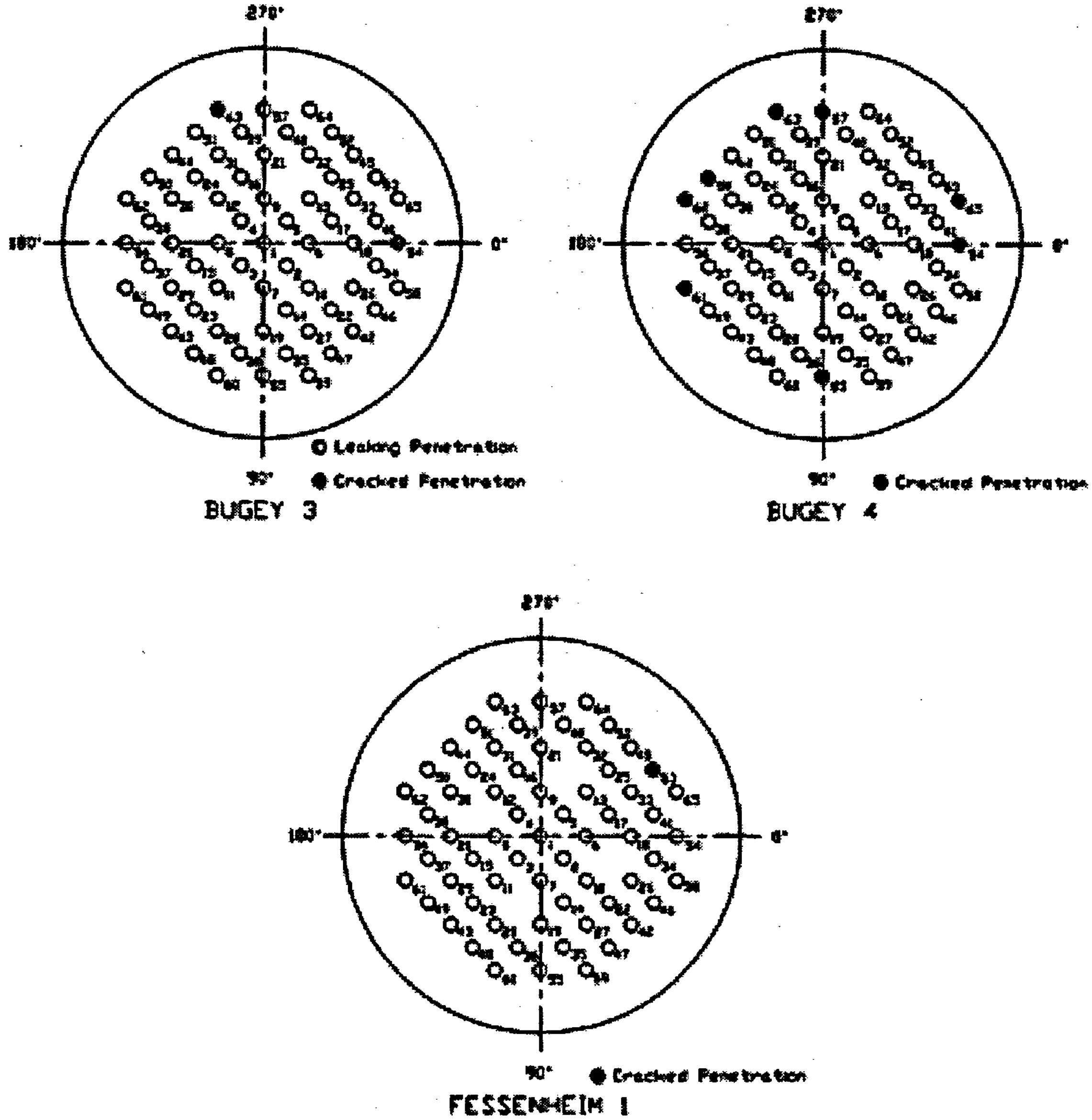

Figure 2-1 French R/V Closure Head CRDM Penetration Cracking EDF Plants – Penetrations with Cracking

The control rod drive mechanism and thermal sleeve were removed from this location to allow further examination. Further study of the head penetration revealed the presence of longitudinal cracks near the head penetration attachment weld. Liquid penetrant and ultrasonic testing confirmed the cracks. The cracked penetration was fabricated from Alloy 600 bar stock (SB-166), was machined before welding to the head, and has an outside diameter of 4 inches (10.16 cm) and an inside diameter of 2.75 inches (7.0 cm).

As a result of this finding, all of the control rod drive mechanisms and thermal sleeves at Bugey 3 were removed for inspection of the head penetrations. Only two penetrations were found to have cracks, as shown in Figure 2-1.

An inspection of a sample of penetrations at three additional plants were planned and conducted during the winter of 1991–92. These plants were Bugey 4, Fessenheim 1, and Paluel 3. The three outermost rows of penetrations at each of these plants were examined, and further cracking was found in two of the three plants.

At Bugey 4, eight of the 64 penetrations examined were found to contain axial cracks, while only one of the 26 penetrations examined at Fessenheim 1 was cracked. The locations of all the cracked penetrations are shown in Figure 2-1. None of the 17 CRDM penetrations inspected at Paluel 3 showed indications of cracking, at the time, but further inspection of the French plants have confirmed at least one crack in each operating plant.

Thus far, the cracking in reactor vessel heads, not designed by Babcock and Wilcox (B&W), has been consistent in both its location and extent. All cracks discovered by nondestructive examination have been oriented axially, and have been located in the bottom portion of the penetration in the vicinity of the partial penetration attachment weld to the vessel head as shown schematically in Figure 1-1.

One small, outside diameter initiated circumferential flaw was found during destructive examination at Bugey 3, and was determined to have resulted from PWSCC as a consequence of leakage of the PWR water from an axial throughwall crack into the annulus between the penetration and head.

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Non-destructive examinations of the leaking CRDM nozzles showed that most of the cracks originated on the outside surface of the nozzles below the J-groove weld, were axially oriented, and propagated primarily in the nozzle base material to an elevation above the top of the J-groove weld where leakage could then pass through the annulus to the top of the head where it was detected by visual inspection. In some cases, the cracks initiated in the weld metal or propagated into the weld metal, and in a few cases the cracks propagated through the nozzle wall thickness to the inside surface.

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The cracking has now been confirmed to be primary water stress corrosion cracking. Relatively high residual stresses are produced due to the welding process. Other important factors which affect this process are temperature and time, with higher temperatures and longer times being more detrimental. It is interesting to note that no head vents have been found to be cracked.

Additional cracks and leaks were found at plants in the fall 2002. The inspection findings for the plants examined thus far (up through fall 2002, plus partial results for spring 2003) are summarized in Table 2-1. The table shows the plants sorted by (a) EDY of first crack or, (b) EDY at last inspection if cracks have never been found. For each plant, additional columns summarize inspection methods and findings, NSSS designer, Material Supplier, and Fabricator. The following are keys for the Material Supplier codes and the Head Fabricators codes used in Table 2-1:

<u>Key for Material Suppliers:</u>
B = B&W Tubular Products
H= Huntington
S = Sandvik
SS = Standard Steel
W = Westinghouse (Huntington)
CL = C. L. Imphy
A = Aubert et Duval

<u>Key for Head Fabricators:</u>
BW = B&W
CBI = Chicago Bridge & Iron
CE = Combustion Engineering
RDM = Rotterdam Dockyard
CL = C. L. Imphy

Table 2-1 Inspection Results and Other Data for U. S. Units (Results through Fall, 2002 Plus Partial Results for Spring 2003 Inspections)

Approx. Outage Date @ 1st Crack or latest ISI	Plant	Inspection Results, adapted from Rev D, 04/4/03, L. K. Mathews and augmented *(Designer, Material, & Fabricator added. Results before & after 1st crack are removed. Only latest Inspection for plants with no cracks preserved)*	Approx. EDY (600F) at Outage	NSSS Design	Nozzle Material Supplier	Head Fabricator
Apr-01	Oconee 2	BMV – 4 leaking nozzles repaired, 1 circ flaw; UT?	22.1	B&W	B	BW
Nov-00	Oconee 1	BMV – 1 leaking nozzle, PT of weld began as dot, grew to linear radial flaw. Boat sample –PWSCC progressed into nozzle base material and to triple point. Flaw ground out and repaired.	21.7	B&W	B	BW
Feb-01	Oconee 3	BMV – numerous leaking nozzles. 9 repaired, UT 9 others. Circ cracks 3 nozzles found during repair	21.7	B&W	B	BW
Oct-02	Robinson 2	BMV plus UT/ET tubes and ET of welds. Everything, including the welds, was clean.	20.3	W	H	CE
Sep-01	North Anna 1	BMV – some suspects UT/ET? – Shallow cracks on tube ID – left in service; ET 26 welds – 14	19.9	W	S	RDM
Mar-01	ANO 1	BMV – 1 leaking nozzle, flaw on OD and into weld. Ground out and welded. Left embedded piece of	19.5	B&W	B/H	BW
Mar-02	Surry 2	BMV – no indications; cleaned head after exam	19.5	W	B/S	BW/RDM
Oct-01	Surry 1	BMV –(4) leaking; PT– 10 cracked, 6 repaired	19.2	W	H	BW/RDM
Feb-02	Davis-Besse	BMV – lots of boric acid and obscured nozzles; UT– 100% 3 leaking, 5 cracked, 1 circ flaw, head being replaced. Wastage of head discovered during repair	19.1	B&W	B/H	BW
Oct-01	North Anna 2	BMV – 3 leaking nozzles, repaired b embedded flaw technique	18.8	W	S	RDM
Mar-03	Turkey Point 3	BMV – no indications of leakage or degradation; UT – 100%, no cracks	18.3	W	H	BW
Oct-01	TMI 1	BMV – 12 suspect nozzles; PT – 4/12 cracked welds; UT – 7/12 axial cracks; 8 total cracked, 6	18.1	B&W	B	BW

Table 2-1 (Cont'd)	Inspection Results and Other Data for U. S. Units (Results through Fall, 2002 Plus Partial Results for Spring 2003 Inspections)					
Approx. Outage Date @ 1st Crack or latest ISI	**Plant**	**Inspection Results, adapted from Rev D, 04/4/03, L. K. Mathews and augmented *(Designer, Material, & Fabricator added. Results before & after 1st crack are removed. Only latest Inspection for plants with no cracks preserved)***	**Approx. EDY (600F) at Outage**	**NSSS Design**	**Nozzle Material Supplier**	**Head Fabricator**
Mar-02	Turkey Pt. 4	Visual – no leakage or BA deposits	17.4	W	H	BW
Sep-01	Farley 1	BMV – no indications of leakage	16.3	W	H/B	BW/CE
Oct-01	Crystal River 3	BMV – 1 leaking nozzle UT – Leaker had small circ flaw above weld, repaired by pressure boundary relocation. 8 other nozzles examined with top down UT – no indications	16.2	B&W	B	BW
Sep-02	Farley 2	BMV – no indications 100% UT of nozzle base material – no cracks; did not examine welds	15.8	W	B/H	BW/CE
Sep-02	St. Lucie 1	BMV – no leakers; UT – almost 100% – no cracks; did not examine welds	15.8	CE	H	CE
Apr-02	Pt. Beach 2	BMV – no indications	15.7	W	H/B	BW/CE
Mar-02	Ginna	Limited visual – insulation removed in 2 areas, visual found no evidence of boric acid there or in gaps in insulation. Selective Head Thickness UT found no voids. Plant had done nozzle ID ET in 1999 w/no	15.6	W	H	BW
Jan-03	San Onofre 3	BMV –no indications of leakage or degradation; UT and ET of 100% of CRDM & ICI nozzles, no indications; ET ~90% of welds, no indications; insulation modified to facilitate visual exam	15.4	CE	SS/H	CE
May-02	San Onofre 2	BMV – no indications; UT – no indications; ET – 46 welds, no indications	15.3	CE	SS/H	CE
Feb-03	Calvert Cliffs 2	BMV – no indications of leakage or degradation; UT in process	15.2	CE	H	CE
Mar-01	Waterford 3	BMV – no indications	15.1	CE	SS/H	CE
Feb-02	Calvert Cliffs 1	BMV – no indications	14.9	CE	H	CE
Sep-02	Pt. Beach 1	BMV – no leakers; UT – almost 100% – no cracks; did not examine welds except PT on nozzle 1	14.6	W	H	BW
Mar-03	Beaver Valley 1	BMV – no indications. UT/ET tubes, ET welds; ET->4 nozzles axial OD cracks below weld, to be overlaid (M3935heat), craze cracking OD on some others.	14.0	W	H/B	BW/CE
Jan-02	Cook 2	BMV –no indications; UT– 100%, no cracks, including ET/UT of previously repaired area. J-Groove –	13.9	W	W	CBI
Dec-01	St. Lucie 2	BMV – no indications	12.8	CE	SS/H	CE
Oct-02	Salem 1	BMV – no leaks or evidence of boric acid	11.9	W	H	CE
Feb-02	Millstone 2	UT 100% – 3 nozzles w/OD tube cracks below and extending into weld zone, all 3 repaired by pressure	11.6	CE	H	CE
May-0	Ft. Calhoun	BMV – no indications	11.4	CE	H	CE
Apr-02	ANO 2	UT– all nozzles, no indications; did not examine welds	11.2	CE	SS/H	CE
Oct-01	Kewaunee	BMV –no indications of leakage	11.1	W	H/B	BW/CE
Feb-03	Diablo Canon 2	BMV – no indications of leakage or degradation	10.9	W	H	CE
Nov-02	Prairie Island 1	BMV – no indications of leakage or degradation	10.7	W	CL	CL
Sep-02	Palo Verde 1	BMV on some peripheral nozzles – clean; UT 100% (96 nozzles) no cracks; ET – 12 welds – clean	10.5	CE	SS	CE
Apr-02	Prairie Island 2	BMV – no indications	10.3	W	A	CL
May-02	Cook 1	BMV –no indications UT – 100%, no cracks ET – 10 welds – no reportable indications	10.0	W	H	CE
Mar-02	Palo Verde 2	UT – 100% no cracks; ET – 19? welds – no indications	9.9	CE	SS	CE

Table 2-1 (Cont'd)	Inspection Results and Other Data for U. S. Units (Results through Fall, 2002 Plus Partial Results for Spring 2003 Inspections)					
Approx. Outage Date @ 1st Crack or latest ISI	**Plant**	**Inspection Results, adapted from Rev D, 04/4/03, L. K. Mathews and augmented *(Designer, Material, & Fabricator added. Results before & after 1st crack are removed. Only latest Inspection for plants with no cracks preserved)***	**Approx. EDY (600F) at Outage**	**NSSS Design**	**Nozzle Material Supplier**	**Head Fabricator**
Apr-02	Salem 2	BMV – no indications	9.2	W	H	CE
Feb-02	Beaver Valley 2	BMV – no indications	9.1	W	H	CE
Oct-02	Indian Pt. 2	Removed insulation for BMV – no indications. UT and or ECT of most nozzles – no cracks. Only one	8.0	W	H	CE
Oct-02	South Texas 2	BMV – no indications	5.3	W	H	CE
Apr-02	Summer	BMV of head. almost 100%, no indications. Hot leg – best effort enhanced UT & ET of hot leg nozzles B&C, found same 4 indications, with some length growth on 1 indication in B.	2.5	W	B	CBI
Sep-02	McGuire 1	BMV – no leaks or evidence of boric acid	2.5	W	H	CE
Oct-02	Callaway	BMV – no indications of leakage or degradation	2.5	W	H	CE
Mar-02	McGuire 2	BMV – no indications; canopy seal weld leak on startup	2.4	W	S	RDM
Mar-02	Wolf Creek	BMV –no indications	2.4	W	H	CE
Mar-02	Vogtle 1	BMV– no indications	2.4	W	H	CE
Mar-03	Catawba 2	BMV – no indications of leakage or degradation	2.3	W	H	CE
Apr-01	McGuire 1	Visual on a few nozzles – no indications	2.2	W	H	CE
Apr-02	Catawba 1	BMV –no indications	2.2	W	S	RDM
Oct-02	Vogtle 2	BMV– no indications	2.2	W	H	CE
Oct-01	Harris	BMV – 2/3 of nozzles – no indications of leakage	2.1	W	B	CBI
Sep-02	Comanche Peak 1	BMV –No indications, canopy seal weld leaks	2.0	W	H	CE
Sep-02	Millstone 3	BMV – no indications	1.9	W	H	CE
May-02	Seabrook 1	BMV – no indications	1.8	W	H	CE
Mar-02	Byron 1	Partial visual – 20% near previous sill – no indications	1.7	W	B	BW
Apr-02	Braidwood 2	BMV – no indications	1.6	W	B	BW
Sep-02	Byron 2	BMV – no indications	1.6	W	B	BW
Apr-02	Comanche Peak 2	BMV – no indications	1.5	W	H	CE
Mar-03	Sequoyah 1	BMV – Nozzle 3 near the center with boric acid and 1 masked peripheral. UT/PT of #3 and 5	1.5	W	S	RDM
Mar-02	Sequoyah 2	BMV – no indications	1.4	W	S	RDM
May-02	Cook 2	BMV – no indications; UT, 4 tubes w/shallow cracks, 2 repaired	15.0	W	W	CBI

3 STATISTICAL ANALYSIS OF DIFFERENTIAL SUSCEPTIBILITY

H. B. Robinson's head is of Westinghouse design, using Huntington material, and was fabricated by Combustion Engineering (CE). Of the 23 plants inspected with these attributes, none have found PWSCC. Although many of these plants have relatively low EDY, five of these plants, including H. B. Robinson, are older than Millstone 2 and St. Lucie 2. Are plants with some or all of these attributes differentially susceptible? In this section, a multivariate statistical analysis is performed on the data in Table 2-1 to disentangle the separate effects of EDY, designer, material supplier, and fabricator. Specifically, the objective is to statistically test to see if:

- B&W NSSS design (BW Design),
- CE Fabrication (CE Fab),
- Huntington material (Hunt. Mat),

and combinations of these categories have any influence on the probability of PWSCC over and above the influence of time and temperature (EDY). The practical significance of this influence is also evaluated.

3.1 STATISTICAL MODEL

The statistical model is known as the log-logistic and can be obtained as a variant of the well-known "Logit" model. Define a variable $Y_i = 1$ if the ith measurement, X_i, is associated with a PWSCC crack or leak and zero otherwise. The variable X will refer to the ith plant's EDY in Table 2-1 (i.e., the EDY at time of first indication of PWSCC or at the latest inspection if PWSCC has never been found). [

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3.2 STATISTICAL HYPOTHESES TEST RESULTS

Using the data in Table 2-1 and the model described in the previous section, five cases are estimated:

Case 1: Time and temperature (EDY) alone.
Case 2: B&W Design added to Case 1.
Case 3: CE Fabrication added to Case 1 (BW Design dropped).
Case 4: Huntington Material added to Case 1 (CE Fabrication dropped).
Case 5: EDY, B&W Design and CE Fabrication are simultaneously included.

Table 3-1 has the results of the regression analysis for each case.

Table 3-1 Synopsis of Regression Results for Five Cases					
Logistic Regression Synopsis[1]					
Variable	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Constant	-22.34 (8.31)*	-15.17 (32.5)*	-45.68 (3.00)	-21.01 (7.03)*	-15.08 (32.04)*
Ln(EDY)	7.76 (7.96)*	5.12 (32.90)*	15.38 (3.19)	7.23 (6.68)*	5.03 (31.68)*
BW Design-Constant		-12.85 (23.30)*			-12.78 (23.02)*
BW Design-Ln(EDY)		4.76 (28.40)'			4.65 (27.01)*
CE Fab-Constant			39.28 (2.44)		0.16 (1.14)
CE Fab-Ln(EDY)			-13.84 (2.59)		-0.20 (8.19)*
Hunt.Mat-Constant				-4.49 (0.32)	
Hunt.Mat-Ln(EDY)				1.8 (0.41)	

Values in () are Wald test statistics
* Indicates statistical significance at the 0.05 level or better
1. Dependent Variable = 1 if PWSCC observed, 0 otherwise. N = 63 plants

The results in Table 3-1 can be summarized as follows:

Case 1: EDY alone is, as expected, a statistically significant explanatory variable for the probability of PWSCC.

Case 2: Adding the BW Design category substantially increases the explanatory power of the model. The changes in the constant and slope coefficients are both statistically significant. For B&W plants, the relation between probability and EDY shifts to the left (higher probability at each EDY) and is steeper. The size of the EDY coefficient is reduced and its statistical significance is increased.

Case 3: Adding CE Fabrication to Case 1 (leaving out BW Design), the estimated relation between probability of PWSCC and EDY shifts to the right (lower probability at each EDY) and is less steep. However, this shift is not statistically significant. That is, because of the high variability in the data, we cannot reject the null hypothesis of no relation between CE Fab and probability of PWSCC. Clearly, the CE Fab category, by itself, is not as powerful a discriminator as is BW Design.

Case 4: Huntington material has no significant discriminatory power. Equivalently, after controlling for time and temperature, we cannot reject the null hypothesis that whether or not a plant has Huntington Material plays no part in its susceptibility to PWSCC.

Case 5: The best model results when BW Design and CE Fab are both included and allowed to interact with EDY. The impact of BW Design is not materially affected but now the impact of CE Fab on the slope of the relation between EDY and probability is seen to be small but statistically significant.

In short, B&W Design and, to a lesser extent (and in a different direction), CE Fabrication, do appear to influence the likelihood of PWSCC over and above time and temperature (as represented by EDY).

3.3 IMPLICATION FOR FINDING PWSCC AT H. B. ROBINSON

As noted earlier, H. B. Robinson does not have a B&W NSSS design and does have a CE fabricated head. EDY, at the fall 2002 inspection, moreover, is estimated to have been 20.3 EDY. Using the regression model for Case 5 described in the previous section, Figure 3-1 calculates the mean estimated probability of PWSCC at different EDY (ranging from 5 to 25) for three categories of plants:

1. Those plants with B&W designs.

2. Those plants that have CE Fabrication (and do not have B&W designs). This is the category into which H. B. Robinson falls.

3. Those plants that do not have B&W designs but also do not have CE Fabrication ("Neither").

The influence of EDY and other variables is now more evident. The categorical variables have a growing influence as hotter-older plants are considered so that when the time-temperature equivalent to that of H. B. Robinson's 20 EDY is reached, the probability of a B&W plant having PWSCC is almost double that of an H. B. Robinson – type plant (the lowest line on the chart). Further, the latter is about 20% lower than for plants that do not have the B&W design but also do not have the CE fabricated head.

3.4 SUMMARY AND CONCLUSIONS

In summary:

1. It can be demonstrated statistically that other factors besides time and temperature significantly influence the likelihood of PWSCC, and

2. Ignoring these other factors may lead, in effect, to substantially overestimating the likelihood of PWSCC in plants with H. B. Robinson-like attributes.

Thus, in determining frequency of inspection, H. B. Robinson-type plants may be sufficiently less susceptible than other plants within the high-susceptibility category to warrant a one-outage deferral in inspection.

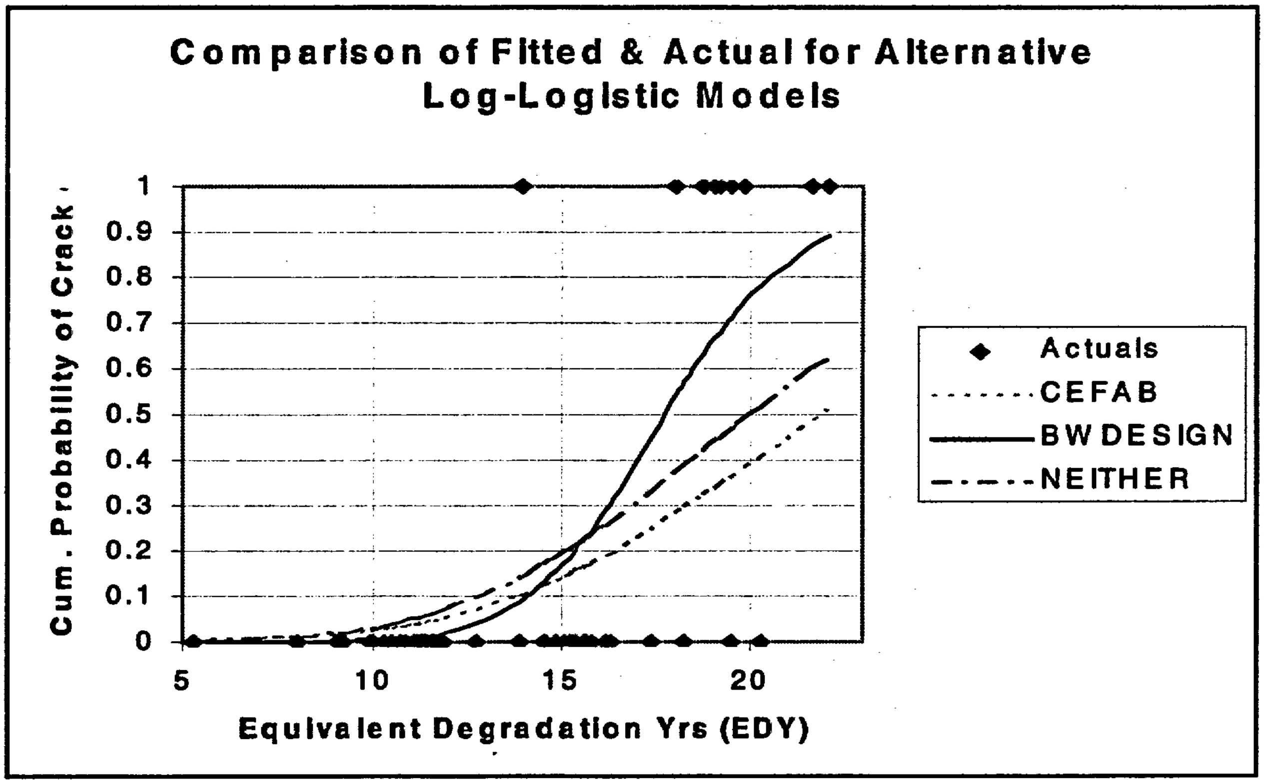

Figure 3-1 Projected Probability of PWSCC for Alternative Plant Categories

4 DETERMINISTIC STRUCTURAL INTERGRITY ANALYSIS

4.1 INTRODUCTION

A flaw evaluation handbook (WCAP 15928) has been developed for H. B. Robinson Unit 2 which provides most of the material needed for a deterministic evaluation of crack propagation in the plant's head penetrations. This section assembles the key results from that report and provides a detailed treatment of the attachment welds.

4.2 FLAW TOLERANCE OF THE HEAD PENETRATIONS

The high toughness of the head penetration tubes ensures that any potential fracture would be completely ductile. Calculations based on ductile limit load have shown that the axial flaw size necessary to cause a failure would be a throughwall flaw, with a length of 13 inches. For a circumferential flaw, the critical flaw length is approximately 90% of the circumference, and through the wall thickness as well.

A series of calculations were made to predict the growth of postulated cracks in the head penetrations at the Robinson plant, in order to provide a view of the time required to lead to a leak. The crack growth model used for these calculations was taken from MRP 55, Rev. 1, which is consistent with recent NRC guidance (4-11-03) on evaluating flaws in head penetrations.

The **axial inside surface flaw** case will be discussed first. Crack growth calculations were carried out for a number of different head penetrations, to encompass the range of intersection angles that exist in the plant. For a given tube, crack growth was predicted for three different axial crack locations, one-half inch below the weld, at the weld, and one-half inch above the weld. In addition, both the uphill side and the downhill side of the penetration were considered. These results were reported in WCAP 15928.

The governing location for the axial flaw case was found to be at the weld, as shown in Figure 4-1, (Figure 6-5 in WCAP 15928). The governing row of penetrations was the next to outermost row, at a nozzle angle of 43 degrees. If it is assumed that an axial flaw has initiated at the inside diameter of the tube, the figure shows that more than four years are required to produce a leak. For other penetrations and locations, the time required for the production of a leak ranges from 4.5 years to over twenty years.

Another way in which a leak could occur is for a **flaw on the outside diameter of the tube** to grow upward past the weld, having initiated below the weld. To conservatively model the time required to produce this leak, a throughwall flaw was postulated below the weld, and its growth was calculated. Again, a wide range of flaws was postulated, in different penetrations, and calculations were completed for both the uphill and downhill sides of the penetration in each case. These calculations are affected by the stresses in the tube, which are affected by the weld size itself, and the way in which the stresses change with distance from the weld.

The governing location was found to be the 27.1 degree location on the uphill side, as shown in Figure 4-2, (Figure 6-16 of WCAP 15928). For a throughwall flaw postulated here, the time required to produce a leak was found to be 8.7 years. For the other penetration locations, the equivalent times were found to range from 8.75 to 15 years. For locations above the weld, the crack growth is slower, because the stresses are lower, as shown for example in Figure 4-3.

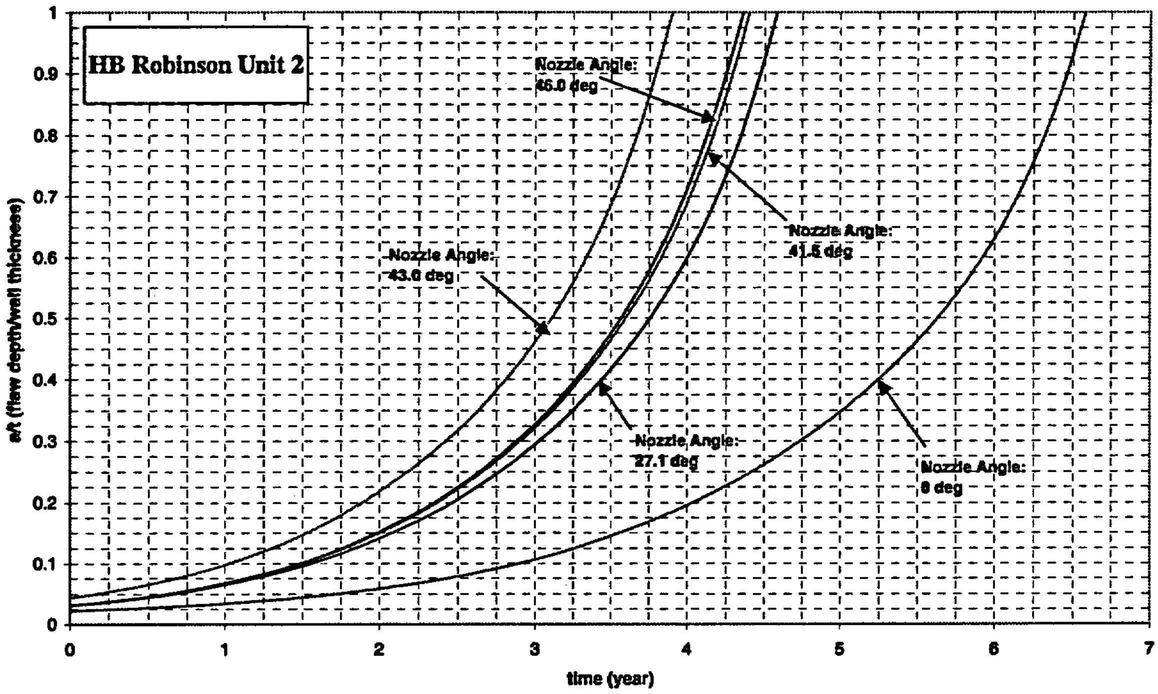

Figure 4-1 **Crack Growth Predictions for Axial Inside Surface Flaws Located in the Attachment Weld Zone – Nozzle Downhill Side**

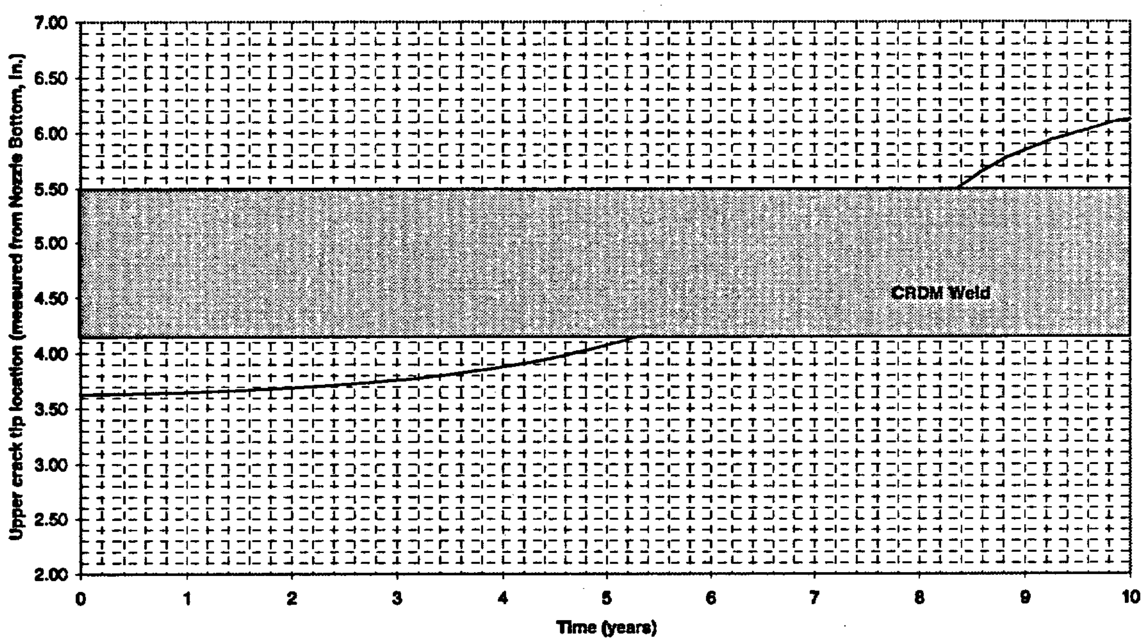

Figure 4-2 **Crack Growth Predictions for Throughwall Axial Flaws Located in the 27.1-degree Row of Penetrations – Uphill Side**

The third way in which a leak could be produced is for a flaw to propagate through the weld itself. Field experience shows that the crack initiation resistance of the Alloy 182 welds is significantly higher than that for the base metal. This way is examined in the following sub-section.

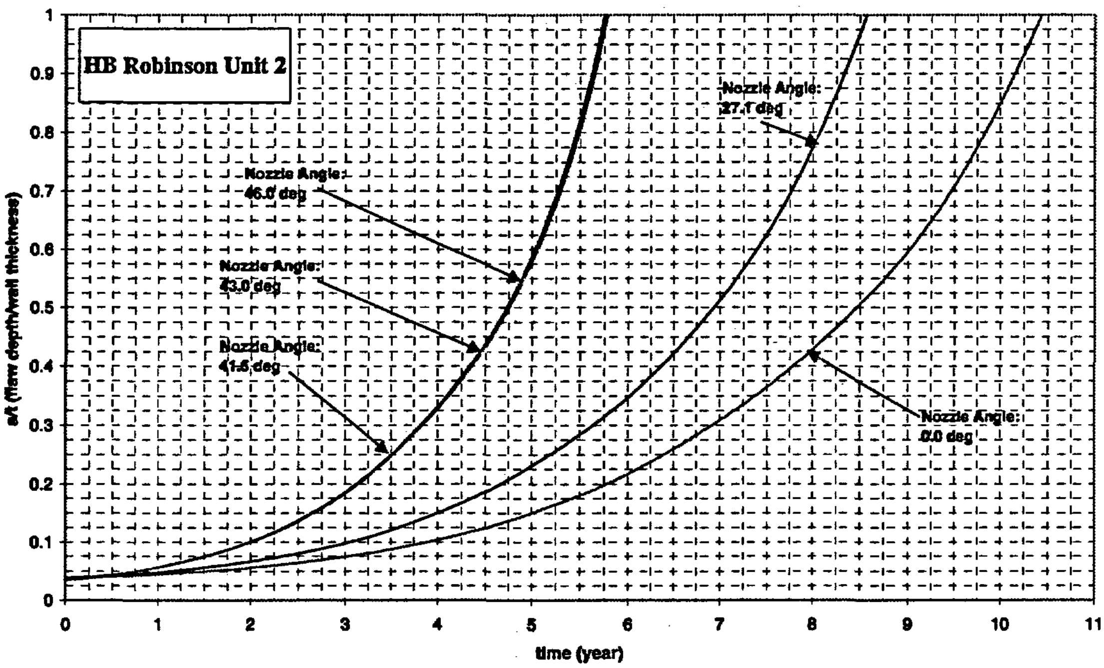

Figure 4-3 Crack growth predictions for Axial Inside Surface Flaws whose lower crack tip is located at 0.5 inch above the Attachment Weld or higher – Nozzle Downhill Side

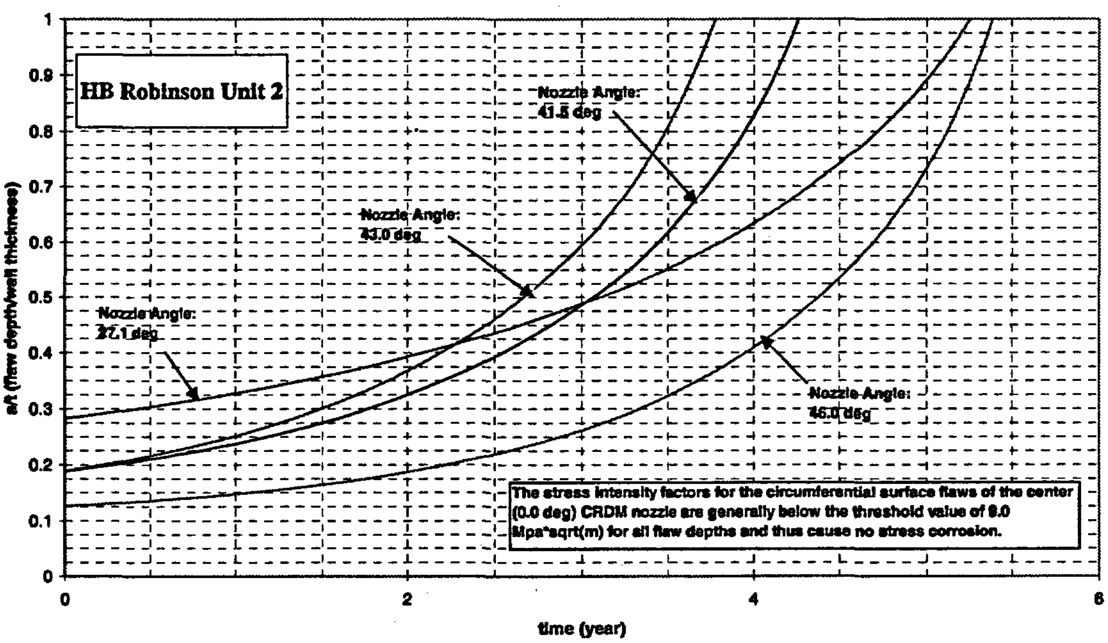

Figure 4-4 Crack Growth Prediction for Circ Outside Surface Flaws Along the Top of the Weld

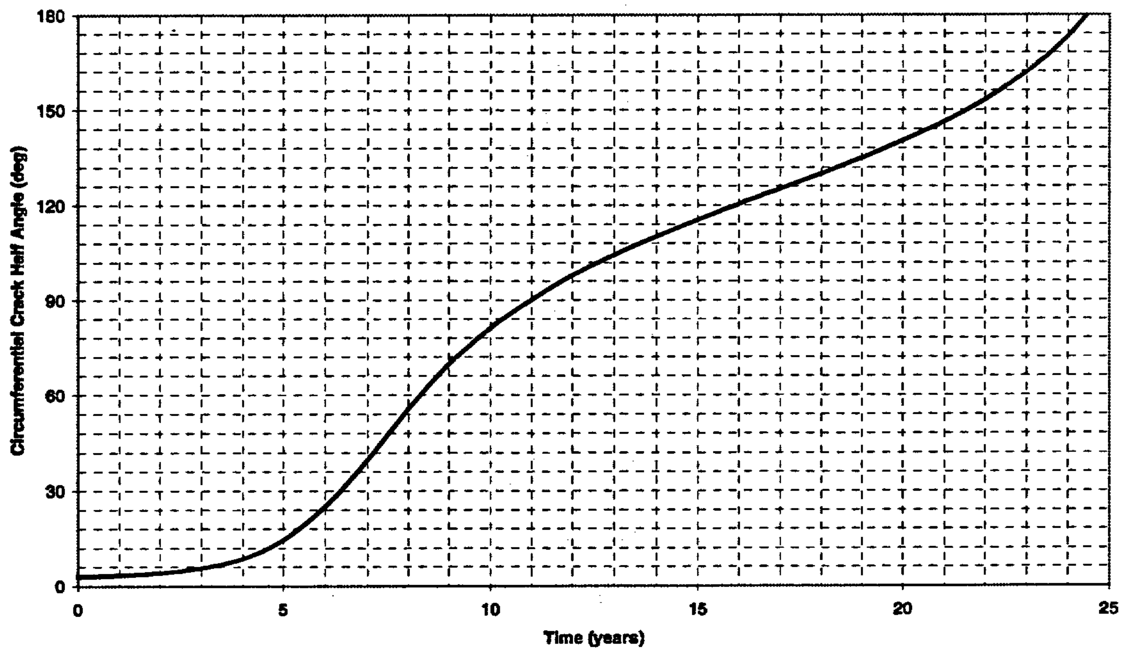

Figure 4-5 Crack growth predictions for Circumferential Throughwall Cracks Near the Top of the Attachment Weld.

4.3 FLAW TOLERANCE OF THE ATTACHMENT WELDS

The crack growth predictions for the attachment welds were carried out using the same general approach as that used for the head penetrations. The geometry is different, so a different stress intensity factor expression was used, as will be described below. Also, the PWSCC crack growth rate for the Alloy 182 welds has been found to be higher than that for the base metal, so a different crack growth model is necessary, and that will be described as well.

4.3.1 Stress Intensity Factor Calculation

One of the key elements in a fracture mechanics evaluation is the determination of the crack driving force or stress intensity factor (K_I). This is based on the information available in the literature.

The stress intensity factors for two corner flaws emanating from the edge of a hole in a plate was taken from the work by [ ].[a,c,e] The use of this stress intensity factor expression requires that the stresses remote from the hole be resolved into membrane and bending stress components. The stress intensity factor can be expressed conservatively in terms of the linearized membrane and bending stress components as follows:

[ ][a,c,e] (4-1)

The Cloud-Palusamy expression is applicable for a range of flaw shapes, with the depth of the flaw defined as "a", and the width of the flaw defined as "l", as shown in Figure 4-6 [ ].[a,c,e]

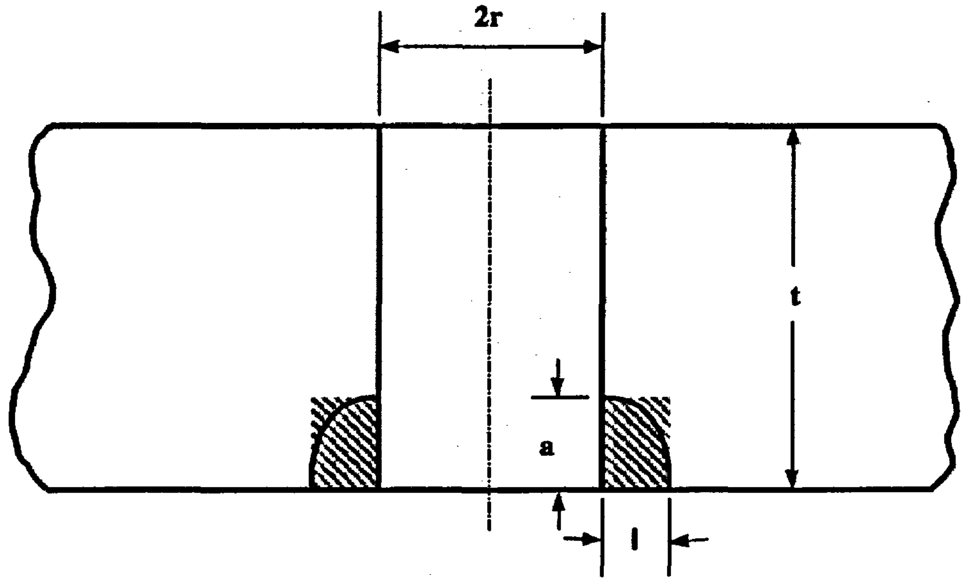

Figure 4-6 Geometry and Terminology as Applied in [ ]^a,c,e

This flexibility is necessary because this expression will be applied to a range of flaw shapes corresponding to different attachment weld shapes in H. B. Robinson Unit 2. The coefficients A and B can be found in [ ].^a,c,e for selected values of r/t, a/l and a/t, where "r" is the outside radius of the penetration nozzle and "t" is the wall thickness of the reactor vessel head. For the r/t, a/l and a/t values not shown in [ ].^a,c,e, the coefficients A and B were determined using interpolation. Since the coefficients are provided for a number of locations around the flaw front, [ ]^a,c,e

4.3.2 PWSCC Growth Rates for Alloy 182

The most important mode of subcritical crack growth is PWSCC for Alloy 182 in a PWR environment, which was the reported mechanism from the root cause analysis of the crack in the Loop A hot leg, at V. C. Summer (Westinghouse Letter CGE-00-019). Recently an experimental program was carried out to measure crack growth rates in Alloy 182, and the results were reported in Bamford and Foster (June 2000). Seventeen specimens from three different welds were tested, and the results showed reasonably consistent growth rates among the three welds.

There is more scatter in the crack growth results for welds than for the Alloy 600 base metal, and there is a very important effect of crack orientation. The growth rate parallel to the dendrites is five to ten times that for flaws propagating through the dendrites. Flaw propagation parallel to the dendrites is a realistic possibility, since the dendrites are oriented in the direction of solidification of the weld. Therefore, the emphasis of the testing has been on this orientation.

Three welds have been studied, and a fourth was characterized at Studsvik. The behavior has been consistent from each weld tested to date. The effect of temperature is similar to that observed for Alloy 600 base metal (Bamford and Foster, December 1997), as shown in Figure 4-7. The effect of stress intensity factor is also similar to that observed for Alloy 600 base metal, but the crack growth rate is

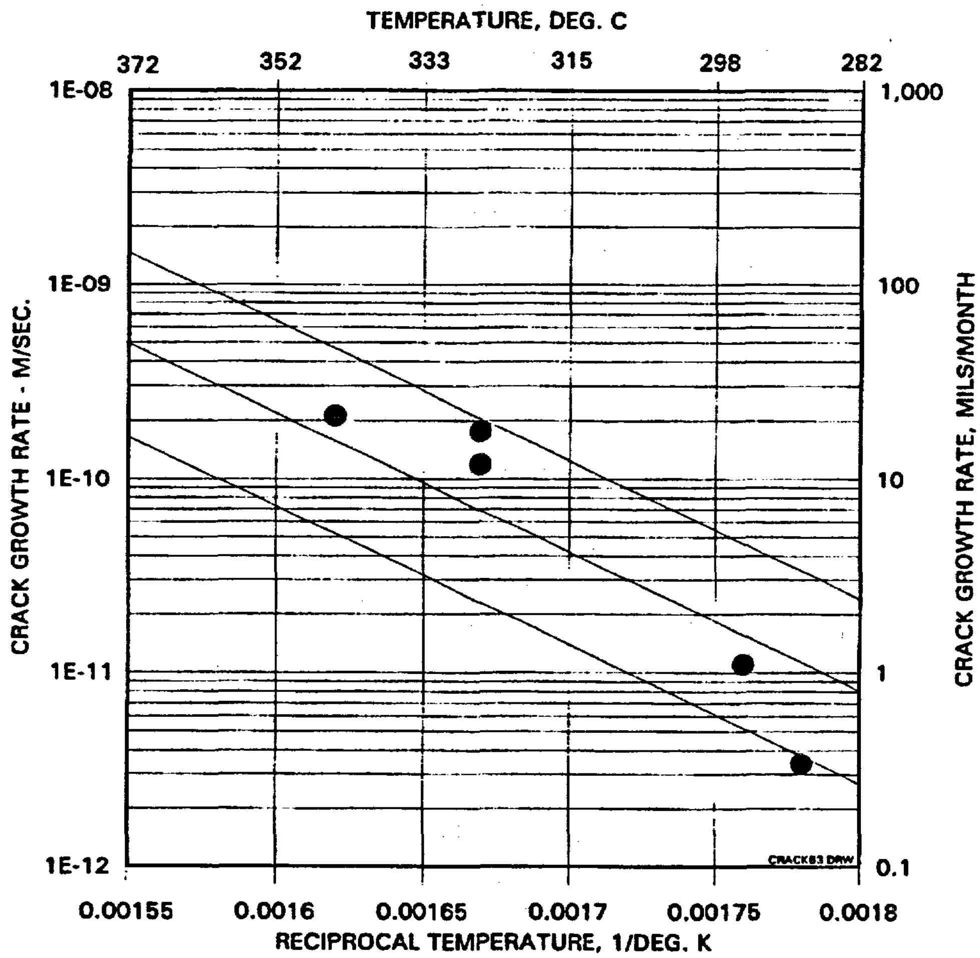

Figure 4-7 Effects of Temperature on Growth Rates: Alloy 182 [3]

higher. It is important to note that the range of stress intensity factors studied was limited to the range of 20-45 Mpa $\sqrt{m}$. Therefore the model cannot be verified beyond this point. A model of the crack growth rate has been developed based on application of the shape and threshold aspects of the modified Scott model, with a factor of five applied to the model as originally used for the Alloy 600 base metal. The Alloy 182 model, along with the data originally developed to support it, is shown in Figure 4-8. The equation for this model at 325°C is:

$$\frac{da}{dt} = 1.4 \times 10^{-11} (K - 9)^{1.16} \text{m/sec} \qquad (4\text{-}2)$$

This model should be viewed as the best presently available. It is interesting to note that the model was originally established with a smaller data set, and did not change when the available data more than doubled.

Recently, data from Vaillant, et al (April 1997) and Lindstrom, et al (August 1997) was obtained, and the results for 325°C were plotted and compared with the model used in the evaluation. Figure 4-9 shows all

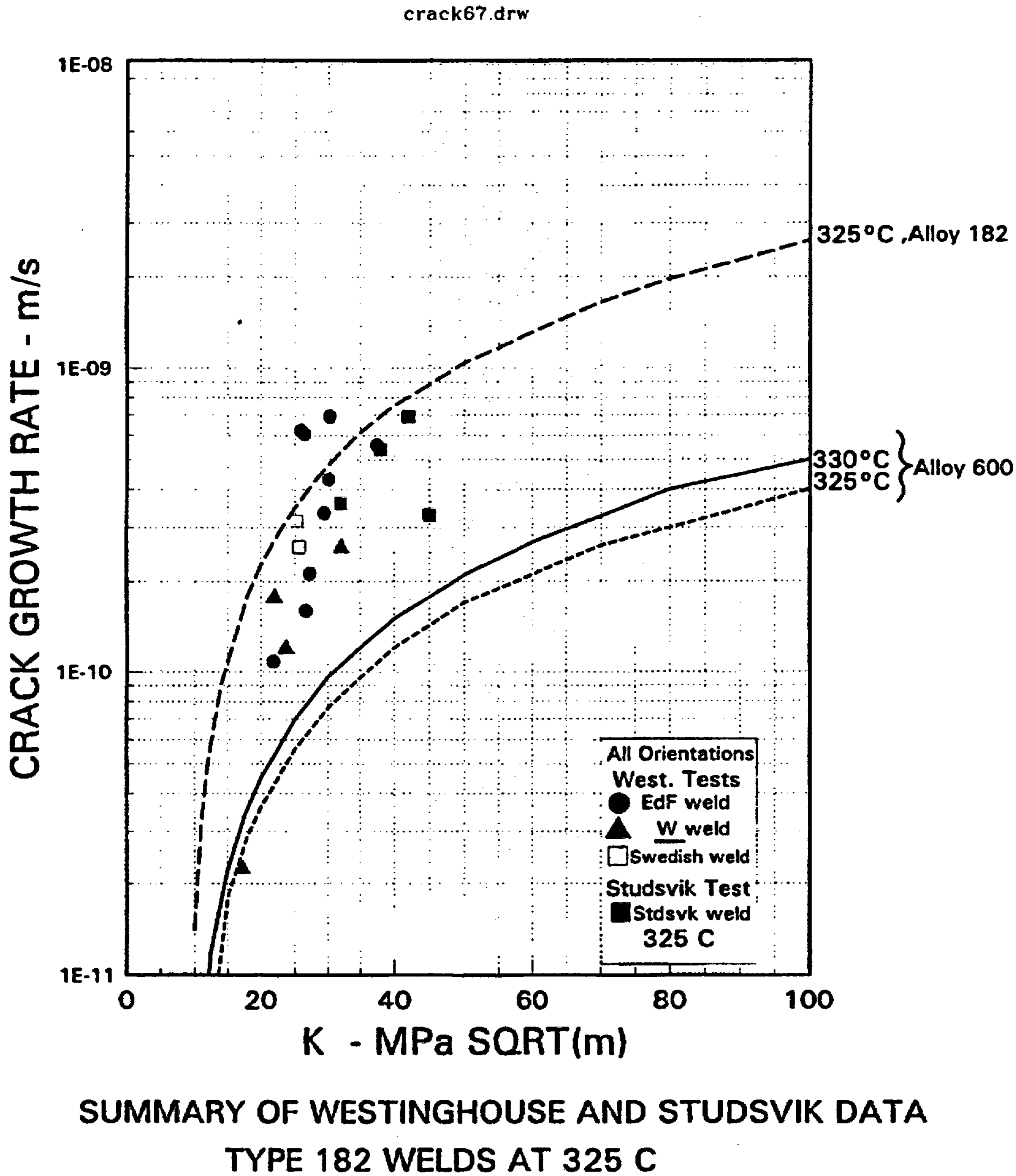

Figure 4-8 Crack Growth Model for Alloy 182 in PWR Environment with Available Data [3]

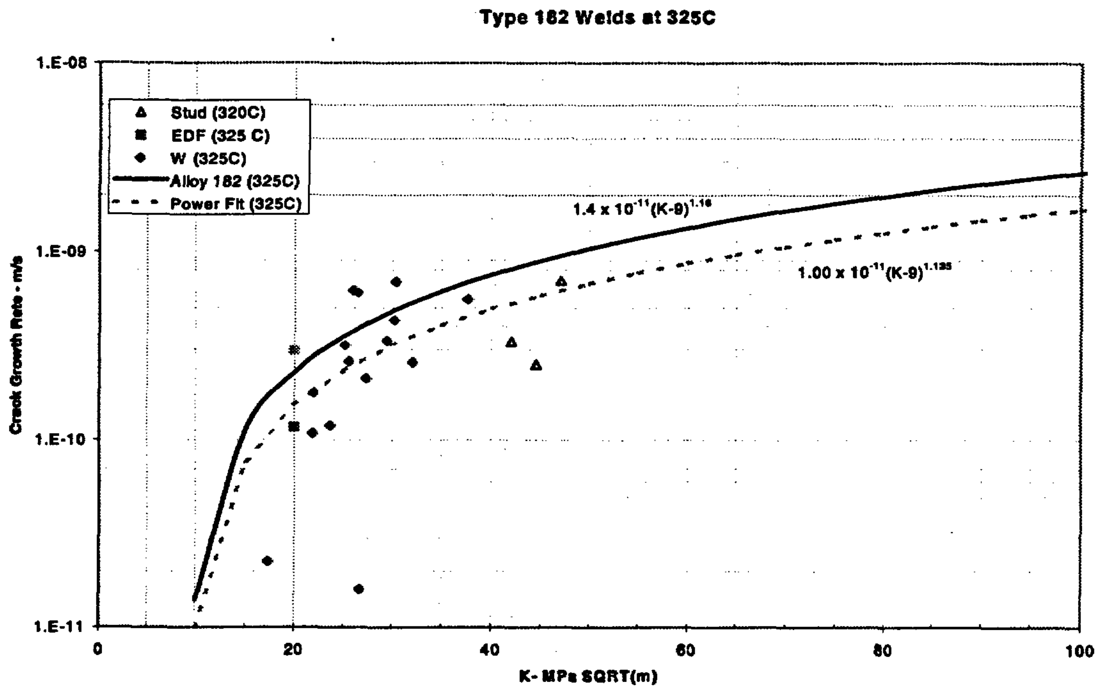

Figure 4-9 Comparison of Alloy 182 Crack Growth Model with Recent Data

the data, along with a best-fit curve through the data. Although the total number of data points is still small, the data seem well behaved. The best-fit curve has nearly an identical form to that used in the evaluation (solid curve), and is lower by a factor of about 1.4. This comparison adds significant credibility to the curve used in the evaluation.

4.3.3 PWSCC Crack Propagation Results for Alloy 182/82 Attachment Welds

The crack growth calculation begins with a postulated flaw assumed to be the same shape as the attachment weld itself, and whose size was set to be slightly greater than the threshold for crack growth. The analysis proceeds over a period of time until the flaw reaches the outer extremity of the attachment weld, where it will stop, because the reactor vessel head is not susceptible to stress corrosion cracking. When the flaw has propagated to this point, the head penetration is leaking, but the flaw is far from the size that could cause failure of the head.

The results of the calculated growth through the weld thickness of the CRDM penetration attachment weld are shown in Figure 4-10. Note that results are shown for the full range of penetrations, from the center to the outermost. The crack growth is somewhat faster for the outermost row because the stresses are higher, and the stress intensity factor is higher due to the weld shape. The outmost nozzle growth rate averages 0.21 inches/year, producing a leak in 5.8 (effective full power) years.

The calculated growth shown in Figure 4-10 is based on the assumption that the flaw maintains a fixed shape as it grows. This assumption is conservative, because the actual stress intensity factor is slightly higher at the long end of the assumed flaw (at the end of the 'a' dimension), as opposed to the shorter end of the flaw (the end of the 'l' dimension). Thus, the flaw would tend to grow longer in the 'a' direction, but this would lead to a lower stress intensity factor, as a result of a larger ratio of a/l, and thus the crack would slow down.

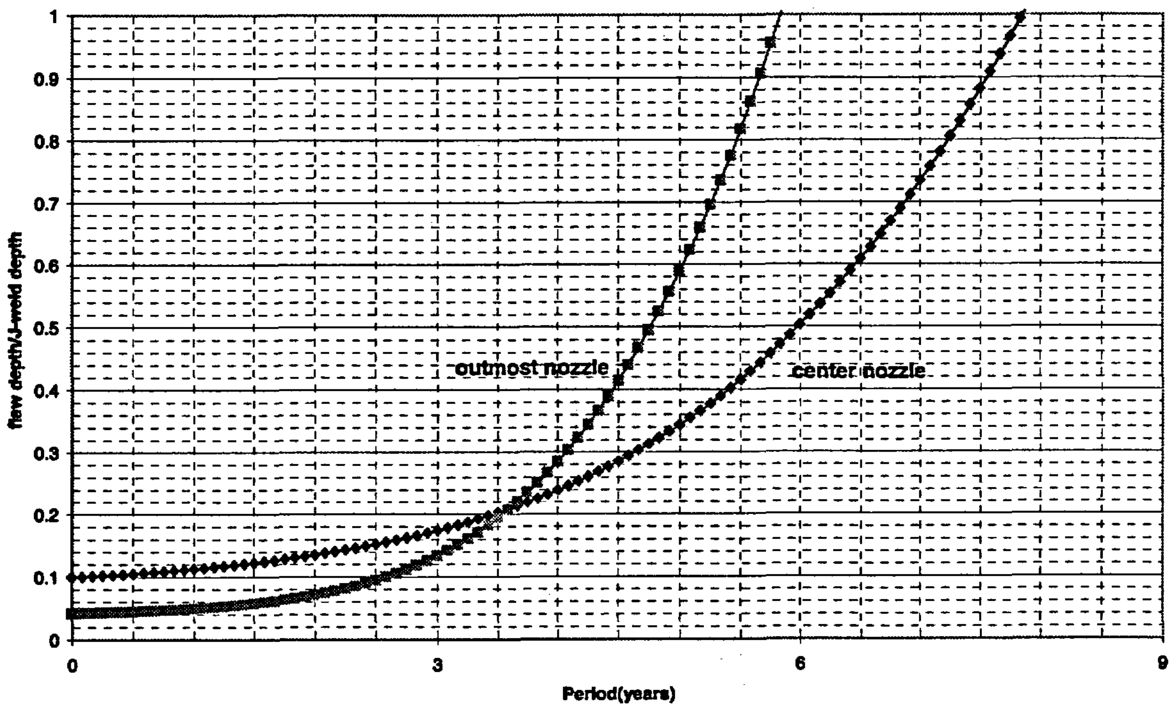

Figure 4-10 Results of Crack Growth Calculations for Attachment Welds

4.4 SUMMARY AND CONCLUSIONS

In summary, the earliest weld leak is 5.8 years. The earliest axial leak is estimated at 3.9 years. The integrity of the tube can also be challenged through propagation of a circumferential crack. The most damaging location for such a crack is just at the top of the attachment weld, and the propagation of a postulated crack at the OD of the tube in this location is shown in Figure 4-4. In this case, the stresses change around the circumference, so the highest stress location was chosen, to make the calculation as conservative as possible. The results showed that about 3.8 years would be required to have a flaw grow through the wall. For the flaw to propagate around the circumference to a complete severance of the tube would take at least an additional 24 years, as shown in Figure 4-5. This is primarily because the stresses change significantly around the circumference, in some cases even becoming compressive.

In summary, the deterministic structural integrity results are as follows:

Flaw Type	Minimum Years to Leak	Minimum Years to Break
Axial ID Flaw – at Weld	3.9	—
Axial Throughwall Flaw	8.5	—
Axial ID Flaw – 0.5" above Weld	5.8	—
Circ. OD Flaw – above Weld	3.8	—
Attachment Weld Flaw	5.8	—
Full Circumferential Break		At least 24
Critical Axial Crack (20" Throughwall)	Not feasible	

Therefore, extending the inspection interval to the fall of 2005 should not lead to a leak.

5 PROBABILISTIC EVALUATION AND RISK ANALYSIS

5.1 INTRODUCTION

This section provides a probabilistic analysis to support a risk-informed basis for deferring future non-visual inspections until fall 2005 (with additional calculations out to spring 2007). This analysis uses a probabilistic model derived from extreme value theory, with values for inputs (initiating and critical sizes and crack growth rates) taken from flaw evaluation handbook described in Section 4 above. The result is a projected probability of leak and, for circumferential cracks, a probability of reaching a critical size. The incremental CDF associated with extending the inspection interval can be calculated based on (a) the calculated probability of a flaw becoming a critical size before the next inspection, (b) the likelihood of a safety-related following event (rod ejection), and the conditional core damage probability. The resulting calculated incremental CDF is then compared to a threshold incremental CDF specified in RG 1.174 to ascertain whether one important condition of a "risk-informed" basis for extending the inspection interval exists.

5.2 OVERALL APPROACH

[

]a,c,e

[

]a,c,e

Equations 5-2 and 5-3 are used to consider three scenarios. The first evaluates the probability of a nozzle (base metal) leak given small axial flaws on the inner diameter of each tube in the regions of the attachment weld and just above the weld. The second evaluates the probability of a critical circumferential crack, given shallow elliptical flaws on the OD of the tube just above the weld. The third scenario evaluates the likelihood of a leak occurring from a flaw in one of the attachment welds. In all three cases, the initial sizes and growth rates are taken from the deterministic flaw tolerance charts in Section 4.

5.3 PROBABILITY OF AN AXIAL LEAK

Figure 4-1 shows crack growth for axial ID surface flaws located in the weld zone for 5 nozzle angles (downhill side). Figure 4-3 shows crack growth for axial ID surface flaws for the same 5 nozzle angles located just above the weld. These figures are the source for axial leak parameters. For this leak analysis, it is assumed that $\theta = 0.04$ inches = average of the exponentially distributed depths of the maximum axial ID flaws across all 69 penetrations. In other words, the analysis considers the possibility of flaw sizes ranging from the microscopic to those near throughwall in the high-stress regions at and just above the weld, with the average depth being 0.04 inches (= the threshold for high detectability). The same column of Table 5-1 also indicates that the average growth rate (calculated from Figures 4-1 and 4-3) from initiation to throughwall of these flaws across all 5 nozzle angles is 0.1002 inches per EFPY. This is taken to be the value of g in Equation 5-2. A value for D, the wall thickness, is given as 0.625 inches.

Table 5-1 Input Values for Axial and Circ Scenarios				
Variable Description	Model Symbol	Axial Scenario	Circ Scenario	Weld Scenario
Avg. Flaw Depth (axial, weld) or Length (circ)	θ	0.04	0.74	0.09
Critical Flaw Depth (Leak) or Length (Break)	D	0.63	11.52	1.23
Avg. Growth Rate (inches per EFPY)	g	0.1002	0.5349	0.1676
Relevant No. of Penetrations	η	69	69	69

Given these values, the probability of the *first* axial throughwall (assumed to generate a leak) occurring in one of the 69 penetrations can be calculated using Equation 3 for incremental additional EFPY to the next inspection ranging from 1 to 5 EFPY (fall 2005 refueling outage corresponds to 3 EFPY for a 100 capacity factor). Table 5-2 has the results. Referring to the column labeled "Axial Leak," the probability of an axial leak originating from the postulated distribution of ID axial flaws occurring on or before 1.5 EFPY years from the last inspection is shown as 3.92E-4. This probability rises to 1.8E-2 by 3 EFPY from the last inspection.

Table 5-2 Conditional Probabilities for Axial Leak and Critical Circ Flaw, by EFPY from Last Inspection			
EFPY	Axial Leak	Critical Circ	Weld Leak
1.0	1.03E-4	1.27E-5	2.57E-4
1.5	3.92E-4	2.34E-5	7.52E-4
2.0	1.42E-3	3.89E-5	2.07E-3
2.5	5.08E-3	6.10E-5	5.57E-3
3.0	1.81E-2	9.28E-5	1.48E-2
3.5	6.30E-2	1.38E-5	3.90E-2
4.0	2.08E-1	2.04E-4	1.01E-1
4.5	5.66E-1	2.98E-4	2.46E-1
5.0	9.52E-1	4.33E-4	5.29E-1

5.4 PROBABILITY OF A CRITICAL CIRCUMFERENTIAL FLAW

In Figure 4-4, a semi-elliptic surface flaw, with length six times its depth, was assumed to exist at the outside surface of each of the penetration nozzles along the top of the weld, and its growth through the wall was calculated as a function of time. Since the stresses along this plane vary considerably as a function of circumferential location, nine different cuts were taken through the thickness. The residual stresses in the axial direction became compressive near the mid-wall location in most cases, so generally only one location could be found where the throughwall crack propagation did not arrest. The flaw was assumed to maintain its 6:1 aspect ratio as it grew. Once the flaw became throughwall, it was assumed to grow circumferentially as shown in Figure 4-5. In applying the crack growth model, *the WCAP 15928 analysis assumed that circumferential growth was twice that of axial growth* (as per MRP guidance).

Table 5-1, in the column labeled "Circ Scenario," indicates that the average initial length of the circ flaws of the 5 nozzle locations is 0.74 inches. For this critical circ flaw analysis, this is assume to be θ = the average of the exponentially distributed lengths of the maximum circumferential OD flaws across all 69 penetrations. In other words, the analysis considers the possibility of flaw sizes ranging from the microscopic to those near critical size (of D= about 11.5 inches) just above the weld, with the average length being 0.74 inches (= the average threshold for growth). The same column of Table 5-1 also indicates that the average growth rate (calculated from Figures 4-4 and 4-5) from initiation to throughwall to critical size of these flaws across all 5 nozzle angles is 0.5349 inches per EFPY. This is taken to be the value of g in Equation 5-2.

Given these input values, the probability of the first critical circ flaw occurring in one of the 69 penetrations can again be calculated using Equation 5-3 for incremental additional EFPY to the next inspection ranging from 1 to 5 EFPY. Again, Table 5-2 has the results. Referring to the column labeled "Critical Circ," the probability of a flaw originating from the postulated distribution of OD flaws occurring on or before 1.5 EFPY years from the last inspection is shown as 2.34E-6. This probability rises to 9.28E-5 by 3 EFPY from the last inspection.

5.5 PROBABILITY OF A WELD LEAK

Figure 4-10 postulates a flaw with the same shape as the attachment weld and with a starting size just slightly larger than the threshold for crack growth. This flaw's subsequent growth is then evaluated for: (a) the outer penetrations (highest stresses) and, (b) the center penetrations (lowest stresses). Table 5-1, in the column labeled "Weld Scenario," indicates that the average initial depth across outer and center penetrations is 0.09 inches (= the average threshold for growth). For this leak analysis, this is assume to be θ = the average of the exponentially distributed depths of the maximum attachment (J-) weld flaws across all 69 penetrations. In other words, the analysis considers the possibility of flaw sizes ranging from the microscopic to those near through-weld, with the average size being 0.09 inches. The same column of Table 5-1 also indicates that the average growth rate (calculated from Figure 4-10) from initiation to throughwall of these flaws across the two extreme (outer and center) penetrations is 0.1676 inches per EFPY. This is taken to be the value of g in Equation 5-2. A value for D, the associated average weld thickness is given as 1.23 inches.

Given these values, the probability of the *first* weld leak occurring in one of the 69 penetrations can be calculated using Equation 5-3 for incremental additional EFPY to the next inspection ranging from 1 to 5 EFPY. Table 5-2 has the results. Referring to the column labeled "Weld Leak," the probability of a weld leak originating from the postulated distribution of ID axial flaws occurring on or before 1.5 EFPY years from the last inspection is 7.52E-4. This probability rises to 1.48E-2 by 3 EFPY from the last inspection.

5.6 COMPARISON TO REGULATORY GUIDE 1.174 GUIDELINES

Regulatory Guide 1.174 suggests that a contribution to plant risk is "very small" if the increment in contribution to plant core damage frequency (CDF) is no more than 1E-6 per reactor year. The probabilities in Table 5-2 can be used to calculate change in plant risk.

Assume that a critical circumferential flaw leads immediately to a rod ejection and small LOCA. The contribution to core damage (Birnbaum) probability (CCDP) for H. B. Robinson is (Dolan, April 8, 2003) 2.02E-2 for a small (1.5" – 3" break sizes) LOCA. The resulting increase in plant risk for postponing the inspection of the CRDM penetrations can then be estimated from

$$\Delta Risk = P(\tau \leq t) * CCDP \quad (5\text{-}4)$$

where the first term on the right side is the probability of a critical flaw taken from Table 5-2 for the indicated incremental EFPY to the next inspection, and CCDP is the previously defined Birnbaum probability.

In the literature on risk analysis for technical specification changes, the expression in 5.4 would be called the "time dependent" change in risk. By contrast, the "time averaged" change in risk is (see Samanta, et al. (NUREG/CR-6141), pages 5-6, 5-7) simply the time dependent risk (ΔRISK) divided by the length of the time between tests or inspections, denoted here by EFPY. Putting ΔRISK on per unit of time basis makes it comparable to the metric typically used in probabilistic safety assessments (i.e., change in core damage frequency per year). Table 5-3 shows the calculated incremental risk for times ranging from 1 to 5 EFPY from the last inspection. For 3 EFPY, the cumulative incremental CDF (i.e., the ΔRisk) is 1.87E-6 and average incremental risk per year (i.e., ΔRisk per EFPY) is 6E-7. This estimated increment in plant CDF per year is 40 percent smaller than the guideline of 1E-6 per year. Further, while the guideline is intended for permanent plant changes, this change in risk is temporary.

Table 5-3 R. G. 1.174 Analysis Results, by EFPY from Last Inspection

EFPY	CCDP	ΔRISK	ΔRISK Per EFPY
1.0	2.02E-02	2.57E-7	2.57E-7
1.5	2.02E-02	4.74E-7	3.16E-7
2.0	2.02E-02	7.85E-7	3.93E-7
2.5	2.02E-02	1.23E-6	4.93E-7
3.0	2.02E-02	1.87E-6	6.25E-7
3.5	2.02E-02	2.80E-6	7.99E-7
4.0	2.02E-02	4.12E-6	1.03E-6
4.5	2.02E-02	6.02E-6	1.34E-6
5.0	2.02E-02	8.74E-6	1.74E-6

Regulatory Guide 1.174 also asks for a calculated increase in Large Early Release Frequency (LERF). This calculation, however, is not necessary for this case. Small LOCAs are "...negligible contributors to (H. B. Robinson's) LERF and they do not even appear in (H. B. Robinson's) listings of LERF contributors...." (Dolan, June 18, 2003).

5.7 SUMMARY AND CONCLUSIONS

This approach has several advantages. First, it is a natural extension of a typical deterministic structural integrity analysis. Second, given a deterministic structural integrity analysis, it requires relatively minimal assumptions. It avoids assumptions about the form of a crack initiation model and thus also avoids the requirement to either estimate failure distribution model parameters from sparse data and/or assume distribution model parameter values which may predetermine the outcome.

It does require the relatively non-controversial assumption that the flaw distribution has an exponential shape. There is also the presumption that the assumed single parameter of the exponential distribution – the average depth (and aspect ratio) of the remaining flaws – is suitably "conservative." In the case of the analysis of the risk of a critical circ flaw, this would appear to be the case. The assumed average post-inspection length of the OD circ cracks is assumed to be 0.74 inches, with an average depth of about 0.12 inches (6:1 aspect ratio). A field expert in inspections (Jack Lareau, Westinghouse, April 14, 2003) estimates that a UT exam has a better than 90% probability of detection of a OD nozzle circ flaw depth as small as 0.06" to 0.10". Using Equation 5-1, with values for the circ scenario from Table 5-1, this study assumes 37% of the penetrations have extreme flaws exceeding 0.74 inches, and assumes 87% exceed the 0.1" threshold for high probability of detection.

For axial flaws, the above-cited field expert sets a POD of greater than or equal to 90% for ECT ability to detect flaws of depth 0.04" or larger in tubing. The assumed values in Table 5-1 imply (Equation 5-1) that 37% of the penetrations have post-inspection maximal flaws exceeding the threshold of high detection. For welds, the comparable probability is 17% of exceeding a depth of 0.16 (= threshold for ECT high POD of flaws in welds). Further, no credit is taken for bare metal visual exams at the next refueling outage, nor for any leak detection capability.

In summary, the probabilistic analysis provides quantitative confidence, based on suitably conservative assumptions, that: (a) leaks and critical flaws will not be generated and, (b) plant risk increase will be within acceptable limits over the contemplated interval between inspections.

6 FABRICATION METHODS

6.1 MATERIALS AND FABRICATION OF H. B. ROBINSON UNIT 2 RPV CLOSURE HEAD

6.1.1 RPV Closure Head Materials

The closure head for the H. B. Robinson Unit 2 reactor pressure vessel (RPV) is fabricated from SA-302 Grade B plates, including the requirements of C-E Spec. P3F6(b). The plate sections were formed and welded into the spherically shaped dome. The closure head dome is comprised of seven separate sections of 9 inch thick plate. After forming, each plate segment was heat treated (quenched and tempered) and tested (mechanical properties, NDE) prior to being welded into a component. A central formed dome piece and six formed peel segments were welded to form the complete top of the closure head. The spherically shaped head was then welded to a closure head flange forged from SA-336 low alloy steel, as modified by Code Case 1236 and C-E Spec. P3C1(a). The assembled head was then machined with a minimum thickness requirement of 7-3/4 inch and clad with nominal 7/32 inch of weld deposited stainless steel cladding in preparation for final assembly of all of the nozzle penetrations.

Material for the RPV head penetrations was ordered to ASME SB-167 requirements for nickel-chromium-iron seamless pipe and tube. The material was ordered as 4.5 inch outside diameter by 2.25 inch inside diameter (1-1/8 inch wall thickness) tubular product cut to various lengths in order to obtain the length required for each penetration. There are a total of 69 control rod drive penetrations on the H. B. Robinson Unit 2 closure head. Nine separate heats of SB-167 material were used to fabricate the 69 penetration tubes for the RPV closure head. The overall distribution of the penetration tubes between the heats is shown in Table 6-1 below. Table 6-2 identifies the drawing identification piece number and the heat of material used for each penetration location on the RPV closure head. The H. B. Robinson Unit 2 closure head does not have an Alloy 600 vent pipe attached by a partial penetration weld on the inside of the head. The vent pipe configuration is atypical from most plants and is described in more detail in the discussion of the closure head fabrication.

Table 6-1 Distribution of RPV Head Penetration Tube Heats

a,c,e

Heat No.	Number of Penetration Tubes	Percentage of Penetration Tubes

The chemical compositions for the ladle analysis as reported on the Certified Material Test Report (CMTR) for each heat and from check analyses performed by the C-E Chattanooga laboratory are shown in Table 6-3. No documentation was located for a check analysis on heat NX-0139. There is very little variation in composition between the nine heats. Carbon content is very consistent with a mean value of 0.06% for the nine heats. The mean chromium content of 15.7% is just about at the middle of the specified range of 14.0 – 17.0%. Iron contents for the nine heats tend more toward the low end of the specified range of 6.0 – 10.0% with a mean value of 6.9%.

Nickel contents had a mean value of 76.7% with a minimum reported value of 74.76%, compared to the 72.0% minimum nickel content required by the specification.

Table 6-2 H. B. Robinson Unit 2 RPV Head Penetrations

a,c,e

Penetration Number	Piece Number	Heat Number	Penetration Number	Piece Number	Heat Number	Penetration Number	Piece Number	Heat Number

Table 6-3 Chemical Composition for H. B. Robinson Unit 2 RPV Head Penetration Material SB-167 UNS N06600 Produced by Huntington Alloys

(Mill Annealed at 1725°F for 1.5 hours followed by Air Cooling)

a,c,e

Heat No.		Carbon	Manganese	Iron	Sulfur	Silicon	Copper	Nickel	Chromium	Cobalt

Table 6-4 Tensile Properties for H. B. Robinson Unit 2 RPV Head Penetration Material SB-167 UNS N06600 Produced by Huntington Alloys (Mill Annealed at 1725°F for 1.5 hours followed by Air Cooling)

Heat No.	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)	Reduction in Area (%)	Hardness (HRB)	Purchase Specification

a,c,e

The mechanical properties reported on the CMTRs for each of the nine heats of penetration tube material are provided in Table 6-4. Also shown in Table 6-4 are the Purchase Specification requirements, as they were noted on the CMTR for each of the nine heats of material. The materials were supplied to either the 1961 or 1964 revision of SB-167 with limits of 0.10% max. on carbon and 0.25% max. on cobalt. Code Case 1336, originally approved in February 1964, provided ASME B&PV Code coverage for several product forms of Alloy 600, including SB-167 pipe or tube, for construction in Class A vessels in accordance with Section III.

There is a relatively wide variation in yield strength of 22 ksi between the heats, as seen in Table 6-4, from a low of 35.5 ksi to 57.5 ksi. There is less variation between heats in the values of tensile strength and ductility, measured by total elongation or reduction in area. Figure 6-1 shows the percentage of RPV closure head penetrations as a function of yield strength. As seen in Figure 6-1, 45% of the penetrations in the H. B. Robinson Unit 2 head have yield strengths greater than 50 ksi. Figure 6-2 shows a reasonably good correlation between the reported hardness and either yield strength or flow stress, defined as (YS + TS)/2, for the SB-167 Alloy 600 material.

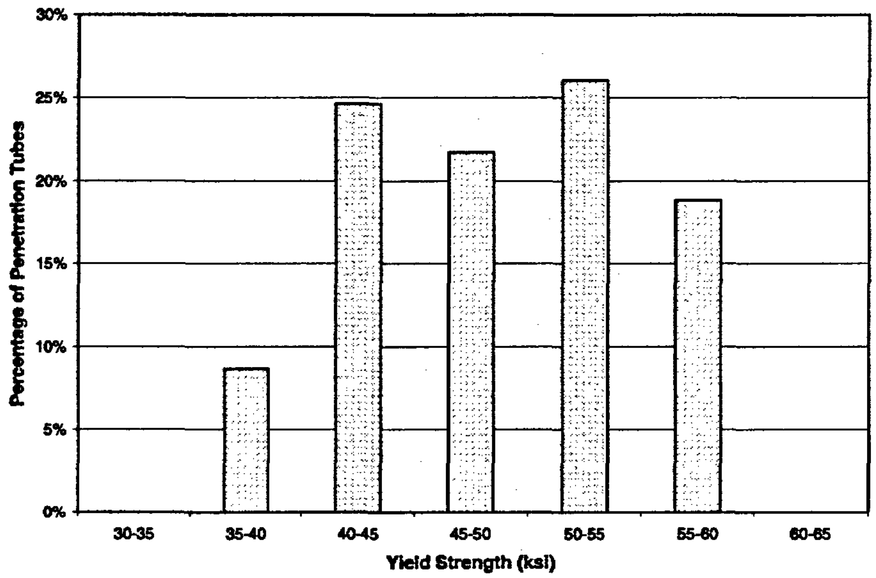

Figure 6-1 Distribution of Yield Strengths for RPV Closure Head Penetration Tubes

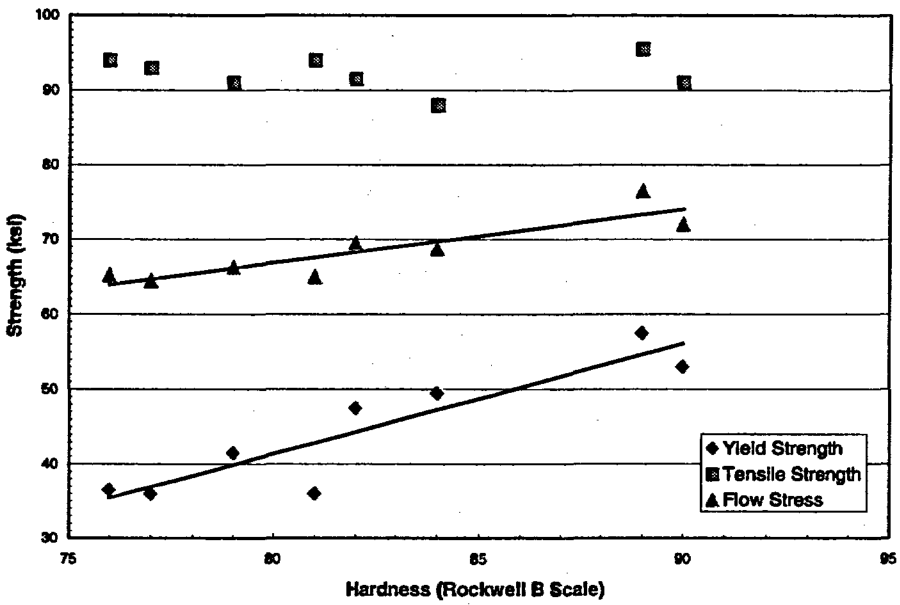

Figure 6-2 Variation in Yield, Tensile and Flow Strength with Hardness for Heats of SB-167

Key parameters for RPV closure head penetrations for 54 Westinghouse plants, including H. B. Robinson Unit 2, and three French units have been previously reviewed and compared (Duran, et al). The review concluded that, in general, trends for closure head penetration material in domestic Westinghouse vessels exhibit higher carbon contents, higher mill annealing temperature, and lower yield strength relative to the materials in the French vessels. Review of the materials for the 10 plants identified as Rotterdam manufactured vessels (Duran, et al), revealed that the majority of penetration tube material was supplied by Sandvik, with some heats from Huntington (Surry 1) and B&W Tubular Products (Surry 2). The carbon content of the Sandvik heats was generally in the same range as the Huntington heats in the H. B. Robinson Unit 2 penetration material. Chromium and iron contents appear to average slightly higher. The yield strengths of the Sandvik material tended to be lower with only one heat reporting a yield strength greater than 50 ksi. The heats of Huntington material used by Rotterdam in one head exhibited the same wide variation as seen in the heats of material used in the H. B. Robinson Unit 2 penetrations.

The material certifications for the H. B. Robinson Unit 2 head penetration material heats are dated from July 1963 through April 1967. Since many of the details of interest about Alloy 600 material are generally not included in the CMTR data, a summary of the materials manufacturing and processing was obtained to provide a better idea about the metallurgical condition of the RPV closure head penetration material [10]. This summary was provided for the same vintage of materials, as those used for the H. B. Robinson Unit 2 penetrations. Chemical composition and mechanical property data for the heats of material considered in the review are very similar to H. B. Robinson Unit 2 head penetration heats of material. The production processes used by Huntington during this time are summarized briefly.

Heats were melted in an induction furnace and cast into ingots nominally 18"x18"x48" long. A sample for chemical analysis was taken at the time the ingots were cast. Ingots were heated to the 2200–2250°F range for hot working. Initial ingot reductions were performed on the forge hammer. The ingots were worked down by reduction and re-heating, as needed, to produce extrusion rounds with a nominal hot finished diameter of 11-5/8" diameter. Finishing temperature of the round off the hammer may have been in the 1600–1700°F temperature range.

The rounds were machined to 10.7" diameter and cut into billets, a maximum of 30" long. For the finished size tubular product for the RPV head penetrations, a 2.5" diameter hole was trepanned in the extrusion round. Extruded tubes were produced on a 4000 ton extrusion press at the Huntington plant. The extrusion rounds were again heated to the 2250°F range for approximately 4 hours prior to hot extrusion. They penetration tubes were then hot-extruded to the 4.5" outside diameter, 2.25" inside diameter final size, using a glass extrusion practice. Extruded tubes were then water quenched. It was estimated that the tube temperature just prior to entering the water quench bath was in the range of 1800°F to 2050°F with the inside diameter being slightly hotter than the outside diameter. The final processing of the tubes included deglassing/descaling, followed by an annealing treatment at 1725°F with air cooling from the annealing temperature. The tubes were then pickled and straightened, if necessary. Tubes were probably rotary straightened on a two-roll straightener. The tubes were then tested and examined to meet the applicable specification and Code requirements. The tubes were then marked, certified and prepared for shipment.

Typical grain size for the tubular product being produced ranged from ASTM #1 to #5 with a estimate of the nominal grain size of ASTM #3-4 being characteristic for heats of material being produced at the time. Actual grain size and microstructure information is not available for any of the H. B. Robinson Unit 2 heats of material. Based on the assumed process history being used by Huntington, the expected microstructure would be a mix of intergranular and intragranular carbides, with a relatively higher percentage of intragranular carbides being present. The microstructure of the extruded product is normally very clean with no significant level of intragranular carbides present. The billet is heated in the 2250°F range and the extruded tube is rapidly water quenched directly after extrusion, leaving little or no time for carbide precipitation. The subsequent anneal at 1725°F will result in significant carbide precipitation. Time in the continuous furnace hot zone would have been approximately 90 to 100 minutes. The tubes would exit the hot-zone into an enclosed chamber where forced air cooling was applied. No actual cooling rate information is available, however, it would have been considered to be a relatively slow rate. The resulting annealed microstructure likely contains a significant level of intragranular carbides that precipitated during cooling.

There is also very little information available on the processing details from other material suppliers that supplied Alloy 600 tubular product or forged bar for nozzle penetrations. The minimum range of annealing temperatures used by B&W Tubular products for material of the same vintage was 1600°F to 1700°F. These temperatures are even lower than that used by Huntington and could have resulted in Alloy 600 material being in a metallurgical condition that may be slightly more susceptible to PWSCC.

6.2 RPV CLOSURE HEAD FABRICATION

Assembly and Machining of RPV Closure Head Penetrations

Each piece of SB-167 penetration tube material was machined with a weld preparation to which a SA-182 F304 forged flange was welded (See Drawing E 232-284-5). The tube and flange assembly, referred to as Control Rod Housings per the drawing were then finish machined as assemblies. Each control rod mechanism housing assembly was finish machined to the final dimensions per Drawing E 232-284-5. The flange was machined with the ACME threads for mating with the CRD Motor Housings and a weld preparation for making the canopy seal welds to the motor housings after installation. The finish inside diameter of the tube is 2-3/4". The outside diameter is machined to a tight tolerance of 4.000 +0.000/ -0.001. Tight tolerance is held for the lower 12-1/2 inches for Assembly Nos. 284-01 through 284-05 and for the lower 15-1/2 inches of the tube for Assembly Nos. 284-06 through 284-13. Rejection Notices Nos. 2011 and 2016 indicated that 48 of the 69 assemblies required polishing to bring the surface finish and tolerance on the 4.000" diameter in to drawing requirements. The polishing was required on the lower length of the tube for these assemblies in the 12-1/2" to 15-1/2" area required for Assembly Nos. 284-06 through 284-13. It is not apparent that the polishing would have any beneficial effects on the area of the tube exposed on the inside of the closure head during service.

Installation of Penetrations in RPV Closure Head

As described earlier, the RPV closure head was fabricated from formed and heat treated sections of SA-302 Grade B plate and SA-336 closure head forging. The closure head assembly consists of a central dome plate, surrounded by six formed peel sections that are assembled by full penetration weld seams. The dome is then welded to the cylindrical closure head forging. The closure head was finish machined with a basic radius of 74-21/32 inches and a minimum wall thickness of 7-3/4 inches in the spherical dome portion of the head. The inside surface of the head was then clad with a nominal thickness of 7/32 inch (min. thickness of 5/32 inch) of stainless steel cladding per Drawing E 232-278-7.

All of the holes for the CRD housing penetration tubes were then rough machined into the head. Dimensions of the rough bore are provided on Drawing E 232-285-3. The holes are bored through the head from the inside surface with a diameter of 3-1/4 inches. The holes are then back-bored on the inside of the head to a depth of about 3 inches. After completion of all of the rough bored holes, they are deburred and cleaned prior to machining of the "J-grooves" for the buttering and partial penetration welds of the CRD housing penetration tubes to the RPV closure head. The "J-grooves" are machined around each bore on the inner surface of the closure head using a device referred to as a "pogo-stick" that is a machine tool specifically designed for machining these grooves into the head. The "pogo-stick" is shown in Figure 6-3. The grooves are machined to the dimensions provided in Drawing E 232-285-3. The depth to the bottom of the groove is 1-1/16 inch. After machining, the grooves were ground flat at the edges of the holes to obtain the correct contour. The grooves were inspected for dimensions and the grooves and holes were examined using magnetic particle inspection technique. The holes were also examined by liquid penetrant.

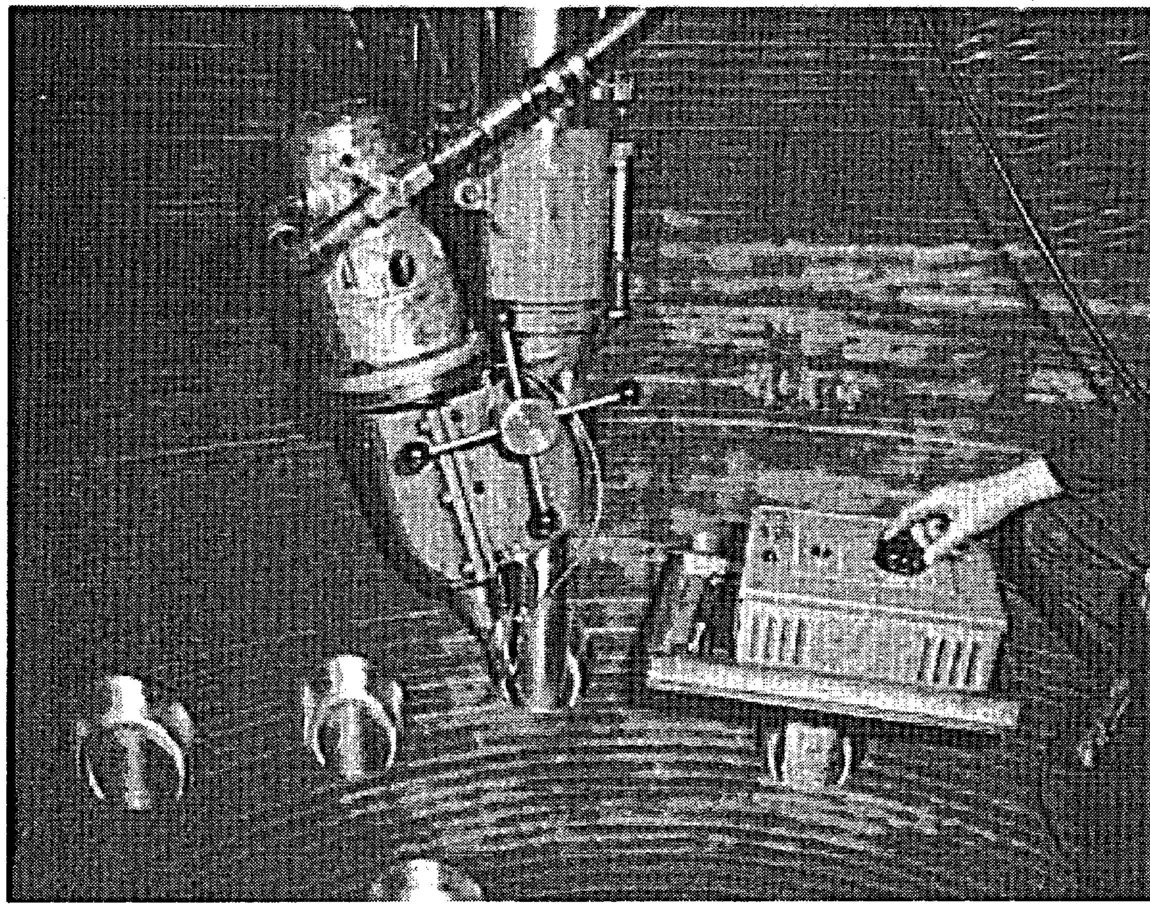

Figure 6-3 "Pogo Stick" Used to Machine J-Grooves in RPV Closure Head for CRD Housing Penetration Tube Partial Penetration Welds

All of the machined partial penetration weld preparations were buttered using shield metal arc welding with Type 182 electrodes. The weld deposit for the buttering is identified as Weld No. 1-285 on Drawing E 232-285-3 and specifies Detailed Welding Procedure (DWP) WA-6866-285 for welding. The drawing notes indicate that a nominal thickness of ¼ inch of buttering should be deposited and that the weld deposit should be ground as required for inspection and accessibility for the subsequent weld. The welding parameters from DWP WA-6866-285 specify a current range of 105-135 amps, direct current/reverse polarity with a voltage of 24 volts. A preheat of 250°F was maintained for depositing the Inco 182 buttering on the SA-302 Grade B plate material, which is classified as a P No. 3 base metal for welding in accordance with Section IX of the ASME B&PV Code. Weld Inspection Records for the buttering, Weld No. 1-285, indicate that one lot No. 1993 of 5/32" diameter Inco 182 electrodes was used for the buttering on the machined weld preparations for all 69 penetrations. A coated electrode deposit made with lot No. 1993 electrodes was analyzed with the following chemical composition:

Inco 182 Electrode – Lot No. 1993	
Element	Composition (%)
Carbon	0.04
Nickel	68.79
Chromium	14.75
Iron	7.03
Manganese	6.82
Columbium	1.55
Tantalum	0.01
Titanium	0.39
Copper	0.02
Silicon	0.49
Cobalt	0.08
Sulfur	0.009

The buttering in the J-grooves was ground for accessibility and to ensure that sufficient buttering layer was present. The surface of the buttering was examined by liquid penetrant. The traveler identified that 10 of the J-groove welds required repair and the balance were acceptable.

After inspection and examination of the buttering deposit by liquid penetrant, the closure head assembly without the CRD housing penetrations installed was given its final post-weld heat treatment (PWHT). The closure head was held at 1150±25°F for a minimum of 10-1/2 hours. Heating and cooling rates were controlled above 600°F so that rates did not exceed 100°F per hour. Following PWHT, the head was cleaned and 100% of clad surfaces and buttering in the J-grooves was liquid penetrant inspected.

After final PWHT, the bores for the penetrations were machined to the final dimensions, including a counter-bore on the outside surface of the closure head. The specified hole dimension for the penetrations is a diameter of 3.997 +0.002/-0.000 inches with a surface finish of 63 rms.

The CRD housing penetration tubes are installed in the RPV closure head by shrink fitting into the finish machined holes using a liquid bath technique to chill the penetration tubes. All of the CRD housing penetration tubes were match fit to the penetration hole sizes to assure the least amount of interference fit of the penetrations in the closure head. The CRD housing assemblies were placed in a bath of acetone and dry ice at a freezing temperature of -88°F to assure approximately 0.003 inch of clearance between the penetration tube and the hole prior to installing. Fixturing was provided to ensure proper vertical positioning of each CRD housing assembly on installation. Each assembly was removed in turn from the acetone/dry ice bath tank, measured quickly for shrinkage, centered over the corresponding hole and lowered quickly into place until the top plate contacted the positioning rails. After checking for proper positioning of the height of each CRD housing assembly, the housings were tack welded in place prior to turning the closure head over for final welding.

The CRD housing assembly penetration tube is welded to the buttering in each of the J-grooves. The partial penetration weld seam is identified as Seam Nos. 1 through 69-279. All welding was performed with Inco 182 shielded metal arc welding electrodes. Both 1/8 and 5/32 inch diameter electrodes were used from four different lot numbers of electrodes. Data on chemical composition from weld deposits was obtained for the two lots of 5/32" diameter electrodes which is most likely to be the weld deposit surface exposed to the primary coolant.

Inco 182 Shielded Metal Arc Electrodes				
	Lot No. 1817	**Lot No. 812**	**Lot No. 2096**	**Lot No. 2215**
	1/8" Dia.	**1/8" Dia.**	**5/32" Dia.**	**5/32" Dia.**
Element	**Composition (%)**	**Composition (%)**	**Composition (%)**	**Composition (%)**
Carbon			0.04	0.03
Nickel	Not Available	Not Available	68.14	68.49
Chromium			14.53	14.94
Iron			7.05	7.36
Manganese			7.39	6.80
Columbium			1.66	1.47
Tantalum			0.01	0.01
Titanium			0.49	0.30
Copper			0.02	0.02
Silicon			0.55	0.48
Cobalt			0.09	0.07
Sulfur			0.009	0.010

Welds were deposited with the 1/8 inch diameter electrodes for the first increment and the remainder using the 5/32 inch diameter electrodes. Welding parameters were 75-105 amps direct current-reverse polarity at 24 volts for the 1/8 inch diameter electrodes and 105-135 amps direct current-reverse polarity at 24 volts for the 5/32 inch diameter electrodes. The weld deposits were visually inspected at each layer for surface defects. Welds were liquid penetrant examined after the root pass and each ¼ inch increment of deposit up to the final weld surface. The weld surface was ground at each increment sufficient to perform the liquid penetrant examination. The amount of grinding on the final pass was left to be determined by engineering but at a minimum would have to have been sufficient to perform the final surface examination of the weld. The approvals for the liquid penetrant surface examinations at each increment did not indicate any repairs made in any of the 69 partial penetration welds to the CRD housing tubes.

Installation of Vent Nozzle Assembly in RPV Closure Head

The H. B. Robinson Unit 2 RPV closure head vent nozzle arrangement is atypical of most other closure heads. The more typical design is to install an SB-167 Alloy 600 tube through the penetration near the top of the closure head and weld it to the closure head with a partial penetration weld that apart from its size looks very much like the welds used to attach the CRD housing penetration tubes to the closure head. The H. B. Robinson Unit 2 vent nozzle actually consists of a forged low alloy steel nozzle, P-3 material similar to the closure head plate material. The nozzle is bored out and then the bore is filled with Inco 182 weld deposit per Weld Seam 4-293. After the hole is completely filled, a new hole is bored, essentially leaving a nozzle with Inco 182 cladding on the inside diameter surface.

A hole is machined in the RPV closure head and the stainless steel cladding is stripped back from the vent nozzle opening. The clad nozzle is then welded into the head with a full penetration weld to the SA-302 Grade B plate material. The weld is backgrooved on the inner surface of the weld and back welded to complete the joint. The remaining unclad surface on the inner surface of the closure head is then back clad from the Inco 182 cladding on the nozzle inside diameter around the nozzle radius and extending out to join with the original stainless steel cladding around the vent nozzle. Backcladding is also done with Inco 182 shielded metal arc welding electrodes. An Alloy 600 transition piece is then welded to the top end of the nozzle with a full-penetration circumferential butt weld to provide for welding of the vent pipe to the nozzle.

Comparison Between H. B. Robinson Unit 2 Closure Head and Other PWR Closure Heads

There are several differences that can be identified from this review of fabrication procedures between the H. B. Robinson Unit 2 RPV closure head and other PWR closure heads, either manufactured by Chattanooga or other fabrication vendors.

1. Interference Fit – Because the H. B. Robinson Unit 2 penetration tubes were matched to the bore hole size to minimize interference, the interference fit will tend to be at the lower end of the 0 to 3 mil interference fit typically used by the Chattanooga shop. Couple the matching of diameters with the use of the higher temperature acetone and dry ice bath used to shrink the tubes, the interference fits should be minimized. Later fabrication of closure heads used a much lower temperature liquid nitrogen bath, allowing for significantly more shrinkage of the tube material.

2. Size of Partial Penetration Weld – The volume of the partial penetration welds is somewhat smaller than other RPV closure heads. The H. B. Robinson Unit 2 machining drawing shows the depth of the machined J-grooves to be 1-1/16 inch deep. This cavity is then buttered with Inco 182 with nominal thickness of 1/4". This would leave a partial penetration weld depth of approximately 13/16". This compares, for example, to a J-groove for Millstone Unit 2 that is machined to a depth of 1-5/16" prior to depositing buttering, nominally 1/4" thick. The prepared buttering for the partial penetration weld is required to have a 1-1/16" depth. Rotterdam details for North Anna Unit 2 closure head also show partial penetration weld dimensions of 1 inch depth or more.

3. Partial Penetration Weld Cracking – Extensive flaw indications were detected during inspections on the North Anna Unit 2 closure head. Two small boat samples were removed and failure analyses performed from two nozzle locations on this head. The evaluation of the boat samples revealed significant amounts of fabrication related hot cracks in the partial penetration weld material. Hot cracks exposed to the water wetted surface of the weld then apparently extended by PWSCC through the weld metal. Similar indications were found in a partial penetration weld at

Ringhals Unit 2. The indication at Ringhals Unit 2 was also attributed to original fabrication weld defects. To date indications from inspection of the partial penetration welds have only been found in heads fabricated by Rotterdam and one head fabricated by B&W. No weld indications have been observed thus far in inspections of heads fabricated by C-E in Chattanooga. There have been some questions raised about the fabrication procedures used by Rotterdam, including the use of thermal cutting processes to produce the weld preparation. However, the complete cause of these indications has not been determined conclusively. There are plans to remove additional samples from the North Anna 2 head that is no longer in service. Additional conclusions about the nature and cause of the weld cracking may be made following these evaluations.

4. CRD Housing Penetration Tube Material – The Huntington Alloys SB-167 tubular product form has had fewer problems to date. Most of the cracking and indications have occurred in B&W designed heads with B&W Tubular products material for the penetrations. On the negative side, there is a high percentage, 45%, of penetrations in the Robinson head that are relatively high yield strength materials, but still haven't shown signs of cracking.

5. Vent Nozzle Configuration – Due to the unique configuration of the vent nozzle assembly, there is no partial penetration weld inside the closure head associated with the vent nozzle. The first Inco 182 weld to any wrought Alloy 600 material occurs above the closure head where an Alloy 600 transition piece is welded to the low alloy steel vent nozzle. In addition, the inside diameter of this weld is finish machined after welding, so that no as-welded material is left on the water wetted surface for this joint.

6.3 SUMMARY AND CONCLUSIONS

Several distinct differences were identified between the materials and fabrication of the H. B Robinson Unit 2 closure head and closure heads from other PWR designers or fabricators. The interference fit between the CRD nozzles and the closure head was minimized by matching tube diameters to bore sizes and the use of a dry ice and acetone cooling bath that does not attain as much shrinkage in the tube as liquid nitrogen. The minimum interference improves the ability to detect leakage from a bare head visual examination by increasing the likelihood of a leak bath through the annulus between the nozzle and the closure head. The thicker nozzle tube wall and smaller volume of the partial penetration welds compared to some other PWR closure heads will result in reduced residual stresses making both less susceptible. The unique vent nozzle configuration eliminates one partial penetration weld in the closure head. A full penetration butt weld is used to make the dissimilar weld joint between the nozzle and the vent line. This weld is made in a lower susceptibility location above the closure head.

Inspections of C-E Chattanooga fabricated heads have identified far fewer indications in CRD nozzles than have been observed in closure heads from other fabricators. There have not been any indications reported in the partial penetration welds of C-E Chattanooga fabricated closure heads. In addition, the CRD nozzles in the H. B. Robinson Unit 2 head were fabricated from materials produced by Huntington Alloys. Closure head inspections have found very few defects in the Huntington Alloy heats of material in closure heads compared to heats of materials from other material producers. In summary, based on review of the materials and fabrication records, there were no unusual processes of repairs during fabrication that would indicate an increased susceptibility to cracking in the H. B. Robinson Unit 2 closure head. Based on inspection results to date, there are several factors that indicate a lower susceptibility to cracking in the H. B. Robinson Unit 2 closure head.

7 REFERENCES

1. Bain, L. J., Statistical Analysis of Reliability and Life Testing Models, Marcel Dekker, Inc., 1978.
2. Bamford, W. H. and Yang, C. Y., "Structural Integrity Evaluation of Reactor Vessel Upper Head Penetrations to Support Continued Operation: H. B. Robinson Unit 2," (WCAP-15928), Westinghouse Electric Co., August 2002.
3. Bamford, W. H. and Foster, J. P., "Crack Growth of Alloy 182 Weld Metal in PWR Environments," (PWRMRP-21), EPRI Technical Report 1000037, June 2000.
4. Bamford, W. H. and Foster, J. P., "Crack Growth and Microstructural Characterization of Alloy 600 PWR Vessel Head Penetrations," EPRI-TR-109136, Final Report, December 1997.
5. [ ]a,c,e
6. Dolan, B., "Small LOCA Birnbaum Measure," correspondence with authors, (email), April 8, 2003.
7. Dolan, B., "Importance of 52 LOCAs for Large Early Release Frequency," correspondence with authors, (email) June 18, 2003.
8. Duran, J., Kim, C., and Pezze, C., "Reactor Vessel Closure Head Penetration Key Parameters Comparison," Westinghouse Electric Co. Report, WCAP-13493, September 1992.
9. England, J. "Process Review for Inconel Alloy 600 Tubes," Personal Communication, June 1994.
10. Kapur, K. C. and Lamberson, L. R., Reliability in Engineering Design, John Wiley & Sons, 1977.
11. Lareau, J. P., "RPVH PODS," correspondence with authors, (email), April 14, 2003.
12. Lindström, R., Lidar, P., and Lagerström, J., "Crack growth of Alloy 182 in a simulated primary side PWR environment," 8th International Symposium on the Degradation of Materials in Nuclear Power Systems-Water Reactors, Amelia Island, Florida, August 1997.
13. Mathews, L. K., "Inspection Results Rev D," (Microsoft Excel file dated 4/4/03).
14. Samanta, P. K., et. al., Handbook of Methods for Risk-Based Analyses of Technical Specifications, (NUREG/CR-6141), U. S. Nuclear Regulatory Commission, December, 1994.
15. U. S. Nuclear Regulatory Commission, Regulatory Guide 1.174, "An Approach to Using PRA in Risk Informed Decisions on Plant-Specific Changes to the Licensing Basis," July 1998.

16. U. S. Nuclear Regulatory Commission, "Issuance of Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors," EA-03-009, February 11, 2003.

17. Vaillant, F. and Le Hong, S., "Crack growth rate measurements in primary water of pressure vessel penetrations in Alloy 600 and weld metal 182," EDF report for EPRI HT-44/96/024/A, 04/97.

18. Westinghouse Letter CGE-00-019, "Metallurgical Investigation and Root Cause Assessment of Cracking of Loop A Hot Leg Nozzle to Pipe Weld at V. C. Summer: Preliminary Findings Summary," December 4, 2000.

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