NRC FORM 658
(9-1999)

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DATE OF MEETING
05/22/2002

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Docket Number(s)	n/a
Plant/Facility Name	n/a
TAC Number(s) (if available)	MB2916
Reference Meeting Notice	2002-0414
Purpose of Meeting (copy from meeting notice)	Update from task group on Alloy 600 Materials Reliability Program Control Rod Drive Mechanism Vessel Head Penetration cracking issue.

NAME OF PERSON WHO ISSUED MEETING NOTICE Beth Wetzel	TITLE Project Manager

OFFICE
NRR

DIVISION
DE

BRANCH
EMCB

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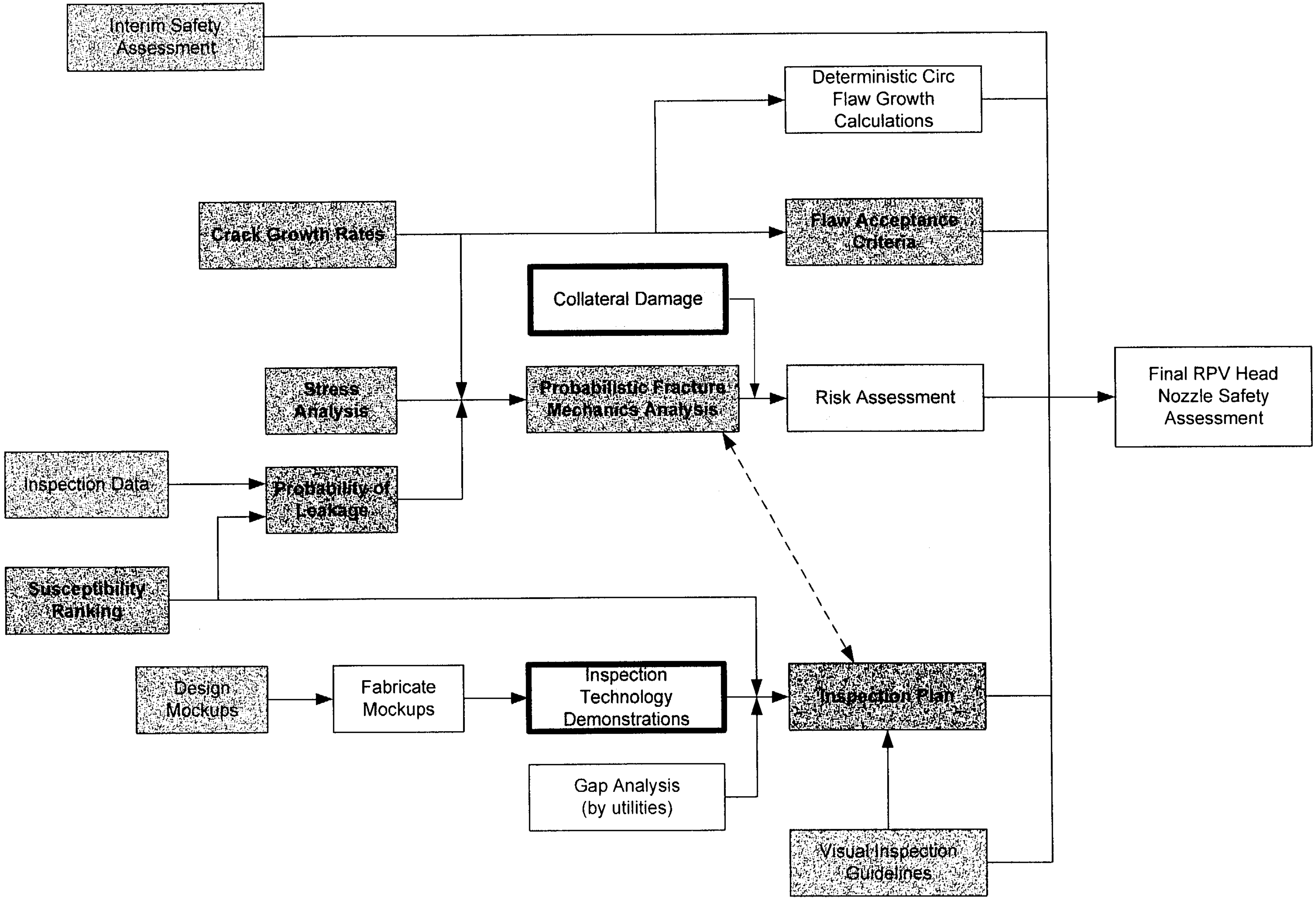
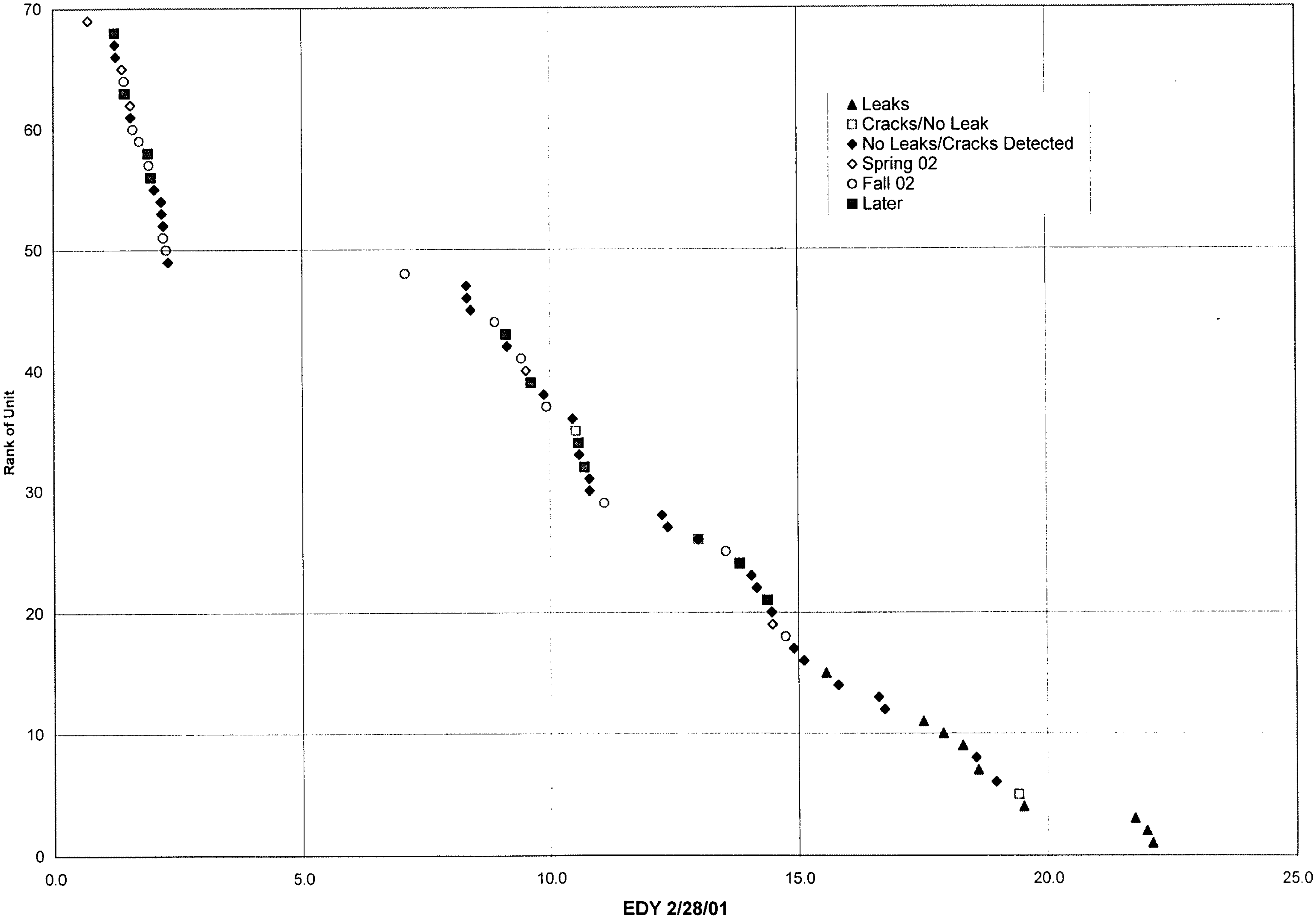
AGENDA

NRC RES-NEI-MRP Alloy 600 Meeting
Washington, D.C.
May 22nd

08:30 – 09:00	Overview of RPV Head Penetration Tasks and Schedule Alloy 600 Crack Growth Rate Summary	Mathews Mathews
	RPV Head Risk Assessment	
09:00 – 09:30	A. Probability of Leakage	White
09:30 – 10:00	B. Critical Flaw Size	White
Break for 15 minutes		
10:15 – 11:00	C. Residual Stress Analysis	Hunt
11:00 – 12:00	D. PFM Model	Riccardella
LUNCH - 1 hour break		
13:00 – 15:00	Inspection Plan RPV Head Penetrations	Lashley
Break for 15 minutes		
15:15 – 17:00	Technical Assessment of RPV Head Degradation	White



Strategic Plan Outline
RPV Head Nozzles



70
60
50
40
30
20
10
0
Rank of Unit
0.0
5.0
10.0
15.0
20.0
25.0
EDY 2/28/01
▲ Leaks
☐ Cracks/No Leak
◆ No Leaks/Cracks Detected
◇ Spring 02
○ Fall 02
■ Later

Crack Growth Rate for Alloy 600 Nozzle Material

Update on developments since February 2002

Larry Mathews
Southern Nuclear
Chairman, MRP Alloy 600 Issue Task Group

EPRI

MRP Crack Growth Rate Approach

- Goal is to establish appropriate CGR guidance for generic application in nozzle base material
- Involvement of MRP 'Expert Panel' (includes ANL/NRC) is ongoing in refining approach
- Crack growth database has been consolidated
- Revised MRP Crack Growth Rate Report will be presented to NRC (proposed date: late May)
- CGR data for base material feeds directly into the probabilistic risk assessment being carried out by SIA

EPRI

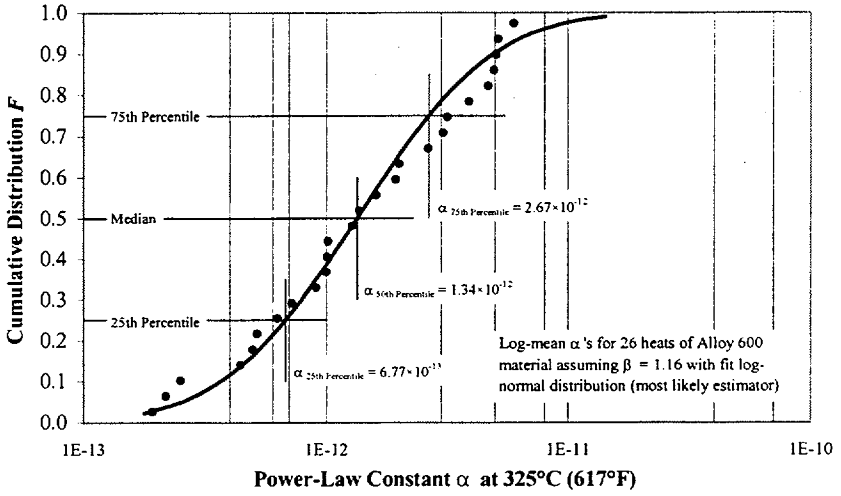
Changes in database since Feb. 02

- French re-evaluation has led to changes in the K values for a significant number of laboratory CGR data points from both EdF and CEA
- General trend is to somewhat lower K values for EdF WOL specimens and to somewhat higher K values for CT specimens tested by CEA
- Screening criteria have been defined more precisely and reasons for eliminating some earlier data points revisited
- Additional, high-quality CGR data has been obtained from Spain (CIEMAT), screened and incorporated
- This results in the inclusion of 4 extra heats of Alloy 600 material, bringing the new database total up to 26 heats

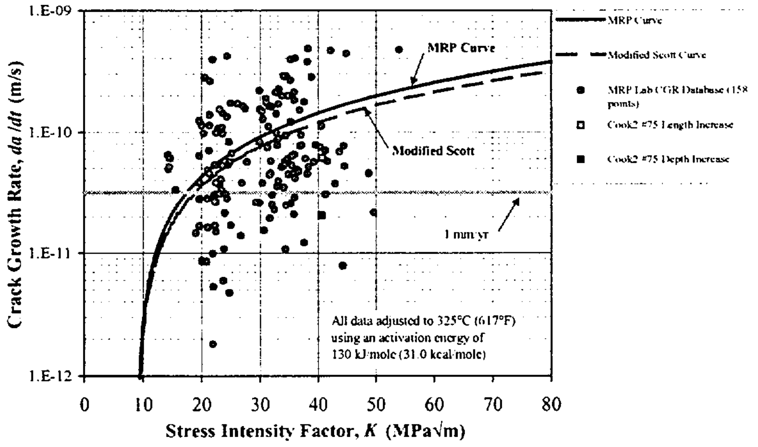
Derivation of MRP CGR Curve

- Approach taken is consistent with ASME code considerations, where the goal is to make a best estimate of the crack growth
- Recommended CGR curve is based on 75th percentile level of the distribution of CGR variability as a function of material heat
- The curve now lies approx. 20% above the modified Scott curve (previously approx. 30% higher)
- Addresses the concern that cracking detected in operating plants would tend to be in components fabricated from more susceptible Alloy 600 heats

Alloy 600 Crack Growth Rates
MRP Log-Normal Crack Growth Rate Distribution



Alloy 600 Crack Growth Rates
MRP Laboratory Database

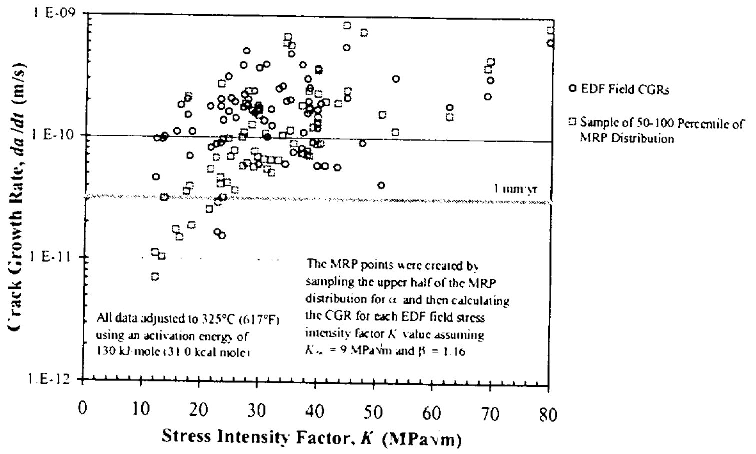


Application of MRP CGR Curve

- The final MRP recommended curve is intended for disposition of detected PWSCC flaws in thick-walled Alloy 600 components exposed to normal PWR primary water
- Thus it will be directly applicable to **axial ID flaws** in RVH nozzle base material
- Newly developed, statistical comparison of MRP database with temperature-corrected French field data shows reasonable agreement (median values of cumulative distributions differ by a factor of about 1.6)
- Approach is considered to be appropriate with regard to the actual nozzle material in US plants

EPRI

Comparison of EDF Plant Data and Samples from MRP Distribution

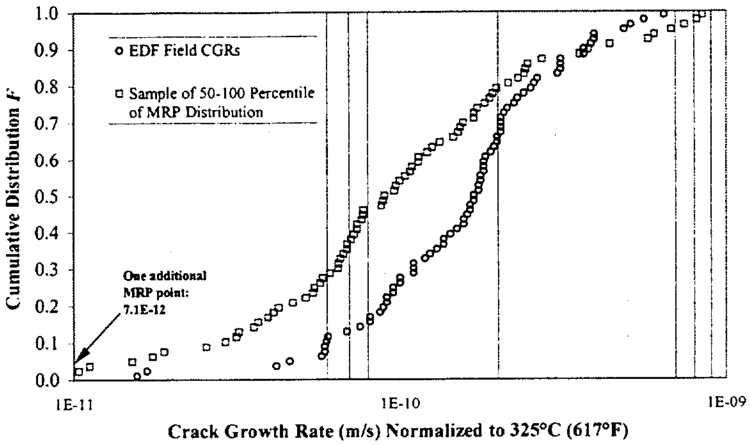


All data adjusted to 325°C (617°F) using an activation energy of 130 kJ/mole (31.0 kcal/mole)

The MRP points were created by sampling the upper half of the MRP distribution for α and then calculating the CGR for each EDF field stress intensity factor K value assuming K_{th} = 9 MPa√m and β = 1.16

EPRI

Cumulative Distributions of EDF Plant Data and MRP Samples



CGR in OD Annulus Environment

- For evaluation of (hypothetical) **OD cracking** above the J-groove weld, the MRP continues to recommend that CGR values from the revised curve be multiplied by 2x to allow for uncertainty in the exact composition of the external chemical environment
- A subgroup of the Expert Panel has revisited the relevant arguments in the light of the Davis Besse experience and found that they remain correct as long as leak rates are low (typically < 1 liter/h or 0.004 gpm)
- Plant experience has shown this to be the usual case
- Analysis would no longer be valid, however, if leak rates were sufficiently high to result in a large, local decrease in temperature and appreciable corrosion of low-alloy steel

Ongoing Work

- Immediate priority is finalization of the MRP-55 report on CGR in Alloy 600 base metal and submission for NRC review (July)
- Work with the Expert Panel continues so as to develop a recommended approach to CGR for the weld metals (Alloy 182/82)
- Some additional experimental work is being initiated by EPRI (e.g. via a DOE/NEPO program)
- MRP will continue to update NRC on all further CGR developments

Probability of Leakage and Critical Flaw Size

Prepared for Meeting With NRC Technical Staff
May 22, 2002

Dominion Engineering, Inc.
G. White
M. Fleming

Topics

- Probability of Leakage
  - Weibull slope
  - Weibull distributions based on plant data
- Critical Flaw Size
  - MRP-44, Part 2 methodology and inputs
  - Comparison with EMC^2 presentation of November 8, 2001

Probability of Leakage
Weibull Modeling

- Probability of future leakage is modeled using the two-parameter Weibull distribution:

$$\text{Probability of Leakage} = F(EDY) = 1 - e^{-\left(\frac{EDY_{600^\circ F}}{\theta}\right)^b}$$

- The accrued effective degradation years (EDYs) is the plant effective full power years (EFPYs) normalized to a head temperature of 600°F:

$T_{ref} = 617^\circ\text{F} + 459.67 = 1076.67^\circ\text{R}$

$Q_i = 50\ \text{kcal/mole}$

$R = 1.103\times10^{-3}\ \text{kcal/mole}\cdot{}^\circ\text{R}$

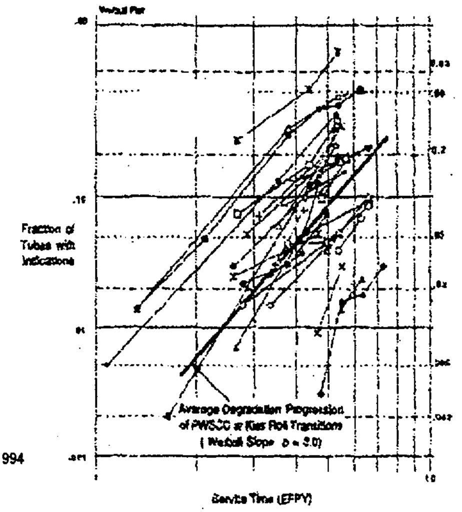
$$EDY_{600^\circ F} = \sum_{j=1}^{n}\left\{\Delta EFPY_j \exp\left[-\frac{Q_i}{R}\left(\frac{1}{T_{head,j}} - \frac{1}{T_{ref}}\right)\right]\right\}$$

Probability of Leakage
Weibull Slope

- Practically no multiple inspections (i.e., at the same plant) have been performed for RPV head leakage
- In the absence of available data for the specific application, Abernethy recommends that "library" values of the Weibull slope for similar applications be used
- This approach is preferable to pooling data for multiple plants because differences in susceptibility will distort the apparent Weibull slope
- Experience with PWSCC of Alloy 600 materials in nuclear power applications indicates that a slope of 3 is appropriate for head nozzle leakage
  - Plant PWSCC in steam generator tubes at various locations
  - PWSCC lab tests (e.g., MRP-68, April 2002, best fit slope of 2.73 for 127 test sets)
- Using the slope of 3, a Weibull characteristic time may be calculated based on head nozzle leakage inspection results

Probability of Leakage
Available Plant Data from Multiple Inspections

Time-to-PWSCC for Steam Generator Hot Leg Kiss Roll Expansion Transitions



Source:
EPRI TR-103696, July 1994

Probability of Leakage
Available Plant Data from Multiple Inspections

Typical Weibull Slopes for Steam Generator Tube PWSCC

Type of PWSCC	Number of Plants	Median	Average	Standard Deviation
At Kiss Roll Transitions (full depth rolled)	14	2.74	3.01	1.4
At Full Depth Roll Standard Transitions	7	4.09	3.72	1.74
Above F* Distance (standard roll transitions plus roll overlaps)	9	3.14	3.04	1.03
At Wextex Transitions (full depth expansion)	7	4.2	3.72	1.64
At Part Depth Roll Standard Transitions	3	4.48	4.14	0.96
At TSP Dents (slope for only one plant)	1	2.66	2.66	None
At Row 1 and 2 U-bends (pooled data for many plants)	--	About 4.4	--	--

Source:
EPRI TR-104030, July 1994

Probability of Leakage
Weibull Distributions Based on Plant Data

- Head nozzle inspection results evaluated assuming a Weibull slope of 3
- The following tables and Weibull plots reflect inspection results through the end of 2001
- Several types of distributions considered
  - B&W plants versus all domestic plants
  - Fraction of nozzles leaking at a plant
  - Fraction leaking in pooled population of nozzles for several plants
  - Fraction of units that have at least one leaking nozzle
- Some distributions treat "non-leaking" nozzles or heads as suspended items

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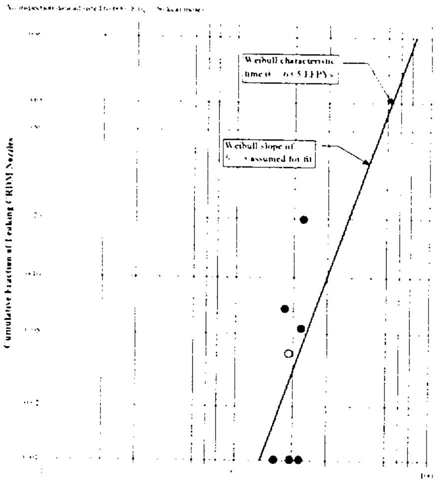
Probability of Leakage
Weibull Plot for B&W Units



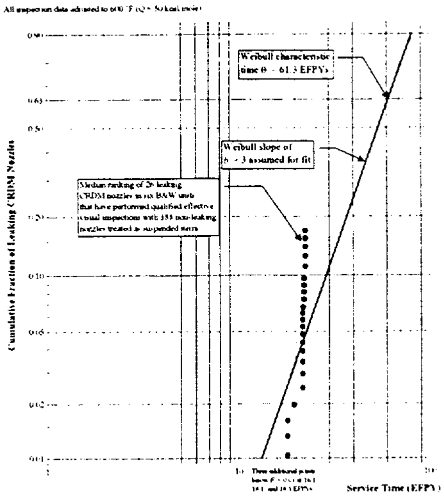
- Fraction of nozzles leaking at each B&W unit
- Weibull characteristic time for fit is 63.5 EDYs
- Equivalent Weibull characteristic time for time to first leaking nozzle is 15.5 EDYs

$$\theta_{1st\,leak} = \frac{\theta}{\sqrt[b]{n}}$$

- Figure reflects data through end of 2001

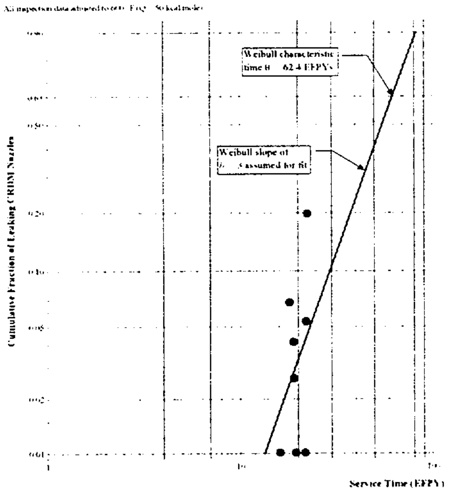
Probability of Leakage
Weibull Plot for B&W Units

- Pooled data for all inspected B&W plants
- Non-leaking nozzles treated as suspended items
- Figure reflects data through end of 2001



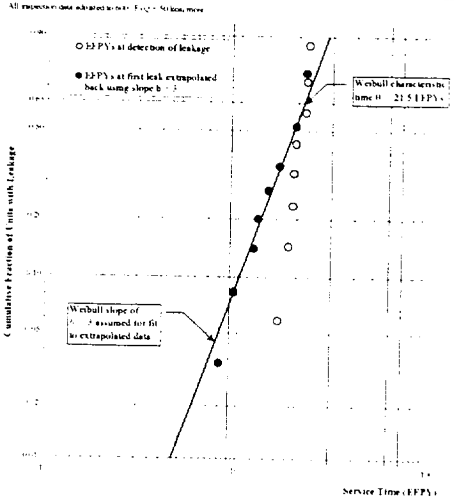
Probability of Leakage
Weibull Plot for All Domestic Units

- Fraction of nozzles leaking at each unit
- Plants that found no leaking nozzles cannot be included in the fit
- Figure reflects data through end of 2001



Probability of Leakage
Weibull Plot for All Domestic Units

- Fraction of units with leakage
- 12 units with no leakers treated as suspended items
- Time to first leakage based on slope of 3
- Figure reflects data through end of 2001



Critical Flaw Size

Critical Flaw Size
MRP-44, Part 2 Methodology

- Because of tight fitting annulus and high ductility of nozzle material, bending loads do not affect the required minimum ligament
- Critical flaw size may be calculated by equating ligament axial stress due to 2500-psig pressure with material flow stress
- Pressure load assumed to act on crack face as well as nozzle bore area
- Flow stress taken as average of yield and ultimate strengths at 650°F for applicable material specs
- Full range of nominal nozzle diameters and thicknesses at the 69 PWRs considered
- MRP-44 calculations are limiting and individual plants may perform less restrictive plant-specific calculations

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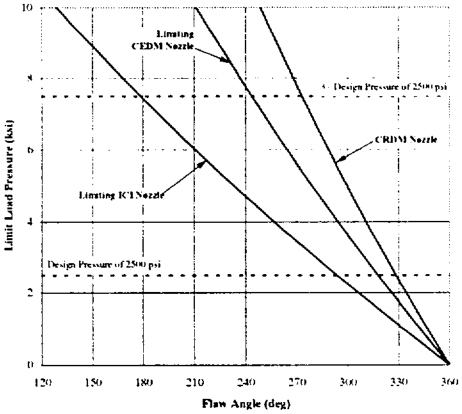
Critical Flaw Size
MRP-44, Part 2 Results



Nozzle Type	Nozzle Geometry	Flow Strength S_f (ksi)	Flaw Angle θ for P_{flow} = 2500 psi (deg)	Flaw Angle θ for P_{flow} = 7500 psi (deg)	Limiting Nozzle of Type
CRDM	CRDM 1	54.85	330.2	277.9	
		51.95	328.7	273.9	
	CRDM 2	51.95	328.4	273.1	X
CEDM	CEDM 1	54.85	331.4	281.2	
	CEDM 2	54.85	331.3	280.7	
	CEDM 3	51.95	323.4	259.5	
	CEDM 4	51.95	317.7	243.8	X
	CEDM 5	54.85	333.5	286.9	
ICI	ICI 1	47.45	293.5	178.6	X
	ICI 2	47.45	308.6	219.9	
	ICI 3	47.45	313.4	232.9	

$$\theta = 360\frac{1-\dfrac{P_{flow}}{S_f}\dfrac{A_{bore}}{A_{wall}}}{1+\dfrac{P_{flow}}{S_f}}$$

Critical Flaw Size
Comparison with EMC^2 Presentation of 11/8/01

- Flow stress difference
  - MRP-44: $S_f = (S_y+S_u)/2.0$
  - EMC^2: $S_f = (S_y+S_u)/2.4$
- Used code properties at slightly different temperatures
  - MRP-44: 650°F
  - EMC^2: 600°F
- Results for CRDM nozzles are similar (at 3 times 2500 psig):
  - MRP-44: 273°
  - EMC^2: 262°
- MRP-44 also includes critical flaw sizes for limiting CEDM and ICI nozzles

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Critical Flaw Size
Comparison with EMC^2 Presentation of 11/8/01

Parameter	**EMC^2 Calc (CRDM)[1]**	**MRP-44 (Limiting CRDM)**	**MRP-44 (Limiting CEDM)**	**MRP-44 (Limiting ICI)**
Design Pressure (psig)	2500	2500	2500	2500
Material Condition	—	SB-167 (hot-worked annealed, <5" OD)	SB-167 (hot-worked annealed; <5" OD)	SB-167 (hot-worked annealed, <5" OD)
Yield Strength, Sy (ksi)	—	23.9	23.9	19.9
Ultimate Tensile Strength, Su (ksi)	—	80.0	80.0	75.0
Basis for Sy and Su Values	Code properties at 600°F	Code properties at 650°F	Code properties at 650°F	Code properties at 650°F
Flow Stress, Sf (relationship)	Sf = (Sy+Su)/2.4	Sf = (Sy+Su)/2	Sf = (Sy+Su)/2	Sf = (Sy+Su)/2
Flow Stress, Sf (value, ksi)	—	51.95	51.95	47.45
θ (1xPdesign) (deg)	—	328	318	293
θ (3xPdesign) (deg)	262	273	244	179

[1] Wilkowski et al., NRC-Funded CRDM Critical Crack Size Analysis, presentation by Engineering Mechanics Corporation of Columbus, 11/08/01

Welding Residual Stress Models
Material Properties

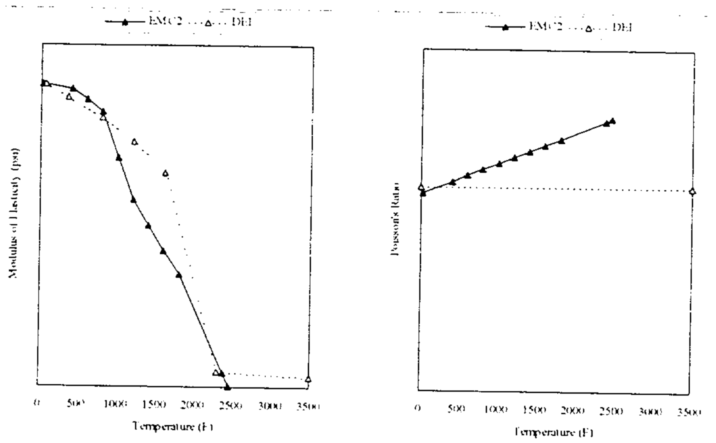
Prepared for Meetings With NRC Technical Staff
May 22, 2002

Dominion Engineering, Inc.
S. Hunt
D. Gross
J. Broussard

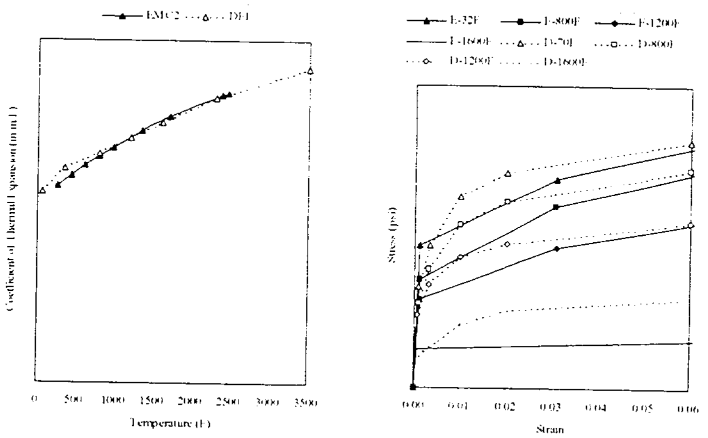
Contents

- Comparison of DEI and EMC^2 Material Properties
- Weld Stress-Strain Curves
- Conclusions

Comparison of DEI and EMC² Material Properties
Alloy 600 - Modulus and Poisson's Ratio

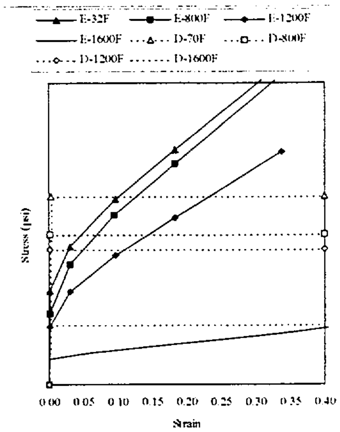


Comparison of DEI and EMC² Material Properties
Alloy 600 - Thermal Expansion and Stress-Strain

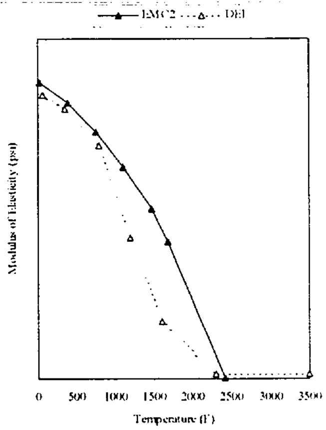


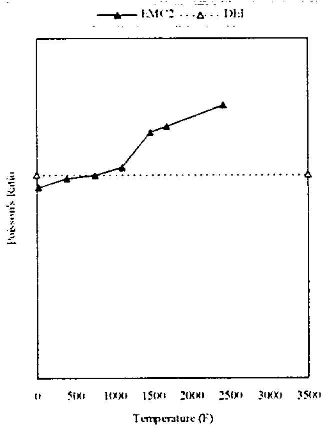
Comparison of DEI and EMC^2 Material Properties
Alloy 182 Weld

- EMC^2 has identical properties for Alloy 600 base metal and Alloy 182 welds
- DEI has two differences between the base metal and weld metal
  - Small difference in coefficient of thermal expansion
  - Significant difference in modeling stress-strain properties (See Slides 10-13 for discussion)

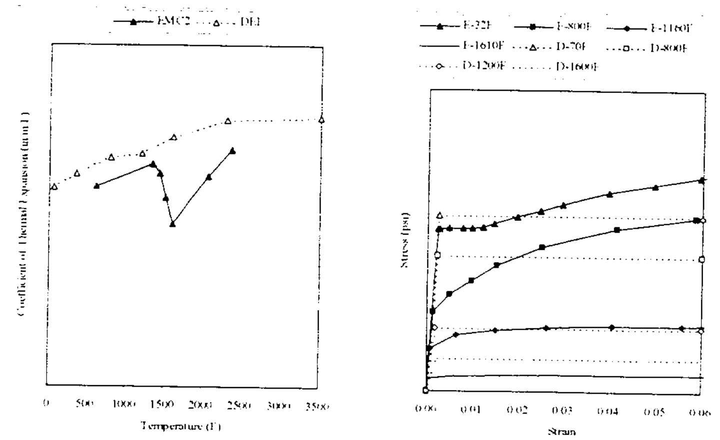


Comparison of DEI and EMC^2 Material Properties
Low Alloy Steel – Modulus and Poisson's Ratio

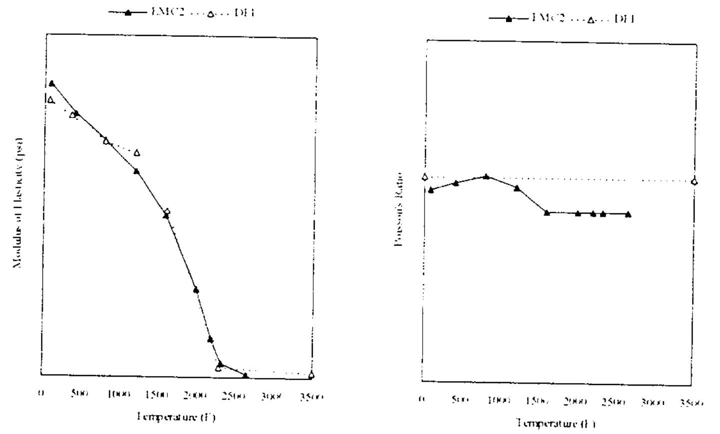




Comparison of DEI and EMC^2 Material Properties
Low Alloy Steel – Thermal Expansion and Stress-Strain

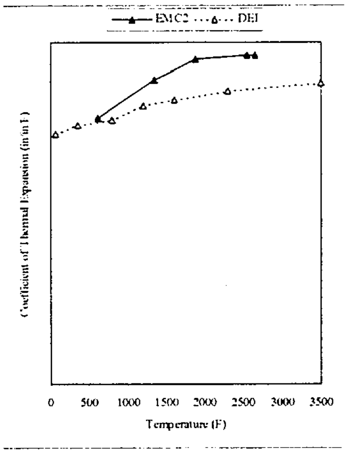


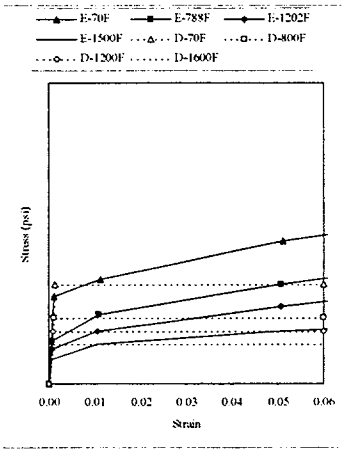
Comparison of DEI and EMC^2 Material Properties
SS Clad – Modulus and Poisson's Ratio



Comparison of DEI and EMC^2 Material Properties

SS Clad – Thermal Expansion and Stress-Strain

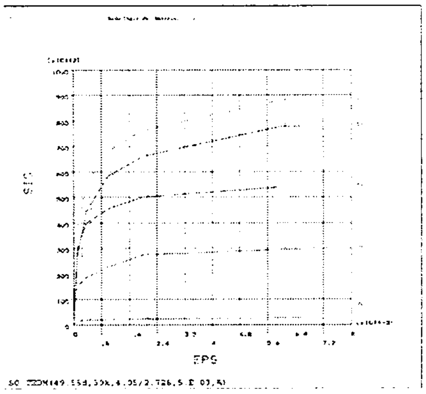




Weld Stress-Strain Curves

Early 1990's Model

- DEI's CRDM welding residual stress model was originally designed in the early 1990's for the purpose of simulating stresses on the nozzle ID surface
- Model made use of multilinear isotropic work hardening curves with similar shapes to those for Alloy 600 base material
- Yield strength as a function of temperature was derived from 0.2% offset yield data in ASME Code



Weld Stress-Strain Curves
Limitations of Original Model

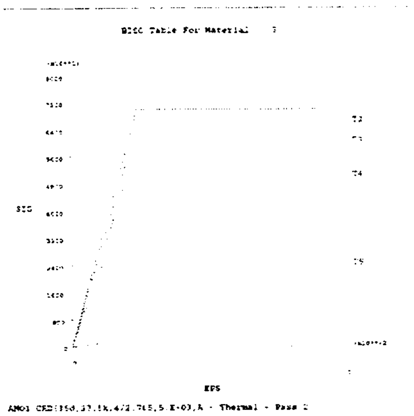
- ANSYS predicted unrealistically high residual stresses in the weld metal (greater than 100 ksi)
  - The high weld stresses did not have a significant effect on nozzle ID stress levels, but were not representative of actual weld stresses
- High weld stresses were traced to work hardening behavior as the weld material solidifies from ≈3500 F to 1600 F
- ANSYS retains the plastic strain calculated at high temperatures, leading to high yield stress levels at lower temperatures
- This behavior is a limitation of the software, and does not represent a realistic model of the material behavior

Weld Stress-Strain Curves
Revised Model (2001 and Later)

- Starting in early 2001, models were used to predict stresses in the weld and on the nozzle OD surface
- The issue of high-temperature work hardening was addressed by assuming elastic perfectly-plastic work hardening for the weld material
- Alloy 182 data published by Huntington Alloys supports the conclusion that the flow stress is a good approximation to the yield stress of the as-deposited weld material

Weld Stress-Strain Curves
Revised Model (2001 and Later)

- Current DEI models use elastic-perfectly plastic stress-strain curves for the Alloy 182 weld metal and buttering to avoid strain hardening issues
- Since stresses in the low-alloy steel vessel head are below yield this material is also modeled using elastic-perfectly plastic properties without compromising accuracy



Comparison of DEI and EMC^2 Properties
Conclusions

- Minor differences in modulus and coefficient of thermal expansion
  - DEI coefficient of thermal expansion for low-alloy steel was extrapolated for temperatures above ≈1200 F (actual steel temperatures <1000 F)
- Significant difference in modeling Poisson's ratio, but expected to have little effect on results
- Stress-strain curves for Alloy 600 base metal are very similar over range of strains encountered
  - DEI curve has more data points in area of greatest interest (near yield)
- Significant difference in modeling of Alloy 182 weld
  - EMC^2 models actual properties
  - DEI assumes elastic-perfectly plastic
  - DEI approach considered to represent actual residual stress levels in weld metal

Probabilistic Fracture Mechanics Analysis of CRDM Nozzles

Presented at:

NRC – MRP Alloy 600 Meeting
Rockville, MD

Presented by:
Dr. Peter C. Riccardella
Structural Integrity Associates
May 22, 2002

Outline of Presentation

- Overview of Methodology
- Software Modifications
  (to address comments from 2/21/02 NRC meeting)
- PFM Analyses in support of MRP RPV Head Penetration Inspection Plan
  - Susceptibility Categories
  - Inspection Types and Frequencies

Key Elements of RPV Head Nozzle PFM Analysis

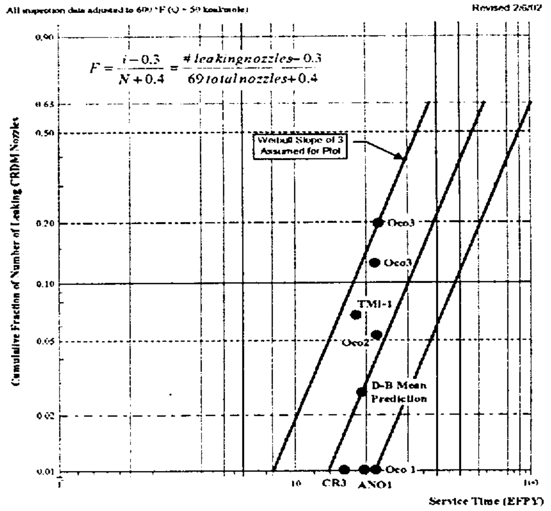
- **Probability of Leakage**
  - Weibull Model based on Experience to Date
  - Incorporated into Monte Carlo Model
- **Fracture mechanics modeling for Stress Intensity Factors**
  - Through-Wall Cracks
  - Part Through Wall Cracks
- **Stress Corrosion Crack Growth Statistics**
- **Effect of Inspections**
  - Inspection Interval
  - Inspection Reliability

Weibull Models for Leakage

- **Analysis by Dominion Engineering – B&W plants w/ Weibull slope of 3**
  - Weibull Slope = 3.0
  - Weibull Theta* = 15.36 (avg.) ; 9.094 (worst case)

*Theta = Characteristic time to 63.3% probability of at least one leak in a head.

Dominion Engineering Weibull Analysis (Beta = 3)



All inspection data adjusted to 600 °F (Q = 50 kcal/mole)

Revised 2/6/02

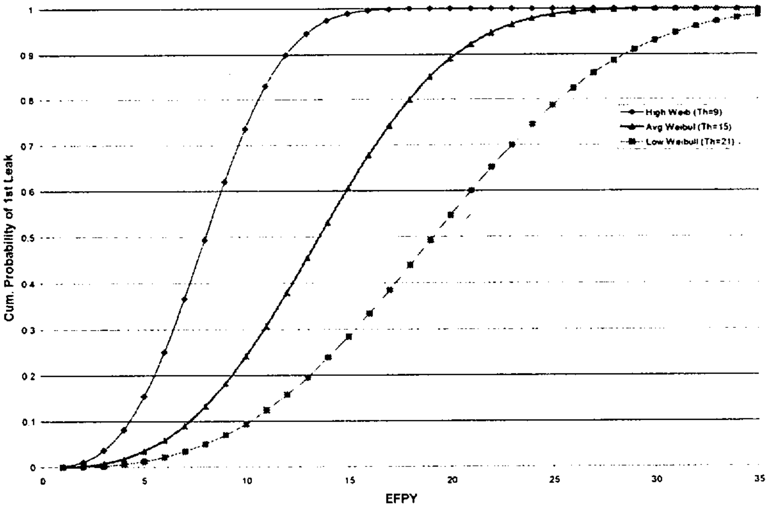
$$F = \frac{i-0.3}{N+0.4} = \frac{\#\,leaking\,nozzles - 0.3}{69\,total\,nozzles + 0.4}$$

EPRI

Structural Integrity Associates, Inc.

Weibull Distributions used in PFM

β=3; θ=15 ± 6



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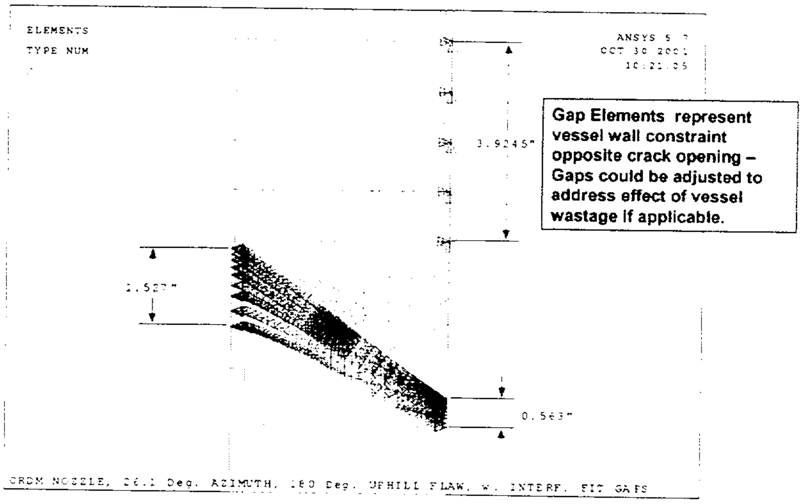
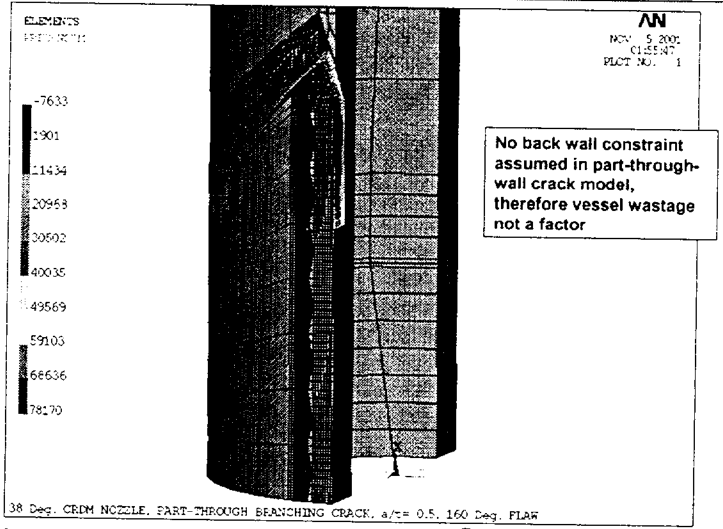
Fracture Mechanics Model
Through-Wall Crack



Gap Elements represent vessel wall constraint opposite crack opening – Gaps could be adjusted to address effect of vessel wastage if applicable.

Part-Through-Wall Flaw Model



No back wall constraint assumed in part-through-wall crack model, therefore vessel wastage not a factor

Stress Intensity Factor Results B&W Type Plant

High Yield, Large Gap Case

Nozzle Angle	Circumferential Crack Length		Stress Intensity 1/2	
	Degrees	Inches	Uphill	Downhill
0°	30	0.9664	20.8	N/A
	70	2.2550	18.8	N/A
	160	5.1540	20.3	N/A
	180	5.3140	0.64	N/A
	220	6.4950	0.63	N/A
	260	7.6760	0.63	N/A
	300	8.8570	0.62	N/A
18°	30	1.0170	27.2	27.2
	70	2.3730	24.0	24.0
	160	5.4240	24.5	24.5
	180	5.5920	23.4	1.0
	220	6.8350	23.8	2.4
	260	8.0770	26.9	6.0
	300	9.3200	26.5	11.5
26°	30	1.0830	29.7	29.7
	70	2.5260	26.1	26.1
	160	5.7750	26.5	26.5
	180	5.9530	28.4	0.4
	220	7.2760	23.2	1.7
	260	8.5990	23.6	7.5
	300	9.9220	24.9	16.6
38°	30	1.2380	34.4	34.4
	70	2.8830	27.1	27.1
	160	6.6020	29.2	29.2
	180	6.8060	37.7	4.5
	220	8.3190	31.2	6.7
	260	9.8310	26.6	12.7
	300	11.3440	29.9	25.9

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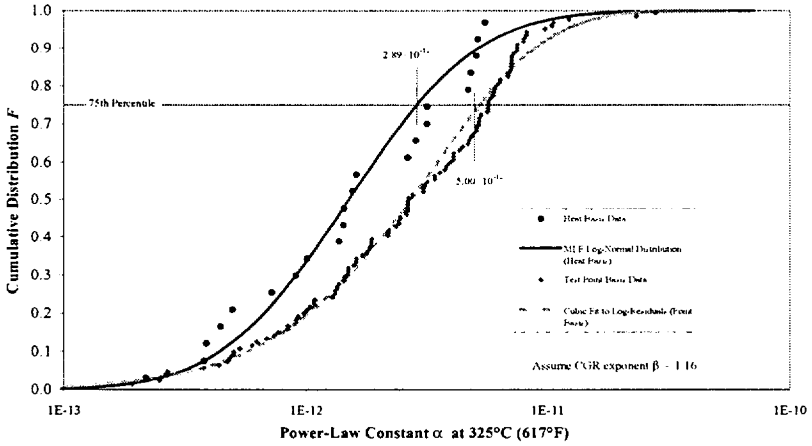
SCC Crack Growth Data for Nozzle Material in Reactor Environment



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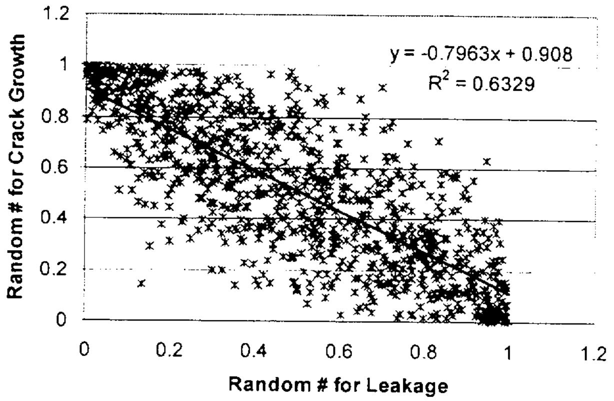
CGR Initiation vs. Growth Correlation

rho = -0.8

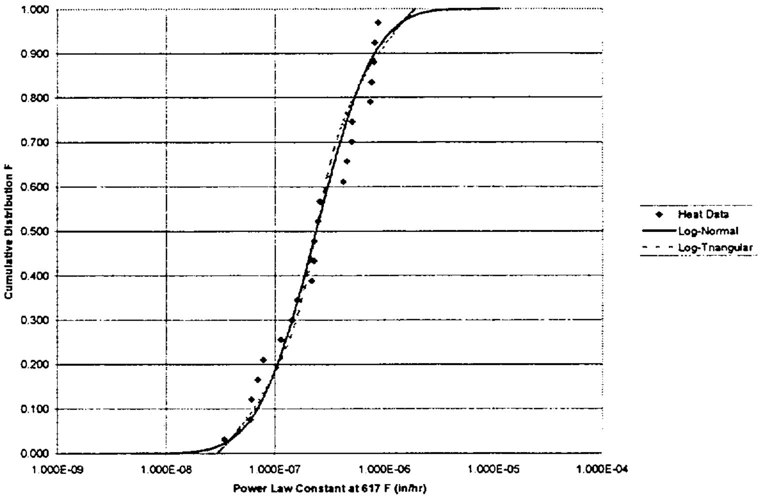


Software Modifications

(to Address Comments from 2/21/02 NRC Meeting)

- **Model Heats of Tubes rather than Individual Tubes**
  - Head modeled by finite number of heats (1 to N_{tubes})
  - Random variables for nozzle leakage and crack growth rate first determined for each heat
  - Second set of random variables then determined for individual tubes within a heat.
  - Correlation factor between leakage and crack growth rates applied to both sets of random variables
- **Truncation of Tails of Distributions**
  - Crack Growth Rate Distributions (both heat-to-heat and within-heat) can be specified as either Log-Normal (un-truncated) or Log-Triangular (truncated)
- **Degraded POD for Subsequent Inspections**
  - Software now accepts "degradation factor" input for subsequent inspections of leaking tubes which were previously inspected and missed

CGR Distributions Based on Heat Data



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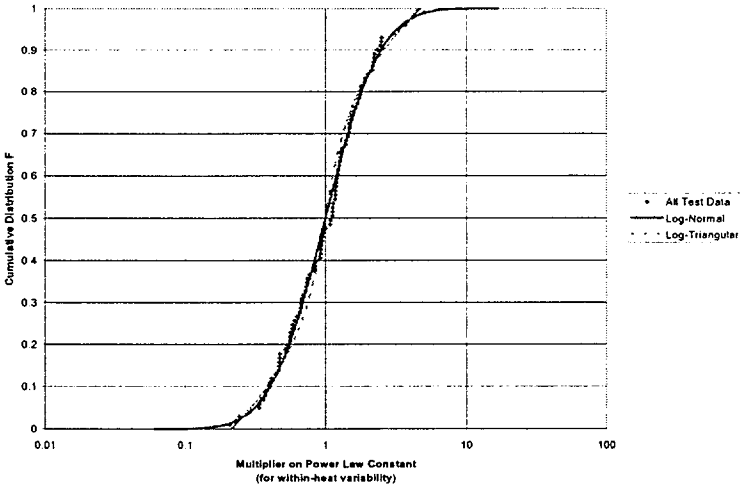
Multiplier on CGR Distribution for Within-Heat Variability



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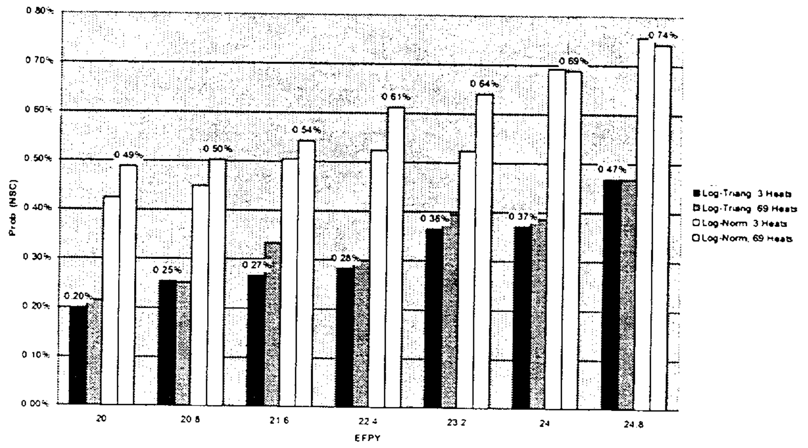
PFM Results w/ Modified Software (602°F Head Temp.; No Inspection)



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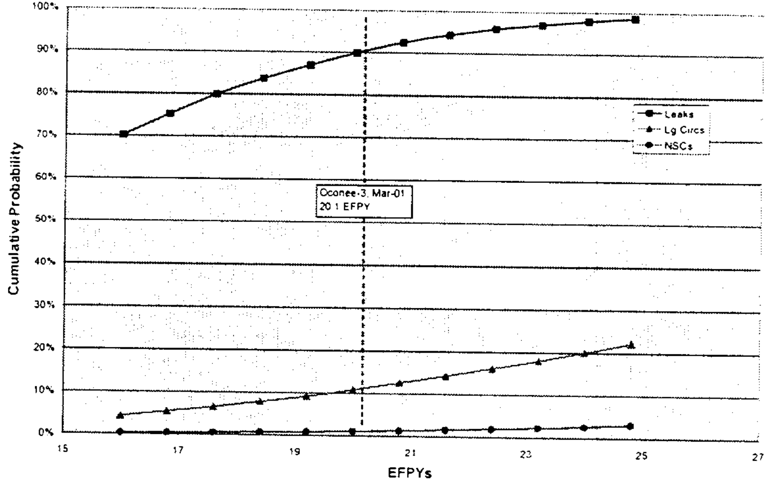
Benchmarking of PFM Results with respect to B&W Plants



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Technical Basis for Inspection Plan

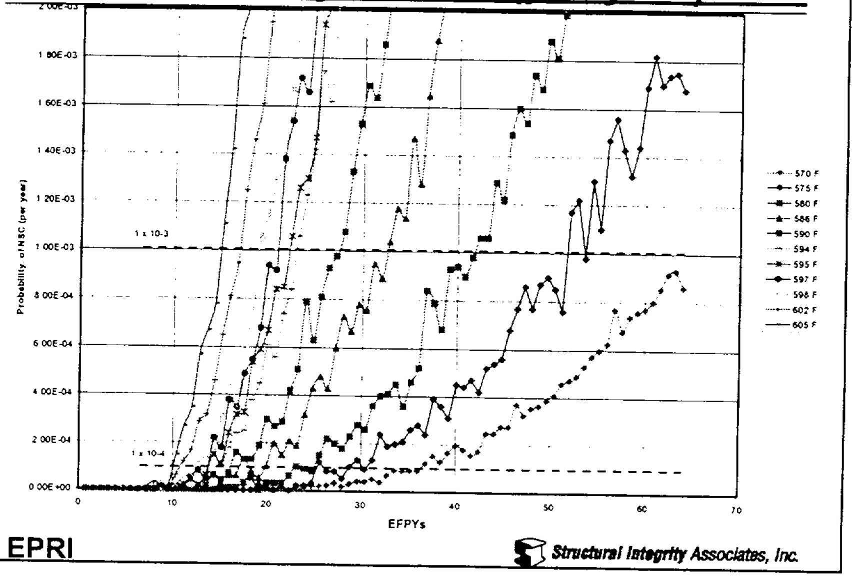
- Basic Concept -

- Start with "benchmarked" analysis parameters from B&W plant analysis
- Analyze plants at various head temperatures
- Set risk categories based on probability of Net Section Collapse (per year) and cumulative leakage probability
- Set inspection intervals based on effect of various inspections on probability of Net Section Collapse (per year)

"Benchmarked" Analysis Parameters

- Head Temperature: Various from 560°F to 605°F
- Weibull Parameters:
  - ◆ Slope = 3
  - ◆ Beta = 15 ± 6 (Triangular)
- Crack Growth Rate Statistics
  - ◆ Heat-to-Heat - Log-Triangular: -15.25 ± 2.212
  - ◆ Within Heat – Log-Triangular: 0 ± 1.6
- Crack Growth vs. Leakage Correlation Factors
  - ◆ 0.8 – Heat-to-Heat
  - ◆ 0.8 – Within-Heat
- Acceptability Criteria: PDF of NSC < 1 x 10^{-3} per year

Inspection Plan PFM Runs: Probability of NSC (per year)



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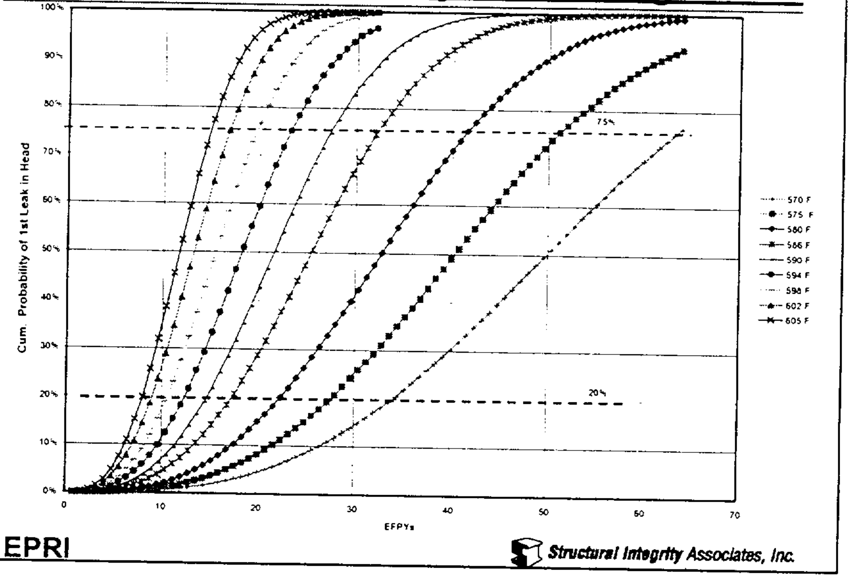
Inspection Plan PFM Runs: Cum. Probability of Leakage



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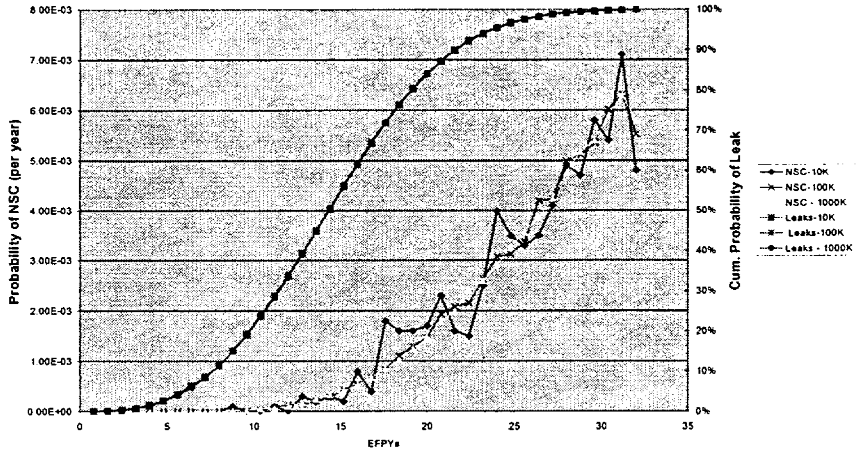
PFM Convergence Study (@ 600°F)



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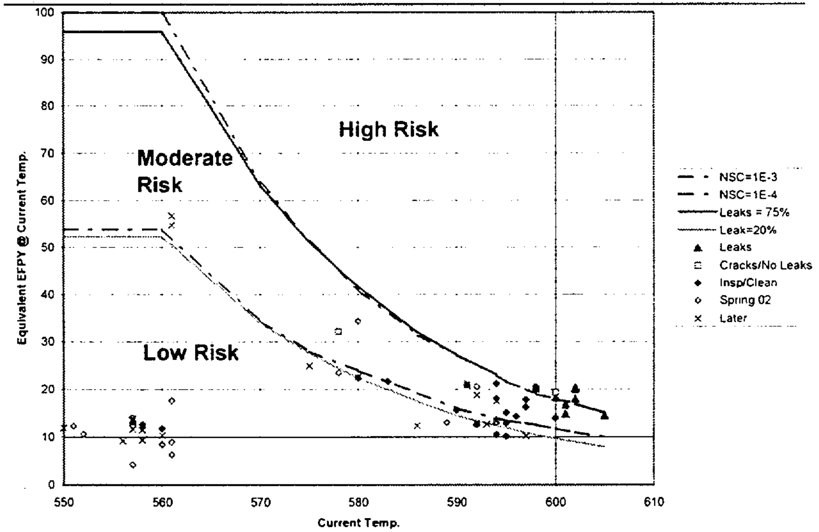
Definition of Susceptibility Categories Based on PFM Results



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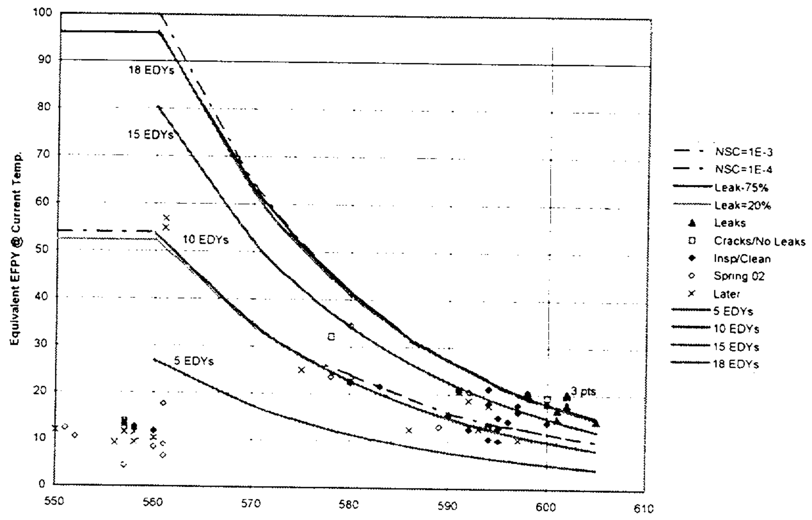
Correspondence of Susceptibility Categories to EDYs



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Inspection Frequency Runs: Probabilities of Detection

- **Bare Metal Visual Inspections (BMV)**
  - Initial POD = 0.6
  - POD for Subsequent Exams = 0.2 x Initial POD (when Leakage missed)
- **Non-Destructive Examinations (NDE)**
  - POD = f(crack depth) per EPRI-TR-102074[1]
  - 80% Coverage Assumed

[1] Dimitrijevic, V. and Ammirato, F., "Use of Nondestructive Evaluation Data to Improve Analysis of Reactor Pressure Vessel Integrity, " EPRI Report TR-102074, Yankee Atomic Electric Co. March 1993

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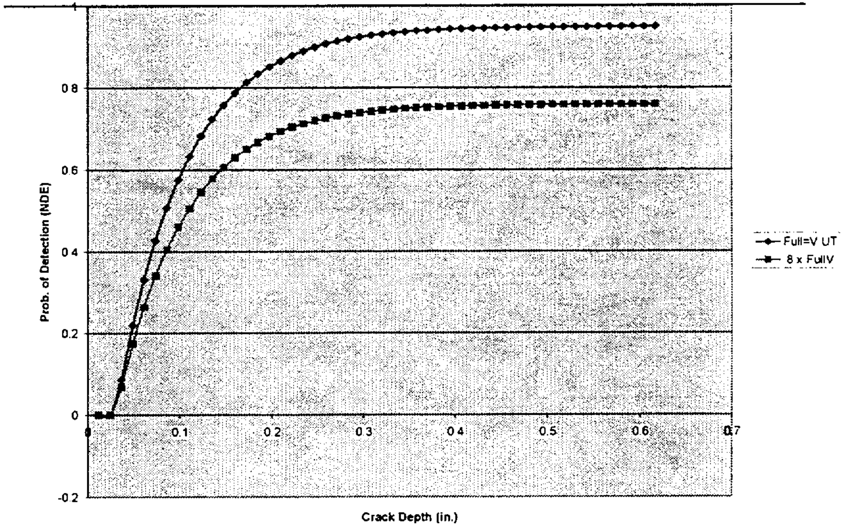
Probability of Detection Curves for NDE



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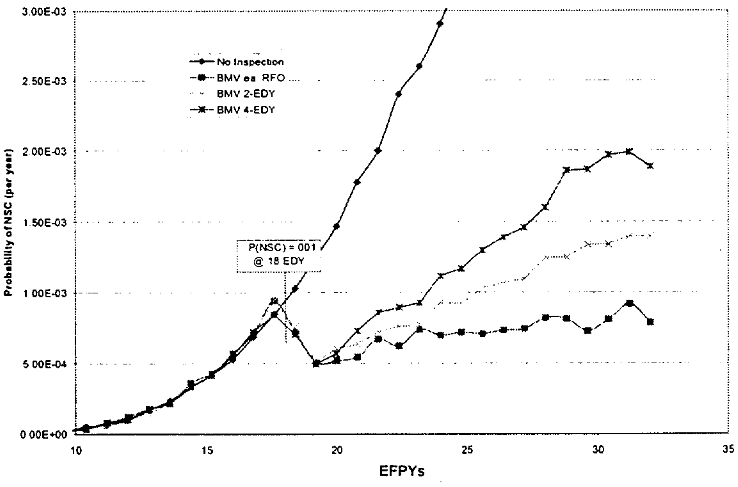
Inspection Plan Technical Basis: Effect of Visual Inspection Runs



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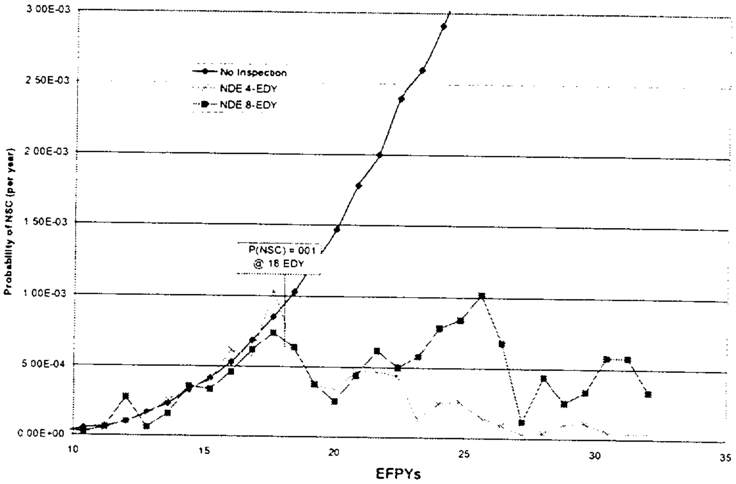
Inspection Plan Technical Basis: Effect of NDE Inspection



Deterministic Crack Growth Analyses

- **Uses Expert Panel recommended crack growth law**
  - 2 x 75th Percentile of all data
  - da/dt = C(K-8.19)1.16

Temperature (°F)	C
580	$3.604\text{x}10^{-7}$
590	$4.665\text{x}10^{-7}$
600	$6.008\text{x}10^{-7}$
602	$6.316\text{x}10^{-7}$
605	$6.806\text{x}10^{-7}$

Deterministic Crack Growth Analyses

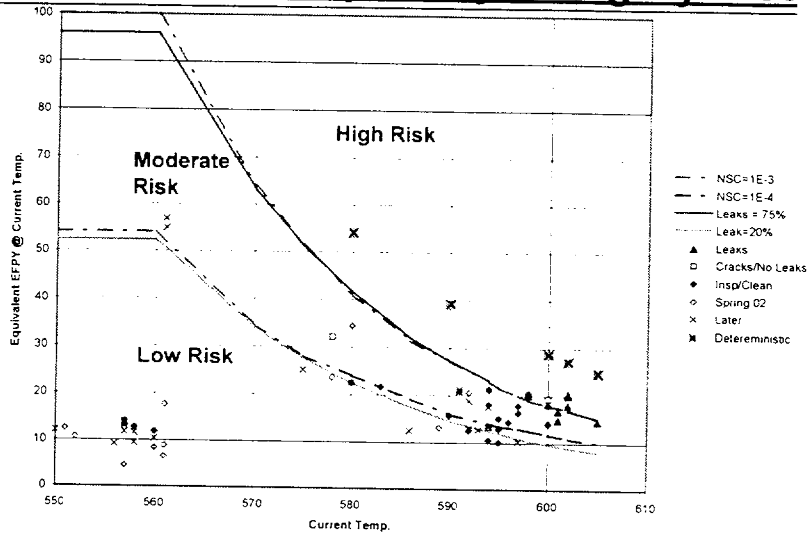
- **Uses Stress Intensity Factors from plant specific analysis of Westinghouse plant**
  - High Angle Nozzle (43.5° nozzle angle)
  - Higher Ks than B&W plant results

Circ. Crack Length		K
Degrees	Inches	Ksi*in $^{1/2}$
30	1.16	34.4
70	2.70	27.1
160	6.16	29.2
180	6.34	47.2
220	7.75	51.9
260	9.16	58.1
300	10.57	63.7

Deterministic Crack Growth Analysis Results

Temperature (°F)	Time for Initial Flaw Size of 30° Circumference to Grow to 165° and 300° (EFPY)	
	Westinghouse-Type Plant	
	165°	300°
580	23.7	31.7
590	18.3	24.6
600	14.2	19.1
602	13.5	18.2
605	12.5	16.8

Deterministic Crack Growth Results Added to Susceptibility Category Plot



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Conclusions

- **PFM Incorporates:**
  - Weibull model of time to leakage
  - Finite Element Fracture Mechanics model for B&W type head
  - Crack growth rate statistics from Expert Panel
  - Effect of various inspection types, intervals and POD
  - Heat-basis analysis from NRC Comments
  - Log-Triangular and Log-Normal CGR Distributions
- **Inspection Plan Technical Basis Runs:**
  - Start with "benchmarked" analysis parameters from B&W plant analysis
  - Analyze plants at various head temperatures
  - Set risk categories based on probability of Net Section Collapse (per year) and cumulative leakage probability
  - Set inspection intervals based on effect of various inspection types and frequency on probability of Net Section Collapse (per year)

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Conclusions (cont'd)

- **Susceptibility Categories Based on PFM Results**
  - Low –Risk:: 0 < EDYs < 10
  - Moderate Risk: 10 < EDYs < 18
  - High Risk: 18 < EDYs
- **Inspection Type and Frequency Results**
  - Inspection cases run with conservative POD assumptions
  - BMV each RFO upon entering High Risk Category reduces probability of NSC to acceptable level indefinitely
  - NDE every 4 EDYs upon entering High Risk Category reduces probability of NSC to essentially nil
- **Deterministic Crack Growth Results**
  - Conservatively bounds times from moderate to high risk susceptibility regions

Probability of Detecting Leaks by Bare-Metal Visual Inspection

Prepared for Meeting With NRC Technical Staff
May 22, 2002

Dominion Engineering, Inc.
S. Hunt
M. Fleming

Contents

- Field Experience
- Gap Opening Displacement Analysis
- Area of Actual Metal-to-Metal Contact
- Roll Expansion Experience
- Probability of Detection

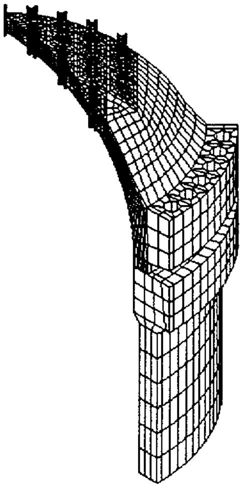
Field Experience

- Leaks have been found from 32 CRDM nozzles at eight plants by visual inspections
- Non-visual inspections have been performed on 481 CRDM and CEDM nozzles at fourteen plants
  - Characterization of leaking nozzles
  - Assess extent of condition at eight plants with leaking nozzles
  - Inspection of plants where insulation precludes bare metal visual inspection
- Non-visual inspections showed three nozzles with leak paths to the annulus
  - These three leaking nozzles were at Davis-Besse where leakage would have been discovered visually had head surface been clean
- Probability of Detection = 35/35 = 1.00

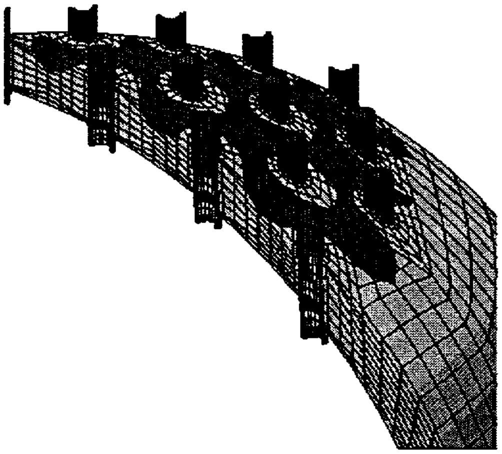
Gap Opening Displacement Analysis

- Based on fabrication records leaks have been detected from
  - Three nozzles with 0.0014" initial interference
  - One nozzle with a 0.002" initial interference (Davis-Besse Nozzle 2)
- Finite element analyses have shown gap opening paths for interference fits up to 0.003" interference
  - Pressure on the nozzle OD surface after a leak reduces interference fit

Gap Opening Displacement Analysis
Typical Finite Element Model



Gap Opening Displacement Analysis
Stress Distribution in Vessel Head



Area of Actual Metal-to-Metal Contact

- Even for cases with a nominal interference fit, the actual area of metal-to-metal contact is small
- Based on tribology considerations
  - Contact Area = Force/(3 x yield strength)
  - Contact Area = 5% of total interface area for typical CRDM nozzle with 0.003" interference
- Over remaining 95% of the interface area
  - Flow paths equal to sum of RMS surface roughness of mating parts
  - Typically 60-90x10^{-6} inches
- Other factors increase flow passage sizes such as
  - Straightness
  - Out-of-Roundness

Roll Expansion Experience

- There are several cases where leaks have occurred from Alloy 600 penetrations despite the penetrations having been roll expanded into the pressure boundary
  - Steam generator drain pipes
  - Pressurizer instrument nozzles (EdF plants)

Probability of Detection

- Probability of detection (POD) for bare metal inspections
- For interference fits up to 0.002"
  - POD = 1.00 (provided a clean head surface)
- For interference fits up to 0.003"
  - Conservatively assumed that leaks will not be detected for interference fits greater than 0.002"
  - Assume normal distribution
  - 75% of nozzles will have fits less than 0.002" for which leakage has been confirmed
  - POD = 1.00 x 0.75 = 0.75

Inspection Plan

PWR Reactor Pressure Vessel Head Penetrations

Michael Lashley, South Texas Project
May 22, 2002

Purpose

- Provide guidance and the basis for a long-term management program for RPV Head penetrations.
- Preserve structural integrity thereby ensuring safe operation.
  - GL 88-05 program remains the primary defense against boric acid wastage.
  - Inspection frequencies have been conservatively established relative to the structural integrity of the RPV Head.
- Provide a graduated approach to inspections to allow early detection of leakage or through-wall cracking prior to challenging structural integrity or significant wastage.
  - Structural integrity is defined as maintaining an acceptably low probability of developing cracking that could lead to nozzle ejection.

Scope

- Applies to the pressure boundary of the RPV head penetrations fabricated from Alloy 600 with Alloy 82/182 weld material.
- Does NOT apply to RPV head replacements and nozzle repairs with Alloy 690 and Alloy 52/152
- Assumes that a GL 88-05 walk down of the plant is effectively performed each refueling outage.

Effective Degradation Years - EDY

- Based on years of operation, normalized to 600F (as of 2/28/01)
- Effective Degradation Years (EDY) may be a more appropriate way to rank for wastage potential
  - Leaking crack as important as large circ flaw
  - Independent of ONS 3
- Although similar to old way, rank for some units changes
  - Old rank - combination of head temperature, operating time to date, and time left to ONS3 equivalence.
  - EDY rank - just time and temperature at current (2/28/01) time

Risk Informed Basis

Probabilistic fracture mechanic (PFM) analyses using a Monte-Carlo simulation algorithm

- Included experience-based time to leakage correlations
  - used a Weibull model of plant inspections to date,
  - fracture mechanics analyses of various nozzle configurations containing axial and circumferential cracks, and
  - MRP developed crack growth rate data for Alloy 600.
- Performed to determine the probability of leakage and failure versus time for a set of input parameters:
  - head operating temperature,
  - benchmarked against experience to date
- Sensitivity studies were performed for various:
  - inspection types (visual or NDE) and
  - inspection intervals.

Risk Based Susceptibility

- Moderate susceptibility boundary:
  - The number of EDYs at which a plant reaches
    - probability of one leaking nozzle = 20% (approximately equal to the probability of net section collapse (NSC i.e. nozzle ejection) = 1×10^{-4}
- High susceptibility boundary:
  - The number of EDYs at which a plant reaches:
    - probability of nozzle ejection = 1×10^{-3} (approximately equal to the probability of one leaking nozzle = 75%)
      - consistent with NRC RG 1.174 guidance for change in Core Damage Frequency.

Plant Categories

- Low Susceptibility:
  - less than 10 Effective Degradation Years, EDY (defined as Effective Full Power Years @ 600F), without a leak or identified crack
- Moderate Susceptibility:
  - greater than or equal to 10 EDY and less than 18 EDY without a leak or identified through-wall crack
- High Susceptibility:
  - greater than or equal to 18 EDY or units that have identified leaks or through-wall cracks.

CRDM/CEDM J-Groove Weld Inspection Bases

- Circumferential cracks in the J-groove weld do not pose a significant risk of nozzle ejection.

- Lack-of-fusion: extent to still maintain structural integrity is similar to the acceptable extent of through-wall circumferential cracking (i.e. >75% of the circumference).

CRDM/CEDM Head Penetration Flaw Acceptance Criteria

- Visual evaluation criteria
  - EPRI Technical Report 1006899, Visual Examination for Leakage of PWR Reactor Head Penetrations on Top of the RPV Head: Revision 1,March 2002.
- Non-visual evaluation criteria
  - MRP and ASME Section XI Code are working to develop final criteria, and until those criteria are issued, NRC-proposed criteria may be used.

Inspection Schedule – Low Susceptibility

For low susceptibility plants (< 10 EDY):

- Perform a Bare Metal Visual (BMV) examination of 100% of the CRDM/CEDM penetrations once per 10 years, beginning no later than the third ISI interval.
- Or, perform NDE (i.e., non-visual examination) of 100% of the CRDM/CEDM penetrations and associated J-groove welds once per 10 years, beginning no later than the third ISI interval.

Inspection Schedule – Moderate Susceptibilty

For moderate susceptibility plants (10 EDY≤X< 18 EDY)*:*

- Perform a BMV examination of 100% of the CRDM/CEDM penetrations at the 1st RFO upon entering this category and once every 2 EDY not to exceed 5 EFPYs.
- Or, perform NDE (i.e., non-visual examination) of 100% of the CRDM/CEDM penetrations and associated J-groove welds at the 1st RFO upon entering this category and once every 4 EDY not to exceed 10 EFPYs.

Inspection Schedule – High Susceptibility

For high susceptibility plants (≥18 EDY)*:*

- Perform a BMV examination of 100% of the CRDM/CEDM penetrations at every RFO upon entering this category. AND
- Perform NDE (i.e., non-visual examination) of 100% of the CRDM/CEDM penetrations and associated J-groove welds within 4 EDY upon entering this category or issuance of this Plan, whichever is later
  - Exceptions to 100% NDE for undue hardship.

OR

- Perform NDE (i.e., non-visual examination) of 100 % of the CRDM/CEDM penetrations and associated J-groove welds at the 1st RFO upon entering this category and once every 4 EDY not to exceed 6 EFPYs.

Inspection Plan

- **Plants with leak(s) or through wall cracks identified:**
  - *Discovery Inspection*
    - Perform a non-visual examination of the CRDM/CEDM penetrations and associated J-groove welds to characterize the crack or leak identified.
    - Indications are evaluated or repaired in accordance with flaw evaluation guidelines.

Plants with leak(s) or through wall cracks

Expansion of Inspection (to be implemented no later than next RFO)

- Perform NDE (i.e., non-visual examination) of 100% of the CRDM/CEDM penetrations and associated J-groove welds.
  - Indications are evaluated or repaired in accordance with flaw evaluation guidelines (Reference 4).
- Or, perform an evaluation to justify continued visual examination until the RVH component is removed from service.
- Or, perform NDE at a frequency to be determined such that the 3x safety margin of a hypothetical circumferential crack growing above the weld is not exceeded prior to the next inspection.

Inspection Plan
PWR Reactor Pressure Vessel (RPV) Head Penetrations
Revision 0
May 17, 2002

Purpose

The purpose of the industry inspection plan for RPV head penetrations is to provide further guidance for PWR licensees subsequent to responding to NRC Bulletins 2001-01 and 2002-01. This inspection plan provides the basis for a long-term management program for the RPV Head penetrations and is not intended to supplant previous inspections, evaluations, or site-specific regulatory commitments. The industry inspection plan goal is to preserve the structural integrity thereby ensuring safe operation. Structural integrity is defined as maintaining an acceptably low probability of developing cracking that could lead to nozzle ejection. A robust GL 88-05 program remains the primary defense against boric acid wastage of low-alloy steel. However, the inspection frequencies within this plan have been conservatively established relative to the structural integrity of the RPV Head. The inspection plan is structured to provide a graduated approach to inspections to allow early detection of leakage or through-wall cracking prior to challenging structural integrity or significant wastage. Industry data is used in conjunction with a risk assessment model to demonstrate that the increase in predicted core damage frequency (CDF) resulting from RPV head penetration cracking is within regulatory guidance (RG 1.174).

Scope

The guidance provided in this document is applicable to the pressure boundary of the RPV head penetrations fabricated from Alloy 600 with Alloy 82/182 weld material. This plan does not address inspection requirements for Alloy 690/52/152 materials. For the purpose of this plan, through-wall cracks are defined as cracks that provide a leak path from the primary side environment to the nozzle annulus. Also for the purpose of this plan, it is assumed that a GL 88-05 walk down of the plant is effectively performed each refueling outage.

Risk Informed RPV Head Penetration Inspection Methodology Bases

CRDM/CEDM Nozzle Inspection Bases and Categorization

A risk informed inspection schedule for the CRDM/CEDM nozzles is presented below. Pertinent information and bases for this risk informed schedule is provided in Reference 1.

Probabilistic fracture mechanic (PFM) analyses using the Monte-Carlo simulation algorithm were performed to determine the probability of leakage and failure versus time for a set of input parameters, including head operating temperature, inspection types (visual or NDE) and inspection intervals. Input into this algorithm included experience-based time to leakage correlations that use a Weibull model of plant inspections to date, fracture mechanics analyses of various nozzle configurations containing axial and circumferential cracks and MRP developed statistical crack growth rate data for Alloy 600. The parameters used in the model were benchmarked against the most severe cracking found to date in the industry (Oconee-3) and produced results that are in agreement with experience to date. The moderate susceptibility limit was defined as the number of effective degradation years (EDYs) at which a plant reaches either a probability of one leaking nozzle = 20%, or a probability of net section collapse (NSC i.e. nozzle ejection) = 1×10^{-4} Effective Degradation Years, EDY, is defined as Effective Full Power Years @ 600F. The high susceptibility limit was defined as the EDYs at which a plant reaches a probability of nozzle ejection = 1×10^{-3}, which is consistent with NRC RG 1.174 guidance for change in Core Damage Frequency.

A comparison of the PFM results with those from deterministic analyses indicated that the risk-based limits are conservative.

The inspection schedule then employs plant categories defined by these risk-informed susceptibility limits (Reference 1) and specified as follows:

- Low susceptibility: less than 10 Effective Degradation Years, EDY (defined as 10 Effective Full Power Years @ 600F), without a leak or identified crack
- Moderate susceptibility: greater than or equal to 10 EDY and less than18 EDY without a leak or identified through-wall crack, and
- High susceptibility: greater than or equal to 18 EDY or units that have identified leaks or through-wall cracks.

Explanation of EDY and the method to relate this parameter to Effective Full Power Years at a given head temperature are provided in Reference 3.

CRDM/CEDM J-Groove Weld Inspection Bases

Circumferential cracks in the J-groove weld do not pose a significant risk of nozzle ejection. Cracking that is completely within the weld metal, even if 360° around the nozzle, will not lead to ejection since the portion of the weld that remains attached to the outside surface of the nozzle will not be able to pass through the tight annular fit.

There would be a risk of ejection for the case of lack-of-fusion between the J-groove weld and outside surface of the nozzle over most of the weld circumference. However, the tolerable extent of lack-of-fusion, which still maintains structural integrity, is similar to the acceptable extent of through-wall circumferential cracking (i.e. >75% of the circumference). There is no precedent for such a large area of lack-of-fusion. Inspections performed to date do not show significant areas of lack-of-fusion.

Therefore, although the nozzle J-groove weld is anticipated to have a higher crack growth rate than the nozzle base metal, no inspection requirements and flaw evaluation procedures specific to the weld are required in addition to those otherwise specified or referenced in this document.

CRDM/CEDM Head Penetration Inspection and Flaw Acceptance Criteria

A penetration whose visual examination detects relevant conditions (See Reference 2) on the surface of the head at the nozzle-to-head interface shall be unacceptable for continued service until supplemental examinations or any evaluations are complete and identified flaws meet applicable acceptance criteria. Such relevant conditions may be evidence of borated water leakage from PWSCC cracks in the CRDM/CEDM nozzle's pressure boundary or evidence of general corrosion of the head from other primary coolant leakage. Guidance for visual examination of applicable relevant conditions is contained in Reference 2.

Leaks or through wall cracks should be further evaluated per the guidance provided below under "*Plants with leak(s) or through wall cracks identified*". Acceptance criteria proposed by the NRC for the flaws were specified in Reference 4. The MRP and ASME Section XI Code are working to develop final criteria, and until those criteria are issued, those of Reference 4 may be used. Additionally, the penetration containing relevant conditions shall be acceptable for continued service if the relevant conditions are corrected by a repair/replacement activity or by other corrective measures necessary to meet the acceptance criteria.

Plant-specific CRDM/CEDM Head Penetration Inspection Schedule

This inspection plan will be implemented at the next refueling outage following the plant's responses to NRC Bulletin 2001-01 or 2002-01. At the plant's option, the inspections in response to NRC Bulletin 2001-01 or 2002-01 may be substituted for the first inspection required by this plan. The subsequent re-inspection frequency will be based on the completion date of that previous inspection. Figure 1 is a flowchart of the inspection plan provided in the text below. The plant categories have been initially defined as noted above (and in Reference 1) based on preliminary bounding risk assessment activities. When a plant moves from one category to another (e.g. by gaining more EDY), the next inspection is dictated by the new category. The following head penetration inspection schedule is based on a risk informed analysis of nozzle cracking within B&W designed and manufactured RPV nozzle material and head geometry (Reference 1). The cracking susceptibility of this material is used to bound the materials contained in the PWR fleet based on experience to date and therefore this inspection plan is considered to be conservative and applicable to all other domestic PWR plants.

For low susceptibility plants (< 10 Effective Degradation Years, EDY):

- Perform a Bare Metal Visual (BMV) examination of 100% of the CRDM/CEDM penetrations once per 10 years, beginning no later than the third ISI interval.
- Or, perform NDE (i.e., non-visual examination) of 100 % of the CRDM/CEDM penetrations and associated J-groove welds once per 10 years, beginning no later than the third ISI interval.

Note: if leakage, or through wall cracking is identified, the plant is reclassified as "high susceptibility". If only part through-wall cracks are identified, the plant is reclassified as "moderate susceptibility". The NDE examination of the J-groove weld should, as a minimum, identify if any cracking exists by either inspecting the wetted surface or inspecting the root of the J-groove weld.

For moderate susceptibility plants (10 EDY≤ X < 18 EDY)***:***

- Perform a BMV examination of 100% of the CRDM/CEDM penetrations at the 1st RFO upon entering this category and once every 2 EDY not to exceed 5 EFPYs.
- Or, perform NDE (i.e., non-visual examination) of 100 % of the CRDM/CEDM penetrations and associated J-groove welds at the 1st RFO upon entering this category and once every 4 EDY not to exceed 10 EFPYs.

Note: if leakage, or through wall cracking is identified, the plant is reclassified as "high susceptibility". If part through-wall cracks are identified, the classification of the plant does not change. The NDE examination of the J-groove weld should, as a minimum, identify if any cracking exists by either inspecting the wetted surface or inspecting the root of the J-groove weld.

For high susceptibility plants (≥18 EDY):

- Perform a BMV examination of 100% of the CRDM/CEDM penetrations at every RFO upon entering this category, and perform NDE (i.e., non-visual examination) of 100% of the CRDM/CEDM penetrations and associated J-groove welds or portions thereof that can be examined without incurring undue hardship within 4 EDY upon entering this category or issuance of this Plan, whichever is later.

Note: the population of examinations is based on providing additional defense-in-depth.

- Or, perform NDE (i.e., non-visual examination) of 100 % of the CRDM/CEDM penetrations and associated J-groove welds at the 1st RFO upon entering this category and once every 4 EDY not to exceed 6 EFPYs.

Note: the NDE examination of the J-groove weld should, as a minimum, identify if any cracking exists by either inspecting the wetted surface or inspecting the root of the J-groove weld.

The following information is provided as guidance for use when leakage and/or cracks are identified.

Plants with leak(s) or through wall cracks identified:

- **Discovery Inspection**
  - Perform a non-visual examination of the CRDM/CEDM penetrations and associated J-groove welds to characterize the crack or leak identified.
  - Indications are evaluated or repaired in accordance with approved flaw evaluation guidelines.

  Note: Nozzles with through-wall indications shall be evaluated for cavities and corrosion of the reactor vessel head adjacent to the penetration. Any identified corrosion shall be evaluated and repaired as necessary.

- **Expansion of Inspection**
  Implement the following expansion guidance either during the Discovery Inspection or no later than the next RFO following discovery of a leak or through-wall crack in any CRDM/CEDM penetration or associated J-groove weld. Either:
  - Perform NDE (i.e., non-visual examination) of 100% of the CRDM/CEDM penetrations and associated J-groove welds.
    - Indications are evaluated or repaired in accordance with approved flaw evaluation guidelines (Reference 4).

- Or, perform an evaluation to justify continued visual examination until the RVH component is removed from service.
- Or, perform NDE at a frequency to be determined such that the 3x safety margin of a hypothetical circumferential crack growing above the weld is not exceeded prior to the next inspection.

Indications Left in Service

- Re-inspection of the indication is performed in accordance with the flaw evaluation guidelines (Reference 4) and projected crack growth.
- Re-inspection of an embedded flaw is performed at 1) the next scheduled refueling outage and once every ISI period thereafter, or 2) in accordance with a site-specific evaluation.

References

1. Technical Basis for CRDM/CEDM Top Head Penetration Inspection Plan, by Peter C. Riccardella and Nathaniel G. Cofie, Prepared for EPRI's MRP Alloy 600 Assessment Committee, DRAFT, May 2002.

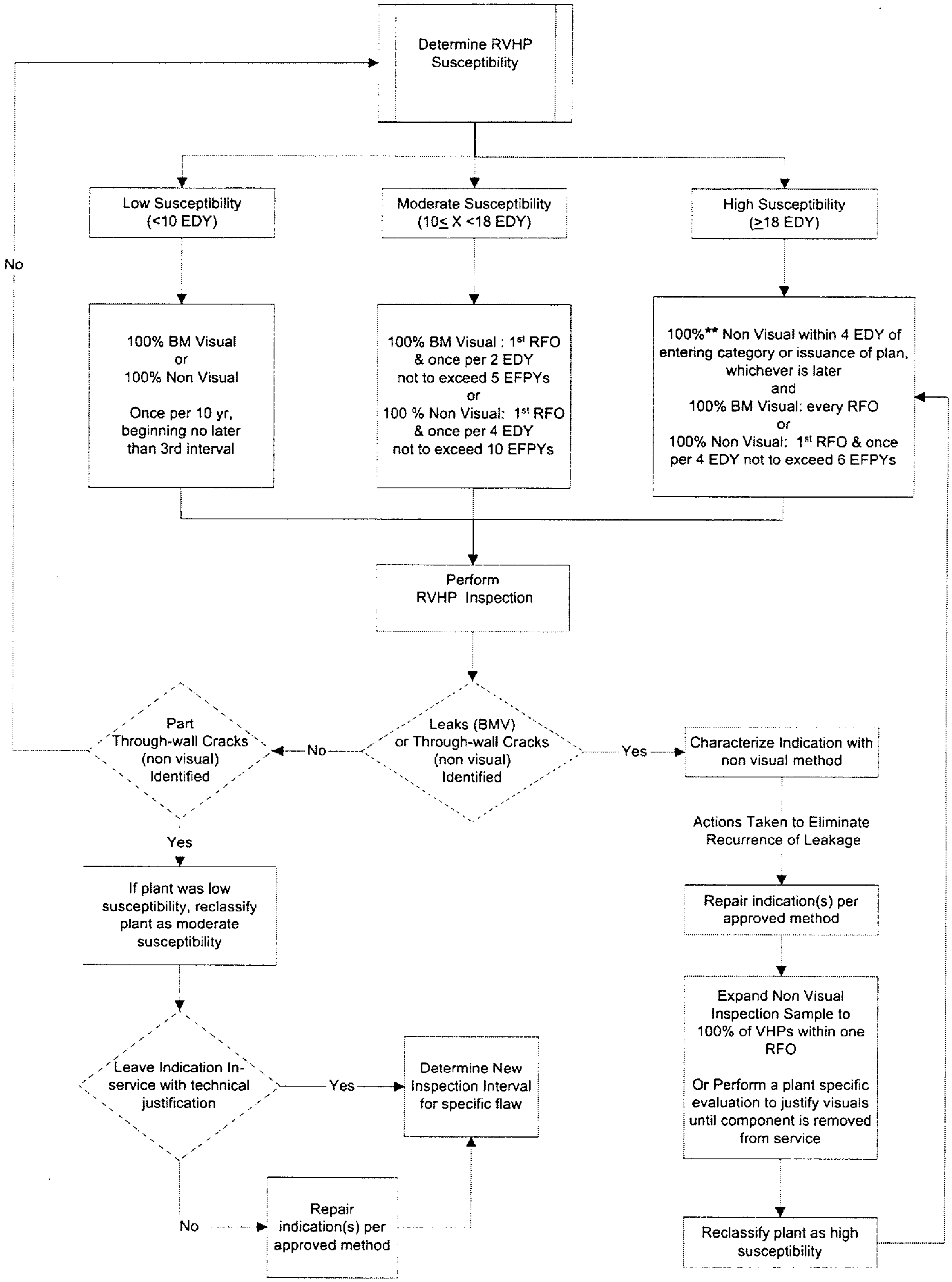
2. EPRI Technical Report, Visual Examination for Leakage of PWR Reactor Head Penetrations on Top of the RPV Head: Revision 1, Report 1006899, March 2002.

3. EPRI Interim Report, PWR Materials Reliability Project Interim Alloy 600 Safety Assessments for US PWR Plants (MPR-44), Part 2: Reactor Vessel Top Head Penetrations, TP-1001491, Part 2, May 2001.

4. Letter, Jack Strosnider, NRC, to Alex Marion, NEI, Subject: Flaw Evaluation Criteria, November 21, 2001.

Figure 1

PWR RPV Head Penetrations Inspection Flowchart



** 100% of the CRDM/CEDM penetrations and associated J-groove welds or portions thereof that can be examined without incurring undue hardship

Technical Assessment of Davis-Besse Degradation

Prepared for Meeting With NRC Technical Staff
May 22, 2002

Prepared by:
G. White
C. Marks
S. Hunt
Dominion Engineering, Inc.

Contents

- Purpose and Approach
- Material Loss Mechanisms
  - Corrosion mechanisms
  - Erosion mechanisms
  - Flow accelerated corrosion
- Degradation Progression
- Boric Acid Corrosion Tests Simulating Nozzle Leakage
- Thermal-Hydraulic Environment
  - Leak rate
  - Expansion cooling
  - Velocity and wall shear stress
- Chemical Environment
  - Volume of boric acid deposits produced
  - Boric acid morphology and properties
  - Concentration of primary water
  - pH
  - Electrochemistry

Purpose and Approach

Purpose

- The purpose of the technical assessments is to complement plant experience in answering the following questions:
  - If a significant amount of RPV head material loss occurs, will it be detectable visually from above the head (either directly or through the presence of deposits)?
  - Could significant material loss occur during a single cycle?
- In addition, the technical assessments also address current questions regarding the progression of material loss mechanisms (i.e., understanding of degradation progression)

Approach

- ➤ The basic approach is to examine how the various potential material loss mechanisms vary as the leak rate is increased from 10^{-6} to 1.0 gpm and the initial tight nozzle annulus becomes a large cavity through material loss. Evaluations focus on:
  - Thermal-hydraulic environment
  - Chemical environment
  - Properties of boric acid and boron compounds
  - Relevant experimental results and plant experience
- ➤ The leak rate is expected to be the key parameter:
  - Expansion cooling increases with leak rate, potentially permitting a liquid film to reach the top head surface
  - Increasing leak rates result in higher velocities and potentially erosion or flow accelerated corrosion

Approach (continued)

- ➤ The leak rate also determines the amount of boric acid deposits that exit the pressure boundary
- ➤ The results of corrosion and erosion rate evaluations are used to bound:
  - The timeframe for significant degradation
  - The volume of low alloy steel material loss versus the volume of deposits produced

Material Loss Mechanisms

- Corrosion mechanisms
- Erosion mechanisms
- Flow accelerated corrosion

Material Loss Mechanisms
Overview

➤ Chemical Mechanisms
  - Low-oxygen, boric acid corrosion (deaerated, concentrated boric acid solutions)
  - Dry boric acid or boric oxide crystal corrosion
  - Classic crevice corrosion (conductive liquid in the crevice forms an ionic path to allow dissolution deep in crevice remote from oxygen at crevice mouth)
  - Galvanic corrosion (driving corrosion potential due to dissimilar metal couple between Alloy 600 nozzle and low-alloy-steel (LAS) head)
  - "Classic" boric acid corrosion (aerated, concentrated boric acid solutions)
  - Molten boric acid corrosion

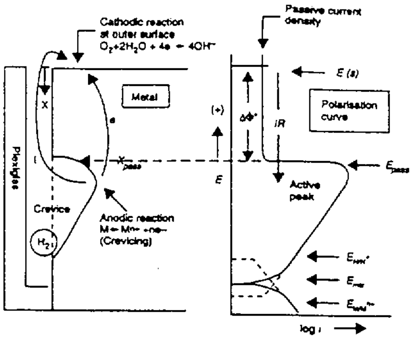
Material Loss Mechanisms
Overview (continued)

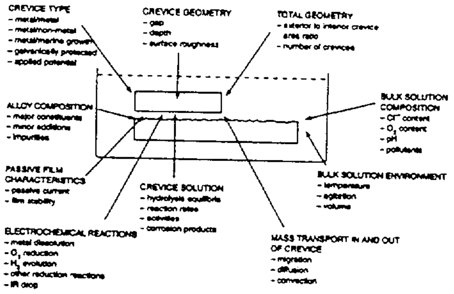
- Flow-Enhanced Chemical Mechanisms
  - Two-phase flow accelerated corrosion (FAC) (low oxygen; boric acid not required)
- Mechanical Mechanisms
  - Droplet or solid particle impingement erosion
  - Flashing-induced erosion
  - Steam cutting erosion
  - Single-phase erosion

Material Loss Mechanisms
Matrix

PRELIMINARY		Extent of Wastage			
		Initial Tight Annulus	Enlarged Annulus	Small Cavity	Large Cavity
Possible Material Loss Mechanisms	Deaerated Boric Acid Corrosion Conc. Boric Acid Corrosion but $DO_2 \approx 0$-10 ppb	Low rates			
	Dry BA or Boric Oxide Crystal Corrosion Corrosion in Contact with Dry Crystals and Humidity	Low rates			
	Single-Phase Erosion Potential Erosion if High Steam Velocities	Possible for high leak rates	Less likely than for tight annulus		Large flow area precludes high velocities
	Flow Accelerated Corrosion (FAC) Low-Oxygen Dissolution through Surface Oxides	Possible if liquid velocities high enough and temperature low enough			Unlikely as oxygen stabilizes
	Impingement / Flashing-Induced Erosion Droplet and Particle Impact Opposite Crack Outlet	Possible if droplets right size and momentum			
	Crevice Corrosion Liquid Ionic Path from Top Head Surface	Believed not to be likely because low alloy steel does not passivate in an aerated, concentrated boric acid			Not possible because no crevice geometry
	"Occluded Region" Galvanic Corrosion Driven by Potential Difference Btw Dissimilar Metals	Possible at locations where liquid solution exists			
	"Molten" Boric Acid Corrosion Corrosion in Pure or Nearly Pure Melted BA Crystals	Possible but rate expected to be lower than for aerated BAC			
	Aerated Boric Acid Corrosion (BAC) Concentrated Boric Acid Solution with Oxygen	Not possible due to low oxygen deep in crevice	Unlikely	Possibly	Up to 1-5 inches per year

Chemical Mechanisms
Classic Crevice Corrosion





CREVICE TYPE
- metal/metal
- metal/non-metal
- metal/marine growth
- galvanically protected
- applied potential

CREVICE GEOMETRY
- gap
- depth
- surface roughness

TOTAL GEOMETRY
- exterior to interior crevice area ratio
- number of crevices

ALLOY COMPOSITION
- major constituents
- minor additions
- impurities

BULK SOLUTION COMPOSITION
- Cl^- content
- O_2 content
- pH
- pollutants

PASSIVE FILM CHARACTERISTICS
- passive current
- film stability

CREVICE SOLUTION
- hydrolysis equilibria
- reaction rates
- activities
- corrosion products

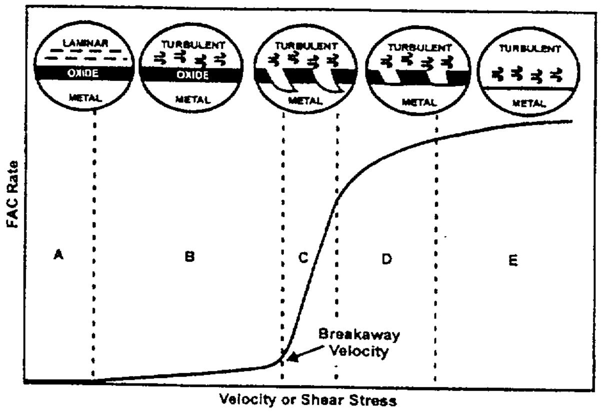
BULK SOLUTION ENVIRONMENT
- temperature
- agitation
- volume

ELECTROCHEMICAL REACTIONS
- metal dissolution
- O_2 reduction
- H_2 evolution
- other reduction reactions
- IR drop

MASS TRANSPORT IN AND OUT OF CREVICE
- migration
- diffusion
- convection

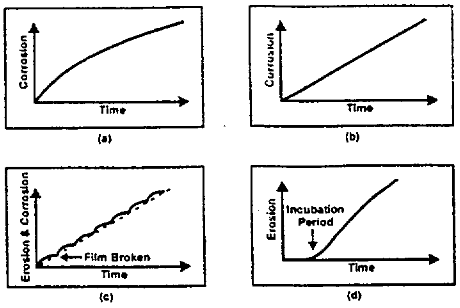
Source: F.P. IJsseling. *Survey of Literature on Crevice Corrosion (1979-1998)*, IOM Communications Ltd., London, 2000.

Flow Accelerated Corrosion
Effect of Velocity on FAC Rate



Source: B. Vyas, *Treatise on Materials Science and Technology*, vol. 16, 1979, p. 357.

Flow Accelerated Corrosion
Time Dependencies of FAC Processes



Stagnant Liquid

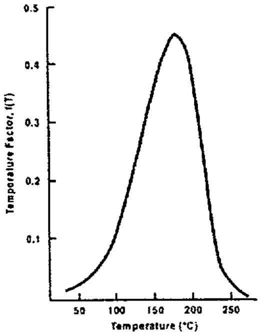
Low Velocities

Velocity > Breakaway

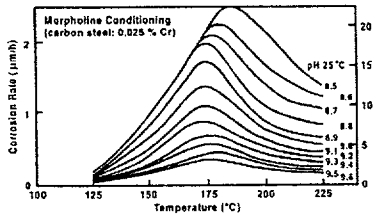
High Velocities (pure erosion)

Source: B. Chexal, et al., *Flow-Accelerated Corrosion in Power Plants*, TR-106611, EPRI, Palo Alto, CA, 1996.

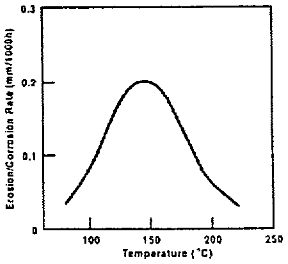
Flow Accelerated Corrosion
Effect of Temperature for Two-Phase Flows



Temperature Dependence of Two-Phase FAC
From Keller, H., VGB Kraftwerkstechnik, 54, (1974), p. 292.

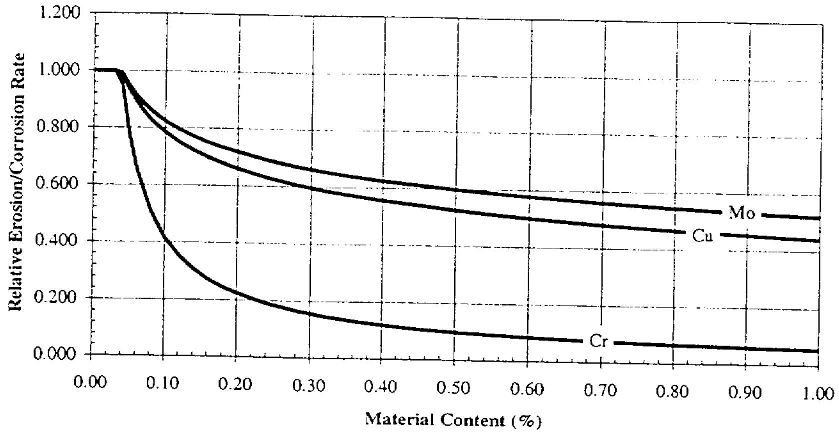


Temperature Dependence of Two-Phase FAC with a Steam Quality of 65% and a Velocity of 185 ft/s
From Bouchacourt, M., EDF Internal Report, (1982), Ref.: HT-PVD. XXX MAT/T.42.



Temperature Dependence of Two-Phase FAC
From Izumiya, M., Water Chemistry and Corrosion Products in Nuclear Power Plants, International Atomic Energy Agency, Vienna (1983), p. 61.

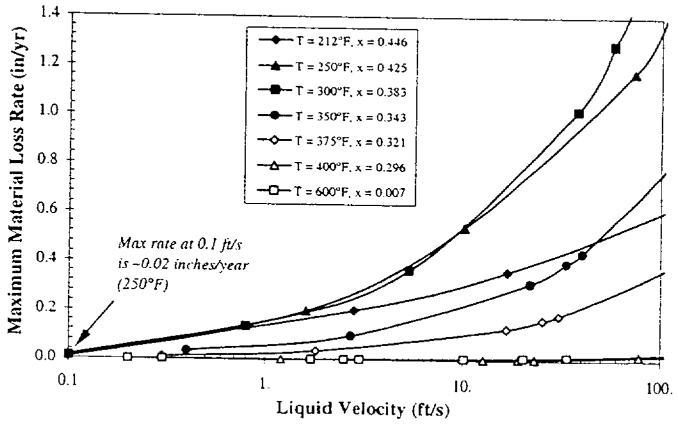
Flow Accelerated Corrosion
Effect of Alloy Content on Erosion / Corrosion Rate



Source: EPRI CHECWORKS

Flow Accelerated Corrosion
EPRI CHECWORKS FAC Predictions

- Predictions for saturated two-phase water flow through a 2-inch Sch 80 90° elbow with R/D = 1.5
- No Cr assumed but 0.5% Mo
- Dissolved $O_2 = 0$
- $pH_{RT} = 7$



NOTE: CHECWORKS is intended to be used to model FAC in secondary cycle piping systems and not in situations such as leaking crevices. These calculations show the rough effects of liquid velocity and temperature that may be expected for leaking CRDM nozzles.

Degradation Progression

Degradation Progression
Leak Rate is Main Controlling Parameter

PRELIMINARY

Increasing Leak Rate →

Nozzle/Weld Condition	leak path to annulus	leak path to annulus	leak path to annulus	likely crack in nozzle wall reaches above top of weld on OD and ID	crack in nozzle wall reaches relatively high above top of weld on OD and ID
Annulus Condition	hypothetical clogged annulus	possibly some opening up of annulus	likely some opening up of annulus	may require some opening up of annulus	likely requires some opening up of annulus
Leak Rate	hypothetical zero leak rate	< on the order of 0.001 gpm	roughly between 0.001 and 0.01 gpm	roughly between 0.01 and 0.1 gpm	> on the order of 0.1 gpm
Liquid Velocity Exiting Crack	0 ft/s	less than on the order of 0.01 ft/s	roughly between 0.01 and 0.1 ft/s	roughly between 0.1 and 1 ft/s	> on the order of 1 ft/s
Local Temperature	600°F	Close to 600°F	at least roughly 500°F	roughly between 212 and 500°F	Close to 212°F
Liquid Location	fills annulus up to hypothetical blockage	all liquid vaporizes close to bottom of annulus	liquid film unlikely to exist high in annulus	liquid film may cover much of annulus walls	liquid film covers local top surface of head
Possible Significant Mechanisms	· none	· possibly very minor galvanic	· possibly some galvanic corrosion; · erosion until annulus opens slightly	· likely some galvanic corrosion; · minor erosion and FAC; · possibly aerated BAC if annulus is opened enough	· aerated BAC on top of head; · possibly molten BAC, galvanic corrosion, erosion, or FAC
Pounds of Boric Acid Deposits Released in 2 years	at least small amount extruded	< on the order of 7 lbs	roughly 7 to 70 lbs	roughly 70 to 700 lbs	> on the order of 700 lbs
		all or most other leaking CRDM nozzles	EPRI & CE Annulus Tests	EPRI & CE Annulus Tests	Davis-Besse Nozzle #3

Degradation Progression

- Condition 1a. If—contrary to plant experience—a leak path crack forms in the absence of leakage to the top surface of the head
  - There will be low oxygen, zero velocity, and no vaporization-driven concentration mechanism, so material loss rates will be small
- Condition 1b. For tight nozzle cracks that allow a leak path
  - The leak rate will be limited and the annulus downstream of the crack will boil dry within a short distance
  - Erosion and FAC will not be active due to very low liquid velocities
  - Small amounts of boric acid or boric oxide crystals will accumulate on the top head surface

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Degradation Progression
(continued)

- Condition 2. As the crack widens and the minimum leak path flow area increases
  - Flashing-induced erosion or FAC may initiate the material loss process
  - Galvanic corrosion may be important if cooling is sufficient to allow liquid to exist over a significant height in the annulus
  - These mechanisms could be expected to produce greater relative material loss deep in the annulus, consistent with Davis-Besse Nozzle #2 and the EPRI BAC leaking annulus tests
- Condition 3. As the leak rate increases and the wastage area grows from a small cavity to a large, open cavity
  - Aerated boric acid corrosion (up to 1-5 inches per year) may occur

Degradation Progression
(continued)

- The geometry of the Davis-Besse Nozzle #3 cavity may indicate that aerated BAC removing material from the top surface down toward the cladding replaced corrosion and/or erosion deep down in the annulus as the dominant degradation mode
  - The slope of the walls of the cavity change with distance from the top head surface
  - Heat transfer calculations show considerable local cooling of the head for the range of leak rates believed to apply to this nozzle, indicating an aerated, concentrated liquid boric acid solution film on the top head surface adjacent to this nozzle
  - Laboratory tests and plant experience indicate relatively high corrosion rates for low alloy steel exposed to aerated, concentrated liquid boric acid solution in comparison to other material loss mechanisms
  - Gravity-driven flow of this liquid film would tend to produce the observed oblong shape of the Nozzle #3 cavity

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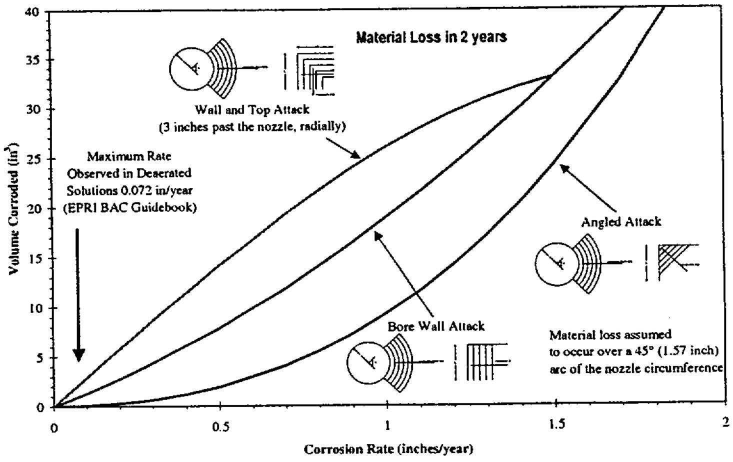
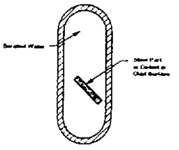
Degradation Progression
Relating Linear Loss Rate to Volume Loss (Example Calcs)



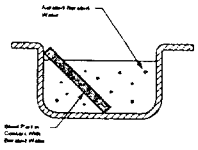
Boric Acid Corrosion Tests Simulating Nozzle Leakage

BAC Tests Simulating Nozzle Leakage
Overview

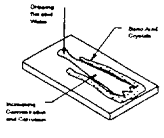
- An extensive set of experimental data has been compiled and reported in the EPRI *Boric Acid Corrosion Guidebook, Revision 1*
  - Tests by several organizations prior to 1995
  - Tests of a range of conditions
    - Deaerated water
    - Aerated water
    - Dripping
    - Impingement
    - Leakage into annulus
  - Tests performed by EPRI at Southwest Research Institute in 1996/97
- Results of additional tests performed by CEA in France have been made available to EPRI



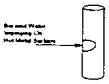
Immersion in Deaerated Water



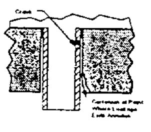
Immersion in Aerated Water



Dripping onto Hot Metal Surfaces

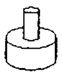
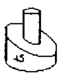
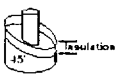


Impingement onto Hot Metal Surfaces



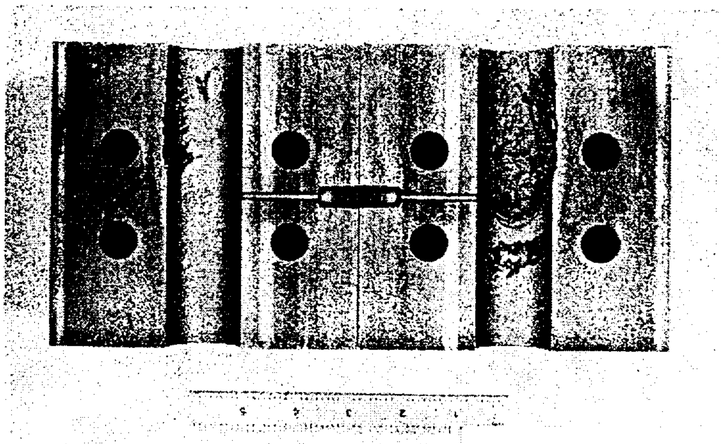
Leakage into Annular Gap

BAC Tests Simulating Nozzle Leakage
EPRI Annulus Test Matrix

NOZZLE CRACK LEAK TESTS	4. 600°F 	5. 600°F 	6. 600°F 

Test Number	Temperature (F)	Flow Rate (gpm)
4a	600	0.01
4b	600	0.10
5a	600	0.01
5b	600	0.10
6a	600	0.01
6b	600	0.10

BAC Tests Simulating Nozzle Leakage
Typical Sectioned EPRI Test Specimen



Test 4a
0°, 600°F, 0.01 gpm, 50 days

BAC Tests Simulating Nozzle Leakage
Test Conclusions

- The maximum corrosion rates in both the EPRI and CE tests were about 2.0 – 2.5 in/yr
- The maximum corrosion rates occurred at leak rates of about 0.01 gpm with decreasing corrosion rate as leak rate was increased above 0.01 gpm
  - However, one test by CE at a low leak rate (0.002 gpm) showed a very low corrosion rate
- While the tests may not represent the initial conditions of a very tight fit, they are considered to represent anticipated conditions once the annulus opens up to about 0.005"
- While the corrosion depth can be greater below the exposed surface than at the surface, the tests showed relatively large amounts of boric acid deposits for the range of flow rates tested

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Thermal-Hydraulic Environment

- Leak rate
- Expansion cooling
- Velocity and wall shear stress

Leak Rate Calculations
Method

- Calculate axial crack length and opening area above the top of the weld using welding residual stress FEA or an available analytical expression from fracture mechanics
- Calculate the leak rate based on industry correlations for choked flow through a crack in a steam generator tube
- Consider the potential additional flow resistance of a tight annulus downstream of the crack

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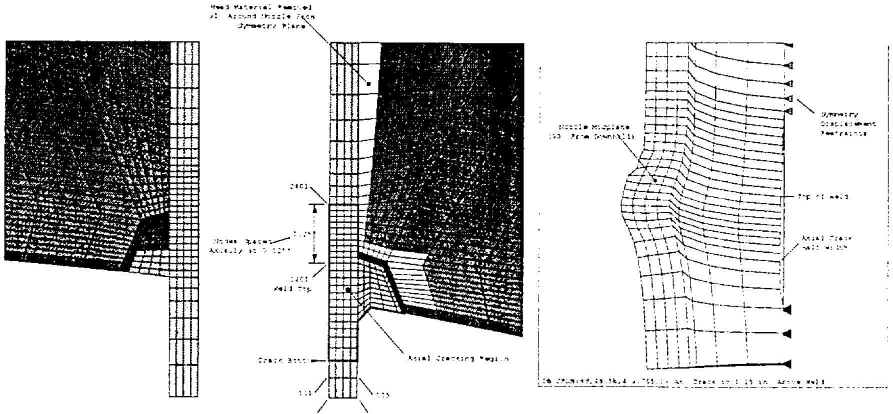
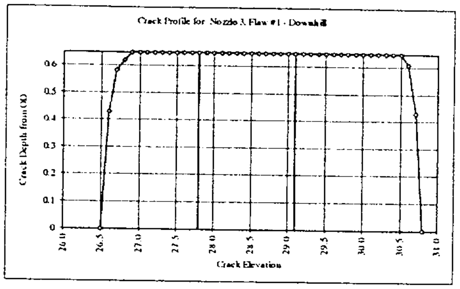
Leak Rate Calculations
Crack Opening Displacement and Area

- Crack opening displacement and area determined using finite element models with welding residual and operating stresses



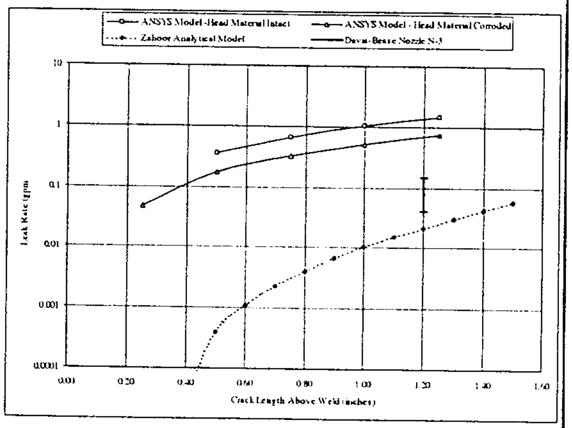
Leak Rate Calculations
Effect of Actual Crack Front Profile

- ➤ Crack opening displacement calculations have assumed crack cuts completely through the nozzle wall, and J-groove weld, from the reported crack bottom to top
- ➤ Subsequent to initial leak rate calculations, the actual crack profiles at Davis-Besse have been determined from top-down UT data

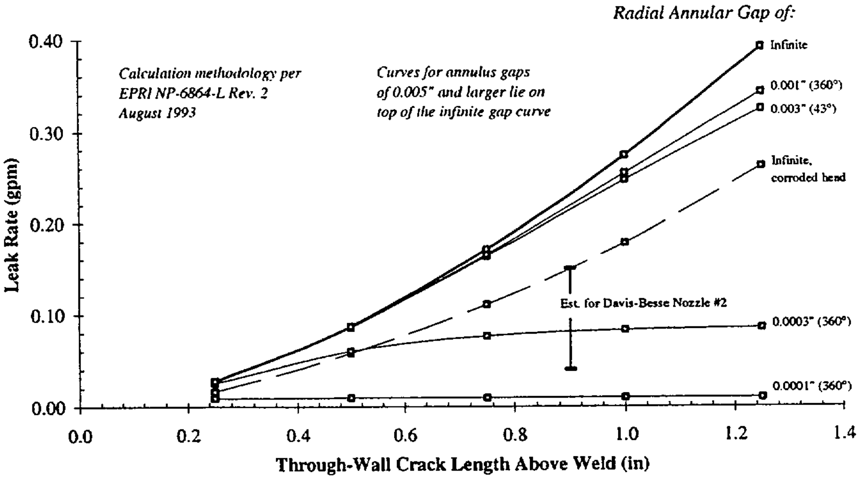


Leak Rate Calculations
Typical Results

- ➤ Actual unidentified leak rate is bounded by leak rates calculated using
  - Crack opening area for a through-wall axial crack in a pipe with length equal to the length that the axial crack extends above the top of the J-groove weld
  - Crack opening area determined using the finite element method for an ideal through-wall crack
- ➤ Calculations show leak rate increases quickly with crack length above the top of the J-groove weld



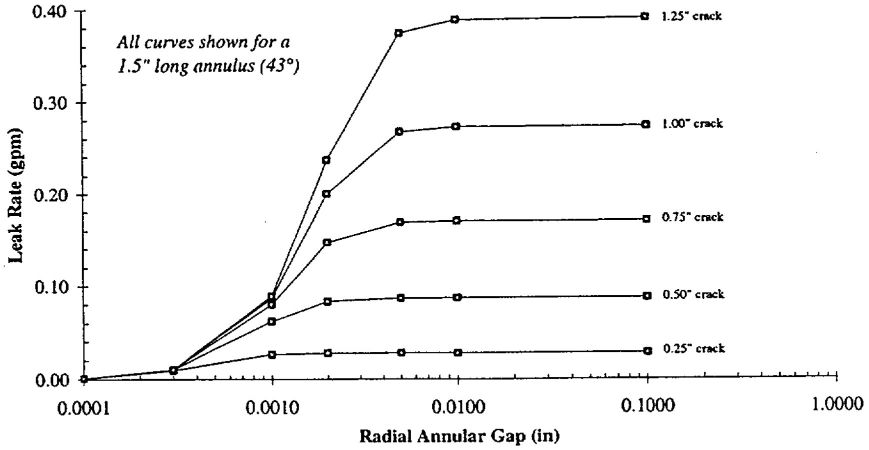
Leak Rate Variation with Crack Length



Calculation methodology per EPRI NP-6864-L Rev. 2 August 1993

Curves for annulus gaps of 0.005" and larger lie on top of the infinite gap curve

Leak Rate Variation with Annular Gap Width

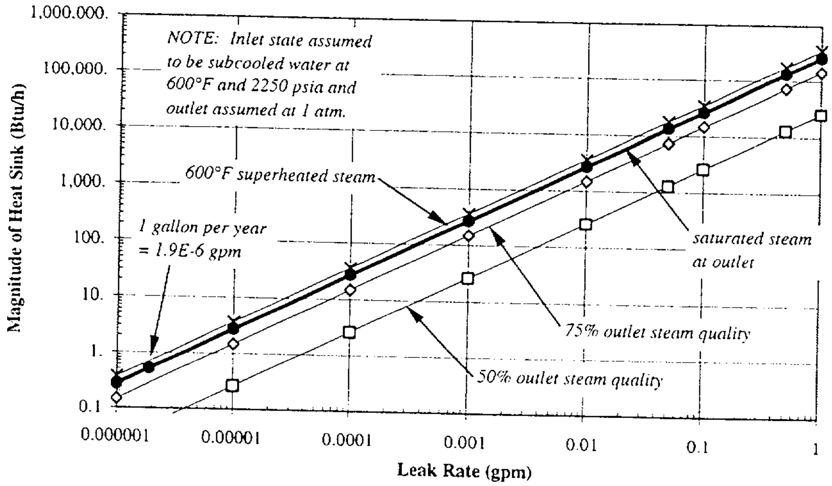


All curves shown for a 1.5" long annulus (43°)

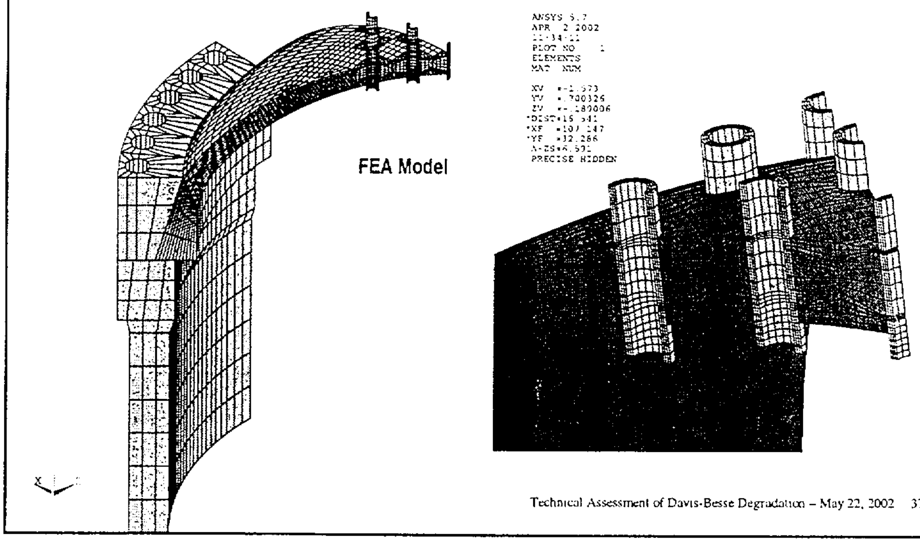
Expansion Cooling Modeling
Overview

- Approach is to determine extent of cooling along the leak path as a function of leak rate using
  - Heat required to vaporize all leaking liquid is the leak rate times the enthalpy increase (from primary water at 613 Btu/lb to saturated steam at atmospheric pressure at 1150 Btu/lb)
  - FEA heat transfer model of conduction within head materials with convection boundary conditions from primary coolant and to space above
  - Correlations for two-phase and single-phase heat transfer coefficients along the leak path
- Extent of cooling affects important parameters including
  - Location of concentrated liquid
  - pH
  - FAC susceptibility

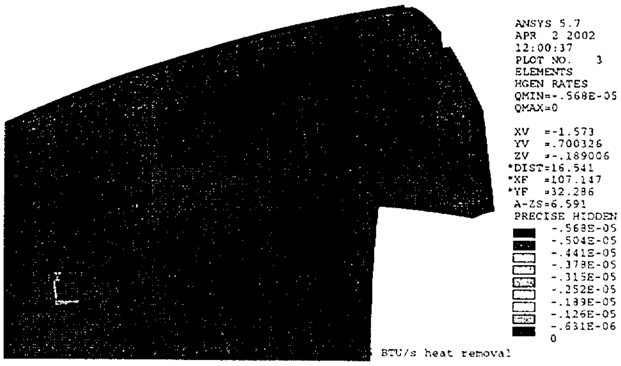
Expansion Cooling Modeling
Magnitude of Heat Sink



Expansion Cooling Modeling
Finite Element Analysis of Head Heat Transfer

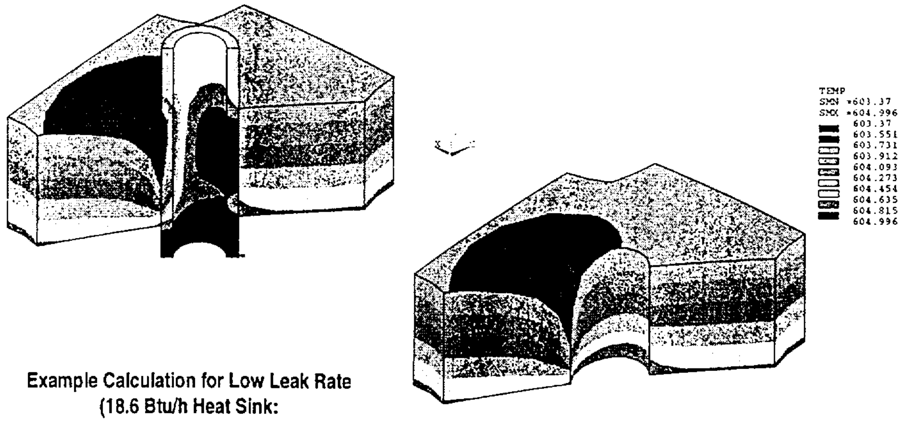


Expansion Cooling Modeling
Finite Element Analysis of Head Heat Transfer



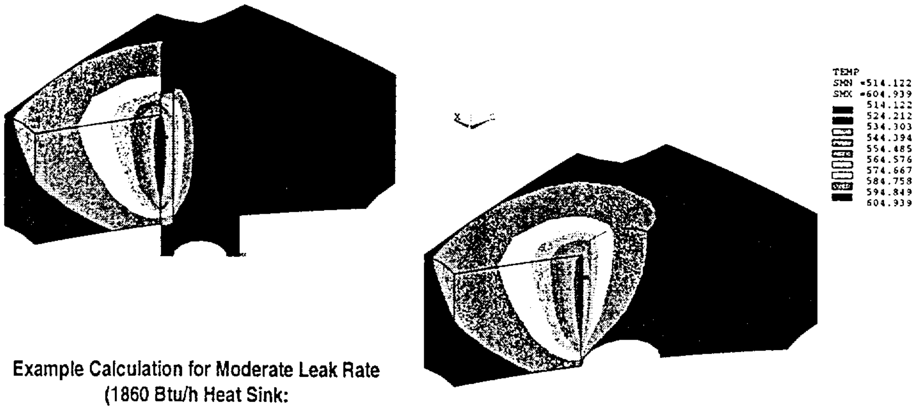
Uniform Surface Heat Sink Along the Leak Path Assumed

Expansion Cooling Modeling
Finite Element Analysis of Head Heat Transfer



Example Calculation for Low Leak Rate
(18.6 Btu/h Heat Sink:
complete vaporization of 7×10^{-5} gpm leak)

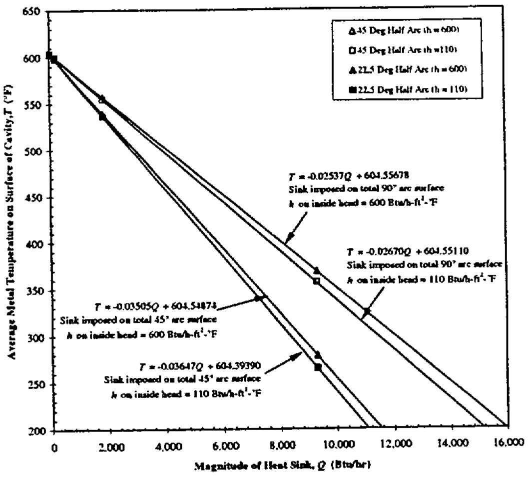
Expansion Cooling Modeling
Finite Element Analysis of Head Heat Transfer



Example Calculation for Moderate Leak Rate
(1860 Btu/h Heat Sink:
complete vaporization of 0.007 gpm leak)

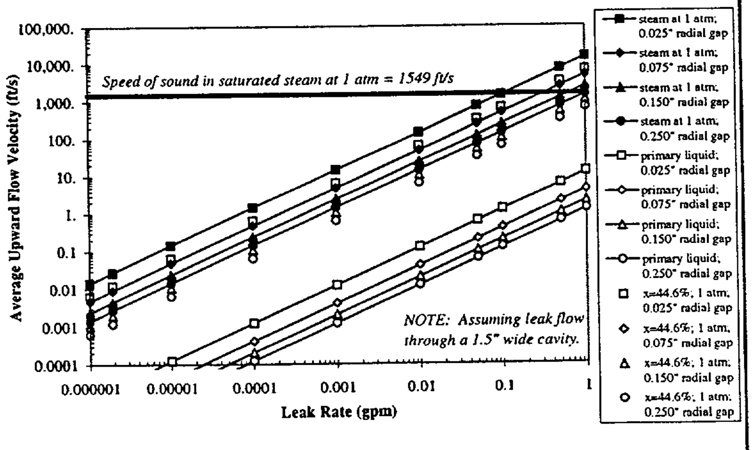
Expansion Cooling Modeling
Finite Element Analysis of Head Heat Transfer

Average Metal Surface Temperature Along the Leak Path



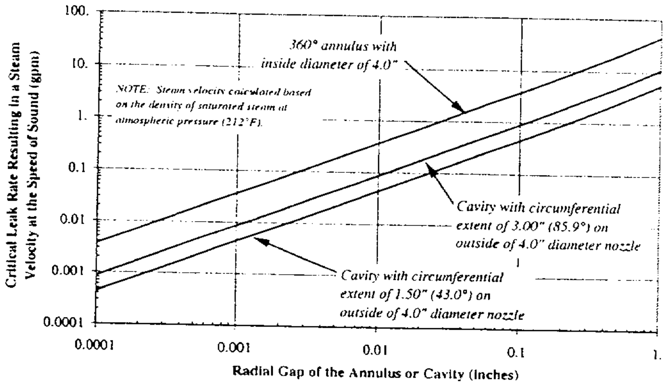
Effluent Velocity
Average Velocities Up Through a 1.5-inch Wide Cavity

➤ Calculations for a uniform cavity with 1.5-inch circumferential extent



Effluent Velocity
Single-Phase Steam Critical (Choked) Velocity

- Figure shows the gap size resulting in sonic steam velocities at the annulus/cavity exit for
  - 360° uniform annulus
  - 3-inch wide cavity
  - 1.5-inch wide cavity



NOTE: Steam velocity calculated based on the density of saturated steam at atmospheric pressure (212°F).

360° annulus with inside diameter of 4.0"

Cavity with circumferential extent of 3.00" (85.9°) on outside of 4.0" diameter nozzle

Cavity with circumferential extent of 1.50" (43.0°) on outside of 4.0" diameter nozzle

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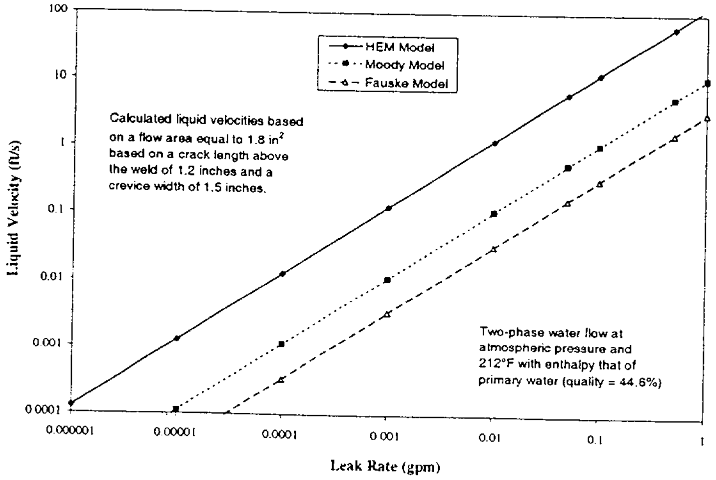
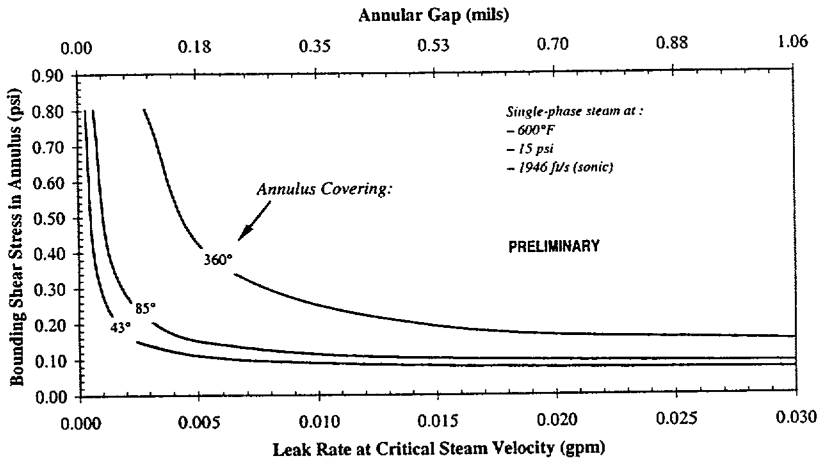
Effluent Velocity
Liquid Velocity Estimates at Exit of Crack



Calculated liquid velocities based on a flow area equal to 1.8 in^2 based on a crack length above the weld of 1.2 inches and a crevice width of 1.5 inches.

Two-phase water flow at atmospheric pressure and 212°F with enthalpy that of primary water (quality = 44.6%)

Wall Shear Stress Calculation
(Single-Phase Steam, 1.25-inch Crack Length Above Top of Weld)



Single-Phase Erosion in Steam
Experimental Data

- Data available from testing of turbine materials in 1950s (*Trans. ASME*, v. 80, 1958)
- Erosion tests carried out for a number of materials:
  - 430°F / 350 psia
  - 9% moisture
  - 460 ft/s steam velocity
  - 1000 h duration
- Key result: 3–4 mils erosion in carbon and ½-Mo steels
  - Represents a rate of 0.025–0.035 inches per year
  - Erosion could be due principally or partly to presence of liquid (9%)

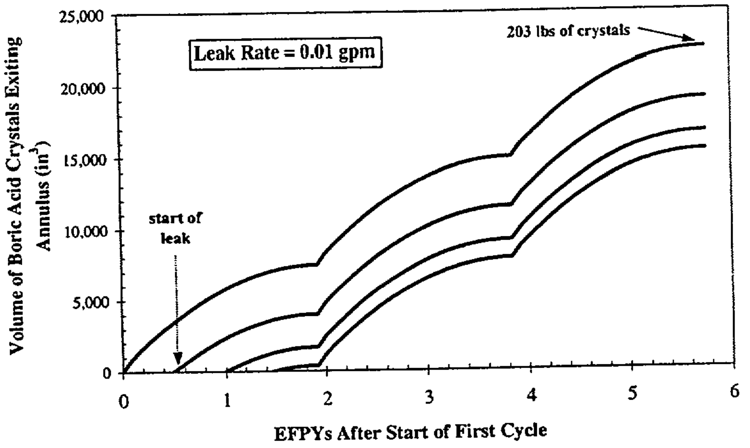
Chemical Environment

- Volume of boric acid deposits produced
- Boric acid morphology and properties
- Concentration of primary water
- pH
- Electrochemistry

Volume of Boric Acid Deposits on the Vessel Head
Methodology

- ➤ Integrate the leaking boron mass over the fuel cycle
- ➤ Calculate the volume of leaked boron based on the density of boric acid (H_3BO_3) or boric oxide (B_2O_3) crystals, conservatively assuming no porosity
- ➤ The fraction of precipitated boron compounds that deposits on the head adjacent to the leaking nozzle may be affected by
  - Droplet entrainment into the steam flow
  - Boric acid volatility (10% or less)

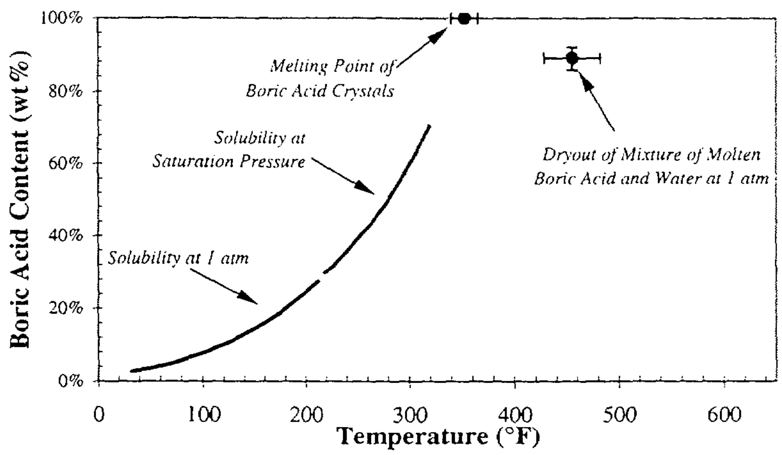
Volume of Boric Acid Deposits on the Vessel Head
Example Integration of Boron Mass



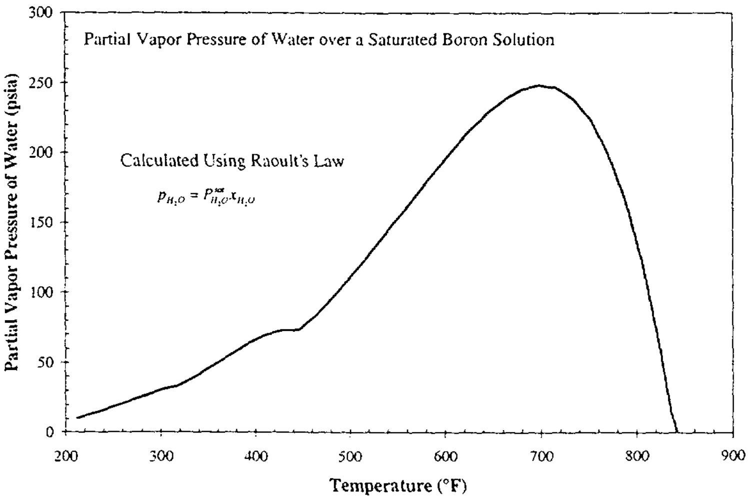
Boric Acid Morphology and Properties
Boron Phases

- <u>Boric acid solutions</u> and dry crystals
  - During evaporative concentration, boric acid solutions precipitate boric acid crystals
  - The end results depend upon the rate of concentration and drying
    - If drying is fast, boric acid powder will result
    - If drying is slow, a single irregularly shaped mass is likely
- <u>Molten boric acid</u>
  - When heated above 340-365°F, solid boric acid melts to form a highly viscous liquid that will fuse into a single mass and flow under the influence of gravity
  - Molten boric acid can contain 8-14% water by weight and is known to be corrosive
- Solid boric oxide
  - Above 302°F boric acid is subject to a dehydration reaction to form boric oxide
  - The resultant crystalline mass is an anhydrous, white, opaque, non-glasslike, stony solid
- Molten boric oxide
  - Above 617°F boric oxide begins to soften and at about 842°F becomes a highly viscous liquid

Boric Acid Morphology and Properties
Key Temperature Behavior



Boric Acid Morphology and Properties
Partial Vapor Pressure



Boric Acid Morphology and Properties
General pH Effects without Large Local Cooling

- For low concentration factors, the solution becomes slightly alkaline, having a small effect on crack growth rates
- For high concentration factors, the solution becomes acidic with a high-temperature pH of 4.5 according to MULTEQ calculations
- The initial high ratio of crevice surface area to volume may allow some buffering by the iron in the head material
- Precipitation of complex lithium and boron compounds occurs and tends to limit pH swings

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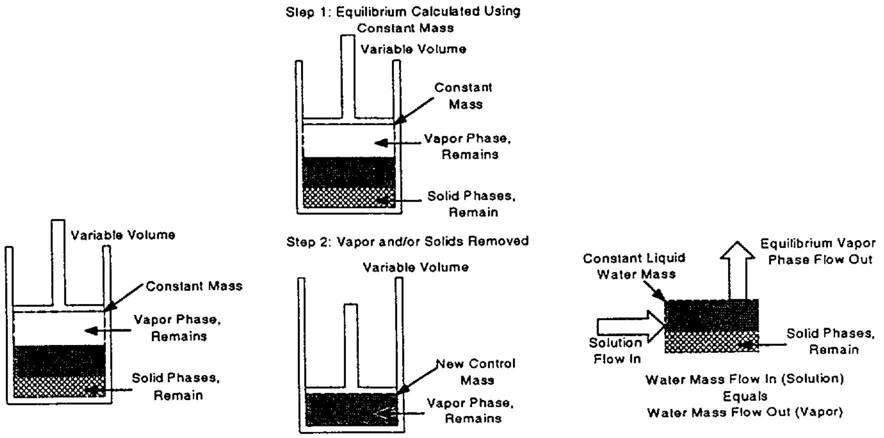
MULTEQ Modeling
Three Main Flow Models Available



Variable Volume

Constant Mass

Vapor Phase, Remains

Solid Phases, Remain

Step 1: Equilibrium Calculated Using Constant Mass

Variable Volume

Constant Mass

Vapor Phase, Remains

Solid Phases, Remain

Step 2: Vapor and/or Solids Removed

Variable Volume

New Control Mass

Vapor Phase, Remains

Constant Liquid Water Mass

Equilibrium Vapor Phase Flow Out

Solution Flow In

Solid Phases, Remain

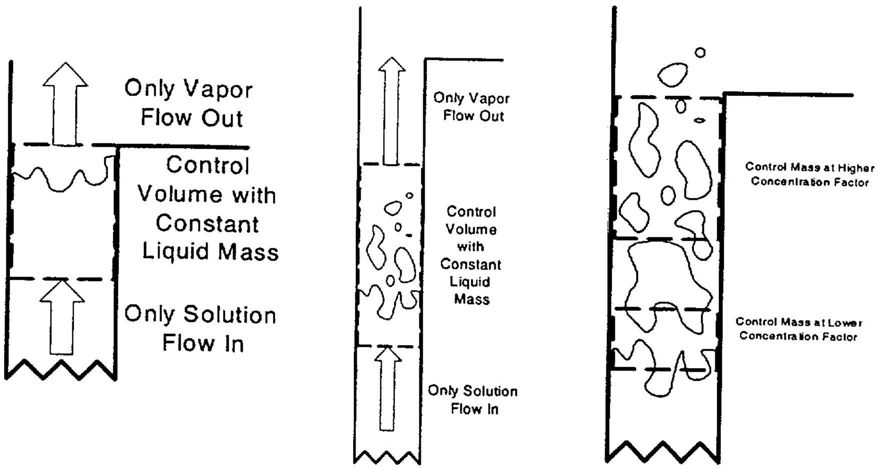
Water Mass Flow In (Solution) Equals Water Mass Flow Out (Vapor)

Static

Static with Removal

Flowing

MULTEQ Modeling
Available Control Volumes



Only Vapor Flow Out

Control Volume with Constant Liquid Mass

Only Solution Flow In

Only Vapor Flow Out

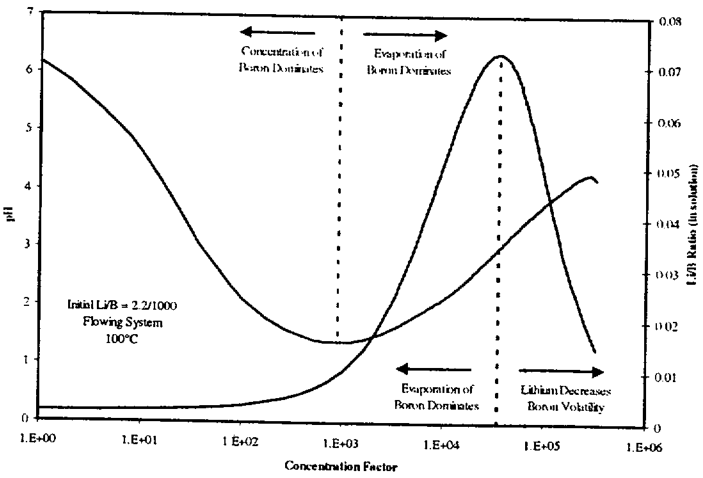
Control Volume with Constant Liquid Mass

Only Solution Flow In

Control Mass at Higher Concentration Factor

Control Mass at Lower Concentration Factor

Example MULTEQ Calculation
pH in a Flowing System at 100°C



Molten Boric Acid

Orthoboric Acid-H_3BO_3 Metaboric Acid-HBO_2 Boric Oxide B_2O_3

- ➤ Corrosion in molten boric acid largely unstudied
- ➤ Degradation:
  - Melting point above the degradation point
    - Orthoboric acid: melts at 170.9°C (340°F); degrades to metaboric acid at 169.6°C (337°F)
    - Metaboric acid: melts at 236°C (457°F); degrades to boric oxide at 235°C (455°F)
  - Degradation reaction is slow
  - Effect of degradation products on corrosion largely unknown
    - (degradation probably lower in boric oxide, B_2O_3, than in either acid)
  - Degradation products highly hygroscopic
    - Analysis of deposits not likely to indicate their at-temperature composition
- ➤ Solubility issues largely unstudied
  - Miscibility limits unknown
  - For pH calculations, molten boric acid could be an additional precipitate
  - Degradation products not included in MULTEQ

Molten Boric Acid
Molten Salt Corrosion

- ➤ Molten salt corrosion is electrochemically very similar to aqueous corrosion, depending on a reaction couple:
  - $Fe \rightarrow Fe^{2+}$ anodic reaction
  - $O_2 \rightarrow OH^-$ or $H^+ \rightarrow H_2$ cathodic reaction
  - Additional cathodic reactions unlikely in molten boric acid
  - Typical molten salt corrosion occurs through de-passivation
    - Not relevant since LAS and CS are not passive in acidic media
- ➤ Acceleration possible due to high conductivity of molten salts
  - Unlikely to lead to a qualitative difference relative to highly concentrated solutions

Molten Boric Acid Issues
Molten Salt Corrosion (continued)

- Solubility of corrosion products likely to be less in molten boric acid than in water
  - Leads to lower corrosion rates
- Molten boric acid corrosion likely to be significantly slower than corrosion in aqueous solution
  - Lower O_2 and H^+ concentrations (slower cathodic reactions)
  - Possibly lower conductivity
  - Likely lower corrosion product solubility (slower anodic reactions)
- Corrosion in molten boric acid is a particular case of corrosion in boric acid solutions, not a separate phenomenon

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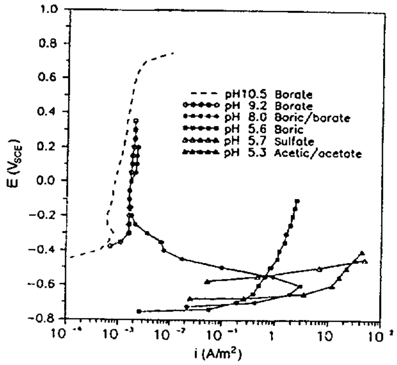
Crevice Corrosion Mechanism
Classic Crevice Corrosion is Not Believed to be Active

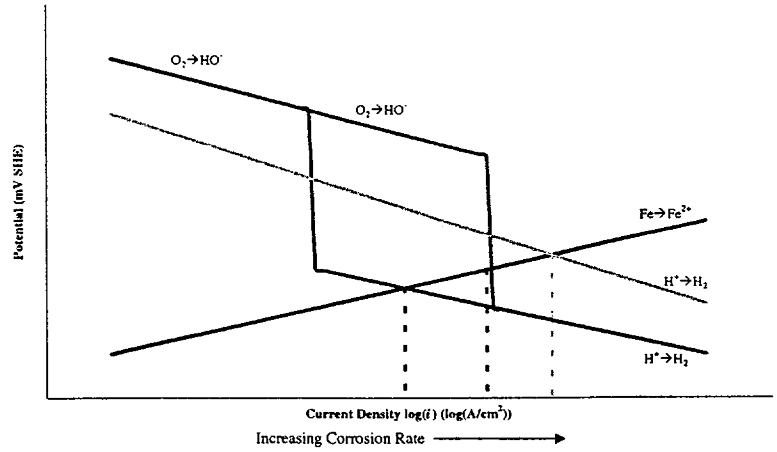
- Crevice corrosion typically requires a passivating material in order to allow separation of cathodic and anodic zones
- Carbon and low alloy steels generally do not passivate in acidic media
- Corrosion testing in boric acid solutions indicates that general corrosion is much greater in aerated environments—*i.e.*, there is no passivation

Iron Corrosion Rates in Various Solutions



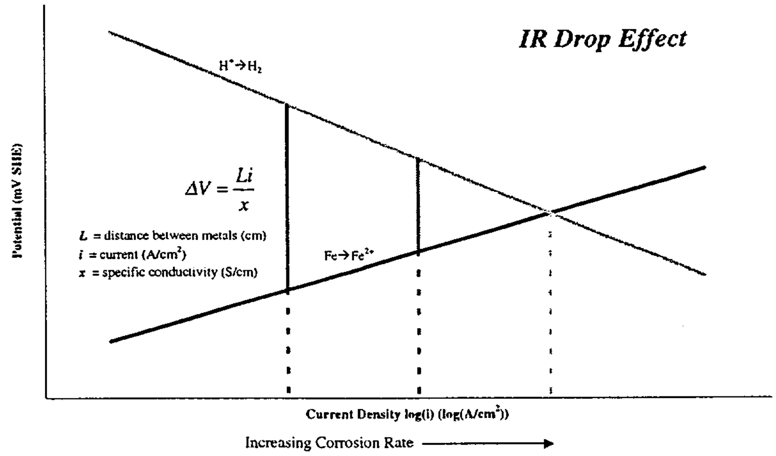
Makar and Tromans, *Corrosion* 52:4 p.250, 1996

Electrochemistry of Corrosion
Galvanic Corrosion Electrochemistry for a Non-Passivating Metal



Electrochemistry of Corrosion
Galvanic Corrosion Electrochemistry for a Non-Passivating Metal

IR Drop Effect



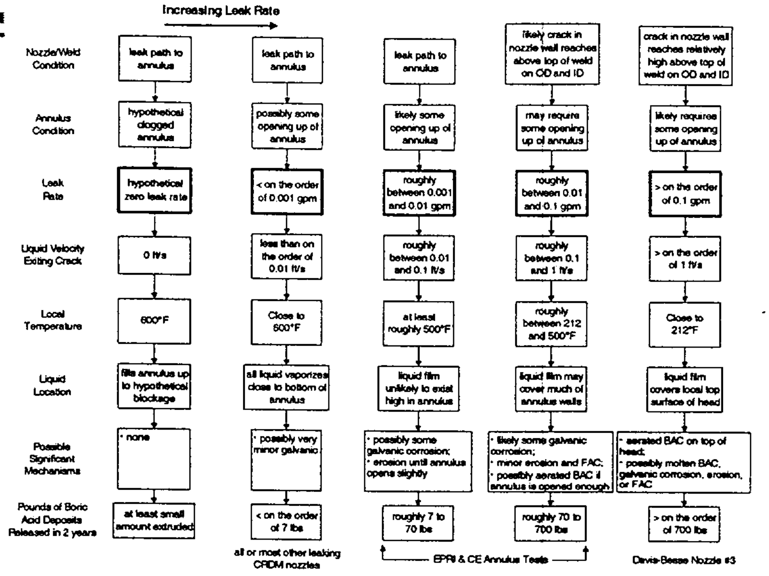
$$\Delta V = \frac{Li}{x}$$

L = distance between metals (cm)
i = current (A/cm^2)
x = specific conductivity (S/cm)

Degradation Progression

Leak Rate is Main Controlling Parameter

PRELIMINARY



Increasing Leak Rate →

Nozzle/Weld Condition	leak path to annulus	leak path to annulus	leak path to annulus	likely crack in nozzle wall reaches above top of weld on OD and ID	crack in nozzle wall reaches relatively high above top of weld on OD and ID
Annulus Condition	hypothetical clogged annulus	possibly some opening up of annulus	likely some opening up of annulus	may require some opening up of annulus	likely requires some opening up of annulus
Leak Rate	**hypothetical zero leak rate**	**< on the order of 0.001 gpm**	**roughly between 0.001 and 0.01 gpm**	**roughly between 0.01 and 0.1 gpm**	**> on the order of 0.1 gpm**
Liquid Velocity Exiting Crack	0 ft/s	less than on the order of 0.01 ft/s	roughly between 0.01 and 0.1 ft/s	roughly between 0.1 and 1 ft/s	> on the order of 1 ft/s
Local Temperature	600°F	Close to 600°F	at least roughly 500°F	roughly between 212 and 500°F	Close to 212°F
Liquid Location	fills annulus up to hypothetical blockage	all liquid vaporizes close to bottom of annulus	liquid film unlikely to exist high in annulus	liquid film may cover much of annulus walls	liquid film covers local top surface of head
Possible Significant Mechanisms	· none	· possibly very minor galvanic	· possibly some galvanic corrosion; · erosion until annulus opens slightly	· likely some galvanic corrosion; · minor erosion and FAC; · possibly aerated BAC if annulus is opened enough	· aerated BAC on top of head; · possibly molten BAC, galvanic corrosion, erosion, or FAC
Pounds of Boric Acid Deposits Released in 2 years	at least small amount extruded	< on the order of 7 lbs	roughly 7 to 70 lbs	roughly 70 to 700 lbs	> on the order of 700 lbs
		all or most other leaking CRDM nozzles	EPRI & CE Annulus Tests		Davis-Besse Nozzle #3