Nutes have Q's for Riccardella model

MRP Update to ACRS Materials Subcommittee June 5, 2002

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

ACRS 4/5/02.1

MRP

MRP Presentations

Alloy 600 ITG Status	Mathews	15 min
Alloy 600 Crack Growth Rate	Hickling	45 min
Probabilistic Fracture Mechanics Model	Riccardella	45 min
Collateral Damage	Mathews	10 min
Technical Assessment of DB Degradation Mechanisms	White	30 min
Industry Inspection Plan	Lashley	60 min

ACRS 6/5/02.2

G/11

Crack growth rate for thick-section Alloy 600 material exposed to PWR primary water

John Hickling, EPRI
for the
MRP Alloy 600 Issue Task Group

MRP

MRP Crack Growth Rate Approach: Overview

- Goal was to establish appropriate CGR guidelines for generic application to thick-section Alloy 600 base material under PWSCC conditions
- MRP panel of international experts on SCC (includes ANL/NRC Research) was established August 2001 and has met several times to date
- Extensive consideration was given to the likely OD environment in the annulus between a leaking CRDM nozzle and the RPV head (prior to Davis Besse incident)
- Relevant arguments remain valid today 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

OD Annulus Environment

- Most likely environments
  - Hydrogenated superheated steam, if pressure drop within SCC crack
  - Normal PWR water, if boiling transition well above the J-groove weld
  - Concentrated PWR primary water, if boiling occurs at the exit of SCC crack:
  - situation has been considered in detail for the case usually observed to date, i.e. low leak rates (< 1l/h) and little or no wastage of LAS vessel head
  - full evaluation has not been performed for Davis Besse type situation involving cavity formation and extensive wastage as a consequence of boric acid corrosion

OD Annulus Environment

- **Consideration of oxygen/hydrogen effects common to all three possible environments:**
- Oxygenated crevice environment highly unlikely because:
  - Back diffusion of oxygen is too low compared to counterflow of escaping steam (2 independent assessments based on molecular diffusion models were examined)
  - Oxygen consumption by metal walls would further reduce concentration
  - Presence of hydrogen from leaking water and diffusion through upper head results in a reducing environment
  - Even if concentration of hydrogen was depleted by local boiling, coupling between LAS and Alloy 600 would keep electrochemical potential low
  - Corrosion potential will be close to Ni/NiO equilibrium, resulting in PWSCC susceptibility similar to normal primary water

OD Annulus Environment

- Possible environment #2: PWR primary water within normal specifications
- Main focus of subsequent CGR data evaluation by Expert Panel

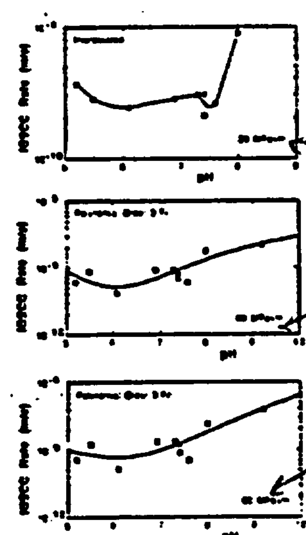
OD Annulus Environment

- Possible environment #3: Concentrated PWR primary water. For low leak rates (< 1 l/h) as mostly observed to date:
  - pH_T between 4 and 9.4 based on MULTEQ calculations
  - Actual pH_T range expected to be narrower due to precipitation of complex lithium-iron borates
  - A French experiment simulating a leak detected such borate compounds and estimated that pH_T of the liquid phase was between 7 and 8
  - A further French test involving slow concentration of a fixed volume of primary water showed no formation of caustic after conc. factor 10^3 (calculated pH_T was ~4.5)
  - Cleaning practices followed during head assembly should minimize contamination by sulfates and chlorides and steam flushing will help to remove any residual impurities

OD Annulus Environment

- Possible environment #3: Concentrated PWR primary water (con.) [redacted]
  - Ohio State study shows no significant effect of pH_T on PWSCC CGR between values of 5 and 6.5 at 330°C
  - For pH_T values between 7.5 and 9, CGR increases slightly, but acceleration factor only around 1.5 even for $pH_T = 9$
  - Expert Panel recommended that a factor of x2 on CGR should conservatively cover uncertainties in the exact composition of the annulus chemistry for $4 < pH_T < 9$
  - More acid environments as a result of large leak rates and local cooling of head were NOT considered, but limited data (Berge et al., 1997) suggests that high chloride and oxygen levels are required for IGSCC of Alloy 600 to occur

OD Annulus Environment: results of Ohio State study on effect of pH

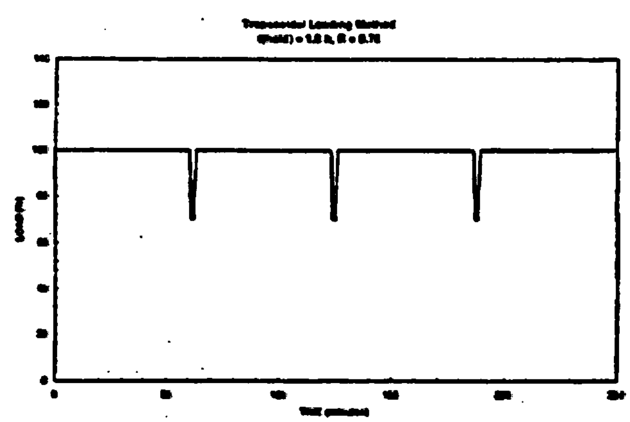


[redacted]

MRP CGR database for Alloy 600: screening of available data

- No attention was paid to numerous tests where no crack growth due to PWSCC was actually observed
- Result of data screening was elimination from further consideration of 203 CGR data points for one or more reasons (main reason individually documented in report)
- Consolidated database contains 158 data points for average CGR during each test (consistent with ASTM practice for measuring fatigue CGRs) plotted at a representative K value (ranged from 14.3 to 54.0 MPa√m)
- All were obtained in controlled primary water using fracture mechanics specimens under either constant load or constant displacement conditions
- Some tests under active load involved periodic unloading (considered to give a potential accelerating effect which is relatively small, at least for susceptible materials)

MRP CGR database for Alloy 600: periodic unloading used in W tests



Derivation of MRP CGR Curve

- Because of the known importance of material processing parameters on CGR, the initial evaluation was based on a heat-by-heat analysis of the screened database
- Insufficient data points were available from any single heat over a wide range of K values to determine the form of CGR dependence on stress intensity factor
- Shape of curve to be fitted was adopted from the Scott equation, originally developed (1991) using inspection data for axial cracks in the roll transitions of SG tubes
- This much larger database of CGR measurements is considered to provide a more reliable indicator for the form of the CGR versus K dependence:
- $da/dt = \alpha(K-9)^{\beta}$ with Scott exponent $\beta = 1.16$

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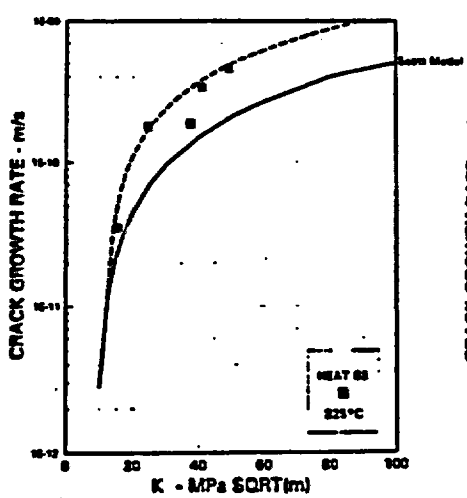
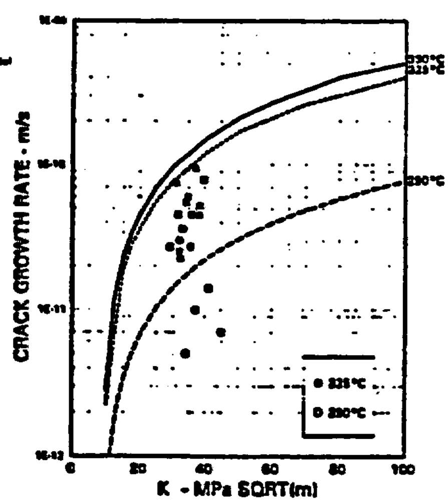
Derivation of MRP CGR Curve: examples of original results (2 labs)





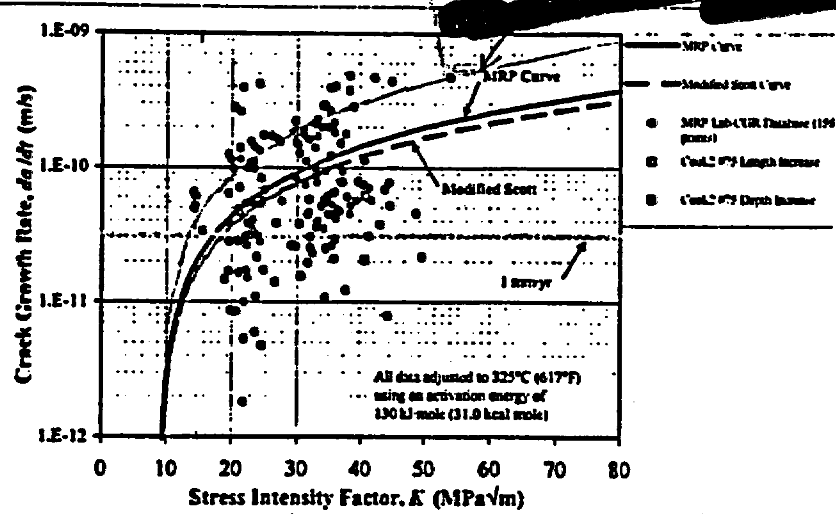
Derivation of MRP CGR Curve

Heat Rank	Material Supplier	Product Form	Number of Data Points	Log-Mean Power-Law Constant α at 325°C (617°F) SI Units	English Units
1	Creusot-Imphy	Forged Bar	21	6.01E-12	8.32E-03
2	B&WTP	Thick-wall Tube	4	5.16E-12	7.15E-03
3	French Supplier	CRDM Nozzle	9	5.08E-12	7.03E-03
4	Tecphy	Rolled Bar	7	4.96E-12	6.88E-03
5	B&WTP	Thick-wall Tube	4	4.71E-12	6.52E-03
6	VDM	Rolled Plate	2	3.92E-12	5.43E-03
7	Schneider-Creusot	Forged Bar	1	3.19E-12	4.42E-03
8	B&WTP	Thick-wall Tube	32	3.07E-12	4.25E-03
9	B&WTP	Thick-wall Tube	1	2.65E-12	3.68E-03
10	Arbed	CRDM Nozzle	3	2.01E-12	2.79E-03
11	Creusot-Imphy	Forged Plate	1	1.94E-12	2.69E-03
12	Schneider-Creusot	Forged Bar	1	1.62E-12	2.24E-03
13	Huntington	Thick-wall Tube	1	1.37E-12	1.90E-03
14	Huntington	Rolled Plate	14	1.29E-12	1.78E-03
15	*Not Listed*	Forged Bar	2	1.02E-12	1.41E-03
16	Sumitomo Metal	Thick-wall Tube	1	1.01E-12	1.40E-03
17	Sandvik	Thick-wall Tube	27	1.00E-12	1.39E-03
18	Standard Steel	Forged Bar	1	9.09E-13	1.26E-03
19	Huntington	Thick-wall Tube	12	7.21E-13	9.99E-04
20	*Not Listed*	Forged Bar	3	6.31E-13	8.74E-04
21	Tecphy	Rolled Bar	1	5.18E-13	7.18E-04
22	Huntington	Plate	1	4.97E-13	6.89E-04
23	Creusot-Ondaine	Forged Bar	4	4.44E-13	6.15E-04
24	Inco	Rolled Bar	1	2.51E-13	3.48E-04
25	Sandvik	Thick-wall Tube	2	2.18E-13	3.03E-04
26	Huntington	Thick-wall Tube	2	1.93E-13	2.67E-04
		Log-Mean for All Data Points	158	1.96E-12	2.72E-03
		Log-Mean of Heat Log-Means	26 Heats	1.34E-12	1.86E-03

Derivation of MRP CGR Curve

- Distribution describing CGR variability was then taken as the log-normal fit to the ordered median ranking of the α values for the 26 heats, using most likely estimator methodology

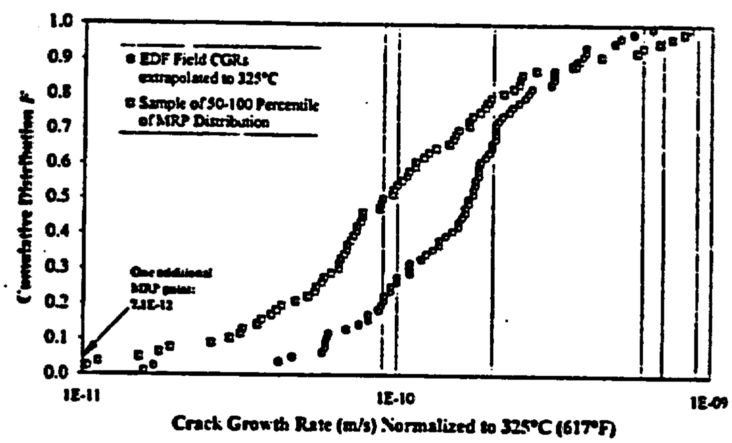
Derivation of MRP CGR Curve



Comparison of MRP database with available plant CGR data

- Large uncertainties exist in reported values of CGRs from operating plants due to:
- uncertainties in ultrasonic measurements of crack size at two or more different times
- uncertainties in the estimates of K, which depend on estimates of residual stress
- uncertainties in the actual operating temperatures of CRDM nozzles in different plants and in different countries
- Limited US data (from D.C. Cook nozzle #75) lie well below the MRP curve

Comparison of MRP database with available plant CGR data



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[redacted]

Comparison of MRP database with available plant CGR data

- Agreement with French field data is quite reasonable considering the uncertainties involved
- Supports the choice of the 75th percentile curve from the MRP distribution as representative of the rates expected for axial crack growth in CRDM nozzles
- In no case did the actual measured CGR in the through-wall direction exceed 4 mm/yr (0.16 in/yr) for data from French plants of fundamentally Westinghouse design
- This figure was adopted in France, independent of nominal upper head temperature, to justify continued operation with axial cracks up to 11 mm (0.43 inches) deep for a one-year fuel cycle

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[redacted]

[redacted]

CGR in OD Annulus Environment

- For evaluation of (hypothetical) OD cracking above the J-groove weld, the MRP recommends that CGR values from the curve be multiplied by 2x to allow for uncertainty in exact composition of the external chemical environment
- A subgroup of the Expert Panel have revisted 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 less than 1 liter/h or 0.004 gpm)
- Plant experience has shown this to be the usual case

CGR in OD Annulus Environment

- 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
- Limited data on SCC in concentrated boric acid solutions indicate that
  - Alloy 600 is very resistant to TGSCC (material design basis)
  - high levels of oxygen and chloride are necessary for intergranular cracking to occur at all
  - effects are then worse at intermediate temperatures, suggesting that mechanism is different from PWSCC

Outline of Presentation

- Overview of Probabilistic Fracture Mechanics Methodology for RPV Top Head Nozzle Cracking
- PFM Analyses in support of MRP 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

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EX5

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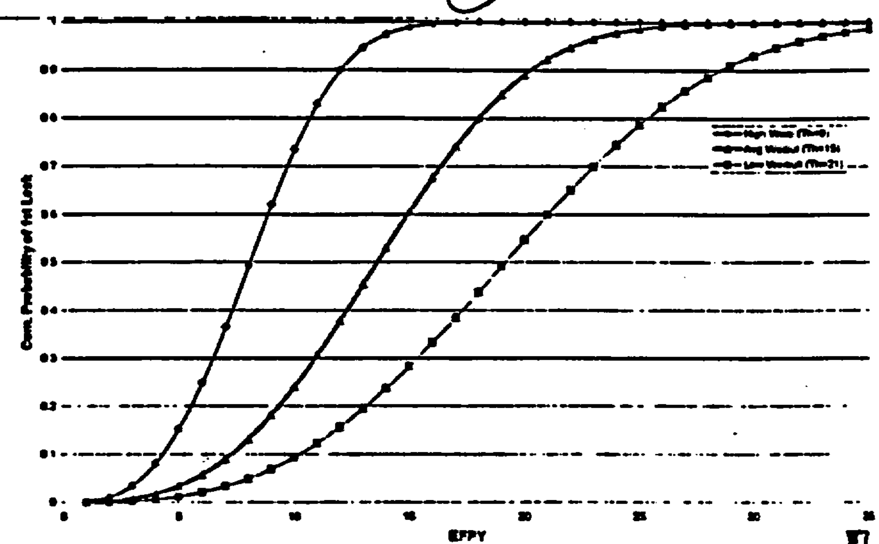
Weibull Distributions used in PFM
$\beta=3;\ \theta=15 \pm 6$



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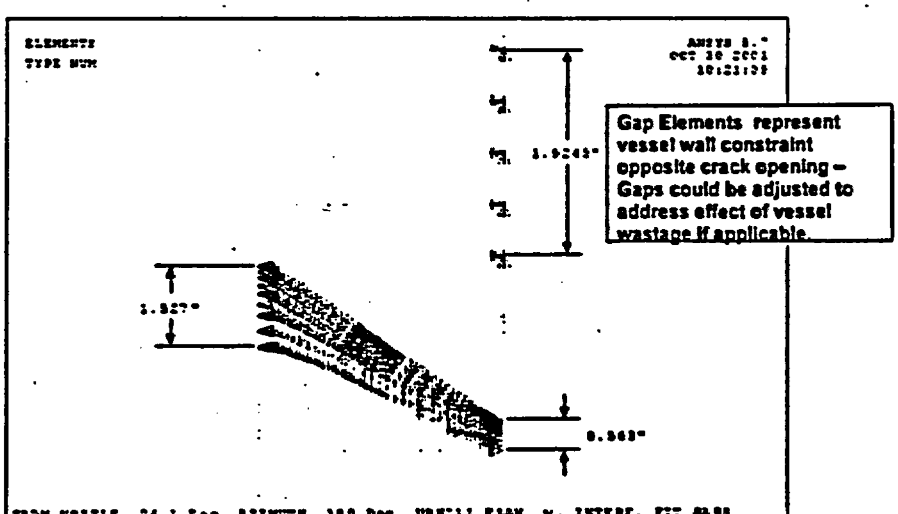
Fracture Mechanics Model
Through-Wall Crack



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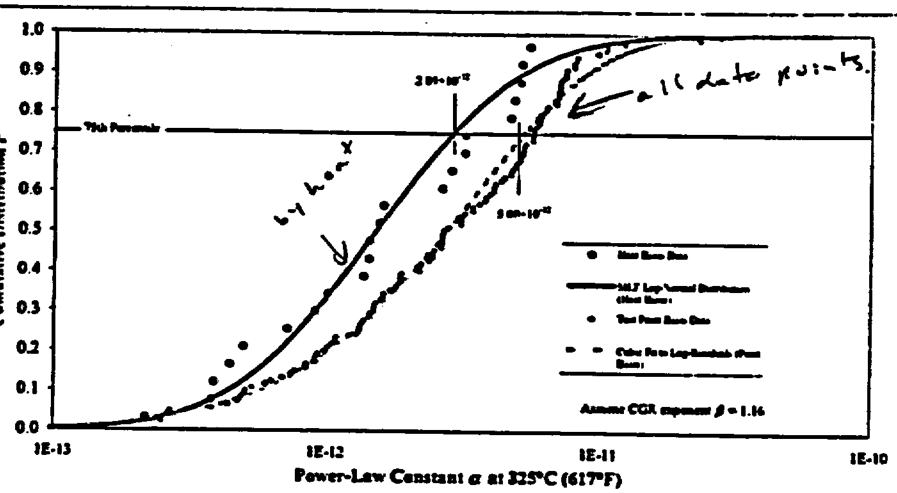
SCC Crack Growth Data for Nozzle Material in Reactor Environment



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EX5

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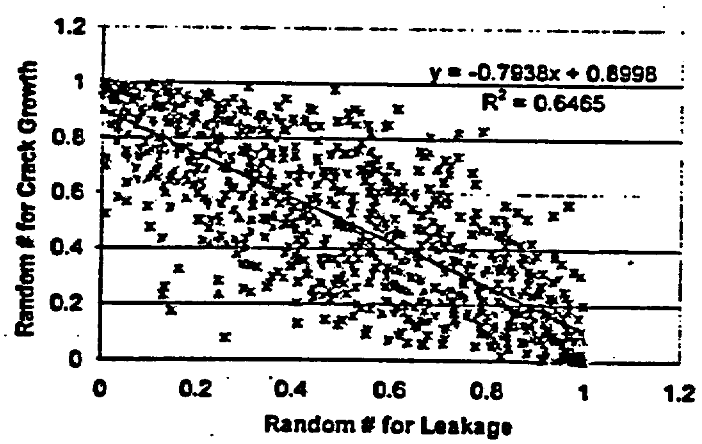
CGR Initiation vs. Growth Correlation

rho = -0.8



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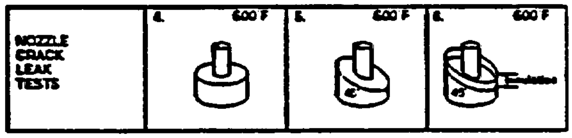
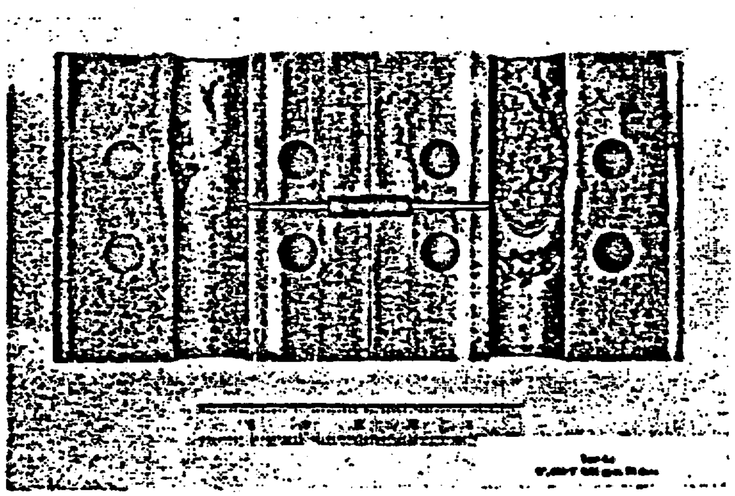
BAC Tests Simulating Nozzle Leakage
EPRI Annulus Test Matrix



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



0.01 gpm

Status of Inspection Plan

- Inspection Plan and technical bases were presented to NRC staff on May 22
  - Technical Bases documents will be provided to NRC in June 2002.
- Comments received in following areas
  - Plan should address inspections for both wastage and nozzle ejection issues
  - Timeframe for wastage development
  - Leakage past tight interferences
  - Policy issue of detecting degradation through leakage
  - Address replacement head

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.

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

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.

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 Plan

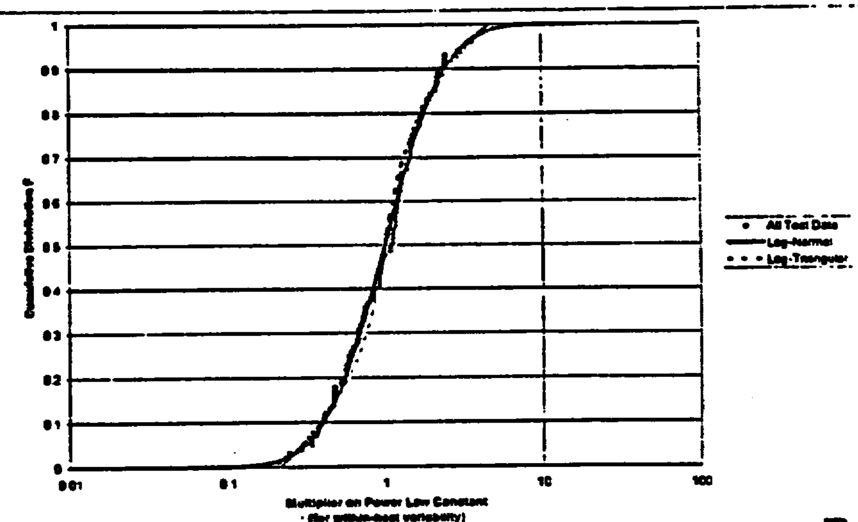
- **Plants with leak(s) or through wall cracks identified:**
  - *Discovery Inspection*
    - Perform a non-visual examination of the CRDM/CEDM penetrations and associated J-groove welds to characterize the crack or leak identified.
    - Indications are evaluated or repaired in accordance with flaw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

Multiplier on CGR Distribution for Within-Heat Variability



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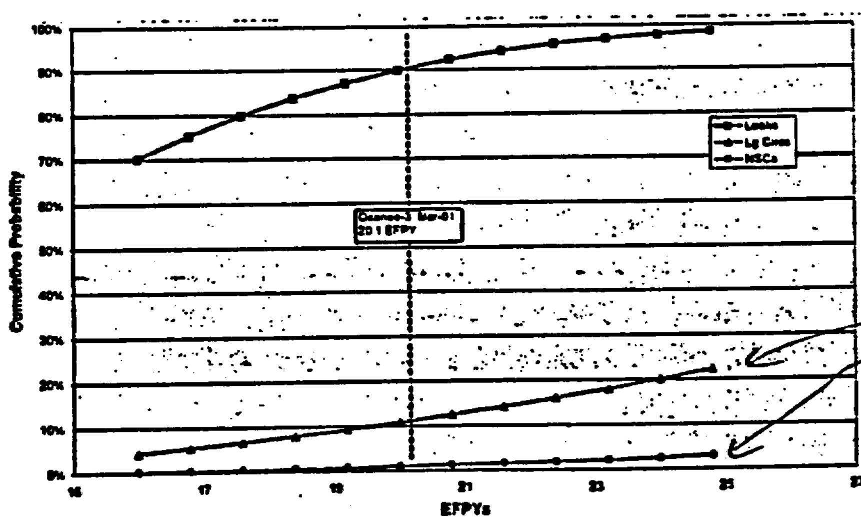
Benchmarking of PFM Results with respect to B&W Plants



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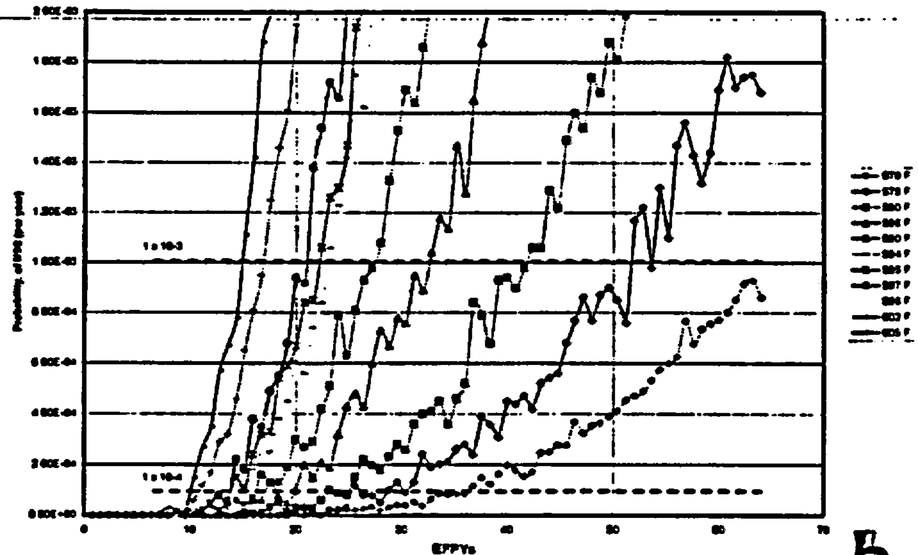
Inspection Plan PFM Runs: Probability of NSC (per year)



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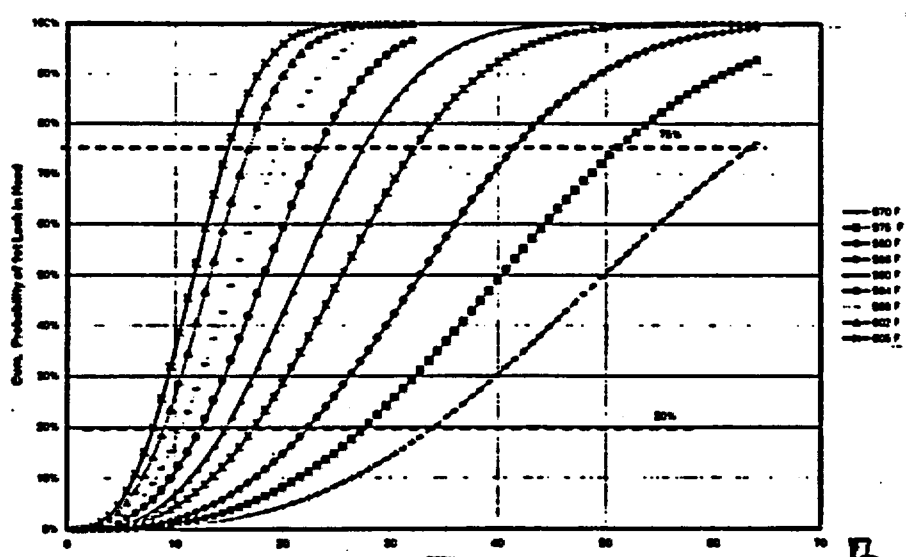
Inspection Plan PFM Runs: Cum. Probability of Leakage



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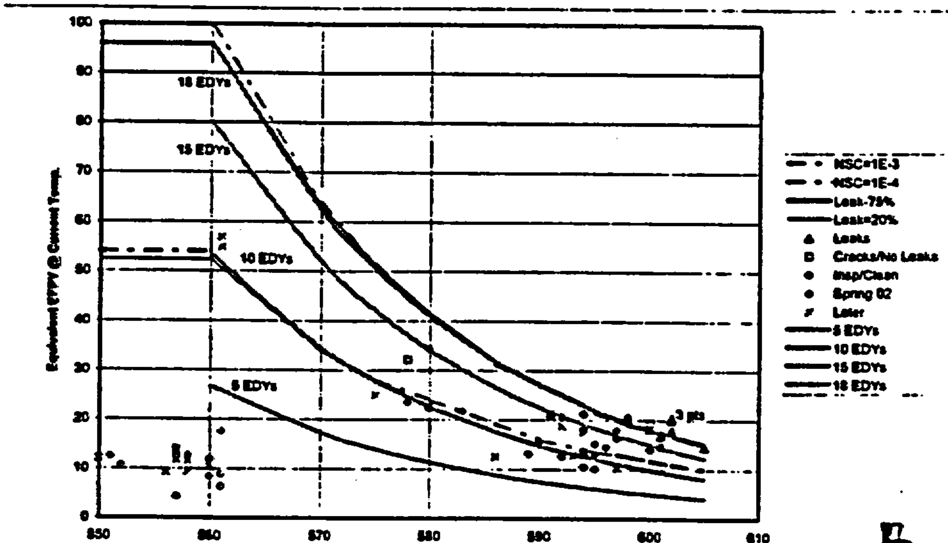
Correspondence of Susceptibility Categories to EDYs



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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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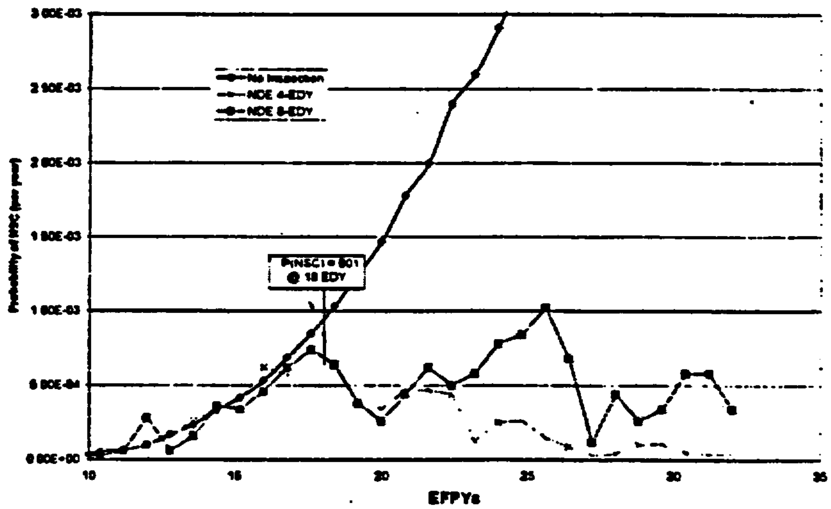
Inspection Plan Technical Basis: Effect of NDE Inspection



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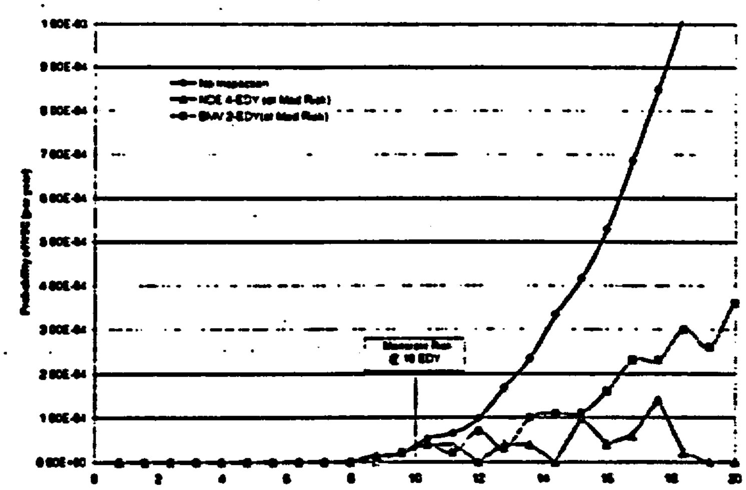
Effect of Inspections upon Entering Moderate Category



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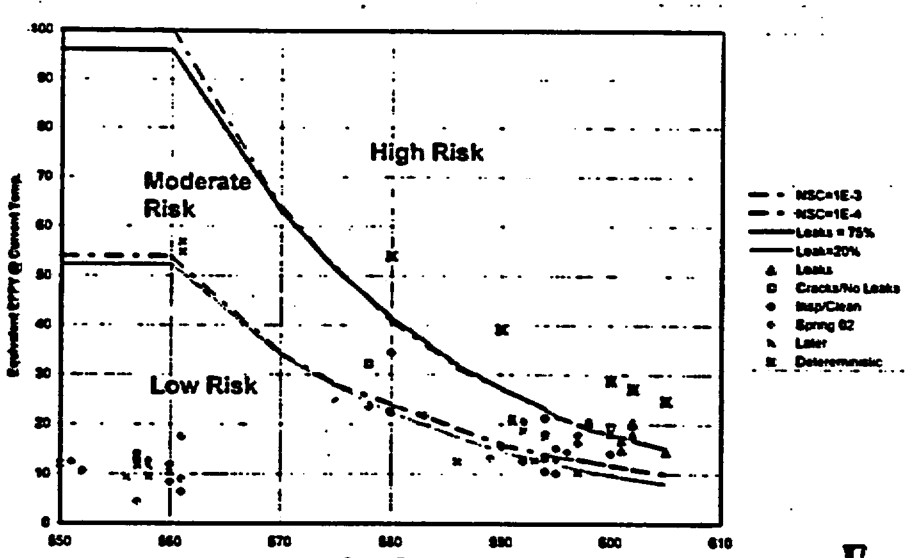
Deterministic Crack Growth Analysis Results

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



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
Matrix

PRELIMINARY

Possible Material Loss Mechanisms	Extent of Wastage: Initial Tight Annulus	Enlarged Annulus	Small Cavity	Large Cavity
Deaerated Boric Acid Corrosion Conc. Boric Acid Corrosion but DO_2 = 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

Ex5

[redacted]

Degradation Progression

Collateral Damage

Collateral Damage

- MRP Performed an Initial Qualitative Assessment of Collateral Damage from CRDM Nozzle Ejection
  - Indicated impact on Conditional Core Damage Probability should be insignificant
  - No impact on ECCS capabilities
  - Effect on shutdown reactivity capabilities minimal
    - Impact and jet loads should not affect significant number of rods
    - Loose parts also have only limited impact

Contents

- Purpose and Approach
- Material Loss Mechanisms
  - Corrosion mechanisms
  - Erosion mechanisms
  - Flow accelerated corrosion
- Degradation Progression
- Boric Acid Corrosion Tests Simulating Nozzle Leakage

NOTE: Additional information and results are provided in the May 22, 2002, presentation to the NRC staff on this subject, which is available on the NRC website area for reactor head degradation.

Purpose and Approach