U.S. Nuclear Regulatory Commission Meeting
with Nuclear Energy Institute, Material Reliability Program, and Operating Pressurized Water Reactor Licensees'

Thursday, November 8, 2001
1:00 p.m. - 5:00 p.m.
Commissioners' Hearing Room

Purpose: To discuss NRC staff's technical assessment for vessel head penetration nozzle cracking associated with NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles."

Success: NEI, MRP, and external stakeholders have a clear understanding of the staff's technical assessment and its' basis.

Introduction:	Jake Zimmerman	1:00 p.m. - 1:10 p.m.
Bulletin 2001-01 Overview:	Allen Hiser	1:10 p.m. - 1:30 p.m.
Discussion of Crack Growth Rate:	Dr. William Shack	1:30 p.m. - 2:00 p.m.
Discussion of Crack Initiation:	Dr. William Shack	2:00 p.m. - 2:30 p.m.
- BREAK -		2:30 p.m. - 2:45 p.m.
Discussion of Stress Analysis and Crack-Driving Force:	Dr. Gery Wilkowski	2:45 p.m. - 3:15 p.m.
Discussion of Critical Crack Size:	Dr. Gery Wilkowski	3:15 p.m. - 3:45 p.m.
Discussion of Deterministic Assessment:	Allen Hiser	3:45 p.m. - 4:15 p.m.
Discussion of Probabilistic Assessment:	Allen Hiser	4:15 p.m. - 4:30 p.m.
Discussion of Inspection Timing:	Allen Hiser	4:30 p.m. - 4:45 p.m.
Comments/Questions from External Stakeholders:		4:45 p.m. - 5:00 p.m.

The NRC staff will be available immediately following the meeting to speak with members of the public.

Attachment 1

OVERVIEW OF BULLETIN 2001-01:

"CIRCUMFERENTIAL CRACKING OF REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLES"

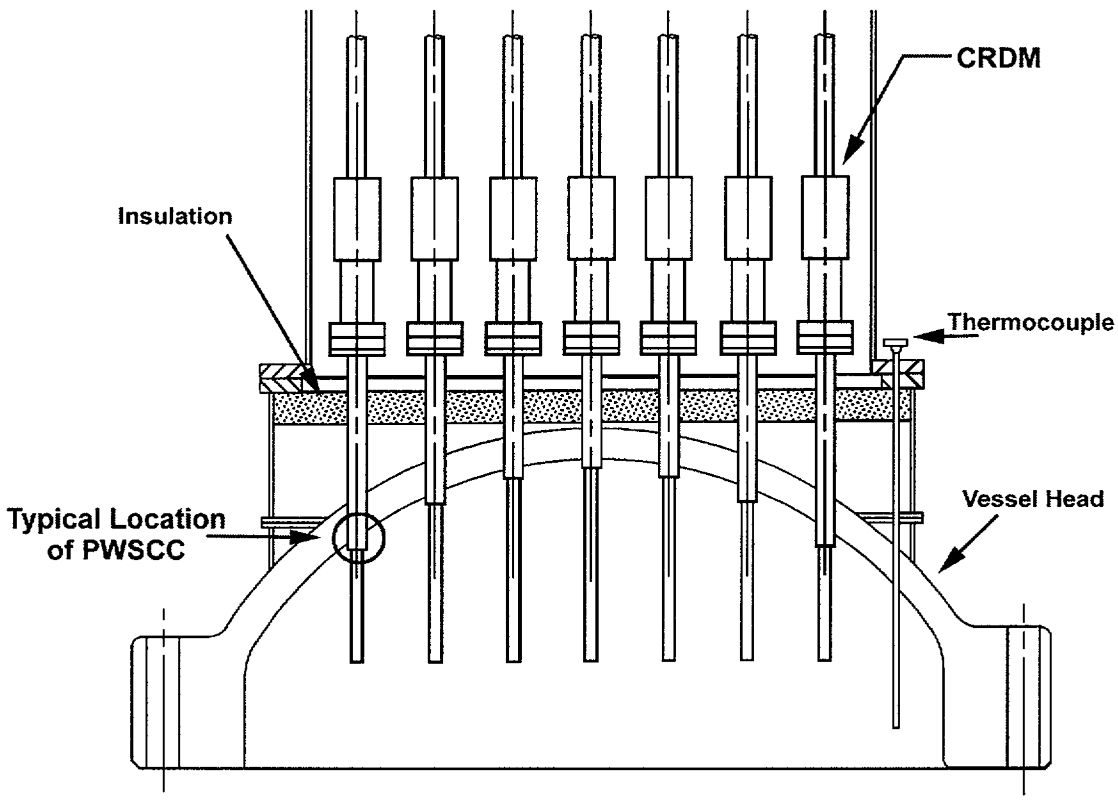
Allen Hiser

Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Division of Engineering

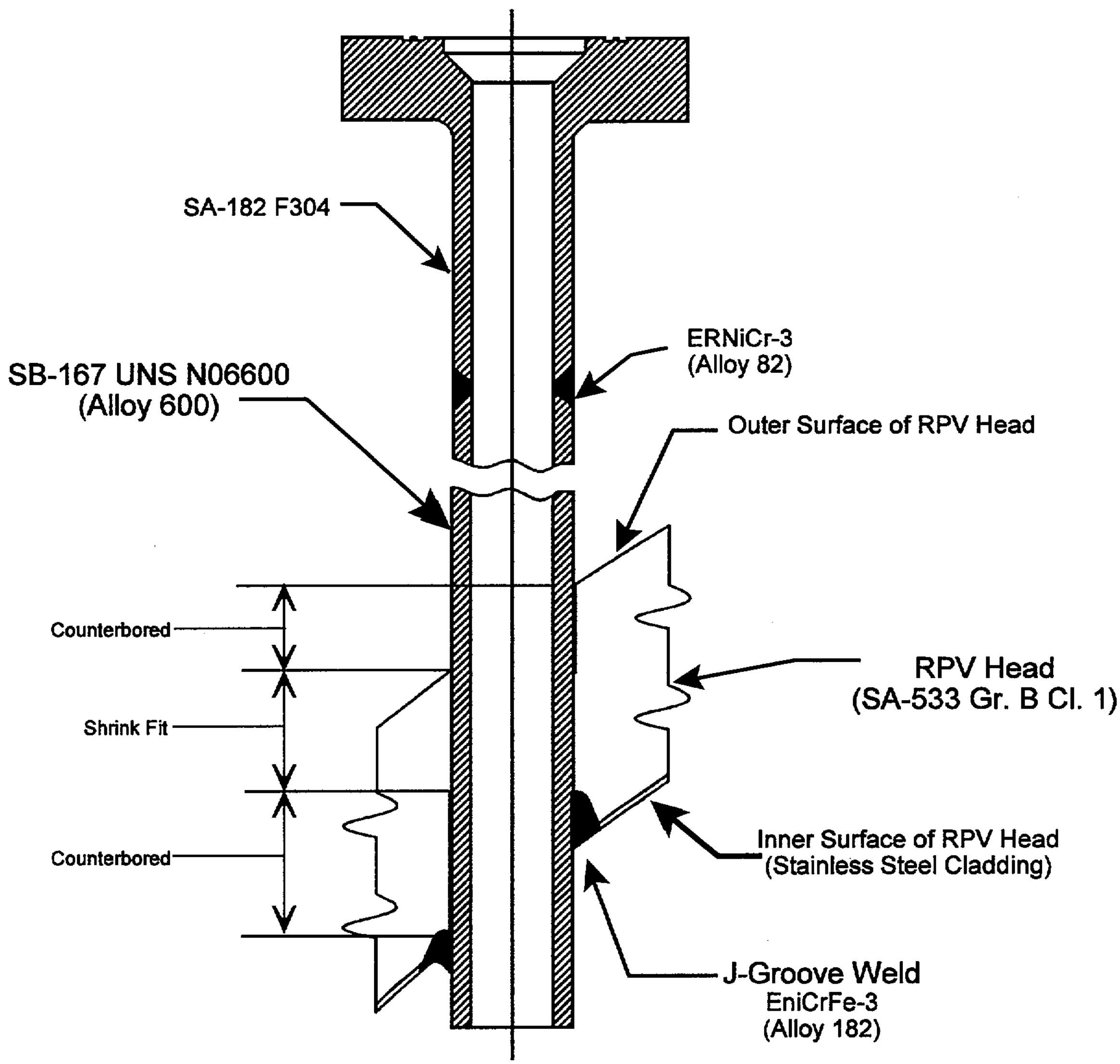
November 8, 2001

Attachment 2

Typical Reactor Vessel Head - Oconee Unit 1 (Babcock & Wilcox)



Schematic View of B&W Design CRDM Nozzle Area



OVERVIEW OF BULLETIN 2001-01

Bulletin was issued on August 3, 2001

Bulletin requested information on:

- All plants:
  - Plant-specific susceptibility ranking
  - VHP nozzles (number, type, ID and OD, materials of construction)
  - RPV head insulation type and configuration
  - Recent VHP nozzle and RPV head inspections
  - Above the head structures, missile shield, cabling, etc.

- Plants that have found cracking or leakage:
  - Extent of cracking and leakage
  - Inspections, repairs and other corrective actions
  - Plans and schedule for future inspections
  - How plans will meet regulatory requirements

- Other plants:
  - Plans and schedule for future inspections
  - How plans will meet regulatory requirements

QUALIFICATION OF EXAMINATION METHODS

- Verify compliance with regulatory requirements through QUALIFIED examinations
  - Graded approach depending on PWSCC likelihood
  - Examinations of 100% of all VHP nozzles
    - ➜ Based on statistics and no identified preferential cracking tendencies
    - ➜ All VHPs - similar materials, etc., only failure consequences vary

- Effective Visual Examination
  - Capable of detecting small amounts of boric acid deposits and discriminating deposits from VHP nozzle and other sources

- Plant-Specific Visual Examination Qualification
  - Plant-specific demonstration that VHP nozzle cracks will lead to deposits on the RPV head (interference fit measurements, etc.)
  - Must be capable of reliable detection and source identification of leakage (insulation, pre-existing deposits, other impediments)

- Volumetric Examination Qualification
  - Demonstrated capability to reliably detect cracking on the OD of VHP nozzles
  - Appropriate if Visual Examination cannot be Qualified

REVIEW OF BULLETIN 2001-01 RESPONSES

Bulletin places PWR plants into 4 groups based on relative susceptibility ranking:

- Plants that have found Cracking or Leakage - 5 plants
  - Suggests qualified volumetric examination by end of 2001
  - Staff accepted qualified visual examination at last outage

- Plants with High Susceptibility (within 5 EFPY of Oconee 3) - 7 plants
  - Suggests qualified visual examination by end of 2001
  - Staff accepted qualified visual examination at last outage

- Plants with Moderate Susceptibility (between 5 and 30 EFPY of Oconee 3) - 32 plants
  - Suggests effective visual examination at next RFO
  - Staff accepted effective visual examination at next RFO

- Plants with Low Susceptibility (more than 30 EFPY of Oconee 3) - 25 plants
  - Suggests no additional actions required
  - No requirement to provide plans or schedule

Staff has addressed clarifications to Bulletin responses, and numerous licensees have provided revised or supplemented Bulletin responses

PLANTS THAT HAVE PERFORMED "BARE METAL" VISUAL INSPECTIONS

Plants	Most Recent Inspection				
	Date	Method & Scope	Summary of Cracked or Leaking CRDM Nozzles		
			Total Number	Circumferential Nozzle Cracks	Number Repaired
Oconee 1	11/2000	Qualified Visual - 100%	1★	0	1
Oconee 3	02/2001	Qualified Visual - 100%	9	3★★	3
ANO-1	03/2001	Qualified Visual - 100%	1	0	1
Oconee 2	04/2001	Qualified Visual - 100%	5	1	5
Robinson	04/2001	Qualified Visual - 100%★★★	0	0	0
North Anna 1	09/2001	Qualified Visual - 100%★★★	8	0	0
Crystal River 3	10/2001	Effective Visual - 100%★★★★	1	1	1
TMI-1	10/2001	Qualified Visual - 100%	8★	0	6
Surry 1 (in progress)	10/2001	Qualified Visual - 100%★★★	10	TBD	5
North Anna 2 (in progress)	10/2001	Qualified Visual - 100%★★★	(3)	TBD	TBD

★ Thermocouple nozzles also cracked/leaking: Oconee 1 (5 out of 8), TMI 1 (8 out of 8)
★★ The size of 2 out of 3 circumferential flaws were identified from destructive examination.
★★★ Pending acceptability of licensee's supplemental response
★★★★ The highest ranked MODERATE susceptibility plant.
Moderate susceptibility plants that have completed effective visual examinations in Fall 2001 with no evidence of boric acid deposits: Beaver Valley 1, Farley 1, Kewaunee, and Turkey Point 3

OVERVIEW OF STAFF PRELIMINARY TECHNICAL ASSESSMENT

Summarizes available data and evaluations related to:

- Environment in CRDM annulus region
- Crack initiation
- Crack growth rate
- Stress analyses and crack-driving force
- Critical crack size

Deterministic assessment

Probabilistic assessment

Inspection timing

CRDM SUPPORT STUDIES

W. J. Shack

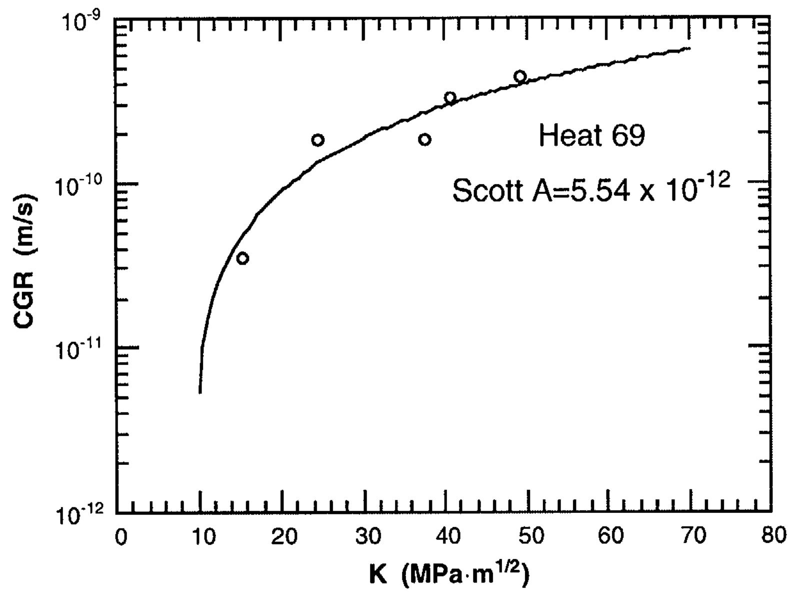
Argonne National Laboratory

November 8, 2001

- Technical Issues addressed by ANL
  - Distribution of crack growth rates in Alloy 600 nozzle materials
  - Impact of potential crevice environments on expected crack growth rates
  - Probabilistic models for initiation of cracks in CRDM nozzles
  - Conditional probability of failure for nozzles
  - Integrated models to estimate probability of failure including initiation and growth

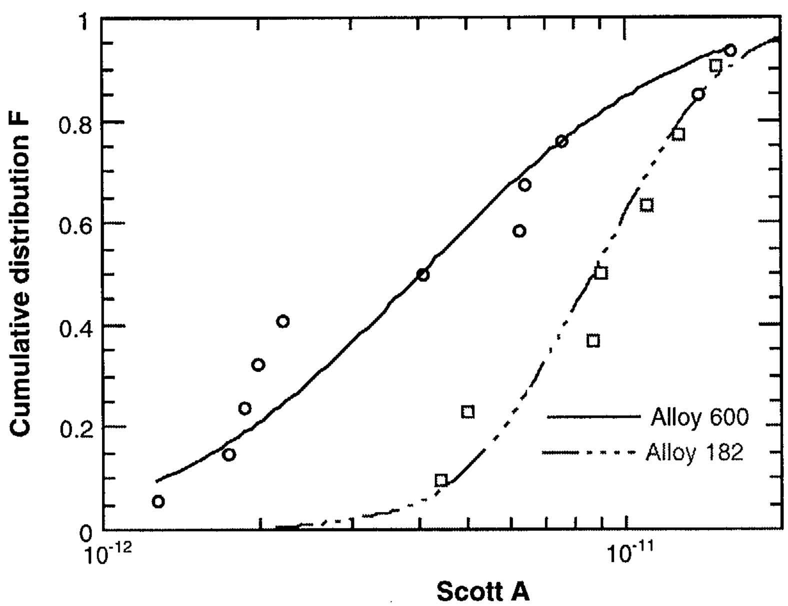
Crack Growth Rates in Alloy 600

- Scott's results on SG tubes suggest strong heat-to-heat variations in CGR are likely. Measurements on nozzle materials support this expectation.
- Critical issue is to estimate range of CGRs that will be encountered in the population of materials in service, not the range of CGRs in the limited number of heats being tested
  - "Weighting" the data by heat gives a better picture of CGRs of population than counting all data points as equal (or even weighting data by quality)
  - Better to determine dependence on basic parameters like K, T, by examining individual tests and test series with better controlled variables than statistical analysis of too large a data bin

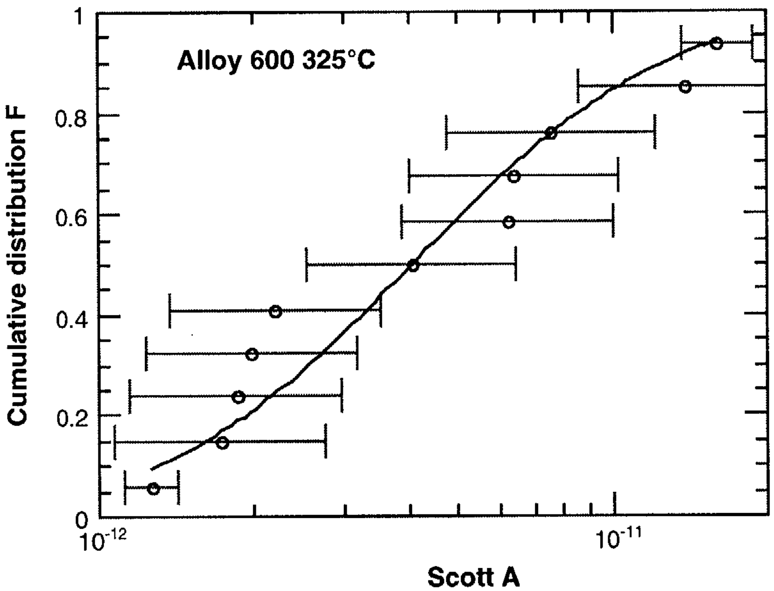


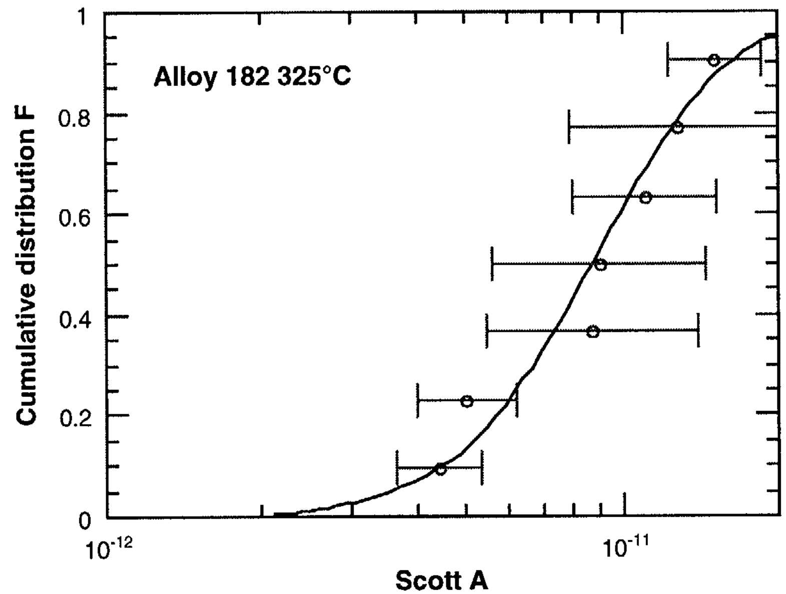
Crack growth rate as a function of stress intensity factor K for Alloy 600 Heat 69. For this heat Scott A = 5.54 x 10^{-12}. A is chosen as the parameter to characterize a heat.

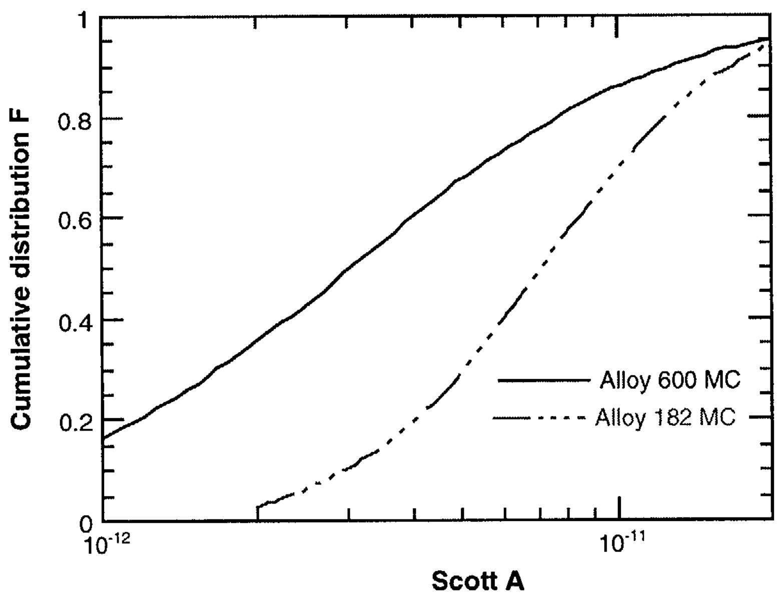
$$\frac{da}{dt} = A(K-9)^{1.16}$$



Cumulative distributions of A at 325°C for Alloys 600 and 182



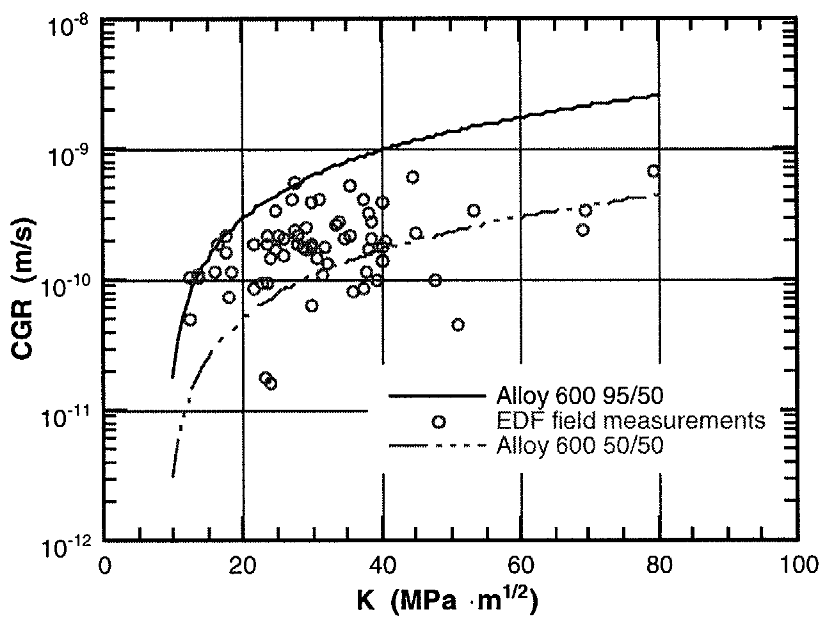


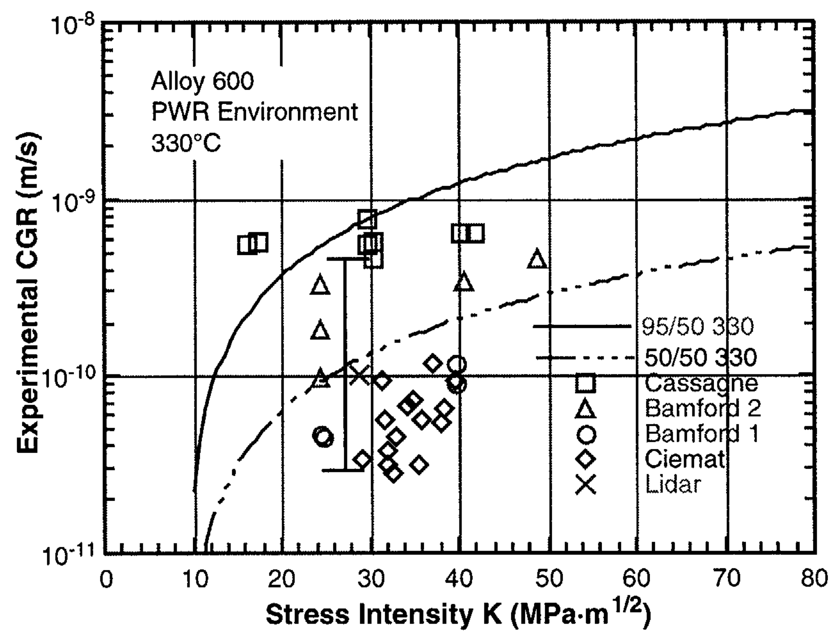


Monte Carlo analysis performed to assess effect of uncertainties. Changes in distribution of A are relatively small especially in region of greatest interest.

Scott A parameter for Alloy 600 nozzle materials at 325°C

Confidence Level	Population Percentage			
	95	90	67	50
50	1.8×10^{-11}	1.2×10^{-11}	5.1×10^{-12}	3.1×10^{-12}
67	2.3×10^{-11}	1.5×10^{-11}	5.8×10^{-12}	3.5×10^{-12}
90	4.2×10^{-11}	2.4×10^{-11}	7.5×10^{-12}	4.4×10^{-12}
95	5.6×10^{-11}	3.1×10^{-11}	8.4×10^{-12}	4.8×10^{-12}



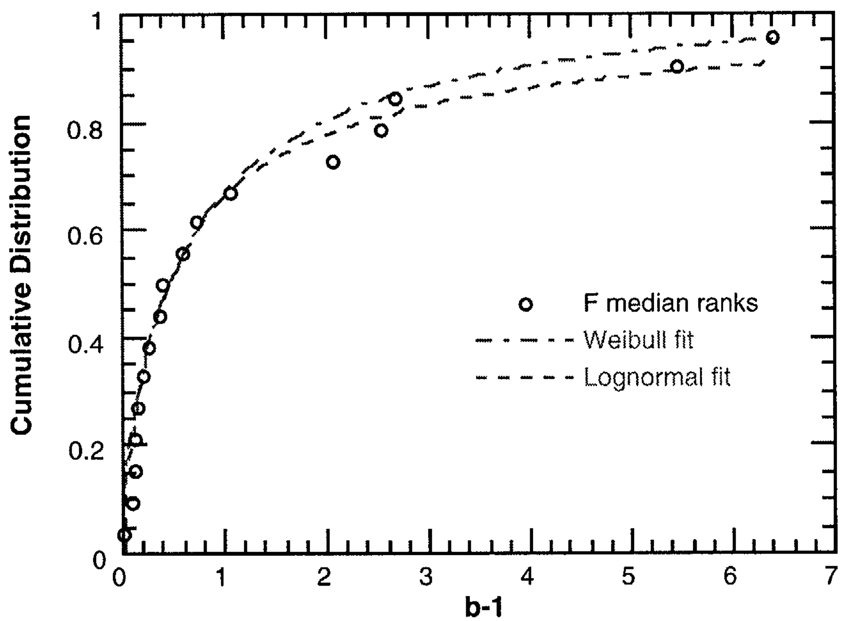


Crevice chemistries

- Nozzle and head form a tight crevice. FEA analysis suggests 0–4 mil gaps at pressure. Deposits suggest leakage even for a nozzle with a 165° crack was less than 1 gallon over the cycle. Depending on the tightness of the crack, the tightness of the interference fit, and blockage by deposits or corrosion products environment can be steam, close to primary water, or concentrated solutions
  - pH changes are limited by precipitation of insoluble species. Industry calculations with MULTEQ show that depending on location of boiling pH can become alkaline (≈8.6) or acid (≈4.6).
  - Because MULTEQ models don't deal with reactions with iron and nickel components these calculations probably overestimate pH shifts
  - Samples from actual crevices are needed to substantiate these preliminary conclusions.
- Predicted shifts can accelerate CGRs by a factor of ≈2. This can affect initiation and throughwall growth of cracks. Once a significant throughwall crack has formed, crevice has good communication with bulk and water chemistry is even more likely to be close to primary water.

Probabilistic initiation models

- Mechanistic initiation models require more knowledge of local stresses and material microstructure. Probabilistic models use inspection data



$$p(t) = \frac{b}{\theta}\left(\frac{x}{\theta}\right)^{b} \exp\left[-\left(\frac{x}{\theta}\right)^{b}\right]$$

$$F(t) = 1 - \exp\left[-\left(\frac{x}{\theta}\right)^{b}\right]$$

Weibull probability density and cumulative probability functions. Distribution of the Weibull slope b for cracking of steam generator tubes.

- Estimates of Weibull parameters for plants that have been inspected and an associated distribution of values

Plant	Leaks	EFPY at 600°F	EFPY at 1st initiation b=1.5	b=3	θ
95th	0.4	20	28	23	608.5
Median	2.0	20	12	13	209.8
5th	9.3	20	10	8	72.3

- Choice of b has impact on when 1st initiation occurs and the credit that can be expected for shorter operating times

	Number of leaks expected		
Plant	95th	Median	5th
		b=1.5	
5	0.05	0.25	1.24
10	0.15	0.71	3.46
		b=3	
5	0.01	0.03	0.17
10	0.06	0.27	1.33

NRC-FUNDED
CRDM STRESS ANALYSIS, CRACK-DRIVING FORCE, AND LEAK-RATE ANALYSES

by

Engineering Mechanics Corporation of Columbus*

G. Wilkowski, D. Rudland, and Z. Feng

and

ORNL

R. Bass and P. Williams

Presented by

Gery Wilkowski

11/8/01 – NRC/Industry meeting

Emc²

Involvement to Date

(1) Expert panel assistance on CRDMs started in late June. Work involved reviewing industry documents and assisting NRC staff with technical information.

Emc² technical efforts involved:

- Stress analysis aspects – weld residual stress
- Crack-driving force and crack-opening displacement
- Leak-rate analyses
- Critical crack length calculations

ORNL technical efforts involved:

- Stress analysis aspects
- Crack-driving force and crack-opening displacement

(2) Technical assistance for plant specific assessments

(3) Future CRDM efforts

Emc² 2

Initial Stress Analysis Efforts
Residual Stresses

Some aspects of the review of work to date:

- The residual stress analysis for this problem is complicated by highly 3D aspect of the geometry. Industry efforts to date are good considering the time frame of efforts.

- Some suggested improvements are;
  - Weld simulation created a whole ring of elements (one pass) instantaneously. (Traveling arc has heat sink in all directions not just normal to weld path.)
  - Using elastic-perfectly plastic stress-strain curve will give lower residual stresses than one with strain-hardening.
    - Distribution of stresses also affected as well as peak values.

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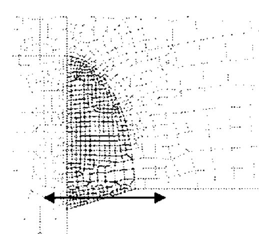
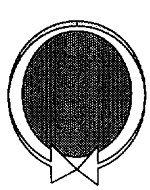
Initial Stress Analysis Efforts
Residual Stresses

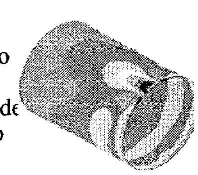
Some suggested improvements, continued;

- Effect of weld sequencing is not explored. Sequencing could be;
  - From the tube to the head in the radial direction (forces stresses in the weld to be higher either closer to the tube or the head), which could also affect OD axial cracking.

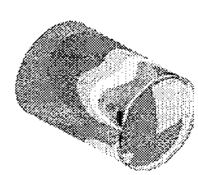




  - Welding around the circumference either continuously or from uphill to downhill side in two half-circumferential steps on opposite side of the tube. (Higher stresses at stop and start positions.)



Single stop-start



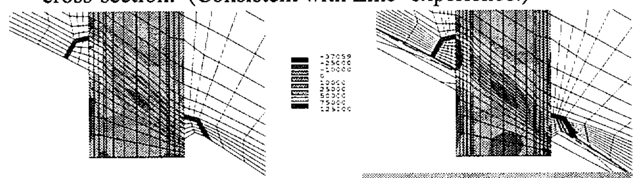
Separate stop-start positions

4

Initial Stress Analysis Efforts
Residual Stresses

- Some suggested improvements, continued;
  - Mesh refinement in the weld bead could perhaps be finer
    - Informal survey of international weld stress analysts showed they typically used a minimum of 12 to 20 element in a *single weld bead* cross-section. (Consistent with Emc² experience.)

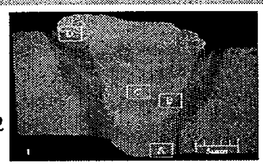
Industry analyses

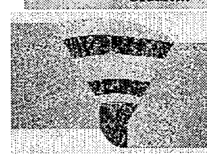


Oconee Nozzle With Uniform Yield Strength

Oconee Nozzle With Yield Strength Gradient

Example of ultra-fine mesh – Emc²





Total of 3,000 elements in weld

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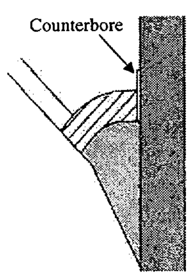
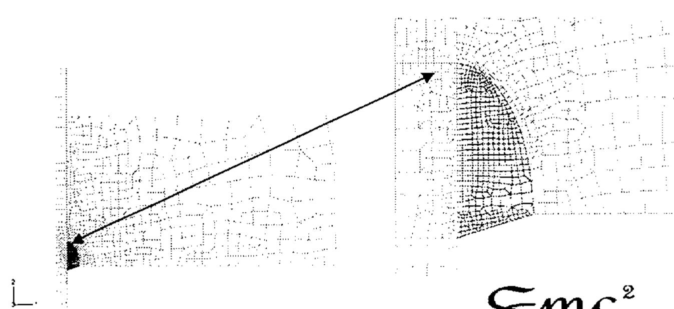
Recent Stress Analysis Efforts
Thermal Expansion Stresses

Thermal expansion and RPV hole expansion from pressure loads increase the annular clearance

- Good from leakage viewpoint, but
- Contributes to crack-driving force at the root of weld





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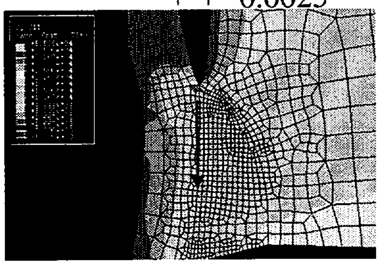
Recent Emc^2 Stress Analysis Efforts
Thermal Expansion Stresses

Stresses from thermal expansion and pressure without residual stresses – simple axisymmetric model.

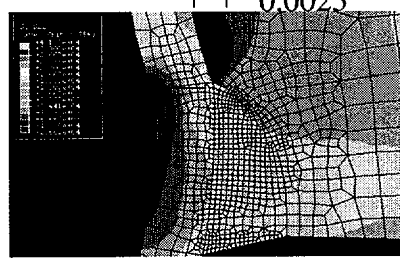
0.0025”



S11

K_1 = 18 ksi-in$^{0.5}$

0.0025”



S22

K_2 = 12 ksi-in$^{0.5}$

Emc^2

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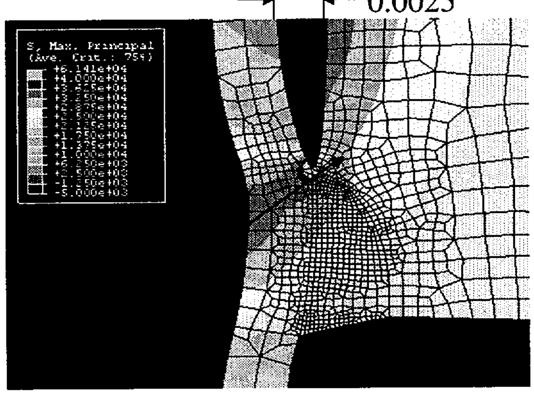
Recent Emc^2 Stress Analysis Efforts
Thermal Expansion Stresses

Stresses from thermal expansion and pressure without residual stresses

0.0025”



Principal stress direction at angle through the thickness?

$K_{45°}$ = 12 ksi-in$^{0.5}$

Emc^2

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Initial Stress Analysis Efforts
Cyclic Thermal Stresses

From analysis at Ringhals in early 1990's, there was concern of cyclic temperatures from water going up and down the nozzle region.

It was expected that the thermal stresses may not be large enough to cause fatigue by themselves, but "may be a contributor to cracking in cold heads".

- Past gas pipeline work on SCC showed that small cyclic stresses (R=0.95) can increase the crack growth rate.

Emc²

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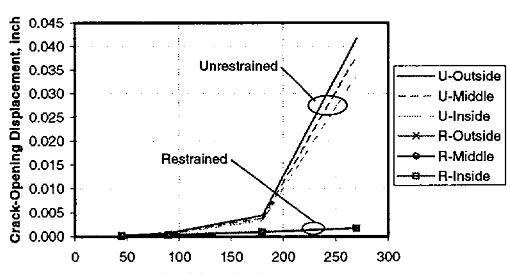
Initial Crack-Driving Force Analyses

Efforts conduced both at Emc² and ORNL to examine K and COD. COD used for leak-rate analyses.

- Emc² analysis was elastic conditions with pressure only, and examined the effect of restraining the pressure-induced bending from the presence of a circumferential through-wall crack. No pressure on crack faces.
- K and COD much lower in restrained condition that simulates CRDM behavior.



Emc²

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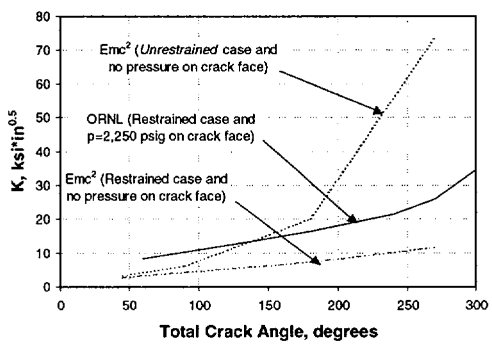
Initial Crack-Driving Force Analyses

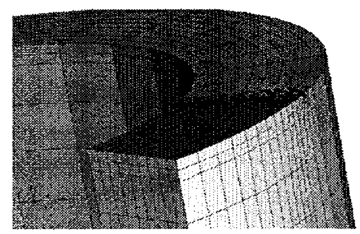
Efforts conduced both at Emc² and ORNL to examine K and COD, continued

- ORNL effort used gap elements to restrain bending and was elastic-plastic with pressure loading only, including full pressure on crack faces.
- Similarly showed lower COD and K values with restrained bending – particularly for longer cracks.



Refined Mesh B
8015 elements
31,629 nodes

ORNL

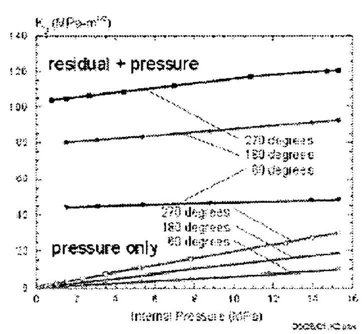


Emc²

Initial Crack-Driving Force Analyses

Efforts conduced both at Emc² and ORNL to examine K and COD, continued

- ORNL also examined effect of applying a residual stress equal to yield in a simplistic manner, i.e., displacement-controlled axial tension stress on tube

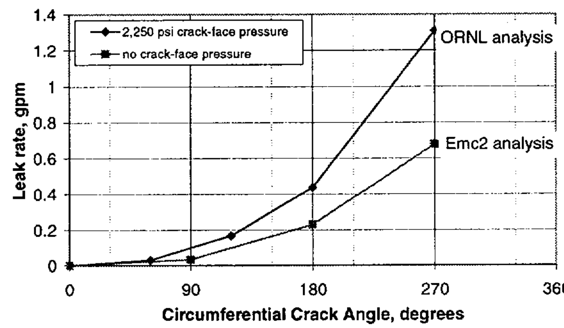


Emc²

Initial Leak-Rate Analyses

Efforts at Emc[2] using COD from Emc[2] and ORNL, continued

- First calculated a leak-rate for a circumferential through-wall crack
  - Used statistical mean crack morphology parameters (roughness, number of turns) for an IGSCC
  - Assumes no back pressure at exit plane
  - Determined leak-rate (0.22 to 0.44 gpm) as well as pressure and temperature of water exiting the crack plane for 180-degree crack. (127 psig and 347 F)



Emc[2]

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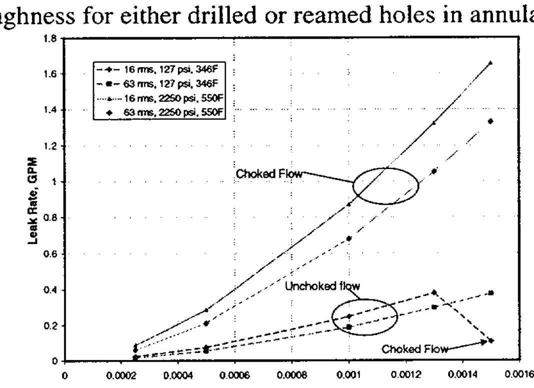
Initial Leak-Rate Analyses, continued

- **Calculated the leak-rate through the annular region (0.1 to 0.3 gpm)**
  - Assumed 180-degree crack exit plane water is entrance water in annular plane
  - Assuming a radial gap of 1.2 mils on diameter (close to industry stated value)
  - Used roughness for either drilled or reamed holes in annular area.



Emc[2]

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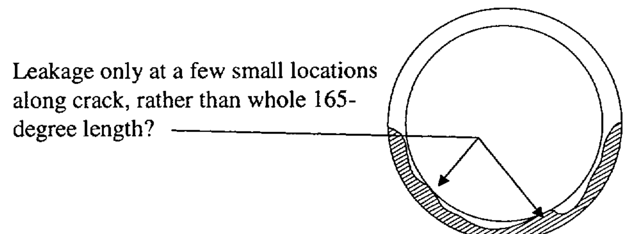
Initial Leak-Rate Analyses, continued

- Determined that for this crack size the annular leakage was limiting
- The calculated leakage rate, however, was about 24,000 time greater than the Oconee 165-degree crack
- Could be explained if the 165-degree crack all the way through the thickness or only over a short length?



- Residual stresses causing crack faces to rotate, and hence pinch off flow?
- Plugging occurring at low leak rates?

Emc²

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Initial Review of Industry Work

- Industry efforts underway are impressive and involve a significant undertaking considering the time frame involved.

- Some suggested improvements if more time was available
  - Redistribution of residual stresses may not be properly handled by putting load-controlled stresses on the crack faces from the uncracked model.
    - Need to map 3D stress and strain field from weld model onto the fracture model to properly determine the redistribution of stresses with crack growth.

Emc²

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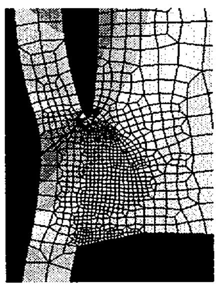
Review of Industry Work

- Some suggested improvements if more time was available, continued
  - It appears that longitudinal (axial stresses) in tube were applied to crack face.
    - Crack was in helical direction, so stresses normal to that direction should be used.
    - Examination of weld model may show that crack growth may not be in a plane normal to the thickness, i.e., the principal stresses may be different than the axial direction or normal to the helical plane of the crack.



$\mathcal{E}mc^2$

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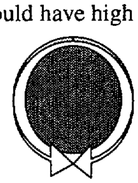
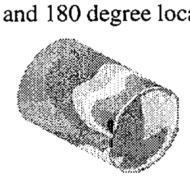
Review of Industry Work

- Some suggested improvements if more time was available, continued
  - Weld sequencing effects on crack-driving force not examined
    - Could have high stress spots at 0 and 180 degree locations





  - Need to examine K from toe of weld as well as K from through-wall crack.
    - Will there be multiple initiation sites?
    - What is the crack growth rate in the radial versus circumferential directions?
    - Could a complex crack form (long surface crack with through-wall crack of shorter length)?

$\mathcal{E}mc^2$

18

NRC-FUNDED
CRDM CRITICAL CRACK SIZE ANALYSES

by

Engineering Mechanics Corporation of Columbus*

G. Wilkowski, D. Rudland, and Z. Feng

Presented by

Gery Wilkowski

11/8/01 – NRC/Industry meeting

Emc²

Involvement to Date

(1) Expert panel assistance on CRDMs started in late June. Work involved reviewing industry documents and assisting NRC staff with technical information.

Emc² technical efforts involved:

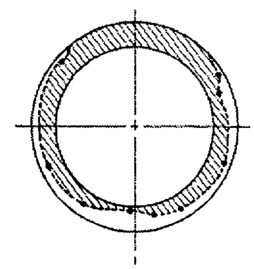
- Critical crack length calculations
- Stress analysis aspects – weld residual stress
- Crack-driving force and crack-opening displacement
- Leak-rate analyses

Emc² 2

Critical Crack Analysis

Limit-load analyses examined to;

- Determine proper limit-load boundary conditions,
- Determine flow-stress definition?
- Determine if toughness of Inconel 600 is sufficient for limit-load to be used?
- Conduct analyses for CRDMs with ideal through-wall crack, surface crack, and complex crack.

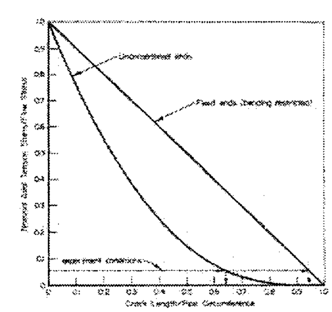


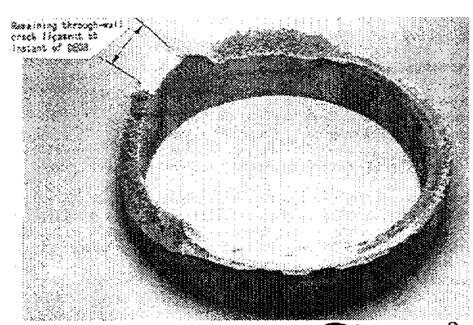
Duane-Arnold Crack Found in Service

3

Determine Proper Limit-Load Conditions

- Solutions exist for axial tension on a cylinder with a circumferential crack
  - End-capped solution most common, but allows for free rotation of cylinder ends due to pressure-induced bending from presence of crack.
  - CRDM tube restrained from bending by RPV head





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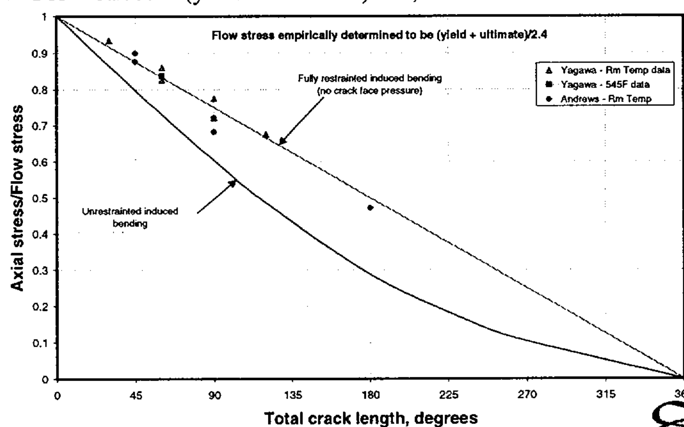
Determine Flow-Stress Definition

- Axial tension tests with restrained-bending on circumferential through-wall-cracked 4" diameter stainless steel pipe conducted in past.
  - Flow stress = (yield + ultimate)/2.4, which is less than average



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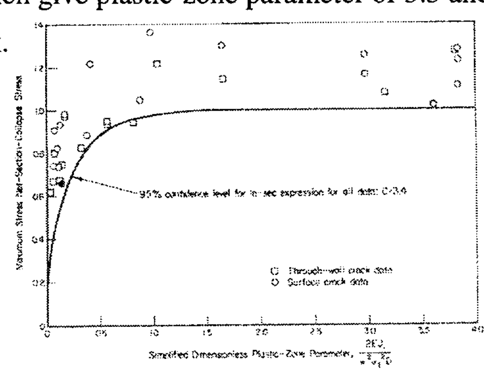
Determine if Inconel 600 Has Enough Toughness to Use Limit-Load Solution

- Dimensionless Plastic-Zone Screening criterion developed to determine toughness requirement for using limit-load analyses.
- From PIFRAC database Inconel 600 J_{Ic} = 9,310 in-lb/in^2 (1.63 MJ/m^2), which give plastic-zone parameter of 3.5 and limit-load should work.



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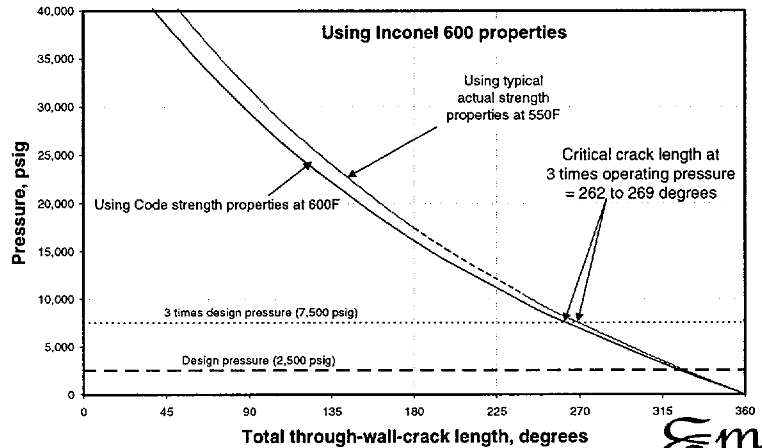
Limit-Load Analysis with Crack-Face Pressure

Longer cracks are more affected by crack-face pressure – idealized through-wall crack example.



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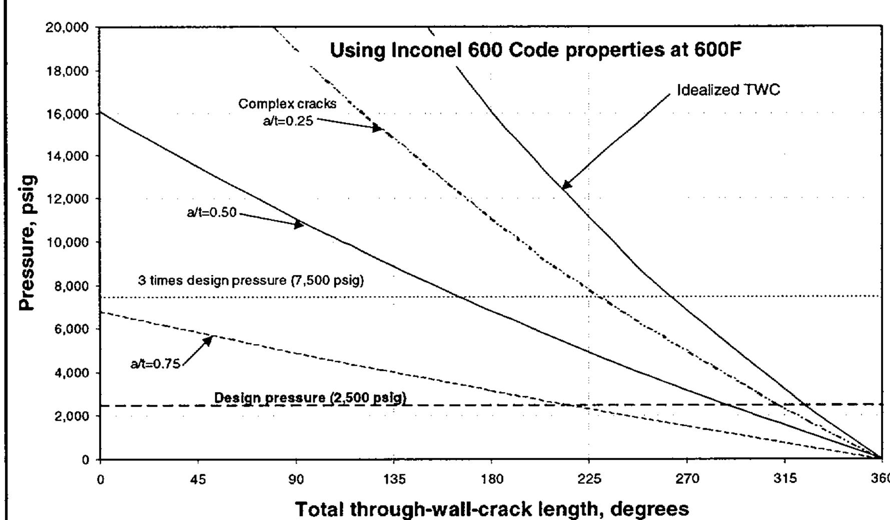
CRDM Critical Crack Length Calculations



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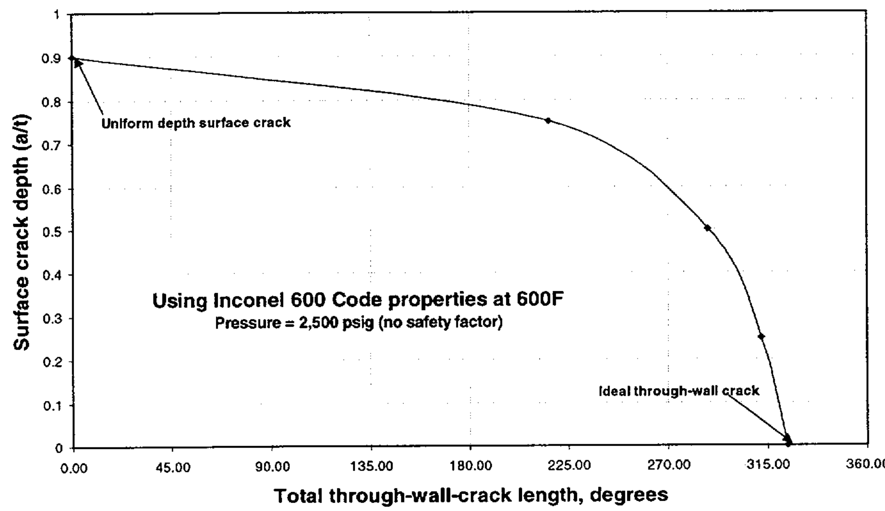
CRDM Critical Crack Length Calculations



9

Critical Crack Length Analyses

Summary

- Restrained-bending limit-load solution is more appropriate for CRDMs.
- Flow stress = (Y+U)/2.4 from pipe tests with similar loading (lower than typical average of yield and ultimate definition).
- Pressure on crack-face important for longer cracks.
- Toughness of Inconel 600 high enough to use limit-load solution.
- Ideal TWC critical length at 3*design pressure = 262 to 269-degrees (slightly less than industry calculated value), but very fracture resistant material.
- Critical surface crack/complex crack/ideal through-wall crack lengths at design pressure given.
    - Critical 360-degree surface crack of constant depth would be 90-percent of thickness. Difficult to get such a crack geometry without getting some through-wall component.

10

DETERMINISTIC AND PROBABILISTIC ASSESSMENTS

Allen Hiser

Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Division of Engineering

November 8, 2001

STAFF CONCLUSIONS

Annulus Environment

- Not expected to be highly aggressive - normal PWR reactor coolant
- Annulus deposits from leaking nozzles should be obtained and analyzed by industry to provide confirmation of the assumed annulus environment

Crack Initiation

- The operating experience of leaking nozzles appears to be well modeled by the Weibull analysis with b = 1.5
- New findings data will continue to be assessed

Crack Growth Rate

- Crack growth rate data for PWSCC is a reasonable approximation for OD VHP nozzle cracking
- Analysis of data provided in Table 3 is appropriate for use at 325°C (617°F)
- The Arrhenius relation can be used for crack growth at other temperatures

STAFF CONCLUSIONS (cont.)

Stress Analysis and Crack-Driving Force

- A single estimate for K as a function of circumferential crack length was provided (with a value of 66 MPa$\sqrt{m}$ (60 ksi$\sqrt{in.}$) due to residual stresses for a crack angle of 90°)

Critical Crack Size

- Critical size with a safety margin of three on pressure is 270°
- Critical size for nozzle failure and possible ejection is 324°

DETERMINISTIC ASSESSMENT

Base Case - Assumptions

- Critical Flaw Size
  - 270° with a safety margin of three on pressure
  - 324° for nozzle failure and possible ejection

- Crack Growth Rate
  - 95/50 statistical bound
  - 318°C (605°F)
  - A for Scott model is 1.303×10^{-11}

- Initial Flaw Size
  - Unknown - basis for issuance of the Bulletin
  - Used as a parameter

Uncertainties and Sensitivity Studies

- Different statistical bounds to crack growth rate
- Effects of temperature on crack growth rate
- Initial flaw size as a parameter

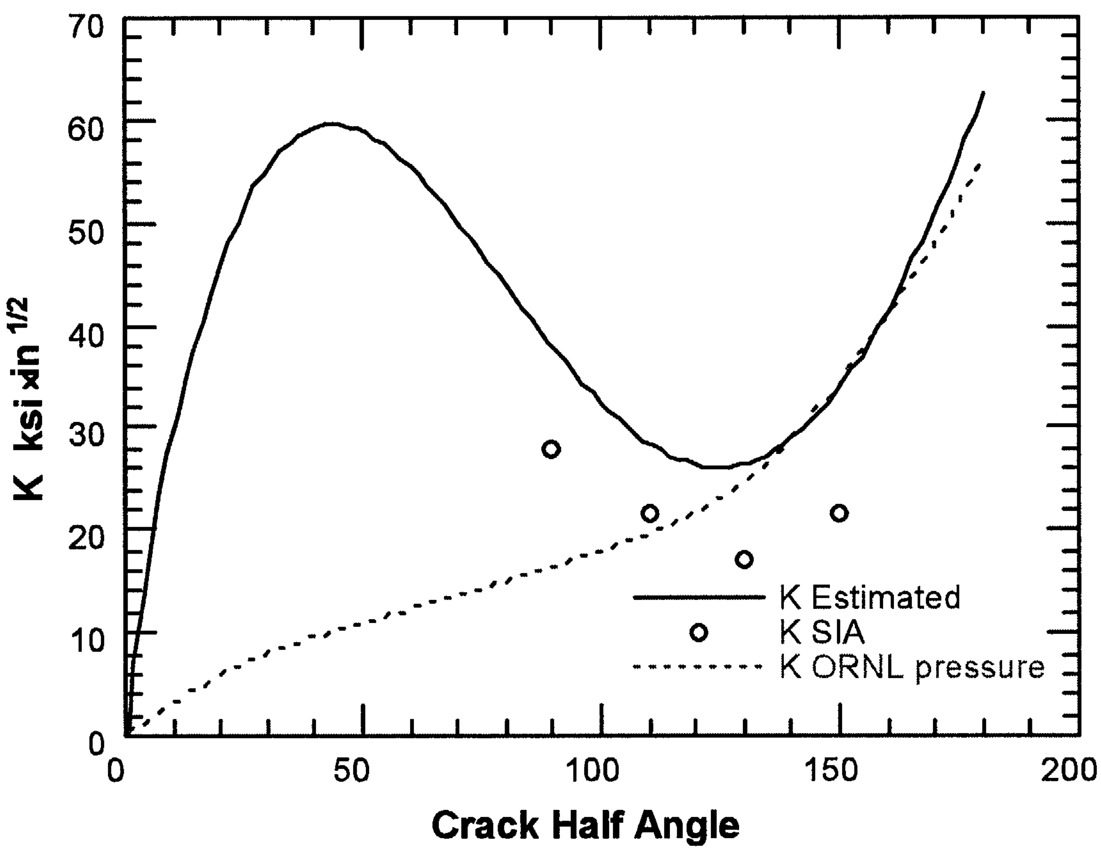


Figure 15 Estimated stress intensity factor K for a CRDM nozzle based on SIA and ORNL results.

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

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

* Crack dimensions estimated from UT data.

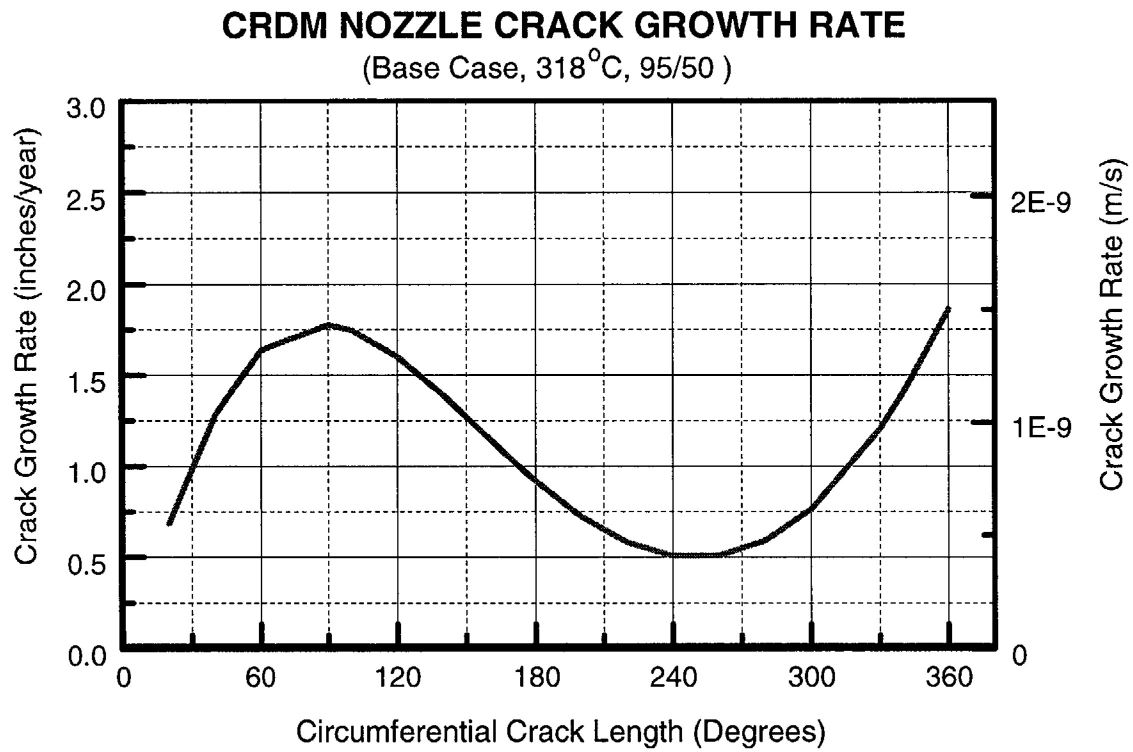


Figure 18 Variation of crack growth rate with circumferential crack length for the base case of 318°C (605°F) 95/50 curve.

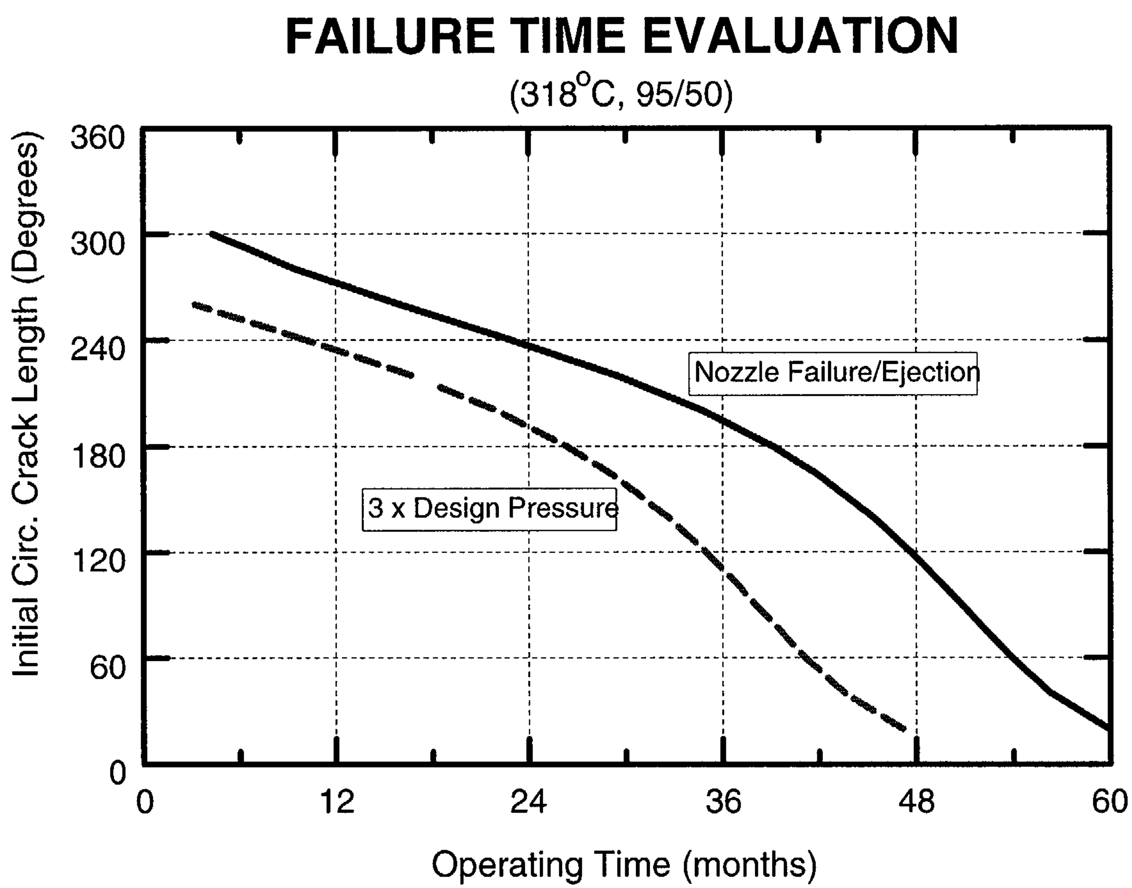


Figure 19 Variation of time to failure as a function of initial crack length, for the base case of 318 °C (605 °F), 95/50, crack growth rate.

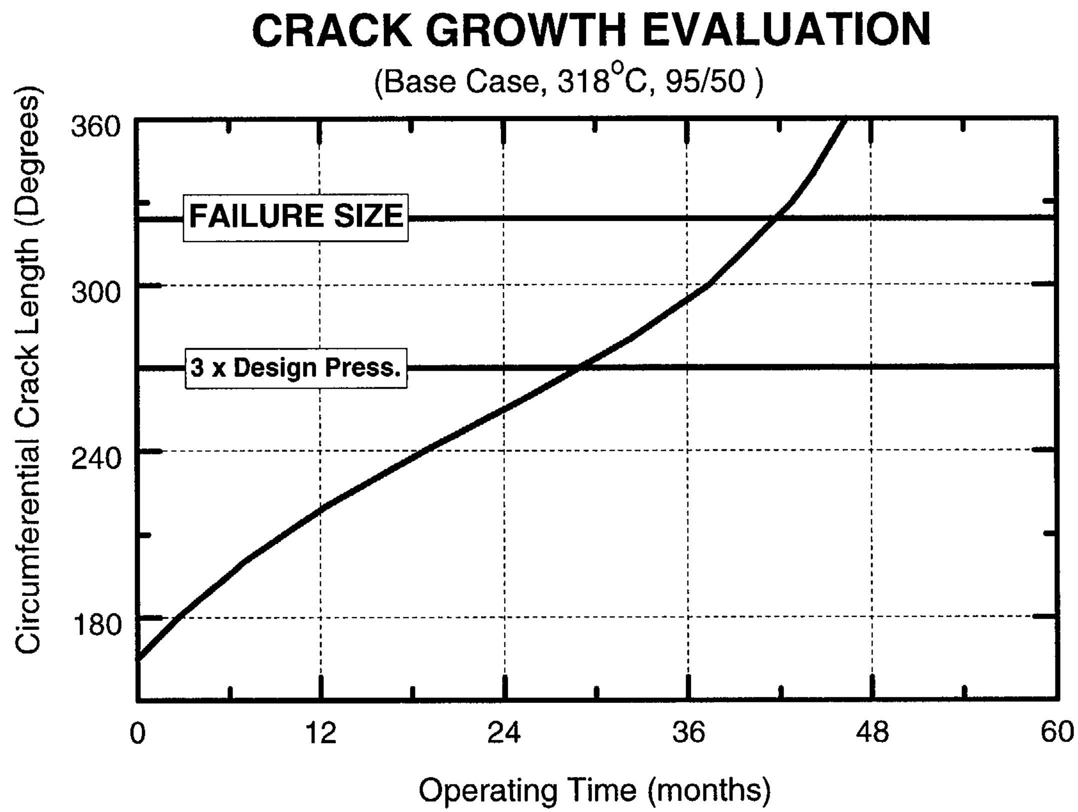


Figure 20 Evaluation of operating time to reach critical flaw sizes at three times design pressure and at nozzle failure/ejection after development of a 165° long circumferential through-wall flaw.

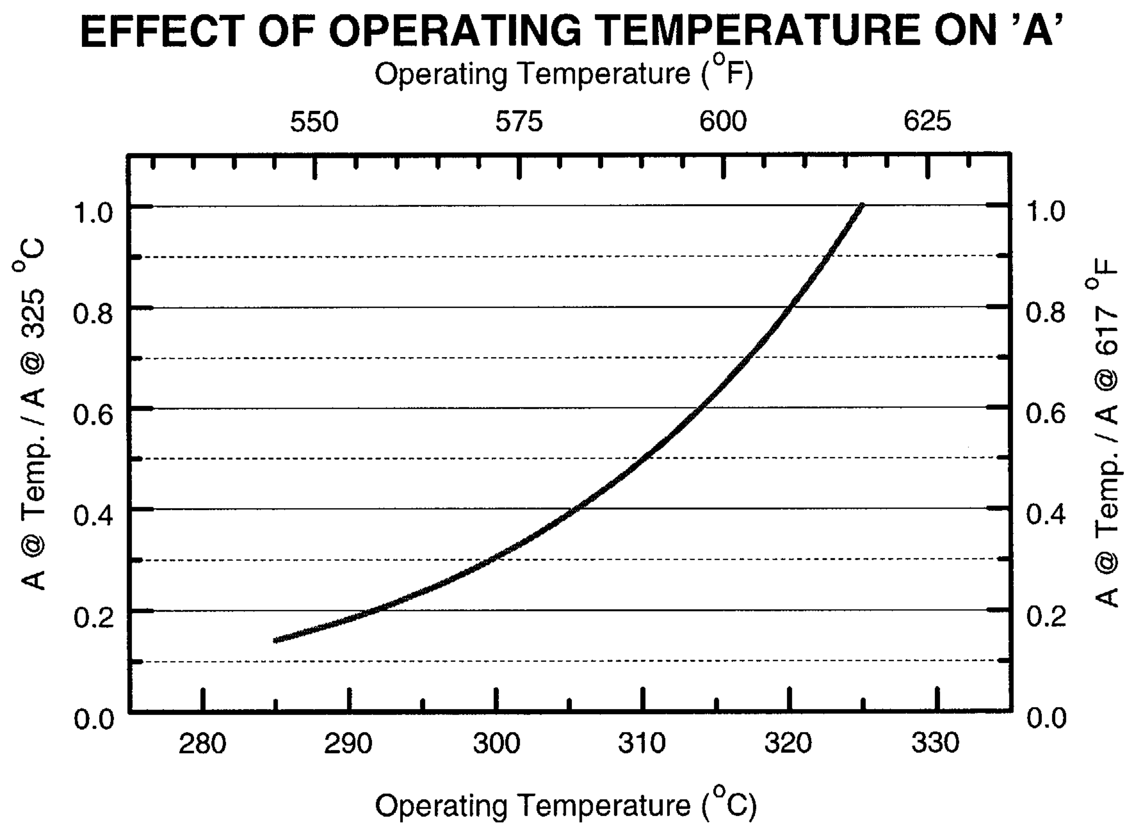


Figure 21 Lower operating temperature results in lower crack growth rates for VHP nozzle materials, within the operating temperature range of the nozzles.

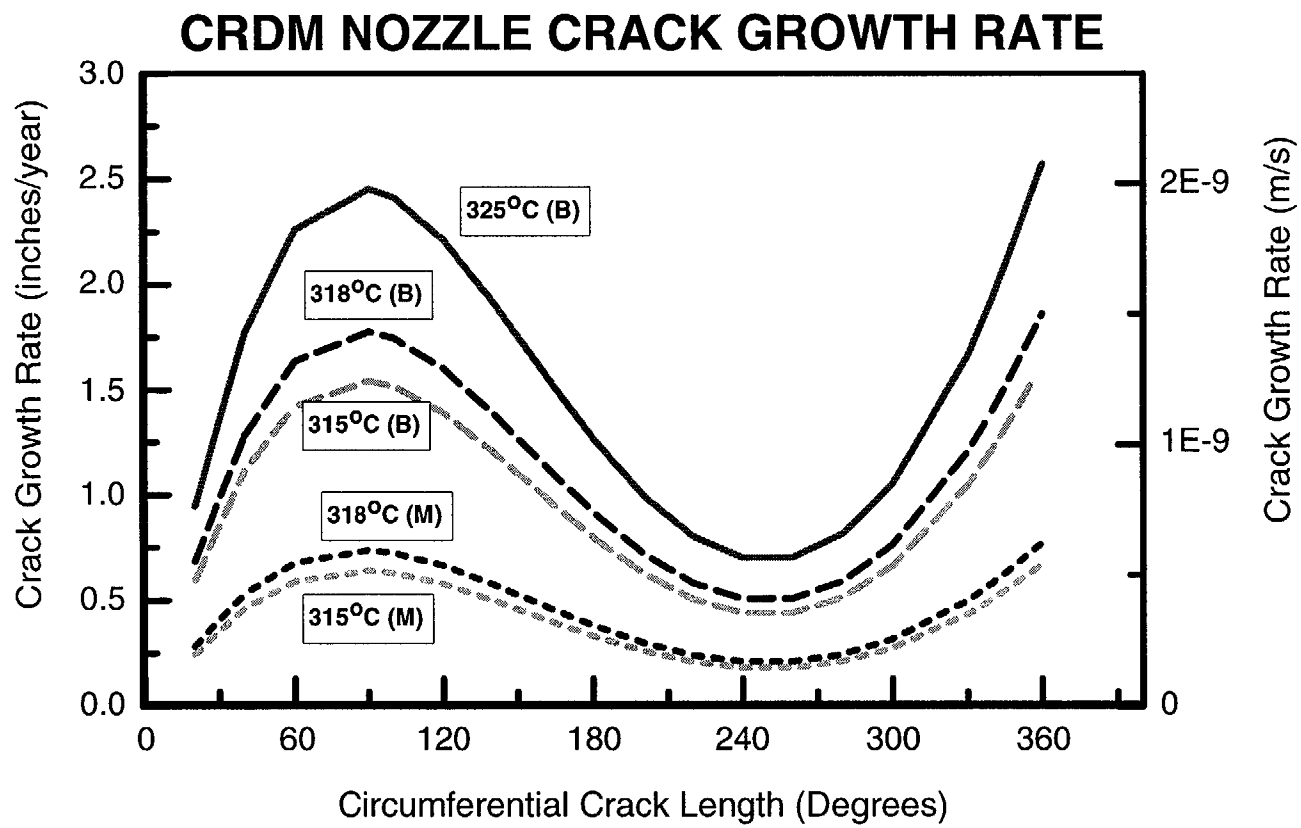


Figure 22 Variation of crack growth rates at several pertinent temperatures and using 95/50 ('B' on the curves) and mean values ('M' on the curves).

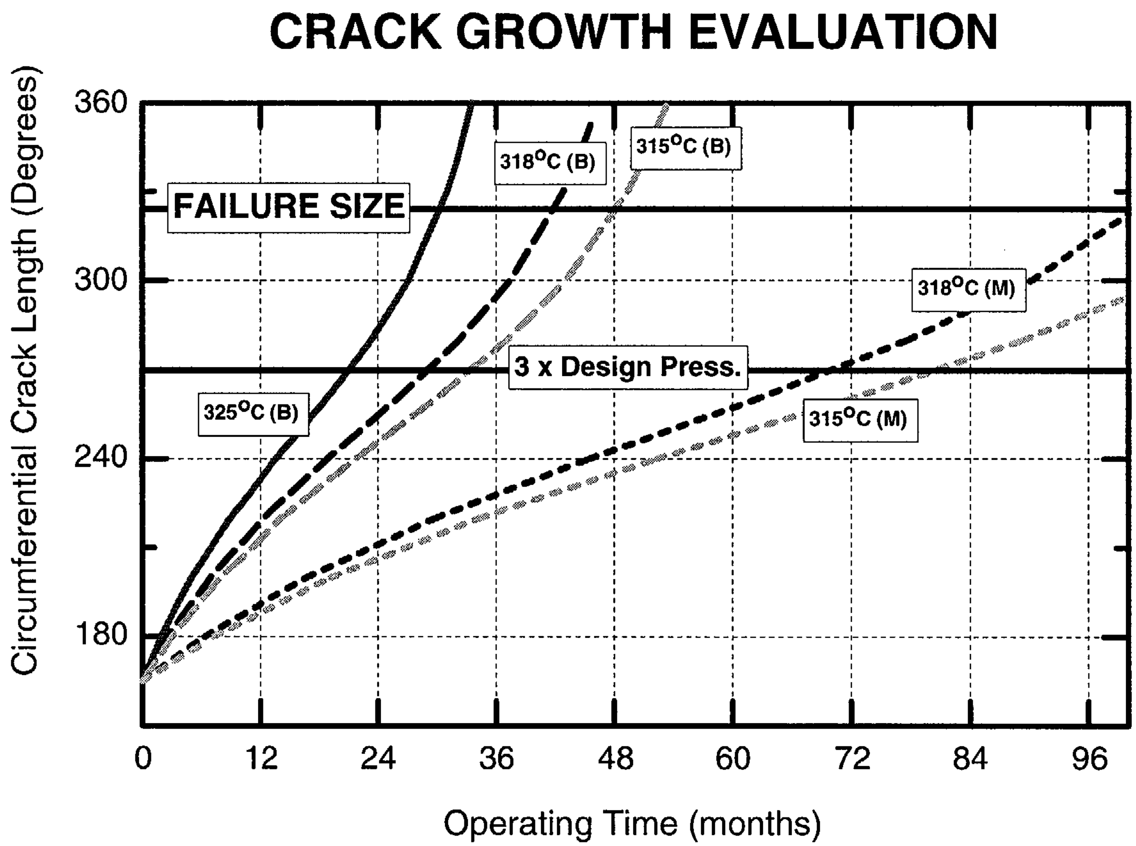


Figure 23 Crack growth analysis using various crack growth rate assumptions, from an initial flaw size of 165°. Although decreasing the temperature has some effect, the most dramatic increases in failure times occur with the mean crack growth curve instead of the 95/50 curve.

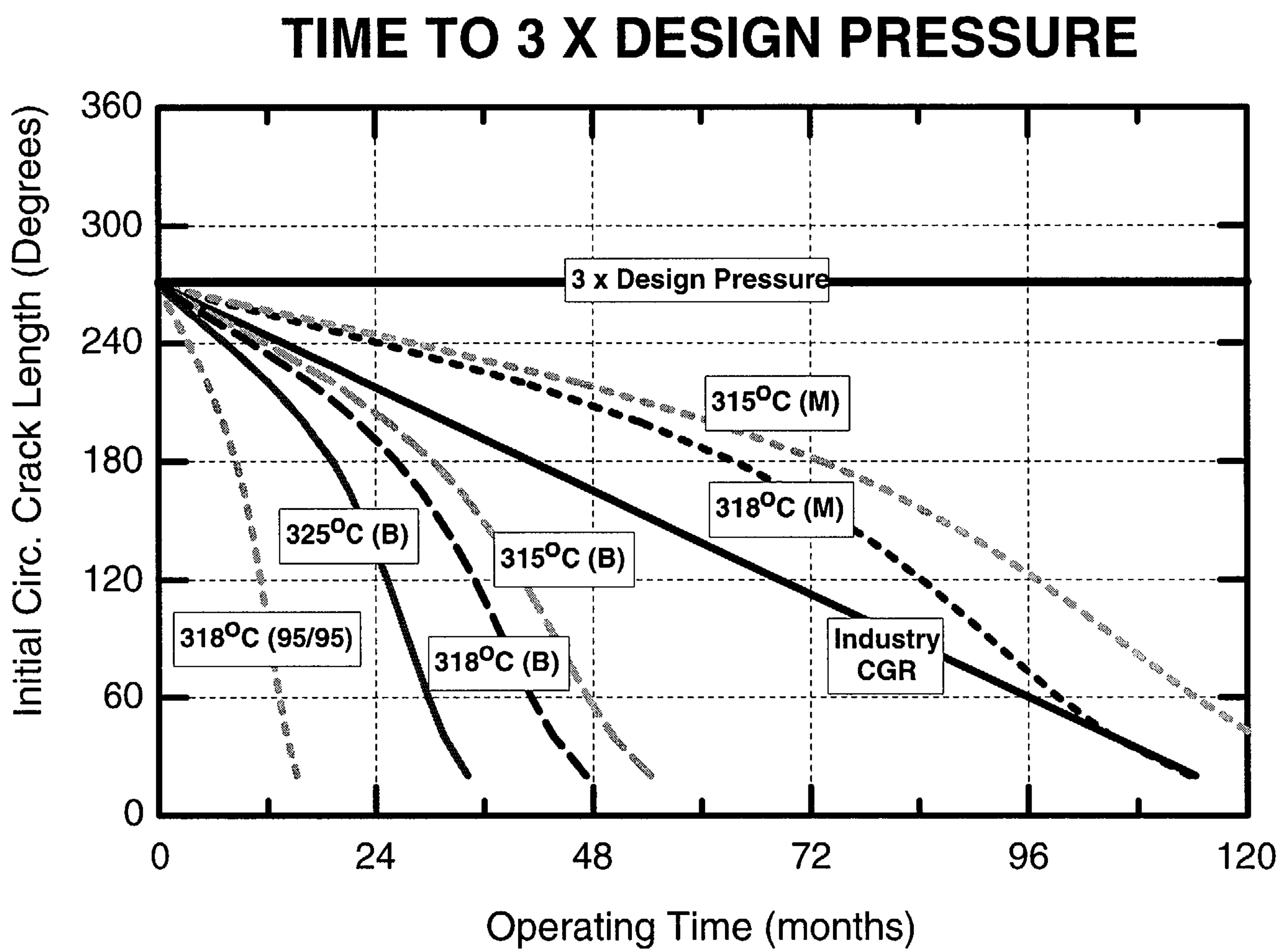


Figure 24 Comparison of time to reach the flaw size representing three times the design pressure, for a variety of crack growth rates and as a function of initial flaw size.

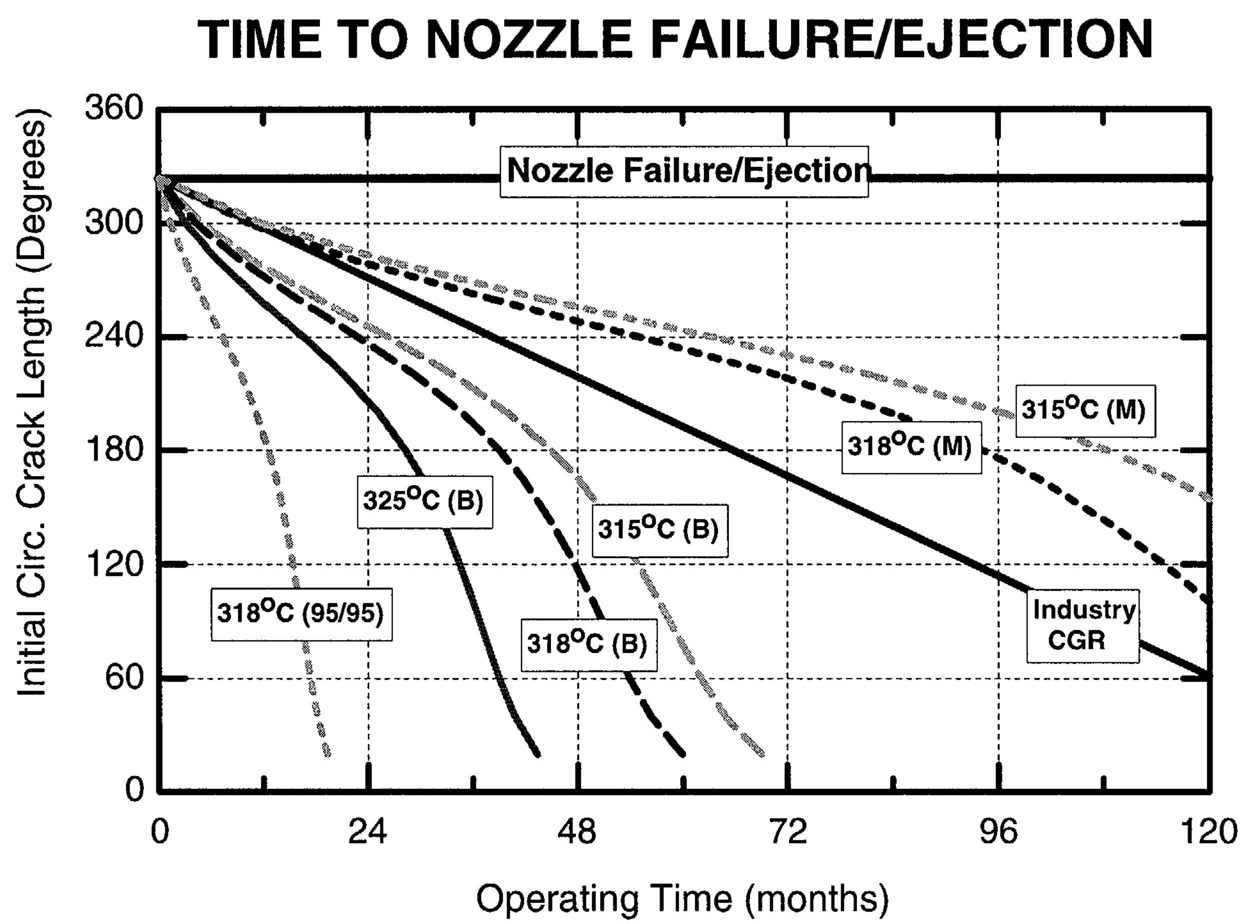


Figure 25 Comparison of time to reach the flaw size representing three times the design pressure, for a variety of crack growth rates and as a function of initial flaw size.

CONCLUSIONS FROM DETERMINISTIC CALCULATIONS

Results are very sensitive to:

- Initial flaw size
- Statistical bound on crack growth rate
- Temperature

Traditional safety margins may not be sufficient to account for large variability in crack growth rates for Alloy 600 in PWSCC conditions

PROBABILISTIC ASSESSMENT

- A Complete Phenomenological Model
  - Requires a better understanding of the complete cracking process
  - Requires data to characterize critical parameters (means & bounds)

- Empirical Model
  - Based on reliable data on number and size of cracks found in service
  - Qualification of NDE sizing an issue
  - Cost of destructive confirmation large

- Need to determine Frequency of Failure to estimate Core Damage Frequency

INSPECTION TIMING

Likelihood of Circumferential Cracking

- High susceptibility plants - 8 out of 9 have identified cracking
- Moderate susceptibility - effective visual examinations will provide additional data

High Susceptibility Plants That Have Performed Effective Inspections

- Can use Figures 23 to 25
- New circumferential cracking can initiate

High Susceptibility Plants That Have NOT Performed Effective Inspections

- Need baseline inspection to provide basis for evaluation

Inspection Method

- Qualified visual examination is appropriate
- Surface or volumetric examinations

Inspection Scope

- 100 percent of nozzles
- Entire surface or metal volume of interest
- "Wetted surface" - J-groove weld, nozzle OD (below the weld), and nozzle ID to a location above the weld
- Volumetric - OD of nozzle above the J-groove weld
- Visual qualification analysis can occur ex-post facto after the inspection

FUTURE STAFF PLANS

- Continue development of probabilistic modeling
- Complete review of Bulletin supplemental responses
- Assemble findings from inservice inspections
- Issue NUREG report
- Long-term inspection plans

INDUSTRY INTERACTIONS

- Interactions on deterministic and probabilistic analyses
- Inspection methods and findings
- Destructive confirmations
  - Flaw sizes
  -
  - Annular conditions

NRC Meeting with Nuclear Energy Institute, Materials Reliability Project and Operating Pressurized Water Reactor Licensees

Thursday, November 8, 2001
1:00 p.m. - 5:00 p.m.
Room: Commissioners' Hearing Room

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