NRC FORM 658
(9-1999)

U.S. NUCLEAR REGULATORY COMMISSION

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DATE OF MEETING
05/07/2002

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Docket Number(s)	**50-346**
Plant/Facility Name	**DAVIS-BESSE NUCLEAR POWER STATION**
TAC Number(s) (if available)	**MB-4881**
Reference Meeting Notice	**ML021150460**
Purpose of Meeting (copy from meeting notice)	**FORTHCOMING MEETING WITH FIRSTENERGY NUCLEAR OPERATING COMPANY ON ROOT CAUSE ANALYSIS REPORT**

NAME OF PERSON WHO ISSUED MEETING NOTICE	TITLE
STEPHEN SANDS	**PROJECT MANAGER**

OFFICE
NRR

DIVISION
DLPM

BRANCH
PD III-2

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DF01

Root Cause Analysis of the Reactor Pressure Vessel Head Degradation at the Davis-Besse Nuclear Power Station

May 7, 2002

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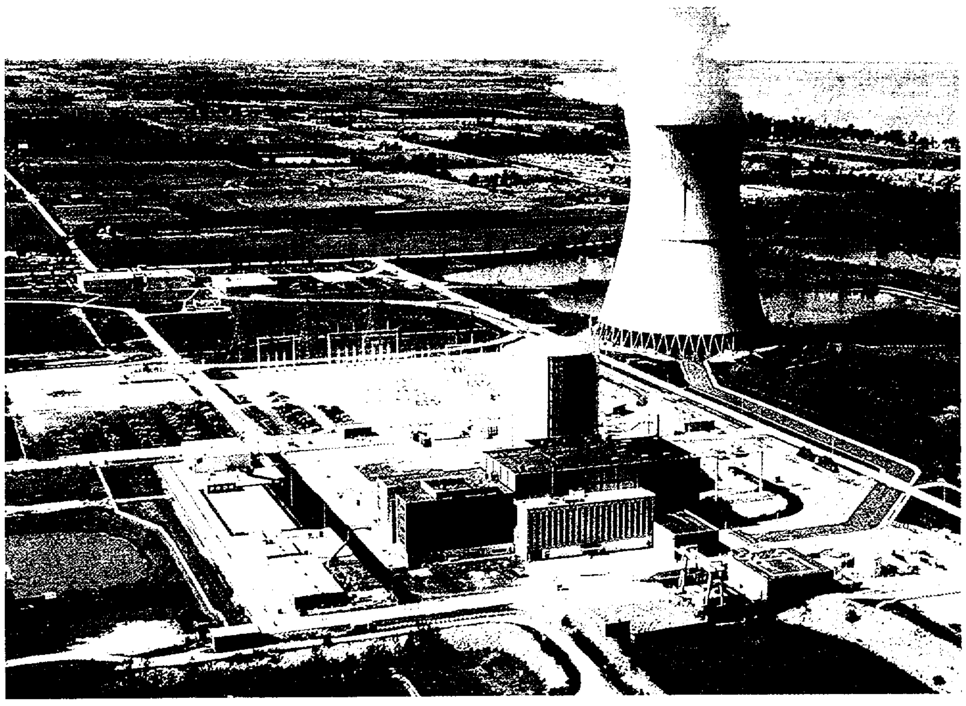
Agenda



- Introduction - John Wood
- Discovery of RPV Head Degradation - Mark McLaughlin
- Root Cause Investigation - Steve Loehlein
- Concluding Remarks - John Wood

Root Cause Summary

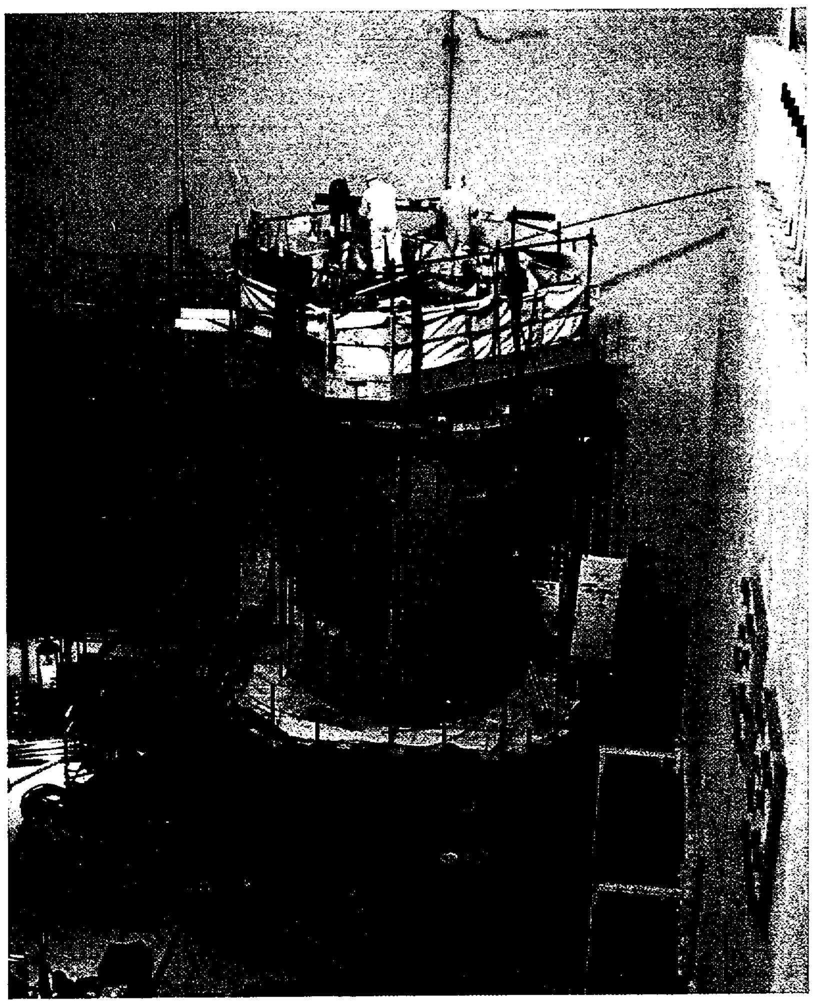
Inadequate inspection of the RPV closure head prevented early detection of nozzle leakage, resulting in prolonged boric acid corrosion and significant degradation.

Discovery of RPV Head Degradation

Mark McLaughlin

Field Activities Team Leader

RPV Head Configuration



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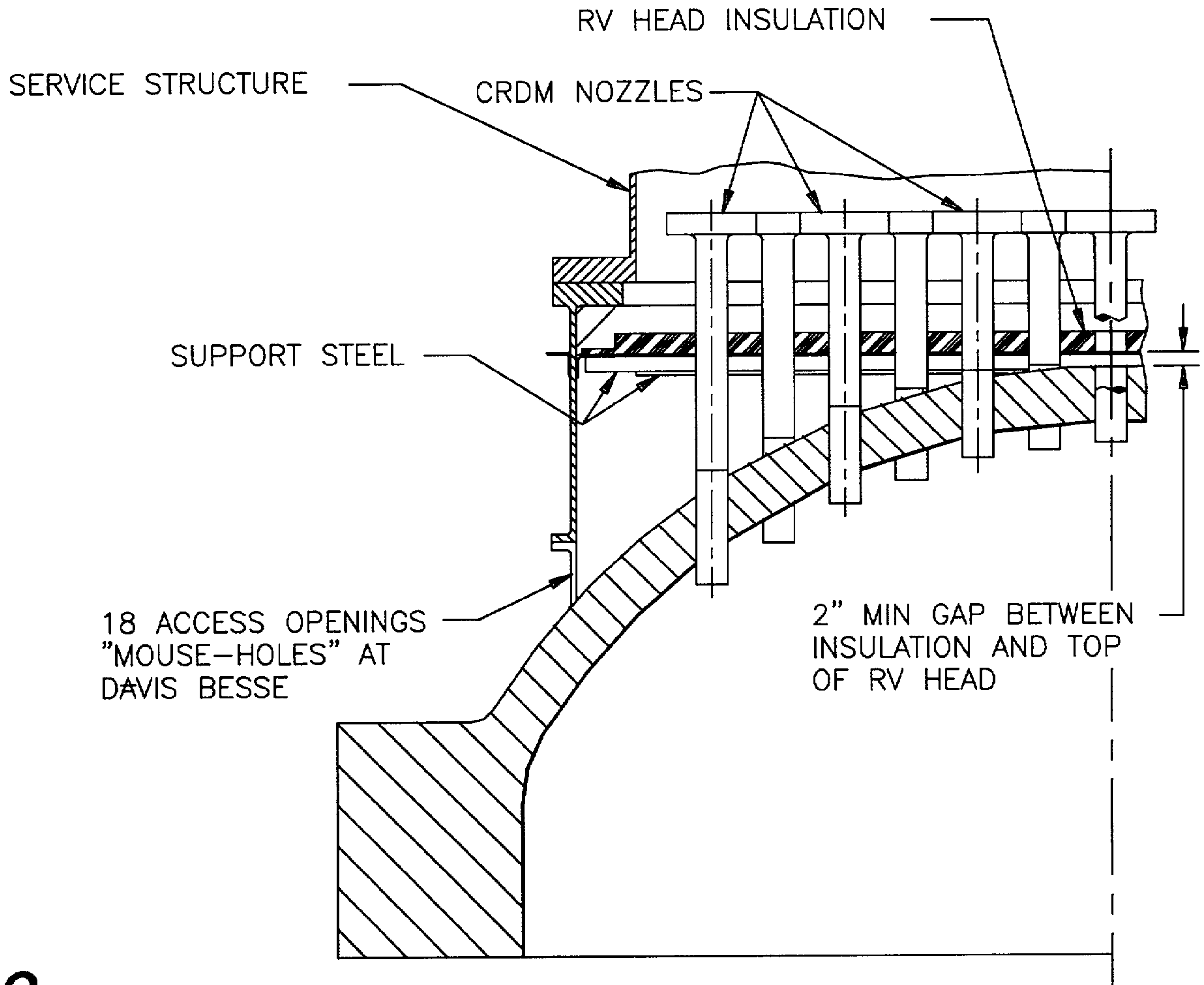
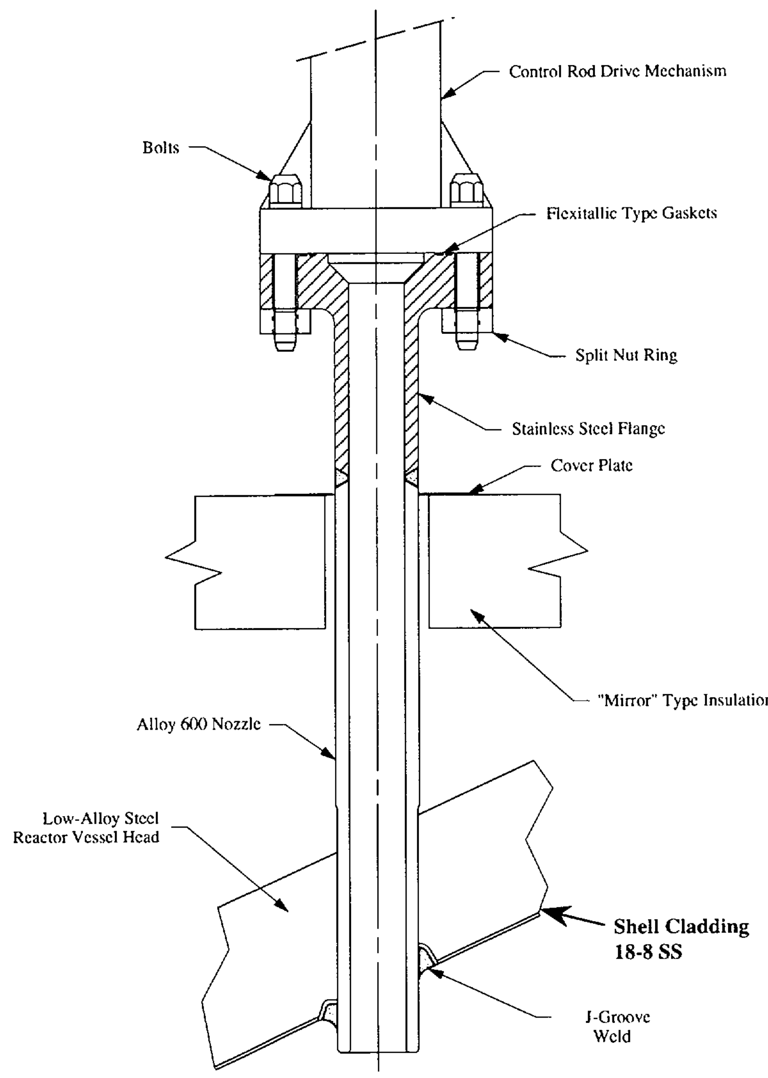
RPV Head Configuration



Access Openings

Control Rod Drive Nozzle

Typical Control Rod Drive Nozzle
(Babcock & Wilcox)



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Discovery Steps

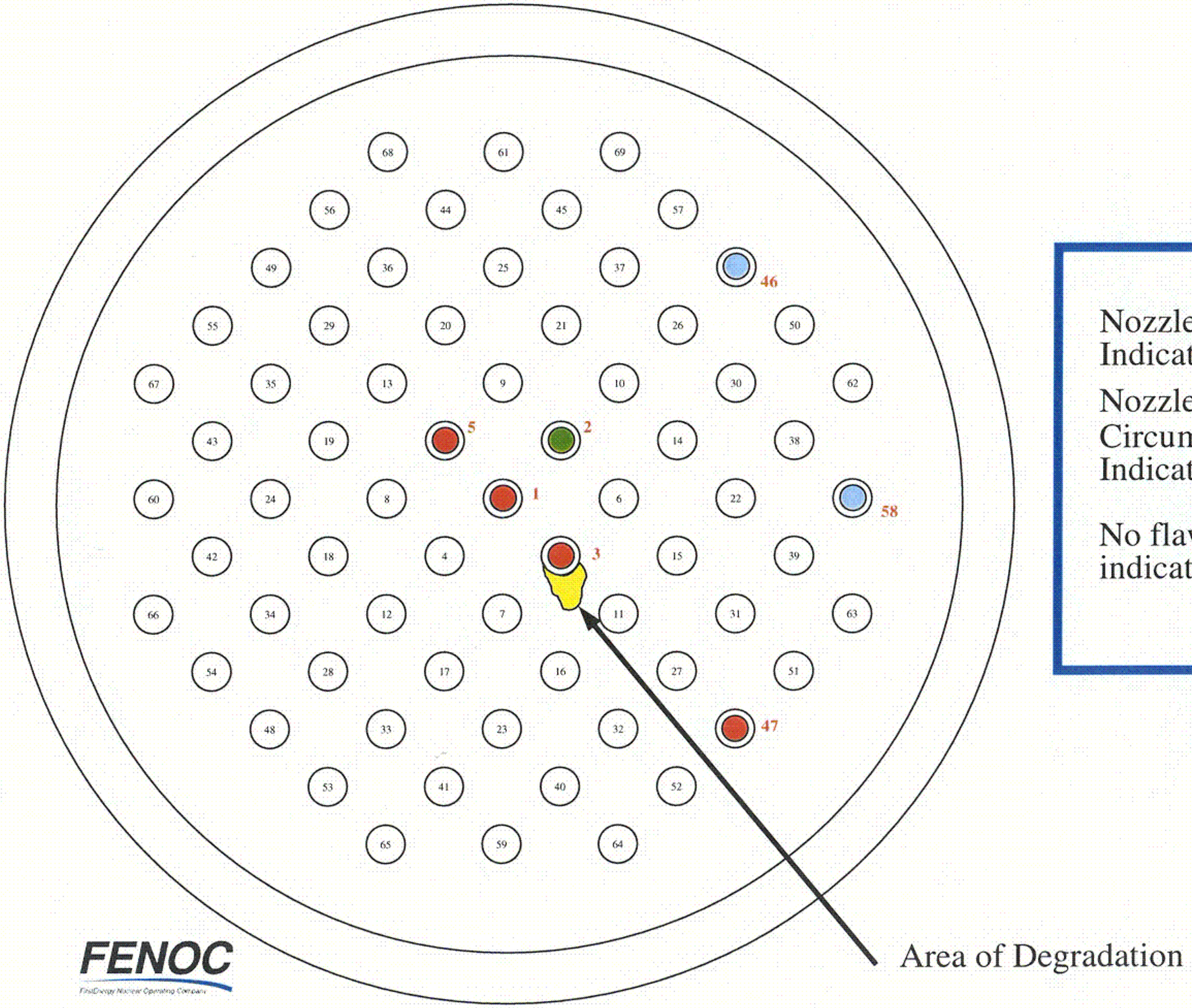
- February 16 13 RFO (refueling outage) starts
- February 24 Visual examination starts
  - Restraint on plant restart due to boron on head
- February 26 Ultrasonic (UT) examinations started
- February 27 Flaw found on nozzle 3
  - Restraint on plant restart due to flaw on nozzle
- March 5 UT examinations completed
  - Nozzle 2 & 3 confirmed leak paths and backwall anomaly
- March 8 Nozzle 3 cavity confirmed and reported to NRC
  - Initial Root Cause Team formed

UT Examination Results

Nozzle #	Summary of Results
1*	9 Axial Flaws, 2 through-wall (TW)
2*	8 Axial Flaws, 1 Circumferential Flaw, 6 TW
3*	4 Axial Flaws, 2 TW
5*	1 Axial Flaw
46	No Flaw Indication
47	1 Axial Flaw
58	No Recordable Indications

* Heat number M3935 material

Facts of Discovery



Nozzle with Axial Indication -

Nozzle with Axial and Circumferential Indication –

No flaw indication -

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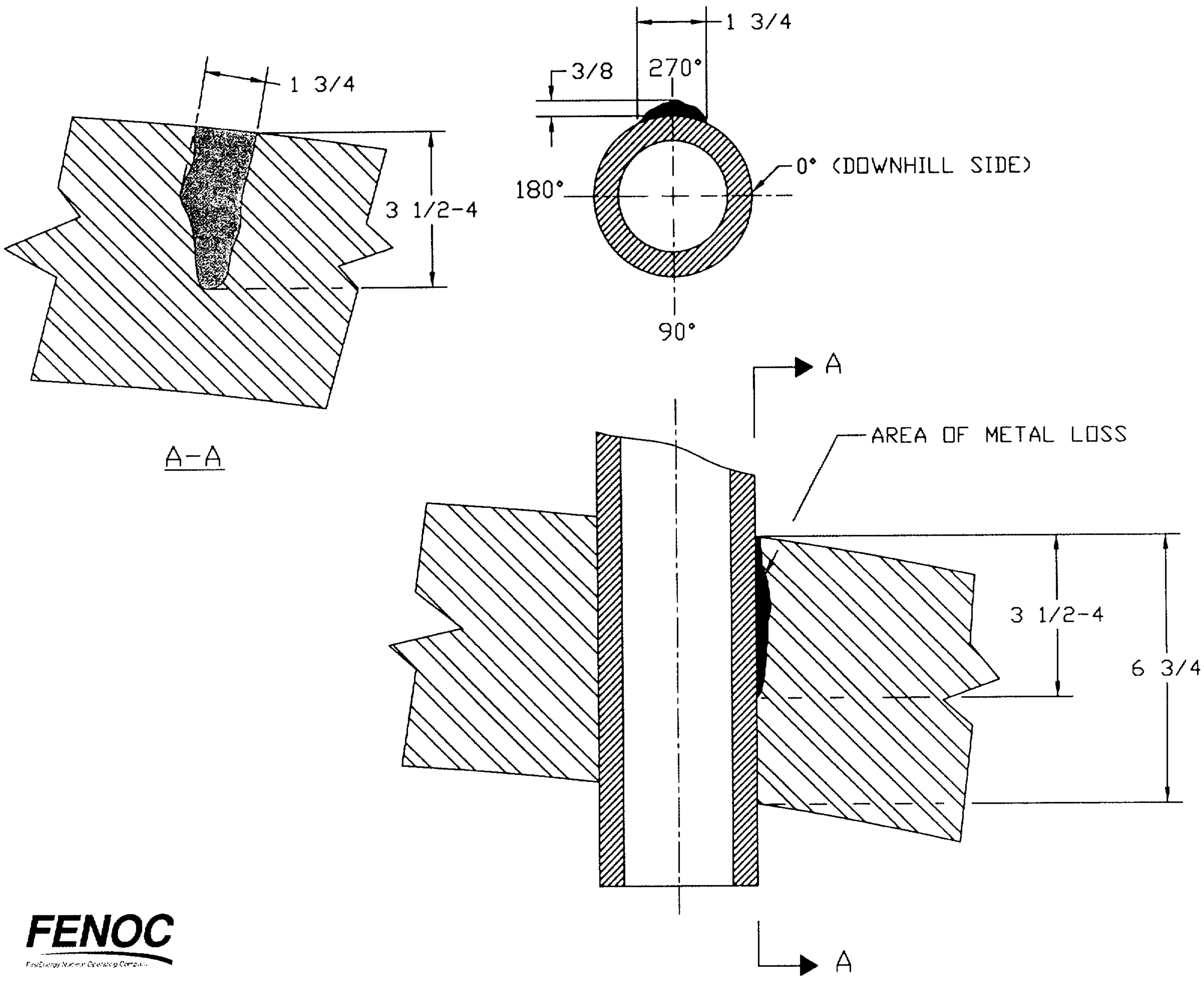
Nozzle 2 Corrosion Profile



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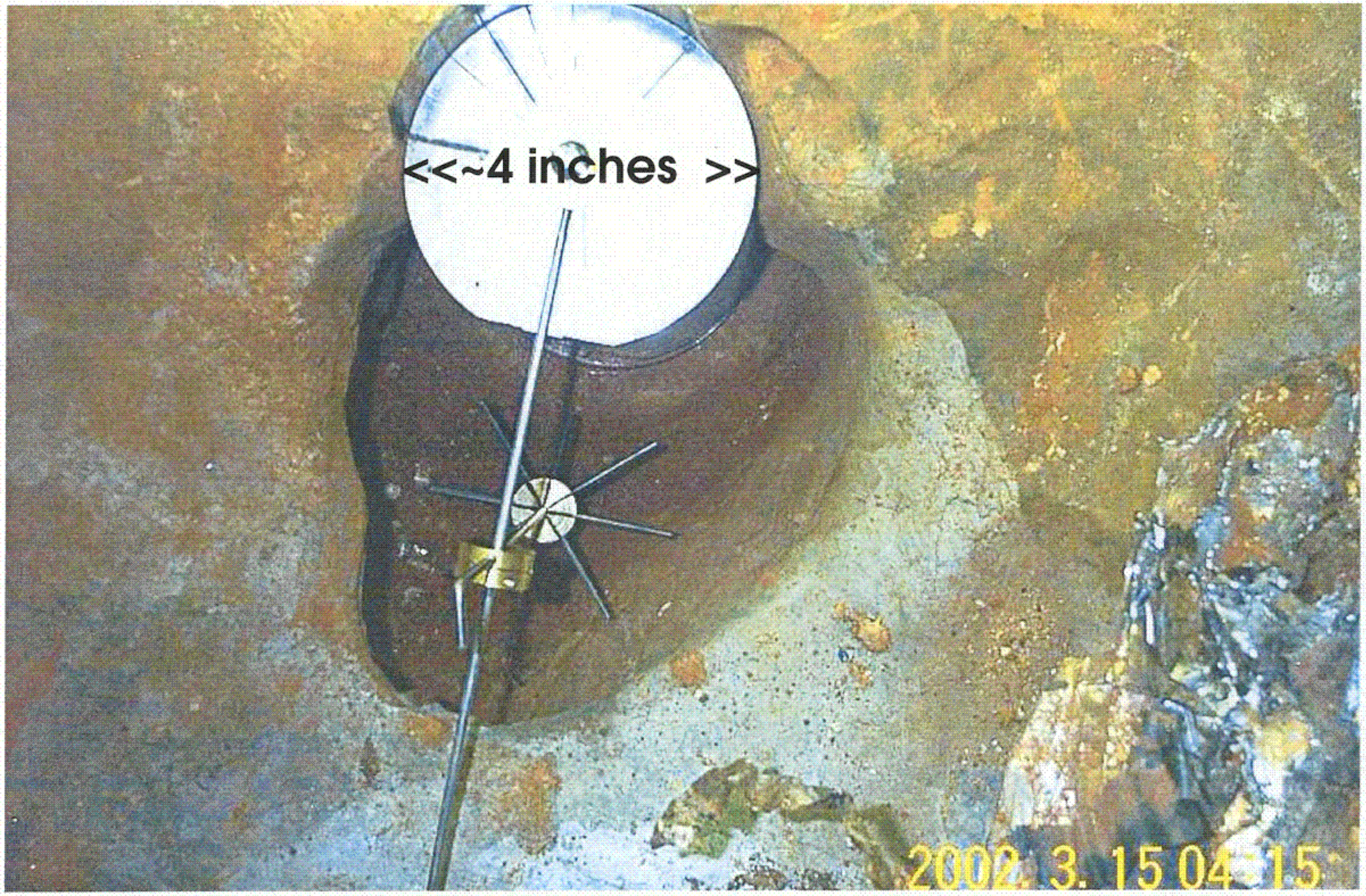
Nozzle 3 Cavity



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Root Cause Investigation

Steve Loehlein

Root Cause Investigation Team Leader

Root Cause Investigation Team

- Team included FENOC staff
  - Steve Loehlein, (Beaver Valley),Team Lead - BS, PE
  - Chuck Ackerman, (Davis-Besse) - BS
  - Ted Lang, (Davis-Besse) - MS, PE
  - Todd Pleune, (Davis-Besse) - PhD
  - Neil Morrison, (Beaver Valley) - BS

Root Cause Investigation Team

- Team augmented by industry experts from FirstEnergy, Framatome ANP, Dominion Engineering, and EPRI
  - Mark Bridavsky, FirstEnergy, Beta Labs - Failure Analysis Expert - PhD
  - Stephen Hunt, Dominion Engineering, Corrosion Expert - PE
  - Steve Fyfitch, Framatome ANP, Metallurgical Expert - MS
  - Christine King, EPRI, Material Reliability Program Manager

Key Questions

- Was there a new mechanism that caused this degradation?
- Was there adequate guidance/knowledge available to have prevented the degradation to the RPV closure head?

Key Conclusions

- The degradation to the RPV closure head was caused by Primary Water Stress Corrosion Cracking (PWSCC) of the Control Rod Drive (CRD) nozzle which led to leaks that were undetected allowing corrosion to occur

- The existing guidance/knowledge is adequate for understanding how to prevent RPV closure head degradation from any CRD nozzle leaks

Root Cause Analysis

- Purpose and Scope
- Root Cause Investigation
    - Data Gathering & Analysis
    - Timeline of Key Events
    - Crack Initiation, Leakage, and Conclusions
    - Corrosion Rates
- Causes

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Purpose and Scope of Investigation

- Determine root and contributing causes for RPV closure head degradation experienced at CRD nozzles 2 and 3

- Perform a prompt investigation to provide the stakeholders with potential impact and insights

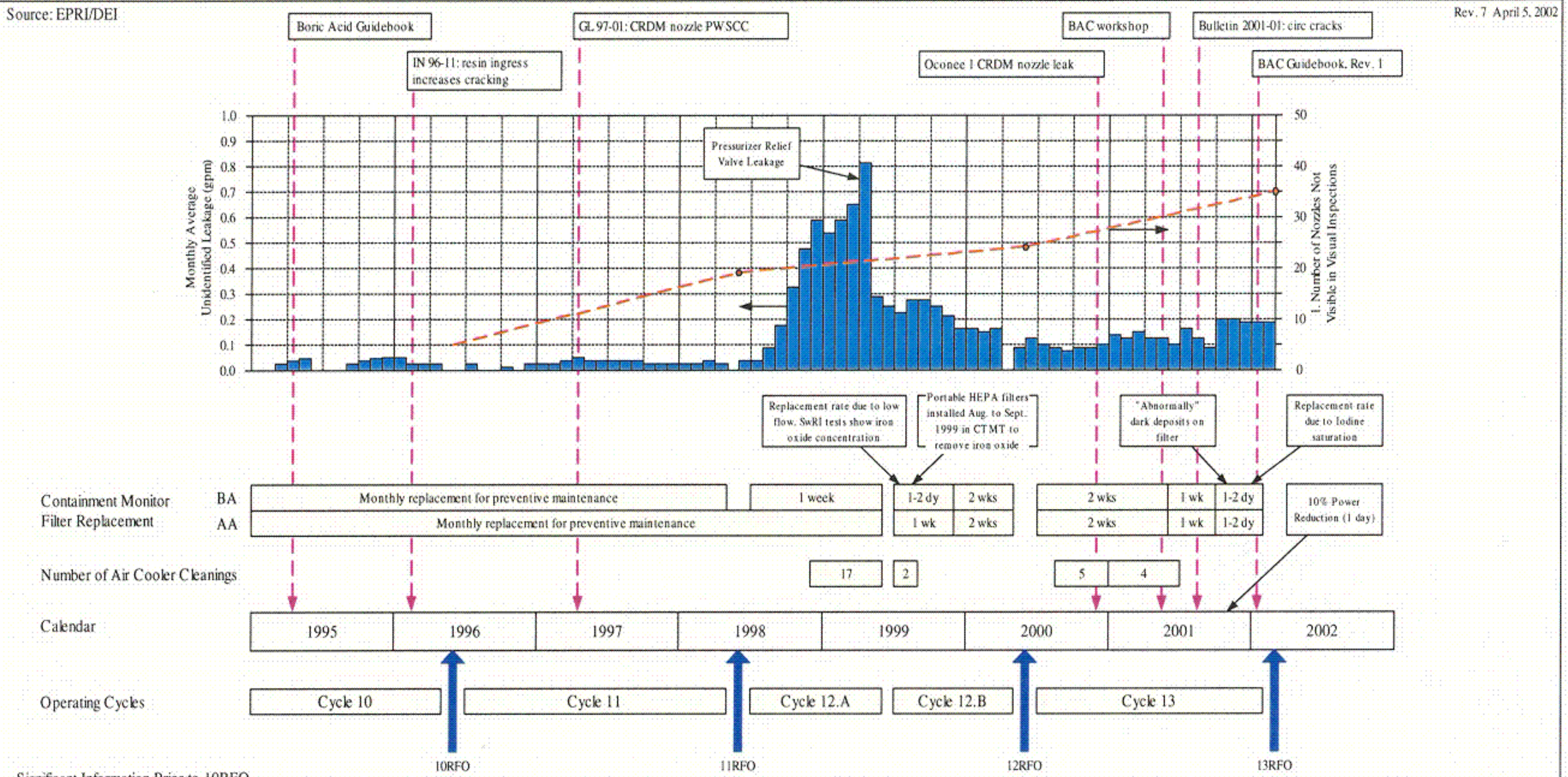
Data Gathering

- Relevant data gathered
  - Condition Reports
  - System Engineer's System Performance Books
  - Photographs of degraded areas
  - Inspection results of degraded areas
  - Plant procedures and other station documents
  - Personnel interviews
  - Reference Documents (NRC, Vendor, INPO, EPRI)
  - Videotapes

Data Analysis

- Data sorted in chronological order to create a Sequence of Relevant Events matrix
- Timeline of Key Events developed
- Events and Causal Factors Chart developed

Timeline of Key Events



Significant Information Prior to 10RFO

1) Nozzle 66 gasket replaced at 7RFO and 8 RFO		1) Nozzle 31 gasket leaks but not changed 2) BA is powder and white	1) Replaced gaskets on flanges 3, 5, 6, 11, 31 2) "Red" deposits under nozzle 3 flange 3) Bottom of nozzle 3 flange not inspected due to hard BA	1) No leakage from flange gaskets 2) "Red" deposits under nozzle 3 flange 3) Difficult to get camera in place due to hard, brown, boric acid	CRDM Flange Conditions
1) Head flange clean in 1994	1) BA flowing towards mouseholes in S-E quadrant	First indication of red colored boric acid deposits from mouseholes in quadrant of S-E quadrant	Significant flow of red colored boric acid deposits from mouseholes, piling to 6" deep behind studs in S-E quadrant	1) Significant flow of boric acid deposits from mouseholes in S-E quadrant 2) BA deposits extend around entire flange 1" deep max	RPV Flange Conditions
1) BA deposits dripping through insulation at 8RFO 2) Head "cleaned" at 8RFO 3) Head not inspected during 9RFO	1) Visual inspection 65/69 nozzles 2) Minor BA deposits around outer nozzles of RV Head 3) BA deposits at center of head	1) Visual inspect 50/69 nozzles 2) Loose BA piling up behind outer nozzles 3) BA brittle, breaks easily	1) Visual inspect 45/69 nozzles 2) BA definitely red and hard to break up (needed crowbar) "lava-like"	1) Visual inspect 34?/69 nozzles N-1: leak [Nozzles 5 & 47 cracked] N-2: leak, circ & minor wastage N-3: leak & major wastage	RPV Head Conditions

Figure 26. Timeline of Key Events Related to Reactor Vessel Head Boric Acid Corrosion

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PWSCC of Alloy 600 Materials

- Alloy 600 materials known to be susceptible to primary water stress corrosion cracking (PWSCC)
  - Both wrought and weld (Alloy 82/182 materials)
- Three main factors:
  - Susceptible material (composition, heat treatment)
  - High tensile stress (operational and residual)
  - Aggressive environment (primary water at high temperature)

Davis-Besse Control Rod Drive Nozzles

- Cracked CRD nozzles are Alloy 600 material with Alloy 82/182 J-groove welds
- Heat treatment of nozzles met code requirements (1600-1700 °F vs >1850 °F)
- Nozzles 1 through 5 are from heat M3935
- Heat M3935 has experienced more leaks in B&W plants than other heats
- High residual tensile stress present adjacent to J-groove weld
- Higher operating temperature (605°F vs 601°F)
- No counterbore on nozzle penetrations
- Interference fit between nozzle and vessel by design

Conclusions Regarding Identified Cracking

- Cracking mechanism is PWSCC
  - Flaw characteristics found at Davis-Besse are similar to other plants with confirmed PWSCC
  - No factors indicating sulfide-induced intergranular stress corrosion cracking (IGSCC) due to chemistry transients
  - No other cracking mechanism deemed credible

Estimated Crack Propagation Timeframe

- Longest through-wall cracks estimated to have initiated in 1990 (+/- 3 years)
- Control rod drive nozzle thickness is 0.62 inch
- Estimated time for flaw to propagate through-wall is 4-6 years
- Consistent with proposed EPRI Material Reliability Program crack growth rate curve

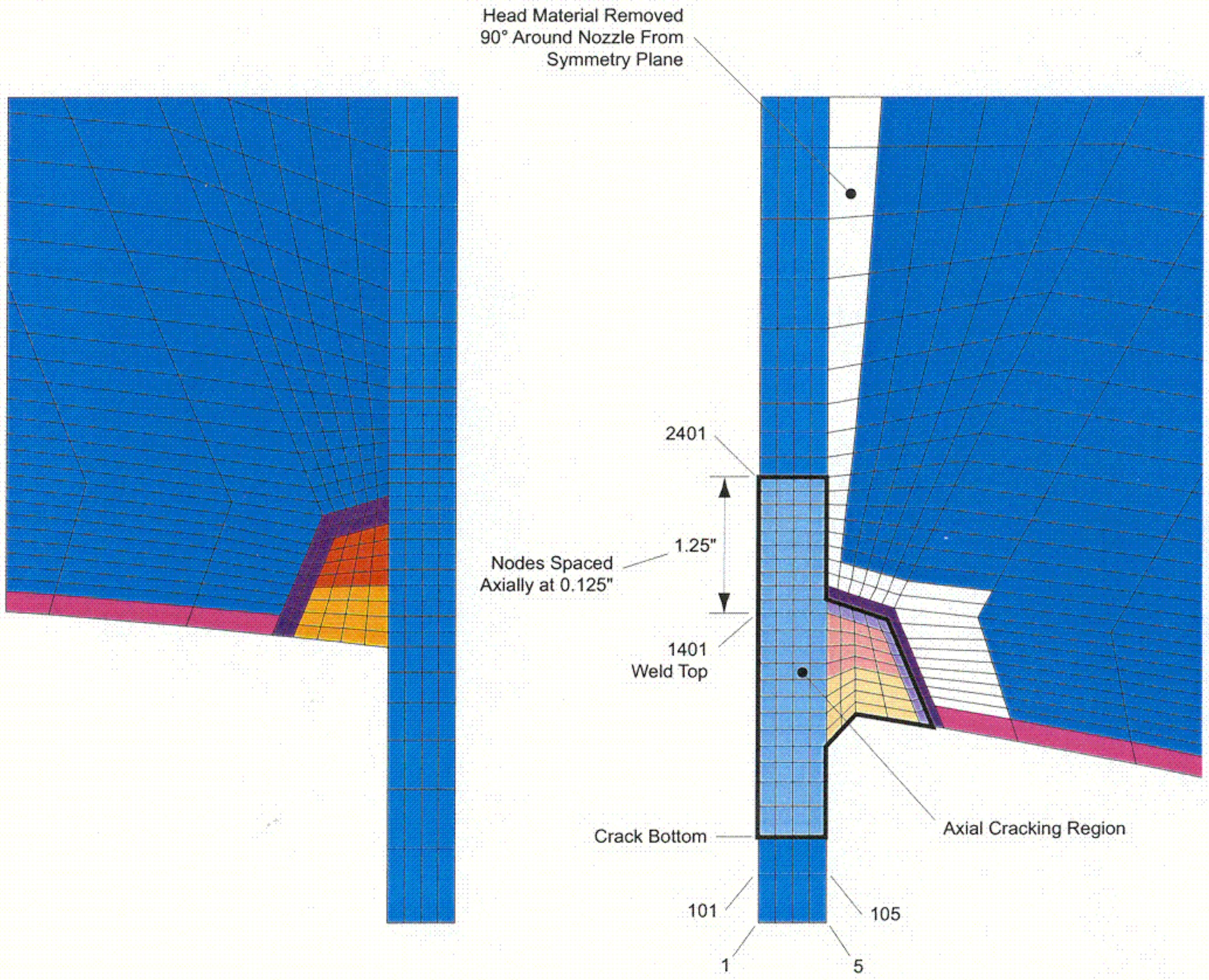
Leakage From Cracked Nozzles

- Through-wall cracking in nozzle or J-groove weld leads to leaks into annulus region
- Leakage rate is a function of crack length above J-groove weld and degree of cracking through the weld
- Leakage rate increases significantly as crack lengthens above the J-groove weld due to increase in crack width
- Previous industry observations indicated very low leakage rates

Davis-Besse
Leakage Rate from Cracked Nozzle

- Davis-Besse axial cracks above weld were longer than reported from other plants (1.1 inches for nozzle 2 and 1.2 inches for nozzle 3)
- Analytical leakage predictions yield wide range of results (.025 to >1 gpm) depending on method and assumed geometry used
- Estimated leak rate based on boric acid deposits and unidentified leakage are in the range of 0.04 to 0.2 gpm

Nozzle 3 Crack Finite Element Model



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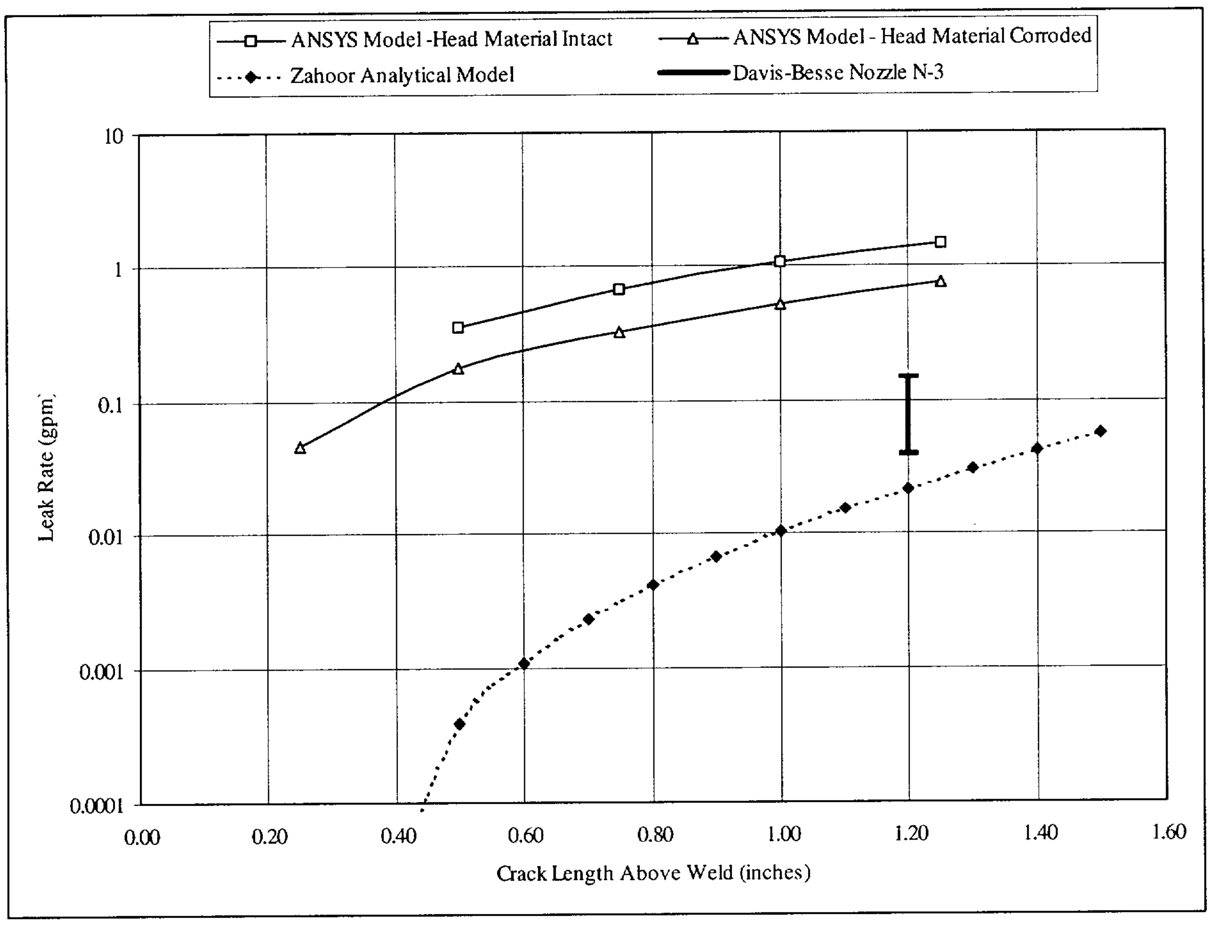
Analytically Predicted Leak Rates



Leak Rate versus Crack Length

Leakage Rate Conclusions

Estimated leakage rate from nozzle 3 crack is consistent with analytical predictions

Source of Corrosion

- Degradation at nozzle 2 and 3 is due to boric acid corrosion
- Boric acid corrosion is a known mechanism capable of producing such significant degradation
- There is a history of boric acid corrosion incidents on RPV heads in the industry

Degradation Sequence

Stage 1 - Crack Initiation Progression
Stage 2 - Minor Weepage / Latency Period
Stage 3 - Deep Annulus Corrosive Attack
Stage 4 - General Boric Acid Corrosion

Stage 1

Crack Initiation Progression

- Nozzle 3 cracks resulted from PWSCC
- Cracks grew at rate consistent with industry data
- RCS leakage miniscule

Stage 2

Minor Weepage/Latency Period

- Leakage entered annulus between Alloy 600 nozzle and low alloy steel RPV closure head
- Fit allowed capillary flow path
- Latency period could involve several mechanisms (e.g., steam cutting, galvanic corrosion, crevice corrosion, and flow accelerated corrosion)
- Annular gap increased due to localized corrosion resulting in leakage flow (residual and dry steam) reaching surface
- Leak rate controlled by number of cracks and size of cracks (length and width)

Stage 3

Deep Annulus Corrosive Attack

- Oxygen penetration in annulus increased due to decreasing velocity and differential pressure in annulus
- Preferential corrosion occurred in the vicinity of crack (consistent with EPRI-6 test)
- Exiting steam mass flow from annulus region not sufficient to wet surrounding areas
- Nozzle 2 progressed to this stage

Stage 4

General Boric Acid Corrosion

- Corrosion progression limited by crack growth rate and leakage through crack
- Annulus flooded with moist steam
- Boric acid accumulates on head
- Increased leakage provides localized cooling of head allowing greater wetted area
- Affected area governed by thermodynamics and material properties (e.g., viscosity, density, slope)
- General corrosion of oxygenated surface

Corrosion Rates From Industry Testing

EPRI and industry testing (effect of boric acid on low alloy steel) demonstrates corrosion rates of 0.6 to 5.0 inches per year

- Test was performed using deaerated, high-temperature water (600°F)
- Orientation, geometry and materials simulated RPV head nozzles
- Flow rates of 0.01 and 0.10 gpm used in test

Davis-Besse Estimated Reactor Vessel Closure Head Corrosion Rates

- 4 years of stage 4 corrosion
- Maximum radial progression ~7 inches
- Average rate ~2 inches per year
- Lateral direction corrosion rate ~1/2 that of axial direction
- Consistent with EPRI Boric Acid Corrosion Guidebook

Probable Timeline

- 1990 (+/- 3yrs) Nozzle 3 cracking initiated
- 1994-1996 Nozzle 3 cracking propagates through-wall
- 1998 and 2000 Nozzle leak not identified
- 2002 Corrosion discovered at nozzle 3, minor degradation at nozzle 2

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Root Cause Summary

Inadequate inspection of the RPV closure head prevented early detection of nozzle leakage, resulting in prolonged boric acid corrosion and significant degradation.

Root Cause Confirmation

- Phases 1 and 2
  - Samples contain iron oxide
  - Chemical form of boric acid

- Phase 3
  - Rule out IGSCC
  - Characterization of nozzle 3 cavity

Root Cause Confirmation

- Sample Phase 1
  - Corrosion products/boric acid deposits from top of head
  - Deposits scraped from CRD nozzle 3 below the flange

- Sample Phase 2
  - Corrosion products/boric acid deposits from nozzle 2 removal

- Sample Phase 3
  - Nozzle 3 and nozzle 3 corrosion area
  - Nozzle 2

Concluding Remarks