MRP - Alloy 600 ITG
RPV Penetrations

Presentation To ACRS Subcommittees

July 10, 2001

Purpose

- Industry Goals:
  - Near Term: Assure Structural Integrity
  - Longer Term: Develop Program to Manage PWSCC
- Explain Background of Head Penetration Issue
- Present Status of MRP Program
- MRP Recommendations for Industry

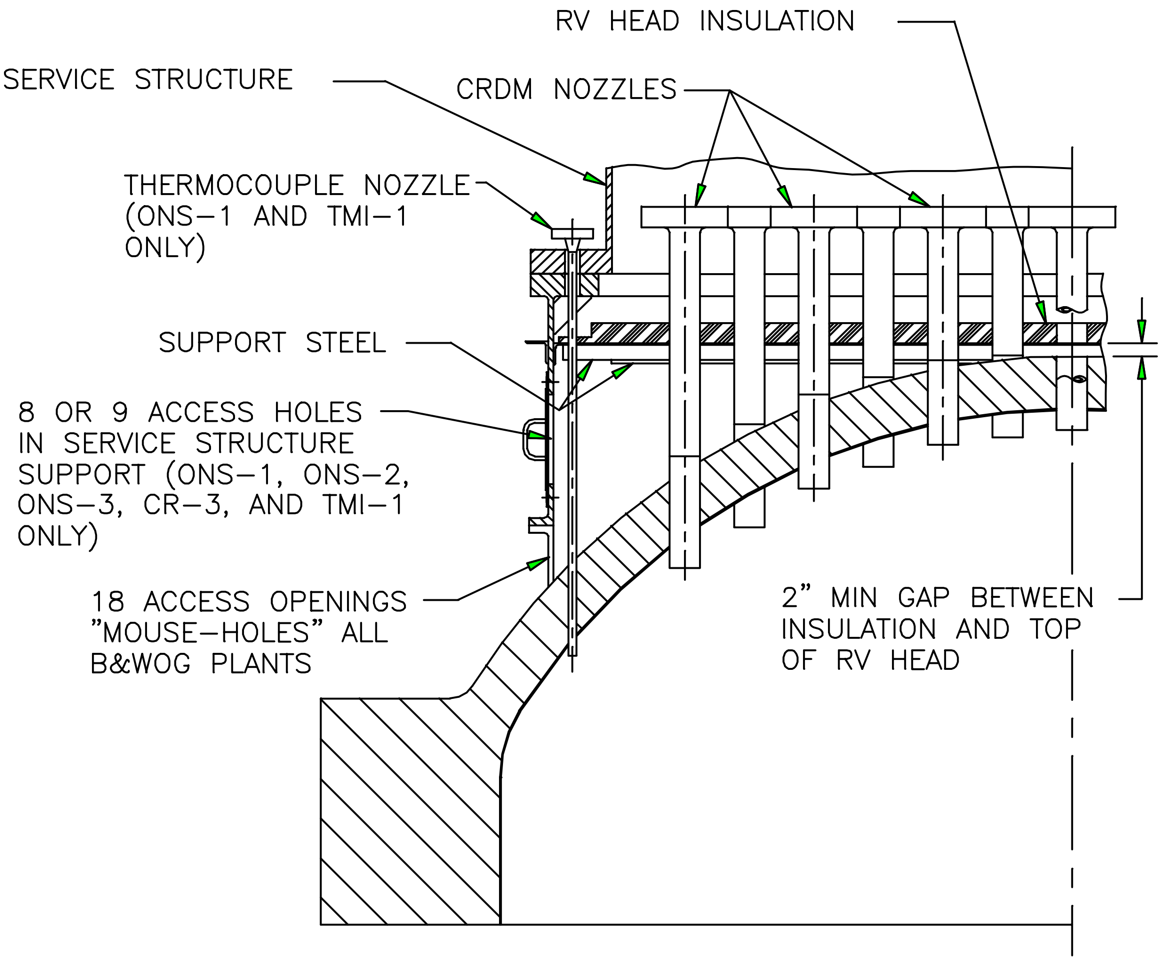
RPV Penetration Summary

- Near Term Conclusions:
  - Axial PWSCC in CRDM nozzles does not impact plant safety
    - Bounded by previously submitted Safety Assessments (1993/94)
  - Reasonable assurance that other PWRs do not have circumferential cracking that would exceed structural margin
    - Oconee and ANO-1 in highest grouping based on effective time-at-temperature
    - Leaks discovered by careful visual inspection of top head surface
    - Volumetric examination of other nozzles found only minor craze cracks
    - Leaks discovered with significant structural margin remaining
    - Several other plants in highest groupings have no evidence of leakage

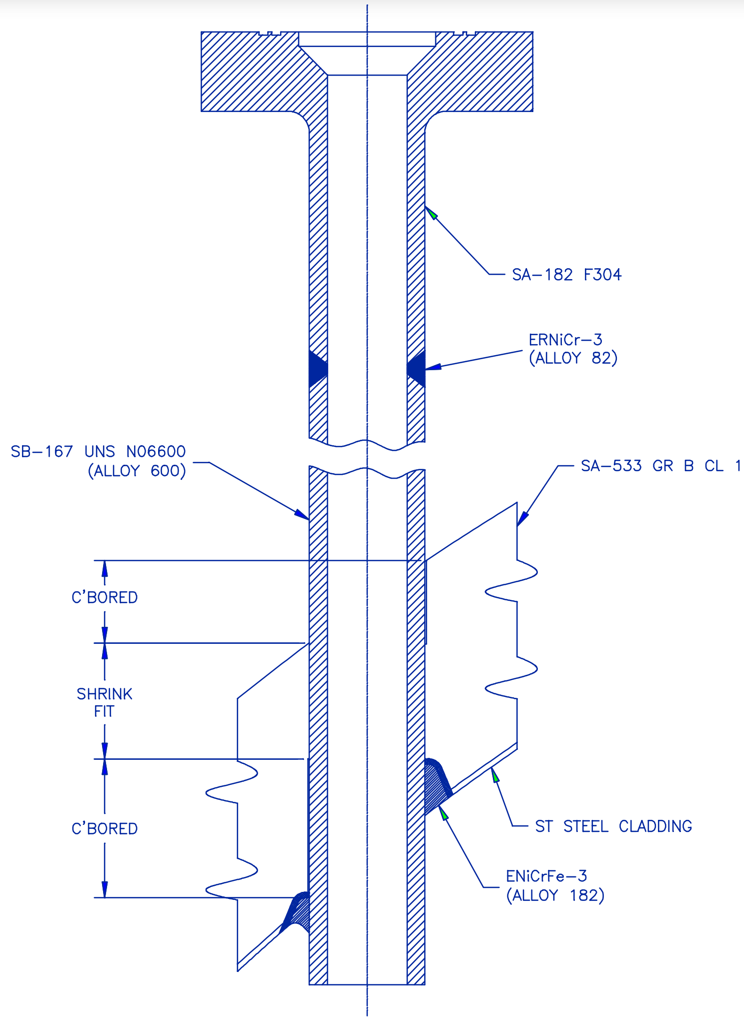
Other Ongoing MRP Activities

- Risk Assessments
- Probabilistic Fracture Mechanics
- Assessment of Crack Growth Data and Needs
- NDE Demonstration
  - Block Design and Fabrication
  - Technique Development and Demonstration
- Information and Training Package for Visual Examination
- Flaw Evaluation Guidelines
- Review of Repair and Mitigation Strategies

Side View Schematic of B&W-Design Reactor Vessel Head, CRDM Nozzles, Thermocouple Nozzles, and Insulation



Schematic View of B&W-Design CRDM Nozzle Area



Issue Background

- Bugey-3 cracking in 1991 characterized as:
  - ID-initiated, through-wall axial flaws
  - Through-wall axial flaw initiated OD circumferential flaw in RV head penetration crevice
- Lack of fusion detected in attachment welds at Ringhals-2 (1992)
- Industry safety assessments prepared (early 90's) for these types of cracking
- Additional European PWRs Discovered Axial Penetration Cracks and Initiated Head Replacements
- DC Cook 2 Found and Repaired a Single Cracked Penetration (1994)
- Owners Groups Programs to Manage for Their Units

Background: GL 97-01

- GL 97-01 Issued April 1, 1997
- Owners Groups Prepared Generic Responses
- Responses Coordinated Between Owners Groups by NEI Task Force
  - Histogram Ranked Plants, Normalizing Both Industry Models to DC Cook 2
- Individual Utilities Supplied Information for Their Plants
- Lead Plants Scheduled for Inspections Based on Histogram
  - ET for Detection
  - UT for Sizing of ID Flaws

Background: GL 97-01 Histogram

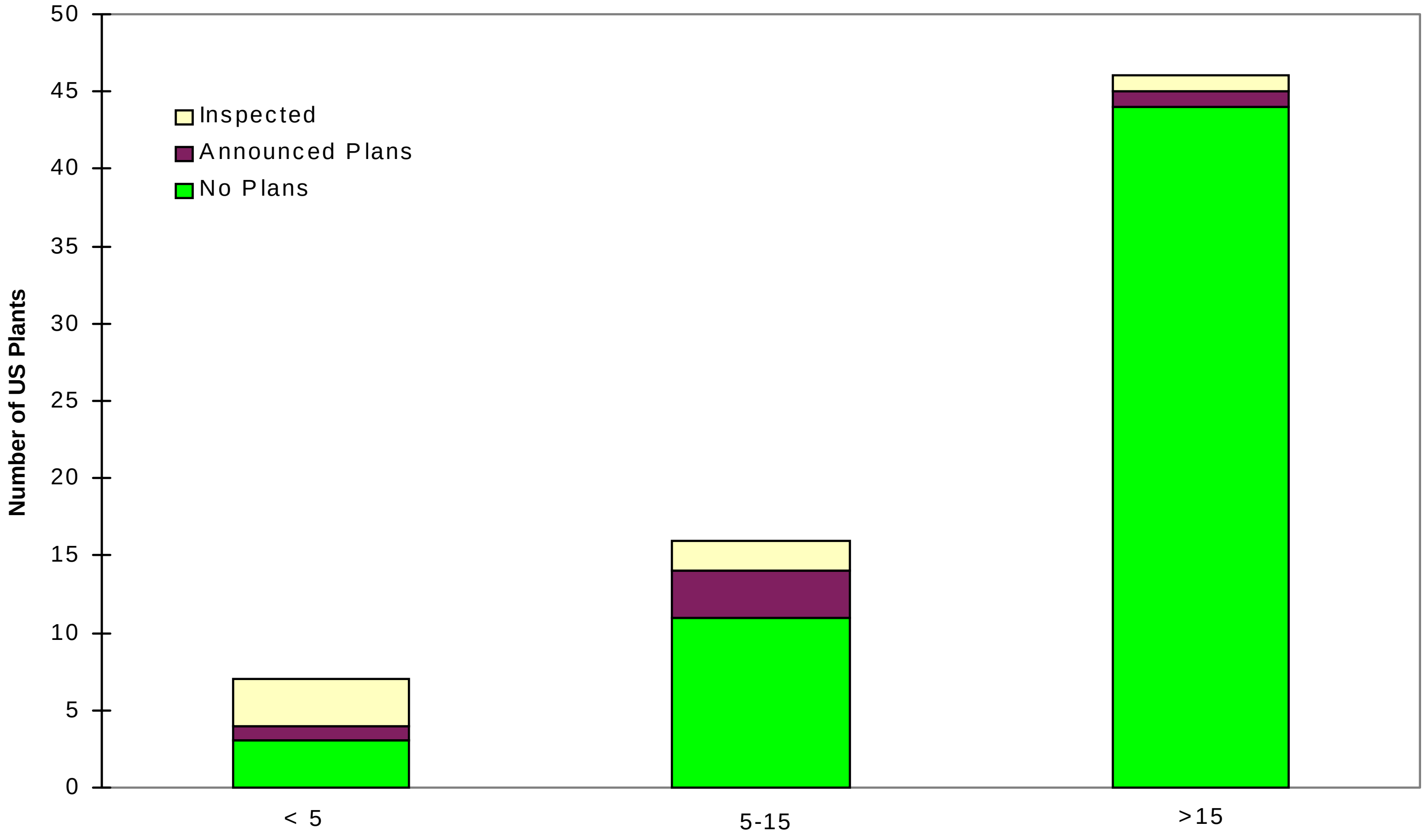
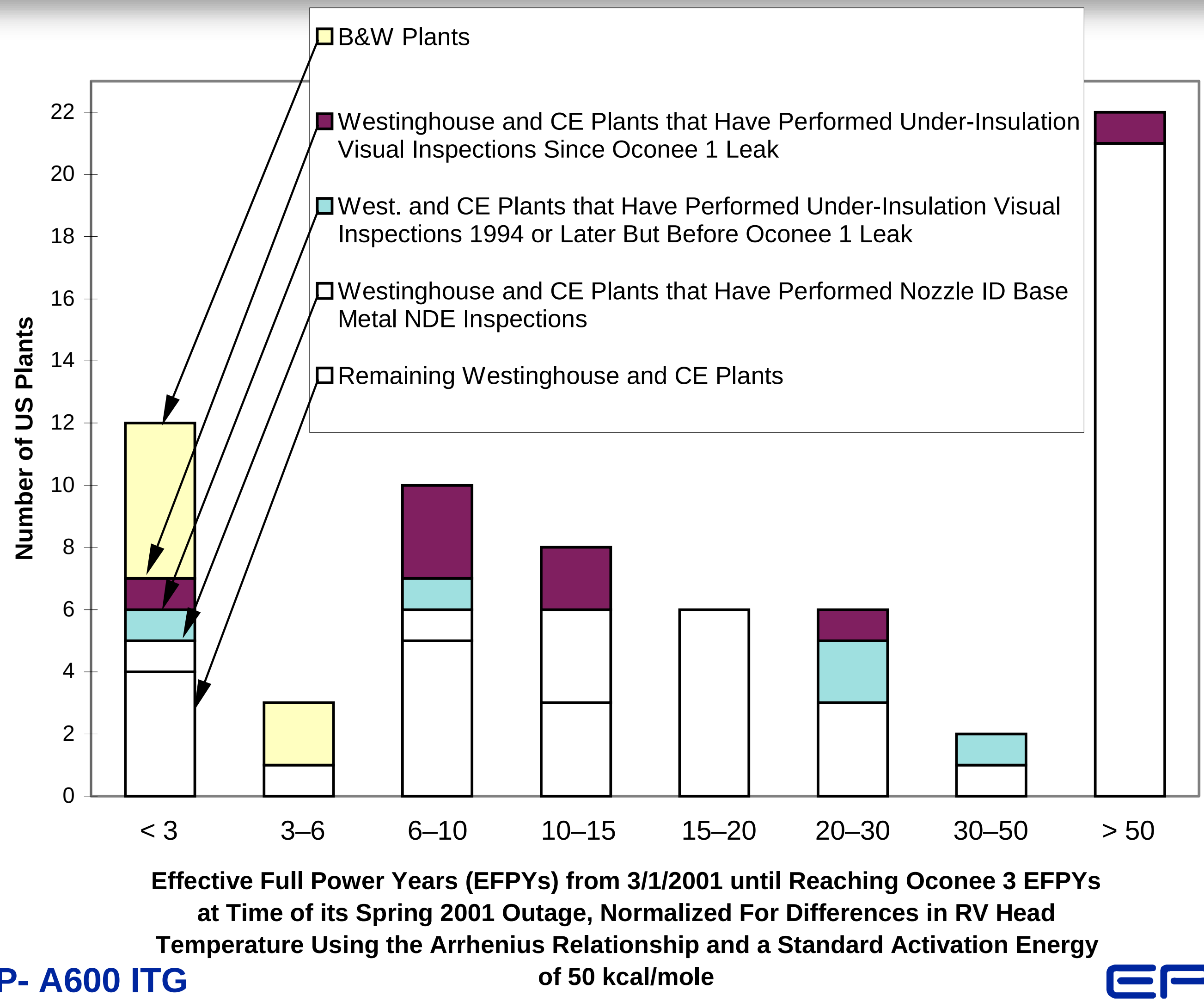


Figure 1: Effective Full Power Years, Measured from January 1997

Recent Experience

- Recent **J-groove Weld and OD-initiated** Cracking Observed at B&W-Design Plants
  - ONS-1 (November 2000)
  - ONS-3 (February 2001)
  - ANO-1 (March 2001)
  - ONS-2 (April 2001)

Time-Temperature Histogram Chart in MRP-44 Part 2 Interim Safety Assessment



Recent Experience

Oconee Experience

- Visual inspection of Unit 1 RV head identified small amounts of boron accumulation at the base of CRDM nozzle 21 and several T/C nozzles.
- Visual inspection of Unit 3 reactor vessel head identified small amounts of boron accumulation at the base of several CRDM nozzles. The suspect nozzles were #'s 3, 7, 11, 23, 28, 34, 50, 56, 63.
- Visual inspection of Unit 2 reactor vessel head identified boron accumulation at the base of CRDM nozzle #'s 4,6,18, and 30

Oconee
Background Information

- Modifications to cut access ports (9 each - 12 in diameter) into the Oconee service structure were completed during outages in Spring 1994, Spring 1993, and Fall 1994 for Units 1, 2, and 3 respectively.

- Modifications to service structure allowed access to domed portion of head for bare metal inspections and wash down of the head to remove old boron deposits.

Oconee
Background Information

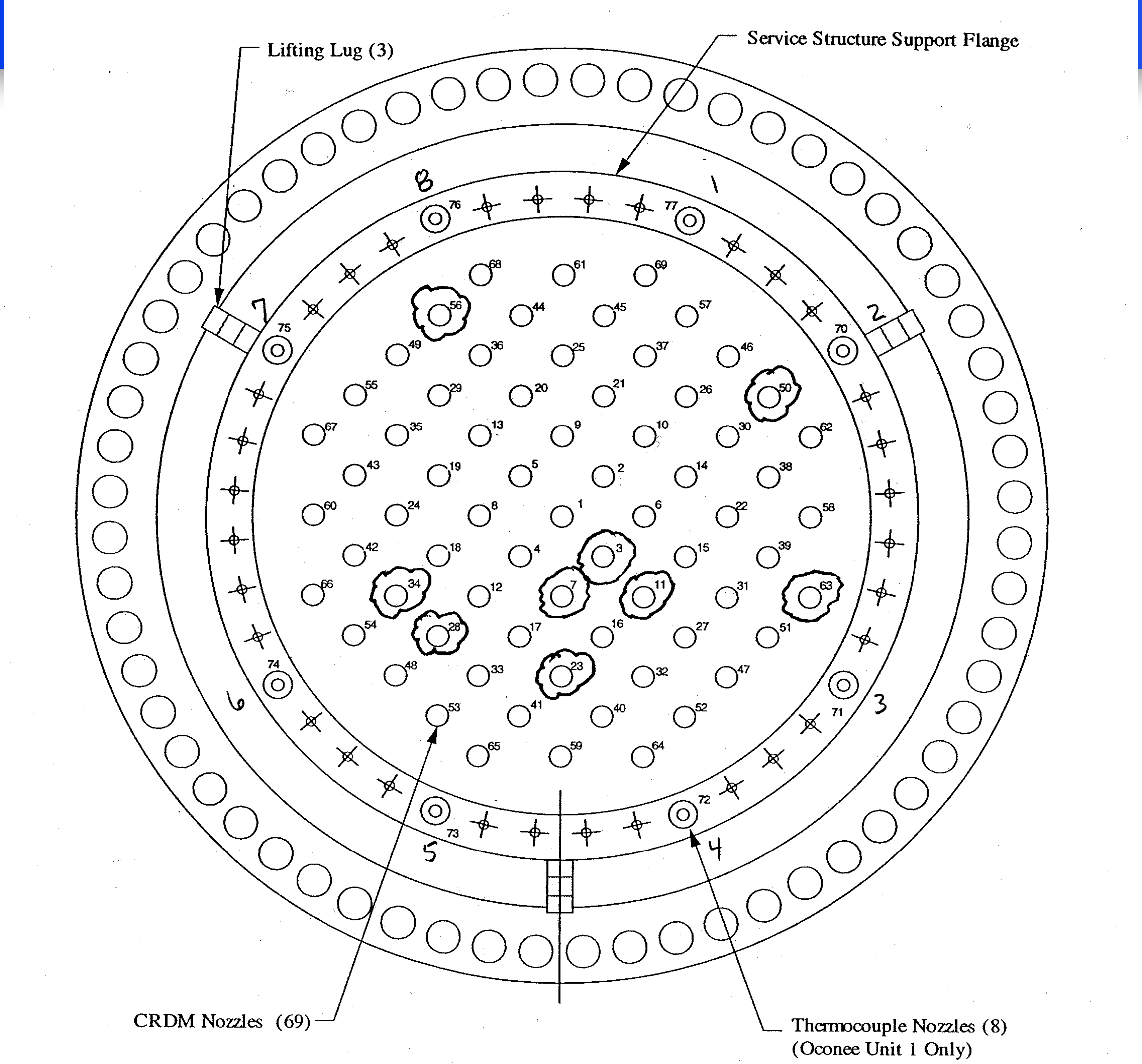
- T/C nozzles installed in Unit 1(only) for instrumentation purposes, but were never put into service.
- Located outboard of the CRDMs and fabricated from 0.75" Schedule 160 Alloy 600 pipe
- Material Specification is SB-167 and procured from Huntington Alloys as cold drawn, ground, and annealed pipe
- Procured to 1965 ASME B&PV Code

ONS-1 RV Head Showing Boric Acid At Thermocouple Nozzle

Oconee
Background Information

- CRDM (69) nozzles are constructed of Alloy 600 and procured in accordance with requirements of SB-167, Section II to 1965 Edition including addenda through Summer 1967 of ASME B&PV Code.
- CRDM nozzle material was hot rolled and annealed by B&W Tubular Products Division.
- CRDM nozzles were shrink fit into reactor vessel head penetration and welded with a J-groove weld with Alloy 600 filler

CRDM Nozzle Layout



Summary of Recent Cracking Incidents

- ONS-1:
  - All eight thermocouple nozzles contained flaws predominantly axial in orientation
    - Five nozzles identified as leaking
    - ID cracking observed on all eight nozzles
    - Cracking penetrated into all eight nozzle welds
  - CRDM nozzle 21 did not contain ID flaws
    - Flaws in weld material, predominantly axial/radial in orientation, identified as leak source
    - Flaw propagated through the weld and nozzle base material

ONS-1 RV Head Showing Boric Acid At CRDM Nozzle 21

Summary of Recent Cracking Incidents (Cont.)

- ONS-3:
  - Nine CRDM nozzles found leaking
    - Numerous axially oriented flaws identified
    - OD-initiated circumferential flaws (relatively deep and below the weld) identified on four nozzles
    - OD-initiated circumferential flaws (above the weld and up to through-wall) identified on two nozzles
    - Some weld cracking also identified

CRDM Nozzle #56

CRDM Nozzle #50

Summary of Recent Cracking Incidents (Cont.)

- ANO 1 CRDM nozzle 56 found leaking
  - No ID axially oriented flaws identified
  - One OD-initiated circumferential flaw below the weld that turned axial identified
  - Flaw propagated through the weld area along the nozzle OD

Visual Inspection
ANO 1

Investigations Performed ONS 1 & 3

- Non-Destructive Examinations
- Metallurgical Examinations
- Analytical Evaluations

Non-Destructive Examinations

- Pre-Repair Inspections Performed
  - Visual inspections of all 69 CRDM nozzles
  - Dye Penetrant (PT)
  - Eddy Current Testing (ECT)
  - Ultrasonic Examination-Axial
  - Ultrasonic Examination-Circumferential

Visual Inspections

- Bare head inspections are performed through the modified openings in the head service structure
- Visual inspections are performed as part of each refueling outage for our response to GL 88-05 and 97-01
  - The same experienced system engineer performs these inspections
- Heads essentially clear of old boron deposits
- Amount of leakage from each leaking nozzle has been very small, which suggests, low leak rates
- No evidence of boric acid corrosion on top of head

Non-Destructive Inspections

- Dye Penetrant (PT) Inspection
  - Surface examination that looks at the weld surface area and the top 1 inch of the nozzle that projects down into the plenum of the head
  - Performed on suspected leaking CRDM nozzles
- Eddy Current (ECT) Inspection
  - Surface examination (plus 2 to 3 mm into the material) from the nozzle ID
  - Performed on suspected leaking nozzles
  - Checks a band 6 inches above the weld down to free end of nozzle
  - Later performed on additional nozzles, to address extent of condition
    - 8 Unit 1 CRDM nozzles
    - 9 Unit 3 CRDM nozzles

Non-Destructive Inspections

- Ultrasonic Examinations (UT) Axial
  - Volumetric examination to locate and depth size axial indications on both the nozzle inside diameter and the nozzle outside diameter
  - Performed on the suspected leaking nozzles and on additional nozzles to address extent of condition
    - 18 nozzles on Unit 3 inspected

- Ultrasonic Examinations (UT) Circumferential
  - Volumetric examination to detect the presence of circumferential cracking or indications and lack of bond
  - Performed on the suspected leaking nozzles and on additional nozzles to address extent of condition
    - 18 nozzles on Unit 1 (lack of bond)
    - 18 nozzles on Unit 3 (circumferential)

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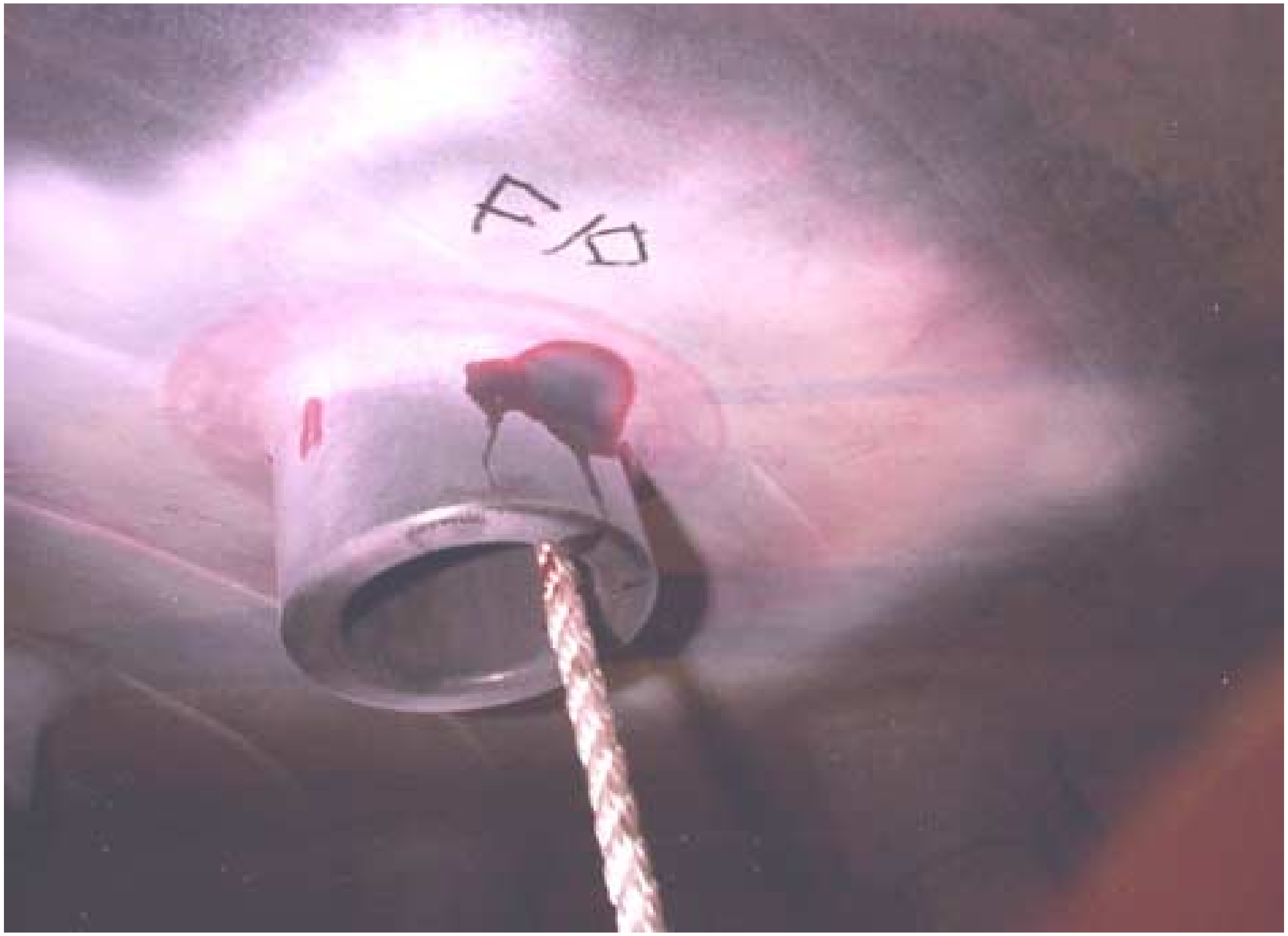
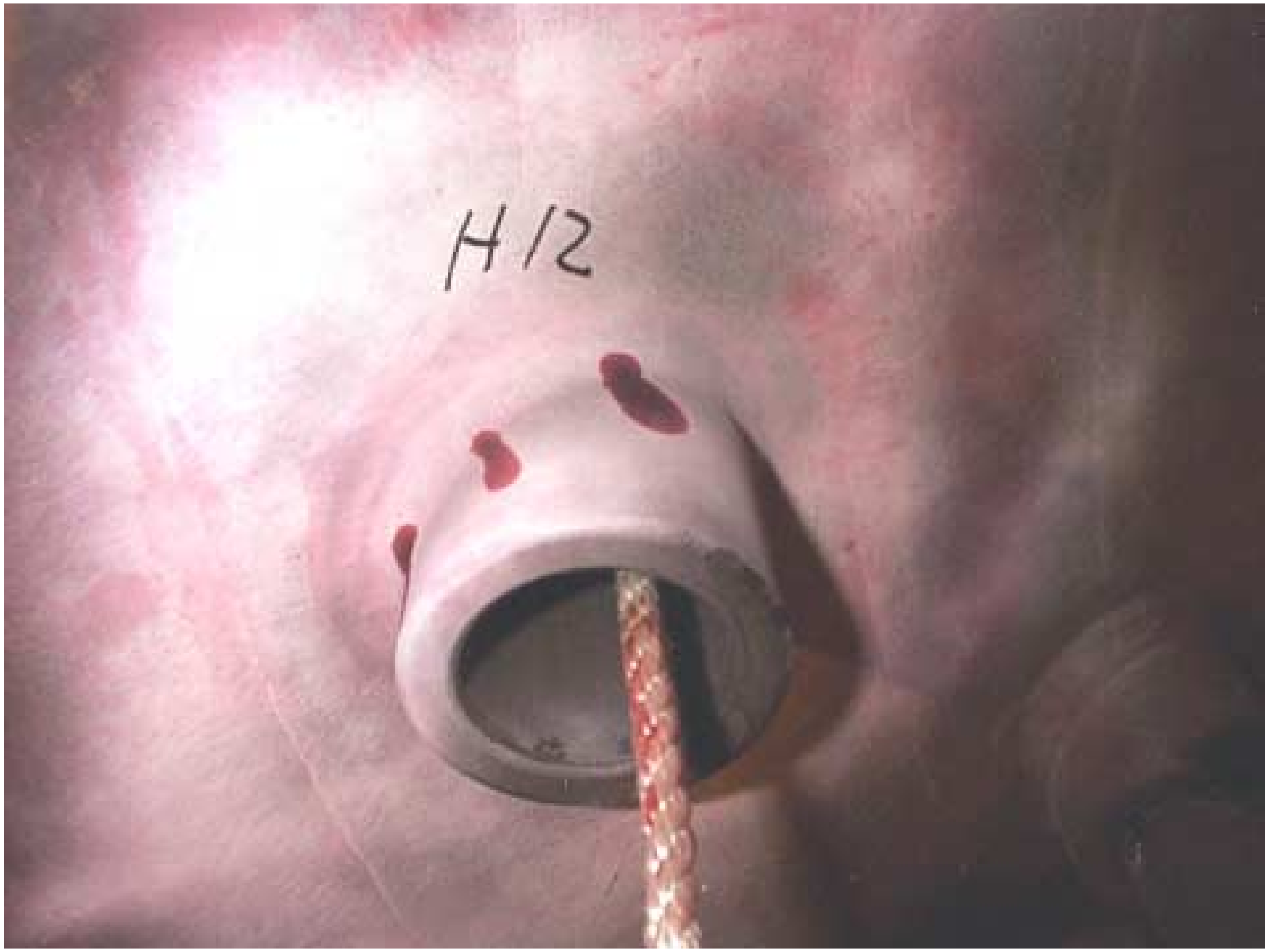
CRDM Nozzle #11



CRDM Nozzle #23



CRDM Nozzle #56

ONS 3: Summary Nozzle Indications and Characterization

- Total of 48 indications in the nine leaking CRDMs
  - 39 are axial and located beneath the weld at the uphill and downhill
  - 16 indications thru wall (39%), all are axial, and occur on 6 of 9 nozzles
- Confirmed two (2) above the weld circumferential cracks
  - Nozzle 56 crack was thru wall
  - Nozzle 50 except for pin hole indications on ID was not thru wall
  - Inspection and metallurgical results indicate the circumferential cracks were O.D. initiated.
- Unit 3 CRDMs extent of condition inspections (9 additional nozzles):
  - Cluster indications above and/or below the J groove weld.

Circumferential Cracks Above Weld

- Discovered during post weld repair NDE of Nozzles 50 & 56
- Circumferential cracks followed the weld profile contour and were O.D. initiated.
- Both ECT and UT inspections identified indications in these areas but were dispositioned as crazed cracks with unusual characteristics
- The original NDE characterization for nozzles 50 and 56 subsequently changed.
- This change in interpretation of the NDE signals is related to the flaw orientation with respect to the sound beam of the UT search units.
- Actions taken as a result of this discovery were:
  - All Unit 1 and 3 ECT and UT data re-reviewed applying the LLs
  - EPRI NDEC led an independent review of ONS 1 & 3 data to confirm results and findings

Metallurgical Examinations

- T/C nozzle specimen (2) from Unit 1
- CRDM #21 182 weld filler material boat sample from Unit 1
- CRDM nozzle end pieces (7) from Unit 3
- CRDM nozzle 56 circumferential crack boat sample, Unit 3

Unit 1: Summary Results of Metallurgical Examinations

- T/C Nozzles:
  - Cracks are intergranular and branched
  - Cracks are axial and radial in orientation
  - Material appears to be typical of mill annealed Alloy 600 with some evidence of cold working on both the OD and ID surfaces
  - Microstructure mixed with both intra and intergranular carbides
  - Microstructure characterized by small clusters of small grain with some large grains; Grain size ASTM 7-8
  - No indication of aggressive chemical species on the crack face
  - PWSCC was the primary mechanism for crack propagation

Unit 1: Summary Results of Metallurgical Examinations

- CRDM Nozzle 21:
  - Crack in weld was completely interdendritic
  - No conclusive evidence of manufacturing defects in the original weld
  - Crack in weld was connected to a branched intergranular crack in the nozzle wall
  - Qualitative comparison of boat sample to a 182 weld pad confirmed alloy type material, as expected
  - PWSCC was the primary mechanism for crack propagation in the CRDM weld and housing

Unit 3: Summary Results of Metallurgical Examinations

- CRDM Housing Material Specimen:
  - Microstructure of all nozzle materials very similar and typical for mill annealed Alloy 600. Grain size is ASTM 4.
  - Grain boundaries contain a semi-continuous carbide decoration
  - No ghost grain boundaries or segregated carbide clusters
  - All cracks in the samples were intergranular with slight branching
  - Micro-hardness survey across the thickness shows a range from about Rb 80 at the ID to Rb 95 at the OD
  - Several nozzles exhibited cracks originating at free end of nozzle
  - All cracks are stress corrosion cracks with PWSCC as the primary mechanism for crack propagation

Unit 3: Summary Results of Metallurgical Examinations

- CRDM 56 Boat Sample (Circ Crack):
  - Boat sample in the area of circ crack that was found above the weld after the weld repairs were completed
  - Boat sample contained a face of the circ crack along with 3 small axial cracks that intersect the circ crack
  - Section through the axial crack confirms crack is totally intergranular with small intergranular branches
  - Scanning electron microscopy of the circ crack face revealed only intergranular morphology.
  - There are no tears or other indications of the origin of the circ crack
  - Circ crack is indicative of PWSCC

Correlation of Observed Crack Locations with FE Stress Analysis

- Cracks are:
  - predominantly axial and located on the uphill and downhill sides of the nozzle
  - most initiate on the OD of the nozzle
  - circumferential cracks found below and above the weld, at the weld toe on the uphill and downhill sides of the nozzle

Correlation of Observed Crack Locations with FE Stress Analysis

- Stress analysis (residual + operation) preliminary results:
  - Hoop stresses exceed axial stresses at most locations which suggests axial cracking would be expected. This is consistent with observed field conditions
  - Axial stresses are higher on the uphill side of the nozzle relative to downhill side of nozzle. Field observed locations of the above the weld circumferential cracks align with this analysis prediction.
  - Microhardness measurements suggest the material yield strength is significantly higher on outside of nozzle than on the inside. The high outside yield strength may explain the preferred OD cracking

Oconee Repairs

- Repairs performed in accordance with 1992 Section XI of ASME Code, applicable Code Cases, and NRC approved alternatives, as required
- Removed flaws from both weld material and nozzle base material for Units 1 & 3
  - Automated weld process to apply protective layer over J groove weld
- Automated repair method used for Unit 2 removed cracked nozzle material and established new pressure boundary location. Cracks left in remaining J-groove weld

CRDM Nozzle #50

ANO 1 Repair

- Embedded Flaw Repair
  - OD axial flaw removed down to the butter
  - Weld repaired, isolating remaining flaw above the weld from the environment
  - Peened repair area
- Post-repair UT to confirm remaining flaw did not grow during repair process

Industry Response

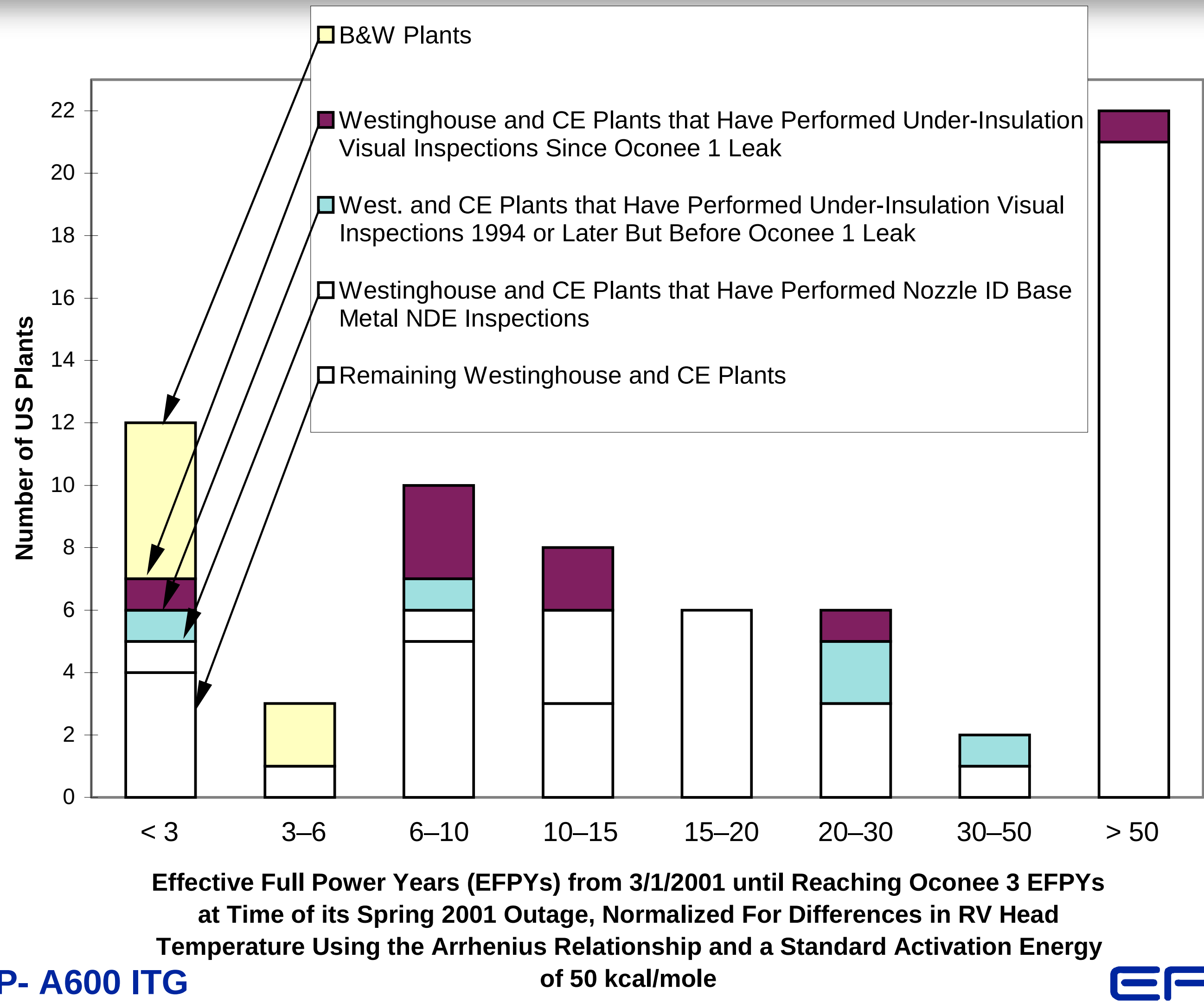
Industry Response Organization

- Integrated effort is being coordinated through
  - EPRI Materials Reliability Project - Alloy 600 ITG
    - NEI - Regulatory Interface
    - Committees Under Alloy 600 ITG
      - Assessment
      - Inspection
      - Repair/Mitigation
    - Owners Groups
- Work is being performed by
  - Utilities
  - NSSS Vendors
  - Contractors

MRP Interim Safety Assessment

- Interim Safety Assessment Submitted May 18, 2001
- Developed a Histogram of Time for Each Unit to Reach the Equivalent Time at Temperature as ONS 3 (normalized to 600F)
  - Sorted plants into bins, <3 EFPY, 3-6 EFPY, 6-10 EFPY, etc.
- Recommended Plants <10 EFPY from ONS 3 with Fall Outages perform visual inspections
  - Capable of detecting small amounts of Boron similar to ONS & ANO

Time-Temperature Histogram Chart in MRP-44 Part 2 Interim Safety Assessment



MRP Interim Safety Assessment

- Bases for No Significant Near-term Impact on Plant Safety:
  - The Three Oconee Units and ANO-1 Are Among the Lead Units in the US Based on Time at Temperature
  - Leaks Were Found by Careful Visual Inspections
  - Structural Integrity Evaluations Showed the Nozzles and Welds Were Well Within Required Margins
  - Leakage Should Also Be Detectable in Other Plants
  - Several Other Lead Units With Long Operating Times and High Head Temperatures Had Already Performed Inspections From Above and Below the Head Without Any Significant Findings
  - A CRDM Nozzle Ejection Is an Analyzed Event in Plant FSARs
  - Existing Symptom Based EOPs and Operator Training Adequate

NRC Questions

- NRC identified several questions on May 25, 2001:
  - Leak detection
    - Effect of initial interference fit on leak detection
  - Time-temperature histogram
    - Effect of activation energy on predictions
    - Benchmarking against foreign plant inspections
    - Basis for ten year inspection criterion
  - Growth rate of circumferential cracks
    - Time until Oconee 3 would have reached allowable flaw size
    - Effect of crack growth rates on histogram
  - Loose parts
  - Risk assessment

NRC Questions

- NRC Documented Those and Asked Additional Questions on June 22, 2001:
  - Photos of visual inspections performed at other units
  - Inspection Capabilities
    - Ability to Perform Volumetric NDE
      - Nozzles for ID/OD Flaws
      - J-groove Welds
    - Estimate of Number, Time, Other Costs to Perform Volumetric and Visual Inspections by 1/1/2002
      - During Scheduled Outage
      - During Unscheduled Outage

Safety Assessment Status

- The Interim Safety Assessment was prepared to demonstrate safety of operating plants
- Additional effort is ongoing in several areas
  - Analysis associated with the Final Safety Assessment
  - Visual inspections of the reactor vessel top head surface for plants coming down for Fall 2001 refueling outages
  - Research into improved inspection and repair technology
  - Risk assessment
- Results will be factored into the Final Safety Assessment

Leakage Detection

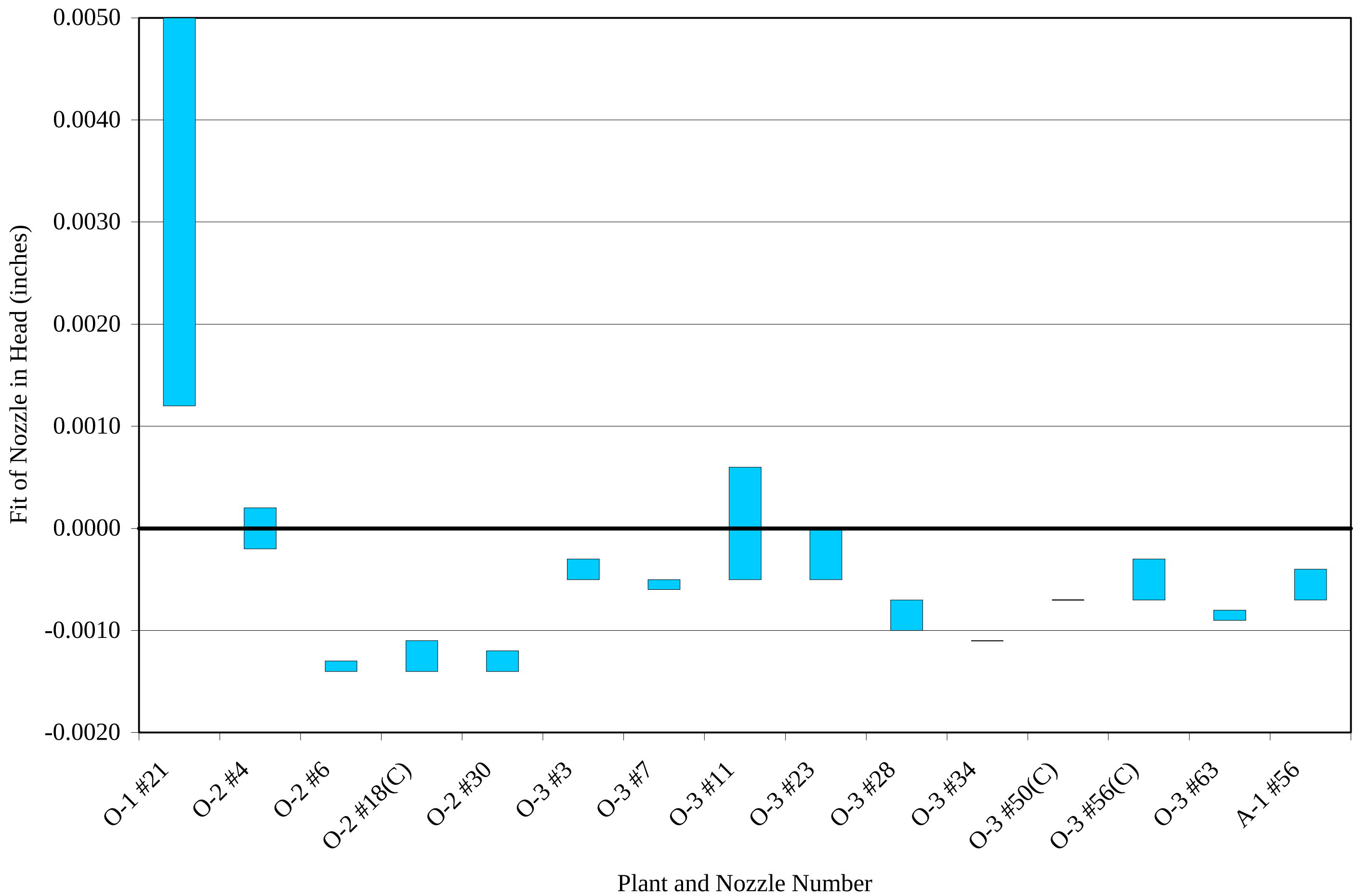
Leakage Detection

- Oconee and ANO-1 detected leakage, but
  - Some other plants have greater interference fits (see Table 3-2 of Interim Safety Assessment)
- Leakage should be detectable at most other penetrations given similar cracks
  - Only minor craze cracking was found in NDE examinations of 17 additional "non-leaking" Oconee 1 and 3 CRDM nozzles. This supports appropriateness of visual inspections for detection of through-wall cracks in CRDM nozzles
  - Interference fits at other plants are only slightly larger than Oconee and ANO-1
  - Further experience has shown that it is difficult to prevent leakage of 2,250 psi water without roll, hydraulic or explosive expansion or use of a sealant

Leakage Detection
Actual Fits at Oconee and ANO-1

- Fabrication records for Oconee 1, 2, and 3 and ANO-1 vessel heads have been reviewed
- The following measurements were taken
  - ID of the hole in the vessel head at the top and bottom of the interference fit region
  - OD of the nozzle
- Results for the 14 leaking CRDM nozzles at Oconee 1, 2, and 3 and ANO-1 are shown on next slide
  - One nozzle had a clearance fit (gap)
  - The remaining nozzles had at least one end within the specified diametral interference range of 0.0005 - 0.0015 inches. Three of the four leaking ONS 2 nozzles had interference fits of 0.0014 inches on one end and at least 0.0011 inches on the other.

Leakage Detection
Actual Fits at Oconee 1, 2, and 3 and ANO-1



Leakage Detection
Effect of Operating Conditions on Fit

- Differential thermal expansion has only a small effect, increasing the initial interference fit by <0.0014”
- The change in fit under operating conditions is primarily due to pressure dilation of the vessel head
- For the example, the change in diametral fit due to pressure dilation is approximately
  - $\Delta D = 0.00402'' - 0.00048'' = 0.0035''$
  - The hole will open up further when the effect of reduced effective modulus due to the effect of multiple nozzles is considered
- Therefore annular gaps are expected for most CRDM nozzles under operating conditions

Leakage Detection
Other Effects on Fit

- Finite element analyses show that outer row CRDM nozzles displace laterally and become slightly ovalized in the vessel head as a clearance opens up under operating conditions
  - The displacement and ovalization reduce the leak path at some locations and increase the leak path at other locations
  - The net effect is to create a spiral flow path which has less resistance than a uniform annular gap
- Finite element analyses also show a minor (~20%) increase in ovality for peripheral CRDMs from flange tensioning and rotation

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Visual Inspections Spring 2001

- Several other plants performed visual inspections during Spring outages
  - Robinson 2
  - Salem 1
  - Farley 2
  - Prairie Island 1
  - McGuire 1 (partial)
  - SONGS 3 (partial)
- Heads reasonably free of masking boric acid deposits
- No evidence of leakage found

Visual Inspection
Salem 1

EPRI

Time Temperature Histogram

Time-Temperature Histogram Background

- The time-temperature model groups plants according to the time (EFPY) required for each unit to reach the equivalent effective time at temperature as Oconee 3 at the time the above-weld circumferential cracks were discovered in February 2001
- The reference date for the time-temperature assessments is March 1, 2001
- The industry standard activation energy of 50 kcal/mole for PWSCC initiation in Alloy 600 material was used to normalize plant operating time to a head temperature of 600°F

Time-Temperature Histogram Effect of Activation Energy (cont.)

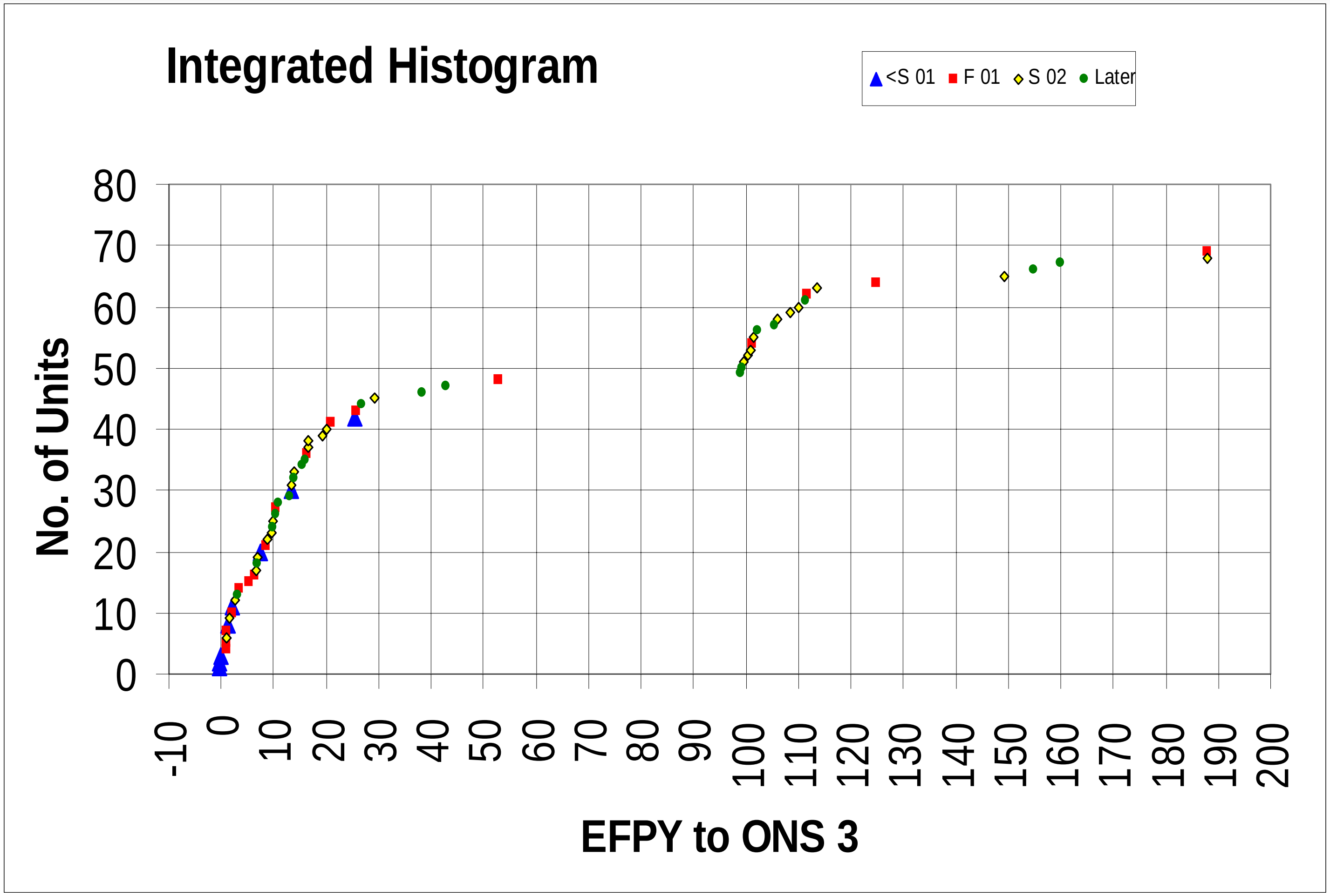
- A sensitivity study for the results of the plant assessments was performed
- The effect is small, as shown below:

Activation Energy	*Assessment Groups*							
	< 3 EFPYs	3–6 EFPYs	6–10 EFPYs	10–15 EFPYs	15–20 EFPYs	20–30 EFPYs	30–50 EFPYs	> 50 EFPYs
50 kcal/mole	**12**	**3**	**10**	**8**	**6**	**6**	**2**	**22**
40 kcal/mole	**12**	**4**	**14**	**9**	**4**	**3**	**2**	**21**

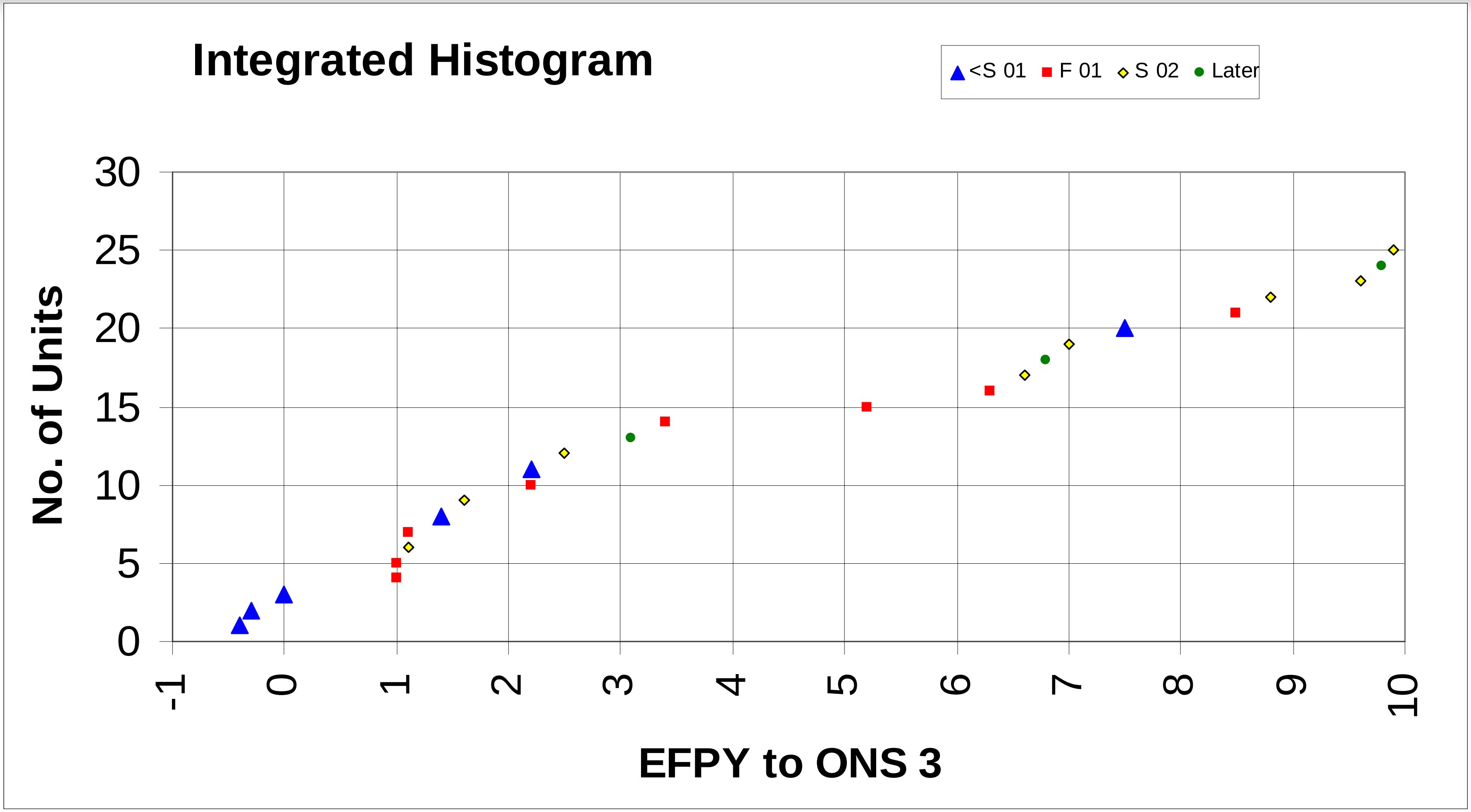
Time-Temperature Histogram
Ten-Year Period

- 10 Year Period for Near-Term Inspection
  - The ten year period for recommending visual inspections of the top of the vessel head for small amounts of leakage similar to that observed at Oconee and ANO-1 was selected to provide some margin for uncertainties
  - Encompasses 25 units
  - All but two will have outages by Spring '02
  - The ten year period will be re-assessed based on results of upcoming outages

Time-Temperature Histogram



Time-Temperature Histogram



Circumferential Crack Growth Growth Rate in Annulus Environment

- Data are available from 5 sources for carefully controlled PWSCC tests of Alloy 600 and 182, using PWR conditions
- OD initiated cracking requires the presence of water or steam, so a pressure boundary leak is necessary
- The crevice region could contain some Oxygen from the containment atmosphere, but at temperature this Oxygen would be quickly consumed by reaction with the low alloy steel nearby
- This reaction, plus the extremely tight fit and the distance to the OD of the head, make a high Oxygen environment unlikely

Crack Growth

Circumferential Crack Growth Growth Rate in Annulus Environment

- Since the fluid will contain lithium hydroxide and boric acid, it will likely be similar to a controlled PWR environment
- Comparison of BWR and PWR crack growth rates for Alloy 600 and 182 shows that, at a given temperature, the growth rates are comparable
- Temperature is a stronger variable than environment for these materials
- MRP has scheduled an international expert panel to assess crack growth rates
  - Initial meeting in August

Circumferential Crack Growth Margin for Oconee 3 Cracks

- Two Oconee 3 nozzles were cracked approximately 165°
- Stress analyses show that cracks initiated in a high stress region and propagated into a lower stress region
- The remaining time for Oconee 3 circ cracks to reach ASME Code allowable ligament (safety factor of 3) was estimated to be 4-5 years, based on the modified Peter Scott model and also by assuming the maximum crack growth measured in lab
- Efforts are underway to refine the stress intensity calculations in the nozzle in the intact and cracked conditions

Loose Parts & Risk Assessment

Loose Parts

- The potential for, and consequences of, loose parts in B&W designed plants such as Oconee and ANO-1 was described to the NRC on April 12, 2001
- Creation of loose parts was deemed unlikely
- Worst postulated condition is a single stuck rod
- While analyses for other plant designs have not been completed, results are expected to be similar
- Loose parts analyses will be included in final report

Risk Assessment

- Risk calculations are in process now
- The effort includes interaction with all PWR vendors and others to ensure applicability to all plants
  - Consistent with past approaches
- Staff has conservatively estimated CCDP about 10-3, assuming rod ejection, but probability of ejection event likely to be a few orders of magnitude less than 1 for all plants

Summary & Ongoing Activities

Summary

- Near Term Conclusion:
  - Axial cracks alone in CRDM nozzles do not impact plant safety
    - Bounded by previously submitted Safety Assessments (1993/94)
    - But through wall axial cracks can be a precursor to circumferential cracking
  - There is reasonable assurance that PWRs do not have circumferential cracking that would exceed structural margin
    - Oconee and ANO-1 in highest grouping based on effective time-at-temperature
    - Leaks discovered by careful visual inspection of top head surface
    - Volumetric examination of other nozzles found only minor craze cracks
    - Leaks discovered with significant structural margin remaining
    - Several other plants in highest groupings have no evidence of leakage

Schedule

- Revised Inspection Recommendations - July-August
- Expert Panel on Crack Growth - First Meeting 8/01
- Inspections during Fall 2001 outages
- Final RPV Penetration Safety Assessment - 12/01
- Reassessment of Inspection Recommendations - 2/02

Other Ongoing MRP Activities

- Risk Assessments
- Probabilistic Fracture Mechanics
- NDE Demonstration
  - Block Design and Fabrication
  - Technique Development and Demonstration
- Information and Training Package for Visual Examination
- Flaw Evaluation Guidelines
- Review of Repair and Mitigation Strategies