



Oconee Unit 1 & Unit 3 Reactor Vessel Head Leakage

Cracking of RV Head Penetrations
Due to Primary Water Stress
Corrosion Cracking (PWSCC)

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Discussion Outline

- ◆ Oconee Unit 1 and 3 Background
- ◆ Investigations Performed
 - Non-Destructive Examinations
 - Metallurgical Examinations
 - Analytical Evaluations
- ◆ Summary of Indications and Characterizations
- ◆ Repair Plans
- ◆ Nuclear Safety Significance

Background

- ◆ 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.

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

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.
- ◆ Four heats of material used in ONS -1 (M1723,C2649,M1228, M2559); Unit 3 has 2 heats of material (M3935,C2649)
- ◆ CRDM nozzles were shrink fit into reactor vessel head penetration and welded with a J-groove weld with Alloy 600 filler

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.

CRDM Nozzle Penetration Machining & Buttering Process



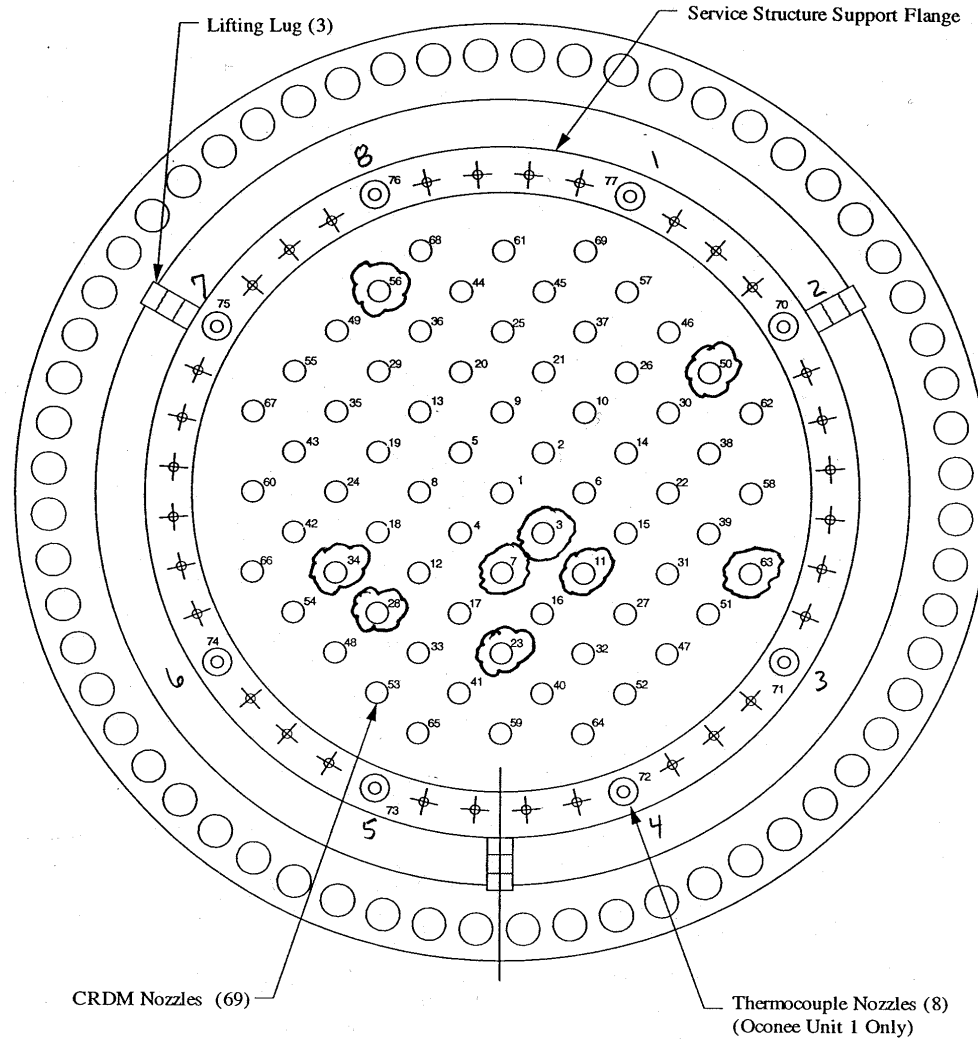
- ◆ Penetration buttered with Alloy 182 weld metal using SMAW
- ◆ Rough machine CRDM penetration in closure head
- ◆ Layout J groove weld preps at each penetration
- ◆ Form J groove weld preps (air arc)
- ◆ Grind J groove for MT and welding
- ◆ Inspect, MT, and repair, if necessary
- ◆ Inspect, and MT repairs, if necessary
- ◆ Butter J groove per Welding Data Sheet
- ◆ Inspect, grind, and PT J groove butter
- ◆ Repair, if necessary
- ◆ Inspect and PT repair, if necessary
- ◆ Final stress relieve closure head at 1100F to 1150F for 8 hours minimum
- ◆ Final machine clad J grooves
- ◆ Grind, inspect, and PT J grooves
- ◆ Final machine CRDM penetrations, including counterbore
- ◆ Inspect and MT penetrations

CRDM Nozzle to Reactor Vessel Closure Head Assembly Process

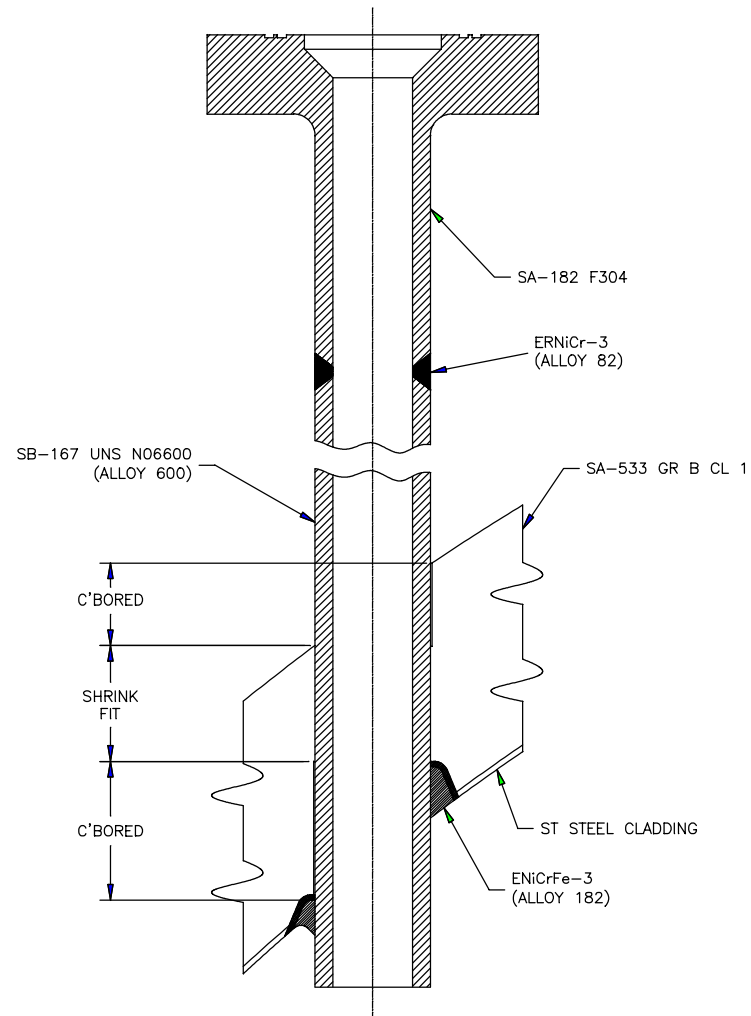


- ◆ Machine OD of nozzle to corresponding closure head penetration diameter
 - Maintain diametrical interference
 - Cool nozzle to -140F
- ◆ Install CRDM nozzle into corresponding closure head penetration
- ◆ Allow nozzle to warm to 70F minimum
- ◆ Inspect nozzles and tack weld per Welding Data Sheet
 - SB-167 to Alloy 182 buttering using E-NiCrFe-3 filler
- ◆ Inspect tack welds
- ◆ Build up CRDM nozzle to head weld per Welding Data Sheet
- ◆ Grind, PT and inspect each 9/32" of weld as it is built up
- ◆ Repair weld as it is built up, if necessary
- ◆ Grind and PT repairs, if necessary
- ◆ Put down grind bead, TIG
- ◆ Grind radius, PT, and repair
- ◆ Final inspection

CRDM Nozzle Layout



Schematic View of B&W-Design CRDM Nozzle Area



CRDM Nozzle #56



CRDM Nozzle #50



CRDM Nozzle #11



Investigations Performed

- ◆ 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

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
 - ◆ 69 Unit 2 CRDM nozzles (1994 inspection)
 - ◆ 8 Unit 2 CRDM nozzles (1999 inspection)
 - ◆ 18 Unit 3 CRDM nozzles

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
 - ◆ 2 nozzles on Unit 2 (1996 inspection)

- ◆ 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)

Inspections: Eddy Current Testing

- ◆ ID ECT inspection using motorized rotating pancake coil probe with 3 coil configurations.
 - Design includes differential pancake coil w/ 45 degree offset operated in differential and absolute modes, a mid-frequency plus coil configuration, and a circumferential oriented coil.
 - Data acquired in a helical scan using FTI top down manipulator as shown during EPRI spring '96 demonstration.
 - All probes were run at frequencies of 600, 280 and 100 kHz.

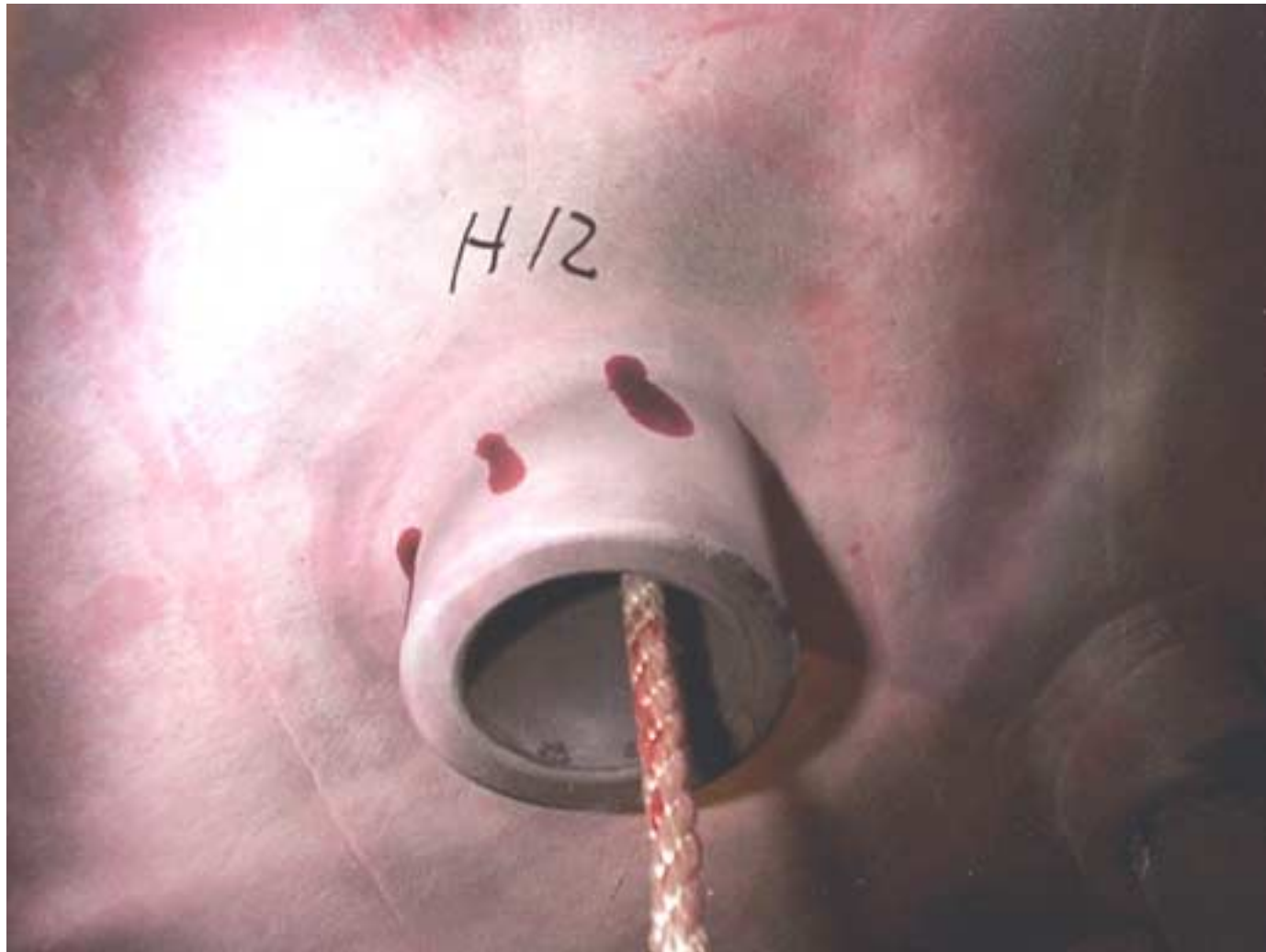
Inspections: Ultrasonic Inspections

- ◆ The ID UT inspection was performed using a CRDM nozzle transducer package that contains three transducer configurations.
 - The package includes a forward and backward scatter time of flight configuration for flaw characterization and a 0 degree longitudinal wave configuration for weld profiling.
 - Data was acquired in a circumferential scan path using the Framatome top down manipulator.
 - CRDM transducer package was demonstrated during an EPRI 1993 performance demonstration.

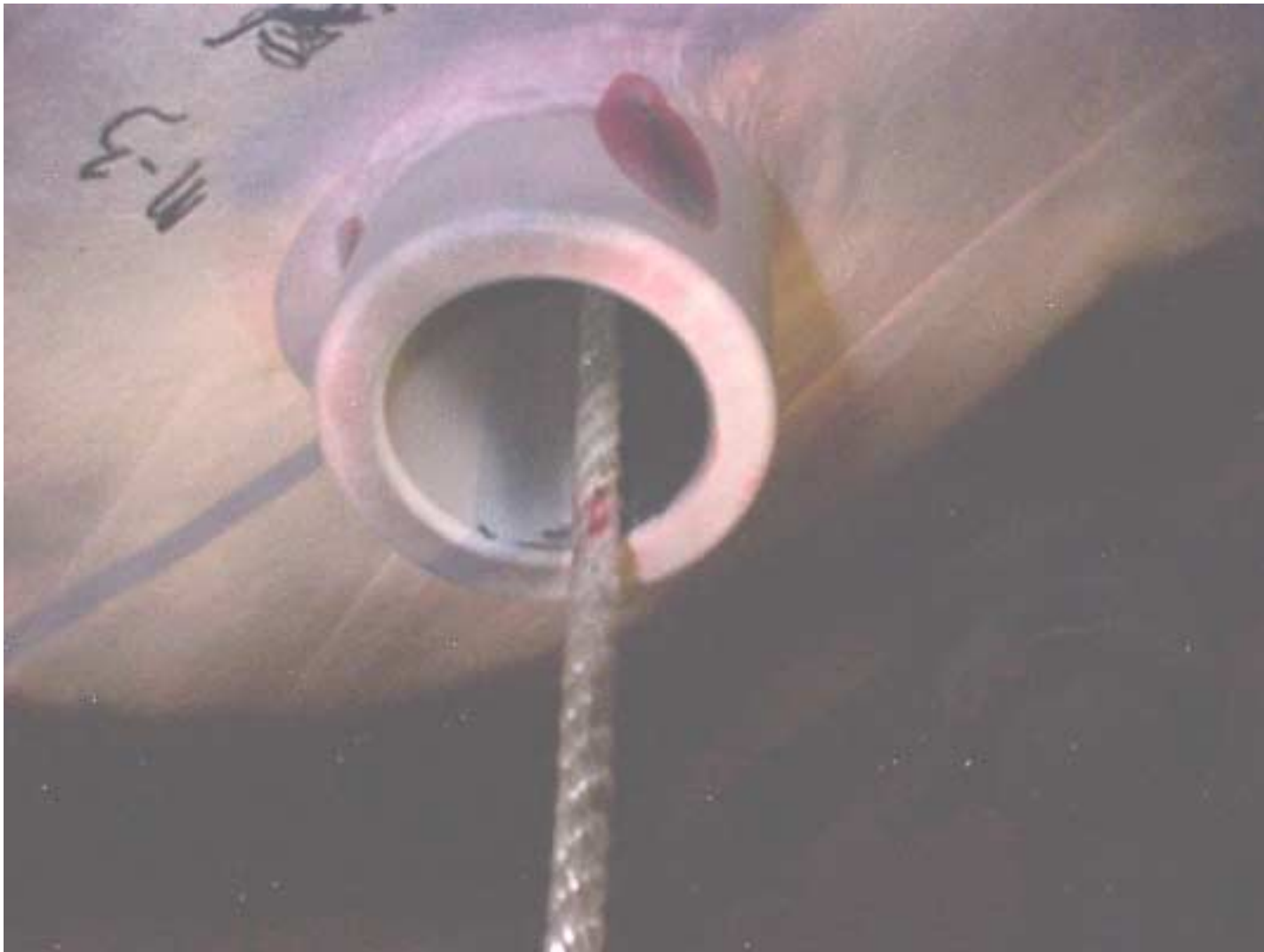
CRDM Nozzle #11



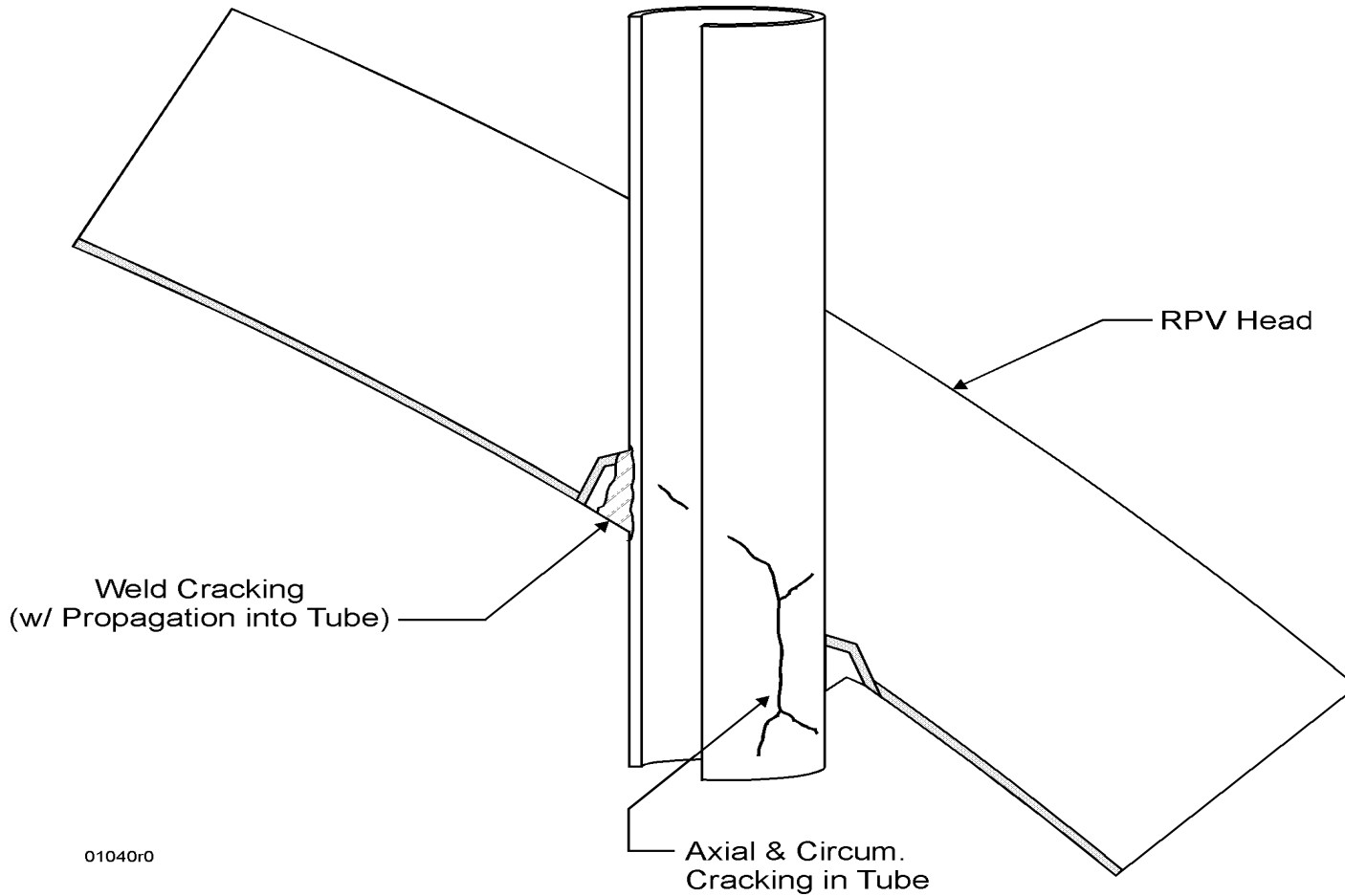
CRDM Nozzle #23



CRDM Nozzle #56



CRDM Nozzle Cracks at ONS 1 & 3



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UNIT 1 - SUMMARY OF NOZZLE INDICATIONS & CHARACTERIZATION



Nozzle	
#21	<ul style="list-style-type: none"> ▪ Crack originated in 182 weld filler material and later moved into wall of CRD nozzle ▪ Crack was radial and axial ▪ No circumferential crack
T/C 1-8	<ul style="list-style-type: none"> ▪ Numerous axial cracks both above and below weld ▪ Weld profile significantly larger than specified by design
21,42, 49,55, 56,61, 67,68	<ul style="list-style-type: none"> ▪ ECT inspection for extent of condition ▪ Nozzles 61,67,68 craze cracks above and below weld ▪ Flaw length about 78mm and about 3mm deep ▪ Other nozzles clear of indications

UNIT 3 - SUMMARY OF NOZZLE INDICATIONS & CHARACTERIZATION



Nozzle	
# 11	<ul style="list-style-type: none"> ▪ 7 Axial and 3 Circumferential Cracks ▪ 3 Axial thru wall, 2 > 75% thru wall, 2 about 50% thru wall ▪ 3 thru wall are 3" long, 2 > 75% are 3" long, 2 about 50% < 1" long ▪ All circ below weld, 1 is 10%, 1 is 57%, 1 is 70% thru wall ▪ Deep circ crack is about 5.3" long, mid circ crack is 3.9" long ▪ Areas of craze cracking above and below weld at high side
#23	<ul style="list-style-type: none"> ▪ 6 Axial and 2 Circumferential Cracks ▪ 2 Axial thru wall, 4 are 30% to 67% thru wall ▪ 2 thru wall are .6" and 3.8" long, 4 are 0.5" to 1.1" long, both circ below weld, 1 is 77% thru wall, other is 67% thru wall ▪ Circ cracks are about 2" long ▪ Areas of crazed cracking above weld at high side

UNIT 3 - SUMMARY OF NOZZLE INDICATIONS & CHARACTERIZATION



Nozzle	
#28	<ul style="list-style-type: none">▪ 5 Axial and 1 shallow Circumferential Crack below weld▪ All 5 axial thru wall, All between 1.2” and 2” long▪ Areas of crazed cracking above weld at high side
#34	<ul style="list-style-type: none">▪ 1 Axial and no circumferential cracks▪ Axial is 35% thru wall and 2” long▪ Areas of crazed cracking above and below weld at high side
#50	<ul style="list-style-type: none">▪ 3 Axial and 2 Circumferential Cracks▪ 2 Axial thru wall, 1 94% thru wall▪ Thru wall are between 1.2” and 3” long▪ Circ below weld was thru wall and 2.4” long▪ Circ crack is above weld and about 2.4” long

UNIT 3 - SUMMARY OF NOZZLE INDICATIONS & CHARACTERIZATION



Nozzle	
#56	<ul style="list-style-type: none"> ▪ 3 Axial and 1 Circumferential Cracks ▪ 1 axial thru wall, One 38% thru wall, One 11% thru wall ▪ Thru wall is 1.7” long, mid depth .75” long, shallow is 1.6” long ▪ Circ crack above weld near high side and about 2.4” long
#3	<ul style="list-style-type: none"> ▪ 7 Axial and no circumferential cracks ▪ No Axial thru wall, all between 33% and 65% thru wall ▪ All between .3” and 1” long ▪ Areas of crazed cracking below weld at high side
#7	<ul style="list-style-type: none"> ▪ 1 Axial and no Circumferential Cracks ▪ Axial is 87% thru wall, 2.3” long ▪ Areas of crazed cracking below weld at high side

UNIT 3 - SUMMARY OF NOZZLE INDICATIONS & CHARACTERIZATION



Nozzle	
#63	<ul style="list-style-type: none">▪ 6 Axial and no Circumferential Cracks▪ 3 axial thru wall, 2 are 80% thru wall, One 49% thru wall▪ Thru wall between 1.7” and 3.3” long, others between .9” and 3.1” long
4,8,10, 14,19, 22,47, 64,65	<ul style="list-style-type: none">▪ Cluster indications on all listed nozzles▪ Maximum depth measured 1.75 mm▪ Examined for extent of condition

Unit 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 has been re-reviewed applying the LLs
 - EPRI NDEC is leading 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
- ◆ The cracks are stress corrosion with primary water as the corrodent

Unit 1: Summary Results of Metallurgical Examinations



CRDM Nozzle 21:

- ◆ Crack in weld was completely interdendritic
- ◆ PWSCC was the primary mechanism for crack propagation in the CRDM weld and housing
- ◆ 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

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:
 - predominately 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
- ◆ Stress analysis preliminary results:
 - Hoop stresses exceed axial stresses at most locations which suggests axial cracking would be expected. This is consistent with observed field conditions

Correlation of Observed Crack Locations with FE Stress Analysis



Stress analysis preliminary results:

- ◆ Hoop stresses are greatest at both uphill and downhill sides of nozzle. Reasonably good agreement with axial crack locations from field observations.
- ◆ Axial stresses tend to be higher on the uphill side of the nozzle relative to downhill side of nozzle. Field observed locations of the circumferential crack locations, under the weld on downhill side does not 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

Root Cause

Root Cause determination for Unit 1 & 3 RPV closure head penetration leakage is PWSCC.

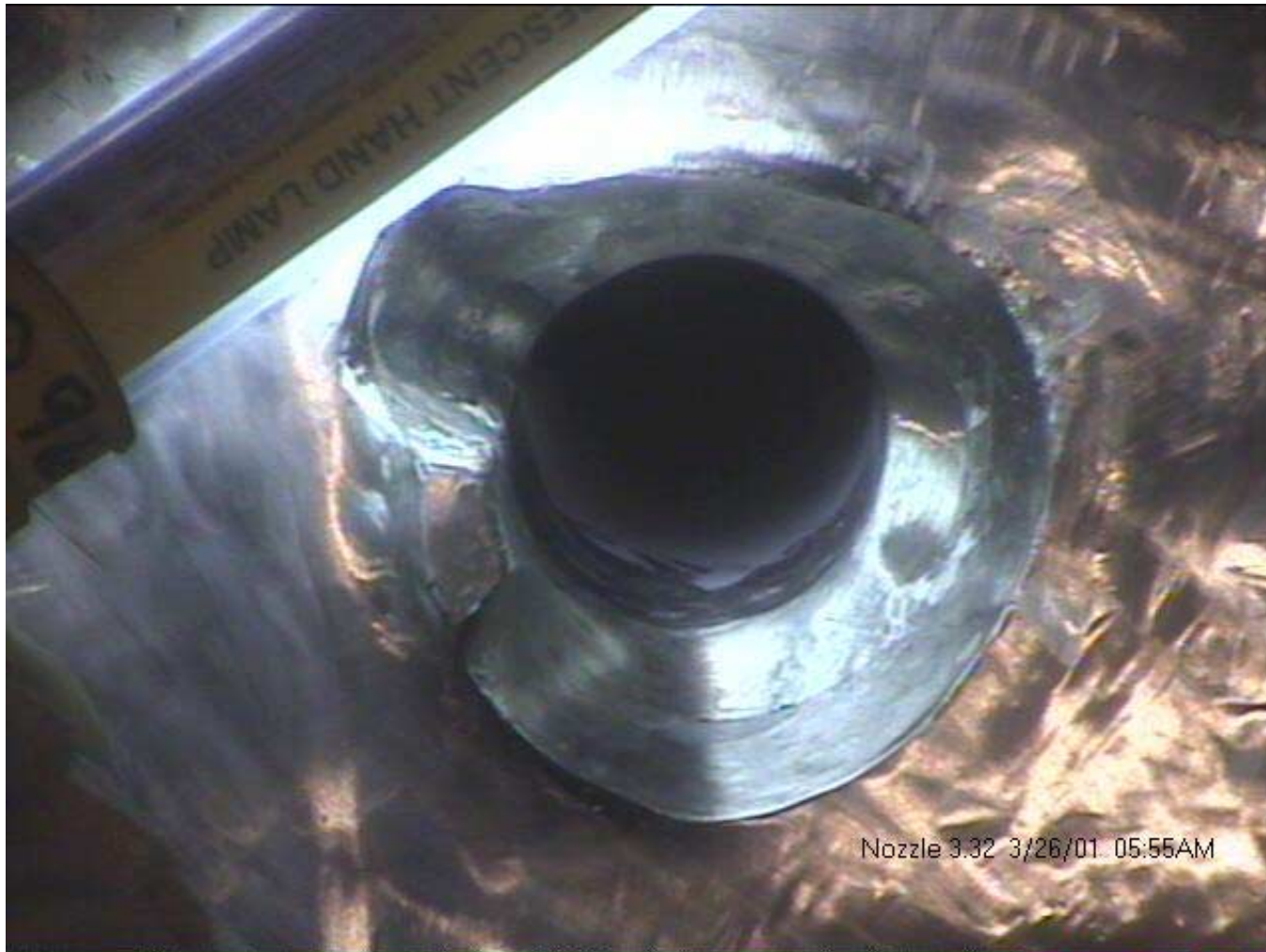
This determination is based on:

- metallographic examinations
- correlation of crack location and orientation with results of FEA
- evaluation & disposition of other potential failure modes

Current Repair Plans

- ◆ Repairs being performed in accordance with 1992 Section XI of ASME Code
- ◆ Removing all flaws entirely from both weld material and nozzle base material
- ◆ Use temper bead weld repair process to replace the weld
 - Code requirement since excavation entered the “buttering”.
 - Involves heating the RV head to 500 degrees F.
- ◆ Automated weld process to apply protective layer over J groove weld

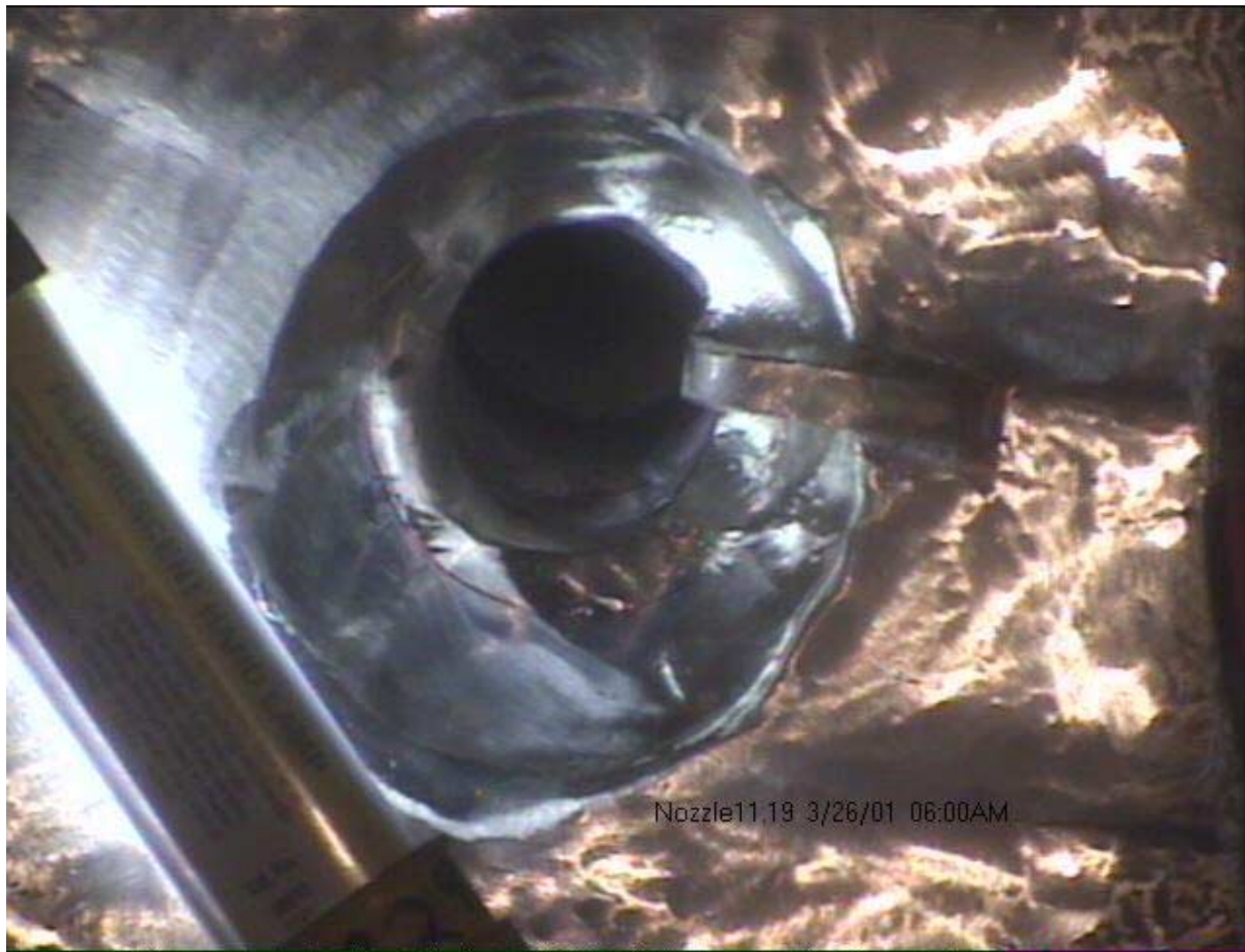
CRDM Nozzle #3



CRDM Nozzle #7



CRDM Nozzle #11



CRDM Nozzle #50



Radiation Dose and Worker Safety

- ◆ Projected dose for the Unit 3 RV head repair is approximately 280 Rem.
- ◆ Unit 1 dose for CRDM and T/C repairs was 67 Rem.
- ◆ Specialized shielding booths have been designed and used to limit dose to personnel performing PTs, grinding and welding under the head.
- ◆ Aggressive decontamination (high pressure spray) performed on the underside of the head to lower dose.
- ◆ Workers are wearing bubble hoods and layers of anti-contamination and protective clothing.
- ◆ Air arc gouging tool is being used to reduce the amount of time spent under the RV head excavating weld material.

Future Plans

- ◆ Continue working with NEI, EPRI, industry groups on inspection and repair techniques.
- ◆ Continue head inspection program, maintaining the RV head clean to enhance inspection capability.
- ◆ An automated ID Temper Bead Repair method which moves the pressure boundary higher in the RV head above the original J-groove weld is being developed for future repairs.
- ◆ Long term solution for Oconee is to replace the RV heads on all three units.

Nuclear Safety Significance

- ◆ We understand why we're having these leaks - - PWSCC with susceptible material.
- ◆ Significant amount of work performed by EPRI, industry and NRC to gain an understanding of this phenomenon and the experiences at ONS will advance level of knowledge.

Nuclear Safety Significance

- ◆ The BWOGE/EPRI MRP is completing a nuclear safety assessment, focusing on PWSCC in CRDM weld materials, loose parts, and circumferential cracks above weld as a result of the Oconee experience.

- ◆ Worldwide operating experience has identified 45 plants with PWSCC issues over the last 15 years.
 - All instances involve minor leakage, not component failure
 - Actual Oconee experience supports conclusion that these components will leak before failure.

Nuclear Safety Significance

- ◆ Accident associated with complete failure of nozzle or weld is rod ejection accident.
 - Safety analysis for this accident is included in the Oconee UFSAR.
 - Procedures and training are in place to respond to this type of accident.

- ◆ Structural failure requires a circumferential crack, either:
 - through the nozzle wall above the weld, initiating from the inside or outside diameter of the nozzle

or

 - through the weld, initiating from the surface and growing both axially and circumferentially up the nozzle-weld interface.

Nuclear Safety Significance

- ◆ Circ Flaw through Nozzle
 - Must leak before circumferential cracking can begin on nozzle O.D.
 - Once initiated, it would conservatively take more than 6 years to grow through wall.
 - Prior to Oconee Unit 3, operating experience identified only one example of circ cracking above the weld and the leak was found prior to significant cracking.
- ◆ Flaw though Weld
 - Would leak prior to crack growing completely through and around weld
 - Hoop stresses would cause axial crack propagation in preference to circumferential cracking
 - Axial crack would leak in as little as 7 years

Nuclear Safety Significance

Conclusions:

- ◆ CRDM nozzles leak well before reaching the point of complete nozzle failure.
- ◆ Axial cracking is the predominant cracking orientation.
- ◆ The amount of leakage is small and plant inspections are successful in identifying nozzles that do leak even a small amount.