PWR Alloy 690 Replacement Pressure Boundary Components

Material Production and Component Fabrication/Installation Practices

Presented To:

Alloys 690/52/152 PWSCC Research Test Materials Meeting
Industry/NRC RES

Presented By:

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Project Goals

- Collect material information relevant to plant installation of Alloy 690 J-groove nozzles
  - Mill manufacturing process for pipes and bars
  - Fabrication and installation practices
  - Data relevant to level of plastic strain
- Investigate applicability of laboratory crack growth rates for highly cold-worked Alloy 690 samples to actual plant installations of replacement Alloy 690 base materials
  - Bettis data
  - ANL data
  - GE/GRC data

Project Status

- Draft EPRI report completed December 31, 2007
  - Section 1: Introduction
  - Section 2: Alloy 690 Material Production and Component Fabrication/Installation Practices
  - Section 3: FEA Calculations of Alloy 690 Base Metal Residual Plastic Strain
  - Section 4: Summary and Conclusions
  - Section 5: References
- Study concentrated on CRDM nozzles because of the large number of U.S. plants that have replaced or plan to replace the reactor vessel head

Alloy 690 Suppliers and RV Head Manufacturers

Alloy 690 Suppliers

- Sandvik
- Special Metals (Huntington Alloys)
- Sumitomo Metals/ Hitachi Metals
- Teledyne Allvac
- Valinox

RV Head Manufacturers

- MHI
- AREVA
- B&W (Canada)
- ENSA

Alloy 690/52/152 Replacements in US PWRs

(excluding SG tubes, through mid-2004, from MRP-110 (EPRI 1009807))

Location	Component Item	Wrought Material	Weld Materials	Plant	Date Replaced	Calendar Years at 3/2004	# Parts	Temp.[3] (°F)	Approx. EFPY at 3/2004	Approx. EDY at 3/2004[4]	Part-EFPYs	Part-EDYs
RV Closure Head	CRDM Nozzle	None	Alloy 52/152	ANO 1	10/2002	1.4	6	602	1.3	1.4	7.9	8.5
		Alloy 690	Alloy 52/152	Crystal River 3	11/2003	0.3	69	601	0.3	0.3	20.5	21.3
		Alloy 690	Alloy 52/152	Ginna	10/2003	0.4	37	580	0.3	0.2	12.9	5.7
		Alloy 690	Alloy 52/152	Millstone 2	03/2002	2.0	3	594	1.9	1.4	5.6	4.3
		Alloy 690	Alloy 52/152	North Anna 1	04/2003	0.9	65	600	0.8	0.8	52.4	52.4
		Alloy 690	Alloy 52/152	North Anna 2	02/2003	1.1	65	600	1.0	1.0	64.9	64.9
		Alloy 690	Alloy 52/152	Oconee 1	12/2003	0.2	69	602	0.2	0.2	13.5	14.6
		None	Alloy 52/152	Oconee 2	05/2001	2.8	4	602	2.6	2.8	10.5	11.4
		None	Alloy 52/152	Oconee 2	10/2002	1.4	15	602	1.3	1.4	19.7	21.3
		Alloy 690	Alloy 52/152	Oconee 3	06/2003	0.7	69	602	0.7	0.7	45.5	49.3
		None	Alloy 52/152	St. Lucie 2	06/2003	0.8	2	596	0.7	0.6	1.4	1.2
		Alloy 690	Alloy 52/152	Surry 1	06/2003	0.7	65	598	0.7	0.6	43.2	39.8
		Alloy 690	Alloy 52/152	Surry 2	11/2003	0.3	65	598	0.3	0.3	17.8	16.4
		Alloy 690	Alloy 52/152	TMI 1	12/2003	0.2	69	601	0.2	0.2	15.6	16.2
Hot Leg	Instrument Nozzle	Alloy 690	Alloy 52	ANO 1	02/2000	4.1	6	602	3.8	4.1	22.7	24.6
		Alloy 690	Alloy 52/152	ANO 2	07/2000	3.7	1	608	3.4	4.7	3.4	4.7
		Alloy 690	Alloy 52	Davis Besse	01/2003	1.2	4	605	0.0	0.0	0.0	0.0
		Alloy 690	Alloy 52	Palo Verde 1	10/1999	4.4	2	614	4.1	7.1	8.2	14.3
		Alloy 690	Alloy 52	Palo Verde 1	05/2001	2.8	15	614	2.6	4.6	39.3	68.7
		Alloy 690	Alloy 52	Palo Verde 1	11/2002	1.3	10	614	1.2	2.2	12.3	21.5
		Alloy 690	Alloy 52	Palo Verde 2	12/1991	12.3	8	614	10.0	17.4	79.7	139.3
		Alloy 690	Alloy 52	Palo Verde 2	11/2000	3.3	9	614	3.1	5.4	27.7	48.4
		Alloy 690	Alloy 52	Palo Verde 3	05/2000	3.8	4	614	3.5	6.2	14.2	24.8
		Alloy 690	Alloy 52	Palo Verde 3	11/2001	2.3	13	614	2.2	3.8	28.0	49.0
		Alloy 690	Alloy 52	Palo Verde 3	05/2003	0.8	10	614	0.8	1.4	7.7	13.5
		Alloy 690	Alloy 152	San Onofre 2	06/1993	10.8	1	595	9.2	7.5	9.2	7.5
		Alloy 690	Alloy 152	San Onofre 2	02/1998	6.1	11	595	5.6	4.6	61.6	50.3
		Alloy 690	Alloy 152	San Onofre 2	02/1999	5.1	20	595	4.7	3.8	93.9	76.7
		Alloy 690	Alloy 152	San Onofre 3	07/1995	8.7	2	595	7.4	6.0	14.8	12.0
		Alloy 690	Alloy 152	San Onofre 3	04/1997	6.9	8	595	5.9	4.8	47.0	38.4
		Alloy 690	Alloy 152	San Onofre 3	03/1998	6.0	7	595	5.6	4.5	38.9	31.7
		Alloy 690	Alloy 152	San Onofre 3	04/1999	4.9	15	595	4.6	3.7	68.3	55.7
		Alloy 690	Alloy 52	St. Lucie 1	04/2001	2.9	1	604	2.7	3.2	2.7	3.2
		Alloy 690	Alloy 52	St. Lucie 2	12/1995	8.3	9	604	7.1	8.3	63.6	74.7
		Alloy 690	Alloy 52	St. Lucie 2	06/2003	0.7	10	604	0.7	0.8	6.9	8.2
		Alloy 690	Alloy 52	Waterford 3	10/2000	3.4	3	605	3.2	3.9	9.5	11.6
	RV HL Safe End	None	Alloy 52	V.C. Summer	10/2000	3.4	1	619	3.2	6.7	3.2	6.7
	Surge Nozzle Weld	None	A52 Weld Overlay (O.D. of Pipe)	TMI 1	12/2003	0.2	1	603	0.2	0.3	0.2	0.3

Alloy 690/52/152 Replacements in US PWRs

(excluding SG tubes, through mid-2004, from MRP-110 (EPRI 1009807)) (cont'd)

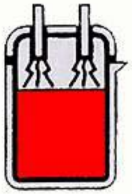
Location	Component Item	Wrought Material	Weld Materials	Plant	Date Replaced	Calendar Years at 3/2004	# Parts	Temp.[3] (°F)	Approx. EFPY at 3/2004	Approx. EDY at 3/2004[4]	Part-EFPYs	Part-EDYs
Cold Leg	Instrument Nozzle	Alloy 690	Alloy 52	Davis Besse	01/2003	1.2	4	555	0.0	0.0	0.0	0.0
		Alloy 690	Alloy 152	San Onofre 2	02/1998	6.1	12	540	5.6	0.4	67.2	5.2
		Alloy 690	Alloy 152	San Onofre 3	04/1997	6.9	1	540	5.9	0.5	5.9	0.5
		Alloy 690	Alloy 152	San Onofre 3	03/1998	6.0	11	540	5.6	0.4	61.1	4.7
RV Lower Head	BMI Nozzle	Alloy 690	Alloy 52/152	South Texas 1	08/2003	0.6	2	561	0.5	0.1	1.0	0.2
Pressurizer	Heater Sleeve	Alloy 690	Alloy 52/152	ANO 2	07/2000	3.7	12	633	3.4	12.4	40.7	148.2
		Alloy 690	Alloy 52/152	Calvert Cliffs 1	02/1994	10.1	2	633	9.3	34.0	18.7	67.9
		Alloy 690	Alloy 52/152	Calvert Cliffs 1	03/1998	6.0	1	633	5.6	20.2	5.6	20.2
		Alloy 690	Alloy 182/82	Calvert Cliffs 2	07/1990	13.7	119	633	10.2	37.2	1,216.6	4,428.3
		Alloy 690	Alloy 52	Palo Verde 2	10/2000	3.4	2	633	3.2	11.5	6.3	23.0
		Alloy 690	Alloy 52	Palo Verde 2	12/2003	0.2	34	633	0.2	0.8	7.8	28.5
		Alloy 690	Alloy 52	San Onofre 3	04/1999	4.9	1	633	4.3	15.6	4.3	15.6
		Alloy 690	Alloy 52/152	Waterford 3	10/2000	3.4	1	633	3.2	11.5	3.2	11.5
	Instrument Nozzle Liquid Space	Alloy 690	Alloy 82	Palo Verde 1	04/1992	11.9	3	633	10.4	37.9	31.2	113.7
		Alloy 690	Alloy 52	Palo Verde 2	03/1993	11.0	3	633	9.2	33.3	27.5	99.9
		Alloy 690	Alloy 52	Palo Verde 3	11/1994	9.3	3	633	8.5	31.1	25.6	93.3
		Alloy 690	Alloy 52/152	San Onofre 2	03/1997	7.0	1	633	6.4	23.2	6.4	23.2
		Alloy 690	Alloy 52	St. Lucie 2	12/1995	8.3	3	633	7.6	27.7	22.8	83.0
	Instrument Nozzle Steam Space	Alloy 690	Alloy 182/82	Calvert Cliffs 2	07/1990	13.7	4	633	10.2	37.0	40.7	148.2
		Alloy 690	Alloy 82	Palo Verde 1	04/1992	11.9	4	633	10.4	37.9	41.6	151.6
		Alloy 690	Alloy 52	Palo Verde 2	01/1994	10.2	4	633	8.9	32.2	35.4	128.9
		Alloy 690	Alloy 52	Palo Verde 3	11/1994	9.3	4	633	8.5	31.1	34.2	124.4
		Alloy 690	Alloy 52/152	San Onofre 2	06/1993	10.8	4	653	9.9	76.3	39.8	305.4
		Alloy 690	Alloy 52/152	San Onofre 3	07/1995	8.7	4	653	8.0	61.6	32.1	246.2
		Alloy 690	Alloy 52	St. Lucie 1	10/1999	4.4	4	633	4.2	15.3	16.8	61.2
		Alloy 690	Alloy 182	St. Lucie 2	04/1994	10.0	4	633	8.8	32.0	35.2	128.1
		Alloy 690	Alloy 52/152	Waterford 3	02/1999	5.1	2	633	4.7	17.1	9.4	34.2
		Alloy 690	Alloy 52/152	Waterford 3	10/2000	3.4	2	633	2.7	9.7	5.3	19.4
	Manway Diaphragm Plate	Alloy 600	Alloy 52/152	Catawba 1	05/2002	1.8	1	650	1.7	11.7	1.7	11.7
						Total	1026			*Total*	2,838	7,639

Notes:
1) Table entries are based on the information currently available. Additional replacements may exist, which are not included in this table.
2) This table reflects replacements that are currently in service (as of 3/04). Overlay weld repairs of CRDM penetrations are not included.
3) For pressurizer component temperatures of 633°F, the temperature value is estimated for the location of the new pressure boundary weld at the pressurizer OD.
4) Effective Degradation Year (EDY) defined as equivalent time at temperature using a reference of 600°F and an activation energy of 50 kcal/mole.
Also, the EDY calculation is based on the current operating temperature at that location; no corrections are made for past changes in temperature.

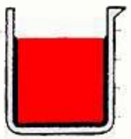
Melt Practice

Melting

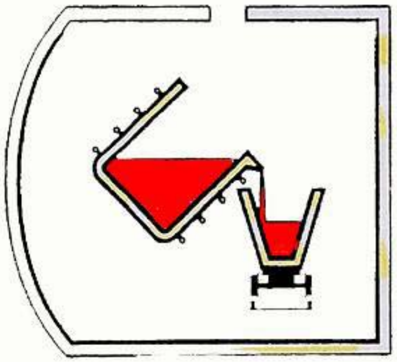
Electric Arc



Air Induction



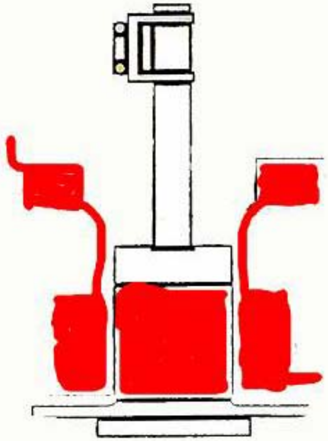
Vacuum Induction Melting (VIM)



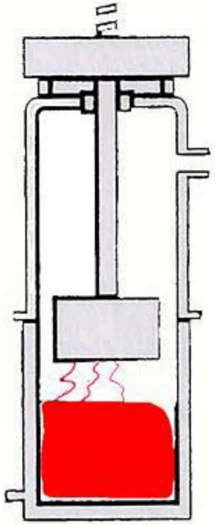
Also: Argon/Oxygen Decarburization (**AOD**)
Vacuum/Oxygen Decarburization (**VOD**)

Remelting

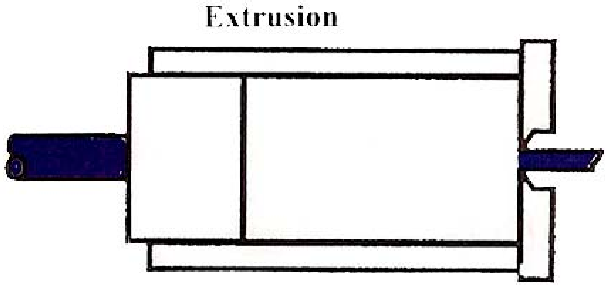
Electro-Slag Remelting (ESR)

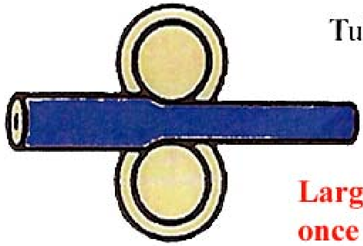


Vacuum Arc

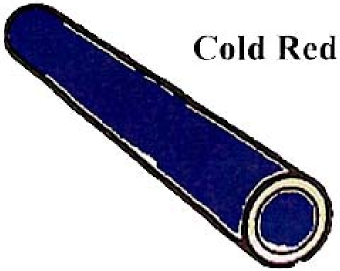


Seamless Pipe Manufacturing (ASTM B-167)



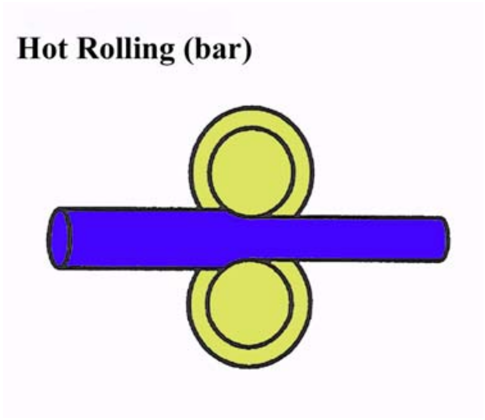


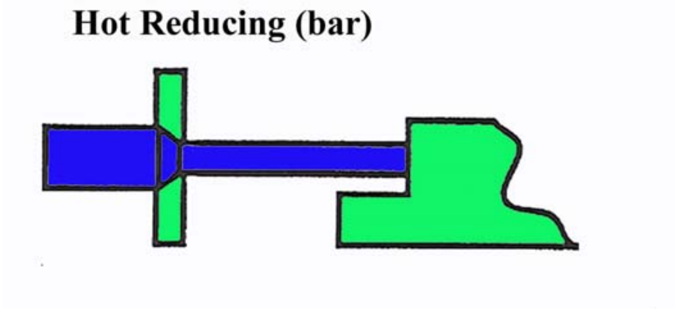
Large sizes can be cold reduced once or twice (35-45%) and re-annealed at 1900 betwen steps

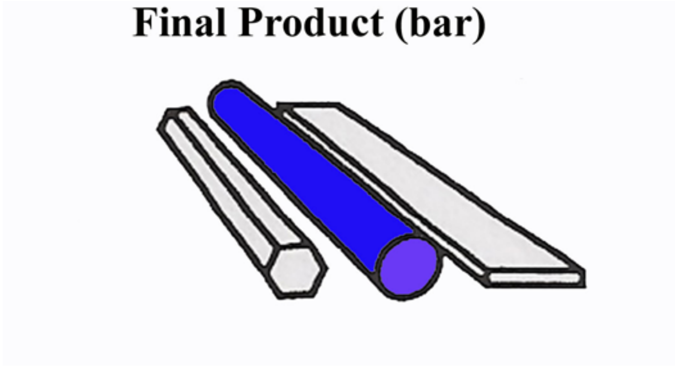


Typical product :
4 " OD - 5/8 " wall

Bar Manufacturing (ASTM B-166)







- **Large diameter hot worked bar**
- **Drilled hole for nozzles**

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Information was solicited from the three main replacement RV head vendors:

- What was the melt practice for the Alloy 690 materials (VIM, AOD, ESR, etc.)?
- What fabrication route was used for the CRDM nozzles (e.g., extrusion, drawing, or forging for pipe material; drilling of solid bar)?
- What heat treatments were used, and for what times and temperatures (e.g., for mill annealing)?
- Was roll straightening performed and, if so, before or after thermal treatment?
- Were there any limits placed on fabrication steps after installation of the nozzles, such as limits on straightening, in order to limit cold work and residual stress?

Fabrication Sequence for Alloy 690 Nozzles

	Draft EPRI Guidelines		MHI	AREVA	BWC
Nozzle Supplier		**Special Metals**	Sumitomo Metals	Tecphy	Tecphy
Melt Practice	• Not specified but must be documented • AOD or VIM followed by ESR are mentioned as acceptable	VIM/ESR	VOD or AOD Remelt not provided	Melting practice not provided ESR	Melting and re-melting not positively identified (assume same as AREVA?)
Extrusion Route Used	• Not specified but must be documented and supplied to purchaser for approval	1150-1260°C (2100-2300°F)	Hot extrusion	• Hot Extrusion between 1110-1210°C (2030-2210°F) by Vallinox • Water quenched • Straightened in one pass	Assume same as AREVA?
Mill Annealing Temperature	1070°C (1958°F) minimum of 2 minutes	1040-1065°C (1900-1950°F)	1075°C (1970°F)	1080°C (1975°F)	Assume same as AREVA?
	Draft EPRI Guidelines – McIlree	J. Crum and J. Martin	S. Asada and T. Yonezawa	F. Vaillant	Presentation by M. Lee Confirmed by P. King

Information was solicited from the three main replacement RV head vendors:

- What was the melt practice for the Alloy 690 materials (VIM, AOD, ESR, etc.)?
- What fabrication route was used for the CRDM nozzles (e.g., extrusion, drawing, or forging for pipe material; drilling of solid bar)?
- What heat treatments were used, and for what times and temperatures (e.g., thermal treatment)?
- Was roll straightening performed and, if so, before or after thermal treatment?
- Were there any limits placed on fabrication steps after installation of the nozzles, such as limits on straightening, in order to limit cold work and residual stress?

Fabrication Sequence for Alloy 690 Nozzles

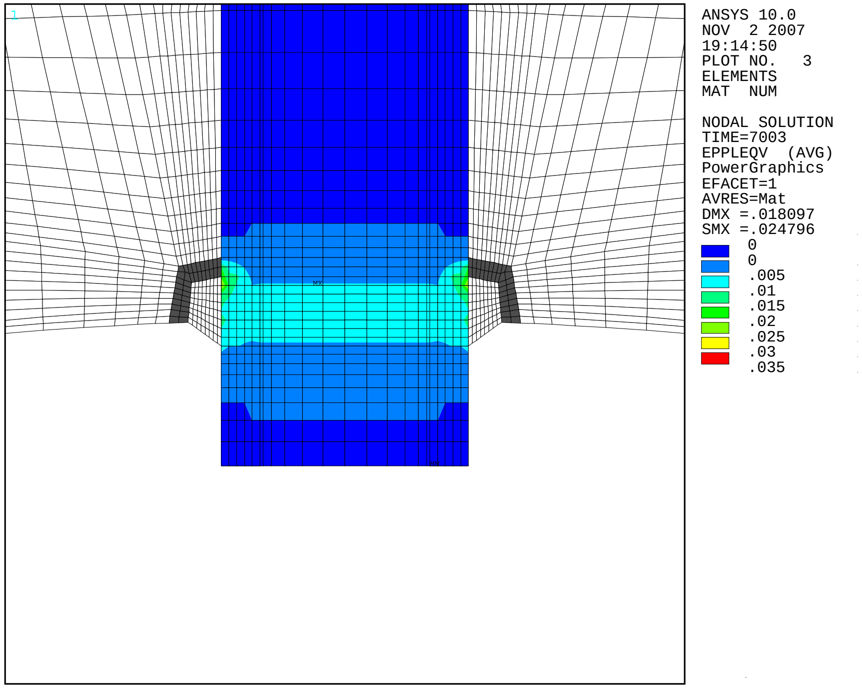
	Draft EPRI Guidelines		MHI	AREVA	BWC
Nozzle Supplier		Special Metals	Sumitomo Metals	Tecphy	Tecphy
Thermal Treatment	• 716°C (+22 –0) (1320°F (+40 –0)) for 10 hours minimum and after straightening • If straightened, machined or ground after TT then additional TT for minimum of 2 hours • Maximum TT time is 35 hours	725°C (1340°F) Typically for 10 hours or per customer's requirements	700°C (1290°F) minimum for 15 hours	715°C (1320°F) minimum for 5 hours	Assume same as AREVA?
Is roll straightening performed?	See note above	3-5% if necessary	Yes, if required before and/or after thermal treatment	Straightening information not provided	Straightening information not provided
Fabrication Procedures and Restrictions			• Narrow gap J-grove welding • Automatic GTAW • Water spray cooling on ID surface to reduce residual tensile stresses • No straightening after J-welding		• J-groove welding • Automatic GTAW with Alloy 52 • Guide tube shrink fit • Electro-polish • No straightening after J-welding

Estimate Plastic Strains for Alloy 690 Nozzle Tubes Due to Welding

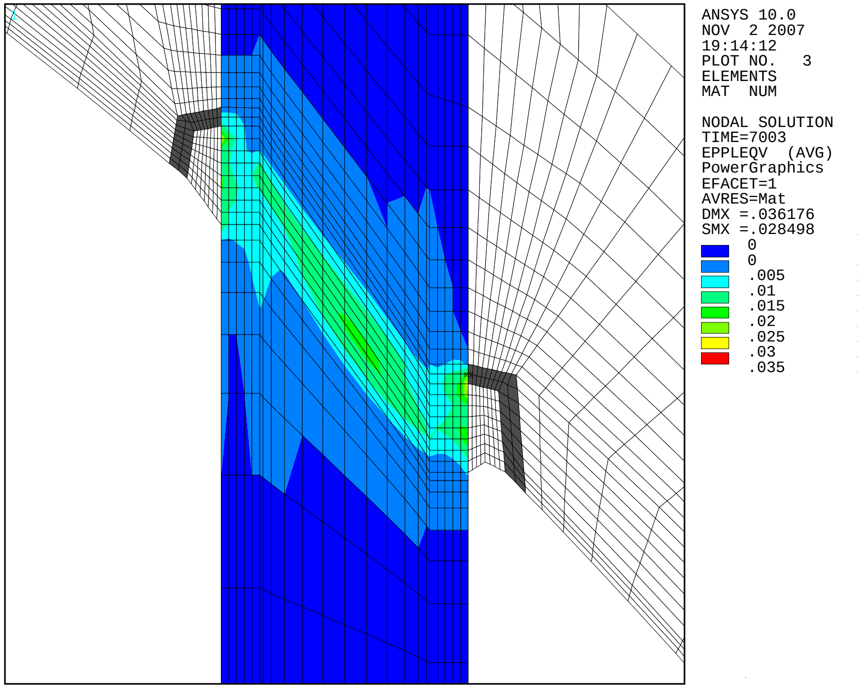
- Desirable to assess likely strain in installed components
- Estimates made using DEI's finite-element analysis modeling approach
  - Alloy 690 material parameters when available
  - Modifications of Alloy 600 material parameters
  - 8 node thermal & structural 3D analysis
- Modeled components:
  - CRDM nozzles at the innermost, intermediate, and outermost penetrations for a replacement reactor vessel head
  - Reactor vessel head vent nozzle (also representative of RCS piping and pressurizer instrumentation nozzles)
  - Bottom mounted instrumentation (BMI) nozzles at the outermost penetrations for two reactor vessel designs (including hypothetical case to represent relatively thick-walled nozzle)
  - Reactor vessel head in-core instrumentation (ICI) nozzle
  - Pressurizer heater sleeve repair, welded to the outside of the pressurizer

Strain Contour Plots

Equivalent Strain at Unloaded Room-Temperature Conditions

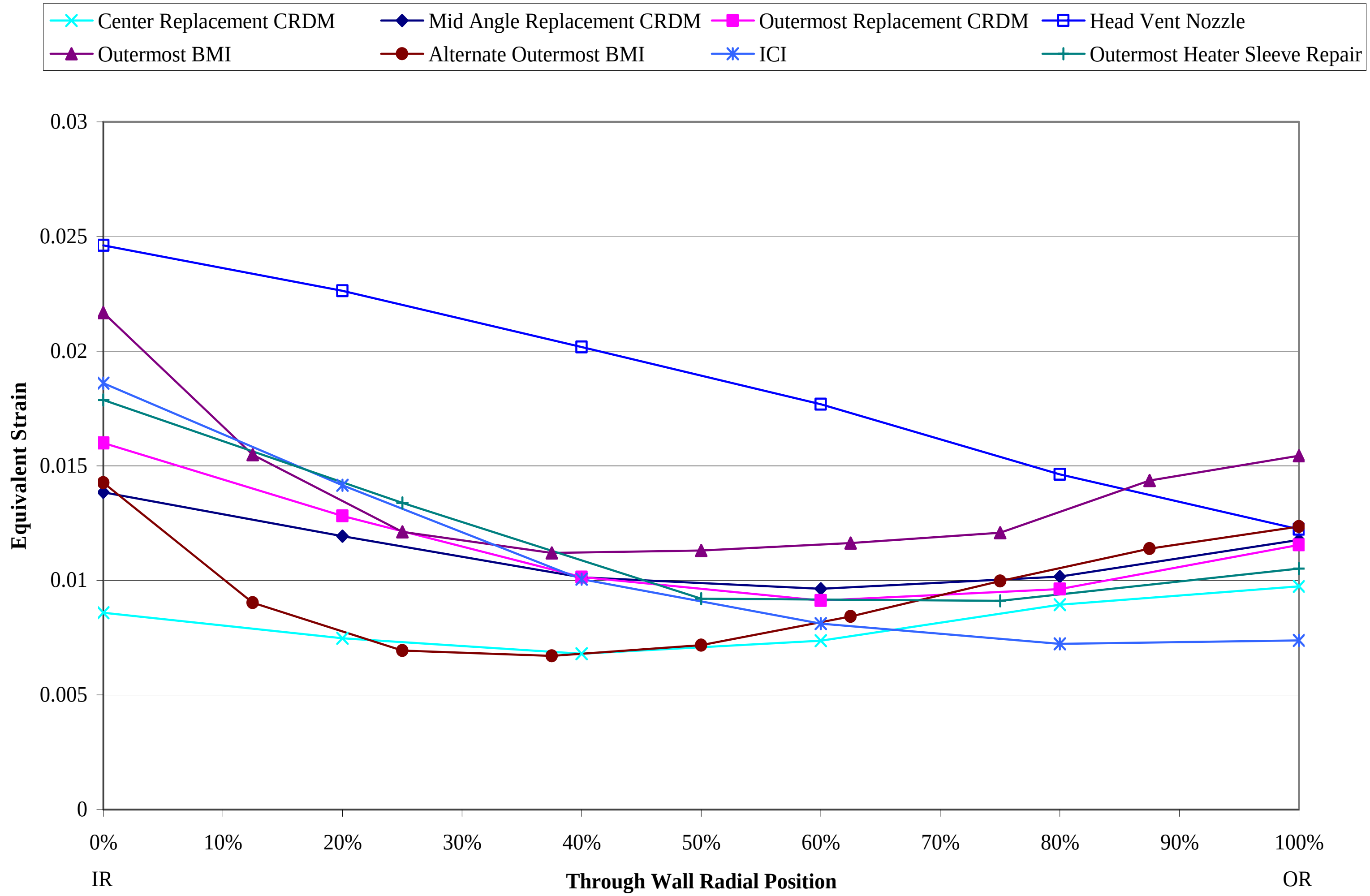


Center CRDM Nozzle
ID = 2.755″, OD = 4.005″



Outermost CRDM Nozzle
ID = 2.755″, OD = 4.005″

Through-Wall Plastic Strain Distributions



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Conclusions of Draft EPRI Report
Material Processing and Fabrication/Installation Practices

- With regard to the PWSCC crack growth resistance of the Alloy 690 nozzle tube material, the most significant material processing and fabrication/installation practices appear to be those associated with material straightening subsequent to final thermal treatment and those associated with the welding installation process.

Conclusions of Draft EPRI Report

Finite-Element Analyses of Representative Nozzles

- Thermal and structural FEA calculations were made for eight representative partial-penetration J-groove welded nozzle configurations in order to estimate the magnitude of bulk macroscopic plastic strain in the nozzle tube due to the welding installation process.
- The calculated bulk macroscopic plastic strain levels (0.005 to 0.025) are much lower than the cold work levels of 24-30% that resulted in laboratory PWSCC crack growth rates for Alloy 690 only roughly 5 to 10 times lower than those for Alloy 600 with similar cold work levels.
- Therefore, it appears that the welding process for partial-penetration J-groove welded nozzles does not result in through-wall macroscopic plastic strain levels in the Alloy 690 base metal material that are sufficiently high to be relevant to the Alloy 690 crack growth rate tests using highly cold-worked Alloy 690 plate samples recently reported.
- The FEA modeling methodology does not consider the processes concentrated at the outer surface of the nozzle tube that may result in elevated strain levels localized to the HAZ of the base metal along the weld fusion line.

Conclusions of Draft EPRI Report

Finite-Element Analyses of Representative Nozzles (cont'd)

- Additional factors when considering the applicability of the Alloy 690 crack growth rate tests using highly cold-worked Alloy 690 plate samples:
  - The FEA modeling methodology does not consider the processes concentrated at the outer surface of the nozzle tube that may result in elevated strain levels localized to the HAZ of the base metal along the weld fusion line
  - Differences in crack orientation for J-groove nozzles versus cold-worked Alloy 690 plate samples
  - Effect of tensile pre-straining versus rolling

Possibilities for Extending Data Collection
Types of Components

- More details on current practices for replacement Alloy 690 CRDM nozzles
- Details specific to replacement Alloy 690 applications other than CRDM nozzles
  - Pressurizer heater sleeves
  - Pressurizer instrumentation nozzles
  - Hot and cold leg instrumentation nozzles
- Practices for past Alloy 690 replacements (dating back to 1990)
- Alloy 52/152 weldments
  - Production of welding consumables
  - Welding practices
  - Post-welding fabrication steps

Possibilities for Extending Data Collection
Types of Information

- Material characteristics
  - melting practice
  - heat treatments
  - material chemistry
  - mechanical properties
  - pipe drawing procedures
  - final straightening
  - final microstructure
- Fabrication details
  - solid bar or pipe
  - machining/grinding operations
  - heat treatments
  - any welding details
  - any straightening after welding
  - any fabrication anomalies
- Concentrate on Alloy 690 material straightening practices after heat treatment?

Possibilities for Extending Data Collection
Sources of Data

- Material suppliers
- RV head fabricators
- J-groove nozzle replacement/repair vendors
- Plants
  - possibly including plant visits

- Challenges to collection of detailed data:
  - Proprietary information / trade secrets
  - Potential changes in practices over time
  - Several material suppliers, replacement head fabricators, and replacement/repair vendors