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CP&L
A Progress Energy Company

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United States Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, DC 20555

H. B. ROBINSON STEAM ELECTRIC PLANT, UNIT NO. 2
DOCKET NO. 50-261/LICENSE NO DPR-23

SUPPLEMENTAL INFORMATION REGARDING
NRC BULLETIN 2001-01, "CIRCUMFERENTIAL CRACKING OF
REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLES"

Ladies and Gentlemen:

The purpose of this letter is to provide the results of additional analyses performed to confirm that leakage paths would exist for the H. B. Robinson Steam Electric Plant (HBRSEP), Unit No. 2, reactor vessel head penetration (VHP) nozzles.

As detailed in the attachments and enclosures to this letter, Carolina Power and Light (CP&L) Company has determined that: 1) research of design and manufacturing information for the HBRSEP, Unit No.2, reactor vessel head penetrations concludes that a value of 0.002 inches credibly bounds the range of interference fits, i.e., the degree of "overlap" between the VHP nozzle diameter and reactor pressure vessel (RPV) head penetration diameter; 2) CP&L evaluation of results from the refined and improved finite element analyses (FEA) shows that a leakage path to the RPV head surface would exist, up to and considerably beyond, the above-stated credible range of interference fits; and 3) the ability to detect VHP nozzle through-wall cracking by evidence of leakage to the RPV head surface has been established. Therefore, CP&L concludes that VHP leakage would pass to the RPV head surface where it would be detected by visual examination, and that VT-2 visual examinations performed for the HBRSEP, Unit No. 2, RPV head during RO-20 were qualified visual examinations as described within NRC Bulletin 2001-01.

This letter supplements the initial HBRSEP, Unit No. 2, response to NRC Bulletin 2001-01, dated September 4, 2001, and subsequent supplemental responses provided by letters dated October 2 and 19, 2001. In addition, a meeting was conducted with the NRC staff on October 24, 2001, to discuss actions taken by HBRSEP, Unit No. 2, to demonstrate that a qualified visual examination of VHP nozzles was performed during Refueling Outage (RO) - 20 in April 2001.

Robinson Nuclear Plant
3581 West Entrance Road
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A088
2/8/2

This supplemental response is provided under oath or affirmation in accordance with 10 CFR 50.54(f). Attachment I provides the required affidavit.

As noted within the HBRSEP, Unit No. 2, letter dated October 19, 2001, the VHP nozzles will receive a qualified visual examination and will be examined by non-destructive examination (NDE) during RO-21 in October 2002.

If you have any questions regarding this matter, please contact Mr. H. K. Chernoff.

Sincerely,

Harold K Chernoff

for B. L. Fletcher III
Manager - Regulatory Affairs

CTB/ctb

Attachments:

I. Affidavit
II. Supplemental Information Regarding NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles"
III. Responses to Requests for Additional Information Regarding NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles"

Enclosures:

I. Example Fabrication Records
II. "Reactor Vessel Top Head Nozzle Operating Fit Analysis," Revision 1, Performed By Dominion Engineering, Inc.
III. "Improved FEM Gap Analysis of CRDM Penetrations (Robinson 2)," Performed By Structural Integrity Associates, Inc.
IV. "Robinson CRDM Nozzle Deflection Analysis," Performed By Dominion Engineering, Inc.
V. Cover Letter Transmitting Original "Finite Element Gap Analysis of CRDM Penetrations," Dated October 18, 2001, Performed By Structural Integrity Associates, Inc.

c: Mr. B. S. Mallett, NRC, Region II
Mr. A. G. Hansen, NRC, NRR
NRC Resident Inspectors

AFFIDAVIT

State of South Carolina
County of Darlington

J. W. Moyer, having been first duly sworn, did depose and say that the information contained in letter RNP-RA/01-0166 is true and correct to the best of his information, knowledge, and belief; and the sources of this information are officers, employees, contractors, and agents of Carolina Power and Light Company.

JMoyer

Sworn to and subscribed before me

this 2nd day of November, 20 01

Notary Public for South Carolina

My commission expires: 9/13/2009

H. B. ROBINSON STEAM ELECTRIC PLANT, UNIT NO. 2

SUPPLEMENTAL INFORMATION REGARDING NRC BULLETIN 2001-01, "CIRCUMFERENTIAL CRACKING OF REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLES"

Summary and Conclusions

Carolina Power and Light (CP&L) Company has determined that: 1) research of design and manufacturing information for the H. B. Robinson Steam Electric Plant (HBRSEP), Unit No. 2, reactor vessel head penetrations (VHP) concludes that a value of 0.002 inches credibly bounds the range of interference fits, i.e., the degree of "overlap" between the VHP nozzle diameter and reactor pressure vessel (RPV) head penetration diameter; 2) CP&L evaluation of results from the refined and improved finite element analyses (FEA) shows that a leakage path to the RPV head surface would exist, up to and considerably beyond, the above-stated credible range of interference fits; and 3) the ability to detect VHP nozzle through-wall cracking by evidence of leakage to the RPV head surface has been established. Therefore, CP&L concludes that VHP leakage would pass to the RPV head surface where it would be detected by visual examination, and that VT-2 visual examinations performed for the HBRSEP, Unit No. 2, RPV head during Refueling Outage (RO) - 20 were qualified visual examinations as described within NRC Bulletin 2001-01.

Background

On August 3, 2001, the NRC issued NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," requesting information related to the structural integrity of the reactor vessel head penetration nozzles, including the extent of VHP nozzle leakage and cracking that had been found to date, the inspections and repairs that had been undertaken to satisfy applicable regulatory requirements, and the basis for concluding that plans for future inspections will ensure compliance with applicable regulatory requirements. By letter dated September 4, 2001, HBRSEP, Unit No. 2, provided the information requested by NRC Bulletin 2001-01 under oath and affirmation in accordance with 10 CFR 50.54(f).

The following information describes actions taken to satisfy the requirement of NRC Bulletin 2001-01 for performance of a qualified visual examination of the HBRSEP, Unit No. 2, RPV head. This information demonstrates that a qualified visual examination of the RPV head was performed during RO-20 in April 2001, and that no indication of VHP nozzle leakage was identified. Therefore, a basis has been provided for continued safe operation of HBRSEP, Unit No. 2, until the next scheduled refueling outage in October 2002.

Visual Examination of Reactor Pressure Vessel Head

HBRSEP, Unit No. 2, performed detailed visual examinations of the RPV head during RO-20. These examinations, conducted April 14 through 19, 2001, were VT-2 visual examinations performed by Quality Control (QC) personnel for the purpose of identifying VHP nozzle leakage. The RPV head insulation was removed prior to these examinations, resulting in a bare-metal visual examination. These visual examinations were conducted prior to cleaning or decontamination in the areas examined, and included the capability to effectively distinguish sources of boric acid deposition. No VHP nozzle leakage or reactor coolant system pressure boundary leakage was identified by these visual examinations.

A detailed chronology of these examinations was previously provided[1] to the NRC staff. Pertinent details related to VHP nozzle examinations are provided below:

April 10, 2001	During RO-20 activities to detension the RPV head studs, evidence of primary system leakage was identified on the surface of the reactor vessel head, including the reactor vessel head insulation and control rod drive mechanism (CRDM) housings.
April 14, 2001	QC inspectors performed an "as-found" VT-2 visual examination of the reactor vessel head with the insulation in place. The purpose of this VT-2 visual examination was to investigate the evidence of primary system leakage, i.e., boric acid deposition, which had been identified on April 10, 2001. The boric acid deposition was primarily located in the vicinity of CRDM locations B10, C9, D8, and D10, with the spray pattern indicating that the majority was centered around location B10. The source of the leakage was identified as the canopy seal weld at CRDM location B10, which did not constitute reactor coolant system pressure boundary leakage.
April 15, 2001	The RPV head lower shroud was partially removed and metallic thermal insulation was removed from areas exposed to boric acid. This included an area approximately two feet wide by seven feet long. This included CRDM locations D8, B8, C9, D10, E11, F12, G13, H14, B10, C11, D12, E13, and F14. Subsequently, a VT-2 visual examination was completed by QC personnel to map the boric acid deposition on the RPV head. Specific orientation, related to the type of boric acid deposition associated with VHP nozzle leakage identified at Oconee Nuclear Station Unit 3 (ONS3), was given to these personnel prior to the examination.

[1] CP&L Letter RNP-RA/01-0153, dated October 2, 2001, from B. L. Fletcher, III to USNRC

	The observed boric acid deposition on the RPV was recorded and attributed to leakage flowing onto the RPV head from the CRDM location B10 canopy seal weld above. No deposition or evidence of leakage was identified by the QC inspectors that could be attributed to leakage or degradation of the VHP nozzle welds or Alloy 600 material.
April 18, 2001	Based on information received from the NRC and the Nuclear Energy Institute (NEI) regarding VHP nozzle cracking, the decision was made to remove the remaining RPV head insulation and perform a VT-2 visual examination of the entire RPV head. This examination focused on identifying evidence of leakage or degradation of the VHP nozzles or Alloy 600 material.
April 19, 2001	The remaining RPV head insulation was removed. Subsequently, QC personnel completed a VT-2 visual examination of the CRDMs and RPV head. Specific orientation, related to the type of boric acid deposition associated with VHP nozzle leakage identified at ONS3, was given to these personnel prior to the examination. This examination was performed prior to cleaning or decontamination activities for the affected area. No VHP nozzle leakage or reactor coolant system pressure boundary leakage was identified.

To analytically demonstrate that through-wall leakage would pass through to the RPV head surface, detailed plant-specific finite element analysis (FEA) modeling of the VHP nozzles and RPV head penetrations has been performed. These analytical demonstrations, in conjunction with evaluation of interference fit data establish that a leakage path would exist to the RPV head surface for through-wall cracking of VHP nozzles. The VT-2 visual examinations performed during RO-20 would have detected evidence of leakage resulting from VHP nozzle cracking. Therefore, the VT-2 visual examinations have been shown to be consistent with the requirements for a qualified visual examination as provided within NRC Bulletin 2001-01.

Evaluation of Interference Fit Data

Summary

Subsequent to the HBRSEP, Unit No. 2, letter dated October 2, 2001, additional information has been obtained regarding manufacture and assembly of the HBRSEP, Unit No. 2, RPV head. CP&L has completed an evaluation of the available information and concluded that VHP nozzle interference fits are well within design tolerances and are credibly bounded by a value of 0.002 inches. The following subsections provide an overview of this manufacture and assembly information, as well as CP&L's evaluation and conclusions associated with this information.

Manufacture

The HBRSEP, Unit No. 2, RPV head was manufactured by Combustion Engineering in their Chattanooga facility. The material supplier for the VHP nozzles was Huntington. Manufacturing and assembly of the HBRSEP, Unit No. 2, RPV head was controlled under the auspices of vendor and CP&L Quality Assurance Programs. These programs provided the framework and controls for ensuring work was performed in accordance with the design documents and procedural controls including the reporting and correction of non-conforming conditions.

In addition, the reactor vessel was constructed in accordance with the requirements of American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III. The Code requires that vessels of this type be independently inspected by qualified inspectors, "...verifying that the vessel as constructed complies with all specific design details necessary for compliance with this Subsection as called for by the design specifications and the design drawings..."

The Quality Assurance Programs in conjunction with the Code inspections required strong independent oversight of the manufacturing and assembly process.

A significant amount of dimensional data can be imputed from review of manufacturing and inspection records, although complete manufacturing records of the dimensions for each VHP nozzle are not available. Documentation for VHP nozzles that were inspected and determined to not fully meet design requirements is clearly traceable and shows resolution of the identified non-conforming condition. Records show that housings having a diameter greater than design tolerance were rejected or re-worked to obtain the specified tolerances. Examples of these records are provided as Enclosure I. These examples have been annotated to highlight information for a single VHP nozzle. Dimensional documentation is available for 35 of the 69 VHP nozzles.

Similar to the VHP nozzles, records of the dimensions for each VHP are not available. Data derived from a study[2] of three Westinghouse plants fabricated during the time frame of the HBRSEP, Unit No. 2, RPV head fabrication showed that the 230 VHPs for these plants were consistently at or above the minimum design VHP size of 3.997 inches. This data has been previously provided[3] to the NRC Staff. These plants had Westinghouse nuclear steam supply system designs; nozzle material manufactured by Huntington; RPV heads manufactured by Combustion Engineering; the same design specifications for the diameter of the VHP nozzles and VHPs as HBRSEP, Unit No. 2; and, a specified design interference fit of 0.000 inches through 0.003 inches. No undersized VHPs existed in this population. Additional data from this study is presented in Table 1.

[2] Westinghouse Report CN-CI-01-1, "Potential for Detectable Leakage in the HB Robinson Reactor Vessel Head," (Proprietary Class 2), dated August 28, 2001.
[3] CP&L Letter RNP-RA/01-0153, dated October 2, 2001, from B. L. Fletcher, III to USNRC

Table 1: Similar Plant VHP Data Summary	
Number of VHPs	230
Number of Undersized VHPs (<3.997 inches)	0
Mean VHP Size for Population	3.9980 inches
Median VHP Size for Population	3.9978 inches

While the data presented in Table 1 is not directly applicable to HBRSEP, Unit No. 2, it is reasonable to conclude that the manufacturing procedures used for the VHPs for these three RPV heads would be typical of those associated with fabrication of the HBRSEP, Unit No. 2, RPV head.

Table 2 provides a tabulation of the VHP sizes for the study group population.

Table 2: Similar Plant VHP Data

VHP Size[4] (Inches)	Number of VHPs	%
4.0010	5	2.17%
4.0008	0	0.00%
4.0005	3	1.30%
4.0003	0	0.00%
4.0000	1	0.43%
3.9998	0	0.00%
3.9995	7	3.04%
3.9993	1	0.43%
3.9990	21	9.13%
3.9988	1	0.43%
3.9985	37	16.09%
3.9983	7	3.04%
3.9980	29	12.61%
3.9978	17	7.39%
3.9975	64	27.83%
3.9973	9	3.91%
3.9970	28	12.17%

The information described above provides the basis for CP&L's determination that the VHP nozzles and VHPs for HBRSEP, Unit No. 2, were manufactured in accordance with design requirements.

[4] Although the inspection records for these penetrations are not available to CP&L, sizes greater than 3.999 inches would have been identified as non-conformances and resolved in accordance with the existing quality assurance programs.

Assembly

As noted above, the HBRSEP, Unit No. 2, RPV head was manufactured by Combustion Engineering in their Chattanooga facility. Mating of the VHP nozzles and VHPs was also performed in this facility in accordance with a Shop Traveler (manufacturing and assembly instructions). The design tolerances specified for this assembly are presented in Table 3 below.

Table 3: Design Tolerances

Design Range of VHP Nozzle Sizes (inches)	Design Range of VHP Sizes (inches)	Maximum Design Interference Fit (inches)
4.000	3.997	0.003
	3.998	0.002
	3.999	0.001
3.999	3.997	0.002
	3.998	0.001
	3.999	0.000

Table 3 shows the range of interference fits, 0.000 inches through 0.003 inches, that could result from the combination of the VHP Nozzle design tolerance of 4.000 inches +0.000 inches/-0.001 inches, and the VHP design tolerance of 3.997 inches +0.002 inches/-0.000 inches. As illustrated in Table 3, to achieve an interference fit at or near the theoretical design maximum of 0.003 inches would require the mating of a VHP nozzle of maximum diameter with a VHP of minimum diameter. Based on reviews of the detailed assembly instructions, this is unlikely to have occurred. Such a mating was virtually precluded by instructions and the physical limits of the process used to assemble the components.

The assembly process was performed in accordance with instructions in a Combustion Engineering Shop Traveler (Job Control No. T-51137-009). In general, assembly involved measuring the size of VHPs; matching VHP nozzles and VHPs sized to minimize the interference fit; shrinking the selected VHP nozzle using a coolant bath assuring approximately 0.003 inch clearance existed between the selected VHP nozzle and VHP; twice measuring the amount of VHP nozzle shrinkage; and, insertion of the VHP nozzle into the VHP. A summary and discussion of pertinent steps of the assembly process, as described in the Shop Traveler, are provided below:

1. Each VHP was "gauged" or measured. This step served to verify VHPs were sized within design tolerances. As previously described the VHP design tolerance was 3.997 inches +0.002 inches/-0.000 inches.

2. Instructions then directed personnel to:

> "Match fit all housings to penetrations for assurance of least possible interference fit."

This step clearly indicates the intention to minimize the amount of interference fit, by methodically selecting combinations of VHP nozzles and VHPs. Although not specifically indicated, a measurement of the VHP nozzles would have been performed at this time, or VHP nozzle measurement would have been available, and compared to the previously taken VHP measurements to complete the matching process. Minimizing the interference fit was a critical step taken to avoid subsequent assembly problems such as VHP nozzle binding during insertion.

3. After the VHP nozzles and VHPs were matched, a VHP nozzle selected for assembly was placed in a coolant bath to shrink the VHP nozzle in preparation for insertion into a VHP. The instructions directed personnel to:

> "Place housings in a bath of acetone & dry ice. Freezing temperature should be minus 88 degrees F to assure approx. 0.003 inches clearance between housing and penetration prior to installing."

For the maximum allowable outer diameter of 4.000 inches, cooling the Alloy 600 housing from 70°F (ambient) to minus 88°F would produce a diametrical shrinkage of approximately 0.004 inches. Therefore, by specifying and obtaining the 0.003 inches installation clearance described within the Shop Traveler, the resulting maximum interference fit would be expected to be approximately 0.001 inches. This 0.003 inches installation clearance also agrees with the Shop Traveler instruction to match fit the housings to penetrations for assurance of "least possible interference fit."

4. The VHP nozzle was removed from the coolant bath in order to "check shrinkage" and then placed back into the coolant bath. The VHP nozzle was again removed from the coolant bath, quickly checked for shrinkage, and inserted into the VHP. Insertion into the VHP was completed without mechanical assistance. Thus, two separate measurements of VHP nozzle shrinkage were made prior to insertion into the VHP. These measurements served to confirm that the stipulated 0.003 inches of clearance would be present during the insertion operation.

CP&L Evaluation and Conclusions

It can be concluded from the assembly instructions that the process controls were designed to provide an interference fit of nominally 0.001 inches. While some variance in achieving the stipulated 0.003 inches of clearance may have resulted in selected assemblies with interference fits of slightly greater than 0.001 inches, it is unlikely that this process resulted in interference fits near the design maximum of 0.003 inches.

In order to approach the design maximum interference fit, the Shop Traveler instruction to "match fit all housings to penetrations for assurance of least possible interference fit" would have to have been circumvented. Circumvention of this step is not deemed credible. Shop Traveler activities were conducted under the auspices of the Combustion Engineering Quality Assurance program with additional oversight provided by the Westinghouse Quality Assurance Program.

Further, the assembly process itself provided additional procedural and physical limits to the degree of interference fit that could be obtained. Although not believed to be credible, if the assembly process instructions were not followed and a VHP nozzle of maximum design tolerance and a VHP of minimum design tolerance were matched, a hypothetical maximum interference fit of 0.003 inches may have resulted. However, the established shrinkage process was designed in a manner that resulted in a approximate shrinkage of only 0.004 inches. In this hypothetical case, a clearance of only 0.001 inches would have been present between the VHP nozzle and VHP after shrinkage.

The two measurements of the VHP nozzle shrinkage, required prior to insertion in the VHP, provided additional barriers and assurance that the specified 0.003 inches clearance was obtained prior to insertion. For the sake of discussion, if these barriers had been ignored and the aforementioned hypothetical situation was assumed to exist, i.e., attempted VHP nozzle insertion into a VHP with approximately 0.001 inches of clearance, insertion without mechanical assistance of a VHP nozzle into a VHP for a depth of up to approximately 6 inches would have been extremely difficult and not practicable.

Information regarding such shop practices have been obtained from a current RPV head manufacturer that supports the conclusion that such a fit-up would not typically be attempted and would most likely be unsuccessful. Specifically, the desired clearance to begin such an assembly using current manufacturing practices was stated to be 0.004 inches. It was further stated that such an assembly using 0.001 inches of clearance would be very difficult. A "rule of thumb" applied by this manufacturer was that 0.001 inches of clearance would be needed for each inch of diameter.

Based on the above information, it has been concluded that an interference fit of less than or equal to 0.002 inches credibly bounds the range of interference fits that exist on the HBRSEP, Unit No. 2, RPV head.

Results of Finite Element Analyses

By letter dated October 19, 2001, HBRSEP, Unit No. 2, provided the results of detailed plant-specific finite element analyses of the VHP nozzles and the RPV head penetrations that were conducted to qualify the visual examinations performed for the RPV head during RO-20 in April 2001. These analyses were performed by Dominion Engineering, Inc., and Structural Integrity Associates (SIA), Inc. In order to provide additional technical discussion, more detailed modeling, and in response to NRC Requests for Additional Information (refer to Attachment III), improved and refined analyses have been completed. Enclosure II provides Revision 1 to the Dominion Engineering, Inc., analysis, and Enclosure III provides the "Improved FEM Gap Analysis of CRDM Penetrations (Robinson 2)" performed by SIA, Inc.

CP&L Finite Element Analyses Conclusions

Based on a review of these refined and improved analyses, CP&L has concluded that, using conservative analysis results, a leakage path exists for VHP nozzles with initial interference fits up through 0.00275 inches. As previously discussed, CP&L has concluded that a value of 0.002 inches credibly bounds interference fits for the HBRSEP, Unit No. 2, VHP nozzles. Therefore, the results of the refined and improved finite element analyses show that a leakage path to the RPV head surface would exist, up to and considerably beyond, the above-stated credible range of interference fits.

CP&L Evaluation of Dominion Engineering, Inc., Analysis

As clearly stated in Enclosure II, the revised Dominion Engineering, Inc., analysis concludes that "all nozzles have a predicted operating condition leak path to the head top surface for initial diametrical interference fits of up to and including 0.00275 inches."

CP&L has determined that these results provide a conservative assessment of the existence of leakage paths to the RPV surface for the credible range of interference fits for the HBRSEP, Unit No. 2, VHP nozzles.

CP&L Evaluation of SIA, Inc., Analysis

As stated in Enclosure III, the improved analysis performed by SIA, Inc., concludes that "for the pressurized cases, all nozzles except the center nozzle exhibit leakage paths to the surface of the head for the initial interference fits evaluated, including 3 mils." Assuming no annulus pressurization for the center nozzle, the remaining interference is 0.0000222 inches, which is at the bottom ring of contact elements, just above the J-groove weld. When annulus pressurization is included, the remaining interference for the center nozzle is 0.0000119 inches.

This minor interference described in the SIA, Inc., report is a fraction of the design surface roughness of the combined VHP nozzle and VHP (0.000032 and 0.000063 inches, respectively). The inherent roughness of the VHP nozzle and VHP would likely allow a leakage path for VHP nozzle leakage to traverse the remaining zone of interference on this center nozzle. Additionally, the SIA, Inc., report does not model the distortion that occurs in the VHP nozzle due to the welding process. More sophisticated modeling of weld and nozzle behavior, such as that used in the revised Dominion Engineering, Inc., analysis, shows that a gap forms between the VHP nozzle and VHP in the region just above the top of the J-groove weld. Since modeling in this manner more closely simulates actual behavior of the VHP nozzle, CP&L has concluded that the results of the improved SIA, Inc., analysis support existence of a leakage path for VHP nozzles with initial interference fits up through 0.003 inches.

Conclusions

Research of design and manufacturing information for the HBRSEP, Unit No.2, reactor vessel head penetrations has determined that an interference fit of less than or equal to 0.002 inches credibly bounds the range of interference fits that exist on the HBRSEP, Unit No. 2, RPV head. This information, when combined with the results of the refined and improved analyses, demonstrate that through-wall leakage from the HBRSEP, Unit No. 2, VHP nozzles would pass through to the RPV head surface where it could be detected by VT-2 visual examination. Therefore, the VT-2 visual examinations performed for the HBRSEP, Unit No. 2, VHP nozzles are consistent with the requirements for a qualified visual examination as provided within NRC Bulletin 2001-01.

H. B. ROBINSON STEAM ELECTRIC PLANT, UNIT NO. 2

RESPONSES TO REQUESTS FOR ADDITIONAL INFORMATION REGARDING NRC BULLETIN 2001-01, "CIRCUMFERENTIAL CRACKING OF REACTOR PRESSURE VESSEL HEAD PENETRATION NOZZLES"

1. The H. B. Robinson Steam Electric Plant (HBRSEP), Unit No. 2, letter dated October 19, 2001, stated that "the results of the Structural Integrity Associates, Inc., analysis show that the VHP nozzles would have a leakage path to the reactor pressure vessel (RPV) head surface with initial interference fits through 3 mils." In Section 6.0 of the Structural Integrity Associates, Inc., (SIA) report, it was stated clearly that "all nozzles show a very lightly loaded residual interference zone just above the J-groove weld for all initial interferences." Moreover, even for cases with annular pressurization, it was stated that "the results of these pressurized analyses indicate that, except for the lightly loaded ring just above the J-groove weld, all nozzles exhibit a leak path even with an initial interference fit up to 3 mils." Please provide justification that the above conclusion is consistent with the findings in the SIA report?

   Response

   The results of detailed, plant-specific finite element modeling provided by the HBRSEP, Unit No. 2, letter dated October 19, 2001, included a "Finite Element Gap Analysis of CRDM Penetrations (Robinson 2)," that was performed by SIA, Inc. This detailed analysis modeled several different conditions and configurations, including a range of initial interference fits, pressurized and non-pressurized annulus conditions, and certain assumptions regarding J-groove weld modeling. The SIA, Inc., report, Section 6.0, "Results," does note that a "lightly loaded" ring just above the J-groove weld would exist for initial interference fits of 0.003 inches, assuming pressurized annulus conditions.

   A further discussion of this condition was provided by SIA, Inc., within their cover letter, dated October 18, 2001, that transmitted the subject report (see Enclosure V). This letter addresses the application of annulus pressure to vessel head penetration (VHP) nozzles that experience a through-wall crack. It is concluded by SIA, Inc., that:

   > "If the benefit of annulus pressurization is taken into account, leakage paths exist for all nozzles for all shrink-fit cases examined, i.e., even up to the maximum shrink-fit of 0.003 inches."

   Therefore, when considering the conclusions communicated within the SIA, Inc., cover letter, the HBRSEP, Unit No. 2, letter dated October 19, 2001, provides a consistent summary of the SIA, Inc., conclusions.

2. Regarding the SIA report, "Finite Element Gap Analysis of Control Rod Drive Mechanism (CRDM) Penetrations (H. B. Robinson):"

a. How was the inner compression surface radius determined?

Response

The inner compression surface radius is the inside radius of the lower RPV head flange, which forms the inner radius for the sealing surface area. This dimension is greater than the inner radius of the upper RPV flange due to the core support shelf. The value used within the SIA, Inc., analysis for inner compression surface radius is consistent with the value provided by design drawings for the HBRSEP, Unit No. 2, RPV closure head and flange.

b. The report indicated that the bottom ring of the interference zone is very lightly loaded for all initial interferences. Provide the range of loads for the bottom ring of CRDM Tube 1 shown in Table C-1 as an example, and describe the significance of these "very light loads" in keeping the fluid from passing through.

Response

Enclosure III provides an "Improved FEM Gap Analysis of CRDM Penetrations (Robinson 2)" that has been performed by SIA, Inc. The results of this improved analysis supercede the SIA, Inc., analysis provided by the HBRSEP, Unit No. 2, letter dated October 19, 2001. As a result, the requested range of loads and their associated significance are no longer applicable and have not been provided.

c. Because solid elements have only three degrees of freedom at each node as opposed to five degrees of freedom for the plate elements, one layer of solid elements have rarely been used for modeling a beam or a pipe having any lateral deflection. Please provide justification for modeling the penetration tube using a single layer of solid elements. In addition, please estimate the error associated with this modeling.

Response

As noted above, Enclosure III provides an "Improved FEM Gap Analysis of CRDM Penetrations (Robinson 2)" that has been performed by SIA, Inc. As noted within Section 2.2, "CRDM Tube Through-Wall Elements," use of only one element was based on conservatism and reduced analysis time. For the improved analysis, the number of elements through the thickness of the CRDM tube was increased from one to four.

3. Regarding the Dominion Engineering, Inc., report, "Results of Reactor Vessel Top Head Nozzle Operating Fit Analysis (H. B. Robinson):"

   a. The finite element analysis (FEA) model applied enforced displacements of 0.004 inch radially (outward) at the midpoint and 0.008 inch radially (outward) at the bottom surface of the weld-tube interface to account for J-groove weld shrinkage. The J-weld has three boundaries: one with the vessel head, one with the penetration tube, and one of free surface. During weld solidification, the free surface of the J-groove weld will move to accommodate the shrinkage of the weld, leaving the other two boundaries virtually unchanged. Historically, weld solidification would only lead to residual stresses in the weld. Provide justification that the weld solidification would also lead to a very large net applied load (enforced displacement is a form of applied load) acting on the welded parts in the model. In addition, please provide the equivalent applied tensile stresses over the weld-tube interface which would produce the same amount of enforced displacements in the penetration tube.

   Response

   Enclosure II provides Revision 1 to the Dominion Engineering, Inc., "Reactor Vessel Top Head Nozzle Operating Fit Analysis." Contained within this revised analysis is Appendix A, "Finite Element Model of Reactor Vessel Head and CRDM Nozzles," which includes a discussion regarding modeling of J-groove weld distortion. While Appendix A to the revised Dominion Engineering, Inc., analysis provides justification for modeling of J-groove weld shrinkage and distortion, additional supporting bases for this approach have been developed.

   Distortion of the VHP nozzle above and below the J-groove weld due to welding was thoroughly analyzed in EPRI Report TR-103696, “PWSCC of Alloy 600 Materials in PWR Primary System Penetrations,” July, 1994. In this report, typical VHP nozzle-to-RPV welds were analyzed for central, middle row, and outer row configurations, using elastic-plastic finite element analyses to simulate the welding process. The results of the finite element analyses clearly show that the welding process produces significant distortion of the nozzle, both ovalization and lateral deflection. Ovalities of up to 0.052 inches and lateral deflections of up to 0.038 inches were calculated. Field measurements of installed VHP nozzles were made and compared to the finite element analysis results of the as-built configurations, with good agreement obtained.

Using the same methodology, Dominion Engineering, Inc., performed an elastic-plastic analyses of a typical nozzle using HBRSEP, Unit No. 2, parameters for the J-groove weld and VHP nozzles (see Enclosure IV). Deflections of the nozzle caused by the welding process were obtained along the length of the housing from the lower end through the J-groove weld area. These results were then used as inputs to the finite element analysis for the leakage path determination. Deflections and related residual stresses in the VHP nozzles are tabulated in Enclosure IV.

Weld metal shrinkage and distortion are discussed in such reference texts as "Jefferson's Welding Encyclopedia," Eighteenth Edition, published by the American Welding Society, 1997. Application of this information to the J-groove weld configuration demonstrates that at the precise time of weld solidification, the weld metal is at its greatest volume as a solid and is applying compressive stresses to the base metal due to expansion. As the weld cools, it contracts and exerts compressive stresses on the weld metal and tensile stresses on all surfaces of the base metals fused with the weld. If the weld were completely restrained by both base metals, the stresses applied would be locked in both the weld and base metal causing high residual stresses. Because the vessel head provides more restraint on the weld than the penetration tube, and because the VHP nozzle tube is much thinner, partial relief of the stresses occurs by movement or distortion of the penetration tube being pulled outward toward the vessel head.

Base metal shrinkage and distortion are also discussed within the above-referenced "Jefferson's Welding Encyclopedia." Shrinkage that produces stresses leading to distortion in the base metal adjacent to the weld further compounds the problem of weld shrinkage. During welding, the base metal near the arc is also heated to the melting point. A few inches away from the base metal near the arc the temperature of the base metal is substantially lower. The sharp temperature differential causes non-uniform expansion, followed by base metal movement or metal displacement if the parts being joined are restrained. As the arc passes further down the joint, thus relocating the source of heat, the base metal begins to cool and shrink along with the weld metal. If the surrounding metal restrains the heat-affected base metal from contracting normally, internal stresses build up. These internal stresses combine with the stresses developed in the weld metal and increase the tendency for distortion.

b. With the enforced displacements in the J-weld due to weld shrinkage and an annulus with vessel fluid of 2235 psig, the FEA model showed that there are still seven nozzles (out of 13 nozzles in the 45 degree FEA model) without a predicted leak path for an initial interference of 0.003 inch. Three qualitative arguments were provided to override the analytical results: (1) low contact stresses in the interference region, (2) short interference length, and experience. Please provide justification based on documented test results or field findings for these qualitative arguments.

Response

The initial "Reactor Vessel Top Head Nozzle Operating Fit Analysis" performed by Dominion Engineering, Inc., was provided by HBRSEP, Unit No. 2, letter dated October 19, 2001. This analysis concluded that, despite a small remaining zone of predicted metal-to-metal interference for about half the nozzles with the maximum design interference fit of 0.003 inches, leakage into the VHP nozzle annulus will pass to the RPV head surface where it can be detected by visual inspection.

As described within Revision 1 to the Dominion Engineering, Inc., "Reactor Vessel Top Head Nozzle Operating Fit Analysis," HBRSEP, Unit No. 2, has a predicted operating condition leak path to the RPV head surface for initial diametral interference fits of up to and including 0.00275 inches (see Enclosure II). A detailed analysis of interference fit data, contained within Attachment II, provides strong assurance that VHP nozzle interference fits are well within design tolerances and are credibly bounded by a value of 0.002 inches. These results and conclusions supercede prior analysis conclusions regarding VHP nozzles that relied on engineering judgment in predicting leakage paths with an initial interference fit of 0.003 inches.

United States Nuclear Regulatory Commission
Enclosure I to Serial: RNP-RA/01-0166
6 Pages

H. B. ROBINSON STEAM ELECTRIC PLANT, UNIT NO. 2

EXAMPLE FABRICATION RECORDS

1446

REPORT OF INSPECTION

COMBUSTION ENGINEERING, INC.
CHATTANOOGA DIVISION

1. WHEN INSPECTED: RECEIVING, IN PROCESS, REPAIR, FINAL.

2. TYPE TEST OR INSPECTION Dim.s

3. DESCRIPTION: Dim.'s checked on These Housings Per Rev. 5 of Drawing

SN-	Part No.	SN-	Part No.
615222	284-07 ✓	615254 ✓	284-09-5
615226	284-09 ✓	~~615248~~	~~284-10~~
615225	284-09 ✓	615246 ✓	284-11
615266	284-12-4 ✓	615259 ✓	284-13-6
615244	284-11 ✓		

These pcs are Listed on Ticket #B51475 Also.

Rej #2016

INSP. PERFORMED AFTER: OPER. NO. ——

SEQ. NO. ——

4. RESULTS: SATISFACTORY—UNSATISFACTORY—INCOMPLETE

DWG. & REV. NO.	SEAM, PC., OR CODE NO.	CONTRACT & UNIT NO.
E-232-284-5	See Above	6866
JOB & CONTROL NO.	CUST. INSP.	USN-HSB INSP.
51144-001	——	——
C. E. INSP.	DATE — SHIFT	RECORDED
T.M. & JWK & others	12/13/67 (1)	B51476

INSPECTION DEPT. COPY

THIS COPY FOR:
WORK ASSIGNMENT
Send to Inspection
When Corrective Work Completed

IN-PROCESS

REJECTION NOTICE

COMBUSTION ENGINEERING, INC.
CHATTANOOGA DIVISION

NUCLEAR 3/

№ 2016

CONTRACT & UNIT [1] 6866 DWG NO. [2] E232-284-5 PART NO. [3] See Attach QUANTITY [4] See Attach.

BAY [5] 29 SHOP ORDER NO. [6] T51144 CONTROL NO. [7] SEQ. NO. [8]

DISCREPANCY: [9]
See Attachment for out of tolerance dims.
due to changes on dwg rev. "5."

DISPATCHER
DEC 13 1967

QUALITY CONTROL
DEC 18 REC'D

NUCLEAR

SEE ATTACHED SKETCH: YES ☑ NO ☐ ISSUED BY [10] JW Knott DATE [11] 12-13-67

DEPARTMENT RESPONSIBLE [12] 628 CAUSE CODE [13] 016 INCOMPLETE [14] ☐ WAIVER [15] ☐
WORKMAN RESP. [16] APPROVAL TO REPAIR [17] ☐

RECOMMENDED CORRECTIVE ACTION: [18]

FOREMAN [19] Rigsby DATE [20] 12-18-67 DISPATCHER REVIEWING FOR COMPLETENESS [21] TEB DATE [22] 12-18-

DISPOSITION: [23] [24] ☐ ENGINEERING APPROVAL TO REPAIR [25] ☐ WAIVER NO.

The surface condition is acceptable as is
to diameter, however must be reworked
into drawing tolerance

See attached disposition

MANUFACTURING ENGINEERING [26] D.O. Weaver DATE [27] 12-18-67 QUALITY ENGINEERING [28] C. Keefe DATE [29] 12-18

PROJECT ENGINEERING [30] DATE [31] APPROVED [32] ☐ DISAPPROVED ☐

COMMENTS: [33]

CORRECTIVE ACTION [34]

Q. E. INITIAL [35]

FORM NO. E-1945 REV. O L-F 3500 2-66

Vendor - If Receiving Insp.

INSPECTION RECORD

Page of

Part Description	Cont.	Pc. No.	Dwg. No.	Rev.
Control Rod Housing	6866	See below	E232-284	5

Actual Dim. put "X" in Box if Out of Tol.

Dwg. Dim. and Tol.	Dwg. Zone	~~Code~~ No. Assy.284-13-6 Serial No. 615259		~~Code~~ No. 284-07 Serial No. 615222		~~Code~~ No. 284-09 Serial No. 615226		~~Code~~ No. 284-09 Serial No. 615225		~~Code~~ No. 284-11 Serial No. 615246	
This sheet covers Changes per Rev. "5"											
32√AA For 12½"		13½"-20AA		OK		50AA	*	50/60AA		OK	
32√AA For Add. 3"		2"-125AA	*	OK		50AA	*	70AA	*	40AA	*
4.000 $\pm^{.000}_{.001}$ For 12½"		3.9995		4.000		3.9995		OK		3.9995	
4.000 $\pm^{.000}_{.001}$ For Add. 3"		~~4.002~~	*	~~4.001~~	*	3.9995		OK		4.0005	*
		4.000 JWK 1-11		4.000 JWK 1-11							
Assy.		615248		615254		615266		615244			
SN		284-10		284-09-5		284-12-4		284-11			
32√AA For 12½"		OK		OK		OK		OK			
32√AA For Add. 3"		40/50AA	*	70/80AA	*	OK		40/50AA			
4.000 $\pm^{.000}_{.001}$ For 12½"		3.9995		3.9995		3.9995		3.9995			
4.000 $\pm^{.000}_{.001}$ For Add. 3"		4.0005	*	4.0003	*	4.0004	*	4.0000			

QUALITY CONTROL

DEC 18 REC'D

H. L. L.

Inspector	Date	Rejection Notice No. 2016

DISPOSITION FOR REJECTION № 2016-01

COMBUSTION ENGINEERING, INC.

Chattanooga Division

THIS COPY FOR: Radio Housing
WORK ASSIGNMENT
) Control

PREFIX ________ DEPARTMENT RESPONSIBLE 628 CONTRACT 68666

SEQ. NO.	OPER. NO.	INSP.	SIGN OFF	OPERATION DISCRIPTION
				ANY MATERIAL IDENTIFICATION NUMBER REMOVED DURING REWORK MUST BE REPLACED IMMEDIATELY
10	9205		JBM	Polish dia. to bring within dwg. tolerance from 12½" to 15½"
		X	CE5	Assy 284-13-6 Serial #61525
		X	CE5	" 284-07 " #615222
		1/11/68		" 284-11 " #61524
		1/11/68		" 284-10 " #61529
		1/11/68		" 284-09-5 " #61525
		1-11-68	CE10	" 284-12-4 " #61526
				Polishing may be done by hand where desired.
		#	CE10	1-11-68 Inspect completed Repairs

DISPATCHER
DEC 19 1967
NUCLEAR

RETURN TO JOB NO. ________ SEQ. ________ OPER ________ AND CONTINUE FABRICATION.

APPROVAL OF ABOVE DISPOSITION

CE. MFG. ENGR.	DATE	CE. QUALITY ENGR.	DATE	CUST. (IF REQ'D)	DATE	INM (IF REQ'D)	DATE
W.O. Weaver	12/18/67	Paul C.	12/18/67				

DISPOSITION SATISFACTORILY COMPLETED

FOREMAN	DATE	INSPECTOR	DATE
G.C. Heardon		[illegible]	1-11-68

Form F-1885

REPORT OF INSPECTION

COMBUSTION ENGINEERING, INC.
CHATTANOOGA DIVISION

1. WHEN INSPECTED: RECEIVING, IN PROCESS, REPAIR, FINAL.
2. TYPE TEST OR INSPECTION Dim.

3. DESCRIPTION:

REWORK ON CONTROL ROD HOUSINGS

SERIAL # 615259	Pc # 284-13-6
615222	284-07
615246	284-11
615248	284-10
615254	284-09-5
615266	284-12-4

INSP. PERFORMED AFTER: OPER. NO. 9205

SEQ. NO. 10

4. RESULTS: SATISFACTORY—UNSATISFACTORY—INCOMPLETE

DWG. & REV. NO.	SEAM PC. OR CODE NO.	CONTRACT & UNIT NO.
E-232-284-5	ABOVE	6866
JOB & CONTROL NO.	CUST. INSP.	USN-HSB INSP.
2016-016		
C.E. INSP.	DATE — SHIFT 2nd	RECORDED
P	1-11-68	√ RW

B 64796

INSPECTION DEPT. COPY

United States Nuclear Regulatory Commission
Enclosure II to Serial: RNP-RA/01-0166
124 Pages

H. B. ROBINSON STEAM ELECTRIC PLANT, UNIT NO. 2

"REACTOR VESSEL TOP HEAD NOZZLE OPERATING FIT ANALYSIS"

REVISION 1

PERFORMED BY
DOMINION ENGINEERING, INC.

DOMINION ENGINEERING, INC.

Reactor Vessel Top Head Nozzle
Operating Fit Analysis
H. B. Robinson 2
Nuclear Power Plant

R-3513-00-1
Revision 1

October 2001

Principal Investigators

D. J. Gross
E. S. Hunt
J. E. Broussard, III

Prepared for:

Progress Energy Service Company, LLC
Carolina Power and Light Company
H. B. Robinson 2 Nuclear Power Plant
3581 West Entrance Road
Hartsville, SC 29550-9487

Contract Number 40834

Record of Revisions

Rev.	Description	Prepared by Date	Checked by Date	Reviewed by Date
0	Original Issue	E. S. Hunt 10/17/01	V. D. Moroney 10/17/01	D. J. Gross 10/17/01
1	Updated to reflect client comments.	E. S. Hunt 10/29/01	V. D. Moroney 10/29/01	D. J. Gross 10/29/01

The last revision number to reflect any changes for each section of the report is shown in the Table of Contents. The last revision numbers to reflect any changes for tables and figures are shown in the List of Tables and the List of Figures. Changes made in the latest revision, except for Rev. 0 and revisions which change the report in its entirety, are indicated by a double line in the right hand margin as shown here.

Table of Contents

List of Tables

List of Figures

List of Attachments

I. INTRODUCTION

Between November 2000 and April 2001, leaks were discovered from CRDM nozzles in the Oconee 1, Oconee 2, Oconee 3, and ANO-1 reactor vessel heads. Figure 1-1 shows leakage from one of the Oconee 3 nozzles. The leakage was discovered by visual inspection of the vessel top head surface performed through inspection ports that were cut into the head shroud as shown in Figure 1-2. The total volume of leakage at each nozzle was low, with the volume of boric acid crystals reported to be less than 1 in^3 at any single nozzle. The interference fit of each Oconee and ANO-1 nozzle was recorded during manufacture. Leakage was observed from nozzles with initial diametral fits ranging from 0.0012" diametral clearance to 0.0014" diametral interference. Three leaking nozzles at Oconee 2 had the maximum 0.0014" diametral interference. In summary, with good access for visual inspection, leakage was discovered from three nozzles with 0.0014" initial diametral interference fit.

NRC Bulletin 2001-01, *Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles*, requested that all plants predicted to be within 5 effective full power years (EFPY) of Oconee 3 based on time at temperature, should perform a "qualified visual inspection" before the end of 2001. As reported in MRP-48, HB Robinson 2 was within 3.0 EFPYs of Oconee 3 as of March 1, 2001. As specified in Bulletin 2001-01, a qualified visual inspection requires two conditions. First, it must be possible to see the locations where the nozzles penetrate the vessel top head surface. Second, it must be demonstrated that leakage from a through-wall PWSCC crack near the J-groove weld elevation will pass through the annulus between the nozzle and hole in the vessel head under plant operating (pressure and temperature) conditions such that leakage can be detected by the visual inspection of the top head surface.

Carolina Power and Light Company has requested that Dominion Engineering, Inc. (DEI) perform analyses to determine operating condition fits for the Robinson head for use in establishing whether the Spring 2001 inspections represented a "qualified visual inspection." Figure I-3 is a plan view of the Robinson vessel head and Figure I-4 is a section view through the head centerline. The section views of the Oconee and Robinson heads show that the general arrangements are similar. Results of the work performed in addressing this issue are included in the following sections of this report

- Section II – contains a summary of the work performed and conclusions,
- Section III – contains analysis requirements,
- Section IV – contains references, and
- Section V – contains the supporting analyses.

Figure 1-1
Leaking CRDM Nozzle at Oconee 3

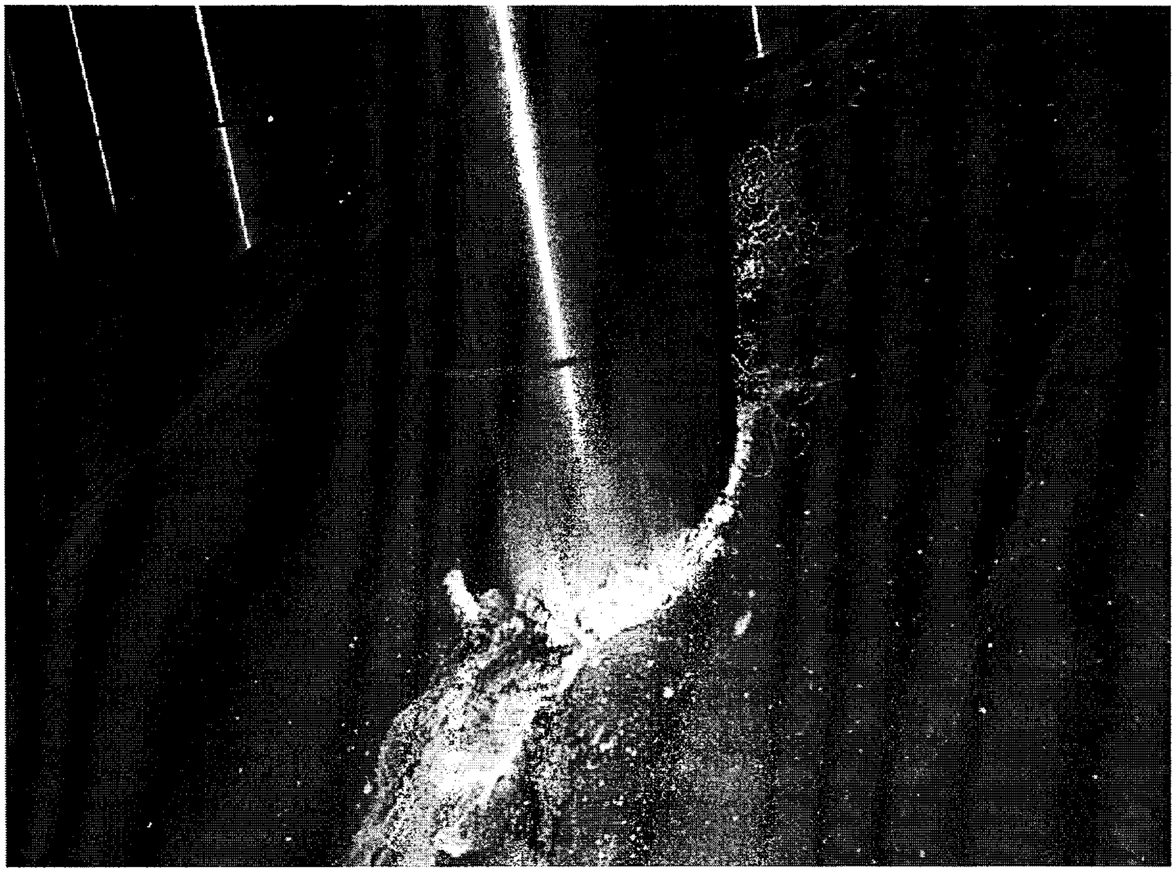


Figure 1-2
Oconee 1 Reactor Vessel Top Head – Section

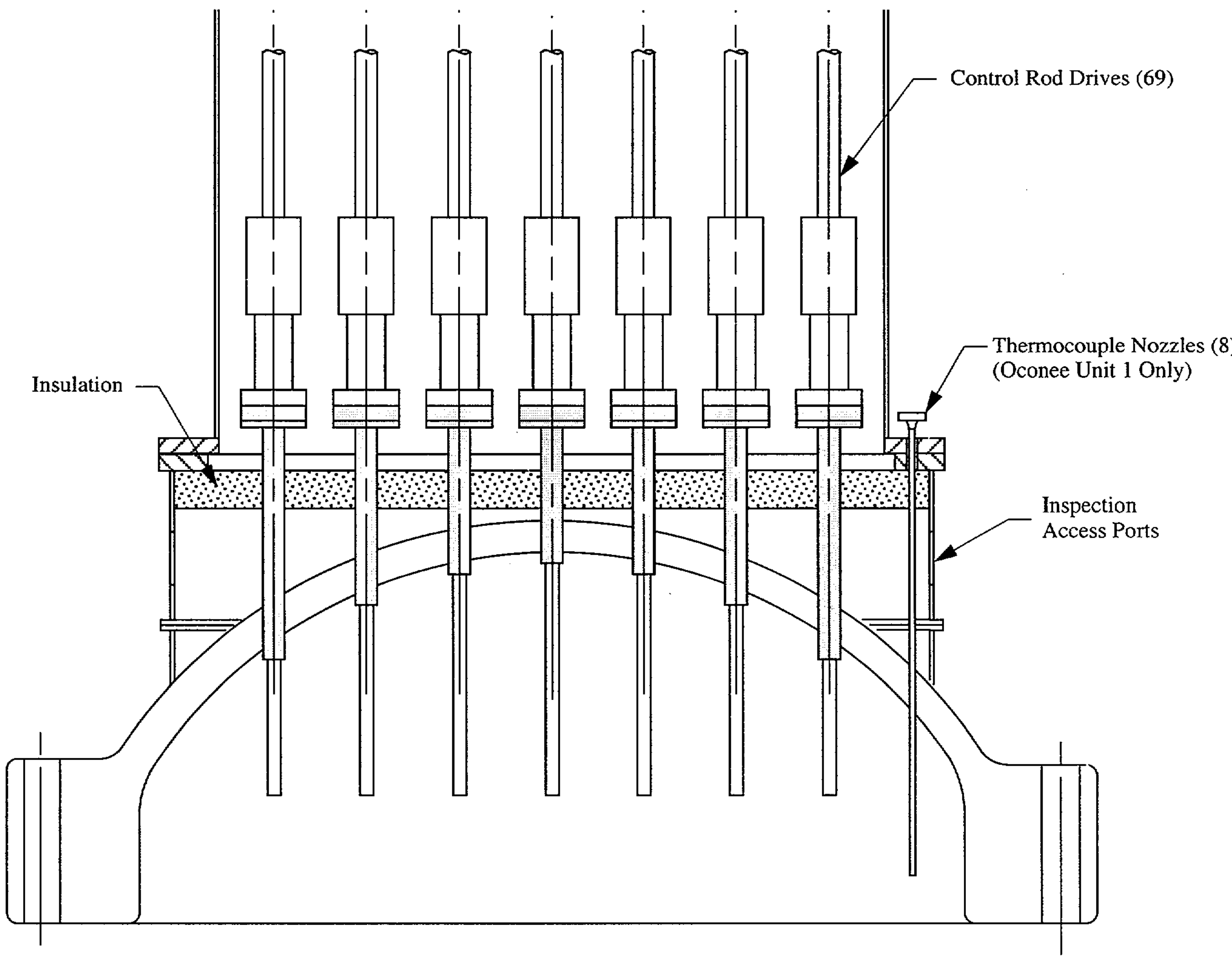


Figure I-3
Robinson Reactor Vessel Top Head – Plan

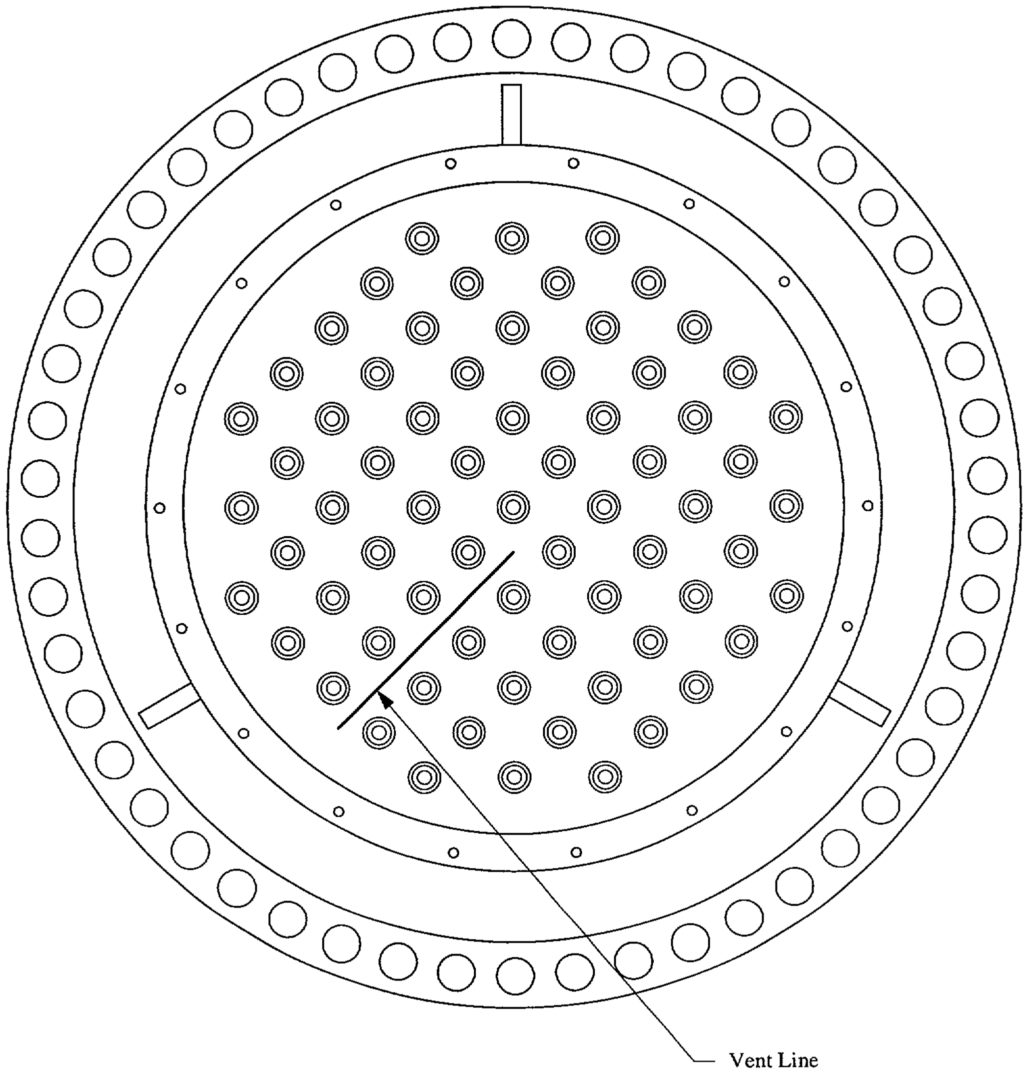
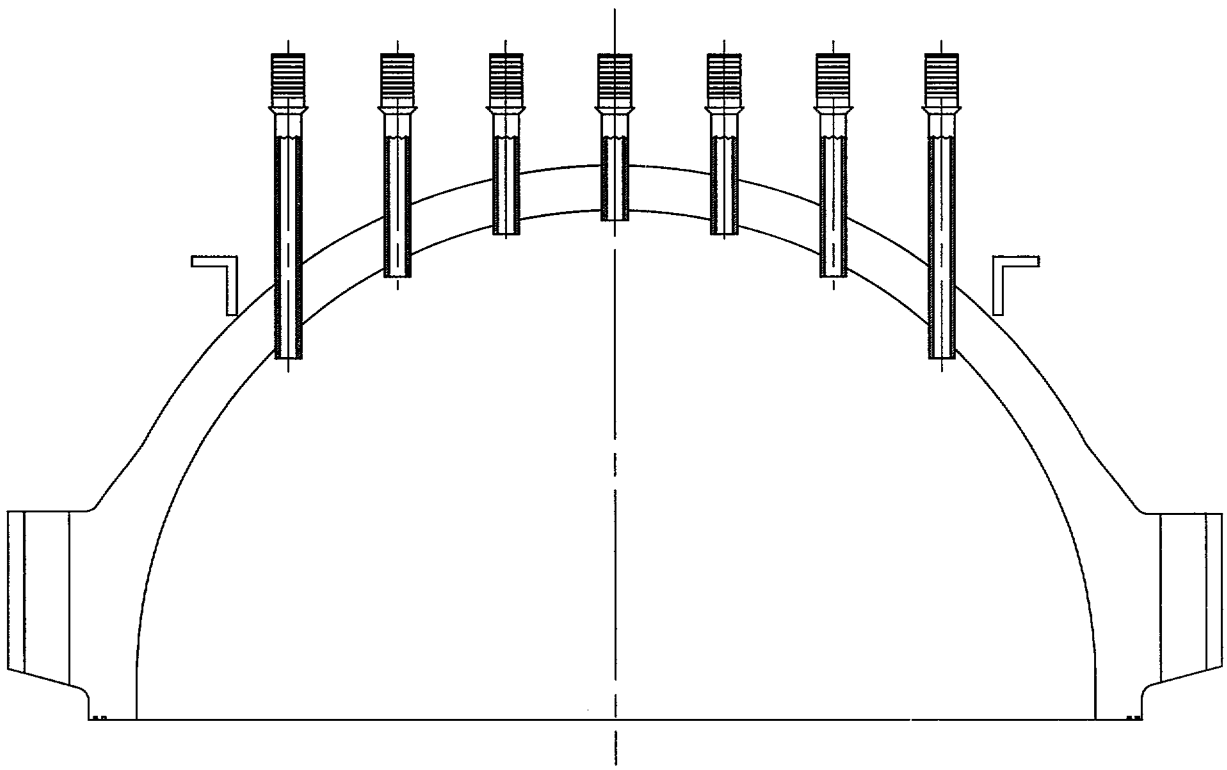


Figure I-4
Robinson Reactor Vessel Top Head – Section



II. SUMMARY AND CONCLUSIONS

The following is a summary of the work performed in this evaluation and the conclusions reached. Further descriptions and details are included in the appendices to the report.

1. Finite Element Modeling

Appendix A is a description of the ANSYS finite element model used for the subject analysis. The model, shown in Figures A-3 through A-8, includes the vessel head and flange, the 69 CRDM nozzles, and a portion of the lower flange and shell. Several key features of the model are as follows:

- A 45° sector of the head was modeled, employing symmetry boundary conditions on the 0° and 45° planes. Using this technique, a one-eighth sector of the head was used to represent the full head.

- The CRDM nozzles are joined to the vessel head at the J-groove weld. Weld shrinkage is simulated by pulling the outside surface of the nozzle radially outward in the area of the weld. This does not represent a full elastic-plastic analysis for welding residual stresses, but has been performed to simulate distortion of the bottom of the nozzle and the tendency of the weld to cock the nozzle to one side in the hole.

- The CRDM nozzles are assumed to be installed in the head with an interference fit. This fit is simulated by gap elements with initial interference conditions. The head has a counterbore at the top of the interference fit region but not at the bottom of the interference fit region near the J-groove weld.

- The vessel head and flange are modeled, including the stud holes. The head and flange are assumed to pivot about a point (reaction radius) determined based on changes in stud elongations during reactor vessel head tensioning.

- Material properties for the analyses are taken from the latest revision of the ASME Boiler and Pressure Vessel Code, Section II, *Materials*.

2. Analysis Cases and Results

Finite element analysis cases and results are provided in Appendix B. Specific cases analyzed and the resultant gap opening displacements are reported in Table B-1. In summary, analyses were performed to determine the maximum initial diametral interference fit that will result in a predicted operating condition leak path. These analyses show that there is a predicted leak path to the top head surface for initial interference fits of 0.002" to 0.0025", depending on nozzle location.

A review of the analysis results showed that there is an operating condition gap between the nozzle and hole in the head near the bottom of the interference fit region, and a tighter fit near the top of the interference fit region. This means that any leakage into this annulus will result in the outside of the nozzle, and the inside of the hole in the head, being subjected to 2,235 psi pressure. This change in boundary conditions results in additional gap opening. Using this more accurate model, there is a predicted leak path to the top head surface for initial interference fits up to and including 0.00275".

3. Conclusions

The conclusion from this analysis is that all nozzles have a predicted operating condition leak path to the head top surface for initial diametral interference fits of up to and including 0.00275".

III. ANALYSIS INPUTS

This section provides analysis inputs used in performing the calculations.

1. Dimensions and Loads

   Reactor vessel head dimensions and loads were taken from the vessel design report and drawings referenced in Section IV. Many of these dimensions and loads were previously documented in Tables III-1, III-2, III-3 and A-1 of DEI Report R-3510-00-1, Revision 0, *Reactor Vessel Bolting Evaluations – HB Robinson 2 Nuclear Power Plant.*

2. J-Groove Weld Distortions

   Deflections induced into the CRDM nozzles by the J-groove welds is important to understanding the local deflections in the vicinity of the weld. This is especially true since there is no counterbore on the underside of the Robinson head. The deflections of the nozzle wall produced by welding were taken from previous DEI analyses of the Robinson J-groove welds performed in support of the EPRI CHECWORKS RPV head nozzle module. This data shows that the nozzle wall is pulled outward by approximately 0.004" at the mid height of the weld and 0.008" at the bottom of the weld. See Paragraph 3 of Appendix A for further details

3. Head Flange Reaction Radius

   The interface between the vessel head and shell flange is a tapered seating surface. It is necessary to know the effective point on the flange about which the flanges rotate. This location was determined by analysis of stud elongations during vessel head tensioning as described in DEI report R-3510-00-1, Revision 0. This radius is 80.072" per Table A-1 of the referenced report.

4. Material Properties

   Material properties for the analysis are taken from the ASME Boiler and Pressure Vessel Code, Section II, *Materials*, 2001 revision.

IV. REFERENCES

This section presents the references used as the basis for the analysis work. References 1-99 are reserved for plant-specific references. References 100 and higher are reserved for generic references.

Plant-Specific References

1. *Analytical Report for Carolina Power and Light Reactor Vessel*, Combustion Engineering, Inc. report number CENC-1111, for contract number 6866.

2. *Instruction Manual - Reactor Vessel - Carolina Power and Light Company*, Combustion Engineering, Inc. Book No. 6866, Revision 2, dated May 1992.

3. Drawings:
   a. Combustion Engineering, Inc. Drawing E-232-271, Rev. 4, *General Arrangement – Elevation*
   b. Combustion Engineering, Inc. Drawing E-232-272, Rev. 3, *General Arrangement – Plan*
   c. Combustion Engineering, Inc. Drawing E-232-275, Rev. 10, *Pressure Vessel Final Machining*
   d. Combustion Engineering, Inc. Drawing E-232-279, Rev. 7, *Closure Head Assembly*
   e. Combustion Engineering, Inc. Drawing E-232-280, Rev. 8, *Stud, Nut and Washer Details*
   f. Combustion Engineering, Inc. Drawing E-232-292, Rev. 5, *Alignment Pin Assembly & Details*
   g. Combustion Engineering, Inc. Drawing E-232-306, Rev. 3, *Miscellaneous Details*

4. Dominion Engineering, Inc. report R-3510-00-1, Revision 0, *Reactor Vessel Bolting Evaluations – H. B. Robinson 2 Nuclear Power Plant.*

5. Miscellaneous details of J-groove weld region provided by fax from T. Huminski (CP&L) to S. Hunt (DEI) on October 1 and 2, 2001.

6. Applicable code revision for material property data provided by e-mail from T. Huminski (CP&L) to S. Hunt (DEI) dated October 16, 2001.

Generic References

101. NRC Information Bulletin 2001-01, *Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles*, August 3, 2001.

102. MRP-048, *PWR Materials Reliability Program Response to NRC Bulletin 2001-01*, EPRI, Palo Alto, CA: August 2001

103. MRP-44 Part 2, *PWR Materials Reliability Program, Interim Alloy 600 Safety Assessments for US PWR Plants (MRP-44): Part 2: Reactor Vessel Top Head Penetrations*, EPRI, Palo Alto, CA: 2001, TP-1001491, Part 2.

104. *ANSYS Engineering Analysis System*, Revision 5.7, ANSYS, Inc.

105. ASME Boiler and Pressure Vessel Code, Section II, *Materials*, 2001 Revision.

106. Rabinowicz, E., *Friction and Wear of Materials*, Second Edition, John Wiley & Sons, 1995.

107. TR-103696, *PWSCC of Alloy 600 Materials in PWR Primary System Penetration*, EPRI, Palo Alto, CA: July 1994.

108. TR-103198-P8, *CHECWORKS: PWR Vessel and Internals Application: RPV Head Nozzle Module, Version 1.1, User Guide*, EPRI, Palo Alto, CA: November 1999.

V. APPENDICES

Appendix A

Finite Element Model of Reactor Vessel Head and CRDM Nozzles

This appendix describes the finite element model of the reactor vessel and CRDM nozzles including the geometry, element types, material properties, boundary conditions, and other modeling assumptions. Analysis results are provided in Appendix B.

1. Finite Element Analysis Software

   Analyses were performed using ANSYS Revision 5.7 on an HP B2000 workstation running under the HP-UX 10.20 operating system. This software is maintained in accordance with requirements of the Dominion Engineering, Inc., *Quality Assurance Manual for Safety-Related Nuclear Work*, DEI-002.

2. Model Geometry

   The finite element analysis was performed using a general purpose reactor vessel top head model developed by Dominion Engineering, Inc. This model was then adapted to the Robinson reactor vessel head geometry.

   Figure A-1 is a plan view of the Robinson reactor vessel head. With the exception of the flange bolt holes, the Robinson vessel head can be modeled using 1/8 (45°) symmetry as shown in Figure A-2. The flange has 50 bolt holes which results in 6.25 bolt holes per sector. Since the bolt holes are a second order factor in the analysis for nozzle gap displacements, the sector has been modeled using six equally spaced bolt holes, with the hole diameter increased from the 7.50" specified in the vessel design report to 7.655" to accurately reflect the amount of material removed in the 6.25 holes per sector.

   Figure A-3 shows the overall finite element model. The model includes the vessel head, CRDM nozzles, vessel head flange, lower shell flange, and a portion of the cylindrical vessel shell. The lower flange and cylindrical shell were included to provide for shear forces between the upper and lower flange. The head lifting lugs, shroud support ring, and vent nozzle are all second order factors and were not modeled. Figure A-4 shows a view of the head in the region of the CRDM nozzles. With the exception of gap elements used to simulate the fit between the head and CRDM nozzles, the entire model shown in Figures A-3 and A-4 is constructed using SOLID45 eight node solid elements.

Figure A-5 shows a typical CRDM nozzle module consisting of the Alloy 600 nozzle and a square section of the vessel head as viewed from the top. Individual CRDM modules are combined to create the CRDM nozzle region of the head. Portions of the nozzle and shell extending beyond the edges of the 1/8 symmetry sector are deleted. This results in there being five full nozzles, seven half nozzles on the symmetry planes, and one 1/8 nozzle at the vessel centerline. Each of the nozzles has a different incidence angle relative to the underside of the vessel head.

Figures A-6 and A-7 show details of a CRDM nozzle module. Key features of these modules are as follows:

- The inside and outside radii of the vessel head are modeled as 74.438" and 82.406" respectively. The resultant 7.968" thickness includes the 7.75" base material thickness and the 0.218" clad thickness. The cladding would not be included in ASME Code strength calculation, but is important for deflection analysis purposes.

- The nozzle is modeled as a tube with 4.000" outside diameter and 2.750" inside diameter over the full length. The hole in the vessel head is also modeled as 4.000" inside diameter. COMBIN40 gap elements with the specified initial radial interference fit are positioned between the nozzle outside surface and the hole inside surface. This element type was selected over other possible choices since it permits modeling of gaps for the case of coincident nodes. Other features of the COMBIN40 elements such as sliding surfaces and damping were not used.

- The Robinson head includes a counterbore from the head OD surface to an elevation approximately equal to the location where the downhill side of the nozzle penetrates the vessel head. The counterbore region is indicated by a horizontal row of nodes. The counterbore region is modeled using the same diameter as the clearance hole in the vessel head, but there are no gap elements such that nozzle deflections are not constrained in this region.

- The nozzle extends the specified distance below the inside surface of the vessel head, and approximately one nozzle diameter above the top of the vessel head. The axial pressure load in the nozzle is simulated by a negative "end cap" pressure on the top surface of the nozzle where the end cap pressure is

$$p_{cap} = \frac{Pd_i^2}{d_o^2 - d_i^2}$$

where

p_{cap} = end cap pressure on nozzle elements
P = vessel internal pressure = 2,235 psig
d_i = nozzle inside diameter = 2.750"
d_o = nozzle outside diameter = 4.000"

Figures A-3 and A-8 show the flange region. As previously noted, the model simulates 48 rather than 50 bolt holes in the head, but the hole diameter has been increased to accurately reflect the actual bolt hole volume. The stud preload force of 1,215 kips on each of the 50 studs is simulated as a downward pressure on the top face of the head flange, and an upward pressure on the top face of the vessel flange. The studs have not been modeled explicitly since this is a minor effect relative to the gap opening displacement. The vessel head flange and vessel shell flange are coupled together axially, radially and circumferentially at the 80.072" effective reaction radius determined from actual stud elongation measurements analyzed for the Robinson reactor vessel tensioning optimization study. Operating pressure is assumed to be applied out to the effective reaction radius which is between the two o-rings. The core barrel spring force was not modeled since it is only about 1% of the total stud preload force and it acts near the effective pivot point.

Dimensions were taken from the vessel design report and drawings, from previous DEI analyses of the Robinson head performed in support of developing optimized tensioning procedures, and from additional information supplied by fax for this project.

3. Modeling of J-Groove Weld Distortion

When a nozzle is welded into a pressure vessel shell by a J-groove weld, weld shrinkage which occurs during cooling produces high residual tensile stresses in the weld. Stresses in the weld apply loads to the adjacent parts, including the nozzle wall, which pulls the nozzle wall radially outward as shown in Figure A-9. This outward displacement of the nozzle wall results in high tensile hoop stresses through the nozzle wall near the J-groove weld. These high welding residual stresses in the nozzle wall are the source of the predominantly axial PWSCC cracks in CRDM nozzles. The presence of outward distortion and resultant residual tensile stresses have been confirmed by dimensional measurements and residual stress measurements. Details are provided in EPRI Report TR-103696, *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*.

For the Robinson CRDM nozzle gap condition analysis, the type 182 weld metal and buttering is modeled as a ring of material with the same height as the root of the weld and with a width that results in approximately the same volume as the actual weld. The nodes on the nozzle and hole corresponding to the weld root location are coupled in all three directions to reflect the nozzle wall pivoting about this location as the weld is applied.

Weld shrinkage is not modeled explicitly in the Robinson gap condition analysis. Rather, the radial outward deflection of the inside surface of the nozzles at the mid and bottom elevations of the weld are simulated by constraint equations which pull these surfaces out by 0.004" radially at the midpoint of the weld and 0.008" radially at the bottom surface of the weld. This outward deflection at the weld causes the nozzle to bend about the buttering region thereby creating a small annular pocket above the weld. Deflections were taken from elastic-plastic analyses of the J-groove welds for the Robinson nozzles performed in support of the EPRI CHECWORKS program.

4. Material Properties

Elements were assigned material properties at 600°F (very close to the 598°F head operating temperature) as given in Table A-1. These data were taken from the 2001 revision of Section II of the ASME Code.

Table A-1
Material Properties

Property	A302 Grade B Shell and Flange Material	Alloy 600 Nozzle and Weld Material
Modulus of Elasticity (psi)	26.4×10^6	28.7×10^6
Coefficient of Expansion (in/in/°F)*	7.8×10^{-6}	7.8×10^{-6}
Poisson's Ratio	0.3	0.3

* Mean coefficient from 70°F to 600°F.

5. <u>Boundary Conditions</u>

The following displacement boundary conditions were imposed on the model:

- The nodes at the bottom of the vessel shell were all fixed in the vertical direction and allowed to move freely in the circumferential and radial directions.

- Circumferential displacements were restrained on the first and last nodal planes (0° and 45°) of the model.

The following coupled degrees of freedom were imposed on the model:

- The nodes associated with the flange reaction radius were coupled together in the axial, radial and circumferential directions, simulating the effects of friction under high normal forces and relatively low shear forces.

The following pressure boundary conditions were imposed on the model:

- Internal pressure was applied to all inside surface of the head, nozzles, flanges, and vessel shell out to the flange reaction radius (between the two o-rings).

- A pressure simulating the hydrostatic end-cap load was imposed on the top surface of each CRDM nozzle.

- Where indicated in Appendix B, the annular region between the nozzle and hole in the vessel head was pressurized.

The following constraint conditions were imposed on the model:

- The nodes in the nozzle and head at the weld root were coupled in all three directions.

- The nodes between the nozzle and weld metal were constrained to simulate 0.004" of outward deflection of the nozzle wall at the mid-elevation of the weld and 0.008" of outward deflection at the bottom of the weld. These deflections were obtained from results of previously performed elastic-plastic analyses of welding stresses and deflections.

Figure A-1
Plan View of Robinson Vessel Top Head

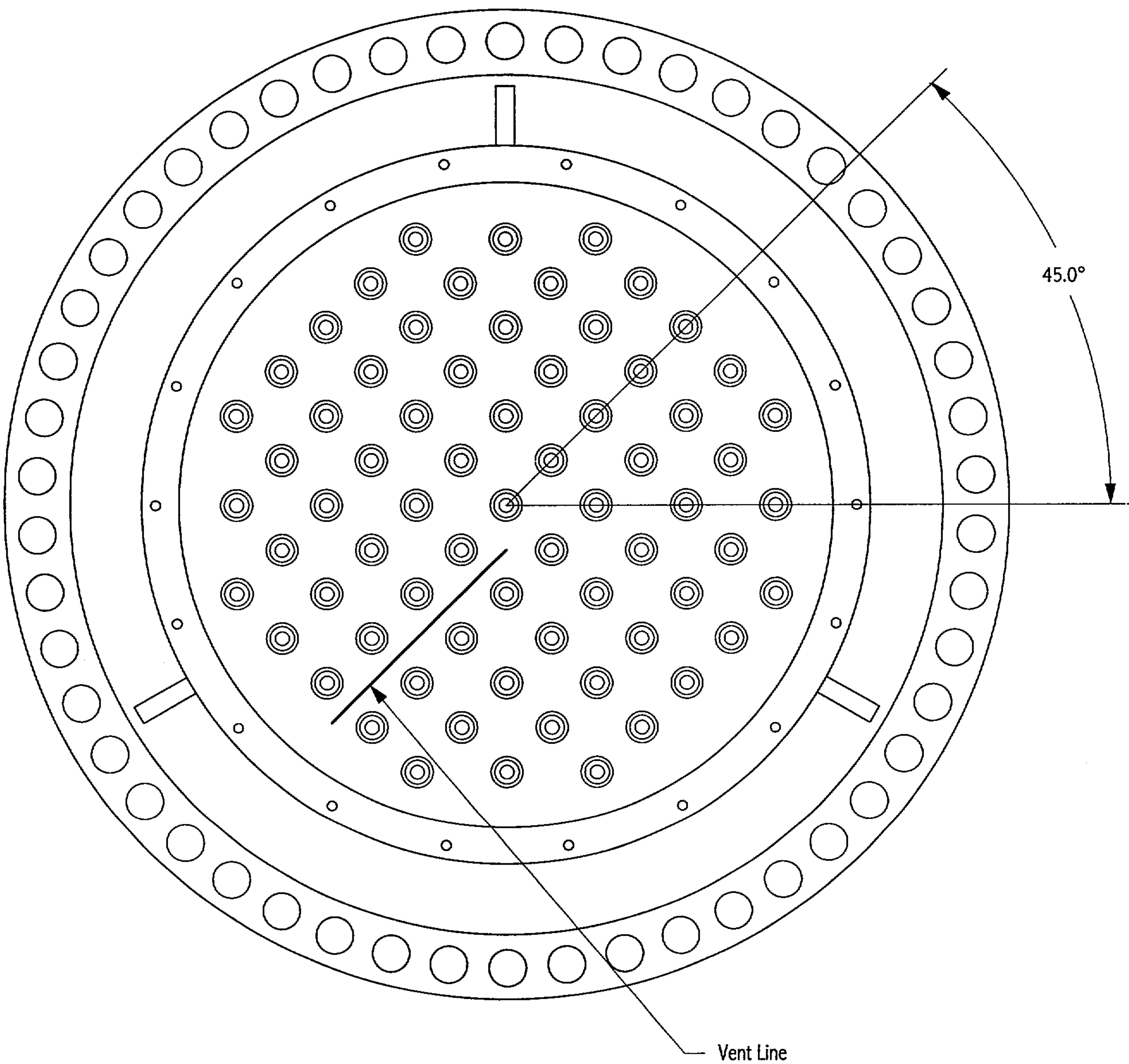
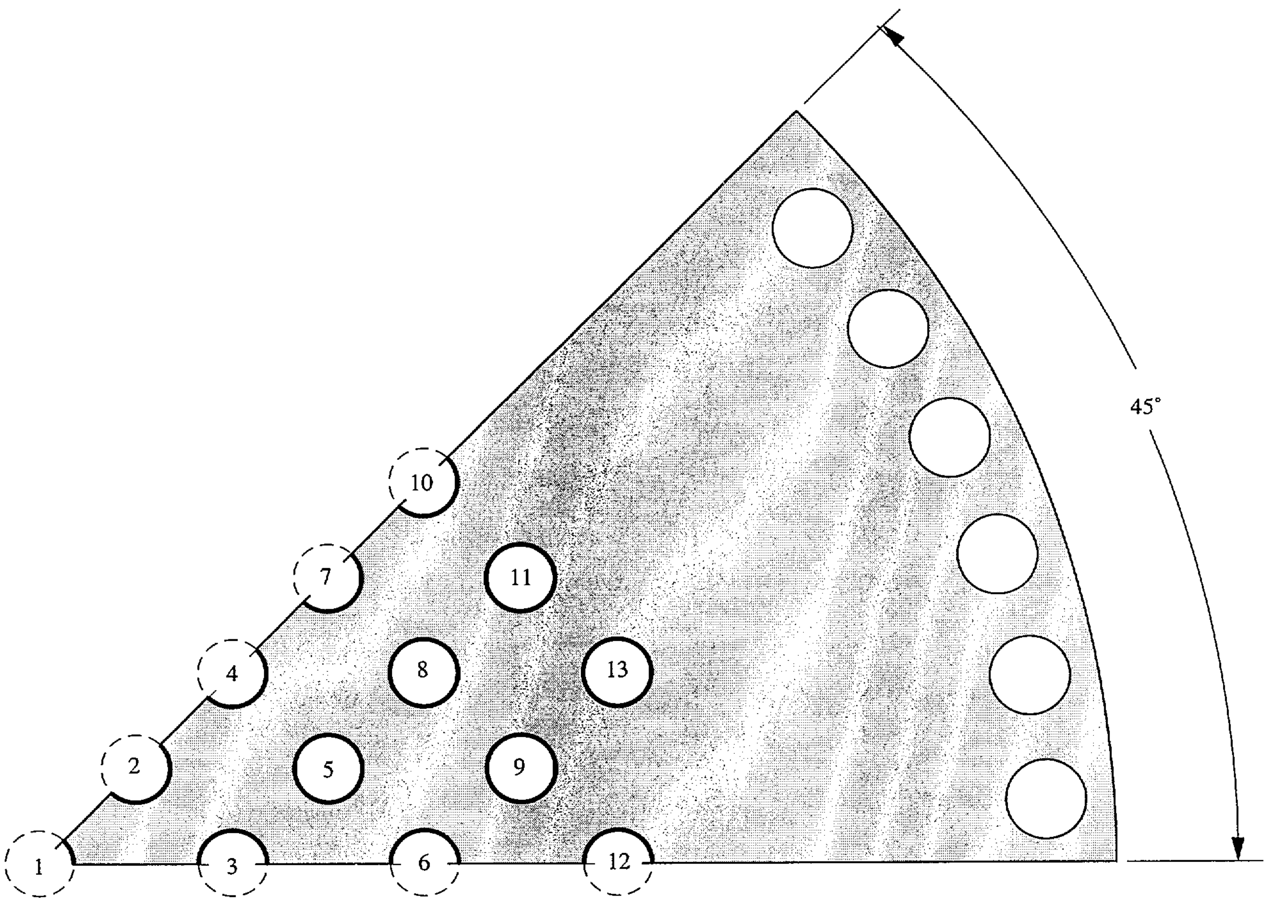
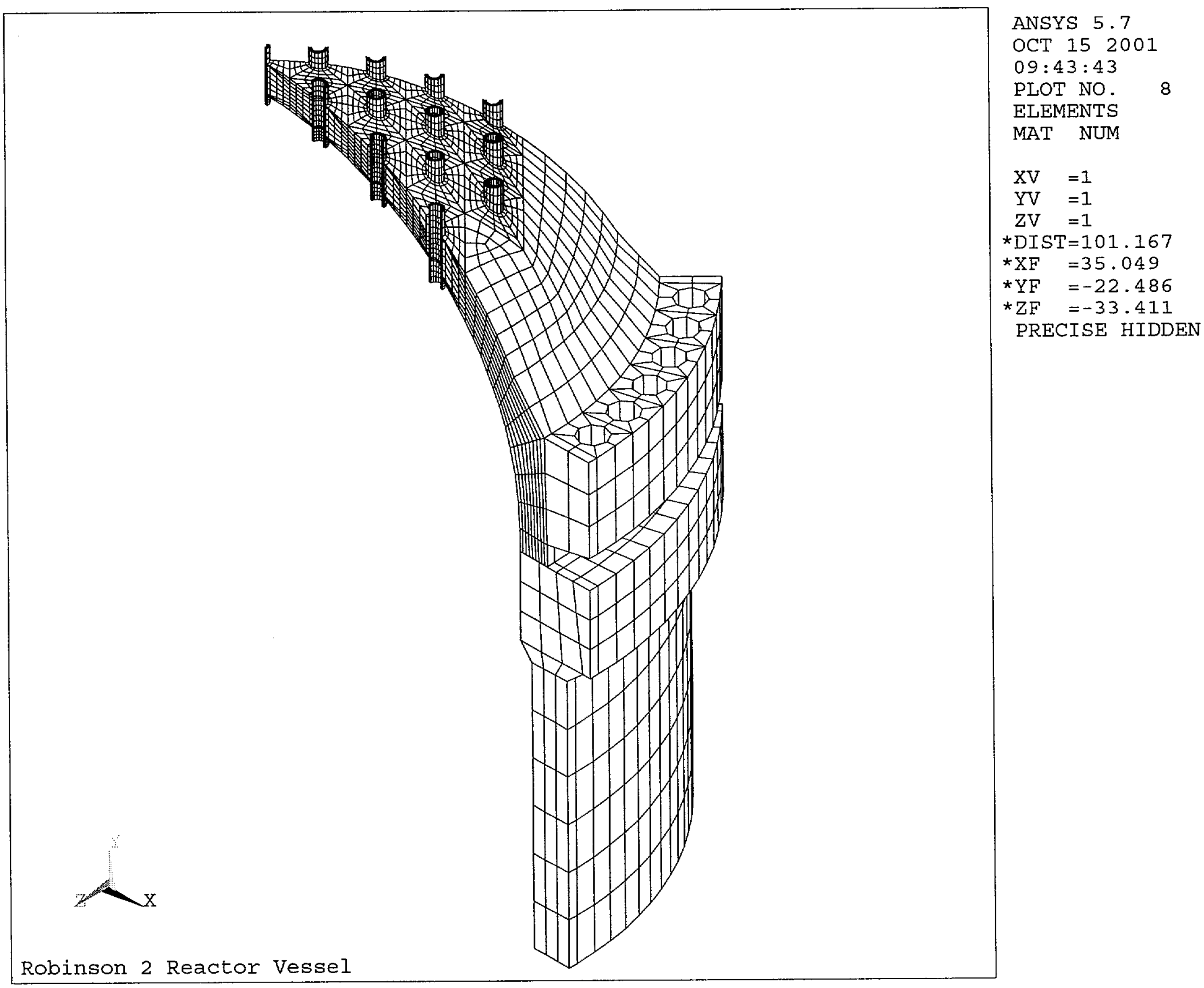


Figure A-2
Modeled Sector of Robinson Vessel Top Head

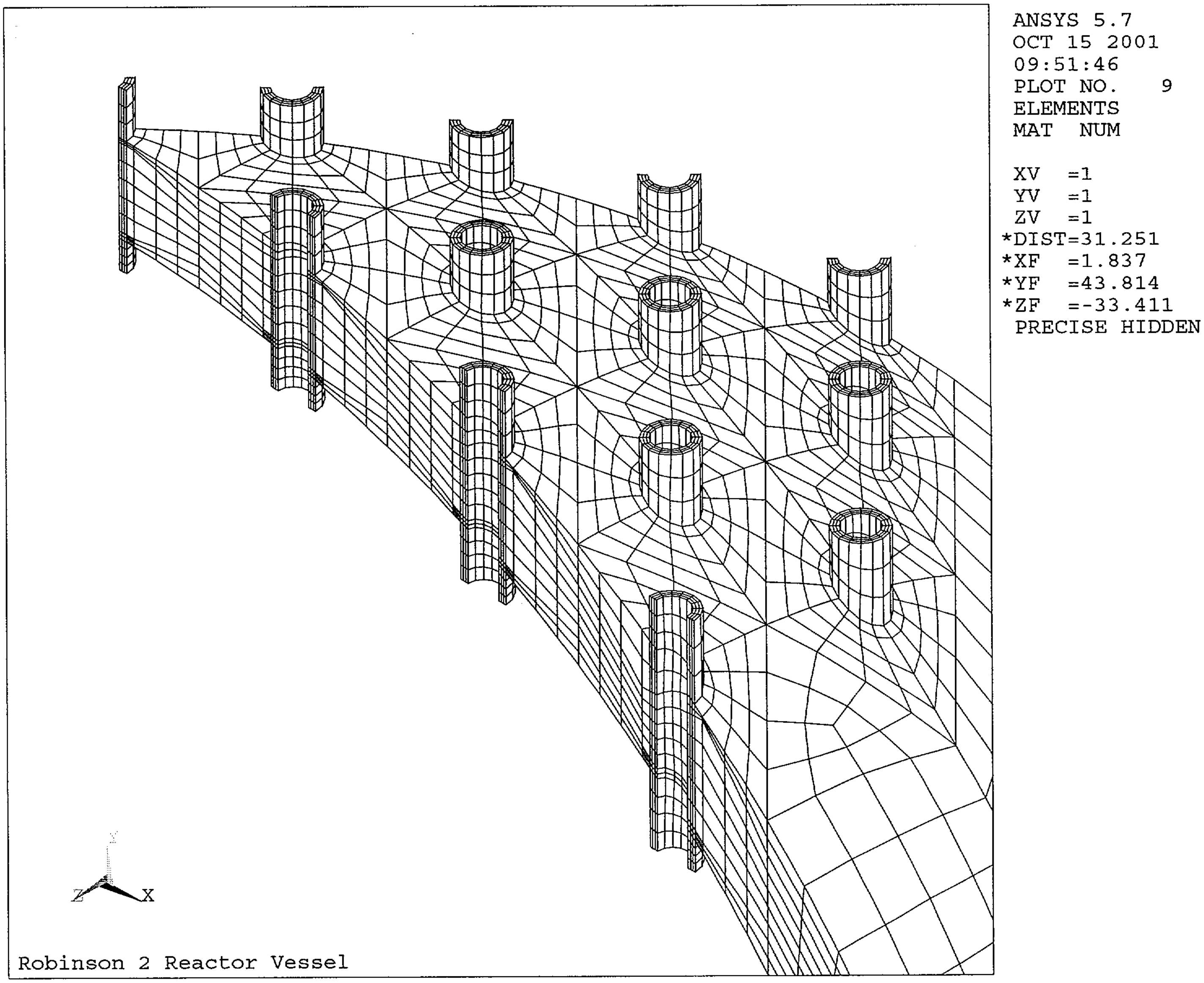


Nozzles numbered in order of increasing incidence angle



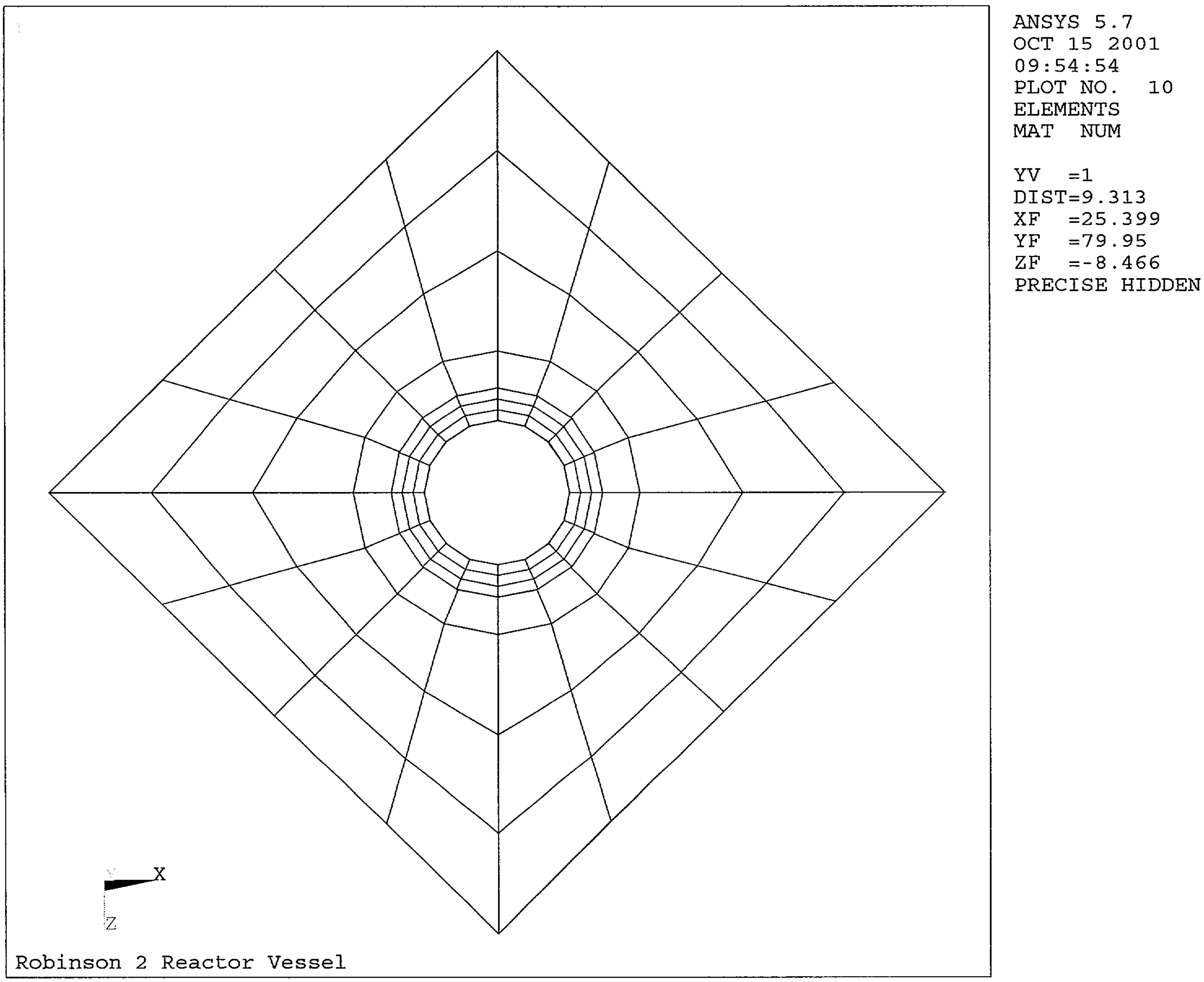
Reactor Vessel Head and Shell Finite Element Model

Figure A-3



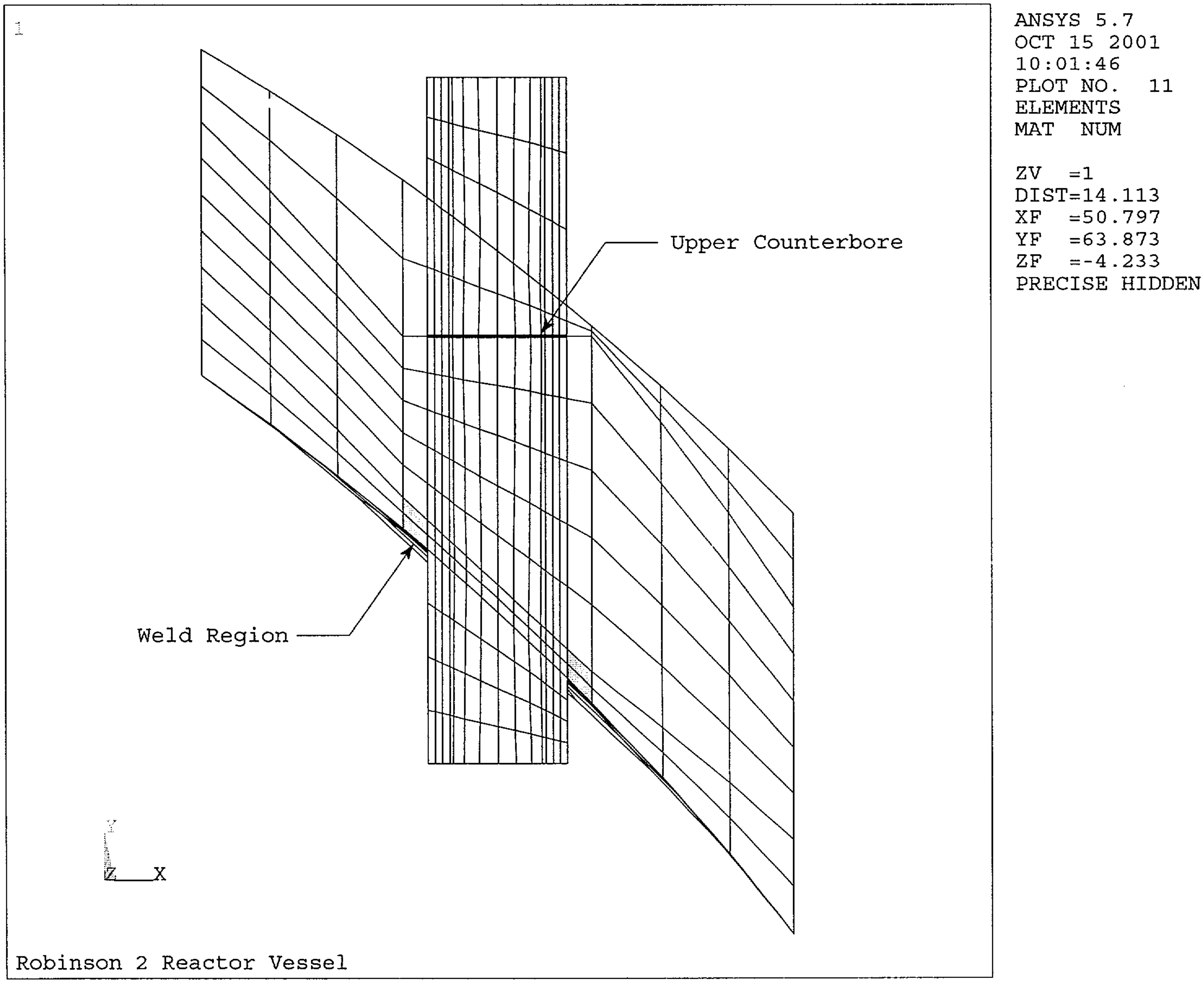
Finite Element Model of Vessel Top Head CRDM Nozzle Region

Figure A-4



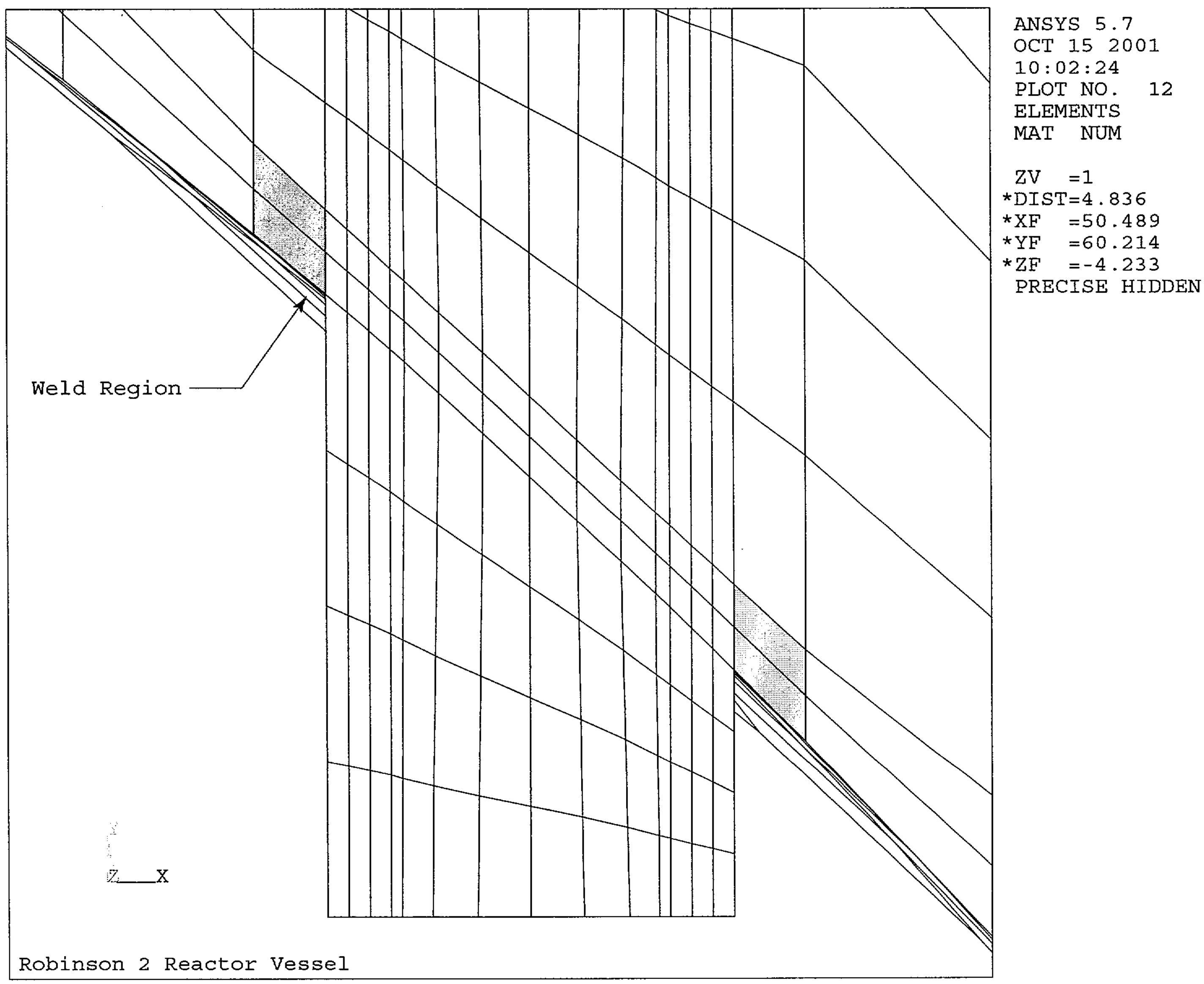
Finite Element Model of Typical CRDM Nozzle Module

Figure A-5



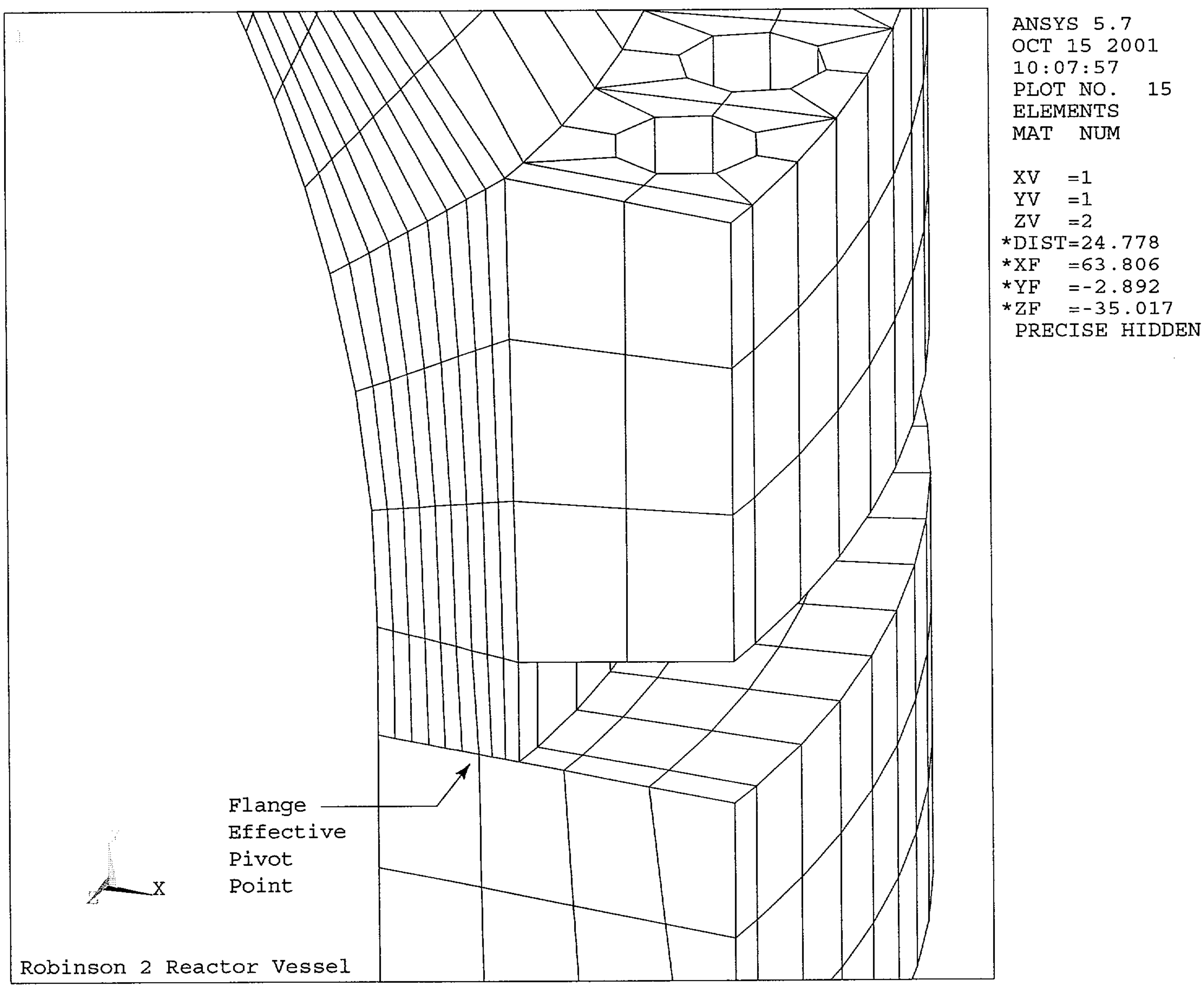
Finite Element Model of CRDM Nozzle Module (Section View)

Figure A-6



Finite Element Model of CRDM Nozzle Module (Weld Details)

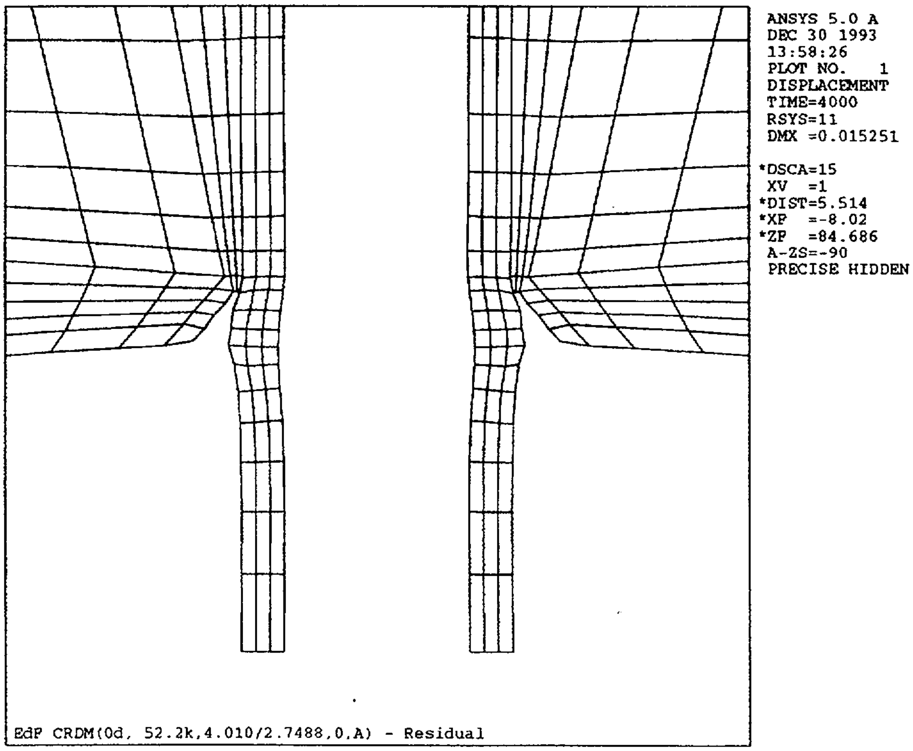
Figure A-7

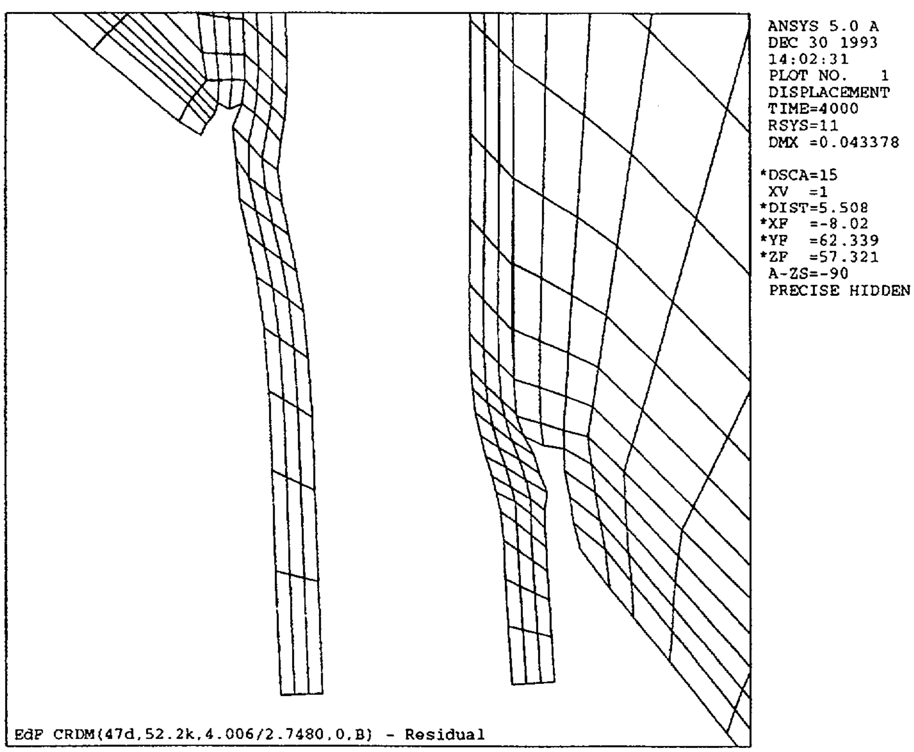


Finite Element Model of Flange Seating Surface

Figure A-8

Figure A-9
Effect of CRDM Nozzle J-Groove Weld on Nozzle Distortion (Ref. EPRI TR-103696)





Appendix B

Finite Element Analysis Results

The finite element model described in Appendix A was used to analyze a number of different cases. The following is a discussion of general model performance followed by complete results for all cases analyzed.

1. General Model Performance

Figures B-1 through B-4 show several plots that highlight model development and performance.

- Figure B-1 shows deflections of Nozzle #11 after imposing the constraint equations simulating the J-groove weld distortion for the case with no initial interference fit. This figure shows the nozzle wall being pulled outward at the weld and being bent around the buttering region thereby creating a small annular pocket above the weld. This figure also shows the laterally outward deflection of the bottom of the nozzle as was reported in EPRI TR-103696, *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*. (See Figure A-9)

- Figure B-2 is identical to Figure B-1 except that it is for the case with a 0.003" initial interference fit. This figure shows the nozzle wall being pinched inward at the upper counterbore region, and the resultant compressive stresses in the nozzle in the interference fit region.

- Figure B-3 shows rotation of the vessel head and shell flanges for the bolt preload condition including the effects of J-groove weld distortion. This figure also shows that stresses induced by flange rotation have largely decayed away at the location of the outermost CRDM nozzles. Therefore, there is little effect of flange rotation on CRDM nozzle stresses and deflections.

- Figure B-4 shows stresses on the vessel head and shell for typical operating conditions including J-groove weld distortion, interference fit, flange bolt preload, internal pressure, and temperature. This figure shows higher stresses in the portion of the head containing CRDM nozzles reflecting loss of head material, and stress concentration effects at the penetrations.

2. Analysis Cases and Output Results

Six cases were analyzed to assess the effects of important variables. The cases are identified in Table B-1. A range of initial diametral interference fits was analyzed to determine the maximum initial interference fit that will result in a predicted flow path to the top head surface under operating conditions. Analyses were also performed for a case in which a single nozzle was assumed to leak and the leakage pressurizes the annulus between the hole in the vessel head and the outside of the nozzle. This case is discussed in greater detail in paragraph B.4.

Selected ANSYS output data for each case is provided at the back of this appendix. The page footers provide a code to the data presented. The first code entry is for the initial diametral interference. The second code entry is for any special conditions such as pressurization of the annulus between the nozzle OD surface and vessel shell ID surface.

The gap element number (ELEM) defines the location of each gap element by nozzle, elevation, and azimuth around the nozzle as illustrated in Figure B-5.

- The 100's place in the element numbers refer to the nozzle number. For example, the 1300's elements refer to Nozzle #13.
- The 00-10's elements refer to the first row of gap elements located above the top of the J-groove weld. The 20-30's elements refer to the bottom quarter point gap elements. The 40-50's elements refer to the mid elevation gap elements. The 60-70's elements refer to the top quarter point gap elements. The 80-90's elements refer to the top row of gap elements at the bottom of the top counterbore.
- The element numbers at each row run sequentially around the nozzle.

The gap condition (GAPSTAT) is defined where 3.000 is an open gap and 1.000 is a closed gap (metal-to-metal contact).

The force at the gap element when in the closed condition (GAPFORCE) is given in pounds. The contact pressure between the nozzle and hole in the head can be determined by dividing the force by the surface area associated with each gap element.

The gap displacement (GAPSTRCH) is given in inches.

The numbers in Table B-1 are the maximum gap opening displacements at the most limiting (tightest) elevations. The output data has been annotated to assist in determining this value. The maximum gap opening at each circumferential ring of gap elements is designated by (<). The smallest of these values for each nozzle is designated as the limiting condition that is reported in Table B-1 (< Limiting).

3. Analysis Results for Normal Conditions

The analysis results in Table B-1 show that all nozzles are predicted to have a gap opening to the top head surface for a 0.002" to 0.0025" initial interference fit without taking into account the fact that leakage will pressurize the annulus between the nozzle and hole in the vessel head.

4. Effect of Leak on Nozzle Pressure Loading

A review of the ANSYS output data shows that the tightest fit for most all cases occurs at the top of the interference fit region. This is illustrated by Figure B-6.a which shows the gap opening for Nozzle #9 for the case of a 0.0020" initial interference fit. A leak into the annulus region would result in application of pressure on the outside of the nozzle and the inside of the hole in the vessel head. This pressure will serve to increase the pressure dilation of the vessel head and reduce the pressure deflection of the nozzle. The net effect of the leak is therefore to increase the gap opening. It is assumed for these calculations that small flow passages created by the surface roughness allow the pressure to act over the full interference fit surface area. This assumption is supported by the model for the actual contact area between two adjacent metal surfaces described by Rabinowicz, *Friction and Wear of Materials*, in which the contact area is the applied load divided by three times the material yield strength. This results in an actual contact area of about 5% for 0.003" of initial diametral interference fit. The remaining approximately 95% of the surface area has small flow passages with an RMS height equal to the sum of the RMS surface roughness of the mating parts, or about 60-90x10^{-6} inches (0.00006-0.00009").

The effect of the external pressure acting on individual leaking nozzles was assessed for initial interference fits of 0.00275" and 0.003". It was conservatively assumed for these cases that there were no leaks in the other nozzles. The analysis shows that all of the nozzles have a leak path for fits up to and including 0.00275". In addition, the analysis shows that six of thirteen nozzles have leakage paths for fits up to and including 0.003" of initial interference.* While the analysis shows some metal-to-metal contact for the remaining seven nozzles for a 0.003" initial interference, the contact force near the surface is very low, and it would be unlikely to be capable of preventing leakage of 2,235 psig steam over the very short contact length given the small percentage of actual metal-to-metal contact. The reasons are as follows:

- Contact stresses tend to be low in the remaining area of interference such that the actual area of metal-to-metal contact at high points between the mating surfaces will be low.
- The length of the remaining interference is short.
- As described in paragraph 3.4.2 of MRP-44, Part 2, experience has shown that it is unlikely that small amounts of operating condition interference fit between machined parts of this size will be capable of preventing steam leaks.

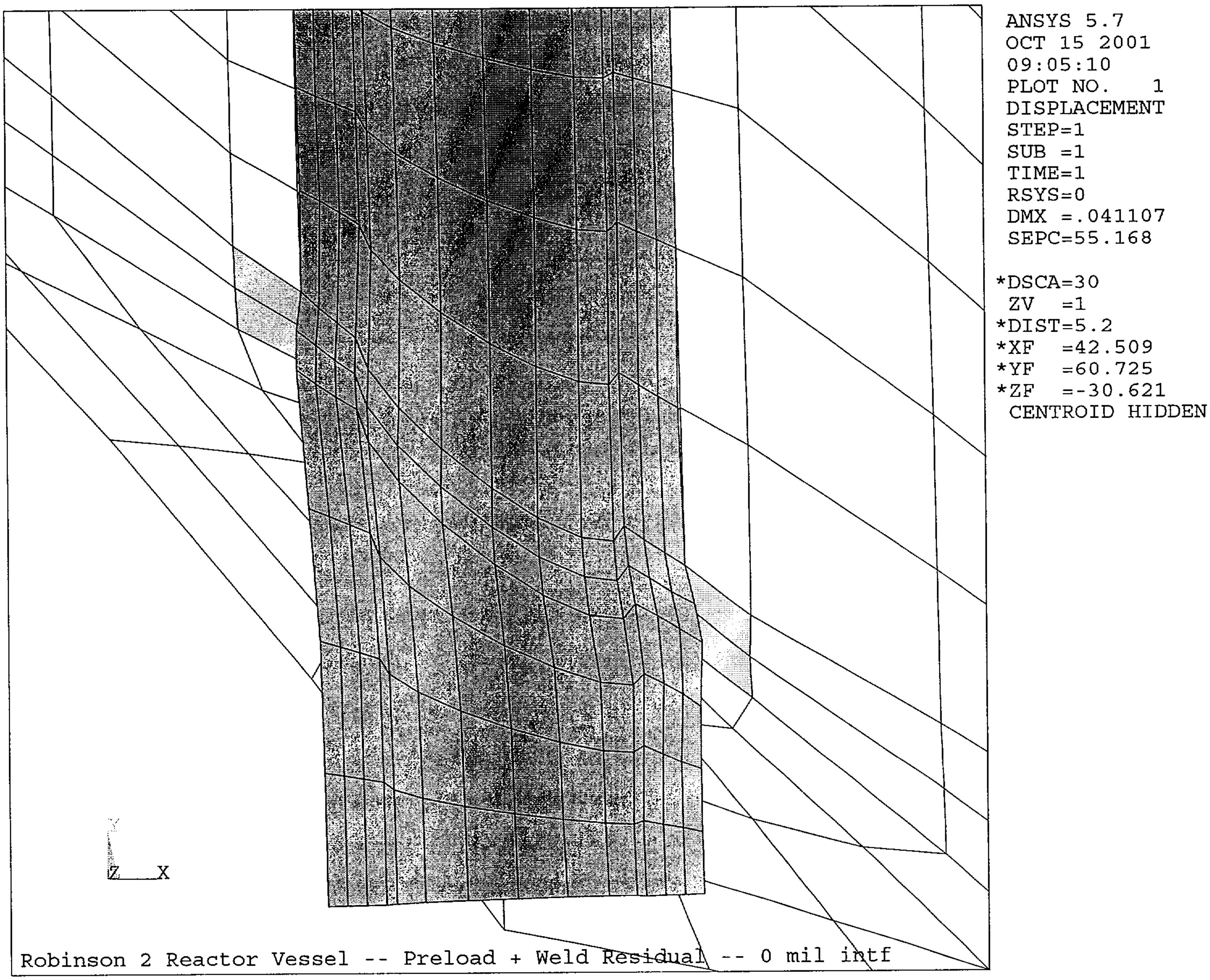
* Number of nozzles is relative to total of thirteen nozzles in one-eighth sector modeled.

Table B-1
Summary of Analysis Results

		Maximum Gap Width (mils) at the Controlling (tightest) Elevation												
Initial Diametral Interference (in)	Special Conditions	1	2	3	4	5	6	7	8	9	10	11	12	13
0.00175	None	0.33	0.83	0.79	0.66	0.60	0.36	0.31	0.32	0.32	0.23	0.37	0.31	0.39
0.00200	None	0.20	0.53	0.49	0.36	0.29	0.11	0.10	0.12	0.09	0.05	0.13	0.12	0.19
0.00225	None	0.07	0.24	0.17	0.02	>0								>0
0.00250	OD Pressure on Nozzle *	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.35	N/A	N/A	N/A	N/A
0.00275	OD Pressure on Nozzle*	0.22	0.73	0.55	0.41	0.34	0.06	0.05	0.11	0.08	0.03	0.12	0.09	0.24
0.00300	OD Pressure on Nozzle*	0.09	0.28	0.22	0.10	0.03								0.03

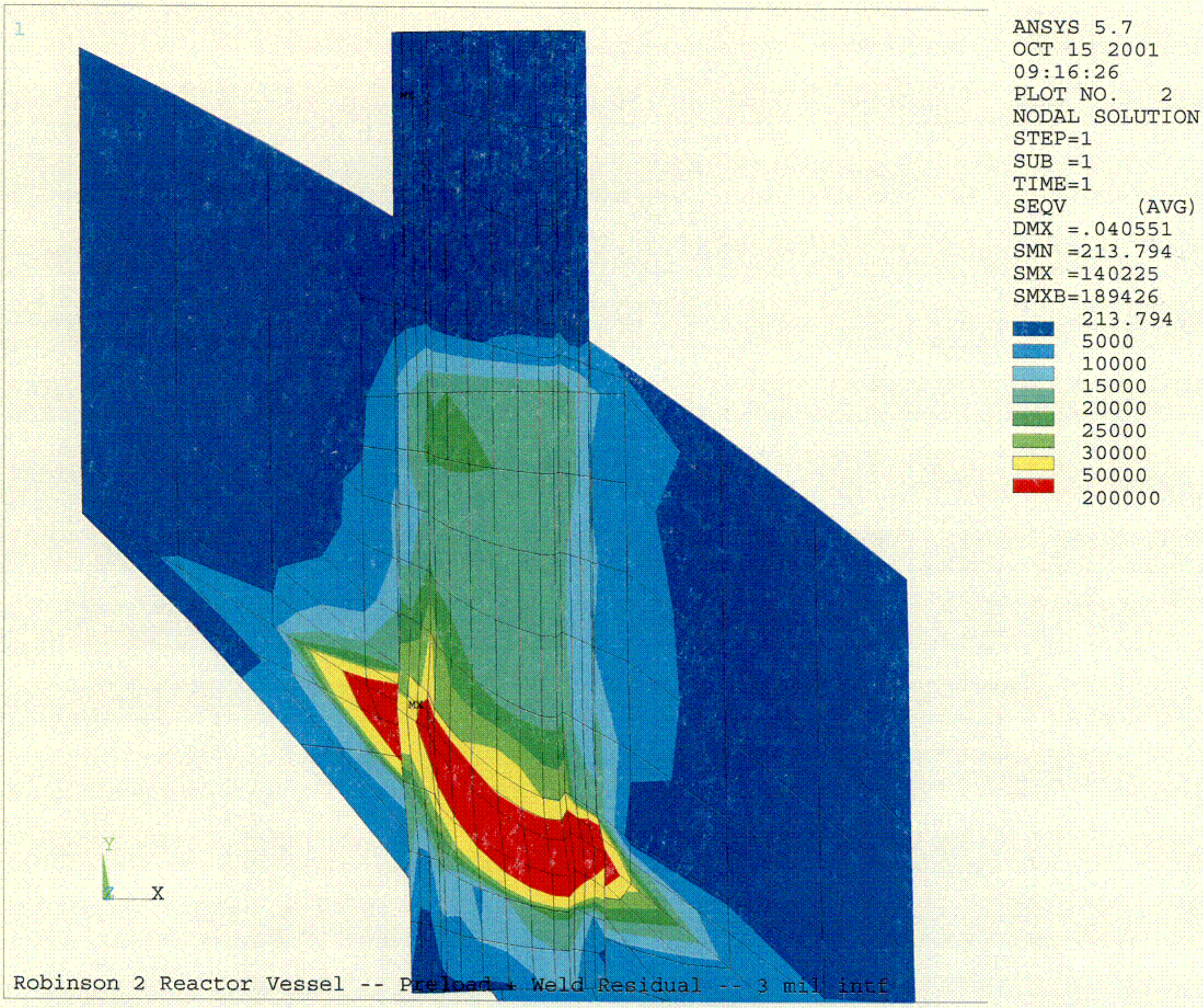
Designates condition in which there is no predicted leak path to the surface.

* These cases are for pressure on the OD surface of the designated nozzle with no pressure on the OD of other nozzles. N/A signifies "Not Analyzed.



Deflections Imposed on Nozzle by J-Groove Weld

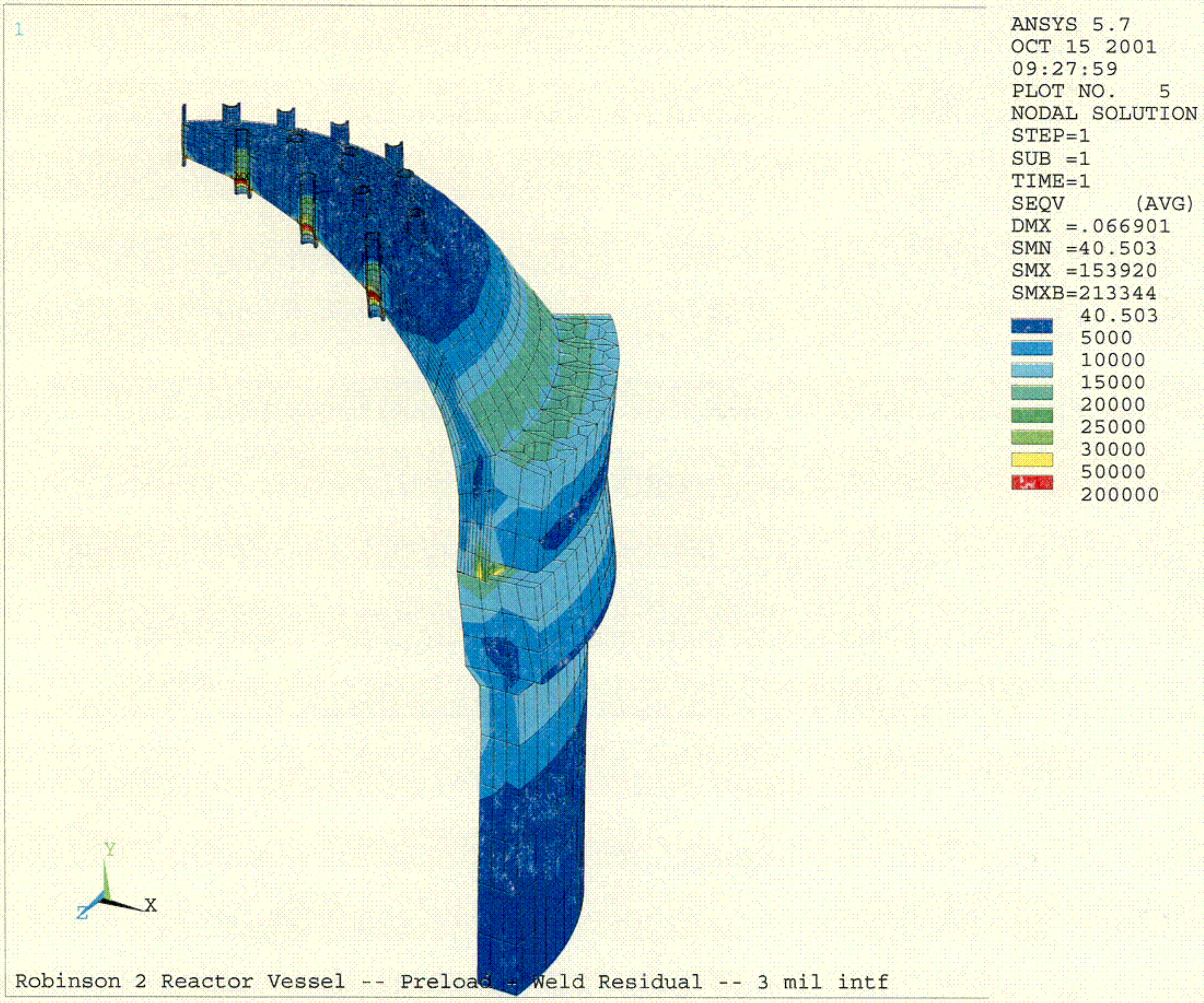
Figure B-1



<u>Nozzle Deflections due to J-Groove Weld and Interference Fit</u>

Figure B-2

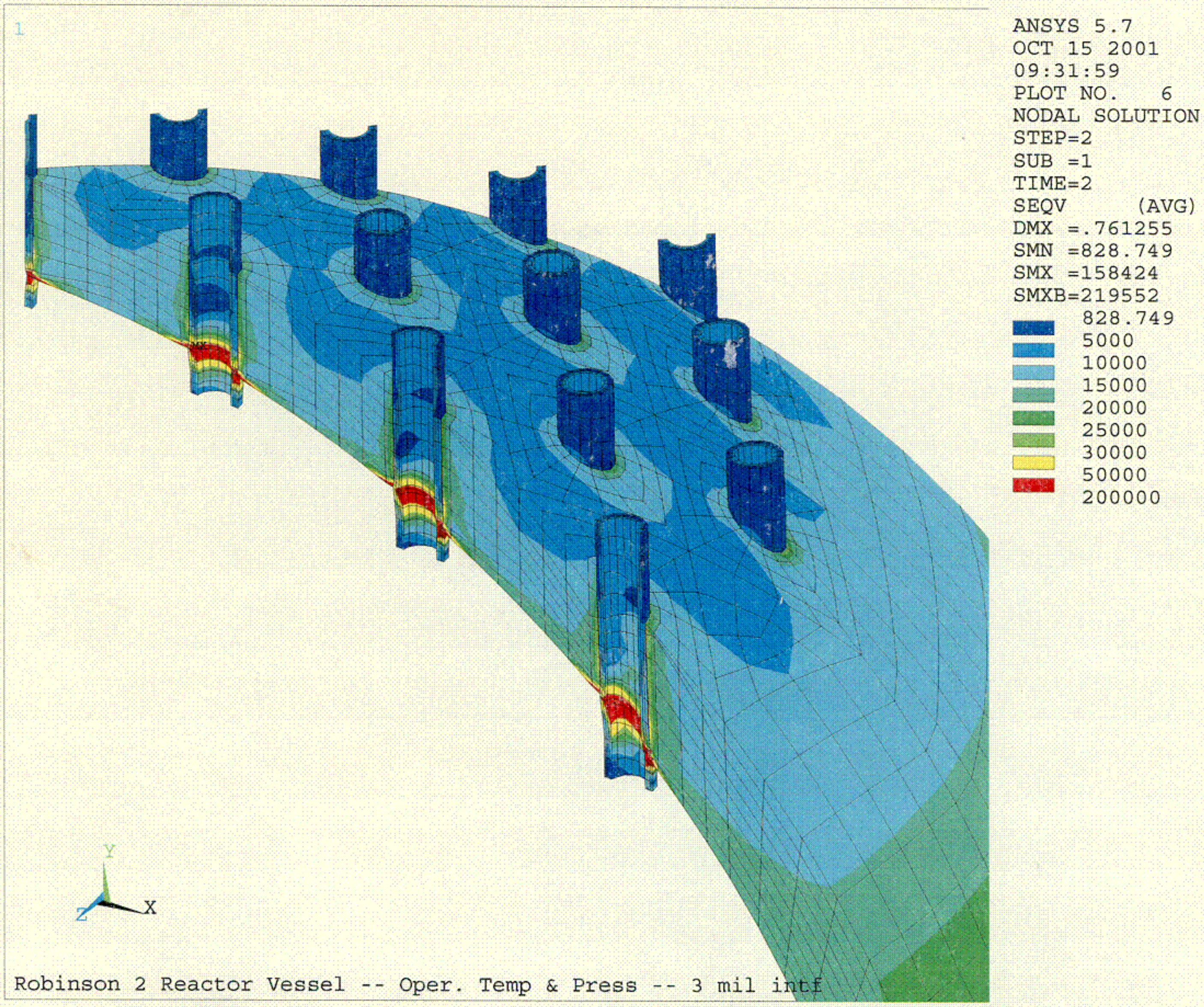
C01



<u>Flange Rotation and Equivalent Stresses due to Flange Bolt Preload</u>

Figure B-3

C02

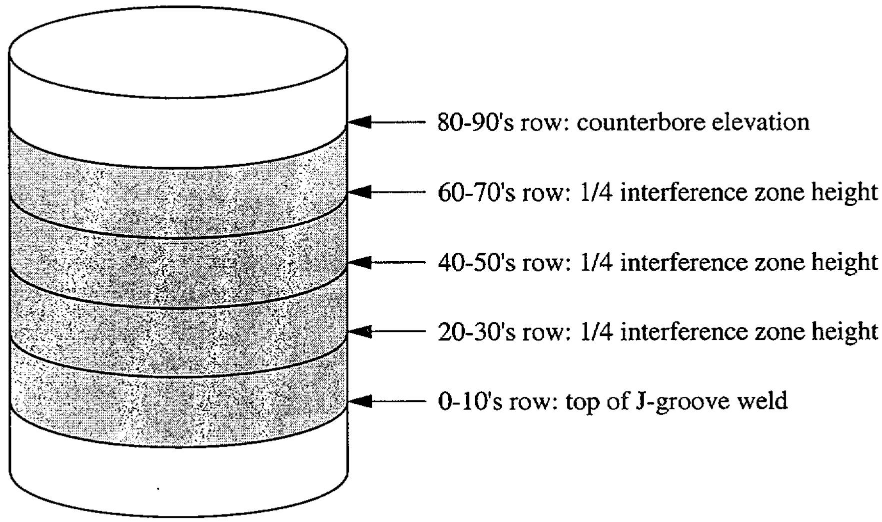


<u>Equivalent Stresses in Vessel Top Head Under Operating Conditions</u>

Figure B-4

C03

Figure B-5
Key to Node Locations for Reported Gaps



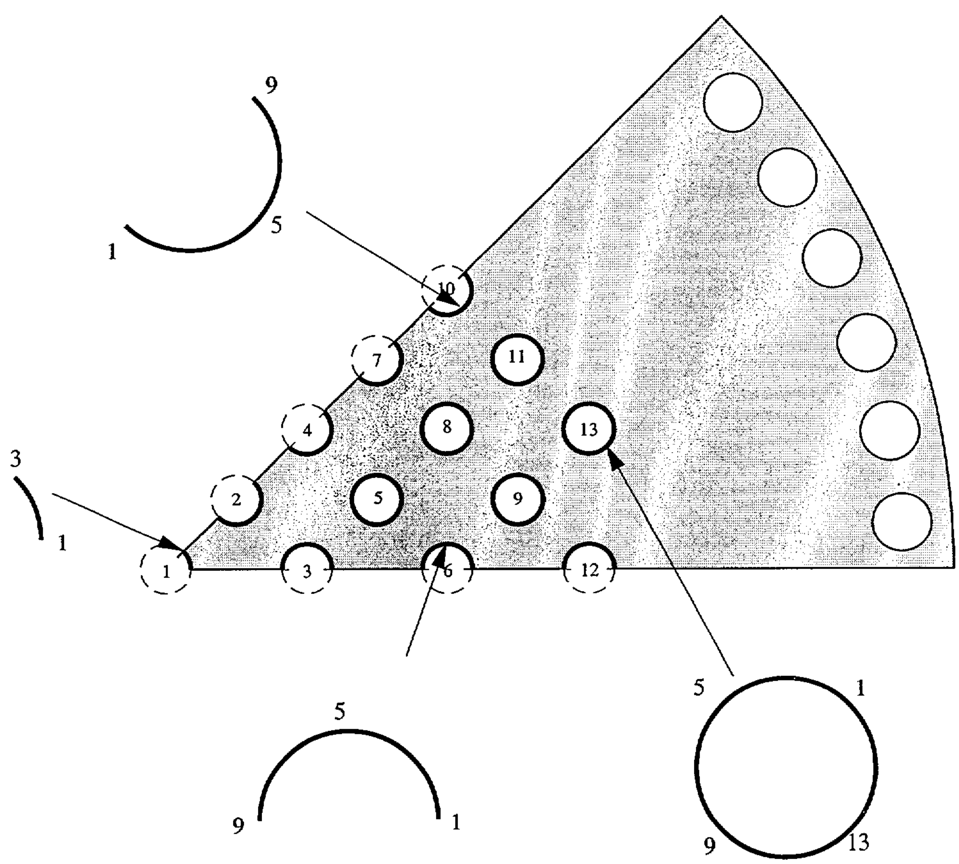
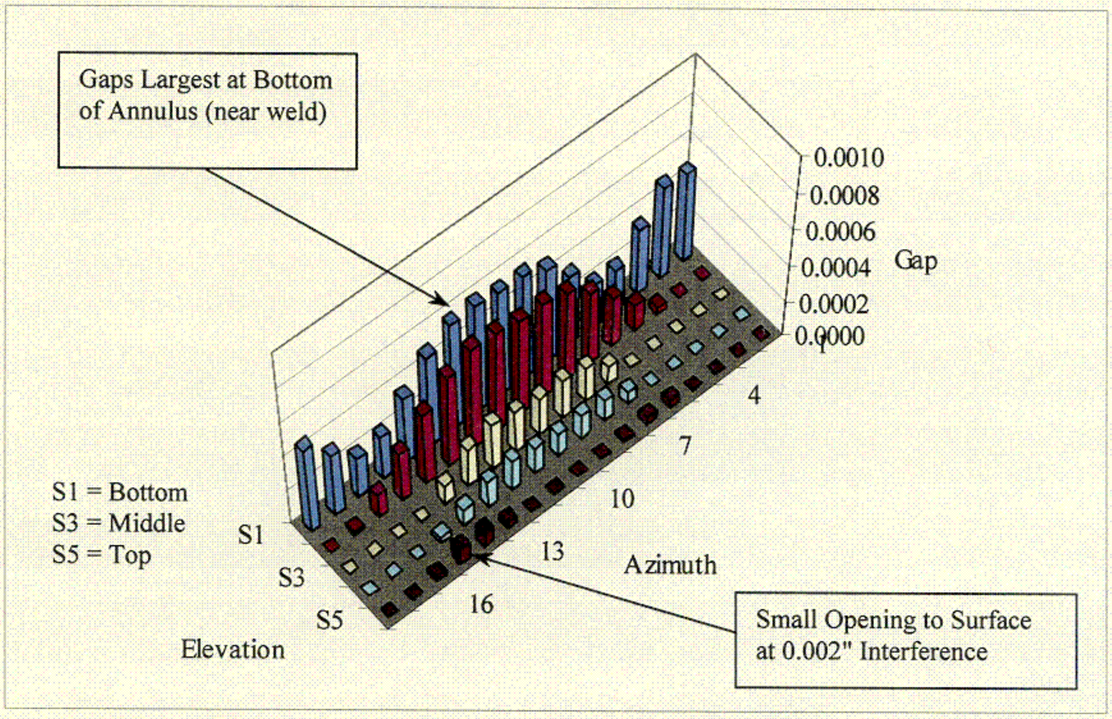
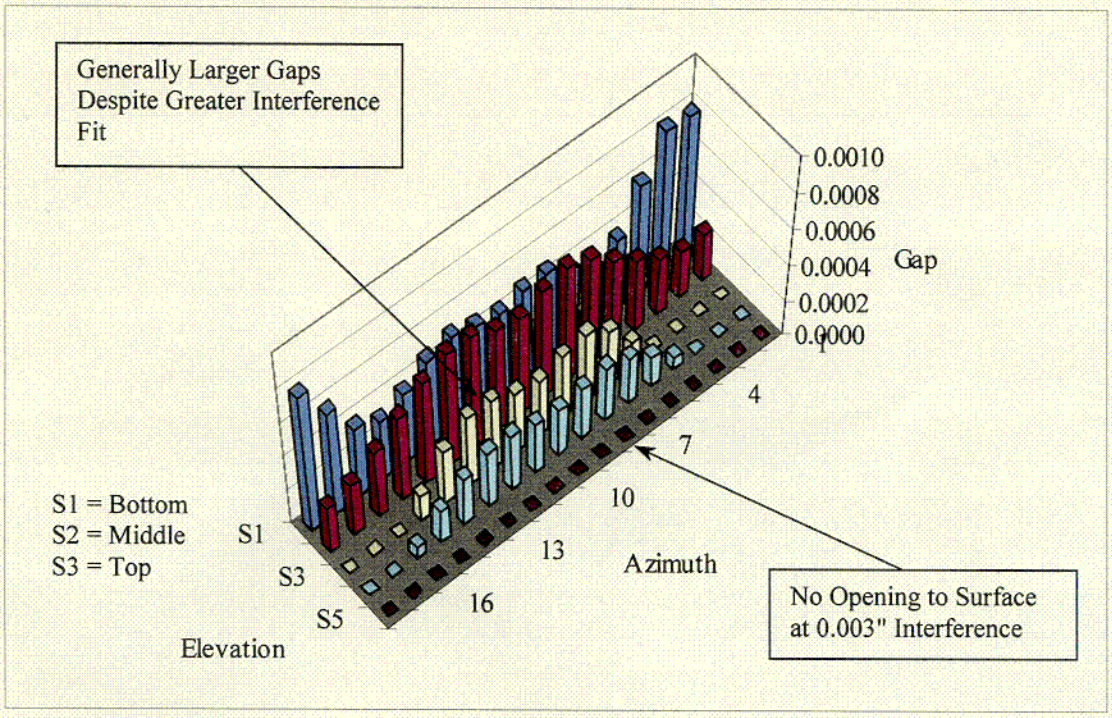


Figure B-6
Gap Opening Displacements for Nozzle #9

a. 0.002" Initial Interference with Annulus Unpressurized



b. 0.003" Initial Interference with Annulus Pressurized



C04