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CP&L
A Progress Energy Company

Serial: RNP-RA/01-0161

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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 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. This letter supplements the initial HBRSEP, Unit No. 2, response to NRC Bulletin 2001-01, dated September 4, 2001, and a subsequent supplemental response that was provided by letter dated October 2, 2001. This supplemental response is provided under oath or affirmation in accordance with 10 CFR 50.54(f). Attachment I provides the required affidavit.

Carolina Power and Light Company (CP&L) has completed detailed finite element analyses (FEA) to address the ability to detect VHP through-wall cracking by evidence of leakage to the reactor pressure vessel (RPV) head surface. The FEA results have been evaluated by CP&L and reviewed by the Plant Nuclear Safety Committee. These analyses are provided as Enclosures I and II to this letter.

The plant-specific FEA results have concluded that VHP leakage would pass to the RPV head surface where it would be detected by visual examination. The conclusions of these analyses, summarized in Attachment II, demonstrate 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.

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A088

The initial HBRSEP, Unit No. 2, response to NRC Bulletin 2001-01, dated September 4, 2001, provided the plan and schedule for future examinations of VHP nozzles. This response described plans to perform a qualified visual examination of VHP nozzles during RO-21 in October 2002. HBRSEP, Unit No. 2, has modified these plans to include non-destructive examination (NDE) of VHP nozzles.

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

Sincerely,

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"

Enclosures:

I. "Reactor Vessel Top Head Nozzle Operating Fit Analysis," Performed By Dominion Engineering, Inc.
II. "Finite Element Gap Analysis of CRDM Penetrations," Performed By Structural Integrity Associates, Inc.

c: Mr. B. S. Mallett, NRC, Region II
Mr. K. N. Jabbour
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/01-0161 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 Caroling Power and Light Company.

JMoyer
____

Sworn to and subscribed before me

this 19th day of OCTOBER, 2001

Peter [illegible]
____
Notary Public for South Carolina

My commission expires: Sept. 13, 2009

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

Summary of Finite Element Analyses Results

In order to qualify visual examinations performed for the reactor pressure vessel (RPV) head during Refueling Outage (RO) - 20 in April 2001, H. B. Robinson Steam Electric Plant (HBRSEP), Unit No. 2, has completed detailed finite element analyses (FEA) of the vessel head penetration (VHP) nozzles and the RPV head penetrations. These analyses were performed by Dominion Engineering, Inc., and Structural Integrity Associates, Inc. (SIA), and are included as Enclosures I and II to this letter. The results of these analyses were evaluated by the Carolina Power and Light Company (CP&L) and have been reviewed by the Plant Nuclear Safety Committee.

The plant-specific FEA results have concluded that VHP leakage would pass to the RPV head surface where it would be detected by visual examination. The results of these analyses demonstrate 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, and provide strong assurance of the continued safe operation of HBRSEP, Unit No. 2, through the remainder of the current operating cycle.

Summary of Dominion Engineering, Inc., Finite Element Analyses Results

As described within the initial HBRSEP, Unit No. 2, response to NRC Bulletin 2001-01, dated September 4, 2001, the HBRSEP, Unit No. 2, design nozzle interference fit is 0.0 to 3.0 mils. The results of the Dominion Engineering, Inc., analysis show that a leakage path to the RPV head surface would exist for interference fits through 2.75 mils. For the most limiting case, i.e., initial interference fits between 2.75 and 3.0 mils, additional analytical work concluded that approximately 46% of the VHP nozzles would have a leakage path to the RPV head surface. Additionally, for those nozzles that did not show a leakage path, the short zone of remaining interference near the top of the interference fit region has very low contact stress, such that leakage through the VHP nozzle to the RPV head surface would be expected despite the small remaining interference. Additional pertinent details regarding the Dominion Engineering, Inc., analysis are provided as follows:

- For the limiting case where pressure and temperature effects do not result in a zero interference, the length of the remaining metal-to-metal interference is small, i.e., 0.025 mils maximum at some locations.

- Experience has shown that small amounts of operating condition interference fit between machined parts of this size would be unlikely to prevent steam leaks. This conclusion is supported within the Electric Power Research Institute (EPRI) Materials Reliability Program (MRP) Report TP1001491, Part 2, "PWR Materials Reliability Project Interim Alloy 600 Safety Assessments for US PWR Plants (MRP-44), Part 2: Reactor Vessel Top Head Penetrations," May 2001 (reference paragraph 3.4).

Summary of Structural Integrity Associates, Inc., Finite Element Analyses Results

As noted above, the HBRSEP, Unit No. 2, design nozzle interference fit is 0.0 to 3.0 mils. The results of the Structural Integrity Associates, Inc., analysis show that the VHP nozzles would have a leakage path to the RPV head surface with initial interference fits through 3 mils.

Evaluation of Interference Fit Data

Subsequent to the HBRSEP, Unit No. 2, supplemental Bulletin response, dated October 2, 2001, additional information has been obtained regarding fabrication of the HBRSEP, Unit No. 2, RPV head. This information provides strong assurance that VHP nozzle interference fits are within design tolerance values. Pertinent aspects of this fabrication information are provided as follows:

- The Shop Traveler for the HBRSEP, Unit No. 2, RPV head (Job Control No. T-51137-009) provides the following instruction in Operation 9200:

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

- The HBRSEP, Unit No. 2, Shop Traveler also provided the following process for cooling the housings for installation in the RPV head holes:

  > "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 CRDM housing from 70°F (ambient) to minus 88°F would produce a diametrical shrinkage of approximately 4 mils. Therefore, by obtaining the 3 mil installation clearance described within the Shop Traveler, the resulting maximum interference fit would be expected to be approximately 1 mil. This 3 mil installation clearance also comports with the Shop Traveler instruction to match fit the housings to penetrations for assurance of "least possible interference fit."

- For VHP nozzle housings that had dimensions noted on inspection reports, fabrication records show that housings having a diameter greater than design tolerance were rejected or re-worked to obtain the specified tolerances, or were specifically evaluated.

- More detailed manufacturing documentation was available and reviewed for instrumentation penetrations on the RPV lower head. Since these RPV lower head penetrations have different design and operational conditions than those associated with VHP nozzles, there are distinct differences between their respective manufacturing processes. However, the manufacturing documentation for the RPV lower head penetrations demonstrates attention-to-detail in dimensional controls, and further shows that out-of-tolerance dimensions were evaluated and dispositioned accordingly. It is reasonable to conclude that similar manufacturing practices were used during fabrication of the RPV head.

- Westinghouse summary report CN-CI-01-1 (Proprietary Class 2) was provided as an enclosure to the HBRSEP, Unit No. 2, supplemental NRC Bulletin response dated October 2, 2001. As shown within this report, "as built" data for plants included in the Westinghouse three-plant interference fit distribution confirmed that none of the 230 RPV penetration holes had diameters less than the design allowable.

The above-referenced Westinghouse summary report provided a preliminary assessment of the potential for HBRSEP, Unit No. 2, to detect leakage associated with VHP nozzles. This assessment included an evaluation of interference fit data for three Westinghouse plants that were fabricated during the time frame of the HBRSEP, Unit No. 2, RPV head fabrication. As found within the EPRI MRP Report MRP-48, "PWR Materials Reliability Program Response to NRC Bulletin 2001-01," dated August 2001, these three plants are consistent with HBRSEP, Unit No. 2, in the following areas:

- Westinghouse performed the nuclear steam supply system (NSSS) design
- The nozzle material supplier was Huntington
- The RPV head fabricator was Combustion Engineering (CE)
- The specified Design Diametral Nozzle Interference Fit was 0.0 to 3.0 mils

Evaluation of this interference fit data involved tabulation of 230 RPV head penetration measurements, with an average interference fit having been calculated based on "as measured" dimensions of RPV head penetrations (holes) and a nominal value for VHP nozzle diameters that was based on a review of design tolerances. The calculated interference fit data was then analyzed to identify the distribution of interference fits. This analysis identified no instances where the interference fit exceeded 2.50 mils. While direct applicability of this data to HBRSEP, Unit No. 2, cannot be assured, it is reasonable to conclude that the manufacturing procedures used for these three RPV heads would be typical of those associated with fabrication of the HBRSEP, Unit No. 2, RPV head.

Since one of the analyses predicted a short zone of remaining interference fit for VHP nozzles with an initial interference fit of greater than 2.75 mils, further evaluation was performed to provide an estimate of the number of HBRSEP, Unit No. 2, VHP nozzles that might have been fabricated with interference fits ranging from 2.75 mils to 3.00 mils. This evaluation focused on the tolerances associated with the applicable fabrication processes, and involved a statistical analysis of manufacturing data for similar vintage plants with a design nozzle interference fit range of 0.0 to 3.0 mils. This analysis determined a mean interference fit of 1.58 mils with a standard deviation of 0.66 mils. Assuming a normal distribution, more than 97% of the VHP nozzles would be expected to have interference fits of 2.75 mils of less.

Through evaluation of manufacturing data for similar vintage plants, combined with a statistical assessment HBRSEP, Unit No. 2, nozzle design tolerances, it can be concluded with a high degree of confidence that fabrication of the HBRSEP, Unit No. 2, VHP nozzles was within the range of design nozzle interference fits, and likely was appreciably less than the maximum design value of 3 mils. This information, when combined with the FEA results provided within Enclosures I and II, support the conclusion that VHP nozzle leakage would pass through to the RPV head surface where it would be detected by visual examination.

United States Nuclear Regulatory Commission
Enclosure I to Serial: RNP-RA/01-0161
124 Pages

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

"RESULTS OF REACTOR VESSEL TOP HEAD NOZZLE OPERATING FIT ANALYSIS"

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 0

October 2001

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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

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.

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Att. To		Last Mod. Rev.
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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 Information 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 Information 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 view 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

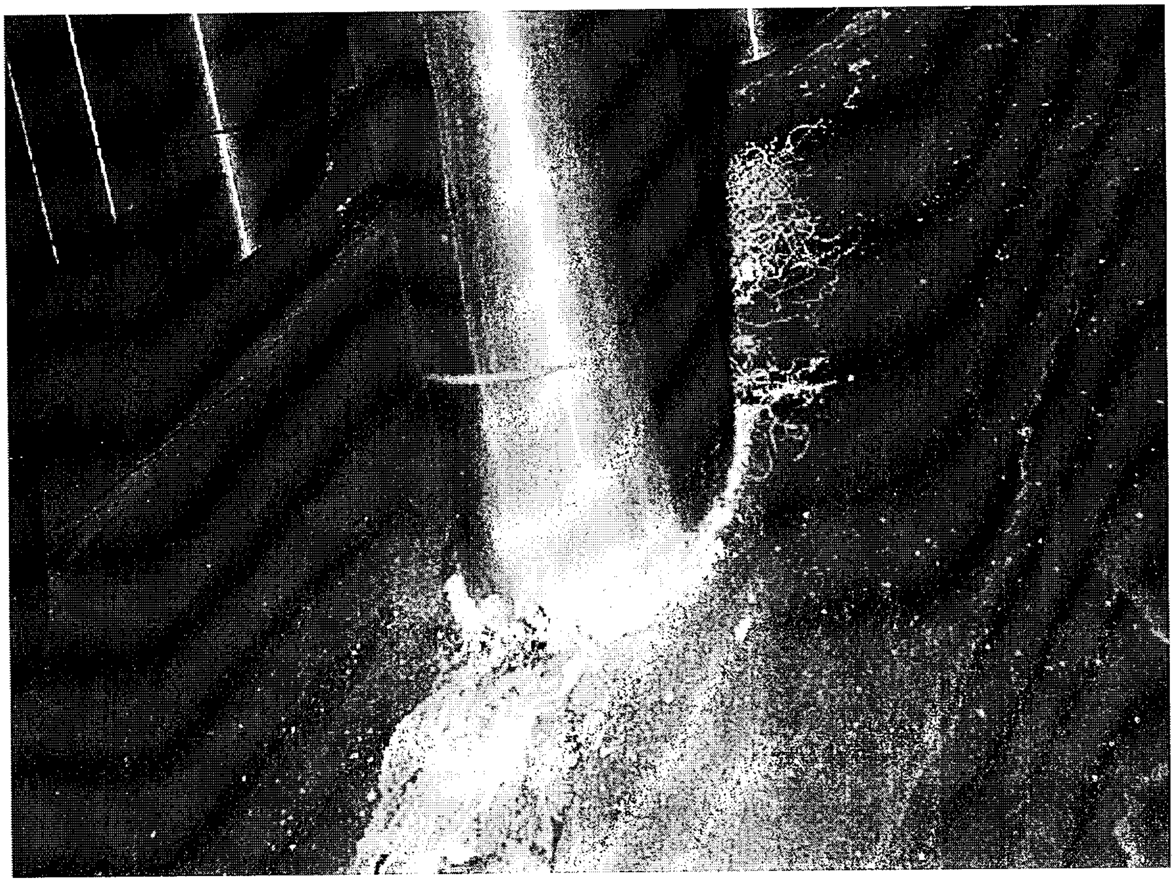


Figure 1-2
Oconee 1 Reactor Vessel Top Head – Section

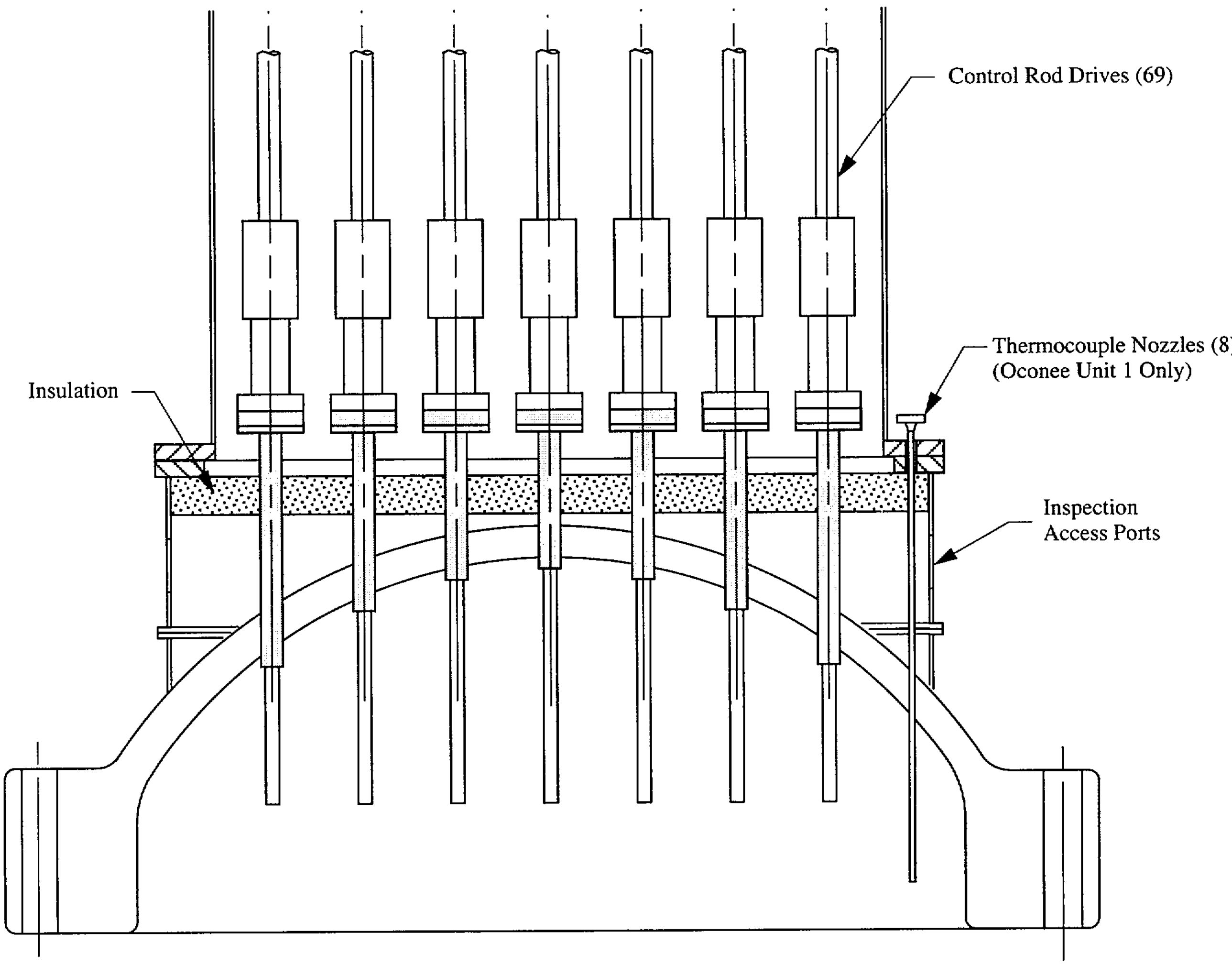


Figure I-3
Robinson Reactor Vessel Top Head – Plan

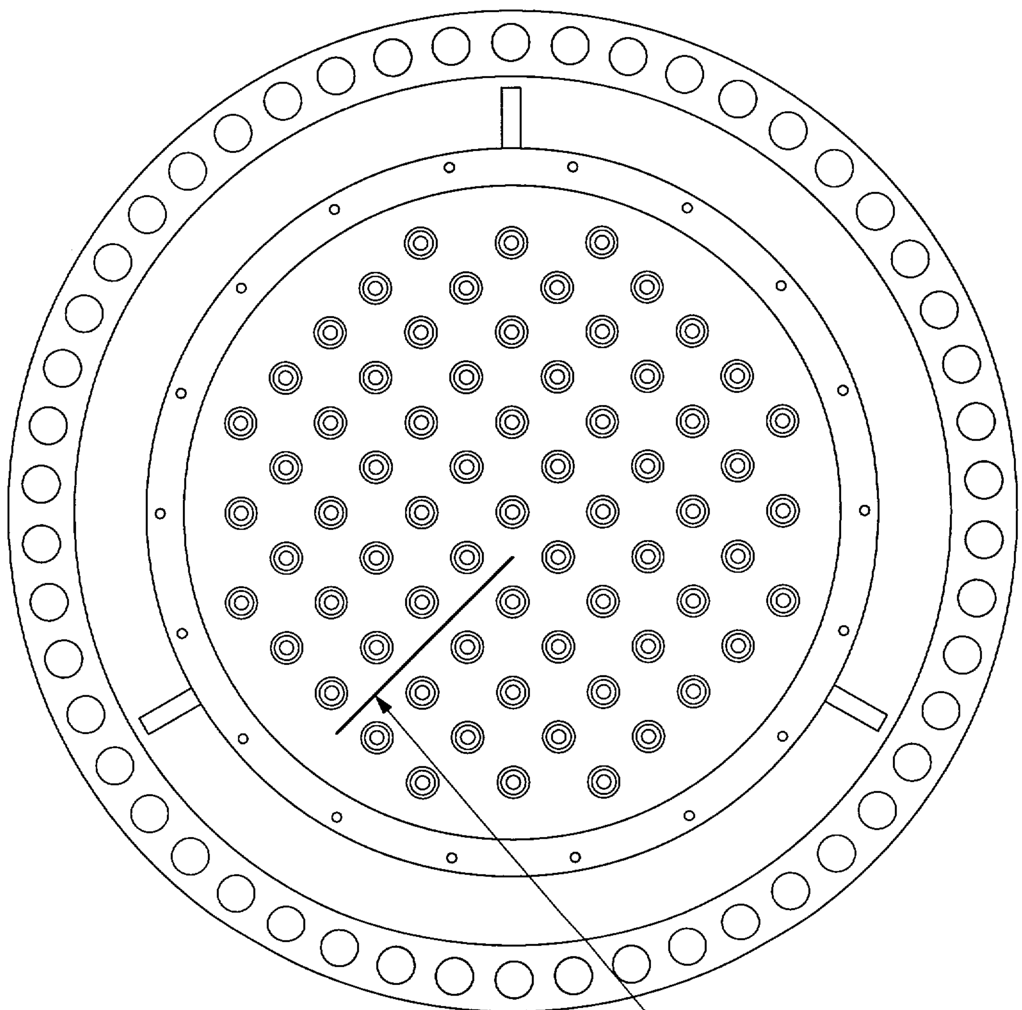
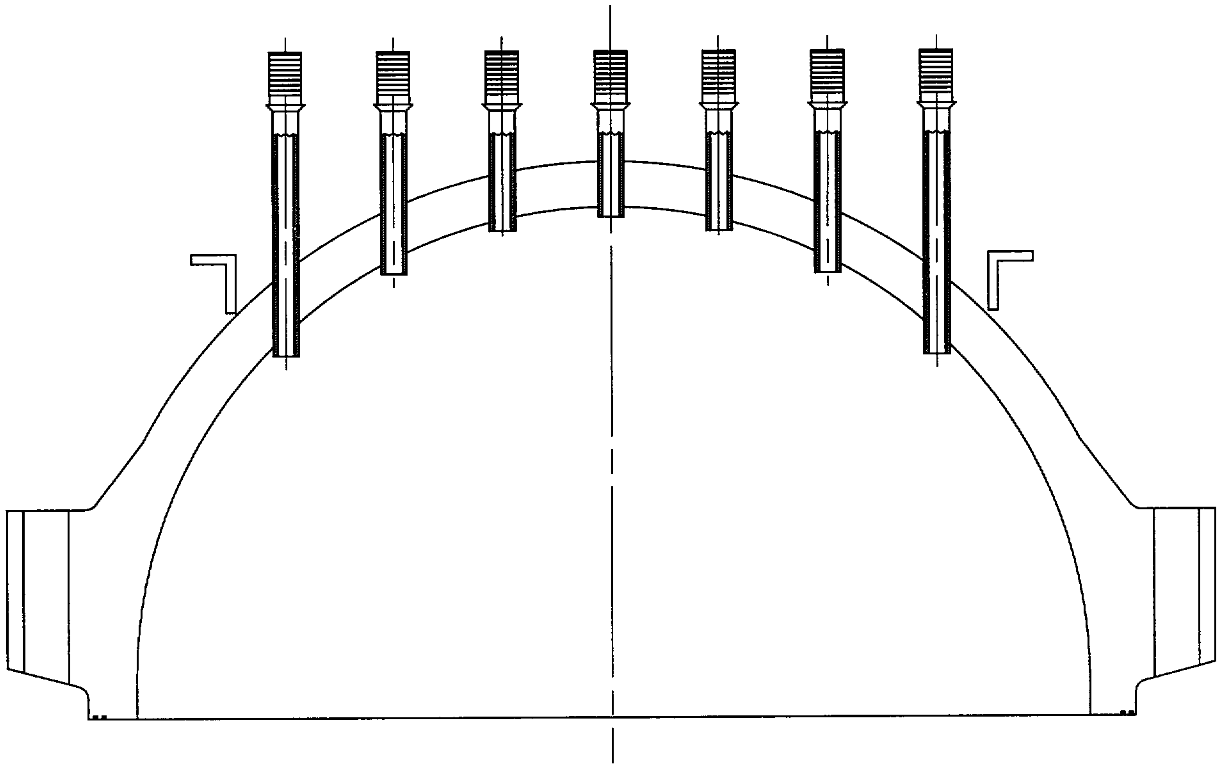


Figure I-4
Robinson Reactor Vessel Top Head – Section



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° segment of the head was modeled, employing symmetry boundary conditions on the 0° and 45° planes. Using this technique, a one-eighth segment 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 up to 0.003" for all but seven nozzles.* For these seven nozzles, there is a predicted leak path to the top head surface for initial interference fits up to 0.00275". For the small number of nozzles without a predicted leak path, the short zone of remaining interference has very low contact stress such that leakage would be expected at 2,235 psig operating pressure.

The above results are summarized in Table II-1.

Table II-1
Maximum Interference Fits Resulting in Predicted Leak Path

Pressure Boundary Conditions	Maximum Interference That Results in Predicted leak Path*	
Nominal Model ID Only Pressurized	7 Nozzles 6 Nozzles	0.002" 0.00225"
Refined Model Where Leakage Pressurizes Gap	7 Nozzles 6 Nozzles	0.00275" 0.003"

4. <u>Conclusions</u>

The conclusion from this analysis is that nozzles have a predicted operating condition leak path to the head top surface for initial diametral interference fits of 0.00275" to 0.003".

Despite a small remaining zone of predicted metal-to-metal interference for about half of the nozzles with the maximum specified 0.003" initial interference, it is considered that leakage into the annulus will pass to the top head surface where it can be detected by a

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

visual inspection. 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 (see Appendix B for further discussion).

- 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.

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.

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.

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 Alloy 600 type 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 pivoting about this location as the weld is applied. Weld shrinkage is not modeled explicitly in

the 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 and 0.008" radially at the bottom surface. These dimensions were taken from elastic-plastic analyses of the J-groove welds for the Robinson nozzles performed in support of the EPRI CHECWORKS program. With the weld pinned to the vessel shell at the root elevation, and the outward deflection due to weld shrinkage simulated by constraint equations, the nozzle wall is effectively bent over the edge of the buttering creating a small annular region immediately above the weld. By simulating the J-groove welding process, the effect of the weld in pulling the nozzle to one side of the hole is simulated.

- 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.

2. 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)	$26.4x10^6$	$28.7x10^6$
Coefficient of Expansion (in/in/°F)*	$7.8x10^{-6}$	$7.8x10^{-6}$
Poisson's Ratio	0.3	0.3

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

3. Boundary Conditions

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

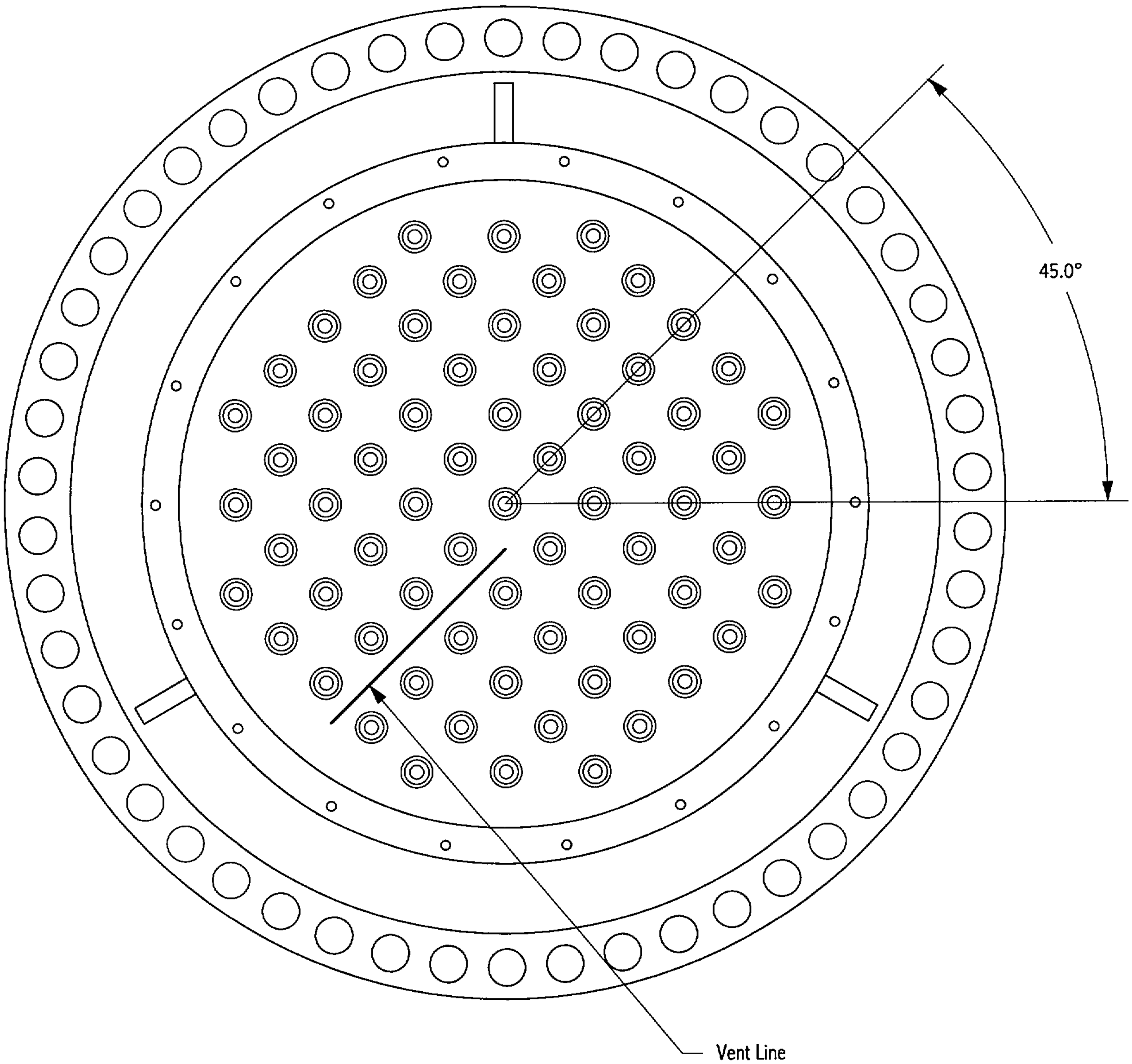
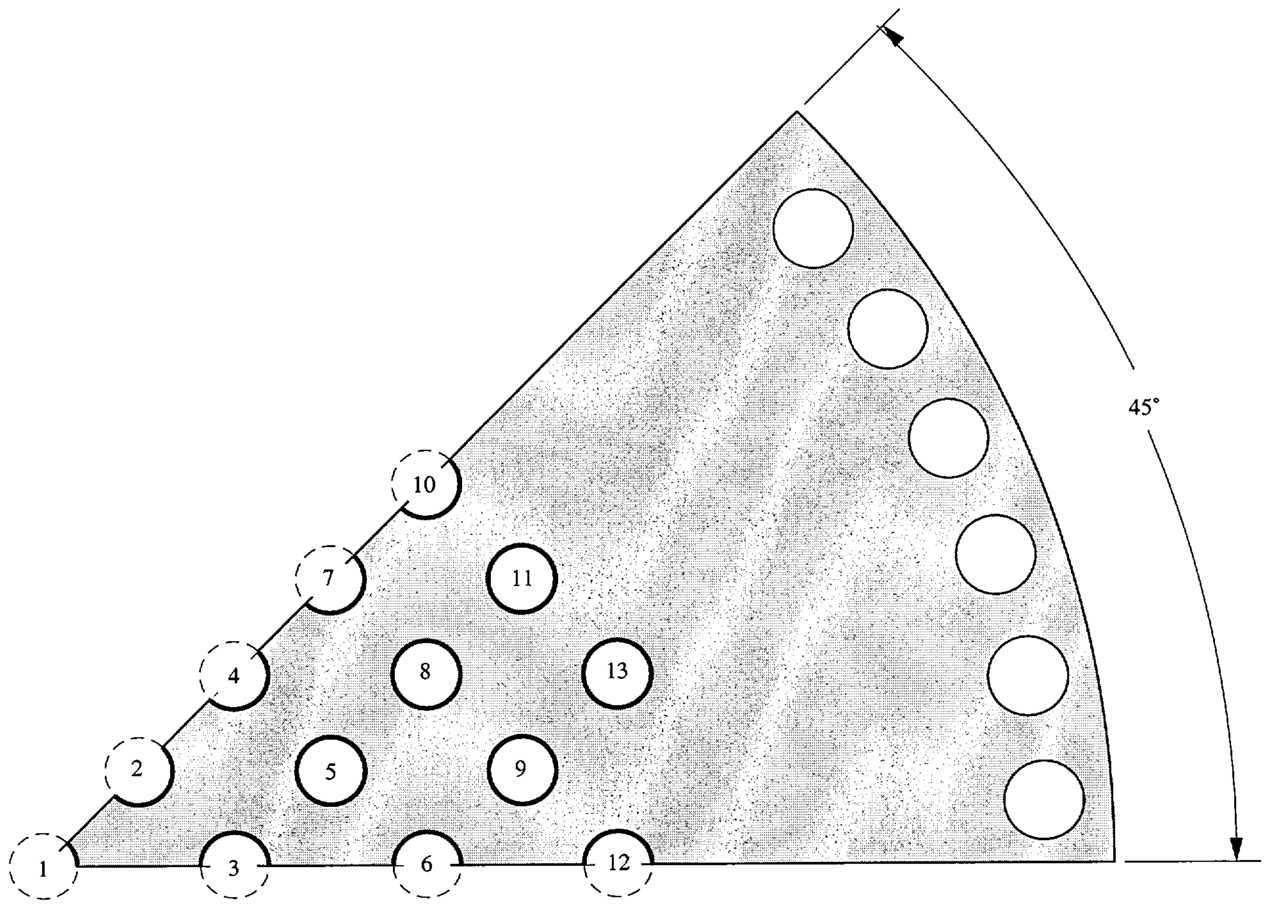
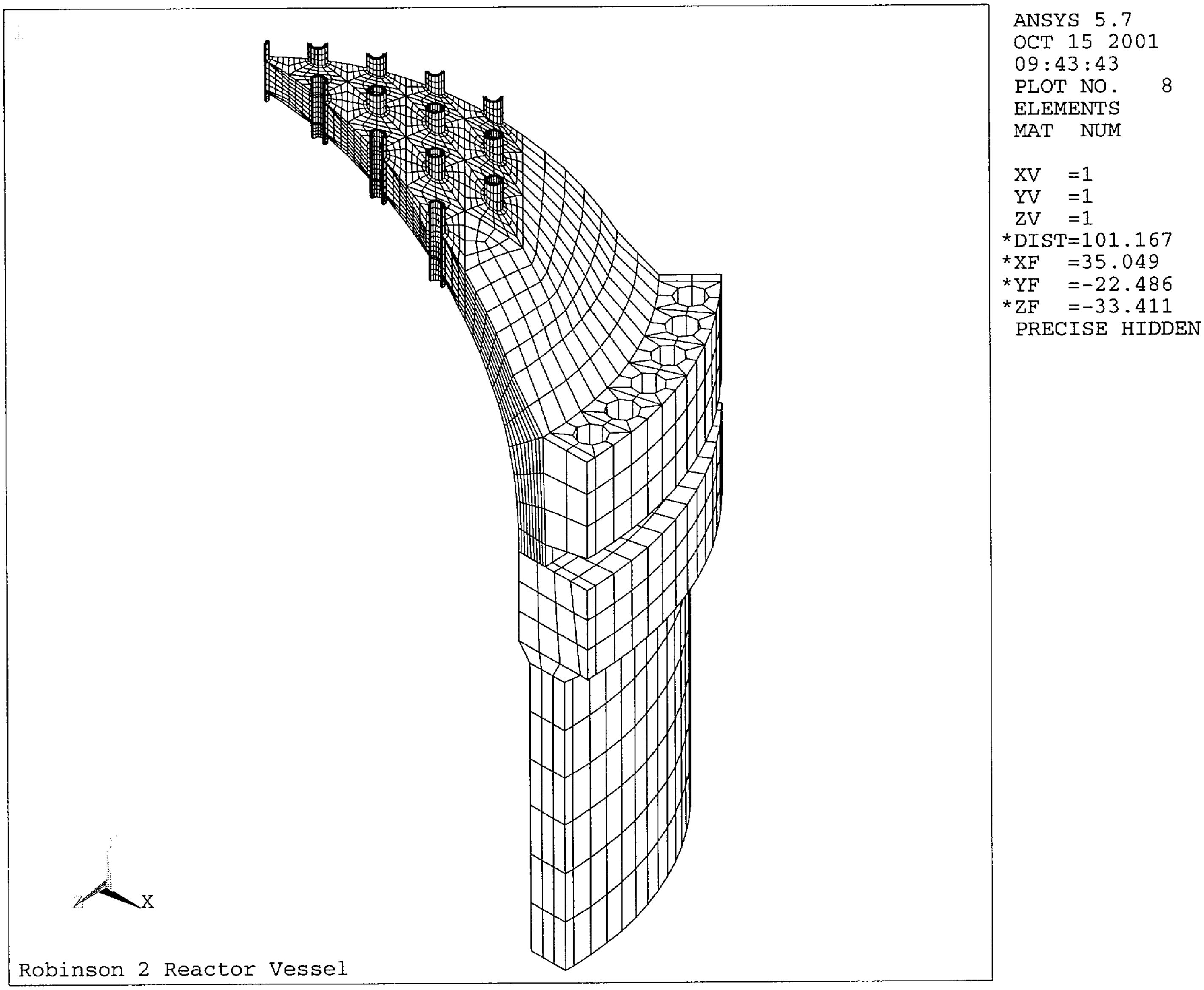


Figure A-2
Modeled Sector of Robinson Vessel Top Head

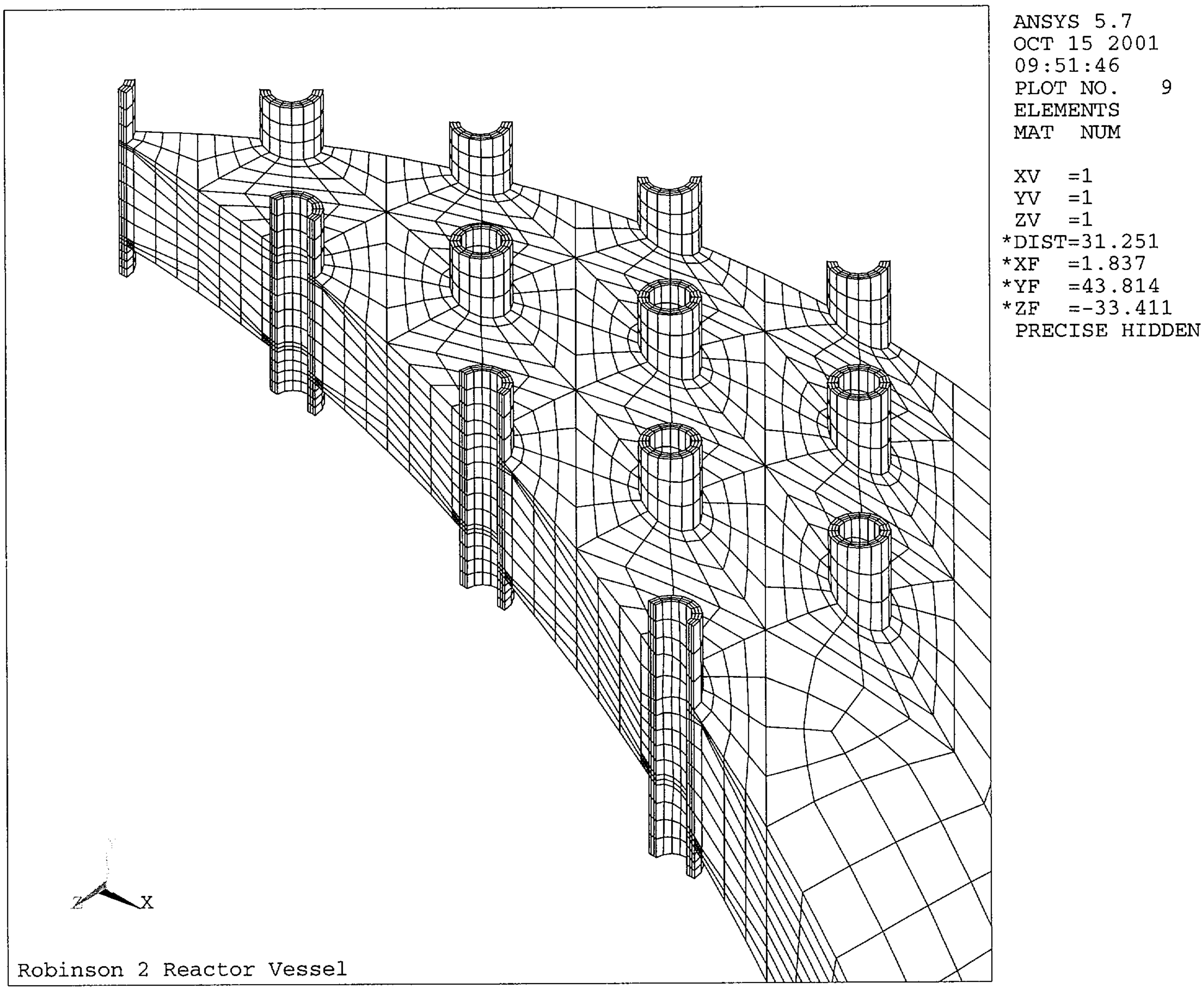


Nozzles numbered in order of increasing incidence angle



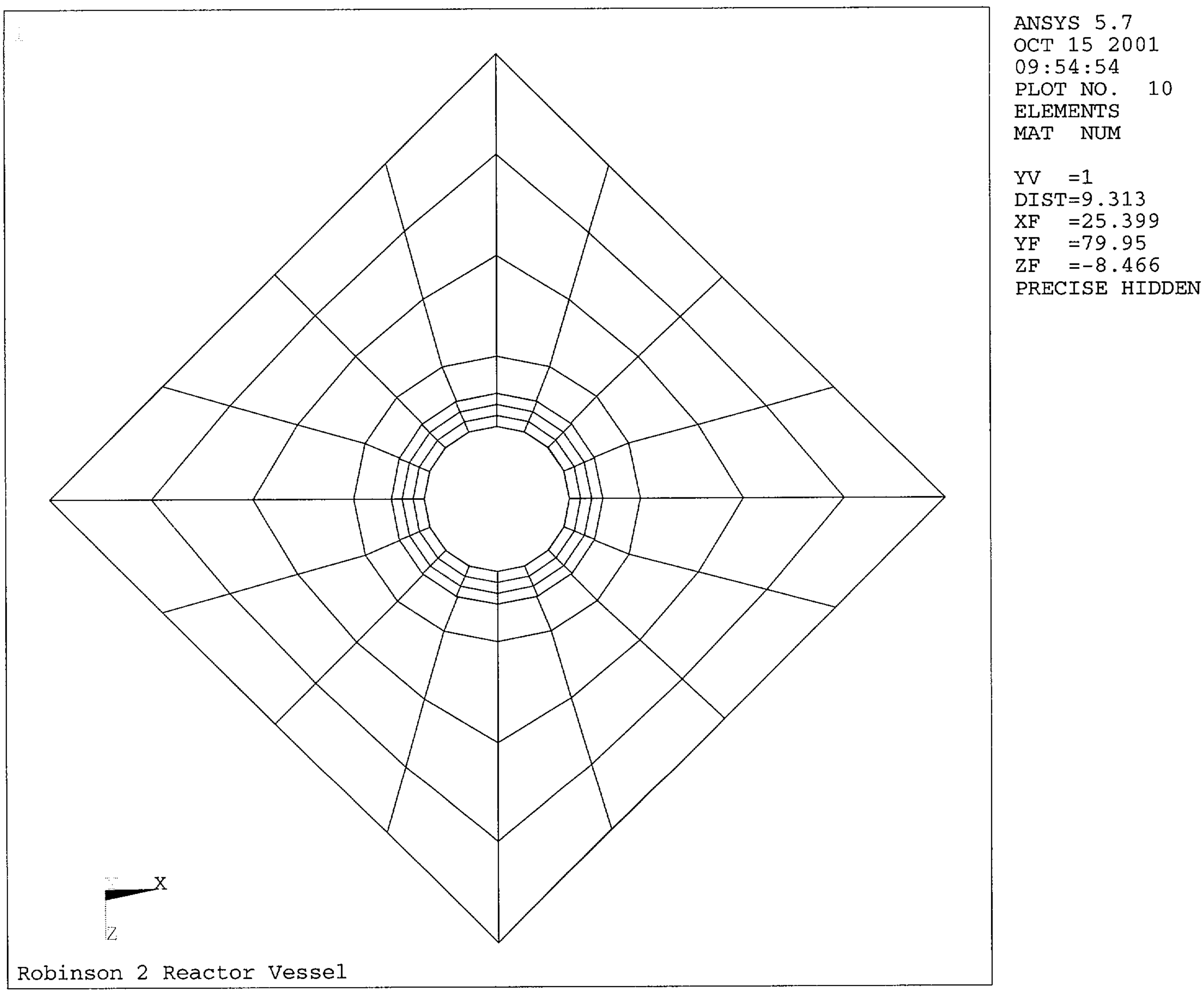
Reactor Vessel Head and Shell Finite Element Model

Figure A-3



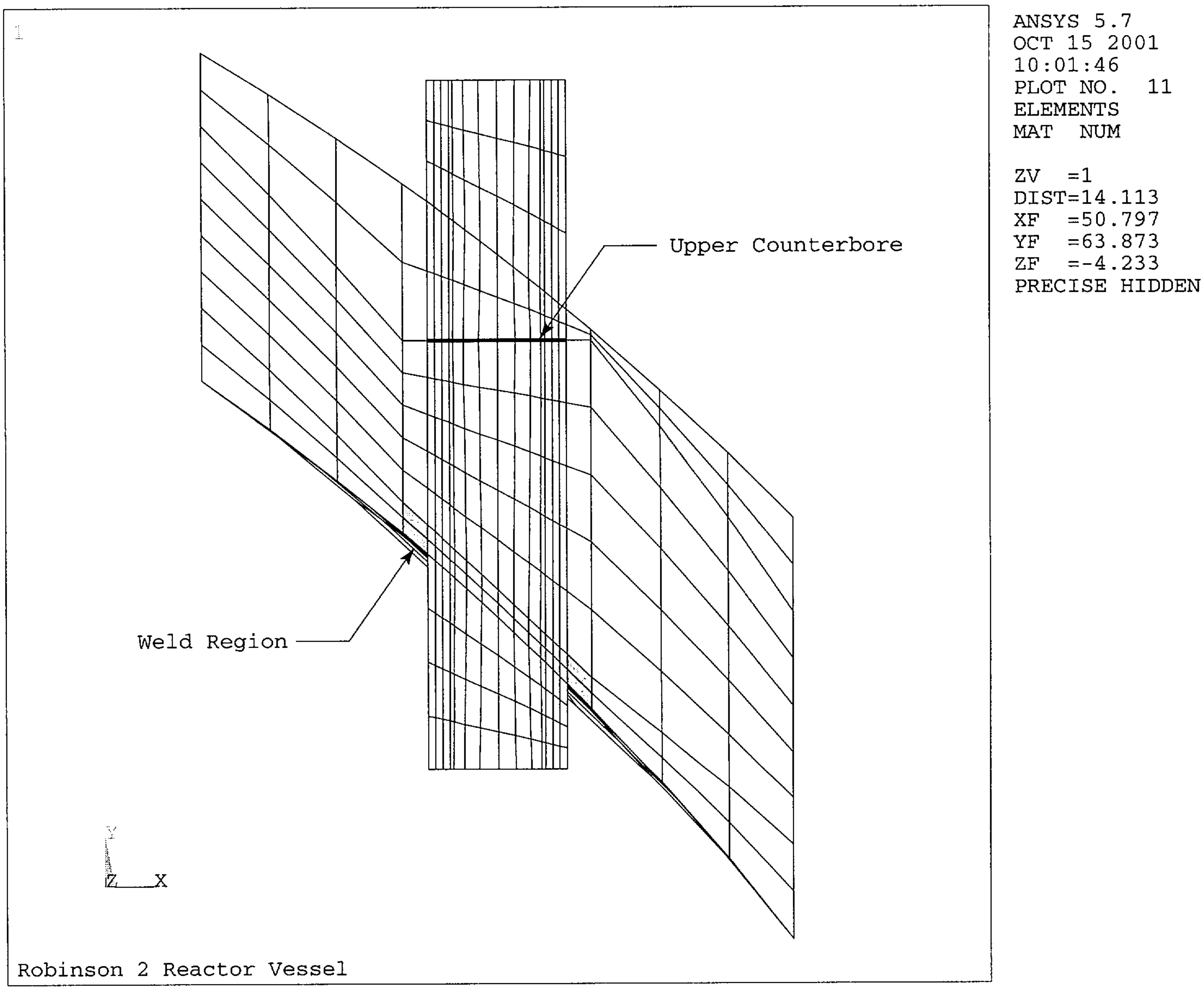
Finite Element Model of Vessel Top Head CRDM Nozzle Region

Figure A-4



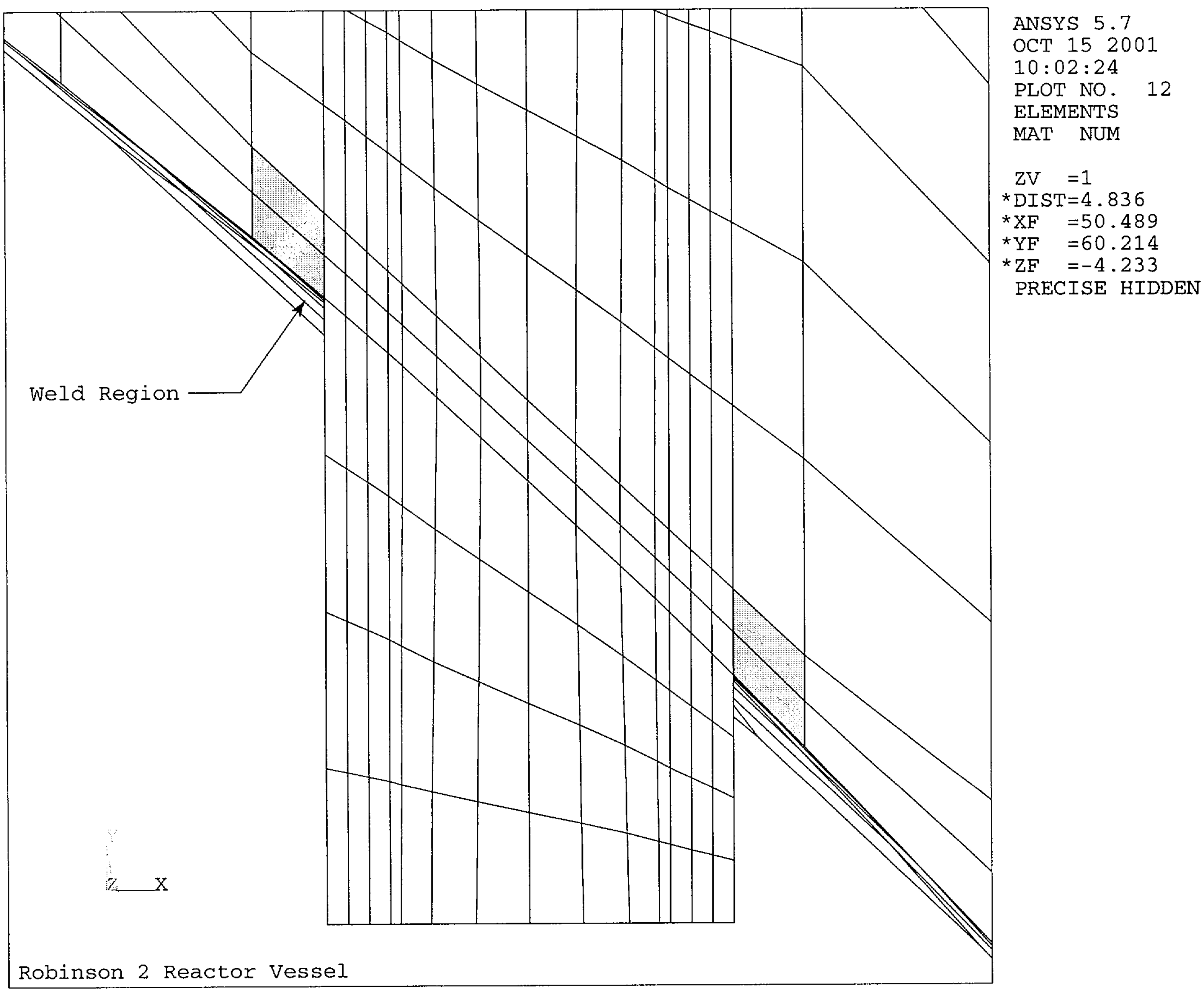
Finite Element Model of Typical CRDM Nozzle Module

Figure A-5



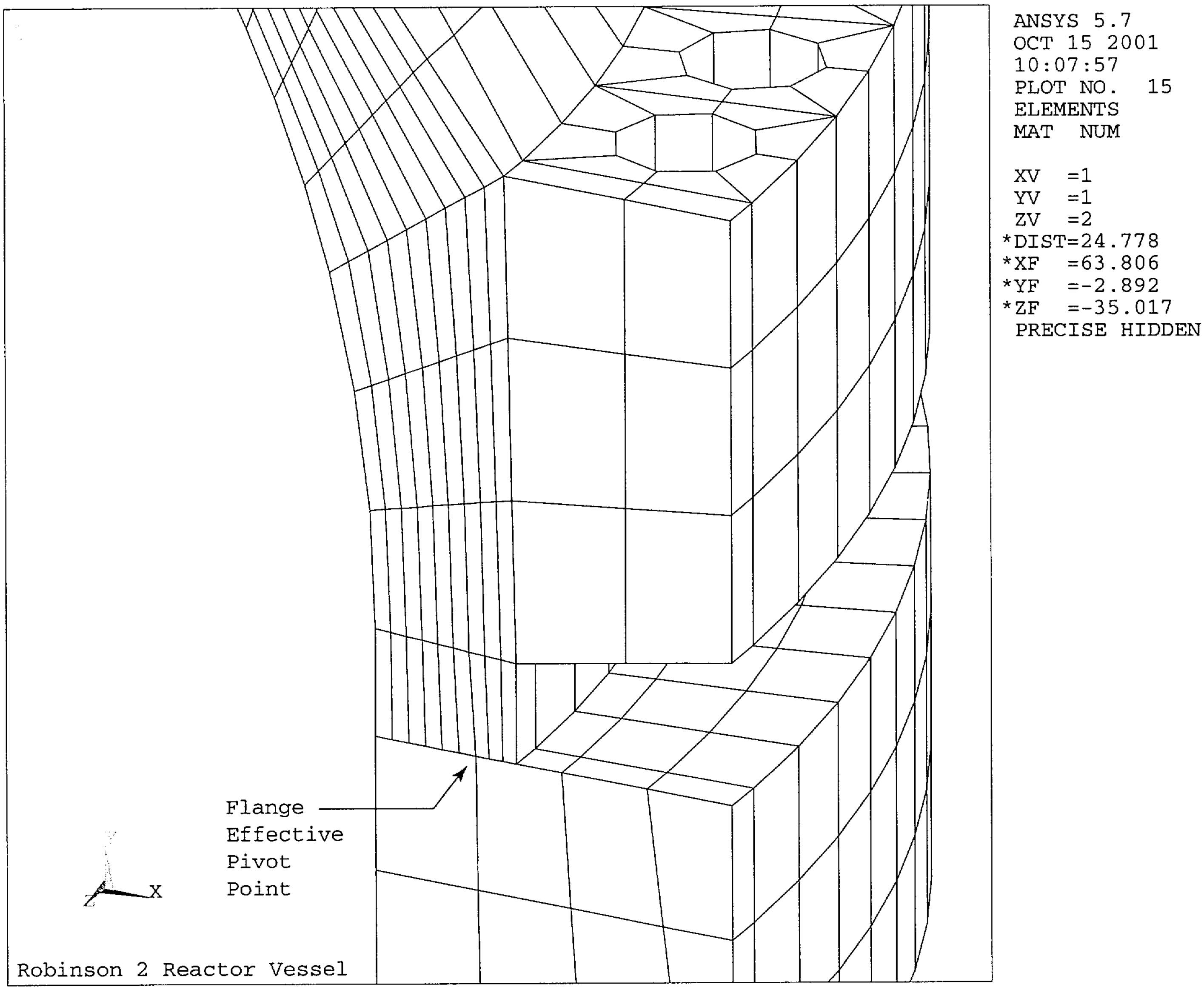
Finite Element Model of CRDM Nozzle Module (Section View)

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

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.*

- 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. It also shows the 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 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 fuil 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 six of the nozzles have a leak path for fits up to 0.003", while the remaining seven nozzles have a leak path for initial fits up to 0.00275".* While the analysis shows some metal-to-metal contact 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.

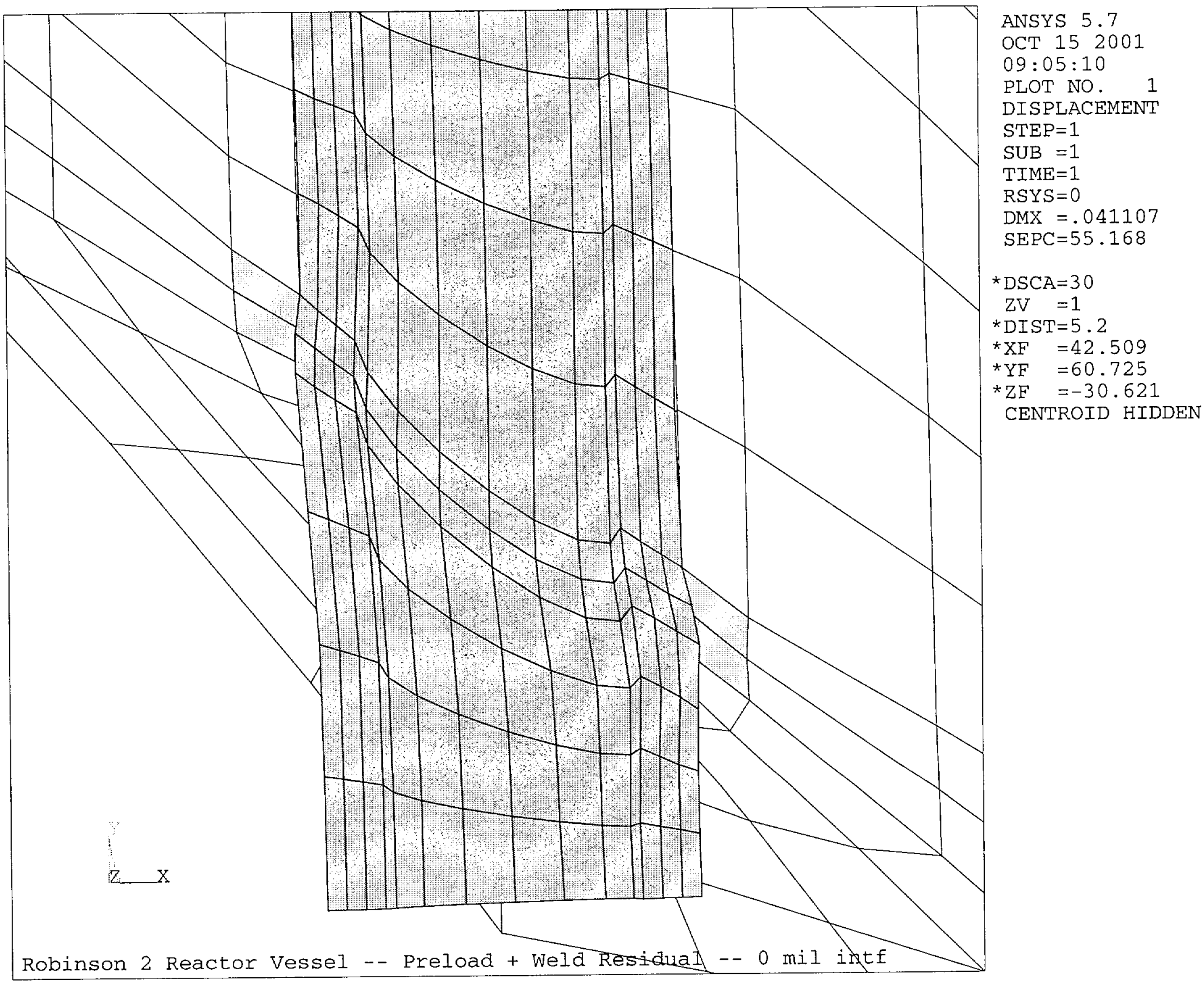
* Number of nozzles is relative to total of thirteen nozzles in one-eighth sector modeled.

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

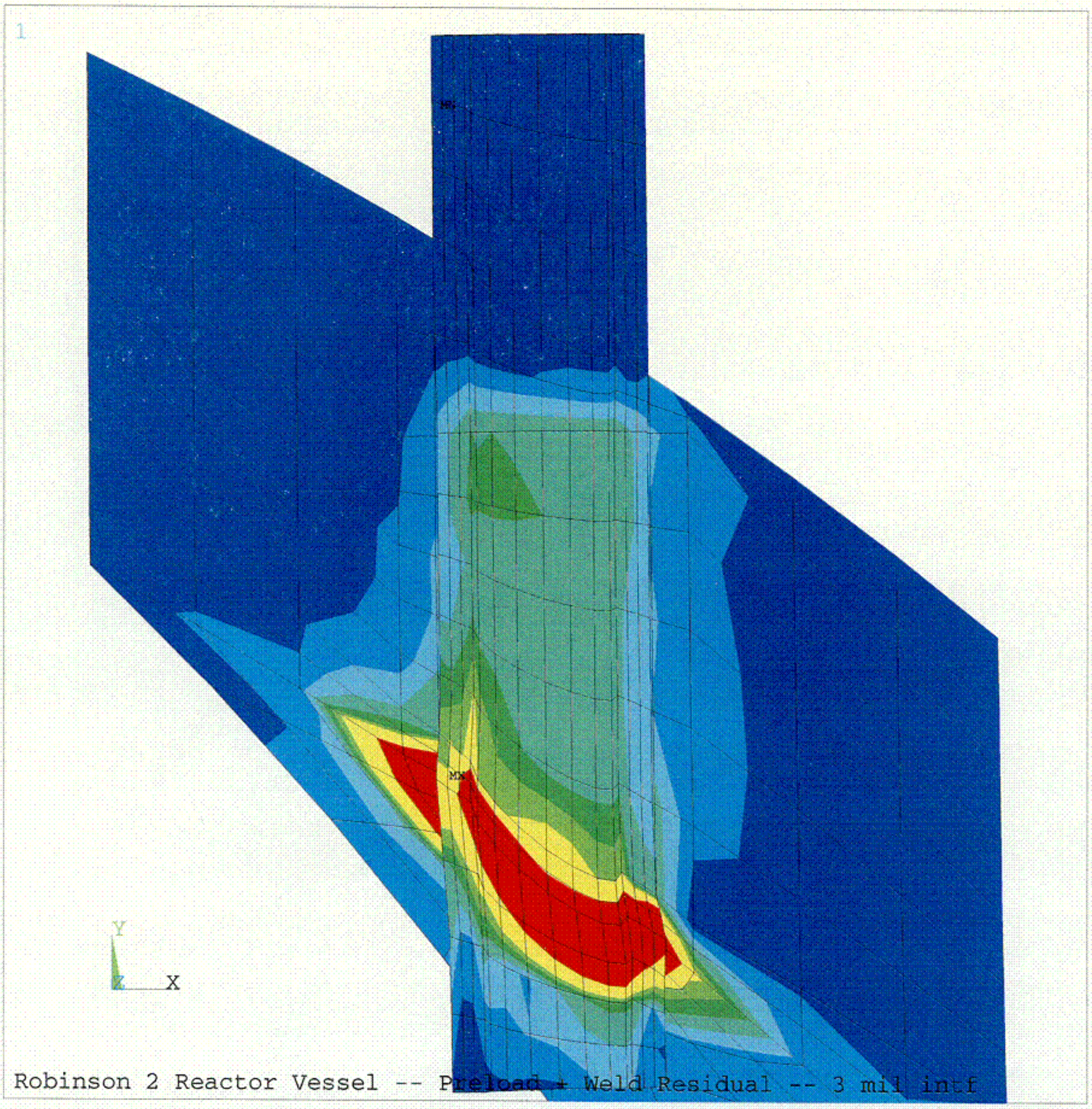
[shaded box] Designates condition in which there is no predicted leak path to the surface.

* These cases are for pressure on the OD surface of the designated nozzle with no pressure on the OD of other nozzles.



Deflections Imposed on Nozzle by J-Groove Weld

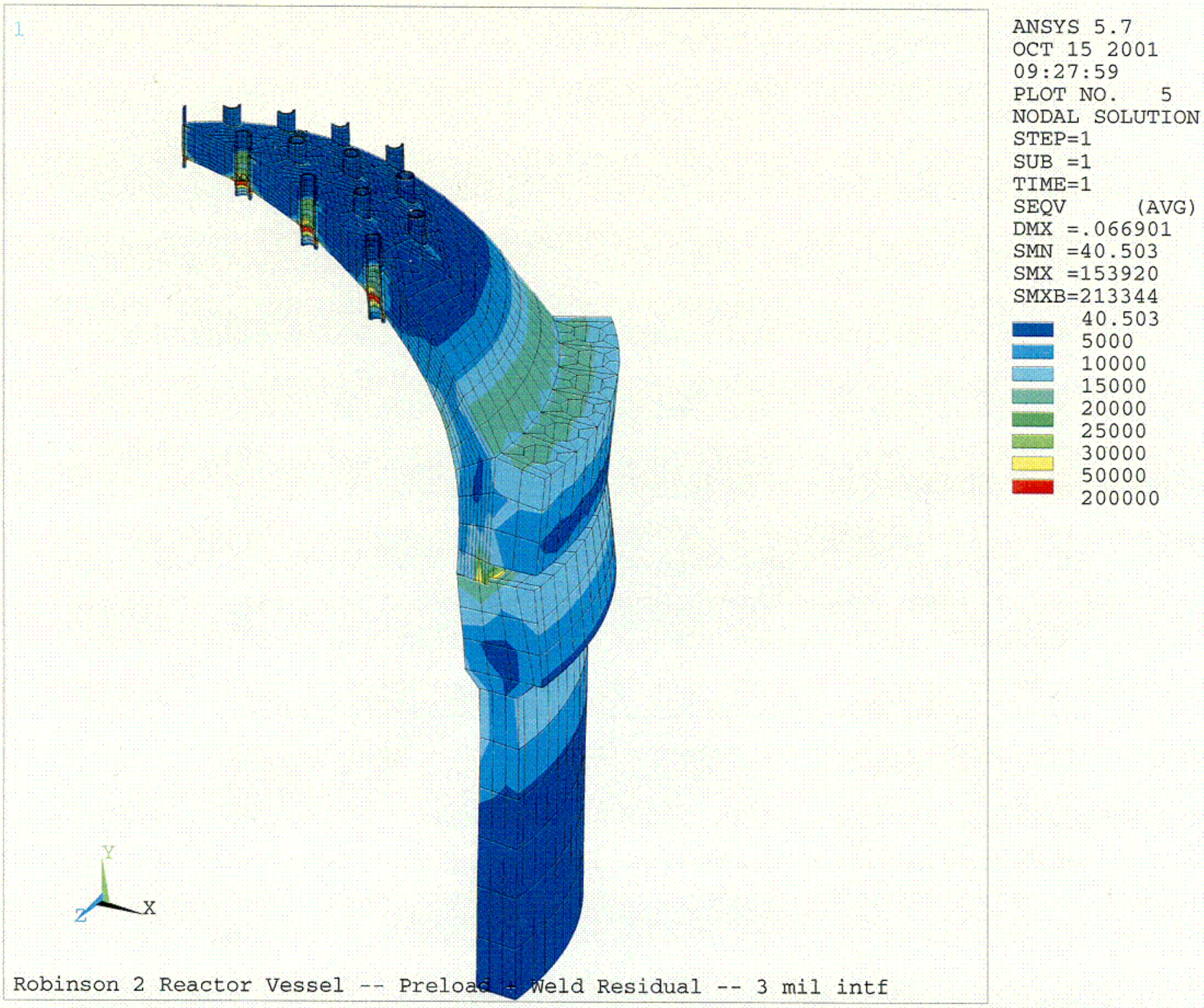
Figure B-1



Nozzle Deflections due to J-Groove Weld and Interference Fit

Figure B-2

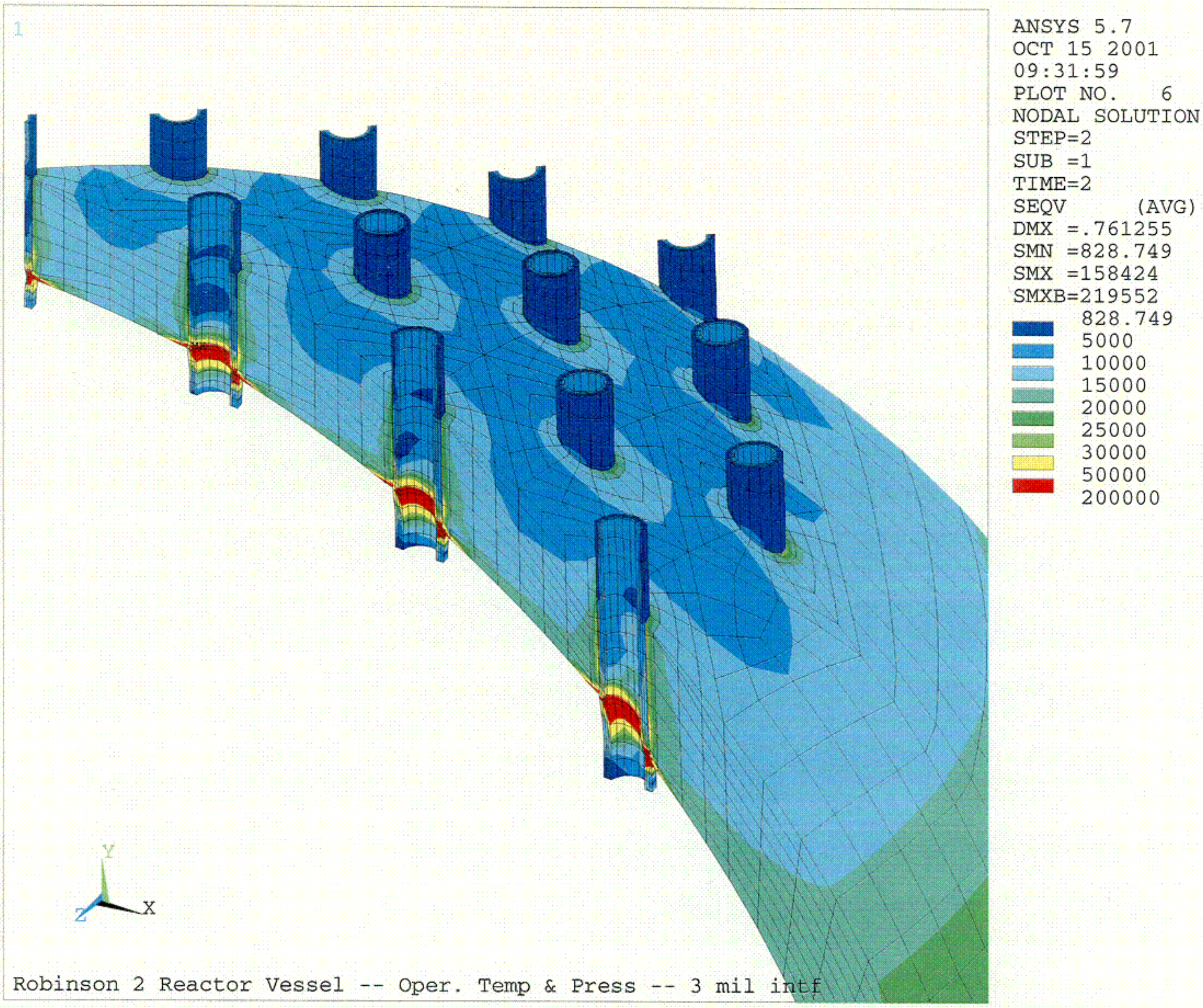
C01



Flange Rotation and Equivalent Stresses due to Flange Bolt Preload

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

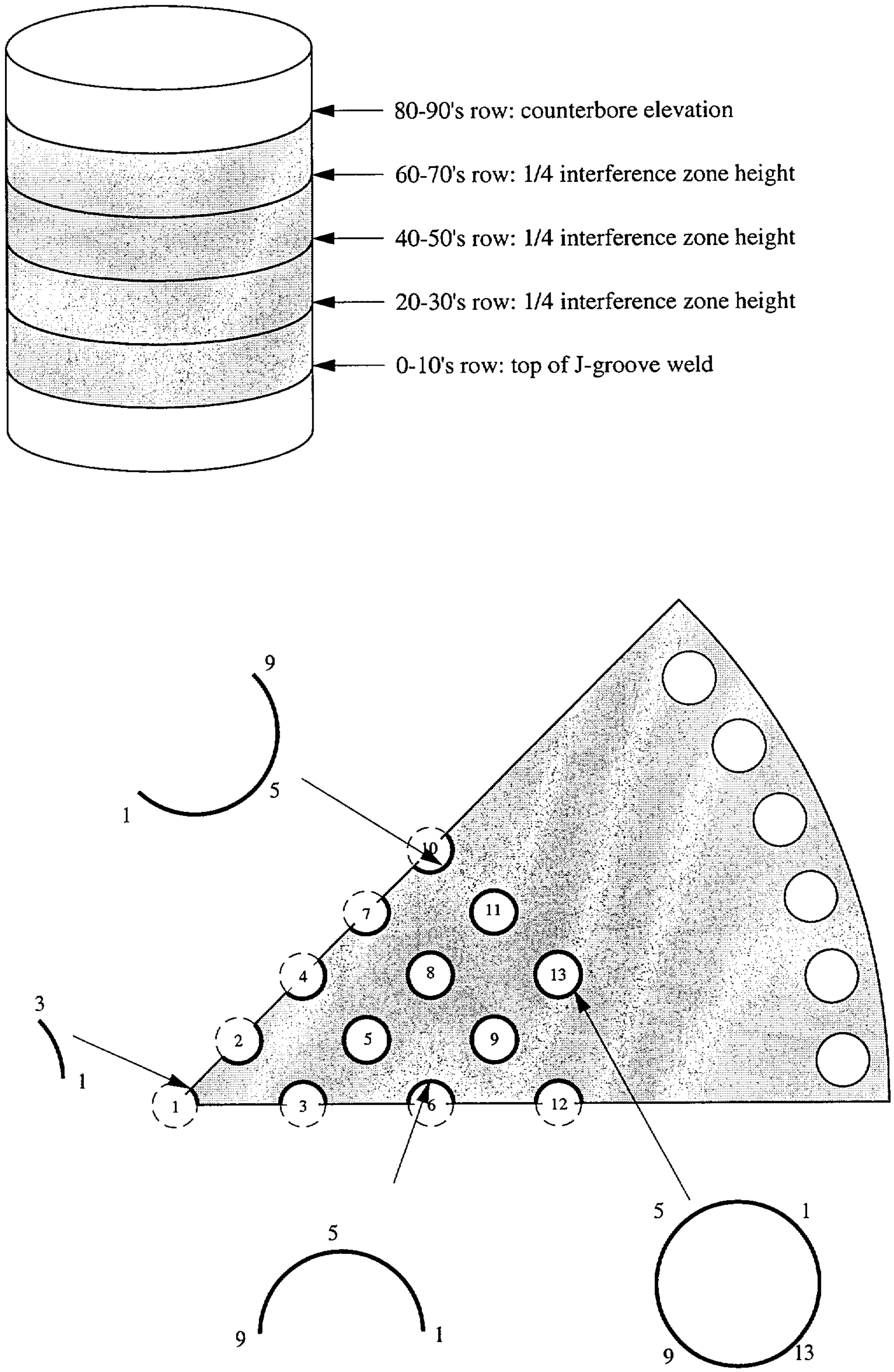
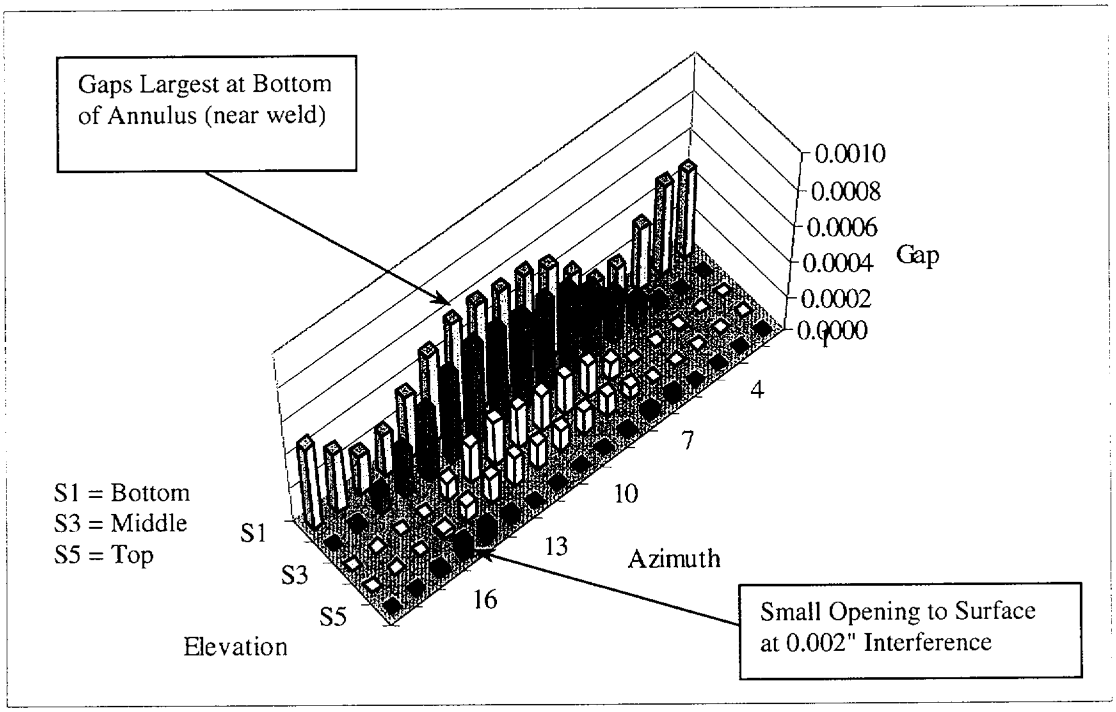


Figure B-6
Gap Opening Displacements for Nozzle #9

a. 0.002" Initial Interference with Annulus Unpressurized



b. 0.003" Initial Interference with Annulus Pressurized