Westinghouse Non-Proprietary Class 3

WCAP-16180-NP
Revision 0

December 2003

Operability Assessment for Combustion Engineering Plants with Hypothetical Circumferential Flaw Indications in Pressurizer Heater Sleeves

Westinghouse

LEGAL NOTICE

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John F. Hall
Reddy Ganta
Warren H. Bamford
Matthew C. Jacob
Joseph Cleary
Raymond E. Schneider
Joseph Congdon

December 2003

Reviewer: ____________________
Bradley F. Maurer
Regulatory Compliance & Plant Licensing

Approved: ____________________
Edward A. Siegel, Manager
Reactor Coolant System Design & Analysis – CE Fleet

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

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EXECUTIVE SUMMARY

As the result of primary coolant leakage from pressurizer heater sleeves in some Combustion Engineering (CE) designed pressurized water reactors (PWRs), Arizona Public Service (APS) initiated a systematic replacement of Alloy 600 pressurizer heater sleeves in the Palo Verde units. During the Fall 2003 Palo Verde-2 outage, APS performed non-destructive testing of the Alloy 600 sleeves prior to replacement. The testing identified axially oriented flaws in six sleeves and circumferentially oriented flaws in six other sleeves.

Additional non-destructive testing of the sleeves with circumferential indications confirmed the flaws in five of the sleeves and a skewed axial flaw in the sixth sleeve. The five circumferentially oriented flaws were located just above the partial penetration weld in the Alloy 600 sleeves and hence were not in the pressure boundary. These flaws were through-wall and extented 56 to 104 degrees around the circumference of the sleeves. The skewed axial flaw was also above the weld, had a length of 0.41 inch and an estimated depth of 40 % through-wall.

As a result of the unexpected discovery of circumferential flaws at Palo Verde-2, the Westinghouse Owners Group (WOG) initiated a task to address the issues associated with potential circumferential flaws in the heater sleeves of CE designed pressurizers and the effects of a potential leak or failure (ejection) of one or more sleeves.

Leakage of primary coolant as a result of through-wall flaws in pressurizer heater sleeves has occurred in CE plants since 1987. In response to leakage from 20 heater sleeves at a CE plant in 1989, CE Owners Group (CEOG) plants initiated an evaluation of pressurizer penetrations and initiated periodic visual inspections of the bottom head of pressurizers to determine if leakage from heater sleeves was occurring. At that time, available laboratory data, stress analyses and field experiences indicated circumferentially oriented cracking was not likely and, thus, catastrophic failure of a heater sleeve was not likely. As a result, boric acid corrosion of the low alloy steel pressurizer bottom head was the major concern. Reference 4 concluded that visual inspection of the pressurizer bottom head was an effective method for detecting a leaking sleeve and for detecting damage to the pressurizer shell as a result of boric acid corrosion. Since 1989, visual inspections have been effective at detecting leaking heater sleeves. These inspections have not only been effective at detecting leakage occurring at very low rates but also in detecting leakage before any corrosion damage occurred to the pressurizer shell.

The circumferential indications in the Palo Verde-2 heater sleeves are assumed to be the result of PWSCC initiation and growth since there are no destructive examination data that would indicate the contrary. The integrity evaluation described in Section 5 of this report shows that at least 7.5 years will be required to propagate a 120° circumferential through-wall flaw that will easily produce observable leakage to the critical size required for sleeve ejection. The equivalent time from first leakage from a smaller flaw would be at least 10 years. Such a period will provide several opportunities to inspect the pressurizer bottom head for evidence of leakage. The size of the flaws and the leak rate associated with the flaws, coupled with the presence of a gap between the sleeve outside surface and pressurizer bottom head bore hole inside surface, will insure that leaking sleeves are identified long before any circumferential flaws approach the critical flaw size for sleeve ejection.

Based on the calculated times to sleeve ejection from a flaw size with easily detectable leakage, the presently implemented visual inspection program for the pressurizer bottom head region will be sufficient to insure that the integrity of the pressurizers will be maintained.

The effects of heater sleeve ejection on plant operations were also considered. Reviews of prior analyses indicate that a postulated heater sleeve ejection is bounded by the prior analyses. Such an ejection would be equivalent to a small break LOCA (SBLOCA). The consequences of such an event are bounded by the results of the SBLOCA ECCS performance analysis. If a postulated sleeve ejection were to occur, the event would be handled by existing Operator Response and Emergency Procedure Guidance which provides adequate guidance to mitigate the transient. A review of the risk assessment of failure (sleeve ejection) on overall plant core damage frequency (CDF) and large early release frequency (LERF) concluded that the impact of failure on CDF would be within the range of 4.2E-08 and 6.3E-07 per year and the incremental LERF due to the postulated failure would be between 4.2E-10 and 6.3E-09. The potential jet impingement/missile damage from a postulated sleeve ejection event is not increased. The design and location of the pressurizer provide protection from a postulated failure of the surge line, which results in a much larger break than a heater sleeve failure. The sleeve failure scenario is also bounded by the surge line break subcompartment pressurization study that is documented in the FSARs.

1 BACKGROUND

1.1 HEATER SLEEVE CRACKING ISSUE

During the Fall 2003 refueling outage at Palo Verde-2, initial non-destructive inspection of 33 of 36 Alloy 600 pressurizer heater sleeves resulted in part-through-wall axial flaw indications in six (6) sleeves and part through-wall circumferential indications in six (6) additional sleeves. Subsequent ultrasonic testing (UT) of the heater sleeves with circumferential indications confirmed that five (5) sleeves had circumferential flaws that extended through-wall. The circumferential indications were above the partial penetration welds between the sleeves and the pressurizer bottom head. Thus, the circumferential flaws were not in the reactor coolant system pressure boundary and did not leak during service.

The axial indications were not unexpected, as several Combustion Engineering (CE) plants have experienced leaks because of axial cracks in Alloy 600 heater sleeves and small diameter nozzles in pressurizer and hot leg applications. Although there have been numerous occurrences of axial cracks in these applications in CE plants, circumferential cracking has been present in only one previous occasion and that cracking was attributed to a problem that occurred during pressurizer fabrication. That cracking was not near or associated with the partial penetration weld as have been all other cracking events. As a result of the recent and unexpected discovery of circumferential flaws in a CE plant, the Westinghouse Owners Group (WOG) initiated a task to address the issues associated with potential circumferential flaws in the heater sleeves of CE designed pressurizers and the effects of a postulated leak or failure of one or more pressurizer heater sleeves.

The purpose of this WOG task was to provide an operability assessment (OA) for the CE fleet of PWRs in the event that circumferential flaws are present in any heater sleeves.

1.2 HISTORY

Combustion Engineering (CE) designed PWRs originally had Alloy 600 in several different applications, including

- pressurizer instrument nozzles and heater sleeves,
- reactor vessel head control element drive mechanism (CEDM) and in-core instrumentation (ICI) nozzles,
- reactor vessel head vent lines,
- reactor vessel bottom head ICI nozzles (3 plants only),
- piping instrument and sampling nozzles,
- steam generator primary head instrument nozzles.

In all of these applications, the Alloy 600 nozzles were attached to the inside surfaces of the pressurizer or other components with J-groove partial penetration welds using Alloy 182 or 82 weld metal.

The first occurrence of leakage from an Alloy 600 nozzle or heater sleeve application occurred in 1986 when a pressurizer instrumentation nozzle at San Onofre-3 developed a leak during the initial cycle of operation (Reference 1). Analysis of the nozzle after its removal indicated that primary water stress corrosion cracking (PWSCC) was the cause of the leakage. In 1987, two heater sleeves at Arkansas-2 leaked as a result of PWSCC caused by the structural failure of pressurizer heaters. The expansion of the insulation material in the heaters as a result of exposure to water resulted in the application of additional stresses to the sleeves, resulting in PWSCC initiation. Destructive examination also indicated that the sleeves had been fabricated from a heat of Alloy 600 with characteristics indicating susceptibility to PWSCC (high strength, fine grains, intragranular carbides (Reference 2)).

Primary water stress corrosion cracking (PWSCC) of heater sleeves resulting from residual stresses imposed by the partial penetration welds occurred in 1989 at Calvert Cliffs-2. Visual inspection of the pressurizer revealed indications of primary coolant leakage from 20 of 120 heater sleeves (References 1, 3). Destructive examination of several heater sleeves indicated the leakage resulted from short axial cracks originating at the sleeves ID surfaces near the location of the partial penetration welds. The heat of Alloy 600 used for these sleeves also had metallurgical characteristics indicating high susceptibility to PWSCC (high strength, fine grains, intragranular carbides). Failure analysis and subsequent testing indicated that a contributing factor was a pre-service machine reaming operation which increased the ID by a small amount in the area of the J-weld. This operation produced a thin layer of cold-worked material (higher strength). Residual stress measurements on welded mockups using removed sleeves indicated that residual stresses in the reamed areas were significantly higher than in the non-reamed areas (Reference 4). This offered an explanation of why none of 240 sleeves of the same heat of material that did not have pre-installation reaming had experienced cracking at that time although they had greater service times in Calvert Cliffs-1 and Maine Yankee.

Additional occurrences of heater sleeve cracking have occurred since 1989 (Reference 5). In 1994, two heater sleeves at Calvert Cliffs-1 leaked. Destructive examination of one sleeve indicated the sleeve had been significantly damaged by post-installation reaming (Reference 6). Cracking in this sleeve, which was remote from the J-weld location, was attributed to this damage. In the other sleeve, the cracking was axially oriented and was near the J-weld. A third heater sleeve at Calvert Cliffs-1 also leaked in 1998. More recently, 12 heater sleeves leaked at Arkansas-2 in 2000 and an additional 6 leaked in 2002. The heater sleeve material at Arkansas-2 had the characteristics of Alloy 600 that was more susceptible to PWSCC (high strength, fine grains, intragranular carbides). At Palo Verde-2, one sleeve leaked in 2000. A second sleeve had an NDT indication that was part-through-wall. This sleeve had been damaged by a failed heater in the same manner as the ANO-2 sleeves that leaked in 1987. The Alloy 600 at Palo Verde-2 was of moderate strength but the microstructure has not been characterized. In 2000, a heater sleeve at Waterford-3 leaked. The heat of Alloy 600 at Waterford-3 was low strength (yield strength of 40 KSI). Low strength Alloy 600 pipe and tubing usually has metallurgical characteristics that are typical of Alloy 600 with resistance to PWSCC. Millstone-2 also had two (2) leaking heater sleeves in 2002. The Alloy 600 at Millstone-2 was also low strength, but the sleeves were not destructively examined to characterize the metallurgical properties. Also, the Millstone-2 sleeves received a pre-installation machine reaming to increase the sleeve ID similar to Calvert Cliffs-2. Other occurrences of sleeve leakage were at Palo Verde-3 in 2003 (two sleeves), Waterford-3 (two sleeves) in 2003 and Millstone-2 in 2003 (two sleeves).

In addition to heater sleeves, other small diameter Alloy 600 nozzles in CE plants have leaked or had part-through-wall flaws identified as PWSCC. The nozzles were procured as a different product form (forged or hot-worked bar stock) that was extensively machined to produce the nozzle configuration. Reference 5 presented a tabulation of most of the cracking events in instrumentation and sampling nozzles and heater sleeves in CE plants.

As a result of the Calvert Cliffs-2 event in 1989, the Combustion Engineering Owners Group initiated a program to address PWSCC of Alloy 600 nozzles and heater sleeves. The various tasks included additional destructive examinations of Calvert Cliffs-2 sleeves, reviews of fabrication processes and materials properties of all Alloy 600 pressure boundary applications, residual stress characterizations of welded mockups, thermal analysis of sleeves to determine temperature distributions down the lengths of the sleeves, inspection development activities, and evaluation of pressurizer shell (low alloy steel) corrosion as a result of exposure to concentrated solutions or deposits of boric acid. References 3, 4, 7-10 present the results of the various CEOG activities. The heater sleeve fabrication processes are summarized in the following section.

The most pertinent findings of the various CEOG tasks included:

1. The heater sleeves have varying degrees of susceptibility to PWSCC as a result of differences in materials properties and fabrication processes (reamed versus non-reamed).

2. Sleeve temperatures adjacent to the J-weld will be only slightly reduced (644 -647°F) from pressurizer operating temperatures while ID surface temperatures where the sleeves exit the pressurizer shell will be significantly reduced (596-622°F).

3. All cracks observed in the field in sleeves and nozzles and cracks in mockups tested in corrosive environments were axially oriented or approximately axially oriented. There was no circumferential extent to any cracks or flaw indications (up to that time).

4. The J-groove partial penetration weld induced significant hoop tensile stresses to the ID of the sleeves in areas adjacent to the weld location. Residual stresses were highest in sleeves that had been reamed prior to installation. However, residual stresses in non-reamed sleeves were sufficiently high to initiate PWSCC.

5. Circumferential cracking leading to catastrophic failure of a heater sleeve is unlikely.

6. If PWSCC does occur, the cracks will be axially oriented and located near the J-weld. The cracks will be contained within the pressurizer shell. Two inch long axial cracks, which are longer than any cracks observed in the field, will not exhibit unstable crack growth. Additional stress corrosion crack growth may occur, resulting in increased leakage that will gradually increase with time and thus should be detected.

7. Visual inspection of the pressurizer bottom head is the best method for detecting leaking sleeves or for detecting damage to the bottom of the pressurizer shell as a result of boric acid corrosion.

8. Data from corrosion tests of pressurizer shell material under prototypic conditions and structural analysis of the pressurizer bottom head indicated that low level leakage from two adjacent cracked heater sleeves, with the cracks oriented so as to minimize the ligament between the sleeve holes, could continue for over 1700 days before ASME code requirements would be exceeded.

2 SUMMARY OF PALO VERDE-2 HEATER SLEEVE INSPECTION

Palo Verde-2 is a Combustion Engineering design PWR operated by Arizona Public Service (APS). As a result of several occurrences of PWSCC in Alloy 600 pressurizer and hot leg nozzles and heater sleeves in CE plants, APS initiated a program to replace all pressurizer and hot leg applications of Alloy 600. During the Palo Verde-2 refueling outage in the fall of 2003, APS replaced 33 of 36 pressurizer heater sleeves. As part of the replacement activity, APS performed eddy current (ECT) examinations of the Alloy 600 heater sleeves prior to their removal. This examination resulted in indications of axial flaws in six heater sleeves and circumferential flaws in six (6) additional sleeves. The circumferential indications were of particular interest since such indications have not been seen previously in Alloy 600 heater sleeves and nozzles. The ECT technique used for the initial assessment was not sufficiently refined to locate the circumferential flaws with respect to the welds or to estimate the size of the flaws. Accordingly, APS conducted additional NDE examinations (ECT and ultrasonic testing (UT)) to obtain more detailed information on these flaws.

APS examined the six circumferential flaws and one axial flaw. The UT technique was a time-of-flight procedure. The additional ECT and UT confirmed the presence of flaws in all seven tubes. Five of the flaws which ECT indicated were SCIs (single circumferential indications) were confirmed as circumferentially oriented flaws located just above the J-groove partial penetration weld location at the 0 degree (downhill) location. UT indicated that all five flaws were through-wall. The extent ranged from 56 degrees to 104 degrees of the circumference.

One sleeve, which the initial ECT indicated had a circumferential flaw, had a skewed axial flaw that appeared to be associated with a gouge in the ID surface. This flaw had an estimated length of 0.41 inch and depth of 40% through-wall. The second axial was confirmed as a skewed axial also with a length of 0.47 inch and depth of 60 % through-wall. The axial flaws were also located above the welds but were near the 180 degree (uphill) location.

As noted above, all of the circumferential flaws and the two axial flaws examined were above the weld. This is significant because flaws above the weld location will not result in heater sleeve ejection should the through-wall extent exceed the critical flaw size nor will these flaws, and the axial flaws examined, leak if the flaws are through-wall.

3 PRESSURIZER HEATER SLEEVE FABRICATION REVIEW

3.1 SUMMARY OF THE 1989 CEOG FABRICATION REVIEW

Reference 3 reviewed the design, fabrication history and materials properties of all heater sleeves in CE plants. The information of Reference 3 is summarized below.

The earlier CE plants (Fort Calhoun, Palisades, Maine Yankee, Calvert Cliffs-1 and -2, Millstone-2, St. Lucie-1 and Arkansas-2) had 72 to 120 low watt density heaters (12.5 KW) that had a diameter of 0.875 inch. The later plants (San Onofre-2 and -3, Waterford-3, St Lucie-2 and Palo Verde-1, -2 and –3) had fewer heaters (30 or 36) but they were larger in size (1.245-inch diameter) and output (50 KW). In all cases, the heater sleeve to pressurizer bottom head attachments were J-groove partial penetration welds with Alloy 82 weld metal. Table 3-1 summarizes the numbers and sizes of pressurizer heaters in CE plants.

The heater sleeve materials were all drawn and annealed Alloy 600 pipe procured to the general requirements of SB-167. The as delivered yield strengths varied from 38.0 KSI to 63.5 KSI. International Nickel (INCO) Huntington Alloys supplied all heater sleeves except for the Palo Verde units which were supplied by Babcock and Wilcox Tubular Products.

The ordering requirements specified pipe inside diameter and minimum wall thickness to minimize the number of machining steps required in manufacture. As a result, the ID surfaces were generally supplied in the final condition, which usually included a grit blasted finish. For several plants, the sleeve material was undersize on the inside diameters. This condition was corrected by machining at CE to increase the IDs to the specified sizes. The sleeves were machined on the OD to the appropriate dimensions prior to installation into the pressurizer bottom head.

Installation of the heater sleeves occurred after weld overlay (cladding) and final heat treatment of the pressurizer bottom head assembly. Thus, the sleeves were in the as-welded condition when they entered service. The heater sleeve holes were bored through the bottom head after which the J-weld "preps" were ground into the bottom head Inconel weld overlay. The sleeves were welded into the bottom head with a J-groove partial penetration weld using a manual tungsten inert gas welding procedure with Alloy 82 filler metal. The design clearances between the heater sleeves and the bottom heads for CE plants varied from 0.002 to 0.009 inch diametrically. Thus, there were distinct crevices between the sleeves and pressurizers.

After installation of the sleeves, a "check rod" was inserted into each sleeve. The acceptance requirement was that the check rod, which was the maximum diameter of the heater sheaths, had to pass freely through the length of the heater sleeves after welding was completed. A common problem with sleeve installation was local weld shrinkage that occurred at the J-weld location. The clearances between the heaters and the sleeves were small (0.011 to 0.018 inch). Local weld shrinkage frequently prevented heater insertion. The initial approach to solving the heater installation problem was to ream the sleeve to a larger ID (but staying within drawing tolerances) for the sleeves that would not accept the check rod. Reaming was accomplished with a portable horizontal-milling machine, inserting the reamer from the outboard end of the sleeve.

For a short time, the above procedure was changed so that the upper 3 to 3-1/2 inches of the sleeves were reamed to a larger diameter prior to installation in the pressurizer bottom heads. The IDs of the sleeves in the pressurizers at three plants (Calvert Cliffs -2, St Lucie-1 and Millstone-2) were increased by 5 to 15 mils (0.005 to 0.015 inch) by the pre-installation reaming operation. The additional operation was not successful since some of these sleeves required additional reaming after welding to pass the check rod gage. The practice of pre-installation reaming was discontinued for the remaining CE plants.

Non-conforming conditions for the heater sleeves were noted from time-to-time, either during inspections performed upon receipt of material or during manufacture. These usually resulted in the initiation of a Rejection Notice (RN) which required a formal disposition relative to use "as-is", replace, repair, etc. Typical RNs and their disposition included inside diameters smaller than required by procurement documents. CE machined these sleeves to the proper size. Sleeves reamed oversize on the ID were accepted if the reduction in wall thickness was not excessive. Sleeves mechanically damaged during manufacture were replaced unless damage was minor. Bent sleeves which were not replaced were straightened to accept the check rod gage and then dye penetrant inspected. Burn-through from the partial penetration welds were ground, weld repaired, penetrant inspected, inspected with the check rod and reamed again, if necessary.

Reference 3 tabulated for all CE plants the Rejection Notices discovered during the records review. Rejection Notices were discovered for

> Maine Yankee – 93 sleeves would not accept the check rod after reaming. After further cleaning and deburring, the sleeves were successfully gauged.
>
> Four sleeves were bent during fabrication. These were straightened, welds were dye penetrant (PT) inspected and then the sleeves were reamed. These four locations were later removed from service because of concern about cold-work induced by bending and straightening and the potential for circumferential cracking as a result.
>
> Calvert Cliffs-1 – During machine reaming from the outboard end after sleeve installation, the reamer broke. The sleeve was removed and replaced with a sleeve from a different lot.
>
> Calvert Cliffs-2 – During the pre-installation reaming, seven sleeves were reamed oversize in the 3 to 3-1/2 inch area at the in-board end. This condition was accepted by Design Engineering
>
> St Lucie-1 – Burn through occurred on 26 heater sleeves during welding. The part of the sleeves above the weld was removed, the burn through areas repaired and PT inspected, the sleeves were gauged and hand reamed as necessary.
>
> St Lucie-2 – Eleven sleeves were undersize on receipt from the material supplier. CE machined the sleeves to the correct ID.
>
> Millstone-2 – Five (5) sleeves were oversize in the 3 to 3-1/2 inch area of the pre-installation reaming. This condition was accepted by Design Engineering.

Arkansas-2 – A sleeve was damaged during reaming and was replaced with a sleeve of the same heat.

95 sleeves were oversize at the in-board end and had damage from the reamer at the outboard end. Design Engineering accepted the condition.

San Onofre-2 – Sleeve material was undersize on the ID. The condition was corrected by machining at CE. During the machining of the ID, seven sleeves were machined oversize by a maximum of 0.004 inch. This condition was accepted by Design Engineering.

San Onofre-3 – Nine sleeves were undersize on the ID. Machining by CE corrected this condition.

Palo Verde-3 – Burn through occurred in one sleeve. The area was ground, weld repaired and reamed. (Review during 2003 indicated the affected sleeve was actually in Palo Verde-2.)

3.2 FABRICATION REVIEW OF THE PALO VERDE UNITS

As a result of the initial NDE findings at Palo Verde-2 (possible presence of circumferentially oriented flaws and visual indications of possible ID reaming), Westinghouse, at Arizona Public Service request, conducted another detailed review of materials and fabrication process records for the three Palo Verde units to determine if there were materials or fabrication process steps that could have enhanced the potential for circumferential flaw initiation and growth. The findings from this review are summarized in this section. A similar review was not conducted for the other CE plants but the basic fabrication processes were the same.

The sleeve material records indicate all material was from the same supplier and was supplied to the requirements of SB-167 as supplemented by CE purchase specification N-P43B6(c) as 2.000 inch diameter pipe with a wall thickness of 0.364 inch (ID of 1.272 inch). The CMTRs for the various heats used at Palo Verde indicate conformance to the procurement requirements. One Rejection Notice for the sleeve material for Palo Verde-2 was completed because the ultrasonic testing for two (2) sleeves was not properly performed by the supplier. The required UT was performed by CE after delivery of the material. There were not any other Rejection Notices filed for the sleeve material.

Sleeve fabrication process – The steps used to fabricate the Alloy 600 heater sleeves are summarized below, based on reviews of the available fabrication records (drawings, shop travelers, rejection notices, certified material test reports, etc.) for Palo Verde-1, -2 and -3. Specific steps in the fabrication process included

- Layout and cut (saw) the SB-167 pipe to the required lengths for the heater sleeves.

- Machine the radius end (anti-ejection collar) of the sleeves. The anti-ejection collar is on the larger diameter sleeves (Palo Verde –1, -2, -3, San Onofre-2 and –3, Waterford-3 and St Lucie-2). The smaller diameter heater sleeves do not have anti-ejection collars.

- Machine the OD of the remainder of each sleeve to the finished dimensions (1.660 + .000 – 002 inches for the larger sleeves).

- Deburr and identify each sleeve

- Inspect and dye penetrant (PT) test all surfaces of each sleeve.

There were not any off nominal conditions that required a rejection notice for Palo Verde-2. At Palo Verde-1, two oversize sleeves were machined because two sleeve penetrations had oversize diameters which were not acceptable. The OD of these sleeves was 1.675 +0.000 – 0.002 inches.

Sleeve penetration machining – The pressurizer bottom heads of all plants were fabricated of low alloy steel plates (SA 533 Grade B class 1) and weld metal. The inside surfaces were covered with a weld overlay (cladding) of Alloy 82 weld metal. A submerged arc automatic (SAA) process was used to deposit the weld metal at Palo Verde. In the area of the sleeves, the weld overlay was a minimum of 0.5 inch thick. At other locations, the overlay was 0.22 inch thick. After final heat treatment of the lower assembly, the heater sleeve penetrations were machined as follows:

- The pressurizer lower assembly (bottom head) was setup on a horizontal boring mill.

- A 1 ½ inch diameter hole was drilled through the bottom head at each sleeve location.

- A 1.630 inch diameter hole was bored at each sleeve location.

- A counter bore with a diameter of 1.672 + 0.015 – 0.000 inch was machined on the bottom head OD at each sleeve location.

- The holes were reamed through the bottom head thickness to a diameter of 1.662 + 0.004 – 0.000 inch at each sleeve location.

- Holes were inspected.

Welding of heater sleeves – Heater sleeves were welded into the bottom head as follows:

- J-groove weld preps with depths of 0.25 inch were ground into the weld overlay.

- Sleeve holes and sleeves were cleaned and inspected.

- Sleeves were fit-up into the holes.

- Welds were completed to ½ thickness using a gas tungsten arc process and Alloy 82 weld metal.

- Welds were cleaned and PT inspected.

- PT indications were removed by grinding.

- The grind out areas were PT inspected.
- Welds were completed to full thickness.
- Welds were cleaned and PT inspected.
- PT indications were removed by grinding.
- Grind outs were PT inspected.
- Grind outs were weld repaired using the same process and weld metal.
- Repair welds were ground and inspected.

At Palo Verde-2, one sleeve had two areas of weld burn through. To disposition the Rejection Notice associated with this finding, the burn through areas were ground to clean up the burn through and the grind outs were inspected by PT. The sleeve was weld repaired, the repairs were ground and the areas were inspected by PT.

Inspection of installed sleeves – After the sleeves were installed and any repairs required completed, the installed sleeves were inspected to insure that heaters could be inserted. The inspection acceptance requirement was "a 1.270 + 0.000 – 0.003 inch diameter gage must pass freely through the entire sleeve after completion of the weld". The inspection process consisted of

- Determine if the check rod (gage) could pass through the sleeves.
- Polish or ream each location that did not successfully pass the check rod until it did successfully pass.

The shop travelers for Palo Verde indicate that all heater sleeves at Palo Verde-2 and –3 were reamed after installation. The records also indicate that some Palo Verde-1 sleeves were reamed but the number or the identities of sleeves reamed were not recorded. Visual inspection of the ID surfaces of sleeves with NDE indications at Palo Verde-2 indicate that these sleeves were reamed. The effect of post-installation reaming on PWSCC initiation is inconclusive.

Conclusions from the Fabrication Review: The review of the previous CEOG task (Reference 3) and the recently completed fabrication review of the Palo Verde units concluded that

1. There were not any fabrication induced conditions identified that would have increased the potential for circumferential flaw indications at Palo Verde-2 nor were there any fabrication related conditions identified that would increase the potential for similar circumferential flaws in the heater sleeves of any other operating CE pressurizers.

2. The Palo Verde-1, -2, and –3 sleeve material was supplied by B&W Tubular Products. For all other CE plants, the heater sleeve material was supplied by International Nickel Huntington Alloys. The yield strengths of the Palo Verde materials were higher than that

of most CE plants; however, there were some sleeves in other CE plants that were fabricated from Alloy 600 with even higher yield strengths.

3. The Palo Verde-2 sleeves did not receive any pre-installation reaming or other machining operations, such as occurred at Calvert Cliffs-2, that could have enhanced the potential for PWSCC initiation. At several plants, the IDs of the as-received sleeve material was undersize. For these sleeves, the IDs were increased to the specified valus by machining at CE.

4. All of the Palo Verde-2 heater sleeves were reamed after installation to insure that heaters could be inserted. The fabrication procedures for all CE pressurizers included such a step for heater sleeves which would not pass a check rod. The fabrication records for some plants indicate all sleeves were reamed after installation. For other plants, the available records do not indicate the number of sleeves that were reamed after installation.

Table 3-1 Types and Numbers of Pressurizer Heaters

Plants	Number of Heaters	Heater Diameter, in.	Heater Output, KW
Fort Calhoun	72	0.875	12.5
Arkansas-2	96	0.875	12.5
Calvert Cliffs 1 & 2 Millstone-2 St. Lucie-1 Palisades Maine Yankee	120	0.875	12.5
Waterford-3 St. Lucie 2 San Onofre-2&3	30	1.245	50
Palo Verde-1,2&3	36	1.245	50

4 OPERATIONAL IMPACTS

This section of the report presents a preliminary assessment of the effects of heater sleeve ejection on the operation of CE design plants. The assessment addresses probability of heater sleeve ejection, consequences of a Loss-of-Coolant Accident (LOCA) resulting from heater sleeve ejection, risk assessment, the impact of jet impingement or missile hazard damage to RCS components and the impact of sleeve failure on subcompartment pressurization.

4.1 ECCS PERFORMANCE

This section provides an assessment of the Emergency Core Cooling System (ECCS) performance for a Loss-of-Coolant Accident (LOCA) that results from a postulated failure of a pressurizer heater sleeve.

A postulated failure of a pressurizer heater sleeve would produce a hole in the bottom head of the pressurizer with a maximum area equal to the area of the penetration in the pressurizer through which the heater sleeves passes. The maximum value for this area is 0.015 ft^2 for the large diameter sleeves. A break area of this size is considered a Small Break LOCA (SBLOCA), and was used in the evaluation here. The large diameter heater sleeves all have anti-ejection collars. Thus, this break area is unlikely to occur. The small diameter heater sleeves do not have anti-ejection collars. The area of these penetrations is typically 0.007 ft^2.

The purpose of the SBLOCA ECCS performance analysis (i.e., the SBLOCA safety analysis), which is typically documented in Chapter 6 or Chapter 15 of a plant's FSAR, is to demonstrate conformance to the ECCS acceptance criteria of 10 CFR 50.46 (Reference 12). The analysis must be performed for a spectrum of breaks that includes the most limiting break area and location. The SBLOCA ECCS performance analysis for Combustion Engineering designed PWRs generally consists of a spectrum of three or more reactor coolant pump (RCP) discharge leg breaks. The break spectrum includes the limiting break area and a minimum and maximum break area that encompass the limiting break area. In very general terms, the limiting break area is generally between 0.04 ft^2 to 0.08 ft^2 and the break spectrum encompasses a minimum area of approximately a 0.01 ft^2 or larger to a maximum area of approximately 0.1 ft^2. In addition, a break representing the inadvertent opening of a pressurizer safety valve (i.e., a break area of approximately 0.03 ft^2 at the top of the pressurizer) has been analyzed for several Combustion Engineering designed PWRs.

The ECCS performance of a SBLOCA that is caused by a postulated failure of a pressurizer heater sleeve is bounded by the results of the SBLOCA ECCS performance analysis for the following reasons.

The primary reason that the ECCS performance of a SBLOCA caused by a postulated failure of a pressurizer heater sleeve is bounded by the results of the SBLOCA ECCS performance analysis is the location of the break. A break in the bottom head of the pressurizer is less limiting for ECCS performance than a break in the RCP discharge leg for a number of reasons. First, a break in the bottom head of the pressurizer will not result in the spillage of any safety injection flow, i.e., 100% of the flow from the ECCS is available to cool the core. In the SBLOCA ECCS performance analysis, all injection to the broken RCP discharge leg is assumed to spill out the break regardless of the size of the break. This results in the spillage of 25% of the flow from the high pressure safety injection (HPSI) pump, the most important component of the ECCS for SBLOCAs.

Because of its elevation (and also because of its separation from the rest of the Reactor Coolant System (RCS)), a break in the bottom head of the pressurizer is less limiting than an equal size break in a RCP discharge leg in terms of the amount of (or the potential for) core uncovery. Since it is located at a higher elevation than a break in the RCP discharge leg, there is less RCS liquid above the break for a break in the bottom head of the pressurizer. Consequently, less RCS liquid will "drain" out the break, thereby leaving more RCS liquid available to flow into the reactor vessel to replace what will be lost by core boil-off.

Also, relative to a discharge leg break of the same size, the break flow for a break in the bottom head of the pressurizer will change from two-phase liquid to steam earlier in the transient. In general, the transitioning of the break flow from two-phase to steam in a SBLOCA is beneficial since it increases the rate of RCS depressurization. This, in turn, results in more HPSI pump flow into the RCS and less break flow out of the RCS. Consequently, there will be less (or no) core uncovery for the break in the bottom head of the pressurizer relative to the equivalent sized RCP discharge leg break.

The results of the SBLOCA analyses for the inadvertent opening of a pressurizer safety valve depict the benefits described above. There is generally no core uncovery predicted for the inadvertent opening of the pressurizer safety valve. In contrast, there is several feet of core uncovery predicted for the limiting break in the RCP discharge leg.

For the reasons cited above, it is concluded that the consequences of a SBLOCA that is caused by the postulated failure of a pressurizer heater sleeve are bounded by the results of the SBLOCA ECCS performance analysis.

Lastly, the definition of a LOCA in 10CFR50.46 excludes consideration of a postulated failure of a pressurizer heater sleeve as a location that needs to be included in the ECCS performance analysis. Paragraph (c) (1) of 10CFR50.46 defines a LOCA as a hypothetical accident that would occur "*...from breaks in pipes in the reactor coolant pressure boundary...*". The failure of a pressurizer heater sleeve is not a pipe break and, therefore, by the definition of a LOCA in 10CFR50.46, is outside the traditional scope of an ECCS performance analysis.

4.2 OPERATOR RESPONSE AND EMERGENCY PROCEDURE GUIDANCE IMPACT

This section provides an assessment of Emergency Operating Procedures (EOPs) available to the operator to respond to a Loss-of-Coolant Accident (LOCA) that would occur as a result of a postulated failure of a pressurizer heater sleeve. The assessment is based on the CE Emergency Procedure Guidelines (EPGs), (Reference 13). The EPGs are used by CE plants to develop their plant specific Emergency Operating Procedures. The EPGs/EOPS are symptom based and functional procedures such that the operator does not need to know what specific event is in progress to successfully protect the core and the public. In addition, the LOCA guideline is written such that the operator does not need to know the size or location of the break to effectively respond to the event.

Table 4-1 provides a chronology / time table of events for a pressurizer heater sleeve break large enough to require reactor trip followed by safety injection (SI) actuation. As a representative size, a failure having an equivalent diameter on the order of 1.66 inch is postulated. A significantly smaller break would be a leak that is within the capability of normal makeup / normal charging, and would most likely be addressed by the plant's Abnormal Operating Procedures and Alarm Response Procedures. For this very small class of breaks, the plant should be able to perform a controlled reactor shutdown; cooldown and depressurization, eventually defuel, and perform the necessary inspections and repairs. A break as large as 1.66 inch would correspond to failure of the entire heater sleeve penetration, essentially a small LOCA at the bottom of the pressurizer. This break size would be addressed by the plant's Emergency Operating Procedures (EOPs) as outlined in Table 4-1. The times provided in Table 4-1 are considered typical and are based on simulator observations for various events. They are not precise since there could be considerable variations just with different operating crews at the same plant. However, the sequence of events listed does correspond to the order expected in accordance with the emergency guidance and the times listed should be representative.

In responding to this event, it is expected that the operators would initially maximize normal charging flow and possibly runback the turbine in response to the system depressurization. Since the break is beyond the capacity of normal charging, reactor trip on over-temperature delta-T or low pressurizer pressure would be expected within the first few minutes of the event. Following the reactor trip, safety injection (SI) actuation on low pressurizer pressure is expected since the RCS would already be somewhat depressurized at the time of the trip. The break location in the bottom of the pressurizer may result in failure of several pressurizer heaters which may be evident by the abnormal response of the normal pressurizer pressure control system following the reactor trip. The time of the reactor trip and SI actuation would be dependent on the break size and to some extent the pre-trip actions taken in response to the failure, but the range of times listed in Table 4-1 would be typical.

The operator first performs the Standard Post Trip Actions (SPTA). The purpose of the Standard Post Trip Actions is to provide the entry point for all EPGs/EOPs when the event is initiated from MODE 1 or 2. All safety functions are checked against acceptance criteria to give the operator a complete status regarding plant conditions and safety. The check of safety functions discriminates between an uncomplicated reactor trip and other more complex events. The safety function acceptance criteria are chosen to be consistent with the plant conditions which would prevail only in the short term after a simple and uncomplicated reactor trip. The operator would observe that Pressurizer Pressure Control and RCS Inventory Control were challenged and required contingency actions to be taken. In this case, he would likely have to take contingency action CA 4.4 "Ensure SI actuation" and CA 4.5 "Ensure two RCPs are tripped" if the trip two/leave two criteria are met. Since the contingency actions were required, he would not conclude that this was an uncomplicated trip and move on to the Diagnostic actions.

Using the Diagnostic Actions procedure, the operator would diagnose a small break LOCA based on an assessment of the post trip response of pressurizer pressure, pressurizer level, RCS subcooling, containment temperature, containment pressure, containment radiation levels and no indications of steam generator tube rupture (SGTR). The operator would then enter the LOCA optimal recovery guideline (ORG), assuming only the one event is diagnosed. For multiple events, or if a diagnosis could not be made, the operator would be directed to the functional recovery guideline (FRG).

Once in the LOCA procedure, the operator confirms that he has correctly diagnosed the event. He does so by performing the safety function status checks (SFSCs). Once confirmed, he performs the required verifications and immediate actions such as verifying SI actuation, and stopping RCPs based on the trip two leave two criteria. In the case of a small break LOCA only two RCPs would be tripped, thus ensuring forced circulation to support RCS cool down using the steam generators. The operator is then directed to locate and isolate the break. In this case, the break can not be isolated. The operator will conclude only that the break is inside containment and not able to be isolated. At this point in the LOCA procedure, the operator will take subsequent actions for an unisolable LOCA and initiate a rapid RCS cool down at <100°F/hr. He will continue to monitor the safety functions and attempt to restore those that are in jeopardy (RCS Pressure Control and Inventory Control).

In conclusion, the CE Emergency Procedure Guidelines are symptom based functional procedures. The operator does not need to know what specific event is in progress to successfully protect the core and the public. The LOCA guideline is written such that the operator does not need to know the size or location of the break to effectively respond. Procedurally, this event (pressurizer heater sleeve failure) would be handled like any other LOCA. The existing guidance provides adequate directions to mitigate the transient. No additional operator guidance is needed to address this event should it occur.

The conclusion documented above is applicable to all plants in the CE fleet, since (1) plant specific EOPs are developed based on the CE EOG, and (2) the CE EOGs are generic guidelines that are applicable to all plant designs in the CE fleet.

4.3 RISK ASSESSEMENT OF CRACKED PRESSURIZER HEATER SLEEVE

The risk assessment of a cracked pressurizer heater sleeve considers the impact of a small break LOCA that is postulated to occur as a result of a failure of a heater sleeve on overall plant core damage frequency (CDF) and the large early release frequency (LERF). The impact of the failure on the CDF was determined using (1) the conditional core damage probability (CCDP) that a small break LOCA would proceed to core damage given that this event occurs, and (2) the frequency of a small break LOCA initiated by the postulated heater sleeve failure. The impact of the failure on CDF can then be written as:

$$\Delta CDF = F_{SBLOCA - \text{Pzr htr sleeve failure}} * CCDP \qquad (4\text{-}1)$$

Several representative plant designs were considered. The frequency of a pressurizer heater induced small LOCA was conservatively bounded by assuming that one third of all small LOCAs is caused by failures of pressurizer heaters. This is a very conservative approach as detection of flaws in the vicinity of the pressurizer heater is highly likely and that the propagation of a flaw to a point where a critical flaw would develop will take many refueling cycles. CCDP parameters were established based on the use of representative CEOG member plant specific data. The SBLOCA frequency was established based on NUREG/CR-5750, "Rates of Initiating Events at U. S. Nuclear Power Plants: 1987-1995" and applied to the risk assessments.

The impact of the postulated failure on LERF was evaluated from the change in CDF due to failure as calculated by equation 4-1 and the conditional LERF associated with a small break LOCA event. The change in LERF then becomes:

$$\Delta LERF = \Delta CDF * PLERF_{SBLOCA - \text{Conditional(}} \qquad (4\text{-}2)$$

In the above equation $PLERF_{SBLOCA - \text{Conditional}}$ is the probability that the LOCA occurs in the presence of an unisolated containment, as small LOCAs do not otherwise challenge the containment. A conservative bounding value of 1.0E-02 was assumed for $PLERF_{SBLOCA - \text{Conditional}}$.

The changes in CDF and LERF for several plants in the CE fleet were calculated using Equations 4-1 and 4-2 and plant specific data for the CCDP and $F_{SBLOCA - Pzr\ htr\ sleeve\ fail}$ obtained from probabilistic Risk Assessments (PRAs).

The results of the above calculations indicated that the values of ΔCDF range between 4.2E-08 to 6.3E-07 per year and ΔLERF values fall between 4.2E-10 and 6.3E-09 per year.

4.4 IMPACT OF JET IMPINGEMENT / MISSLE HAZARD

Potential jet impingement/missile hazard damage to the reactor coolant system components (reactor vessel, SGs, RCS piping, RCPs) due to a failure of the pressurizer heater sleeve is prevented by a thick concrete compartment within which the pressurizer is enclosed (for example, Palo Verde drawings Nos. 13-P-00B-003 and 13-P-00B-007). The pressurizer is located several feet away from RCS components in this compartment and is connected to one of the hot legs of the RCS piping through the surge line. The surge line break has been considered both from the pressurization of the compartment and the potential jet impingement/missile hazard damage of the RCS components of risk significance.

The design and location of the pressurizer within the concrete compartment has been determined to provide adequate protection from jet impingement/missile hazard for the surge line break. Therefore, no additional impact is expected for a postulated heater rod ejection failure as this failure leads to a significantly smaller break area and there are no risk significant targets in the path of the ejected heater rod. Furthermore, the pressurizer compartment is considered to give more than adequate protection from jet impingement/missile hazard due to the isolated location of the pressurizer and the thick concrete compartment surrounding the pressurizer.

The discussion above is applicable to all plants in the CE fleet. This is because, for these plants, (1) the pressurizer is typically enclosed within a concrete compartment away from risk significant plant components and systems, (2) the surge line break is evaluated from a jet impingement/missile hazard consideration, and (3) the postulated heater rod ejection failure leads to a significantly smaller break than for the surge line break.

4.5 IMPACT OF SUBCOMPARTMENT PRESSURIZATION

The postulated pressurizer heater sleeve failure could discharge high energy fluid into the pressurizer subcompartment enclosed by concrete walls and could potentially challenge its structural integrity by internal pressurization. This scenario was compared against the design basis subcompartment pressurization calculation documented in the Palo Verde UFSAR (Reference 11). Chapter 6, Section 6.2.1.6 of the UFSAR describes the various subcompartment analyses that were completed in support of the containment structural analyses. This section includes the analysis of the pressurizer compartment pressurization resulting from the break of the pressurizer surge line.

The surge line break is 161 square inches in size and is shown to result in acceptable pressurization of the pressurizer compartment. The largest hole size for a postulated pressurizer heater sleeve failure is 1.66 inches in diameter which results in a break area of about 2.17 square inches. In comparison to the surge line break, the heater sleeve ejection would lead to significantly smaller rates of mass and energy releases to the pressurizer compartment since these releases are proportional to the break area. Consequently, the rate and magnitude of the pressurization of the pressurizer compartment would be correspondingly smaller. Thus, the surge line break pressurization study documented in the UFSAR for the pressurizer compartment provides bounding subcompartment pressurization for the heater sleeve failure scenario.

The discussion in this section is also applicable to all plants in the CE fleet. Reasons for this are (1) the surge line break area is much larger than that for the pressurizer heater sleeve ejection failure, (2) the mass and energy releases for the surge line break scenario are relatively larger resulting in larger pressurizer compartment pressurization, and (3) the pressurization from the surge line break is analyzed to show that the pressurizer compartment can adequately and safely accommodate the pressurization.

Table 4-1: Typical Time Table of Events / Chronology for the Pressurizer Heater Sleeve Break-Small Break LOCA Scenario

Event	Typical Times (minutes)
Pressurizer Heater Sleeve Break Occurs (1.66" or 0.015 ft^2 Break)	0
Reactor Trip followed by SI Actuation	~ 5 minutes for a small break, including heater sleeve
Operator Performs Standard Post Trip Actions (SPTA). He will ensure SI actuation (CA 4.4) and Ensure two RCPs are tripped if criteria are met (CA 4.5)	8 – 10 minutes
Operator performs Safety Function Status Checks and Diagnostic Actions.	~ 12 minutes
Operator diagnoses a LOCA based on PZR pressure (SI actuation), PZR level, RCS subcooling, no indications of SGTR and containment T/P and radiation levels. (SIAS)	~ 12 - 15 minutes
Operator implements LOCA ORG (assuming only one event diagnosed)	~ 15 minutes
Operator confirms correct diagnosis (performs SFSCs), verifies SFAC satisfied, ensures SI actuated, Stops two RCPs (T2/L2), if criteria is met.	~ 15-20 minutes
Operator attempts to locate and isolate break and concludes that break is in containment and unisolable	~20 – 25 minutes
Operator initiates a rapid RCS Cooldown at < 100°F/hr and continues to monitor SFSCs and restore safety functions in jeopardy (RCS Pressure Control and Inventory Control)	30 to 40 minutes

5 PRESSURIZER HEATER SLEEVE INTEGRITY EVALUATION

5.1 GENERAL APPROACH

To evaluate the integrity of the heater sleeves, through-wall circumferential flaws were postulated to exist in the high stress region just below the J-groove attachment weld. This assumption is conservative for a number of reasons. No such flaws have been detected in operating plants (the Palo Verde-2 flaws were inboard of the welds). The stresses vary significantly around the circumference of the sleeves, thus the flaws would likely initiate only in a few areas of high stress. A more realistic flaw might be a part-through-wall circumferential flaw, but such a flaw would have to extend continuously around the sleeve and have a depth exceeding 80 to 90 % of wall thickness to cause a sleeve ejection. Such a flaw is extremely unlikely without the flaw breaking through to cause a leak because of the stress variation around the circumference. Axial flaws were not considered because they are not a threat to cause ejection.

A structural integrity evaluation was, therefore, conducted to determine whether the heater sleeves with hypothetical circumferential through-wall cracks will produce detectable leakage before the flaws can propagate around the circumference of the sleeve and result in ejection.

To accomplish this goal, the first step was to determine the critical flaw size which could lead to ejection of the sleeve and then to estimate the crack size as a function of time, starting with a flaw whose leakage would surely be detected.

The results of this calculation will contribute directly to decisions about the safety of the heater sleeves in the presence of cracking, and help formulate the guidelines and recommendations for future inspections.

The technical approach used here consisted of the following evaluations:

- A series of detailed stress analyses of local sleeve regions to estimate weld residual stresses and stresses due to operating stresses at various locations on pressurizer bottom heads for the two different size sleeves used in the CE fleet
- A fracture mechanics evaluation to compute the stress intensity factors for various crack lengths around the circumference of the sleeves using the stresses calculated in the first step
- Evaluation of crack growth with time to estimate the time necessary for the flaws to grow to the limiting sizes
- Computation of critical crack lengths that will result in ejection of the sleeves
- Estimation of the leakage rates as a function of the hypothetical flaw sizes.

5.2 STRESS ANALYSIS OF HEATER SLEEVES

5.2.1 STRESS ANALYSIS OBJECTIVES

The objective of these analyses was to obtain accurate stresses in each bottom head heater sleeve penetration and its immediate vicinity. This required a detailed three-dimensional elastic-plastic finite element analysis that considered all the pertinent loadings on the penetrations.

For the large heater sleeve design, three locations were considered: the outermost row of heater sleeves at 52°, and rows at 35.5° and 27.2°. For the small heater sleeve design, three locations (59.7°, 38.5°, and 23.5°) were also evaluated. Not all plants with the large diameter heater sleeves contain the outermost row discussed here.

A separate evaluation of the effects of the vicinity of the bottom support skirt on the stresses at the outermost sleeve bore hole region was also performed.

The analyses were used to provide stresses in the sleeve tubes for a subsequent evaluation of the hypothetical circumferential flaws in the sleeves.

5.2.2 FINITE ELEMENT STRESS ANALYSIS MODELS

Three-dimensional finite element models comprised of isoparametric solid type elements with mid-side nodes on each face were developed for these analyses. Detailed stresses and deflections were obtained for all the geometries analyzed. A sample plot for the large diameter heater sleeve at the 27.2° orientation model is shown in Figure 5-1. All other models for the different angles have the same nodal pattern. Taking advantage of symmetry through the vessel and penetration centerlines, only half of the penetration geometry plus the surrounding vessel were modeled. This same grid was used for all the models, with only the dimensions changed.

In the models, the lower portion of the heater sleeve, as well as the adjacent section of the pressurizer bottom head and the joining weld were modeled. The pressurizer to heater sleeve weld was simulated with two layers of elements. The heater sleeve and the weld metal were modeled as Alloy 600. The cladding was modeled as Alloy 182 weld metal whereas the pressurizer bottom head shell was modeled as low alloy steel. The analysis reported here for the outermost row utilized the highest yield strength for those plants that contain a third row of heater sleeves, which was 48.5 ksi.

The only loads used in the analysis were the weld residual stresses and the steady state operating pressure (2250 psi). External loads, such as seismic loads, have been studied and have no impact, because the heater sleeves are captured by the full thickness of the pressurizer head (approximately four inches of steel) into which the sleeves were fit during construction. The area of interest is in the penetration near the attachment weld, which is unaffected by these external loads. The stress analyses were performed by Dominion Engineering, Inc., (References 22, 23) using a three dimensional elastic plastic finite element approach, which has been discussed and compared with similar approaches in Reference 14.

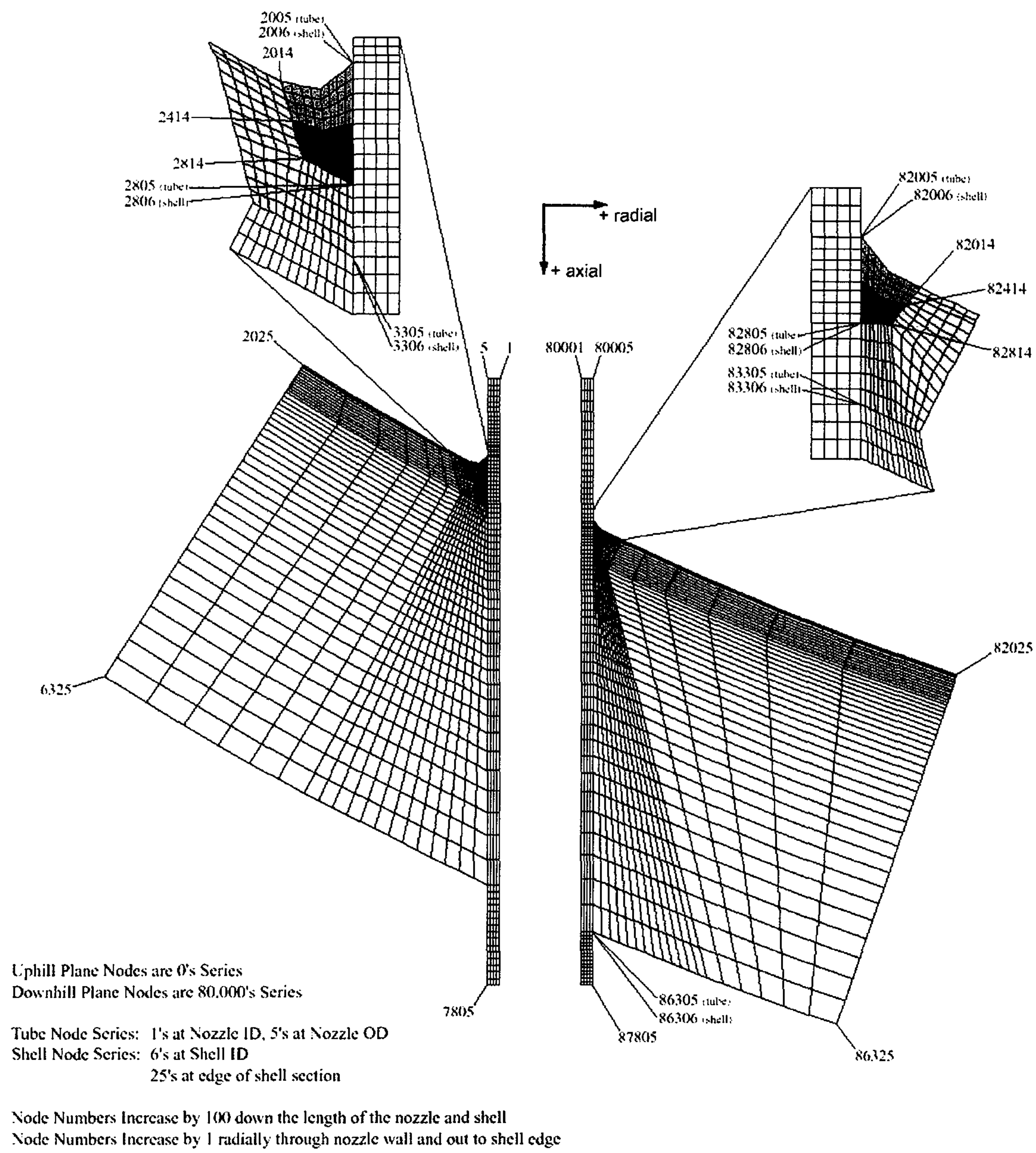

Figure 5-1: Typical Finite Element Model of Heater Sleeve, Surrounding Bottom Head Region and J-Groove Weld

5.2.3 STRESS ANALYSIS RESULTS – OUTERMOST HEATER SLEEVES

Figures 5-2a and b presents the hoop and axial stresses for the steady state condition for the outermost large diameter heater sleeve. Similar results for a small diameter heater sleeve are shown in Figures 5-3a and b.

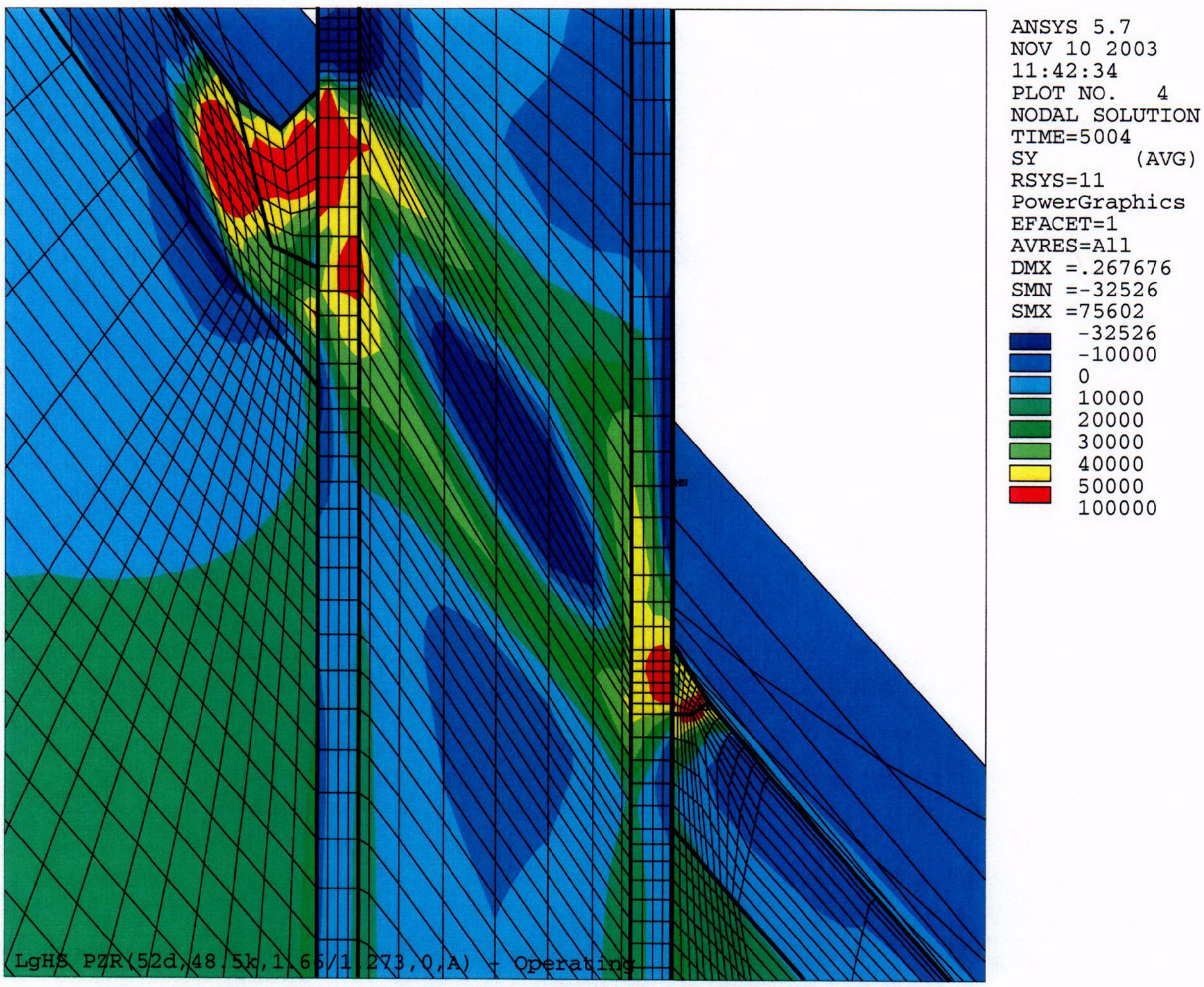

Figure 5-2a: Hoop Stresses for the Steady State Condition for the Outermost (52.0°) Large Diameter Heater Sleeve

C-01

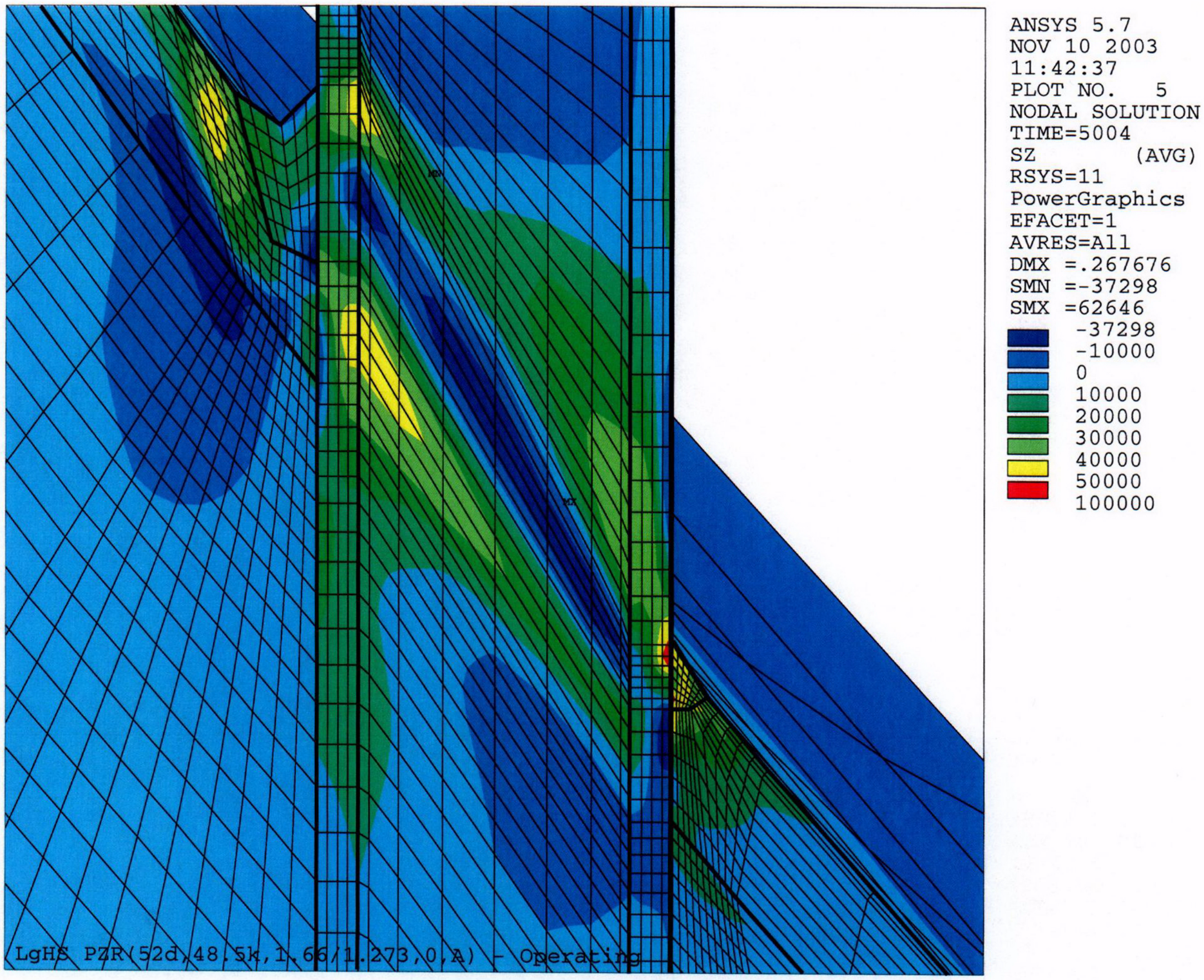

Figure 5-2b: Axial Stresses for the Steady State Condition for the Outermost (52.0°) Large Diameter Heater Sleeve

C-02

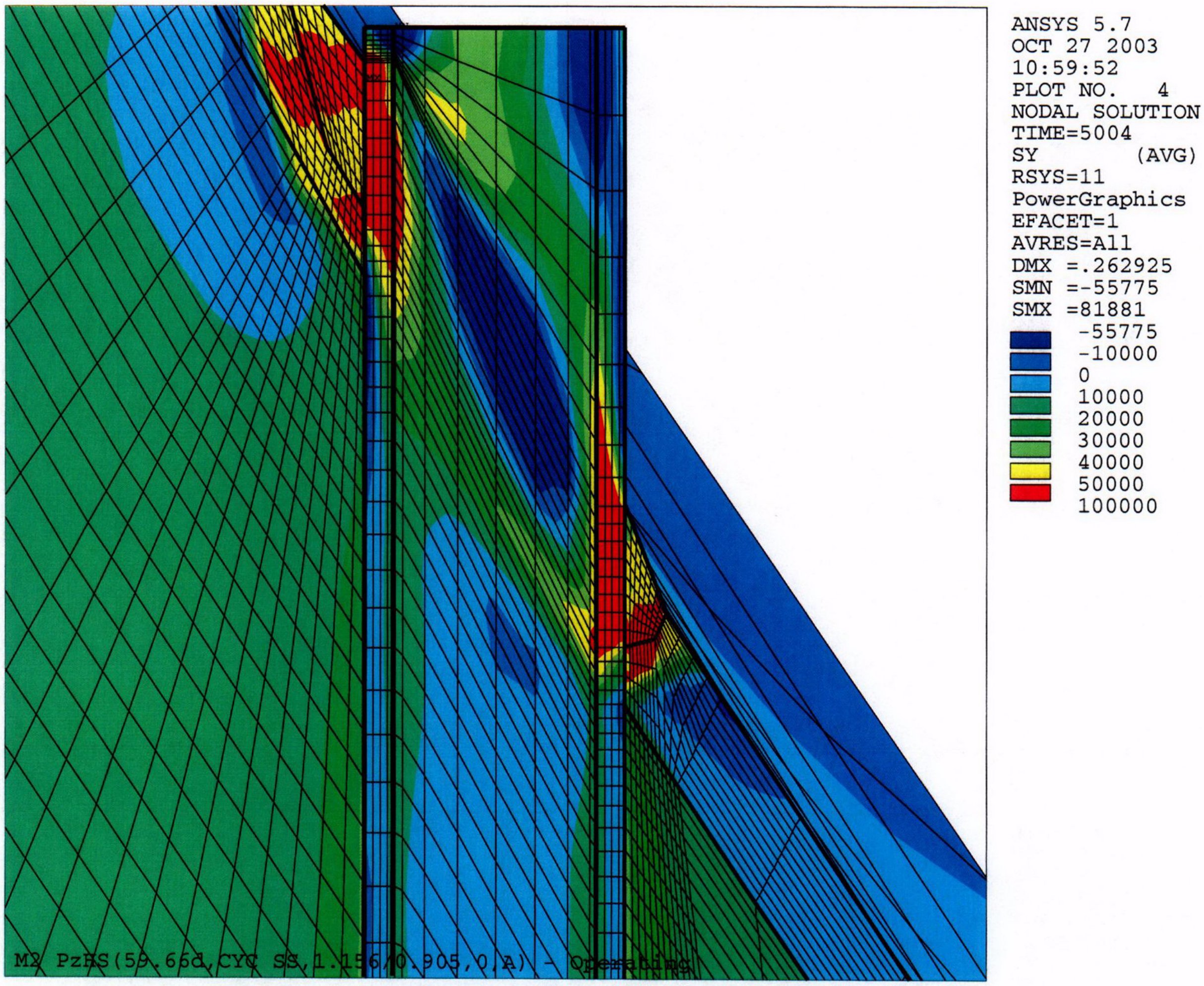

Figure 5-3a: Hoop Stresses for the Steady State Condition for the Outermost (59.7°) Small Diameter Heater Sleeve

C-03

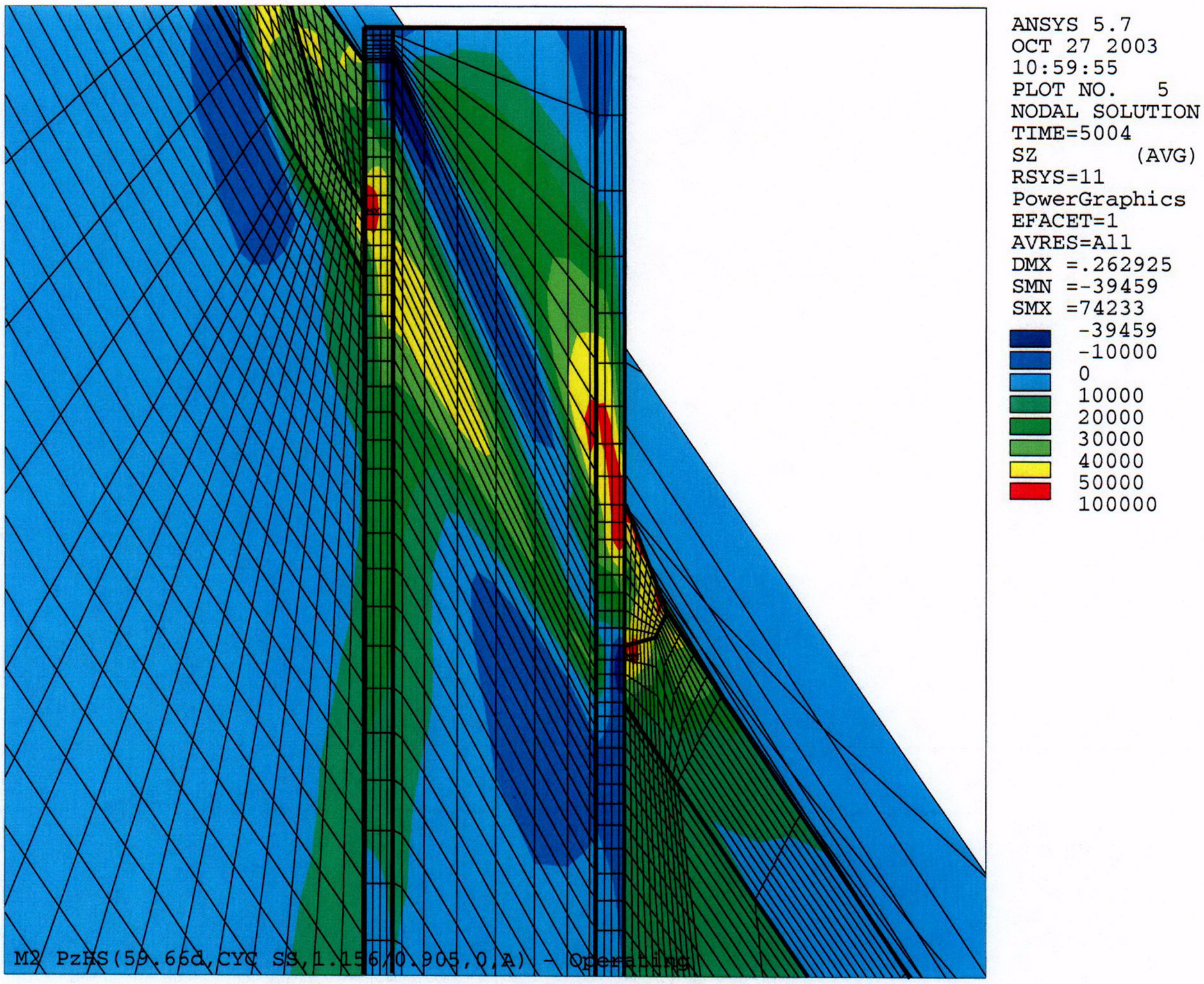

Figure 5-3b: Axial Stresses for the Steady State Condition for the Outermost (59.7°) Small Diameter Heater Sleeve

The hoop stresses for steady state operation are much greater than the axial stresses. This is consistent with the field findings, where the cracks discovered are generally oriented axially. Typically, in-service cracks will orient themselves perpendicular to the largest stress component. Also it should be noted from Figures 5-2 and 5-3 that the highest tensile hoop stresses are at the uphill side and downhill side locations rather than midway around the penetration, where they are compressive. This is consistent with the flaw locations as found in service. These steady state stresses were used to predict crack extension in the sleeves, as will be discussed further in Section 5.5.

C-04

5.2.4 STRESS ANALYSIS RESULTS – INTERMEDIATE HEATER SLEEVE LOCATIONS

The stresses in these penetrations are similar to those at the outermost locations. Figures 5-4a and b show the hoop and axial stresses at steady state for the large diameter sleeve at the 35.5° location. Figures 5-5a and b show the same results for the 38.5° small heater sleeve. As with the outermost sleeves, the hoop stresses for steady state operation are greater than the axial stresses.

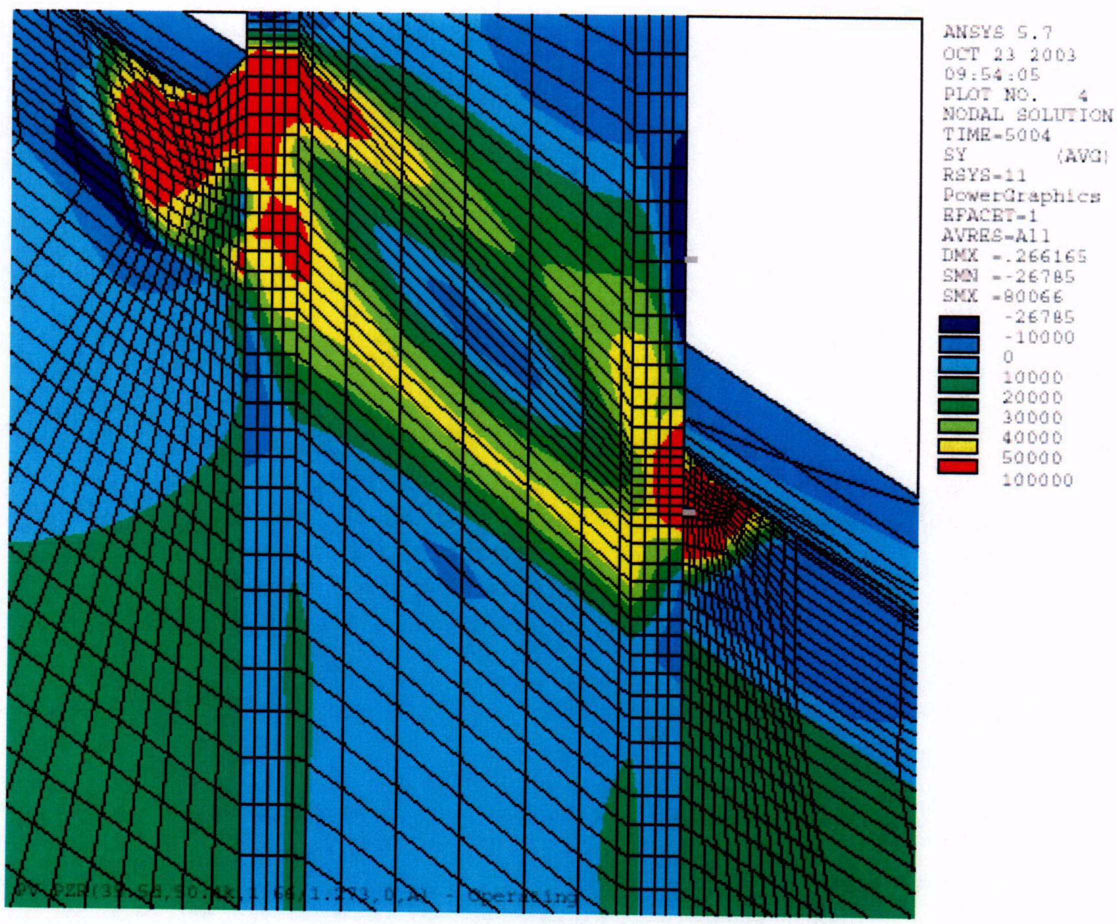

Figure 5-4a: Hoop Stresses for the Steady State Condition for the 35.5° Penetration for the Large Diameter Heater Sleeve

C-05

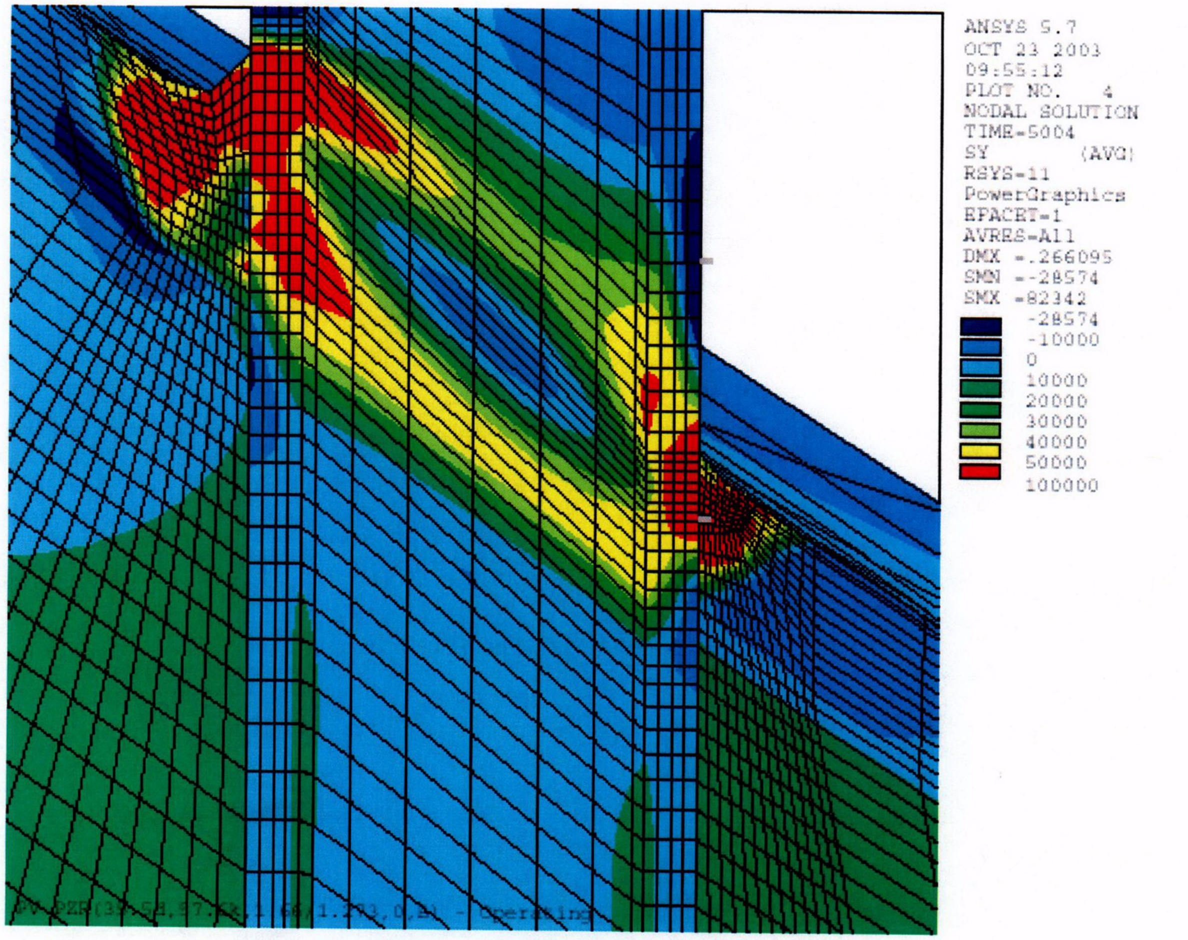

Figure 5-4b: Axial Stresses for the Steady State Condition for the 35.5° Penetration for the Large Diameter Heater Sleeve

C-06

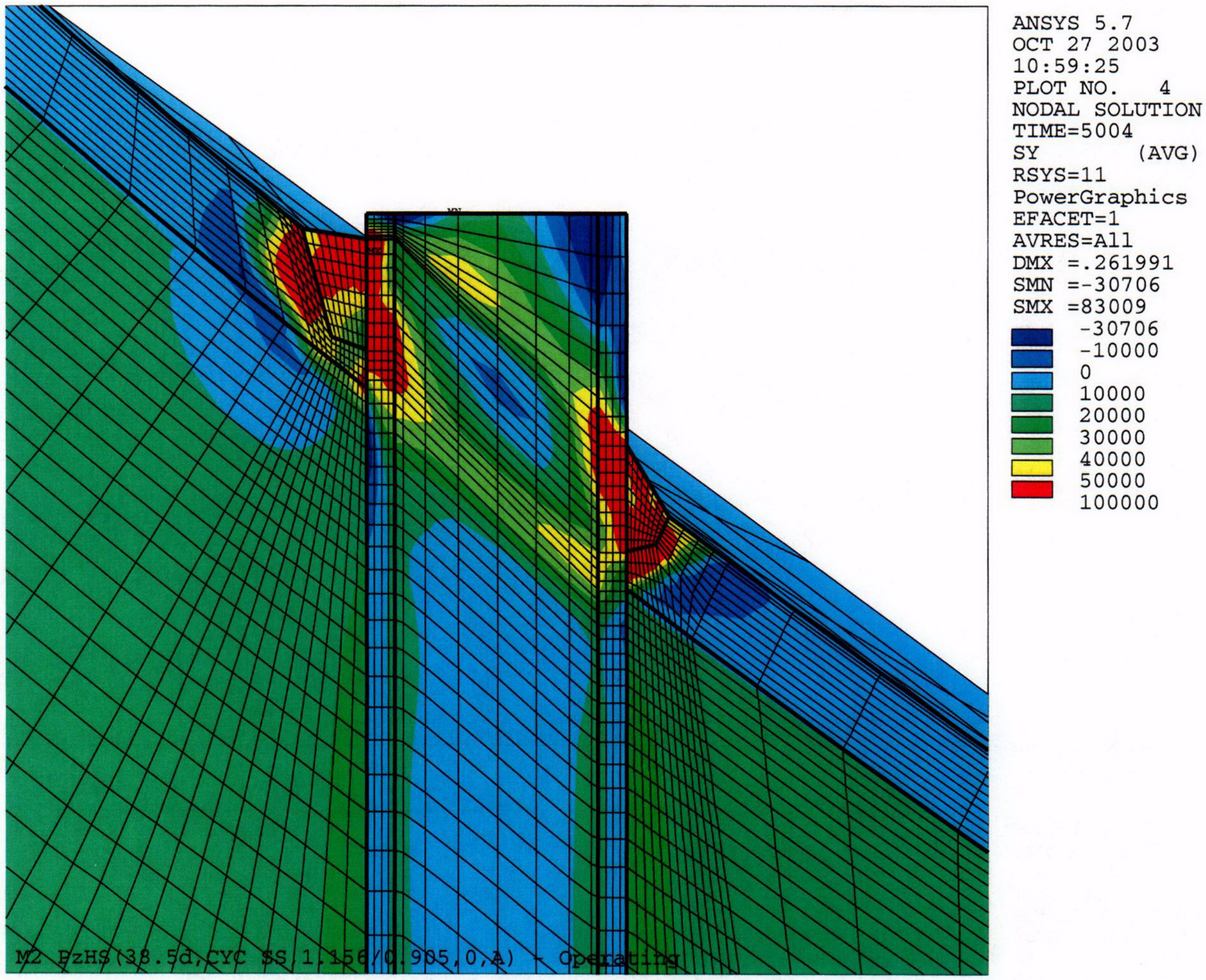

Figure 5-5a: Hoop Stresses for the Steady State Condition for the 38.5° Penetration for the Small Diameter Heater Sleeve

C-07

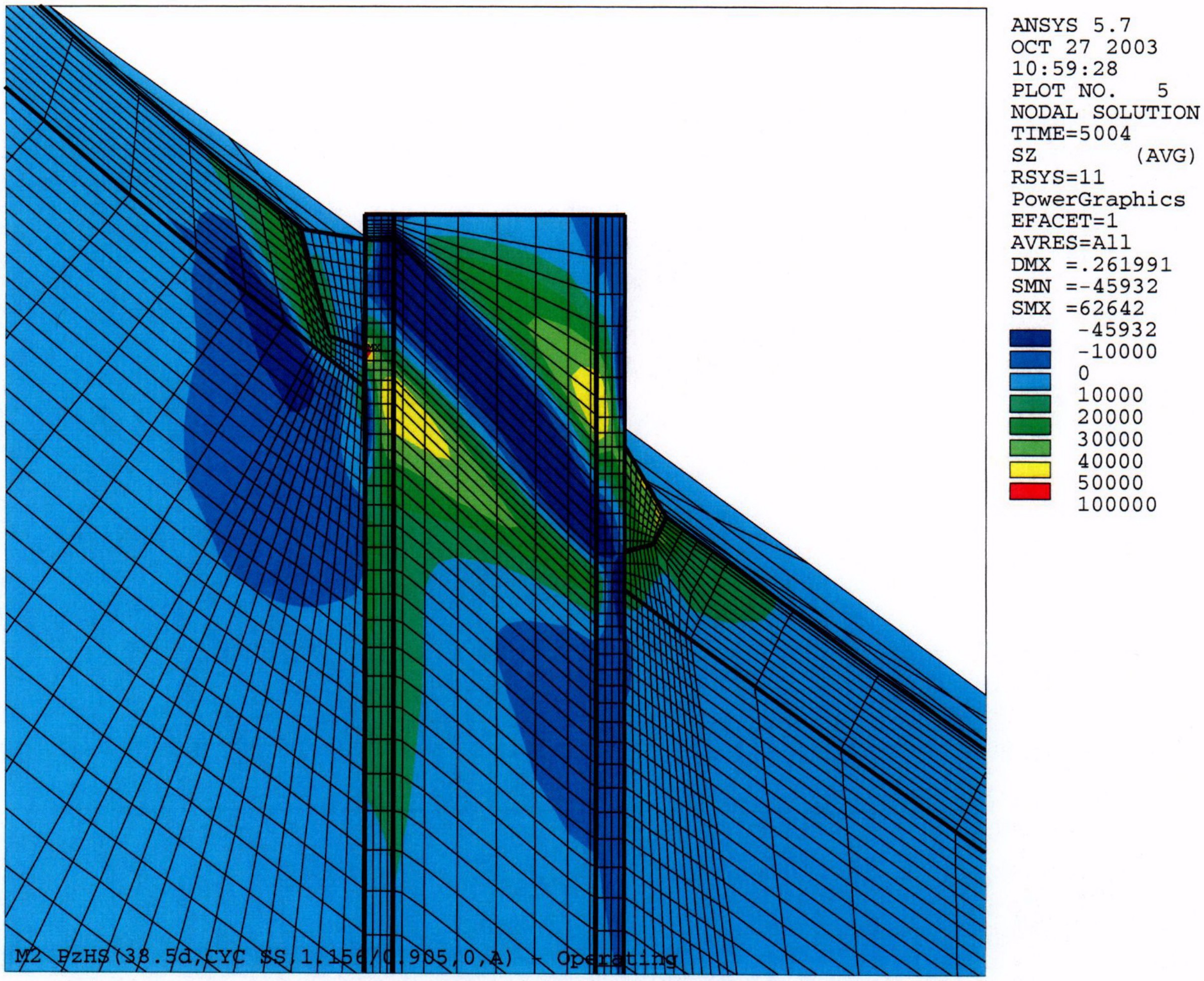

Figure 5-5b: Axial Stresses for the Steady State Condition for the 38.5° Penetration for the Small Diameter Heater Sleeve

5.2.5 STRESS ANALYSIS RESULTS – HEATER SLEEVES CLOSEST TO THE PRESSURIZER CENTERLINE

The stresses in these penetrations are similar to those in the intermediate and outermost penetrations. Figures 5-6a and b show the hoop and axial stresses at steady state for the 27.2° location in the large diameter heater sleeves. Figures 5-7a and b show the same results for the 23.5° small diameter heater sleeve penetration. As with the other sleeves, the hoop stresses for steady state operation are greater than the axial stresses.

C-06

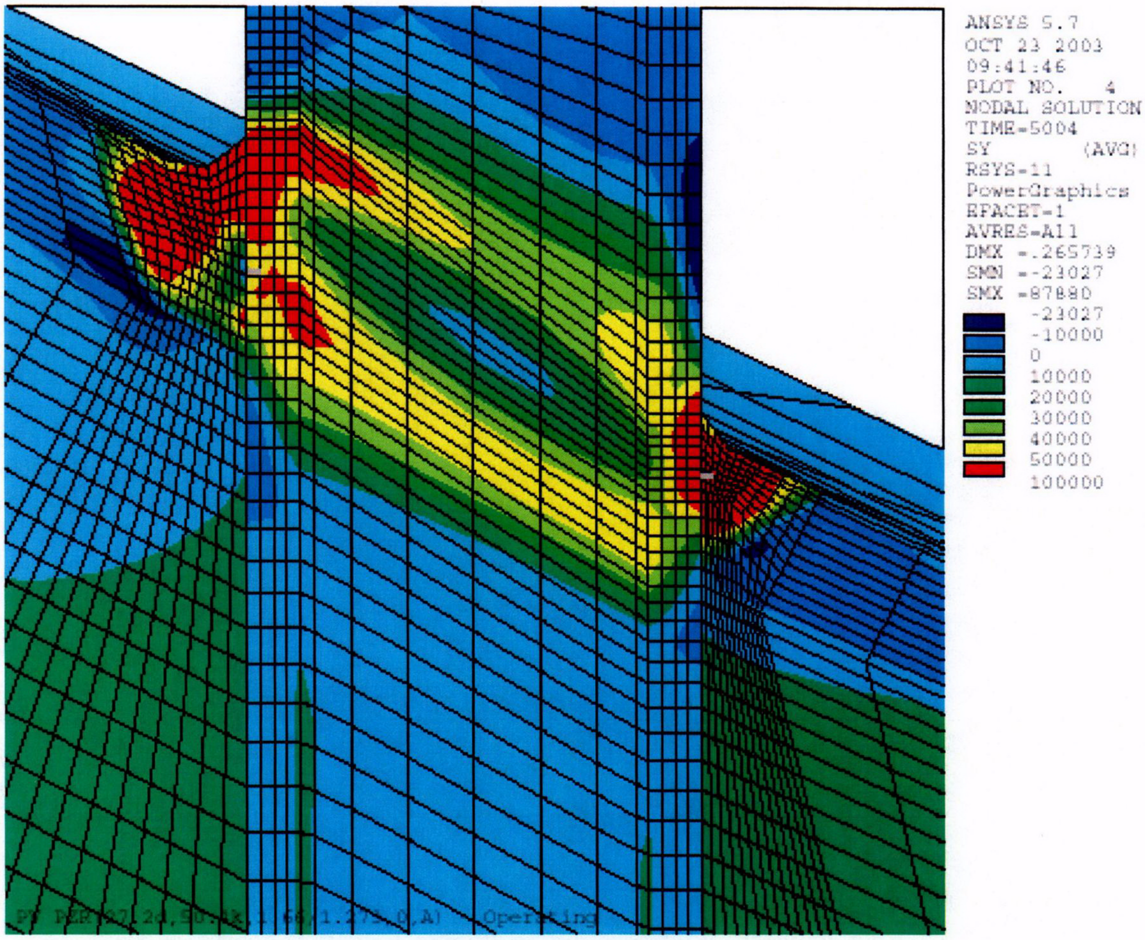

Figure 5-6a: Hoop Stresses for the Steady State Condition for the 27.2° Penetration for the Large Diameter Heater Sleeve

C-09

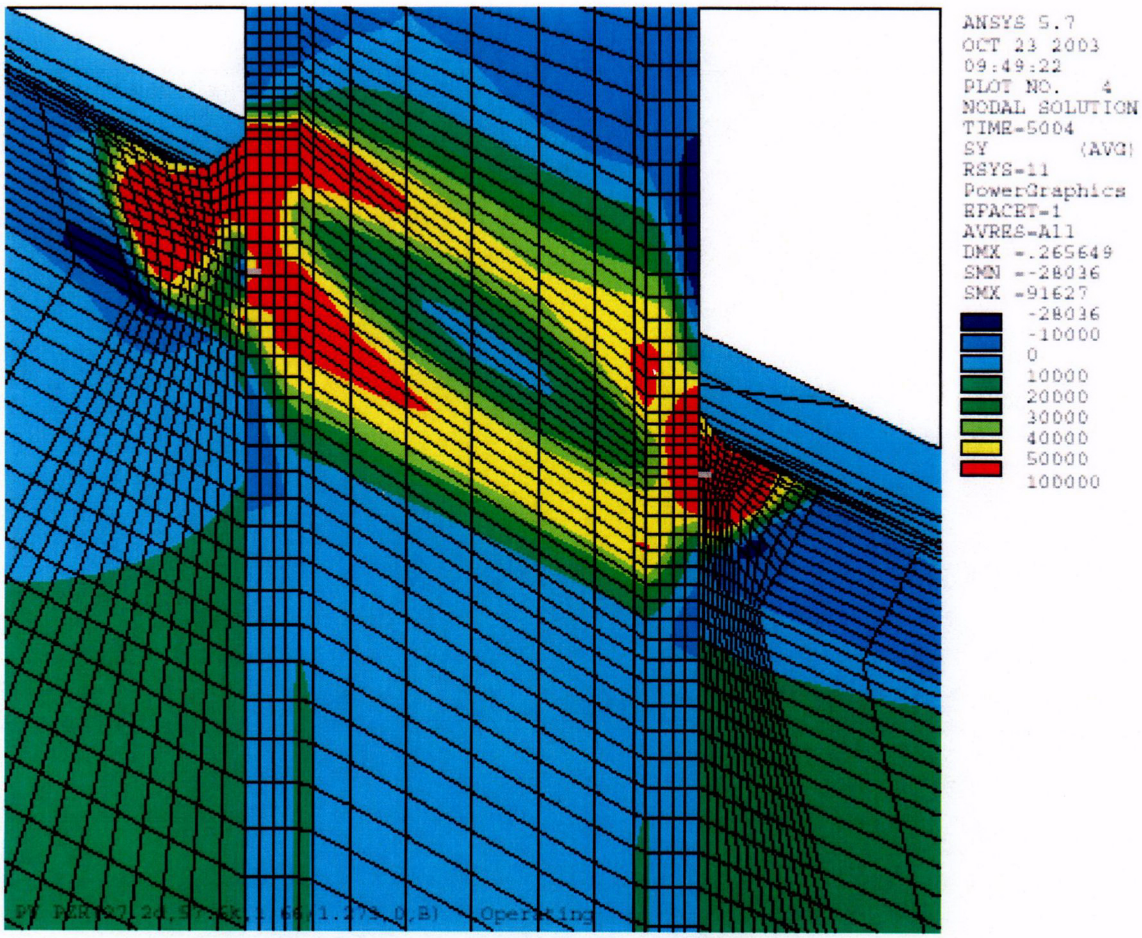

Figure 5-6b: Axial Stresses for the Steady State Condition for the 27.2° Penetration for the Large Diameter Heater Sleeve

C-10

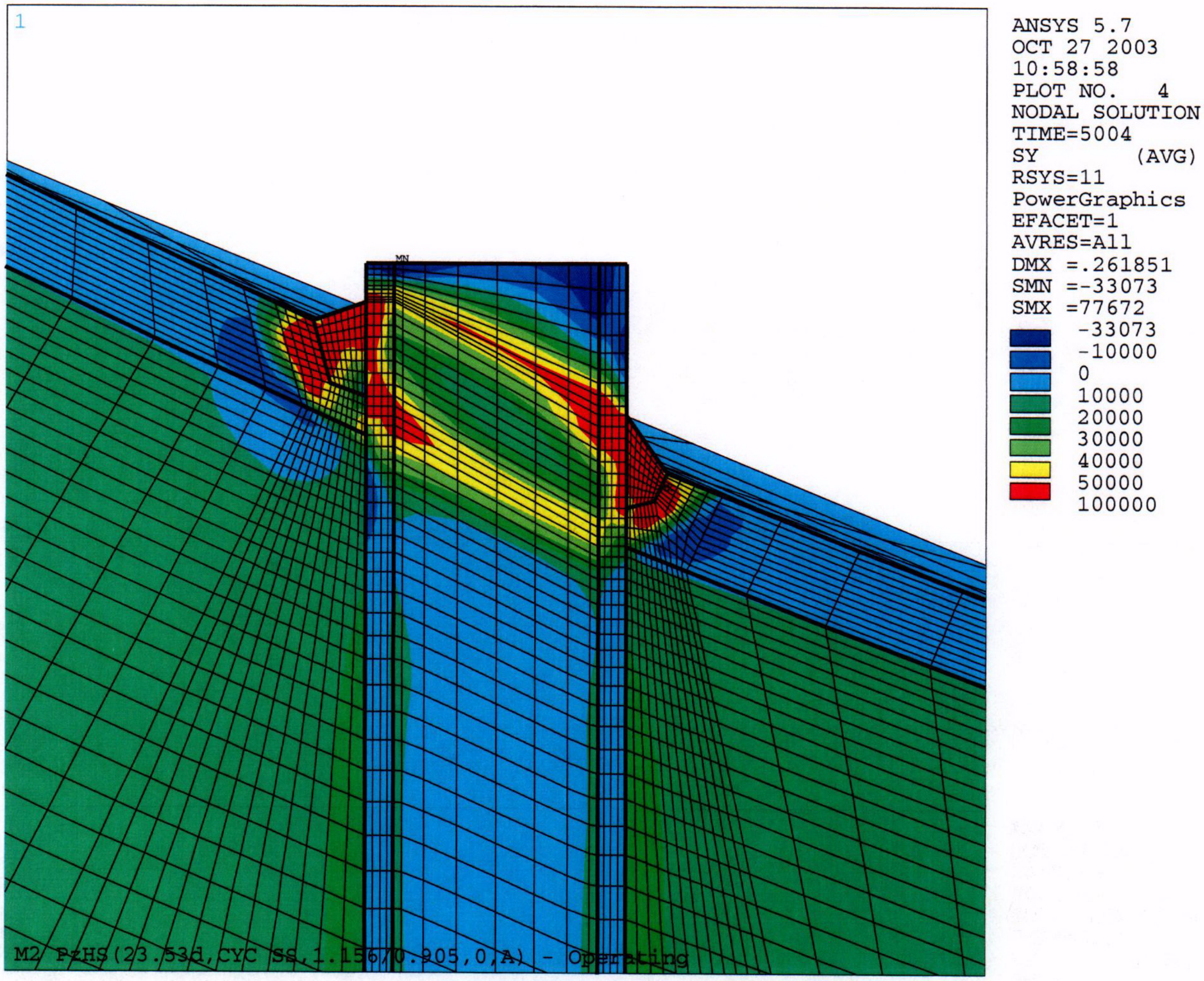

Figure 5-7a: Hoop Stresses for the Steady State Condition for the 23.5° Penetration for the Small Diameter Heater Sleeve

C-11