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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

REGARDING CRACKING OF INCONEL ALLOY 600 COMPONENTS

CONSUMERS POWER COMPANY

PALISADES NUCLEAR PLANT

DOCKET 50-255

1.0 INTRODUCTION

1.1 Purpose

The purpose of this evaluation is to assess the licensee's analyses and repairs of cracks in the power-operated relief valve (PORV) line and in two instrument nozzles.

1.2 Background

On September 16, 1993, Palisades was heating up after a refueling outage. The primary coolant system (PCS) was in a hot shutdown condition (532 degrees F and 2060 psia) when plant personnel identified an increase in the containment sump level. A few minutes later, an auxiliary operator conducting rounds in the containment reported a steam leak in the PORV line near the pressurizer nozzle. The plant was returned to cold shutdown. The unisolable leak originated from a circumferential crack about 3 inches in length (about 30% of the circumference) in the weld joining the Inconel 600 safe-end to stainless steel pipe. Review of containment sump level information during the event indicated the steam leak was about 0.2 gpm equivalent water.

The licensee conducted a root-cause evaluation that included reviews of design records, heat treatments, and thermal cycles associated with the subject pipings. The PORV safe-end to pipe weld (PCS-4-PRS-1P1-1A) had been inspected several times. In October 1990, a scheduled ultrasonic test (UT), limited by the configuration of the weld, and liquid penetrant test (PT) were performed as part of the inservice inspection (ISI) program. As part of its routine ISI program the licensee radiographed the PORV safe-end weld on June 19, 1993, and found an indication about 2½ inches long. It reviewed the original archival radiographs for comparison. The licensee then ground the weld crown in the region of the flaw indication and performed another limited UT from the stainless steel pipe side of the weld. The licensee interpreted the combined radiographic and ultrasonic results as an embedded slag inclusion with no significant depth on the Inconel side of the weld. The NRC Mobile NDE Laboratory was on site during June 15-25, 1993, and conducted independent radiography and UT of this weld. The UT procedures used were qualified to detect intergranular stress-corrosion cracking (IGSCC). The NRC characterized the condition as a thermal fatigue crack with dimensions less than one-third wall thickness by about 17/8 inches long. To address the difference in the interpretations, the licensee performed a fracture mechanics evaluation and concluded that the flaw indication detected by the NRC staff would not grow. However, during startup on September 16, 1993, the weld leaked in the region where the weld crown was removed for nondestructive examination (NDE).

The licensee then developed an evaluation and repair plan that included metallography, additional examinations, and an engineering analysis. The NRC staff conducted onsite inspections to observe selected NDE and repair activities. The licensee and NRC staff held periodic telephone conference calls and the staff prepared two requests for additional information both dated October 8, 1993 (letters, Hsia to Slade).

After repairing the PORV line, the licensee detected a leak on top of the pressurizer in an instrument nozzle in the vapor space on October 9, 1993. Further visual examinations revealed another leak in an instrument nozzle in the liquid space. The licensee developed a second repair plan to address the new cracks.

2.0 PORV, SAFETY-RELIEF VALVES (SRV), SPRAY, AND SURGE LINES

2.1 Licensee's Activities

2.1.1 PORV Line

2.1.1.1 Failure Analysis and Root Cause Evaluation

The licensee removed a section of the safe-end with the crack and a part of the stainless steel pipe for metallurgical examination. The section was then divided. One part was evaluated by the metallurgical staff of the Consumers Power Company (CPCo) and ABB-Combustion Engineering and the other part was given to the NRC for an independent evaluation.

The following are the results of the licensee's metallurgical examination of the Inconel 600 safe-end weld crack:

(1) The failure was attributed to primary water stress corrosion cracking (PWSCC). (PWSCC is IGSCC that occurs in primary water.) The cracking initiated at the inner diameter (ID) of the pipe in the heat-affected zone (HAZ) of the weld. The cracking mode was intergranular and followed a path through the Inconel safe-end HAZ until failure occurred at the outside surface of the pipe.

(2) The cracks ran perpendicular to the inner surface of the pipe wall, without significant propagation in the axial or azimuthal direction. The crack location on the outside surface consisted of six discontinuous cracks each about ½-inch long. The total crack length on the outside surface was about 3 inches. The cracking remained almost entirely in the Inconel 600 alloy base metal.

(3) An original weld root repair, apparently made during construction from the inside of the pipe, was found in the segment of the weld

next to the crack initiation point in the safe-end HAZ. There was evidence of grinding on the root of the weld. A mismatch (1/16 inch) existed between the ID of the safe-end and the ID of the PORV header line.

(4) The presence of a black oxide on the fracture surfaces indicates that the crack had existed for some time and had not developed during the current refueling outage. Numerous areas of shallow intergranular attack were present on the inner wall of the HAZ in a region away from the crack.

The licensee determined that PWSCC was the cause of failure, based on the three factors of susceptible material, stress, and environment:

(1) The safe-end was made from a batch of material with a high yield stress (77.5 ksi) and metallurgical condition that made it prone to PWSCC.

(2) The safe-end was exposed to an environment known to cause PWSCC (high temperature steam).

(3) Stresses from operation were relatively low. However, high stresses can result, even with low piping loads, from the original field welding process, weld root repair and grinding, the geometrical mismatch between the stainless pipe and Inconel 600 safe-end, and the mismatch in the thermal expansion rates between the carbon steel nozzle and the pipe materials. The combined residual and operating stresses can result in crack initiation and propagation at the HAZ of the affected weld.

2.1.1.2 Repair

The licensee removed the entire cracked safe-end to pipe weld along with about 1½ feet of stainless pipe downstream of the crack. It machined a weld preparation on the remaining safe-end material and performed a liquid penetrant test on the machined surfaces and the original safe-end ID. Initial examinations of the ID of the original safe-end to pipe weld indicated that a flush root ID on the repair weld would be desirable. The licensee decided to fabricate the replacement stainless piping in two pieces--one 3 inches long and the other about 1 foot 3 inches long.

First, the 3-inch spool piece was welded to the safe-end with Inconel filler metal. This piece allowed access to the root of the safe-end to pipe dissimilar weld. The welding processes used were gas tungsten arc (GTAW) and shielded metal arc welding. After welding, the root between the safe-end and 3-inch spool piece was ground flush followed by flapper wheel grinding of the ID in the root and safe-end counterbore and subsequently radiographed. After welding to about 5/16 to 7/16 inch by GTAW, the remainder of the weld was completed by the shielded metal arc process. The second spool piece was welded in place by an automated GTAW process with stainless steel filler metal.

2.1.2 The Safety-Relief Valve (SRV), Spray and Surge Lines

The surge, SRV, and spray lines are all susceptible to PWSCC. These lines are of Inconel 600, a material known to be susceptible in primary water and steam at elevated temperatures. Main sources of stress are the residual stresses from welding. An internal report by the Combustion Engineering Owners Group (CEOG) stated that PWSCC would occur first in the pressurizer because of the high temperatures there.

Surge Line

The surge line nozzle safe-end was made from a different heat of Inconel 600 than that used for the cracked PORV line safe-end. Its yield strength was lower, 51.2 ksi., but is still considered susceptible to PWSCC. The licensee states that this weld is exposed to high temperatures, but it is less likely to crack from PWSCC than the PORV nozzle because the weld is exposed to water rather than steam. Most observed PWSCC in pressurizers has been in the vapor space. The licensee cites a study that shows the relationship between yield strength and the time to PWSCC in Inconel 600 partial-penetration welds. Based on this study, the licensee concluded that the projected lifetime for the surge line nozzle will be about 4 times that of the PORV nozzle safe-end weld.

The surge line is connected to the PCS piping by a nozzle with an Inconel 600 safe-end from the same heat as in the surge line nozzle safe-end on the pressurizer. The yield strength effects also are applicable to the PCS pipe weld. Moreover, the temperature experienced by this nozzle will be about hot leg temperature (600 degrees F). The licensee concluded that this reduced temperature will significantly increase the lifetime of this nozzle safe-end relative to the pressurizer nozzle safe-end (which operates at about 640 degrees F.)

SRV Lines

The nozzles for the three SRVs also are made from the same Inconel high strength heat used for the cracked PORV line safe-end. They are subject to high temperatures in the pressurizer vapor space. These nozzles have been inspected this outage by ID PT, radiography, and IGSCC sensitive UT from the pipe side; no indications were observed. The nozzles were stress relieved in the shop during fabrication, and this treatment will reduce weld-induced residual stresses. The licensee concluded that the absence of defects indicates these nozzles can remain in service for another cycle of operation.

Spray Line

The spray line was fabricated from the same high strength Inconel heat as the cracked PORV line safe-end. The coolant flowing through the spray line comes from the cold leg of the PCS and is at a temperature of about 540 degrees F. Laboratory studies of PWSCC in Inconel 600 show that a decrease of about 20 degrees F in temperature will double the lifetime of an application assuming all other conditions are unchanged. The licensee, applying this assumed temperature dependency to the spray line predicted a lifetime of about 30 times that of the cracked PORV safe-end.

Safe-End to Nozzle Welds

After the shop welds joining the safe-ends to the PORV, safety valve, spray line, and surge line nozzles were completed, the nozzles were stress relieved at 1150 degrees F. Thus, the in-board welds of the safe-ends were all stress relieved and have reduced residual stresses. This heat treatment will reduce the probability of PWSCC in these locations.

2.1.3 NDE Activities

The licensee performed NDE on a sample of Inconel 600 butt welds it ranked the most susceptible to circumferential cracking. These were the PORV, spray, safety-relief, and surge lines. The results are summarized as follows:

(1) The shop weld of the carbon steel nozzle to safe-end on the PORV line was inspected by radiography, ID PT, and outside diamater (OD) PT.

(2) The licensee used a segment of the safe-end of the failed weld in the repair. The replacement weld was examined by radiography and ID/OD PT.

(3) The shop weld of the spray nozzle to safe-end and the field weld of the safe-end to pipe were both examined by radiography and OD PT.

(4) The shop welds on the flanges of the three safety valves were examined by UT, radiography, and ID and OD PT.

(5) The shop and field welds on the surge line were inspected by UT and OD PT.

2.1.4 Flaw Growth Evaluations

Crack growth calculations were used to estimate the time during which an assumed crack could propagate in susceptible butt welds. Calculations were based on the methodology used to estimate lifetimes of control rod drive mechanism (CRDM) penetrations with partial penetration welds in plants designed by Combustion Engineering (CE). Yield strength levels of stress were assumed. Various aspect ratios and yield strengths were used as input. For the materials used at Palisades the shortest time for a 0.003-inch crack to propagate through wall was 20 months in the PORV line.

The minimum size defect that would propagate through wall in a 15-month operating cycle was calculated to be 0.039-inch deep x 0.234-inch long for a material with 77 ksi yield strength, at a 77 ksi stress level, and with a crack aspect ratio of 6:1.

2.1.5 Licensee Conclusions about Continued Operation

The licensee's evaluation concluded:

(1) that the projected lifetime for the surge line nozzle will be about 4 times that of the PORV nozzle safe-end weld.

(2) that the absence of defects in the SRV welds indicates that these lines can remain in service for another cycle of operation.

(3) that the predicted lifetime for the spray line was about 30 times that of the cracked PORV safe-end.

The licensee further concluded that should any leakage from PWSCC occur, the plant has monitoring systems capable of detecting it, including containment humidity and sump level monitors. The licensee's response to the leak in the pressurizer relief valve safe-end at hot shutdown conditions shows that leaks can be detected and the plant can be safely shut down. The leakage was readily recognized on containment sump level instrumentation within about an hour after the leak began.

The licensee has proposed the following corrective actions:

(1) The design of the pressurizer relief valve nozzle safe-end and PORV line will be reviewed and appropriate modifications will be made during the next refueling outage to ensure a suitable lifetime for the pressurizer relief valve nozzle safe-end. This review will address the material properties of the safe-end and stresses imposed on the safe-end by the PORV line. The review also will be coordinated with the safety-related piping reverification project review of the PORV line.

(2) A comprehensive program to deal with Inconel 600 issues at Palisades will be developed. The program will guide future inspections and replacements of Inconel 600 components in the PCS.

(3) NDE techniques for detecting PWSCC will be further evaluated and qualified. This effort will include:

- Evaluating the June 1993 NDE results and implementing lessons learned.

- Reviewing past (second interval) ISI results to ensure the effectiveness of radiography interpretation. A sample of past radiography performed on other Class 1 welds will be reviewed by an independent Level III examiner.

- Developing a representative mockup and qualifying UT techniques to detect PWSCC.

2.2 NRC Evaluation

The NRC reviewed the submittals docketed by the licensee in letters dated October 7, 15, and 20, 1993, as described in previous sections of this report. The staff review included information from an inspection by the NRC Mobile NDE Laboratory in June 1993 and from several inspections performed by Region III staff in September and October 1993 and from a site visit by the Office of Nuclear Reactor Regulation personnel in September 1993. Department of Energy contractors from Idaho National Engineering Laboratories (INEL) and Brookhaven National Laboratories (BNL) also provided technical assistance. Finally, the review included information from a public meeting held with the licensee on October 12, 1993.

2.2.1 The PORV, SRV, Spray and Surge Lines

Considering the materials, stresses, and environment, the staff agrees that the crack in the PORV line was caused by PWSCC. This is the first circumferentially oriented PWSCC in an Inconel alloy 600 butt weld in a pressurized water reactor (PWR). All previous PWSCC in Inconel 600 PWR components (i.e., control rod drive penetrations, instrument lines, and heater sleeves) have occurred in partial penetration welds, and cracks have been axial rather than circumferential.

Metallurgical Examinations

Metallurgical examinations of the cracked PORV safe-end were performed by the licensee, CE, and BNL.

The NRC staff agrees with the licensee's metallurgical findings stated in Section 2.0 of this report. The BNL report included some additional observations: metallography and visual observations indicated the original field weld was poor; visual observations of the inside surface showed the repair and a mismatch in fit; and the weld repair may have been performed to correct a lack of fusion. Metallography by both BNL and the licensee showed areas that lacked fusion. A rather large area of lack of fusion above the weld repair was estimated to be about ¾- to 1-inch long by 0.1-inch deep along the fusion line on the stainless steel pipe side of the weld. This observation is important because the licensee's standard radiography did not detect this defect. BNL also detected microfissuring in the weld metal, another indication of a problem weld, and extremely large grains, indicating perhaps an overheated forging.

The BNL report notes that the microfissuring, areas that lacked fusion, weld repairs, and bad fit up indicate that the joint may have been subject to substantial rework. This amount of rework and repair indicates that relatively high tensile stresses were present (up to and possibly over yield).

The licensee does not have data on the actual properties of the Inconel 600 materials, the parameters associated with the original welding process, repairs, and heat treatments during fabrication. It cannot determine whether the crack was present during construction because of the poor quality of the construction radiographs. It also did not try to correlate the location of the crack with that of the repair weld. This correlation would have been desirable as part of the failure analysis and as a check on the NDE findings.

2.2.2 Effectiveness of NDE

The NRC staff evaluated the NDE performed by the licensee on the Inconel 600 butt welds between June 1993 and the completion of the repair of the PORV line. Most of the work was performed using existing plant examination procedures, available instrumentation, and corporate NDE personnel. Contractor personnel were used to perform specialized examinations.

Radiography and Ultrasonic Testing of a PORV Safe-end Weld

In June 1993 the pressurizer PORV safe-end weld (PCS-4-PRS-1P1-1A) had a crown and geometric discontinuity that limited UT. The licensee performed radiography to complete an ASME Section XI volumetric examination without limitations. The radiographic inspection showed an indication that the licensee reported to be a 2.5-inch elongated slag inclusion. The weld crown was then ground off from about one-half the circumference to permit the licensee to disposition the indication detected by the Code examination (radiography).

During a site visit, an NRC contractor's review of the radiographs taken by the licensee in June 1993 showed a narrow irregular linear indication about 2.5 inches long with sharp tips. Several areas along the length of the linear indication showed evidence of branching. The INEL Level III radiographer concluded that an indication of this size and shape is a classic crack indication and should have been dispositioned as such. The licensee also had an independent Level III contractor review the same radiographs and he reached a similar conclusion.

The NRC staff determined that although the crack was visible in the licensee's June 1993 radiography, the licensee interpreted the indication as embedded slag. The licensee made this interpretation despite having an internal report dated May 22, 1991, that identified this weld as one of the most susceptible to PWSCC.

Radiography of the Repair and of Other Butt Welds

During the repair and additional examinations of susceptible butt welds, the licensee selected its standard radiography as the primary volumetric method for detecting potential PWSCC. The reasons were that access to the ID surface of the pressurizer spray line was not feasible and this weld had an OD geometry that prevented effective UT. However, radiographic test (RT) from the weld centerline is not normally regarded as effective for reliable detection of tight cracks, like PWSCC, that could propagate along the weld fusion line. This conclusion is supported by the fact that the lack of fusion was not detected in the PORV safe-end by similar RT techniques.

NDE of the Safety-Relief Flanges

The licensee's May 22, 1991, engineering evaluation also identified these nozzles as high risk to develop PWSCC. The relief valves were removed from locations RV-1039 and RV-1040 to provide access for a PT on the inside surface. An initial PT was performed about 8 inches down the bore of the 6-inch nominal pipe size flange fitting. The ID surface was machined smooth as part of the shop fabrication process. No surface preparation or cleaning was performed before the PT. Mirrors and flashlights were used for the examination. The bore of the pipe was coated with an apparent black oxide film. A low confidence level existed that a significant crack would be detected.

After discussions with the NRC staff, the licensee repeated the PT. Mockups with surface connected flaws were used to develop the techniques and understand the detection capabilities. The surface film was cleaned from the bore of the pipe. Fiber optics instrumentation and supplemental lighting were used during the re-examination. The licensee reported that the confidence level increased significantly for the detection of inservice cracking on all three safety-relief nozzle welds.

The licensee contracted CE and Virginia Corporation to perform independent UT with examiners certified through Electric Power Research Institute to detect and size IGSCC. The OD of the butt weld limits UT examination to scanning from the pipe side. The two contractor UT examiners, as well as the CPCo Level III examiner, used IGSCC examination procedures to perform a one-side access examination on the three safety-relief butt welds. No recordable indications were detected.

Manual examination instrumentation and recording was used for all UT associated with the PORV crack evaluation and repair. Mockups of the specific configurations, with appropriate flaws, are necessary to define the confidence level that can be associated with detection and sizing with IGSCC in the Palisades pressurizer nozzle attachments.

2.2.3 Crack Growth Evaluations

The staff has the following concerns about the licensee's engineering analysis that determined the predicted life of the existing welds:

(1) Records of weld repairs, stress relief heat treatment, and cold work of ID surfaces of welds are not available. This information could affect the PWSCC susceptibility and crack growth rate.

(2) The licensee calculated that cracks can grow through wall in 20 months. This period is relatively short when compared with the Palisades operating cycle of 15 months.

(3) The crack growth calculations may not be conservative because the magnitude and distribution of the residual stresses are not known.

(4) The licensee ranks susceptibility to PWSCC according to the service temperature in specific locations in the pressurizer. In an internal report dated May 22, 1991, the nozzles for the temperature element are rated moderately susceptible. However, since the nozzle for the temperature element cracked, the validity of the licensee's susceptibility ratings, which were used to determine the longer lifetimes for the spray and surge lines, (also rated moderately susceptible) is questionable.

(5) The flaw sizes (3 mils and 39 mils) assumed in the crack growth calculations have not been shown to be detectable by the NDE techniques used. The licensee's assertion regarding the flaw detectability is not based on demonstrations.

(6) The licensee cites a study relating yield strengths to time to failure for partial penetrations to conclude that the surge line nozzle will have a projected life of 4 times that of the PORV nozzle. Although the surge line nozzle is of a lower strength material (51.2 ksi), the CEOG has shown that material with a yield strength as low as 36 ksi has failed. A CEOG status report on PWSCC of Inconel 600 material (Attachment 6 to the licensee Engineering Analysis EA-SC-93-087-01 included in the licensee letter of October 27, 1993) states that the relationship between yield strength and PWSCC is unknown for hot forged products (nozzles).

(7) The licensee concludes that the surge line nozzle safe-end weld is less susceptible to PWSCC than the PORV nozzle because the safe-end weld is exposed to water and not steam, the environment where most PWSCC has occurred. However, a temperature element nozzle exposed to water did crack.

2.2.4 Overall Conclusions

(1) The licensee needs to demonstrate the performance of the NDE. The NDE performed does not ensure detection of the initial flaw size that could grow through wall.

(2) The licensee needs to perform a failure modes analysis on all affected lines to provide additional assurance of safety until it completes the NDE performance demonstration or makes modifications to eliminate the susceptibility to PWSCC.

(3) The repair welds in the PORV line and instrument nozzles are acceptable for the operation of one fuel cycle. This conclusion is based on the repair, the NDE performed, the existing leak rate monitoring requirements and capabilities, the licensee's evaluations, the licensee's failure modes analysis submitted on November 30, 1993, and on the fact that a failure of one of the subject lines is bounded by the small break loss-of-coolant accident (LOCA) described in the Final Safety Analysis Report.

3.0 INSTRUMENT PENETRATIONS

3.1 Licensee's Activities

On October 9, 1993, while installing insulation on the upper head of the pressurizer that had been removed to repair the leaking PORV line, personnel noticed water leaking from the base of the TE-0101 temperature element nozzle. At that time the pressurizer was filled solid with water and the PCS was cold and at 250 psia.

The nozzle is connected to the upper head by a partial penetration weld at the ID. The licensee determined that the leakage occurred from an annular space between the Inconel 600 nozzle and the carbon steel head. As a solution, the licensee decided to modify the nozzle design by welding a pad to the exterior surface of the pressurizer to re-establish the structural support and pressure boundary.

On October 12, 1993, a visual inspection of the other pressurizer temperature nozzle on the lower shell, TE-0102, showed that it also was leaking. The licensee decided to modify that nozzle with an external weld pad.

3.1.1 Root Cause Evaluations

The licensee cites industry experience for ascribing the cause of the leaking to PWSCC. To date, the nuclear industry has experienced leakage from similarly designed nozzles, especially in high-temperature environments like that of the pressurizer. The CEOG had studied this problem and determined that PWSCC of Inconel 600 was the cause of previous leaks. The licensee determined that the pressurizer temperature nozzles were moderately susceptible to PWSCC. (As a result, the licensee inspects these nozzles visually, with the insulation installed, as part of the pre-startup inspections during each refueling.)

3.1.2 NDE

ABB-Combustion Engineering performed an eddy current examination on the upper nozzle with a 3-coil rotating pancake probe. The examination was performed using a calibration standard with axial and circumferential notches of various sizes located on the ID of the standard. The results of the examination of TE-0101 detected four axial crack indications emanating from the inside of the pressurizer nozzle with a length of about ½ inch. To indicate the approximate size of the defects, a voltage setting was established on one of the axial notches in the calibration standard. Based on a comparison with the voltage measurement from the largest axial crack in TE-0101, CE determined that the crack was deeper than 10% of the wall thickness.

The licensee concluded that the examination results were typical of those in Inconel nozzles in other PWRs with PWSCC. The licensee concluded the cracks are not a safety problem because they occur axially rather than circumferentially. Accordingly, the licensee did not perform an eddy current examination of TE-0102.

3.1.3 Repairs

To stop the leaks, the licensee replaced the original pressure boundary weld on the interior surface of the shell, the "J" weld, with a weld pad around each nozzle on its exterior surface. This exterior weld re-establishes the pressure boundary downstream of the original "J" welds, replaces the structural support that may have been weakened by the cracks, and bypasses the cracked part of the nozzles.

Welding the nozzles to the shell at both the ID and outer surface can cause high stresses in the nozzle because of the differences in thermal expansion between the Inconel 600 nozzle and the carbon steel plate pressurizer. The residual stress, caused by having the nozzle fixed at two locations to the shell, was evaluated. The evaluation showed that the nozzle for TE-0101 needed to be severed within the thickness of the upper head to prevent the stresses caused by differences in thermal expansion during heatup and cooldown from exceeding the ASME allowable stresses. Severed, the outer part of the nozzle can expand at the same rate as the exterior of the upper head.

The nozzle for TE-0102, located in the lower section liquid environment, was not severed since it does not experience as large a thermal gradient during heatup and cooldown. For this nozzle, an axial residual stress field between the new weld (outside) and the J-weld (inside) may exist due to the existing restraint during the welding process.

The axial stress developed on the lower nozzle as a result of accident transients is still within ASME Code stress and fatigue allowables even with the nozzle constrained at the inner and outer surface of the pressurizer.

3.1.4 Licensee Evaluation of Continued Operation

The licensee intends the modifications to last for one fuel cycle. This is based on the following considerations:

(1) Corrosion

Severing the nozzle for TE-0101 and the leak location of TE-0102 leads to another potential problem: corrosion of the carbon steel pressurizer by the borated primary coolant that will come in direct contact with the carbon steel in the annulus. Calculations using data from an industry study on corrosion of low alloy steel relating to PWSCC failures in Inconel 600 concluded that the Palisades pressure boundary material could corrode at a maximum rate of 3 mil/year. The corrosion rate would not significantly affect the integrity of the pressure boundary during one fuel cycle.

(2) Residual stresses

The licensee states that "the modifications incorporate pad-to-sleeve welds that are essentially the same as the existing J-welds as far as their impact on residual stress fields is concerned. The new welds have the appearance of a fillet weld. These welds are not as efficient as butt welds in inducing axial stress into the instrumentation nozzle.

For the modification where the nozzle is cut, the temperature element will be essentially free on either side of the exterior weld when the pipe is cut. The cut may reduce axial residual weld stresses induced by the weld shrinkage with the restraint of the element by the inside J-weld.

For the modification where the nozzle is not cut, an axial residual stress field between the new weld (outside) and the J-weld (inside) may exist due to the existing restraint during the welding process. No similar residual stress field will exist external to the new weld. Therefore, an undesirable residual stress loading exists between the welds while all the axial operational loads (internal pressure) will be reacted by the new weld only. While any potential axial residual tensile stress loading is undesirable, that resulting from the current modification is not of immediate concern. The reasons are as follows:

- There are essentially no externally applied mechanical loads to the nozzle

- The potential axial stress distribution from the modification will be new and will require time for the initiation and propagation of the cracks"

The licensee concludes that "the joint configuration and the fabrication process combine to limit the impact of any deleterious effects of weld residual stress in the design of the temperature instrumentation nozzle modification. These considerations along with an awareness of the time limitation of the duty cycle for the joint combine to provide assurance that a catastrophic failure due to circumferential cracking will not occur."

3.2 NRC Evaluation

The staff agrees that the modification is acceptable for one cycle of operation as shown by the licensee's analyses.

4.0 OTHER INCONEL APPLICATIONS IN THE PRIMARY SYSTEM

4.1 Licensee's Evaluations

The licensee evaluated the susceptibility of the other nozzles that contain Inconel 600 in the pressurizer. Of these, 120 are for heater wells and 8 for level instruments. The licensee also addressed applications outside the pressurizer.

Pressurizer Heater Sleeve Penetrations

The 120 heater sleeves are attached by partial penetration welds. These welds were not post-weld stress relieved. Until the PORV line nozzle crack, all PWR industry experience with Inconel 600 penetration cracking has involved partial penetration welds. The CEOG's studies of Inconel 600 cracking in partial penetration welds indicate that the most susceptible locations can be identified by material and environmental conditions, the cracks will be axial, the penetrations will not fail catastrophically, and their occurrence is not a safety issue. These conclusions are presented in its reports: CEN-393-P, "Evaluation of Pressurizer Heater Sleeve Susceptability to Primary Water Stress Corrosion Cracking," November 1989; CEN-406-P, "A Status Report on CEOG Activities Concerning Primary Water Stress Corrosion Cracking of Inconel-600 Penetrations," May 1991; and CE NPSD-690-P, "Evaluation of Pressurizer Penetrations and Evaluation of Corrosion after Unidentified Leakage Develops," January 1992.

Pressurizer Level Instrument Penetrations

The eight level instrument nozzles use Inconel 600 spool pieces welded to Type 316 stainless steel safe-ends. The butt weld was not stress relieved. Concern about these nozzles prompted CPCo to sponsor a study of residual stresses associated with the butt weld in these nozzles. The study showed the presence of only compressive or low tensile residual stresses. This is because these nozzles are not restrained during welding.

Inconel 600 Applications Outside the Pressurizer

Inconel 600 is used throughout the PCS. In addition to the pressurizer, the alloy is also used in:

(1) Reactor pressure vessels - CRDM nozzles, instrumentation nozzles, vent pipes, leakage monitoring tubes and bottom head instrumentation nozzles.

(2) PCS piping - instrument/resistance temperature detector (RTD) nozzles, surge nozzles, shutdown cooling nozzles, drain nozzles, sample nozzles.

As for the pressurizer applications, both cold drawn and annealed and forged or hot rolled products are used and are attached to the major components by both the partial penetration and butt welds. The licensee concluded that basically all types of Inconel 600 pipe, forgings, and tubes have shown susceptibility to PWSCC in high temperature and steam given enough exposure time and high enough stresses.

4.2 NRC Evaluation

Industry experience to date with cracking in partial penetration welds is in accordance with the licensee's predictions. Cracks found at partial penetration welds have been axial and their occurrence is not a safety issue. However, butt welds of Inconel 600 are subject to circumferential cracking as shown by the PORV line cracking. The licensee should include all applications of Inconel 600 in its plan for addressing the PWSCC of Inconel 600.

5.0 CONCLUSION

The staff finds the repair welds in the PORV line and instrument nozzles acceptable for the operation of one fuel cycle. This finding is based on the repairs, evaluations and inspections performed by the licensee, existing leak rate monitoring requirements and capabilities, and the fact that a failure of one of the subject lines is bounded by the small break LOCA described in the Final Safety Analysis Report.

Although the staff was not completely satisfied with the inspections performed on the pressurizer surge and spray lines, no unacceptable indications were identified. For this fact and the reasons stated above, the staff finds these welds acceptable for one cycle of operation. Further, on November 11, 1993, the licensee submitted a failure mode analysis for the pressurizer spray and surge lines. The analysis also discussed leak detection capabilities as adequate leak detection capability is the primary line of defense against pipe failure. The NRC staff will review this analysis to determine whether the licensee's conclusions are consistent with this safety evaluation.

In the long-term corrective actions described in its letter dated October 7, 1993, the licensee committed to developing a plan for addressing the PWSCC of Inconel 600 components in the Palisades PCS. This plan should include the technical bases for planned inspection, modifications, repairs, and replacements, particularly for the PORV, surge line and spray line nozzles. The licensee should submit this plan 3 months before the next refueling outage.

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