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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

APPLICATION OF LEAK-BEFORE-BREAK STATUS TO PORTIONS OF THE SAFETY INJECTION AND SHUTDOWN COOLING SYSTEM

NORTHEAST NUCLEAR ENERGY COMPANY

MILLSTONE NUCLEAR POWER STATION, UNIT NO. 2

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1.0 INTRODUCTION

By letter dated July 24, 1998, Northeast Nuclear Energy Company (NNECO/licensee) requested that the NRC review and approve NNECO's application to remove consideration of the dynamic effects of postulated ruptures of portions of the safety injection system (SIS) and shutdown cooling system (SCS) piping from the Millstone Nuclear Power Station, Unit No. 2 (Millstone 2), licensing basis. The licensee's submittal was based on the provisions of General Design Criterion 4 (GDC 4) of Title 10 of the Code of Federal Regulations, Part 50 (10 CFR Part 50), Appendix A, which states in part:

> [h]owever, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping.

For the purposes of this demonstration, the licensee submitted leak-before-break (LBB) analyses prepared by Structural Integrity Associates (SIA) for the subject portions of the SIS and SCS piping. LBB evaluations developed using the analysis methodology contained in NRC NUREG-1061, Volume 3, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, Evaluation of Potential for Pipe Breaks," (Ref. 1) and/or Draft Standard Review Plan (DSRP) Section 3.6.3 have been previously approved by the Commission as demonstration of an extremely low probability of piping system rupture.

2.0 REGULATORY REQUIREMENTS AND STAFF POSITIONS

Nuclear power plant licensees have, in general, been required to consider the dynamic effects that could result from the rupture of sections of high energy piping (fluid systems that during normal plant operations are at a maximum operating temperature in excess of 200 °F and/or a maximum operating pressure in excess of 275 psig). This requirement has been formally included in 10 CFR Part 50, Appendix A, GDC 4, which states, "[s]tructures, systems, and components important to safety...shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit." For facilities such as Millstone 2, which were licensed prior to the advent of the GDC, these requirements were included as part of plant-specific licensing reviews.

Enclosure

The licensee recently identified a condition at Millstone 2 in which sections of closed loop piping near the unit's American Society for Mechanical Engineers (ASME) Code Class 1 SIS piping and the Class 1 SCS hot leg suction piping would not be adequately protected from the failure of either the SIS or SCS line. The licensee identified this condition to the NRC staff in Licensee Event Report (LER) 98-005-00 and, as discussed in Section 1.0 of this SE, has addressed the problem by performing an LBB evaluation of the subject SIS and SCS piping. The philosophy of "LBB" behavior for high energy piping systems was developed by the NRC in the early 1980s, used in certain evaluations stemming from Unresolved Safety Issue A-2, "Asymmetric Blowdown Loads on PWR Primary Systems," and was subsequently expanded for application toward resolving issues regarding defined dynamic effects from high energy piping system ruptures. The methodology developed by the NRC for performing LBB analyses was thoroughly detailed in NUREG-1061, Volume 3, and summarized in DSRP Section 3.6.3, "Leak-Before-Break Evaluation Procedures," which was published for public comment in August 1987.

3.0 LICENSEE'S DETERMINATION

The following discussion contains information supplied by NNECO in its July 24, 1998, letter to the NRC and the attachments to that letter. These attachments included two reports prepared by SIA for NNECO: SIR-98-048, Rev. 0, "Leak-Before-Break Evaluation, High Energy Safety Injection Piping, Millstone Nuclear Power Station, Unit 2," and SIR-98-070, Rev. 0, "Leak-Before-Break Evaluation, High Energy Shutdown Cooling Piping, Millstone Nuclear Power Station, Unit 2."

3.1 Identification of Analyzed Piping and Piping Material Properties

The licensee's submittal identified and analyzed the following sections of high energy piping for LBB behavior verification. For each of the four Millstone 2 SIS branches, the licensee addressed the ASME Code Class 1 portion of the system from its connection to the reactor coolant system cold leg, to its respective safety injection tank at one end of the branch piping, and to the first containment isolation valve in the other branch of the piping. This piping is shown in Figures 1 through 4 (attached). For the Millstone 2 SCS piping, the licensee addressed the ASME Code Class 1 portion of the system from the SCS connection to the reactor coolant system hot leg to the first containment isolation valve. This piping is shown in Figure 5 (attached).

Each branch of the SIS piping was identified as having the following material components. The nozzle material connecting the SIS lines to the reactor coolant system cold leg was a low alloy carbon steel forging, American Society for Testing and Materials Specification (ASTM) A-182, Grade F1. A cast stainless steel (CSS) safe end manufactured from ASTM A-351, Grade CF8M material was attached to the nozzle forging by a bimetallic weld fabricated by the shielded metal arc welding (SMAW) process using Inconel 182 filler metal. The remainder of the piping to the first isolation valve was made from ASTM A-376, Type 316 wrought SS and the piping welds were fabricated using SS filler materials and gas tungsten arc welding (GTAW), submerged arc welding (SAW), SMAW, or a combination of these processes.

The SCS piping was identified as having the following material components. The nozzle material connecting the SCS line to the reactor coolant system hot leg was a low alloy carbon steel forging ASTM A-105, Grade II. A CSS safe end manufactured from ASTM A-351, Grade CF8M material was attached to the nozzle forging by a bimetallic weld fabricated by the SMAW process using Inconel 182 filler metal. The remainder of the piping to the first containment isolation valve was made from ASTM A-376, Type 316 wrought SS and the connecting welds were fabricated using SS filler materials and GTAW, SAW, SMAW, or a combination of these processes.

For the material properties used in the SIS and SCS LBB evaluations, NNECO/SIA used consistent sets of stress-strain and J-resistance (J-R) curve information based on the material being evaluated at a particular location (carbon steel, CSS, wrought SS, or SS weld metal). Archival samples and/or test data specific to the Millstone 2 materials were not available. The stress-strain curves and the J-R data for the carbon steel nozzles, wrought SS piping, and the SS weld metal were taken from generic characterizations in the EPRI Ductile Fracture Handbook (Ref. 2) The welds were assumed to be fabricated using SAW processes since the J-R curve provided in Reference 2 for SAWs was more conservative than the J-R curve provided for SMAWs. For the CF8M CSS safe ends, the material properties used in the analysis explicitly accounted for the effects of thermal aging. Since no direct measurement of the amount of δ-ferrite phase present in these safe ends had been acquired, conservatively high amounts were assumed (which increases the materials' sensitivity to thermal aging). Results from work at Argonne National Laboratory (References 3 and 4), sponsored by the NRC, were used as the basis for developing the J-R and stress-strain curves for the CSS material.

3.2 General Aspects of the Licensee's LBB Analysis

The analyses provided by the licensee sought to address four principal areas that were consistent with the criteria established for LBB analysis acceptability in NUREG-1061, Vol. 3, and/or DSRP Section 3.6.3: (1) Demonstrate that the subject piping is a candidate for LBB analysis by showing that the piping is not particularly susceptible to active degradation mechanisms or atypical loading events; (2) Establish the critical through-wall flaw size under which analyzed locations would be expected to fail under normal operation (NOP) plus safe-shutdown earthquake (SSE) loading conditions; (3) Establish the leakage behavior of smaller through-wall flaws under NOP loads alone for each location; and (4) Evaluate the margin between the critical through-wall flaw size, and an appropriate leakage through-wall flaw size and the stability of the through-wall leakage flaw under loading conditions of $\sqrt{2}$ * (NOP+SSE) loads.

3.3 Evaluation of Safety Injection System Piping

The analysis of the SIS piping that was submitted to the staff as Attachment 3 to the July 24, 1998, letter was prepared for the licensee by SIA as report number SIR-98-048, Rev. 0. This section summarizes the results of the NNECO/SIA results for the four subject areas noted in Section 3.2 of this SE.

Initially, the licensee's submittal addressed the issue of potential piping degradation mechanisms and atypical loading conditions. According to the discussion of the limitations of LBB analyses in NUREG-1061, Volume 3, the LBB approach should not be considered when operating experience has indicated particular susceptibility to failure from the effects of corrosion, waterhammer, or fatigue. The licensee's submittal concluded that pressurized-water reactor safety injection system piping like that at Millstone 2 has not been shown to be particularly susceptible to the effects of waterhammer, intergranular stress corrosion cracking, or flow-assisted corrosion. The licensee included a fatigue analysis that indicated that the circumferential growth of postulated surface flaws (which were in excess of the size allowed following preservice inspection by the ASME Code) due to cyclic stresses would not be significant for the nozzle-to-safe end weld location, which was selected as the location most likely to experience significant fatigue damage. Any significant through-wall growth of these large surface flaws without circumferential extension was concluded to be within the technical basis of LBB behavior. The fatigue growth of flaws, which would be acceptable under ASME Code Section XI IWB-3514 criteria, was determined to be insignificant.

Next, the NNECO/SIA analysis evaluated the SIS piping by developing the applied stresses under normal operation NOP plus SSE loading from the facility's piping stress design analysis (Ref. 5) and determining the critical through-wall flaw size for various locations along the piping. These stresses are given in Table 1 (attached). In the determination of the applied stresses, the analysis included the tensile stress resulting from the internal pressure, and the outer fiber bending stress resulting from deadweight, thermal expansion, and SSE loads. In the load combination, the deadweight and thermal moments were added algebraically at the component level and then the resulting moments were used to determine the outer fiber stresses for deadweight plus thermal loadings. The SSE outer fiber stress was calculated from the SSE moments and the stresses were then combined to determine the critical flaw size.

For the purposes of LBB analyses, the critical flaw size can be defined as the longest preexisting through-wall flaw that could exist without growing unstably to double-ended pipe rupture under NOP plus SSE stresses. The analysis performed by SIA was based on the J-integral/Tearing Modulus (elastic-plastic fracture mechanics) approach to flaw stability, which is applicable for the materials of most interest in this analysis. Formally, piping failure is predicted when the applied J exceeds J_{IC} (the material property value at which crack growth initiates) and the rate of increase of the applied J with crack extension (dJ/da) exceeds the rate of increase of the piping material's J-R curve with crack extension (d(J-R)/da).

The analysis in SIR-98-048, Rev. 0, calculated the critical flaw size by using SIA's pc-CRACK™ code. To do this, SIA first assumed that the stresses applied at an analyzed location were all tensile stresses and determined a critical flaw size (a_t) under these conditions. Then it was assumed that the stresses applied were all bending stresses and determined a critical flaw size (a_b) under such conditions. A linear interpolation was then performed between the two results as:

$$a_c = a_t * (\sigma_t / (\sigma_b + \sigma_t)) + a_b * (\sigma_b / (\sigma_b + \sigma_t))$$

where σ_b and σ_t were the bending and tensile components, respectively, of the overall stress and a_c was the combined critical flaw size. Subsequently, in recognition of the margin of 2 required in NUREG-1061, Vol. 3, between the critical flaw size and the acceptable leakage flaw size, the analysis then established the values for each SIS piping location in Column 5 of Table 2 (attached) (which represent one-half of the calculated critical flaw size) as a candidate value for the acceptable leakage flaw size.

NUREG-1061, Vol. 3, however, also requires that the acceptable leakage flaw size be demonstrated to be stable under loads that are equivalent to √2 times the NOP plus SSE loads. Using the methodology previously outlined, the analysis then determined what size flaw would be stable under such conditions. Column 5 of Table 3 shows these results for all SIS piping locations. The licensee then noted that the acceptable leakage flaw size would be the minimum value for each location when Column 5 of Table 2 was compared to Column 5 of Table 3. When compared in the leakage margin analysis, the absolute minimum values (about 4.30 inches, in Table 3) would then be demonstrated to be the bounding leakage flaw size for the entire SIS analysis, with nodes 170 (which included the CSS safe end) and 175 (piping to elbow SS weld location) being the bounding locations. However, the leakage margin analysis included an analysis for all node locations in order to demonstrate that the nodes 170 and/or 175 were bounding.

Having established the acceptable leakage flaw size from applying the appropriate factor of safety to the critical flaw size, the NNECO/SIA analysis then determined the leakage behavior of the postulated leakage flaw. The leakage analysis performed by SIA was based on the use of the Pipe Crack Evaluation Program (PICEP, Revision 1) computer code developed by the Electric Power Research Institute (EPRI) for calculating two-phase flow through cracks in light-water reactor piping. By inputting the piping cross-section description, material property characteristics for the SS SAW, and normal operating loads (or stresses) for nodes 170 and 175 into the program, the NNECO/SIA analysis determined that the 4.30-inch leakage flaw at these locations would leak at a rate of approximately 11.0 gallons per minute (gpm) under NOP conditions using a crack surface roughness of $\epsilon = 0.000197$ inch. Therefore, the licensee concluded that since the Millstone 2 containment leakage detection system has the capability of detecting 1 gpm of leakage in the course of 1 hour (consistent with NRC Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems," guidance), a margin on leakage greater than 10 (consistent with the requirements of NUREG-1061, Vol. 3), was demonstrated and that the subject SIS piping was within the requirements for LBB designation.

3.4 Evaluation of Shutdown Cooling System Piping

The analysis of the SCS piping that was submitted to the staff as Attachment 4 to the July 24, 1998, letter was prepared for the licensee by SIA as report number SIR-98-070, Rev. 0. This section summarizes the results of the NNECO/SIA results for the four subject areas noted in Section 3.2 of this SE.

Initially, the licensee's submittal addressed the issue of potential piping degradation mechanisms and atypical loading conditions. The licensee's submittal concluded that pressurized-water reactor SCS piping, like that at Millstone 2, has not been shown to be susceptible to the effects of waterhammer, intergranular stress corrosion cracking, or flow-assisted corrosion. The licensee included a fatigue analysis that indicated that the circumferential growth of postulated surface flaws (which were in excess of the size allowed by the ASME Code following preservice inspection) due to cyclic stresses would not be significant for the nozzle-to-safe end weld location, which was selected as the location most likely to experience significant fatigue damage. Any significant through-wall growth of these large surface flaws without circumferential extension was concluded to be within the technical basis of LBB behavior. The fatigue growth of flaws, which would be acceptable under ASME Code Section XI IWB-3514 criteria, was determined to be insignificant.

Next, the NNECO/SIA analysis evaluated the SCS piping by developing the applied stresses under NOP plus SSE loading from the facility's piping stress design analysis (Ref. 6) and determining the critical through-wall flaw size for various locations along the piping. These stresses are given in Table 4. In the determination of the applied stresses, the analysis included the tensile stress resulting from the internal pressure, and the outer fiber bending stress resulting from deadweight, thermal expansion, and SSE loads. In the load combination, the deadweight and thermal moments were added algebraically at the component level and then the resulting moments were used to determine the outer fiber stresses for deadweight plus thermal. The outer fiber SSE stress was calculated from the SSE moments and the stresses were then combined to determine the critical flaw size.

For the purposes of LBB analyses, the critical flaw size can be defined as the longest preexisting through-wall flaw that could exist without growing unstably to double-ended pipe rupture under NOP plus SSE stresses. The analysis performed by SIA was based on the J-integral/Tearing Modulus (elastic-plastic fracture mechanics) approach to flaw stability, which is applicable for the materials of most interest in this analysis. Formally, piping failure is predicted when the applied J exceeds J_{IC} (the material property value at which crack growth initiates) and the rate of increase of the applied J with crack extension (dJ/da) exceeds the rate of increase of the piping material's J-R curve with crack extension (d(J-R)/da).

The analysis in SIR-98-070, Rev. 0, calculated the critical flaw size by using SIA's pc-CRACK™ code. To do this, SIA first assumed that the stresses applied at an analyzed location were tensile stresses and determined a critical flaw size (a_t) under these conditions. Then it was assumed that the stresses applied were bending stresses and determined a critical flaw size (a_b) under these conditions. A linear interpolation was then performed between the two results as:

$$a_c = a_t * (\sigma_t / (\sigma_b + \sigma_t)) + a_b * (\sigma_b / (\sigma_b + \sigma_t))$$

where σ_b and σ_t were the bending and tensile components, respectively, of the overall stress and a_c was the combined critical flaw size. Subsequently, in recognition of the margin of 2 required in NUREG-1061, Vol. 3, between the critical flaw size and the acceptable leakage flaw size, the analysis then established the values for each SCS piping location in Column 4 of Table 5 (which represent one-half of the calculated critical flaw size) as a candidate value for the acceptable leakage flaw size.

NUREG-1061, Vol. 3, however, also requires that the acceptable leakage flaw size be demonstrated to be stable under loads, which are equivalent to √2 times the NOP plus SSE loads. Using the methodology outlined above, the NNECO/SIA analysis then determined what size flaw would be stable under such conditions. Column 4 of Table 6 shows these results for each SCS piping location. The licensee then noted that the acceptable leakage flaw size would be the minimum value for each location when Column 4 of Table 5 was compared to Column 4 of Table 6. When compared in the leakage margin analysis, the flaw size of about 7.85 inches in Table 5 for node 10 (which included the carbon steel nozzle, the CSS safe end, and the adjoining welds) based on the properties of the limiting austenitic material would then be demonstrated to be the bounding leakage flaw size for the entire SCS analysis. However, the leakage margin analysis included a leakage flaw analysis for all locations to demonstrate that node 10 was the bounding location.

Having established the acceptable leakage flaw size from applying the appropriate factors of safety to the critical flaw size, the NNECO/SIA analysis then determined the leakage behavior of the postulated leakage flaw. The leakage analysis performed by SIA used the PICEP, Rev. 1, computer code. By inputting the piping cross-section description, material property characteristics for the SS SAW, and normal operating loads (or stresses) for node 10 into the program, the NNECO/SIA analysis determined that the 7.85-inch leakage flaw at these locations would leak at a rate of 12.1 gallons per minute (gpm) under NOP conditions using a crack surface roughness of $\epsilon = 0.0003$ inch. Therefore, the licensee concluded that since the Millstone 2 containment leakage detection system has the capability of detecting 1 gpm of leakage in the course of 1 hour (consistent with NRC Regulatory Guide 1.45 requirements), a margin on leakage greater than 10 (consistent with the requirements of NUREG-1061, Vol. 3) was demonstrated and that the subject SCS piping was within the requirements for LBB designation.

4.0 STAFF EVALUATION

Based on the information provided by the licensee regarding the materials comprising the Millstone 2 SIS and SCS lines and their loads under NOP and SSE conditions, the staff independently assessed the compliance of these systems with the LBB criteria established in NUREG-1061, Vol. 3. While the staff has concluded that the analyses submitted by the licensee were sufficient to demonstrate that LBB behavior would be expected from the subject piping, the following sections will focus on the differences between the details of the staff's analysis, conducted according to NUREG-1061, Vol. 3, and the licensee's.

4.1 Identification of Analyzed Piping and Piping Material Properties

The staff examined the list of materials identified for the SIS and SCS lines and concluded that the materials of primary interest for the LBB analysis would be the CSS safe ends or the SS welds because of their susceptibility to thermal aging. However, in evaluating the fracture behavior of the SS welds, the stress-strain properties of the surrounding base metals (e.g., the wrought SS piping) would also play a significant role.

NUREG-1061, Vol. 3, specifies particular aspects that should be considered when developing materials property data for LBB analyses. First, data from the testing of the plant-specific piping materials is preferred. However, in the absence of such data, more generic data from the testing of samples having the same material specification may be used. More specifically, it was noted in Appendix A of the NUREG that "[m]aterial resistance to ductile crack extension should be based on a reasonable lower-bound estimate of the material's J-resistance curve," while Section 5.2 of the NUREG stated that the materials data should include, "appropriate toughness and tensile data, long-term effects such as thermal aging and other limitations."

Given the above, the staff concurred with the use of information from References 2 and 3 for the development of J-R and stress-strain curves for the CSS material in that it explicitly accounted for the effects of long-term thermal aging. The J-R curve characterization as given in Table 4-2 of either SIA report was appropriately conservative and, after the licensee clarified that the ultimate stress values given in the tables was in fact the flow stress used in NNECO's analysis, the Ramberg-Osgood representation of the stress-strain properties for the CSS and wrought SS piping were also acceptable.

The staff did not concur with the NNECO/SIA methodology for establishing the stress-strain and J-R curve properties of the SS weld materials. The licensee justified the use of the information from Reference 2 by noting that it had been used as the basis for the flaw evaluation criteria in ASME Section XI though the information did not account for the effects of thermal aging. It is the staff's position that an LBB analysis is significantly different from a flaw evaluation and that the thermal aging of SS weld materials must be explicitly addressed. An additional study from Argonne National Laboratory (Ref. 7) was the staff's reference for this information and the staff's characterization of the J-R curve and stress-strain properties of aged SS weld material for this evaluation is given in Table 7. The mean minus one standard deviation lower bound J-R curve used by the staff was actually developed by Wilkowski and Ghadiali at Battelle Columbus Laboratory as a fit to unaged SS weld data, but the conclusions of Reference 6 noted that there was little observed change in the fracture toughness behavior with thermal aging for those welds that began with inferior fracture toughness properties. The J-R curve used by the staff was more conservative than that used by the licensee.

The staff's analysis was performed in accordance with the guidance provided in NUREG-1061, Vol.3. Based on the information submitted by the licensee, the staff determined the critical flaw size at the bounding location for each piping system using the codes compiled in the NRC's Pipe Fracture Encyclopedia (Ref. 8). For the purposes of the staff's evaluation, the critical location was defined by those locations at which materials with low postulated fracture toughness existed in combination with high ratios of SSE-to-NOP stresses. This was because high SSE stresses tend to reduce the allowable critical flaw size while low NOP stresses increase the size of the leakage flaw required to produce 10 gpm of leakage. In particular, when evaluating the critical flaw in the thermally-aged CSS base materials, the staff used the LBB.ENG2 code developed by Brust and Gilles [9], and when evaluating pipe welds, the staff used the LBB.ENG3 code developed by Battelle [9] for that express purpose. The LBB.ENG3 methodology is significantly different from the other codes in the Reference 8 and from the licensee's analysis in that LBB.ENG3 explicitly accounts for the differences in the stress-strain properties of the weld and a adjoining base material when determining the effective energy release from the structure with crack extension. The same criteria as discussed in sections 3.3 and 3.4 with regard to the applied J exceeding the material J_{IC} and the applied dJ/da exceeding the material's d(J-R)/da were used to identify the critical crack size.

The staff then compared the critical flaw at the bounding location to the leakage flaw which provided 10 gpm of leakage under NOP conditions to determine whether the margin of 2 defined in NUREG-1061, Vol. 3 was achieved. The leakage flaw size calculation was carried out using the same PICEP analytic code used by the licensee, with a minor difference in the assumed crack surface roughness. The 10 gpm value was defined by noting that the compliance of the MNPS 2 containment leakage detection system with the positions in Regulatory Guide 1.45 indicates that this system would be able to detect a 1 gpm leak in the course of one hour and a factor of 10 is applied to this 1 gpm detection capability to account for thermohydraulic uncertainties in calculating the leakage through small cracks. The stability of the leakage flaw under loadings a factor of $\sqrt{2}$ greater than the combination of SSE+NOP loads was subsequently evaluated to check the final acceptance criteria of NUREG-1061, Vol. 3.

4.3 Evaluation of the Millstone Unit 2 Safety Injection System Lines

Based on the licensee's results and the loadings supplied by the licensee, the staff concluded that the locations which would be expected to be limiting for the SIS piping evaluation would be nodes 170 (at loop 1B nozzle location) or node 175 (piping to elbow SS weld location). At node 170, the staff's evaluation considered both the possibility of a crack in the CSS safe end between the carbon steel nozzle and the wrought SS piping or a flaw in the SS weld between the safe end and the piping. The staff's evaluation showed of these two possibilities, the postulation of a flaw in the weld metal provided a bounding analysis when compared to a flaw in the safe end. The weld metal evaluation is detailed below and the safe end evaluation can be summarized by noting that the critical flaw was found to be 11.8 inches in length under SSE+NOP loading conditions while the 10 gpm leakage flaw was found to be 4.35 inches, providing a margin of 2.71 on the crack sizes. The leakage flaw in the safe end was stable under $\sqrt{2}$ * (SSE+NOP) loads.

Since the weld at node 170 existed between the aged CSS safe end and the wrought 316 SS piping while the weld at node 175 was between two sections of 316 SS piping, the staff evaluated the allowable critical flaw size for the welds in two parts. Since the LBB.ENG3 code does not provide an option to specify different base materials stress-strain properties on each side of the weld, the staff first evaluated the weld by assuming that the weld was flanked on both side of the weld, the staff first evaluated the weld by assuming that the weld was flanked on both sides by the aged CSS of the safe end. This resulted in a calculated critical flaw size of 12.4 inches. Then it was assumed that the weld was flanked by the wrought 316 SS piping material. Four different wrought 316 SS stress-strain property representations were used: two of which assumed "typical" yield strength (YS) and ultimate tensile strength (UTS) properties for the material (YS = 25 ksi, UTS = 75 ksi) and differed only in their Ramberg-Osgood paramaterizations (α = 6.9, n = 4.8 or α = 5.8, n = 3.6), one submitted by the licensee in Table 4-3 of report SIR-98-048 (YS = 29.6 ksi, UTS = 86.6 ksi [corrected], α = 12.0, n = 4.8) and one which used ASME Code minimum strength values at the system's operating temperature (YS = 18.8 ksi, UTS = 71.8 ksi). These three analyses gave critical flaw sizes of 7.70, 8.30, 7.50, and 11.20 inches, respectively, with the nonconservative critical flaw size based on the ASME Code minimums as the outlier. Based on these results, the staff concluded that the appropriate critical flaw size determined by assuming 316 SS properties would be an average of the three non-Code minimum calculations, 7.83 inches. Furthermore, it was concluded that node 175 (where the NOP and SSE loads were essentially equivalent to those at node 170), which would be directly represented by the 7.83-inch critical flaw size, would be the bounding location inasmuch as a calculation based on the consideration of the CSS safe end properties on one side of the weld at node 170 and would be expected to lengthen the critical flaw size.

The staff then used the PICEP code to determine the leakage flaw size for node 175. Using the surface roughness value that the staff has used in previous LBB evaluations of ϵ = 0.003 inch, the staff determined that 10 gpm of leakage would be expected from a 4.35-inch through-wall flaw. Therefore, the margin between the critical flaw size and the leakage flaw size for node 175 was found to be (7.83 / 4.35) = 1.8, slightly less than the margin of 2 recommended in NUREG-1061, Vol. 3. In addition, the leakage size flaw was found to be stable only up to 1.36 * (SSE+NOP) loads instead of 1.414 * (SSE+NOP) loads.

However, in previous LBB evaluations, the staff has concluded that margins of slightly less than 2 on the critical-to-leakage flaw size are acceptable provided that a full margin of 10 is maintained on the leakage uncertainty. It is the staff's position that relaxation from the guidance written in 1984 on this point and on the margin of $\sqrt{2}$ on the loads for the leakage flaw stability evaluation is acceptable based on the work that has been completed in the areas of piping fracture (e.g., the International Piping Integrity Research Group work) and the evaluation of minimum material properties to more appropriately bound the behavior of primary system piping materials. Therefore, the staff has concluded that the preceding evaluation confirms the licensee's conclusion that the analyzed portions of the Millstone 2 SIS piping will exhibit LBB behavior.

4.4 Evaluation of the Millstone 2 Shutdown Cooling System Line

Based on the licensee's results and the loadings supplied by the licensee, the staff concluded that the locations that would be expected to be limiting for the SCS piping evaluation would be node 10 (at SCS nozzle location) or node 20 (piping to elbow SS weld location). At node 10, the staff's evaluation considered both the possibility of a crack in the CSS safe end between the carbon steel nozzle and the wrought SS piping or a flaw in the SS weld between the safe end and the piping. The staff's evaluation of node 10 was carried out with a method equivalent to that explained in detail for node 170 in the SIS evaluation (Section 4.3 of this SE). However, in this case, the staff's evaluation showed of these two possibilities the postulation of a flaw in the CSS safe end provided a bounding analysis when compared to a flaw in the weld adjoining the safe end. The safe end evaluation can be summarized by noting that using the LBB.ENG2 code gives a critical flaw size of 14.0 inches in length under SSE+NOP loading conditions while the 10 gpm leakage flaw was found to be 6.75 inches, providing a margin of 2.07 on the crack sizes.

The leakage flaw in the safe end was stable under √2 * (SSE+NOP) loads. For the SS weld adjoining the safe end at node 10, using the CSS properties in the LBB.ENG3 code, predicted a critical flaw size for the weld of 17.6 inches, while the use of "typical" 316 SS properties (YS = 25, UTS = 75, $\alpha = 6.9$, $n = 4.8$) predicted a critical flaw size of 15.0 inches. PICEP was then used to calculate a leakage flaw size for the weld material of 6.70 inches for a margin on the crack sizes of 2.24. The leakage flaw in the weld adjoining the safe end was stable under √2 * (SSE+NOP) loads.

For node 20, the staff reevaluated the predicted critical and leakage flaw size since the applied loading under NOP and NOP+SSE conditions differed from those at node 10. Since node 20 represented a piping-to-piping weld location, the base metal properties used in the LBB.ENG3 analysis were the "typical" 316 SS properties (YS = 25, UTS = 75, $\alpha = 6.9$, $n = 4.8$) and the predicted critical flaw size was 16.0 inches. PICEP was then used to calculate a leakage flaw size for the weld material of 6.80 inches for a margin on the crack sizes of 2.25. The leakage flaw in the weld and node 20 was stable under √2 * (SSE+NOP) loads.

Based on this information, the CSS safe end at node 10 was identified as the bounding location for the SCS LBB evaluation, and the staff concurred with the licensee's evaluation that the margins of 2 on crack size, 10 on leakage, and √2 on loadings were met for the analyzed portion of the system. Therefore, the staff has concluded that the preceding evaluation confirms the licensee's conclusion that the analyzed portions of the Millstone 2 SCS piping will exhibit LBB behavior.

5.0 CONCLUSION

Based on the information and analysis supplied by the licensee, the staff was able to independently assess the LBB status of the analyzed portions of the Millstone 2 SIS and SCS piping. The staff has concluded that the licensee has demonstrated that these sections of piping will exhibit LBB behavior. Furthermore, the licensee is permitted to credit this conclusion for eliminating the dynamic effects associated with the postulated rupture of these sections of piping from the Millstone 2 facility licensing basis, consistent with the provisions of 10 CFR Part 50, Appendix A, GDC 4.

Attachments: References
Tables (1-7)
Figures (1-5)

Principal Contributors: Matthew Mitchell
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Date: November 9, 1998

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7. Gavenda, D.J., et al., "Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds," NUREG/CR-6428, ANL-95/47.

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TABLES
(1 - 7)

Table 1: Stresses for the Safety Injection Lines (psi)

Model	Node	WT + TE	P + WT + TE	WT + TE + SSE	P + WT + TE + SSE
TMR-001 (Loop 1A)	210 (N)	8,023	11,840	11,623	15,439
	210 (SE)	8,949	13,659	12,963	17,674
	220	10,413	15,124	11,640	16,351
	240	10,437	15,148	11,343	16,054
	270	9,084	13,795	9,988	14,699
TMR-005 (Loop 1B)	170 (N)	11,193	15,009	15,040	18,856
	170 (SE)	12,484	17,195	16,774	21,485
	175	12,480	17,191	16,760	21,471
	185	12,060	16,771	14,243	18,954
	195	5,353	10,064	7,618	12,329
TMR-009 (Loop 2A)	340 (N)	6,985	10,801	9,733	13,549
	340 (SE)	7,790	12,501	10,855	15,566
	350	7,815	12,526	8,979	13,690
	370	7,680	12,391	8,553	13,264
	405	3,838	8,549	5,532	10,243
TMR-011 (Loop 2B)	190 (N)	11,545	15,361	14,457	18,273
	190 (SE)	12,876	17,587	16,124	20,835
	200	12,866	17,577	16,096	20,807
	220	12,323	17,034	14,308	19,019

Notes:

P = pressure
WT = dead weight
TE = thermal expansion
SSE = seismic inertia for safe shutdown earthquake
N = nozzle to safe end weld, OD = 12.75", ID = 10.125"
SE = safe end to piping weld, OD = 12.75", ID = 10.5"

Table 2: Half Critical Flaw Lengths Using Normal + SSE Stresses (Safety Injection Lines)

Model	Node	Half Critical Length (in)		
		Bending (a_b)	Tension (a_t)	Combination (a_c)
TMR-001 (Loop 1A)	210(NC)	6.2168	4.7233	5.8476
	210(NS)	6.3453	4.8903	5.9857
	210 (SE)	5.7751	4.2360	5.3648
	220	6.1613	4.6348	5.7215
	240	6.2480	4.7242	5.8008
	270	6.6901	5.1637	6.2009
TMR-005 (Loop 1B)	170 (NC)	5.1624	3.7864	4.8839
	170 (NS)	5.3848	3.8797	5.0802
	170 (SE)	4.7598	3.0766	4.3908
	175	4.7634	3.0807	4.3942
	185	5.4211	3.8389	5.0278
	195	7.5349	5.9964	6.9471
TMR-009 (Loop 2A)	340 (NC)	6.8940	5.3114	6.4483
	340 (NS)	6.9751	5.5104	6.5626
	340 (SE)	6.4058	4.8816	5.9445
	350	7.0333	5.5032	6.5068
	370	7.1903	5.6576	6.6459
	405	8.3703	6.8326	7.6632
T[illegible]R-011 (Loop 2B)	190 (NC)	5.3282	3.9444	5.0392
	190 (NS)	5.5402	4.0450	5.2279
	190 (SE)	4.9250	3.2668	4.5501
	200	4.9321	3.2749	4.5569
	220	5.4033	3.8184	5.0108

Notes:

NC = nozzle (based on carbon steel)
NS = nozzle (based on limiting austenitic material)
SE = safe end

Table 3: Critical Flaw Lengths with Factor of $\sqrt{2}$ on Normal + SSE Stresses (Safety Injection Lines)

Model	Node	Critical Length (in)		
		Bending $2a_b$	Tension $2a_b$	Comb. $2a_c$
TMR-001 (Loop 1A)	210 (N)(2)	9.274	5.9164	8.4441
	210 (SE)	7.7356	4.0986	6.7662
	220	8.687	5.1942	7.6806
	240	8.9002	5.4398	7.8848
	270	9.8742	6.5816	8.8125
TMR-005 (Loop 1B)	170 (N)(2)	6.8350	3.3120	6.1200
	170 (SE)	4.9862	1.8214	4.2923(1)
	175	4.9952	1.8274	4.3002(1)
	185	6.8042	3.3158	5.9372
	195	11.6662	8.6290	10.5056
TMR-009 (Loop 2A)	340 (N)(2)	10.6022	3.5624	9.7508
	340 (SE)	9.2508	5.8434	8.2196
	350	10.6212	7.4228	9.5206
	370	10.9482	7.8002	9.8302
	405	13.5196	10.4636	12.1150
TMR-011 (Loop 2B)	190 (N)(2)	7.2852	3.7130	6.5392
	190 (SE)	5.4350	2.1664	4.6960
	200	5.4552	2.1834	4.7145
	220	6.7566	3.2760	5.8945

Notes:

(1) This flaw size controls for the leakage flaw size

(2) Case for carbon steel nozzle not evaluated because leakage size flaw at this location clearly governed by Table 5-1.

N = nozzle (based on limiting austenitic material)

SE = safe end

Table 4: Stresses for the Shutdown Cooling Line (psi)

Node	WT + TE	P + WT + TE	WT + TE + SSE	P + WT + TE + SSE
10 (N)	3598	7414	5994	9810
10 (SE)	4013	8724	6685	11396
20	3332	8043	5444	10155
40	2575	7286	3592	8303
70	2452	7163	4082	8793
120	2236	6947	4017	8728
132	1729	6440	3719	8430
85	1543	6254	3187	7898

Notes:

P = pressure
WT = dead weight
TE = thermal expansion
SSE = seismic inertia for safe shutdown earthquake
N = nozzle to safe end weld, OD = 12.75", ID = 10.125"
SE = safe end to piping weld, OD = 12.75", ID = 10.5"

Table 5: Half Critical Flaw Lengths Using Normal + SSE Stresses (Shutdown Cooling Lines)

Node	Half Critical Flaw Size (in)		
	Bending a_b	Tension a_t	Comb. a_c
10 (NC)	8.4749	6.7638	7.8093
10 (NS)	8.4171	6.9548	7.8482
10 (SE)	7.8959	6.3553	7.2590
20	8.4075	6.8701	7.6943
40	9.0664	7.7326	8.3096
70	8.9631	7.4922	8.1750
120	8.9768	7.5241	8.1927
132	9.0396	7.6702	8.2743
85	9.1303	7.9362	8.4180

Notes:

NC = nozzle (based on carbon steel)
NS = nozzle (based on limiting austenitic material)
SE = safe end

Table 6: Critical Flaw Lengths with Factor of √2 on Normal + SSE Stresses (Shutdown Cooling Lines)

Node	Half Critical, Bending a_b	Half Critical, Tension a_t	Critical Flaw, Comb. $2a_c$
10 (NC)	6.7733	5.2045	12.3260
10 (NS)	6.8621	5.3997	12.5864
10 (SE)	6.2298	4.7055	11.1993
20	6.8008	5.2735	12.1846
40	7.7585	6.2179	13.7688
70	7.4960	5.9582	13.3442
120	7.5299	5.9915	13.3990
132	7.6872	6.1466	13.6526
85	7.9858	6.4452	14.1336

Notes:

NC = nozzle (based on carbon steel)
NS = nozzle (based on limiting austenitic material)
SE = safe end

Table 7: Parameters used in Staff Evaluation of Millstone 2 Aged SS Pipe Welds

Parameter	Value
Young's Modulus	25000 ksi
Yield Strength	49.4 ksi
Ultimate Tensile Strength	61.4 ksi
Sigma-zero	49.4 ksi
Epsilon-zero	0.00197
Ramberg-Osgood Alpha	9.0
Ramberg-Osgood n	9.8
J_{IC}	73.4 KJ / m^2
C	83.5 KJ / m^2 mm
n	0.643

Note: $J = J_{IC} + C(\Delta a)^n$ and a point-by-point representation was converted to English System units after the calculation was completed in metric units.

FIGURES
(1 - 5)

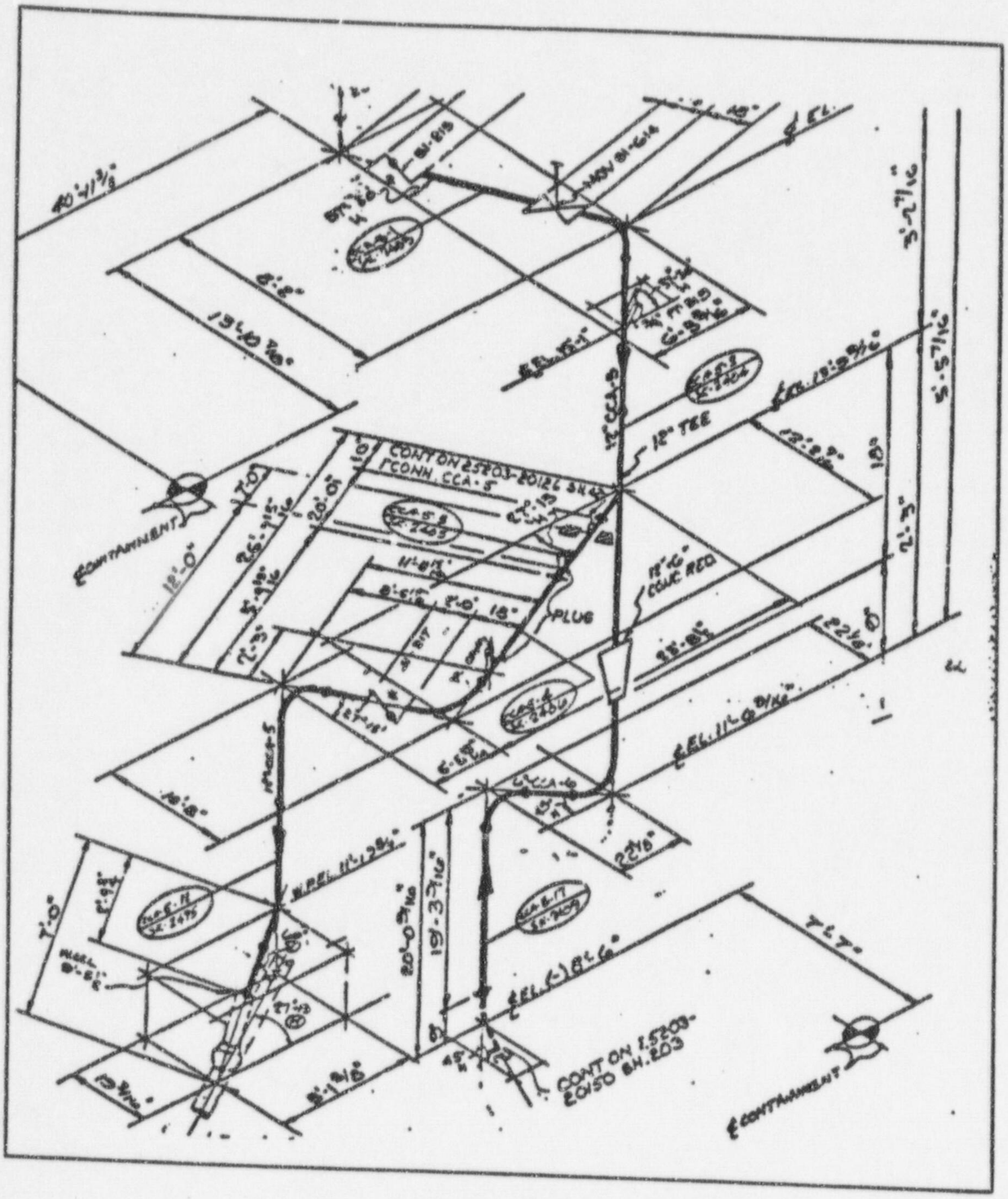

Figure 1: Loop 1A Safety Injection Line

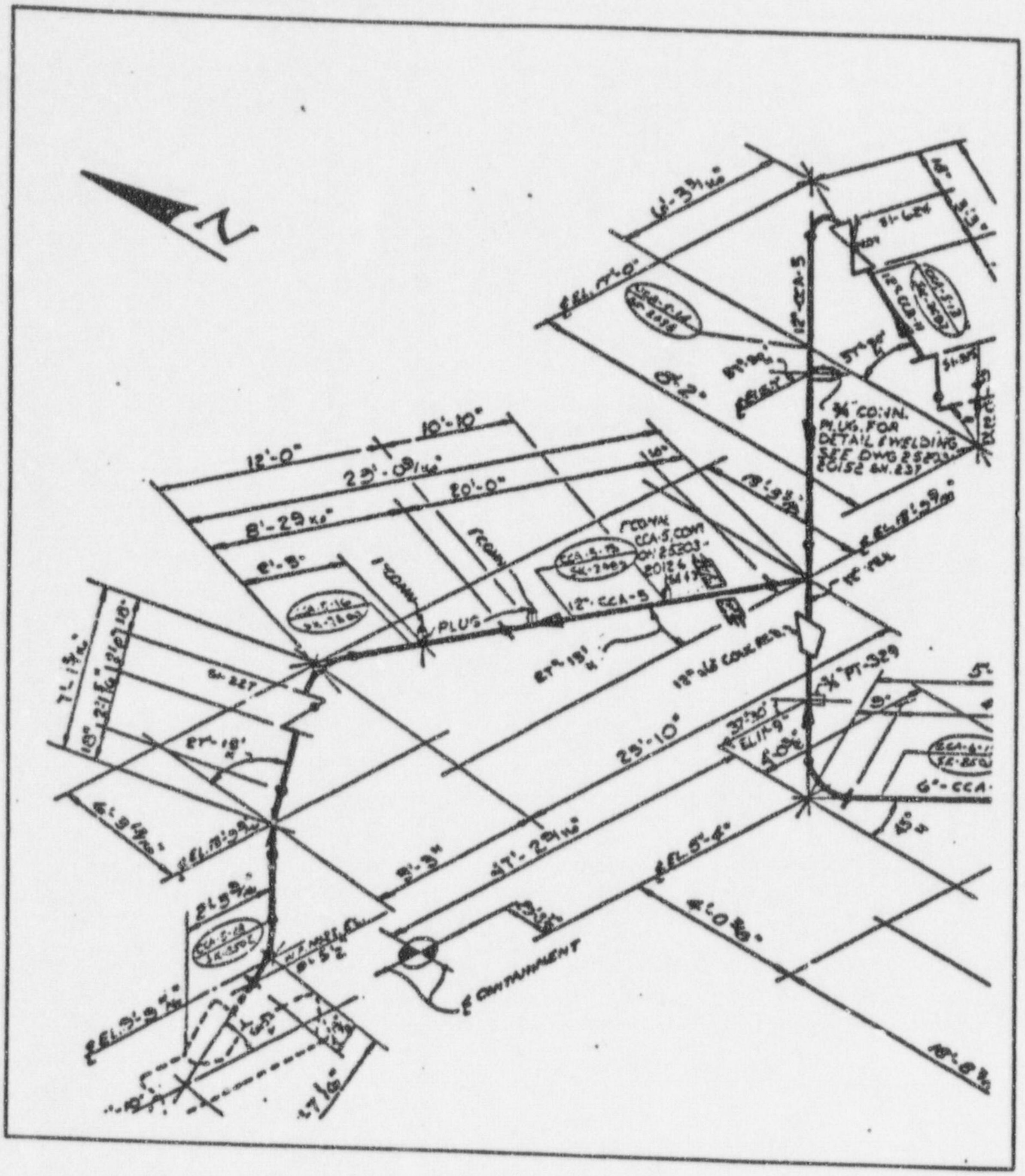

Figure 2: Loop 1B Safety Injection Line

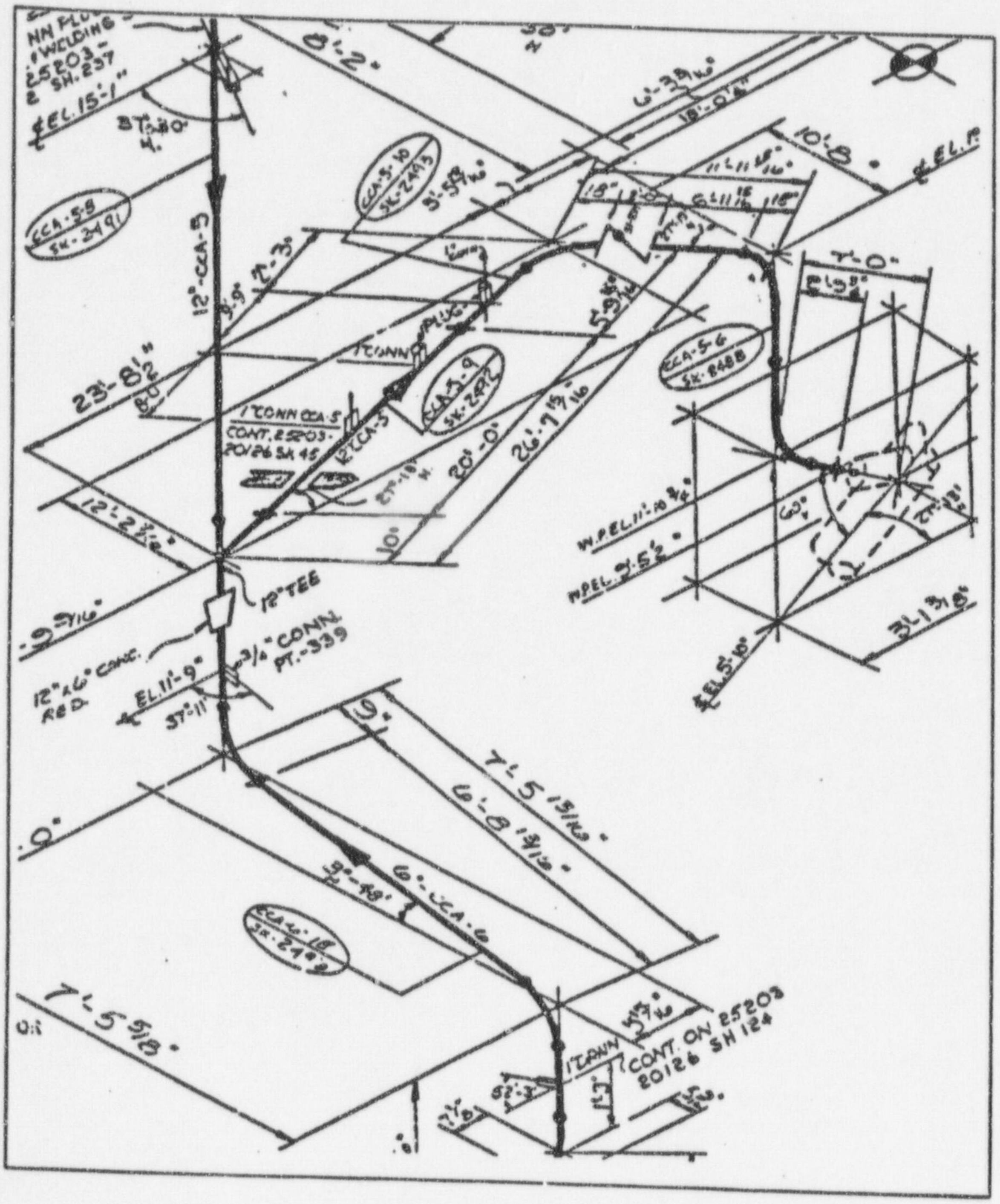

Figure 3: Loop 2A Safety Injection Line

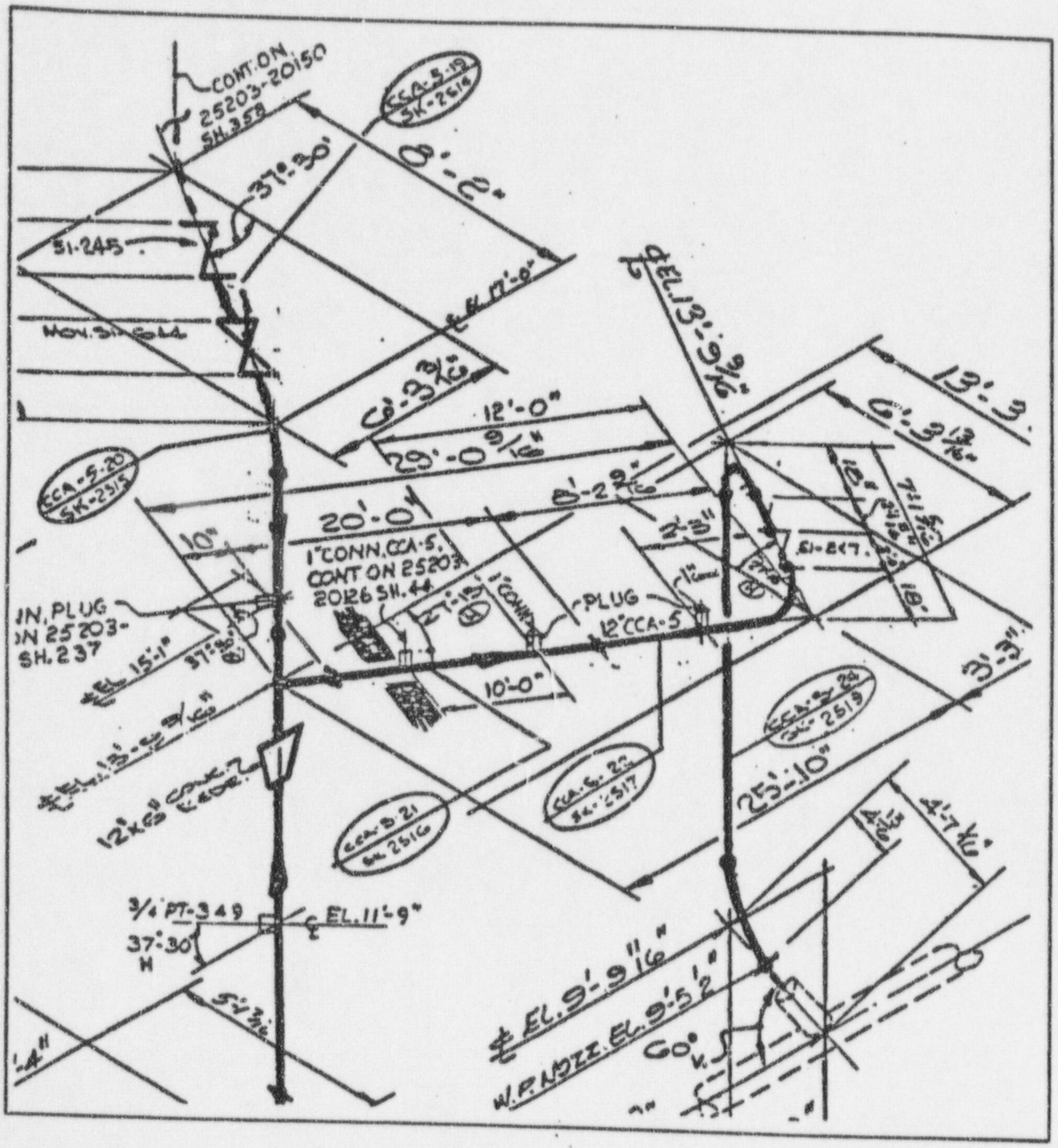

Figure 4: Loop 2B Safety Injection Line

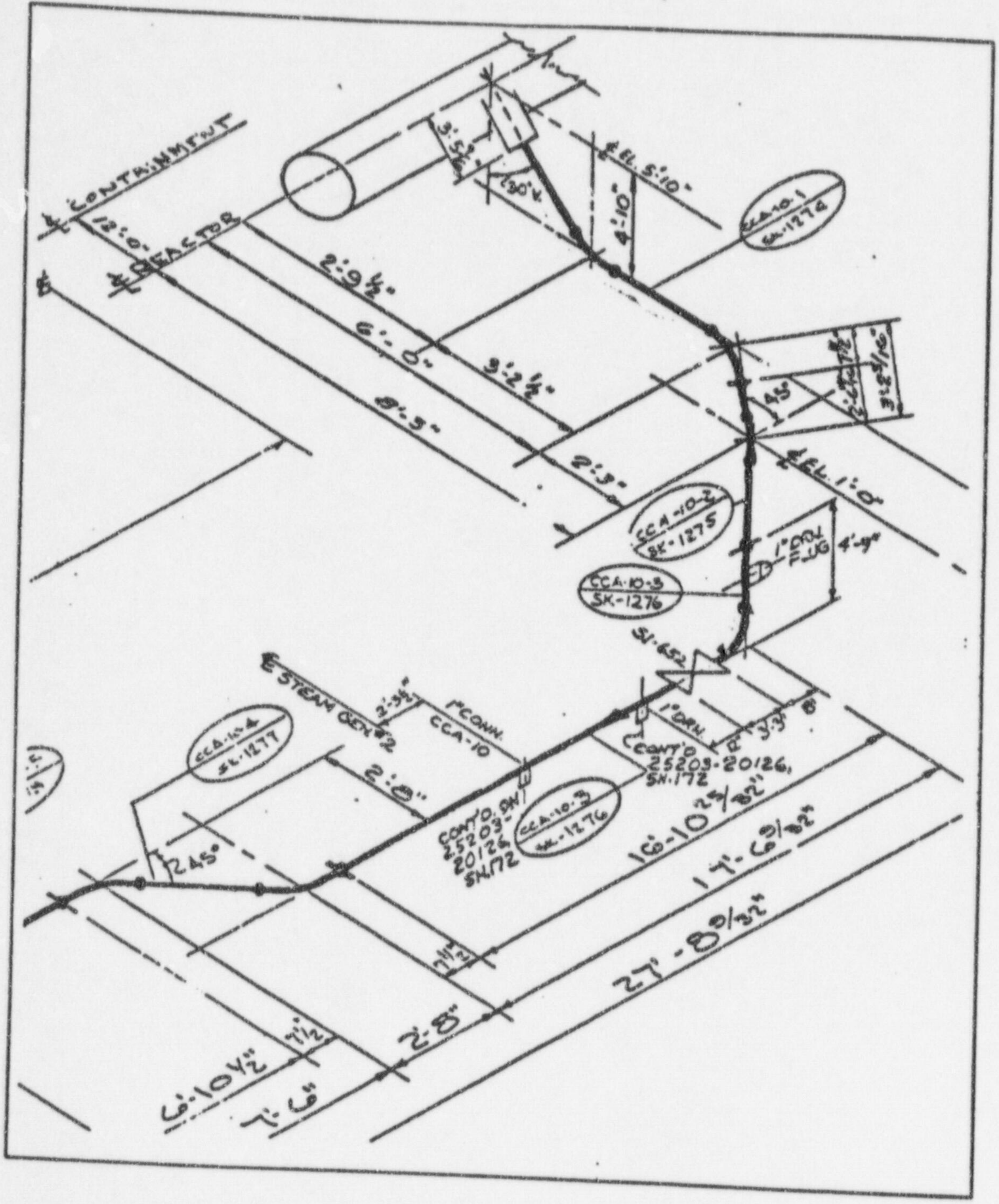

Figure 5: Shutdown Cooling Line

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The enclosed Safety Evaluation provides the details of the staff's review. This completes all staff actions related to the referenced TAC number. If ther are any questions, please contact me at (301) 415-1408.

Sincerely,

Original signed by:

Daniel G. McDonald, Jr., Senior Project Manager
Millstone Project Directorate
Division of Reactor Projects - I/II
Office of Nuclear Reactor Regulation

Docket No. 50-336

Enclosure: Safety Evaluation

cc w/encl: See next page

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