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Leak-Before-Break Evaluation
Main Steam Piping Inside Containment
Diablo Canyon Power Plant Units 1 and 2

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Structural Integrity Associates Report SIR-03-146, Revision 1, "Leak-Before-Break Evaluation, Main Steam Piping Inside Containment, Diablo Canyon Power Plant Units 1 and 2," dated December 2003

SUMMARY

This report presents a leak-before-break (LBB) evaluation for the main steam piping inside containment at Diablo Canyon Power Plant (DCPP), Units 1 and 2 (operated by Pacific Gas & Electric Company). The evaluation was performed to address high-energy line break concerns with these lines. The LBB evaluation was performed in accordance with the 10 CFR 50, Appendix A GDC-4 and NUREG-1061, Vol. 3 as supplemented by NUREG-0800, Standard Review Plan 3.6.3.

The methodology used in determining LBB capabilities of the main steam piping at DCPP consisted of several steps. First, the relationship between the critical through-wall flaw length and the applied stress (or moments) was determined on a generic basis for circumferential flaws. The critical flaw size as used herein refers to the through-wall flaw length that becomes unstable under a given set of applied loads. Critical flaw sizes were calculated using the elastic-plastic fracture mechanics (EPFM) J-Integral/Tearing Modulus (J/T) approach with conservative material properties. NUREG-1061 requires that the load combination considered in determining the through-wall flaw length include the normal operating loads (NOP), which consists of internal pressure, dead weight, and thermal expansion loads, plus the seismic SSE and other dynamic loads. In this evaluation, the other dynamic load consists of the piping loads generated by rapid actuation of the main steam isolation valves (MSIV), which are located outside containment. The dynamic load considered (DYN) is the highest of SSE and MSIV. Hence, once the NOP+DYN load for a given location is known, the critical flaw length can be determined from the generic relationship. The "leakage flaw size" was determined as the minimum of one half the critical flaw size with a factor of unity on normal operating plus DYN loads or the critical flaw size with a factor of $\sqrt{2}$ on normal operating plus DYN loads. Thus, the leakage flaw size as referred herein maintains a safety factor of 2 on the critical flaw size under normal plus DYN loads or a safety factor of $\sqrt{2}$ on the loads.

Leakage rates were determined as a function of stress (or moment) on a generic basis for a given through-wall flaw length. NUREG-1061, Vol. 3 requires that the NOP loads be used to

determine the leakage. On a generic basis, a family of curves was developed relating the leakage with the NOP loads to the through-wall flaw length.

Given the relationships between the leakage flaw size versus NOP+DYN moments and leakage flaw size versus NOP moments above (for a particular level of leakage), a relationship was developed between the NOP+DYN moments and the NOP moments that would result in a particular leakage. The actual piping NOP+DYN and NOP loads were then applied to determine if the combination of those loads would meet that leakage. This particular scheme is very convenient for determining whether or not a particular leakage will be met for a piping system with many nodal points and associated moments, such as the main steam piping considered in this evaluation.

A fatigue crack growth analysis was also performed to determine the growth of postulated semi-elliptical, inside surface flaws with an initial size based on ASME Code Section XI acceptance standards. This showed that crack growth due to cyclic loadings was not significant such that it could be managed by the Section XI inspection program.

The following summary of the LBB evaluation is formatted along the lines of the "Recommendations for Application of the LBB Approach" in the NUREG-1061 Vol. 3 executive summary:

(a) The main steam piping systems are constructed of SA-516, Grade 70 carbon steel piping, At the operating temperature of 519°F, this material is very ductile and it is not susceptible to cleavage-type fracture. In addition, it has been shown that these systems are not susceptible to the effects of corrosion, high cycle fatigue or water hammer.

(b) Loadings have been determined from the original piping analysis, and are based upon pressure, dead weight, thermal expansion, and safe shutdown earthquake and other dynamic loads such as MSIV rapid closure loads. Three seismic cases were considered in the Diablo Canyon design basis: DE, DDE, and Hosgri. The highest of these, Hosgri, was considered in this evaluation as the SSE case. The Hosgri case was enveloped with

the MSIV loads. All stress locations in the main steam piping inside containment at DCPP were considered.

(c) Plant specific certified material test report (CMTR) data was used to establish conservative lower bound stress-strain properties to be used in the evaluations. For the fracture toughness properties, lower-bound generic industry material properties for the piping and welds have been conservatively used in the evaluations.

(d) Crack growth analysis was conducted at the most critical locations on all the evaluated piping, considering the cyclic stresses predicted to occur over the life of the plant. For a hypothetical flaw with aspect ratio of 10:1 and an initial flaw depth of approximately 15% of pipe wall, the final flaw size after considering all plant transients for 40-year plant life is 41%, which is significantly less than ASME Code Section XI allowable flaw size of 75%. Hence, fatigue crack growth is not a problem for the main steam piping.

(e) Based on evaluation of all weld locations in the piping system, including axial welds and elbows, it was determined that the leakage at the limiting location was 2 gpm. NUREG-1061 Vol. 3 recommends that the leakage detection system be capable of measuring leakage 1/10 of this amount.

(f) Each of the eight main steam lines considered in this evaluation is approximately 90 feet in length and is not geometrically complex. All other dynamic loads that could occur in the systems, such as MSIV actuations, were considered with the SSE loads to determine the dynamic loads to be used in the evaluation.

(g) Crack growth of a leakage size crack in the length direction due to a DYN event was shown to be no more than 1% of the leakage flaw size. This is not significant compared to the margin between the leakage-size crack size and the critical crack size.

(h) For all locations, the critical size circumferential crack was determined for the combination of normal plus safe shutdown earthquake (SSE) loads or MSIV loads,

whichever is greater. The leakage size flaw was chosen such that its length was no greater than the critical crack size reduced by a factor of two. Axial cracks were considered and were shown to exhibit much higher leakage and more margin than circumferentially oriented cracks.

(i) For all locations, the critical crack size was also determined for the combination of $\sqrt{2}$ times the normal plus DYN loads. The leakage size crack was selected to be no greater than this critical crack size. (The minimum of the crack sizes determined by this criterion, and that of the criterion of (h) above, was chosen for calculation of the leakage rate for each location.)

(j-n) No special testing (other than information in the CMTRs) was conducted to determine material properties for fracture mechanics evaluation. Instead, information from the piping CMTRs was used to derive lower bound material toughness and tensile properties in the evaluations. The material properties so determined have been shown to be applicable near the upper range of normal plant operation and exhibit ductile behavior at these temperatures.

(o) Limit load analysis was not utilized in this evaluation since the main steam piping material is carbon steel. EPFM J/T analysis approach was used to determine the critical flaw sizes.

Thus, it is concluded that, using methodology conforming to the requirements of NUREG-1061 Vol. 3, the main steam piping at Diablo Canyon Units 1 and 2 evaluated in this report qualifies for the application of leak-before-break analysis. The limiting leakage is determined to be 2 gpm for Unit 1 and 3.5 gpm for Unit 2. NUREG-1061 requires a safety factor of 10 on these leakages for demonstrating leak detection capability.

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1.0 INTRODUCTION

1.1 Background

This report documents evaluations performed by Structural Integrity Associates (SI) to determine the leak-before-break (LBB) capabilities of the high energy main steam piping inside containment at Diablo Canyon Power Plant (DCPP) Units 1 and 2. The portion considered is that from the steam generators to the containment penetrations. These evaluations were undertaken to address the potential for high energy line break at these locations. The approach taken to address LBB for the main steam lines at DCPP is consistent with that used by SI in other recent LBB submittals for other plants [1, 2, 3].

1.2 Leak-Before-Break Methodology

NRC SECY-87-213 [4] covers a rule to modify General Design Criterion 4 (GDC-4) of Appendix A, 10 CFR Part 50. This amendment to GDC-4 allows exclusion from the design basis of all dynamic effects associated with high energy pipe rupture by application of LBB technology.

Definition of the LBB approach and criteria for its use are provided in NUREG-1061 [5], supplemented by NUREG-0800, SRP 3.6.3 [6]. Volume 3 of NUREG-1061 defines LBB as "...the application of fracture mechanics technology to demonstrate that high energy fluid piping is very unlikely to experience double-ended ruptures or their equivalent as longitudinal or diagonal splits." The particular crack types of interest include circumferential through-wall cracks (TWC) and part-through-wall cracks (PTWC), as well as axial or longitudinal through-wall cracks (TWC), as shown in Figure 1-1.

LBB is based on a combination of in-service inspection (ISI) and leak detection to detect cracks, coupled with fracture mechanics analysis to show that pipe rupture will not occur for cracks smaller than those detectable by these methods. A discussion of the criteria for application of LBB is presented in Section 2 of this report, which summarizes NUREG-1061, Vol. 3 requirements.

The approach to LBB which has gained acceptance for demonstrating protection against high energy line break (HELB) in safety-related nuclear piping systems is schematically illustrated in Figure 1-2. Essential elements of this technique include critical flaw size evaluation, crack propagation analysis, volumetric nondestructive examination (NDE) for flaw detection/sizing, leak detection, and service experience. In Figure 1-2, a limiting circumferential crack is modeled as having both a short through-wall component, or an axisymmetric part-through-wall crack component. Leak detection establishes an upper bound for the through-wall crack component while volumetric ISI limits the size of undetected part-through-wall defects. These detection methods complement each other, since volumetric NDE techniques are well suited to the detection of long cracks while leakage monitoring is effective in detecting short through-wall cracks. The level of NDE required to support LBB involves volumetric inspection at intervals determined by fracture mechanics crack growth analysis, which would preclude the growth of detectable part-through-wall cracks to a critical size during an inspection interval. A fatigue evaluation is performed to ensure that an undetected flaw acceptable per ASME Section will not grow significantly during service. For through-wall defects, crack opening areas and resultant leak rates are compared with leak detection limits.

The net effect of complementary leak detection and ISI is illustrated by the shaded region of Figure 1-2 as the largest undetected defect that can exist in the piping at any given time. Critical flaw size evaluation, based on elastic-plastic fracture mechanics techniques, is used to determine the length and depth of defects that would be predicted to cause pipe rupture under specific design basis loading conditions, including abnormal conditions such as a seismic event and including appropriate safety margins for each loading condition. Crack propagation analysis is used to determine the time interval in which the largest undetected crack could grow to a size which would impact plant safety margins. A summary of the elements for a leak-before-break analysis is shown in Figure 1-3. Service experience, where available, is useful to confirm analytical predictions as well as to verify that such cracking tends to develop into "leak" as opposed to "break" geometries.

Risk Informed Inservice Inspection (RI-ISI) methodology has been implemented at Diablo Canyon, which has resulted in a reprioritization and net reduction in volumetric weld examinations. The main steam system is classified as Category 6, low risk, due to the absence of active degradation

mechanisms. However, in conjunction with the application of leak-before-break methodology, supplementary inspections of the limiting weld location on each main steam line inside containment will be performed.

In accordance with NUREG-1061, Vol. 3 [5] and NUREG-0800, SRP 3.6.3 [6], the leak-before-break technique for the high energy piping systems evaluated in this report included the following considerations.

- Elastic-plastic fracture mechanics analysis of load carrying capacity of cracked pipes under worst case normal loading, with safe-shutdown earthquake (SSE) and other dynamic loads included. Such analysis includes elastic-plastic fracture data applicable to pipe weldments and weld heat affected zones where appropriate.

- Limit-load analysis in lieu of the elastic-plastic fracture mechanics analysis described above. In this evaluation, limit load analysis was not applied due to the carbon steel material.

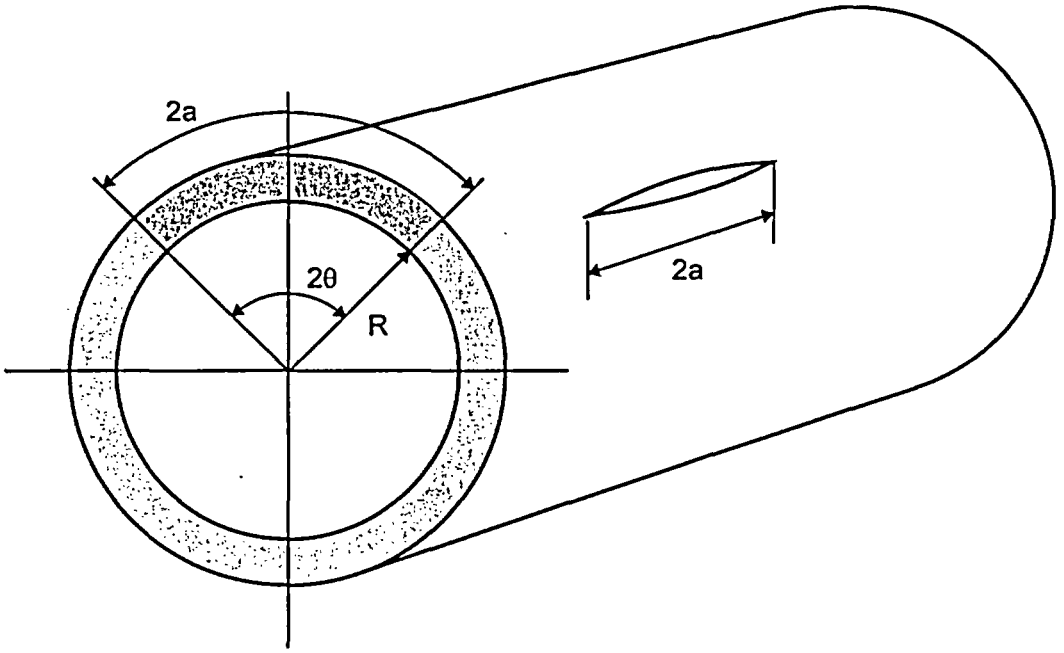
- Linear elastic fracture mechanics analysis of subcritical crack propagation to determine ISI (in-service inspection) intervals for long, part-through-wall cracks.

- A piping system evaluation to determine the effect of piping restraint on leakage for small diameter piping.

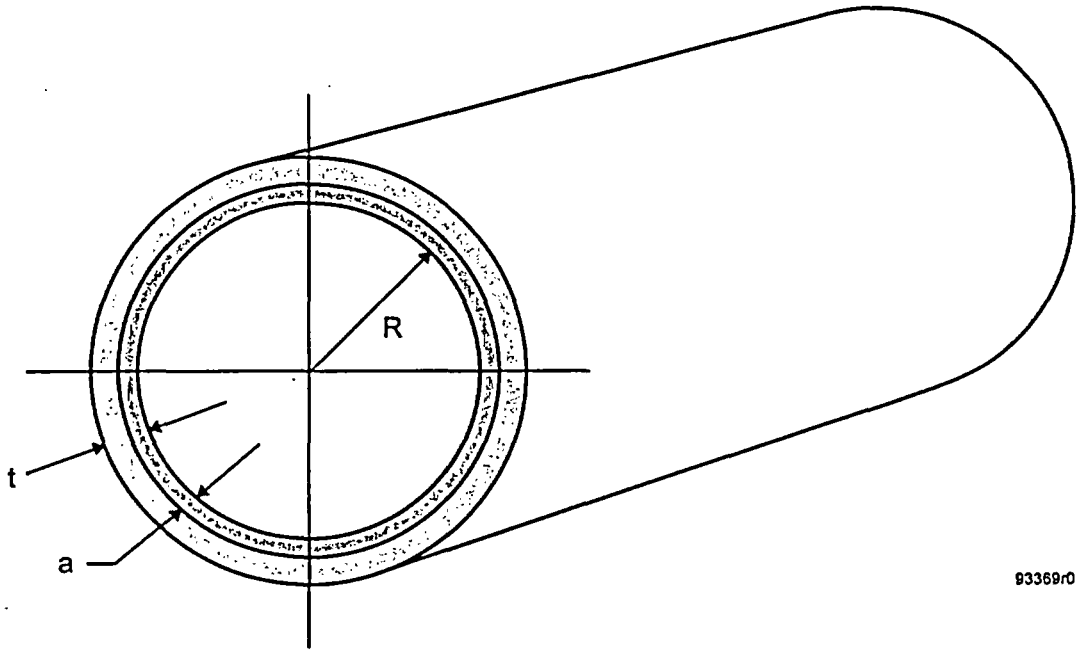
Piping stresses have a dual role in LBB evaluations. On one hand, higher maximum (design basis) stresses tend to yield lower critical flaw sizes, which result in smaller flaw sizes for assessing leakage. On the other hand, higher operating stresses tend to open cracks more for a given crack size and create a higher leakage rate. Because of this duality, the use of a single maximum stress location for a piping system may result in a non-conservative LBB evaluation. Thus, the LBB evaluation reported herein has been performed for each nodal location addressed in the plant piping system analysis.

1.3 Leak Detection Requirement

Application of LBB evaluation methodology is predicated on having a very reliable leak detection system at the plant. This evaluation will determine the minimum leakage rate based on the normal operating and normal plus dynamic loads for the eight main steam lines. NUREG-1061 requires the demonstration of leak detection capability of leak rates of 1/10 of this amount.



a. Circumferential and Longitudinal Through-Wall Cracks of Length 2a.



b. Circumferential 360 Part-Through-Wall Crack of Depth a.

Figure 1-1. Representation of Postulated Cracks in Pipes for Fracture Mechanics Leak-Before-Break Analysis

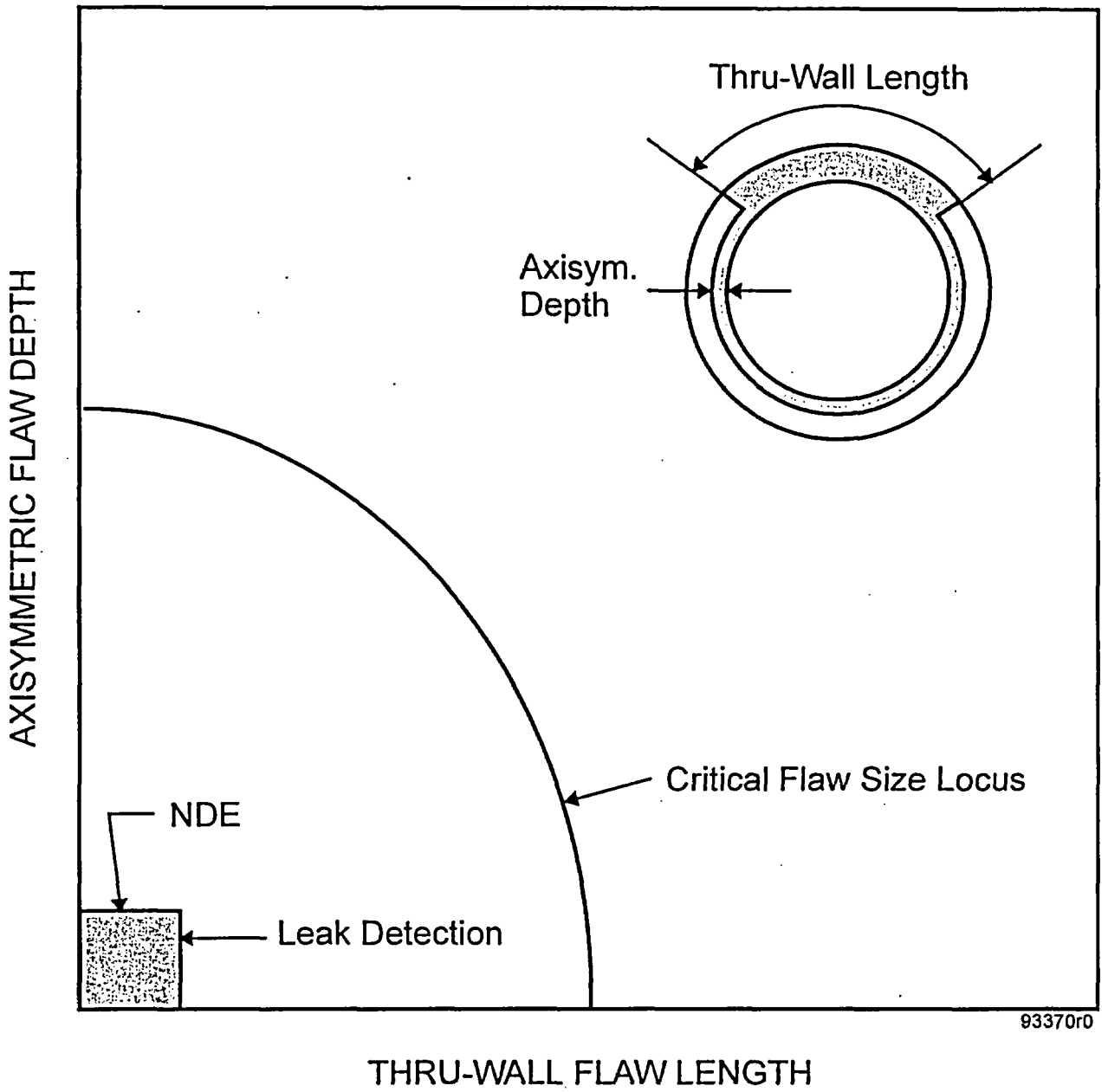


Figure 1-2. Conceptual Illustration of ISI (UT)/Leak Detection Approach to Protection Against Pipe Rupture

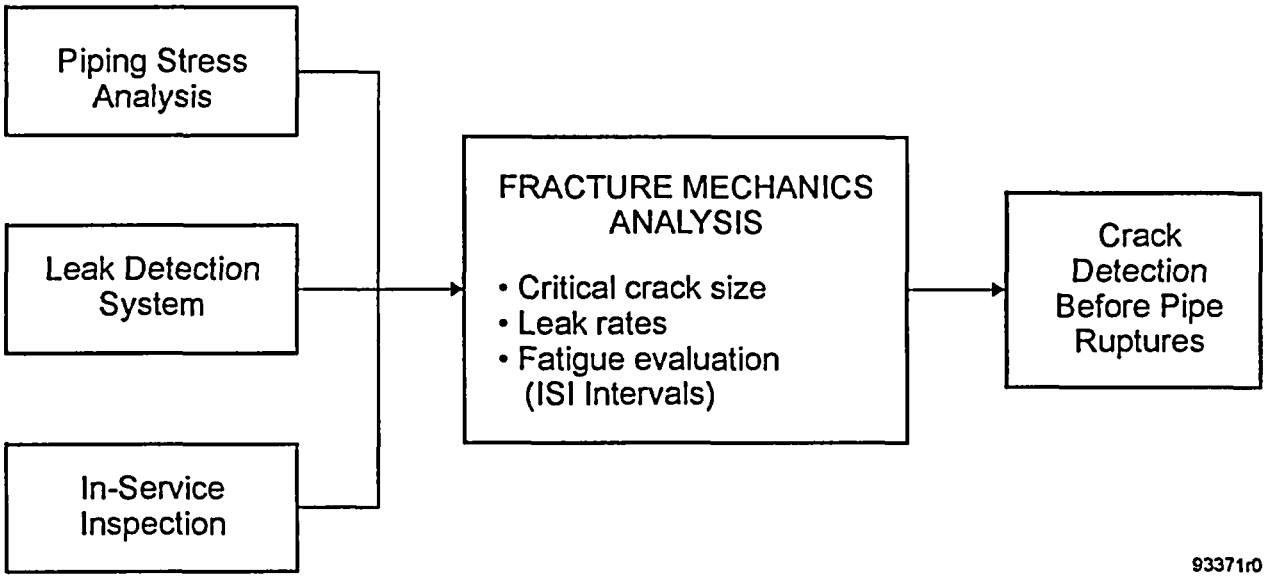


Figure 1-3. Leak-Before-Break Approach Based on Fracture Mechanics Analysis with In-service Inspection and Leak Detection

2.0 CRITERIA FOR APPLICATION OF LEAK-BEFORE-BREAK

NUREG-1061, Vol. 3 [5] identifies several criteria to be considered in determining applicability of the leak-before-break approach to piping systems. Section 5.2 of NUREG-1061, Vol. 3 provides extensive discussions of the criteria for performing leak-before-break analyses. These requirements are restated in NUREG-0800, SRP 3.6.3 [6]. The details of the discussions are not repeated here; the following summarizes the key elements:

2.1 Criteria for Through-Wall Flaws

Acceptance criteria for critical flaws may be stated as follows:

1. A critical flaw size shall be determined for normal operating conditions plus safe shutdown earthquake (SSE) loads. Leakage for normal operating conditions must be detectable for this flaw size reduced by a factor of two.

2. A critical flaw size shall be determined for normal operating conditions plus SSE loads multiplied by a factor of $\sqrt{2}$. Leakage for normal operating conditions must be detectable for this flaw size.

It has been found in previous evaluations conducted by Structural Integrity Associates (SI) that in general, the first criterion bounds the second. However, in this evaluation, both criteria were considered for completeness. Also, it has been found in previous evaluations that circumferential flaws are bounding. However, in this evaluation, both circumferential and axial flaws are considered, since the main steam piping at DCPP is seam-welded and the possibility of axial flaws in the seam welds needs to be considered.

Either elastic-plastic fracture mechanics instability analysis or limit load analysis may be used in determining critical flaw sizes. Since the material of the main steam piping at DCPP is carbon steel, which is semi-ductile to ductile at high temperatures, the more conservative elastic-plastic J-Integral/Tearing analysis methodology is used in this evaluation to determine the critical flaw sizes.

2.2 Criteria for Part-Through-Wall Flaws

NUREG-1061, Vol. 3 [5] requires demonstration that a long part-through-wall flaw which is detectable by ultrasonic means will not grow due to fatigue to a depth which would produce instability over the life of the plant. This is demonstrated in Section 6.0 of this report, where the analysis of subcritical crack growth is discussed.

2.3 Consideration of Other Mechanisms

NUREG-1061, Vol. 3 [5] limits applicability of the leak-before-break approach to those locations where degradation or failure by mechanisms such as water hammer, erosion/corrosion, fatigue, and intergranular stress corrosion cracking (IGSCC) is not a significant possibility. These mechanisms were considered for the main steam piping at DCPP, as reported in Section 3 of this report.

3.0 CONSIDERATION OF WATER HAMMER, CORROSION AND FATIGUE

NUREG-1061, Vol. 3 [5] states that LBB should not be applied to high energy lines susceptible to failure from the effects of water hammer, corrosion or fatigue. These potential failure mechanisms are thus discussed below with regard to the affected main steam piping at DCPP, and it is concluded that the above failure mechanisms do not invalidate the use of LBB for this piping system.

3.1 Water Hammer

A comprehensive study performed in NUREG-0927 [7] indicated that the probability of water hammer occurrence in the main steam system of a PWR is very low. In NUREG-0927, eight water hammer events were reported for the entire PWR fleet. Out of these eight events, four were due to sudden valve closures or openings, three were due to steam-water environment, and one was due to relief valve discharge. No water hammer event has occurred in the main steam piping system inside containment at Diablo Canyon since the units went into operation. In addition, PG&E follows the guidelines recommended in EPRI Topical Report No. TR-106438 [8] to manage and prevent water hammer events at DCPP. As such, water hammer is highly unlikely for the main steam piping system at DCPP. Loads due to MSIV rapid closure are being considered and are sometimes controlling in determining critical flaw sizes.

3.2 Corrosion

Two corrosion damage mechanisms which can lead to rapid piping failure are intergranular stress corrosion cracking (IGSCC) in austenitic stainless steel pipes and flow-assisted corrosion (FAC) in carbon steel pipes. IGSCC has principally been an issue in austenitic stainless steel piping in boiling water reactors [9] resulting from a combination of tensile stresses, susceptible material and oxygenated environment. IGSCC is not typically a problem for carbon steel piping such as that under consideration for the main steam piping at DCPP.

FAC is a problem for carbon steel piping with two-phase flow [10]. The main steam piping at DCPP is not susceptible to FAC since the system contains high quality steam.

3.3 Fatigue

Although there have been numerous cracks in steam generator feedwater piping-to-nozzle welds, no similar mechanism exists, nor has there ever been any reported cracking in steam generator main steam piping. The thermal transients for the main steam piping occur very slowly such that the major loading is that due to piping thermal expansion combined with pressure. These loadings and the resultant possible crack growth have been considered by the analyses reported in Section 6.0 of this report. Based on the results presented in Section 6.0, it is concluded that fatigue is not a significant degradation mechanism for the main steam piping at Diablo Canyon Units 1 and 2.

4.0 PIPING MATERIALS AND STRESSES

4.1 Piping System Description

The main steam piping is used to transport high quality steam from the steam generators to the turbine. There are a total of eight main steam lines, four for each unit. The lines originate from the four steam generators in each unit. Only the portions of the main steam piping inside containment are considered in this evaluation. Schematics of the mathematical models for these lines, including selected nodal points, are shown in Figures 4-1 through 4-8 [11-18]. The lines are 28-inch nominal pipe size, and are fabricated from SA-516, Grade 70 seam welded carbon steel. A 28-inch by 32-inch reducing elbow connects the main steam piping to the main steam nozzle of each steam generator. There are two elbows downstream of each nozzle inside containment, that are fabricated from SA-106, Grade C [19, 20]. At the containment penetration, the main stream piping connects to a flued head fabricated from SA-105 material [19, 20]. The portion of the main steam piping considered in this evaluation starts at the weld connecting the reducing elbow to the nozzle, and extends to the weld connecting the main steam piping to the flued head.

4.2 Material Properties

The material properties of interest for fracture mechanics and leakage calculations are the Modulus of Elasticity (E), the yield stress (S_y), the ultimate stress (S_u), the Ramberg-Osgood parameters for describing the stress strain curve (α and n), the fracture toughness (J_{IC}) and power law coefficient for describing the material J Resistance curve (C and N).

NUREG-1061, Vol. 3 requires that actual plant specific material properties including stress-strain curves and J-R material properties be used in the LBB evaluations. In lieu of this requirement, material properties from the certified materials reports (CMTRs) are used to derive lower bound material properties to provide a conservative assessment of critical flaw sizes and leakage rates.

The material for the main steam piping at DCPP is SA-516, Grade 70 [19, 20]. The pipe is seam welded. The reducing elbows connecting the piping to the steam generator nozzles are also fabricated with SA-516, Grade 70 material. The material for the downstream elbows in the piping

system is SA-106, Grade C. The flued head connecting the piping to the containment penetration is SA-105, Grade II. Review of the fabrication records indicate that all welds (both the seam welds and butt welds) were fabricated using both submerged arc welding (SAW) and shielded metal arc welding (SMAW) with E7018 weld electrodes and equivalent insert material.

For the purpose of determining the material properties to use in the evaluations, the mechanical properties from the CMTRs were reviewed and summarized in Tables 4-1 and 4-2, for both the base materials and the weld metals. As can be seen from these tables, the yield strength (S_y) varies from 42.1 ksi to 48 ksi for the SA-516, Grade 70 base material, and 40 ksi to 50 ksi for the SA-106, Grade C elbow materials. The ultimate strength (S_u) for the SA-516 Grade 70 base material varies from 74.1 ksi to 79.9 ksi, 74.6 to 78.8 ksi for the SA-106 elbow, and 70.3 to 79.6 ksi for the weld material. The elongation of the SA-516, Grade 70 base material varies from 21% to 37%. It should be noted that only the value of S_u is provided in the CMTRs for the weld material. However, in general, the weld material is not limiting with regards to S_y and the percent elongation. The lower bound values of S_y, S_u and the percentage elongation are compared with the ASME Code [21, 22] minimum properties for SA-516, Grade 70 and SA-106, Grade C in Table 4-3, and as can be seen from this comparison, the lower bound values are only marginally greater than the Code values. For this reason, the Code minimum values for S_u, and E for SA-516, Grade 70 are conservatively chosen to be used in this evaluation.

The Ramberg-Osgood stress-strain parameters used to describe the true stress-strain curve were obtained from the mechanical properties using the correlations developed in Reference 23. The true stress-true strain curve can be represented by the following relationship:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{4-1}$$

where: ε, σ are the true strain and true stress,

ε_o, σ_o are the yield strain and yield stress, and

α, n are the Ramberg-Osgood parameters.

The values of α and n are then obtained from the relationship provided in Reference 23 as:

$$n = \frac{1}{\ln(1+e_u)} \tag{4-2}$$

$$\alpha = \left[\frac{\ln(1+e_u)}{\ln\left(1+\frac{S_y}{E}\right)} - \frac{S_u(1+e_u)}{S_y\left(1+\frac{S_y}{E}\right)}\right]\left[\frac{S_u(1+e_u)}{S_y\left(1+\frac{S_y}{E}\right)}\right]^{-n} \tag{4-3}$$

where, e_u is the ultimate elongation, and E is the elastic modulus.

All the stress-strain properties used in this evaluation are provided in Table 4-4.

The lower bound fracture toughness properties for SA-516, Grade 70 steel and associated weldments provided in the technical basis documents for flaw evaluation of carbon steel piping in the ASME Code Section XI was used in the evaluation [24, 25]. This fracture toughness curve is provided in a power law format and the parameters are provided in Table 4-4, together with J_{IC}.

4.3 Piping Moments and Stresses

The piping moments and stresses considered in the LBB evaluation are due to pressure (P), dead weight (DW), thermal expansion (TE) and safe shutdown earthquake inertia and anchor movements (SSE) consistent with the guidance provided in NUREG-1061, Vol. 3. An additional dynamic load due to MSIV rapid closure was considered for the main steam piping. The maximum of either the SSE load or MSIV load for a location is used in the evaluation. Per the guidance provided in NUREG-1061, other secondary stresses such as residual stresses and through-wall thermal stresses were not included in the evaluation.

For calculation of leakage, the normal operating (NOP) loads consisting of pressure, dead weight and thermal expansion loads are used. For calculation of critical flaw size, the maximum of the SSE and MSIV loads is added to the NOP loads (referred to as the NOP + DYN loading condition). Summaries of the piping moments for those load conditions are shown in Tables 4-5 through 4-12 [26] for each of the eight main steam lines at DCPP. For calculation of critical flaw

size, the moments and stresses due to pressure, dead weight, thermal expansion and SSE loads were combined according to the Diablo Canyon design basis load combinations, and a factor of safety of $\sqrt{2}$ was applied. An additional case was considered with a factor of unity on loads and a factor of safety of 2 on critical flaw size. Stresses were calculated directly from the piping analysis moments for the various lines considered in this evaluation. The limiting seismic case, Hosgri, was used in the load combinations. The resulting stresses used in the fracture mechanics analysis do not include the effects of stress indices.

The axial stress due to normal operating pressure is calculated from the expression:

$$\sigma_p = \frac{pD_i^2}{D_o^2 - D_i^2}$$

where p is the internal pressure, D_o is the outside diameter of the pipe and D_i is the inside diameter.

The bending stress due to dead weight, thermal expansion and SSE is calculated from the bending moments using the expression:

$$\sigma_m = \frac{M_r}{Z}$$

where:

Z	=	the section modulus and,
M_r	=	the resultant moment.

Axial forces due to dead weight, thermal expansion, seismic, and MSIV actuation were not considered in the evaluation. The stresses due to axial forces are not significant compared to those from pressure loads, so their exclusion does not significantly affect the results of this evaluation. This has been shown in a previous LBB submittal [3].

Table 4-1

Mechanical Properties for DCPP Main Steam Piping from CMTRs – Unit 1

Spool	Item No.	Description[1]	Heat No.	Material	Sy (ksi)	Su (ksi)	% Elongation
55	1	26" ID Pipe	CU4MAC	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	70.3	---
	2	26" ID Red. Elbow	CX4BH	SA-516 GR 70	48.0	74.1	25.0
		Center Weld			---	77.5	---
	4	26" ID Std. Elbow	86A742	A-106 GR C	40.3	77.5	33.0
56	1	26" ID Pipe	DJ4BJ	SA-516 GR 70	43.5	75.2	43.0
		Center Weld			---	70.5	---
	2	26" ID Pipe	CU4MS	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	76.0	---
58	1	26" ID Pipe	DH4RH	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	70.9	---
	2	26" ID Pipe	DH4RK	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	70.2	---
	4	26" ID Std. Elbow	86A742	A-106 GR C	40.3	77.5	33.0
59	1	26" ID Pipe	CU4MAA	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	72.5	---
	5	26" ID Pipe	CU4MS	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	76.0	---
63	1	26" ID Pipe	CU4LN	SA-516 GR 70	44.6	79.8	21.0
		Center Weld			---	76.8	---
	2	26" ID Red. Elbow	CX4BH	SA-516 GR 70	48.0	74.1	25.0
		Center Weld			---	77.5	---
	4	26" ID Std. Elbow	86A742	A-106 GR C	40.3	77.5	33.0
64	1	26" ID Pipe	DH4RN	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	70.4	---
	2	26" ID Pipe	CU4MAA	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	72.5	---
66	1	26" ID Pipe	DH4RL	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	74.0	---
	2	26" ID Pipe	DJ4BJ	SA-516 GR 70	43.5	75.2	43.0
		Center Weld			---	70.5	---
	3	26" ID Elbow	86A742	A106 GR C	40.3	77.5	33.0
67	1	26" ID Pipe	CU4MAA	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	72.5	---

Table 4-1

Mechanical Properties for DCPP Main Steam Piping from CMTRs – Unit 1 (continued)

Spool	Item No.	Description[1]	Heat No.	Material	Sy (ksi)	Su (ksi)	% Elongation
71	1	26" ID Pipe	CU4LN	SA-516 GR 70	44.6	79.8	21.0
		Center Weld			---	76.8	---
	2	26" ID Red. Elbow	CX4BH	SA-516 GR 70	48.0	74.1	25.0
		Center Weld			---	77.5	---
	4	26" ID Std. Elbow	86A742	A-106 GR C	40.3	77.5	33.0
72	1	26" ID Pipe	DH4RR	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	71.3	---
	2	26" ID Pipe	CU4MAA	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	72.5	---
74	1	26" ID Pipe	CU4MAC	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	70.3	---
	2	26" ID Pipe	DH4RH	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	70.9	---
	3	26" ID Std. Elbow	86A742	A-106 GR C	40.3	77.5	33.0
75	1	26" ID Pipe	CU4MAC	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	70.3	---
	5	26" ID Pipe	CU4MAA	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	72.5	---
79	1	26" ID Pipe	CU4MAB	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	71.3	---
	2	26" ID Red. Elbow	CX4BH	SA-516 GR 70	48.0	74.1	25.0
		Center Weld			---	77.5	---
	4	26" ID Elbow	86A742	A-106 GR C	40.3	77.5	33.0
80	1	26" ID Pipe	DH4RM	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	70.8	---
	2	26" ID Pipe	CU4MAA	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	72.5	----
82	1	26" ID Pipe	CU4MAF	SA-516 GR 70	42.1	74.7	22.5
		Center Weld			---	81.5	---
	2	26" ID Pipe	DH4RK	SA-516 GR 70	46.8	78.7	25.5
		Center Weld			---	70.2	---
	3	26" ID Elbow	86A742	A106 GR C	40.3	77.5	33.0
83	1	26" ID Pipe	FA4TH	SA-516 GR 70	46.8	75.8	25.0
60, 68, 76A, 84C	6	40" x 28" flued head	4R8740	SA-105 GR II	43.3	73.6	29.6

[1] For the center weld, only the S_u value is listed in the CMTR.

Table 4-2

Mechanical Properties for DCPP Main Steam Piping from CMTRs – Unit 2

Spool	Item No.	Description[1]	Heat No.	Material	Sy (ksi)	Su (ksi)	% Elongation
58	1	26" ID Pipe	DH4MX	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	72.2	---
	2	26" ID Red. Elbow	DK4CH	SA-516 GR 70	44.7	79.5	26.0
		Parent			50.3	77.0	34.0
		Center Weld			---	75.8	---
	4	26" ID Std. Elbow	259556	A-106 GR C	49.5	78.8	31.4
		Parent			54.3	78.4	30.0
59	1	26" ID Pipe	DH4MAA	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	73.8	---
	2	26" ID Pipe	DH4MZ	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	78.1	---
60	1	26" ID Pipe	DH4MAG	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	74.6	---
	2	26" ID Pipe	DH4MAH	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	72.8	---
	3	26" ID Std. Elbow	DK4NJ	A-106 GR C	40.5	74.6	26.0
		Parent			47.9	75.9	32.0
		Center Weld			---	74.1	---
61	1	26" ID Pipe	DJ4BL	SA-516 GR 70	43.5	75.2	43.0
		Center Weld			---	73.4	---
65	1	26" ID Pipe	DJ4LJ	SA-516 GR 70	43.9	81.6	18.0
		Center Weld			---	76.6	---
	2	26" ID Red. Elbow	DK4CH	SA-516 GR 70	44.7	79.5	26.0
		Parent			50.3	77.0	34.0
		Center Weld			---	75.8	---
	4	26" ID Std. Elbow	259556	A-106 GR C	49.5	78.8	31.4
		Parent			54.3	78.4	30.0
66	1	26" ID Pipe	DH4MAL	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	73.6	---
	2	26" ID Pipe	DH4MAK	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	71.4	---
67	1	26" ID Pipe	DH4MAF	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	79.6	---
	2	26" ID Pipe	DH4MY	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	74.6	---
	3	26" ID Std. Elbow	DK4NJ	A-106 GR C	40.5	74.6	26.0
		Parent			47.9	75.9	32.0
		Center Weld			---	74.1	---

Table 4-2

Mechanical Properties for DCPP Main Steam Piping from CMTRs – Unit 2 (continued)

Spool	Item No.	Description[1]	Heat No.	Material	Sy (ksi)	Su (ksi)	% Elongation
68	1	26" ID Pipe	DH4MAN	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	71.2	---
72	1	26" ID Pipe	DH4MAH	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	72.8	---
		26" ID Red. Elbow	DK4BH	SA-516 GR 70	45.6	76.2	26.0
	2	Parent			46.2	71.6	34.0
		Center Weld			---	72.9	---
	4	26" ID Std. Elbow	259556	A-106 GR C	49.5	78.8	31.4
		Parent			54.3	78.4	30.0
73	1	26" ID Pipe	DJ4LH	SA-516 GR 70	43.9	81.6	18.0
		Center Weld			---	71.3	---
	2	26" ID Pipe	DH4MY	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	74.6	---
74	1	26" ID Pipe	DH4MAD	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	73.8	---
	2	26" ID Pipe	DH4MZ	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	78.1	---
	3	26" ID Std. Elbow	DK4NJ	A-106 GR C	40.0	74.6	26.0
		Parent			47.0	75.9	32.0
		Center Weld			---	74.0	---
75	1	26" ID Pipe	DH4MAB	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	70.2	---
80	1	26" ID Pipe	DH4MW	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	74.1	---
	2	26" ID Red. Elbow	DK4BH	SA-516 GR 70	45.6	76.2	26.0
		Parent			46.2	71.6	34.0
		Center Weld			---	72.9	---
	4	26" ID Std. Elbow	259556	A-106 GR C	49.5	78.8	31.4
		Parent			54.3	78.4	30.0
81	1	26" ID Pipe	DJ4LK	SA-516 GR 70	43.9	81.6	18.0
		Center Weld			---	78.9	---
	2	26" ID Pipe	DH4MAJ	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	70.4	---
82	1	26" ID Pipe	DH4MAC	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	73.4	---
	2	26" ID Pipe	DH4MAA	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	73.8	---
	3	26" ID Elbow	DH4XK	A-106 GR C	50.2	76.3	24.0
		Parent			49.7	77.9	32.0
		Center Weld			---	75.1	---
83	1	26" ID Pipe	DH4MAM	SA-516 GR 70	44.7	79.3	21.0
		Center Weld			---	71.6	---
62, 69 76, 84	6	40" x 28" flued head	4RA8740	SA-105 GR II	36.4	71.8	30.6

[1] For the center weld, only the S_u value is listed in the CMTR.

Table 4-3

Lower Bound ASME Code Properties

Description	T (°F)	100	200	300	400	500	519*	600
SA-516, Grade 70	Sy (ksi)*	38	34.6	33.7	32.6	30.7	30.2	28.1
	Su (ksi)*	70	70	70	70	70	70	70
SA-106, Grade C	Sy (ksi)*	40	36.5	35.5	34.3	32.4	31.9	29.1
	Su (ksi)*	70	70	70	70	70	70	70
SA-105, Grade II	Sy (ksi)*	36	32.8	31.9	30.8	29.1	28.6	26.6
	Su (ksi)*	70	70	70	70	70	70	70

*Reference 21, Table I-2.1 and Table I-3.1. Values at 519°F are linearly interpolated from values at 550°F and 600°F.

Table 4-4

Lower Bound Material Properties Used in the LBB Evaluation

Parameter	Value
Temp (°F)	519
E (ksi)	27.19×10^3
$S_y = \sigma_O$ (ksi)	30.2 (4) (6)
S_u (ksi)	70.0 (4)
Ramberg-Osgood Parameter α	0.17 (5)
Ramberg-Osgood Parameter n	6.74 (5)
J_{IC} (in-lb/in^2)	600 (1), (3)
J-R Curve Parameter C_0 (in-lb/in^2)	0.0 (2), (3)
J-R Curve Parameter C_1 (in-lb/in^2)	2563 (2), (3)
J-R Curve Parameter N	0.274 (2), (3)

Notes:

(1) Based on Reference 25.
(2) Based on Reference 25. Coefficients for: $J = C_0 + C_1(\Delta a)^N$.
(3) Value at 550°F used for 519°F.
(4) From Table 4-3 at 519°F.
(5) Based on 21% elongation as per ASME Code (Reference 22).
(6) Lower of SA-516 and SA-106 Code minimum, and SA-105 CMTR

Table 4-5

Moments for DCPP Unit 1 Main Steam 1-1

Node #	NOP (in-kips)	NOP+DYN (in-kips)
20	232.2	7437.3
20A	721.0	5856.3
40	1439.5	2752.1
50	1729.8	2307.6
70B	1928.6	2812.2
70M	2142.4	3781.0
70E	2030.7	3827.9
80	1848.2	3481.6
80A	1264.5	2780.8
90	685.2	3208.3
100	515.3	3180.1
100A	286.1	3378.9
110	142.1	3795.2
110A	369.3	4271.2
115	697.7	5030.4
120	785.6	4692.8
120A	1168.2	3397.6
170	1553.1	2723.5
180B	2018.3	4039.2
180M	2095.1	3628.6
180E	1853.0	3228.9
202	1515.7	2597.3
205	1098.6	2738.9
210B	1089.0	2962.4
210M	1088.7	3177.0
212	1104.0	3954.2
215M	1132.5	4626.2
220	1158.9	5407.0

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

Table 4-6

Moments for DCPP Unit 1 Main Steam 1-2

Node #	NOP	NOP+DYN in-kips
20	623.4	7877.9
20A	862.9	6159.1
20B	1170.5	4437.6
40	1446.6	2776.3
50	1709.0	2523.6
70 B	1875.2	2918.2
70 M	2004.6	3575.4
70 E	1877.7	3748.3
80	1713.1	3403.0
80A	1388.8	2827.9
80B	1107.8	3077.7
90	910.9	3705.8
100	775.2	3830.3
110	527.2	4406.6
110A	615.4	4332.0
120	886.6	4322.0
150	1086.8	4367.0
170	1602.7	2887.5
180 B	2056.1	3341.1
180 M	2167.3	3772.6
180 E	2016.4	3538.9
202	1884.7	3240.5
202A	1587.2	2657.0
205	1497.7	3002.7
210 B	1507.1	3257.7
210 M	1511.2	3453.4
212	1490.9	3800.2
215 M	1450.3	4251.2
220	1391.9	4509.0

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

Table 4-7

Moments for DCPP Unit 1 Main Steam 1-3

Node #	NOP (in-kips)	NOP+DYN (in-kips)
20	655.8	7192.6
20A	520.4	5144.0
20B	888.4	3721.9
40	1314.1	2381.3
50	1662.6	2206.9
70 B	1856.1	2704.6
70 M	2071.7	3554.6
70 E	1982.3	3634.7
80	1813.1	3268.1
80A	1350.8	2802.9
90	1019.2	3437.9
100	882.6	3458.4
105	589.5	3761.6
110	562.5	3827.2
110A	558.5	3849.8
120	783.0	4090.3
130	1009.6	4329.6
170	1564.6	2830.5
180 B	2012.6	3321.1
180 M	2093.3	3644.6
180 E	1879.2	3315.9
202	1789.0	3125.3
202A	1390.0	2339.6
205	1325.7	2778.2
210 B	1345.4	2945.5
210 M	1384.5	3236.6
212	1415.2	3792.7
215 M	1433.1	4485.1
220	1429.9	4880.0

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

Table 4-8

Moments for DCPP Unit 1 Main Steam 1-4

Node #	NOP (in-kips)	NOP+DYN (in-kips)
20	136.5	6556.0
30	173.8	6239.2
30A	825.2	5173.8
40	1372.6	2545.4
50	1670.2	2487.1
70 B	1856.0	2848.6
70 M	2022.8	3480.6
70 E	1903.3	3513.3
80	1717.3	3098.2
80A	1356.9	2707.9
80B	998.0	2879.0
90	642.8	3301.7
100	488.4	3354.6
110	158.3	3966.2
110A	408.7	4183.3
120	757.5	4615.9
150	861.5	4790.2
150A	1221.1	3624.0
170	1582.6	2974.6
180 B	2019.7	3425.1
180 M	2108.9	3790.6
180 E	1921.3	3395.2
202	1795.9	3115.8
202A	1471.6	2639.1
205	1273.2	3155.2
210 B	1250.0	3334.5
210 M	1200.6	3596.0
212	1145.6	4218.8
215 M	1094.5	4629.3
220	1048.5	4819.1

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

Table 4-9

Moments for DCPP Unit 2 Main Steam 2-1

Node #	NOP (in-kips)	NOP+DYN (in-kips)
5	1104.9	3956.6
7 B	1104.9	3996.2
7 M	1099.3	3996.2
8	1094.5	3686.0
9 B	1094.5	3688.3
9 M	1101.3	3175.5
19	1117.6	3063.7
20	1129.1	2841.8
24	1140.6	2764.4
28	1440.2	2495.7
29	1687.1	2742.9
30	1743.0	2815.2
35 B	1810.6	2906.1
35 M	2031.4	3139.4
35 E	1950.2	2777.8
40	1919.9	2725.3
41	1874.5	2649.6
45	1466.6	2264.8
45A	1156.5	2458.6
50	847.6	2708.3
55	802.7	2746.4
58	659.9	2867.4
59	497.7	3013.7
60	157.9	3700.4
70	450.7	3658.3
71	494.3	3658.5
80	626.8	3667.0
85	790.7	3695.7
85A	1164.6	3139.6
85B	1540.3	3273.4
90	1916.9	3784.4
95 B	2057.2	3947.4
95 M	2169.0	3072.3
95 E	1966.3	5146.9
101	1775.3	5865.0
105	1442.7	4689.4
110	1373.4	4449.2
120	1309.0	4227.6
120A	710.7	2628.7
120B	134.3	3252.0
121	702.7	4825.3
125	795.1	5038.7

Table 4-10

Moments for DCPP Unit 2 Main Steam 2-2

Node #	NOP (in-kips)	NOP+DYN (in-kips)
5	1401.7	4441.5
7 B	1401.8	4472.0
7 M	1431.3	4426.4
8	1441.0	3997.4
9 B	1441.0	3996.4
9 M	1433.4	3612.5
9 E	1408.4	3386.6
20	1390.4	3186.7
24	1384.5	3093.3
24A	1460.7	2560.5
30	1790.0	2854.9
40 B	1864.5	2970.8
40 M	2037.5	3186.4
41	1936.3	2886.0
45	1482.4	2241.5
50	920.3	2797.5
55	881.5	2848.1
59	762.4	3014.3
60	696.4	3120.1
65	666.1	3173.8
70	645.9	3212.2
70A	530.9	3572.7
75	579.4	4127.7
80	780.8	4144.5
85	921.3	4193.4
90	1076.0	4273.3
90A	1271.0	3512.7
90B	1543.6	3539.5
95	1860.1	4057.3
100 B	2027.3	4270.5
100 M	2134.4	3082.9
100 E	1959.6	5814.1
106	1759.4	6868.7
110	1458.7	5615.8
112	1401.7	4441.5
115	1401.8	4472.0
115A	1431.3	4426.4
115B	1441.0	3997.4
120	1441.0	3996.4

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

Table 4-11

Moments for DCPP Unit 2 Main Steam 2-3

Node #	NOP (in-kips)	NOP+DYN (in-kips)
5	1395.8	4410.6
7 M	1422.0	4370.9
8	1428.5	3946.6
9 M	1418.7	3541.3
9 E	1393.0	3310.5
20	1376.7	3129.6
24	1370.8	3035.5
24A	1392.8	2591.6
25	1528.1	2501.5
30	1594.1	2551.4
35	1860.3	2900.1
40 M	2038.4	3118.4
40 E	1941.0	2827.4
40A	1716.8	2416.6
45	1495.5	2223.2
45A	1197.3	2443.7
50	916.7	2741.4
55	878.2	2787.9
58	641.8	3126.9
58A	526.3	3458.5
60	571.9	3975.3
65	911.7	4083.0
70	1072.7	4169.8
70A	1265.0	3426.9
70B	1532.0	2875.6
75	1841.5	2997.2
80 B	2016.4	3187.0
80 M	2120.6	3064.4
80 E	1942.9	3946.7
86	1734.1	4408.2
90	1444.4	3623.1
90A	816.7	2722.6
90B	418.5	3628.3
100	971.6	5562.8

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

Table 4-12

Moments for DCPP Unit 2 Main Steam 2-4

Node #	NOP (in-kips)	NOP+DYN (in-kips)
5	1104.7	4651.8
7 M	1099.9	4440.9
8	1095.3	3958.5
9 B	1095.3	3956.4
9 M	1101.7	3321.4
19	1117.3	3041.9
20	1133.7	2828.8
24	1146.7	2739.2
24A	1274.1	2497.1
30	1489.5	2688.3
31	1587.2	2834.0
35	1802.5	3169.9
45	2023.1	3434.8
46	1943.1	2992.7
47	1897.9	2831.5
47A	1492.4	2585.1
50	1182.3	3231.0
55	873.4	4190.3
65	828.8	4344.7
70	690.6	4839.7
70A	540.2	5412.8
75	265.0	4933.4
79	163.5	4727.6
80	538.8	3848.4
85	582.6	3769.8
85A	744.7	3503.0
85B	1109.6	3049.3
90	1476.9	2825.5
95 B	1845.1	3274.0
95 M	2040.9	3488.8
95 E	2151.1	3123.0
101	1947.8	4397.6
106	1724.3	4958.8
110	1362.2	3818.8
110A	1286.8	3620.6
120	423.6	3332.7

NOP = Normal operating load = Dead Weight and Thermal Expansion Loads at 100% power
DYN = Dynamic loads consisting of either SSE loads or MSIV loads, whichever is greater

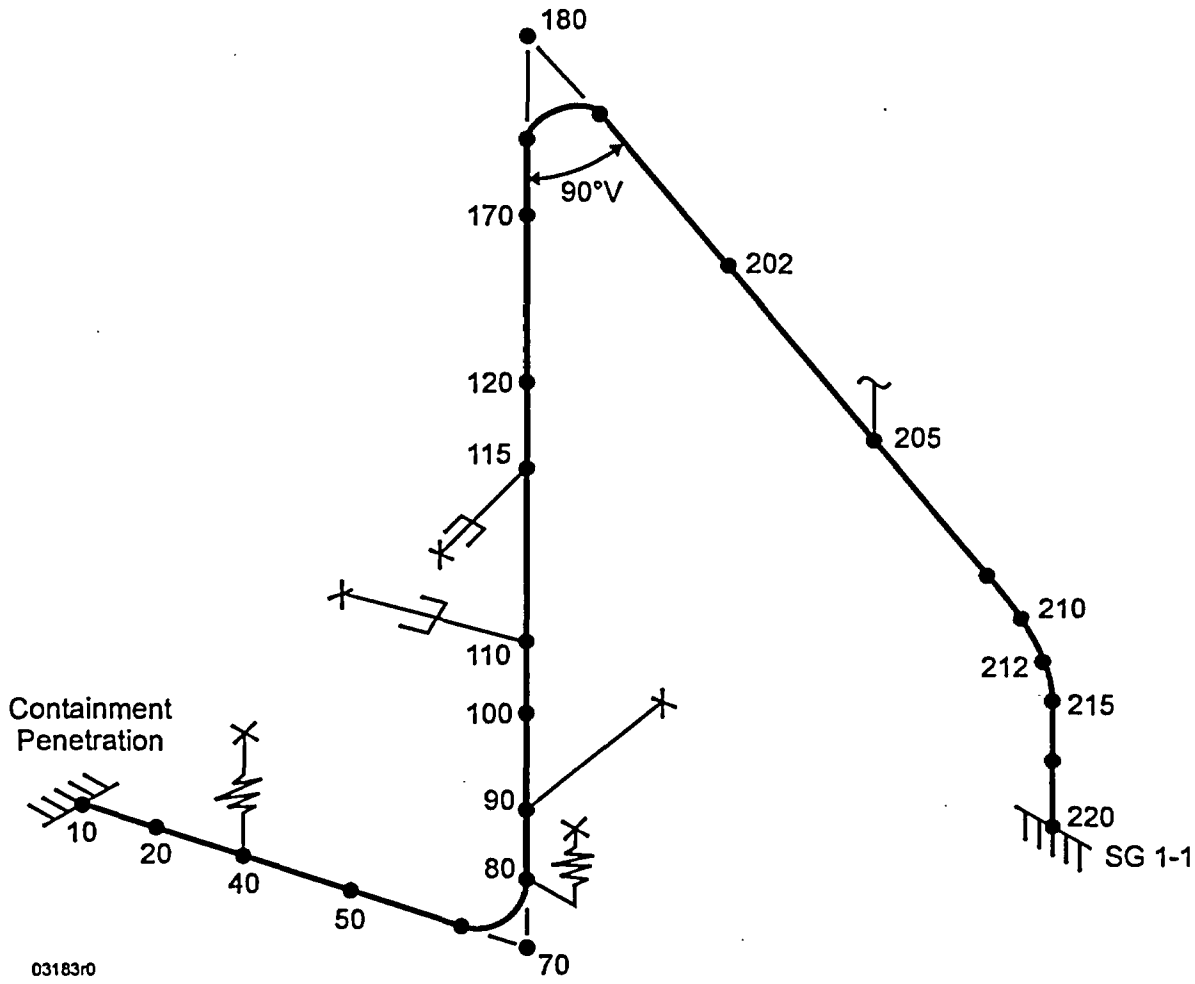


Figure 4-1. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 1, Steam Generator 1-1

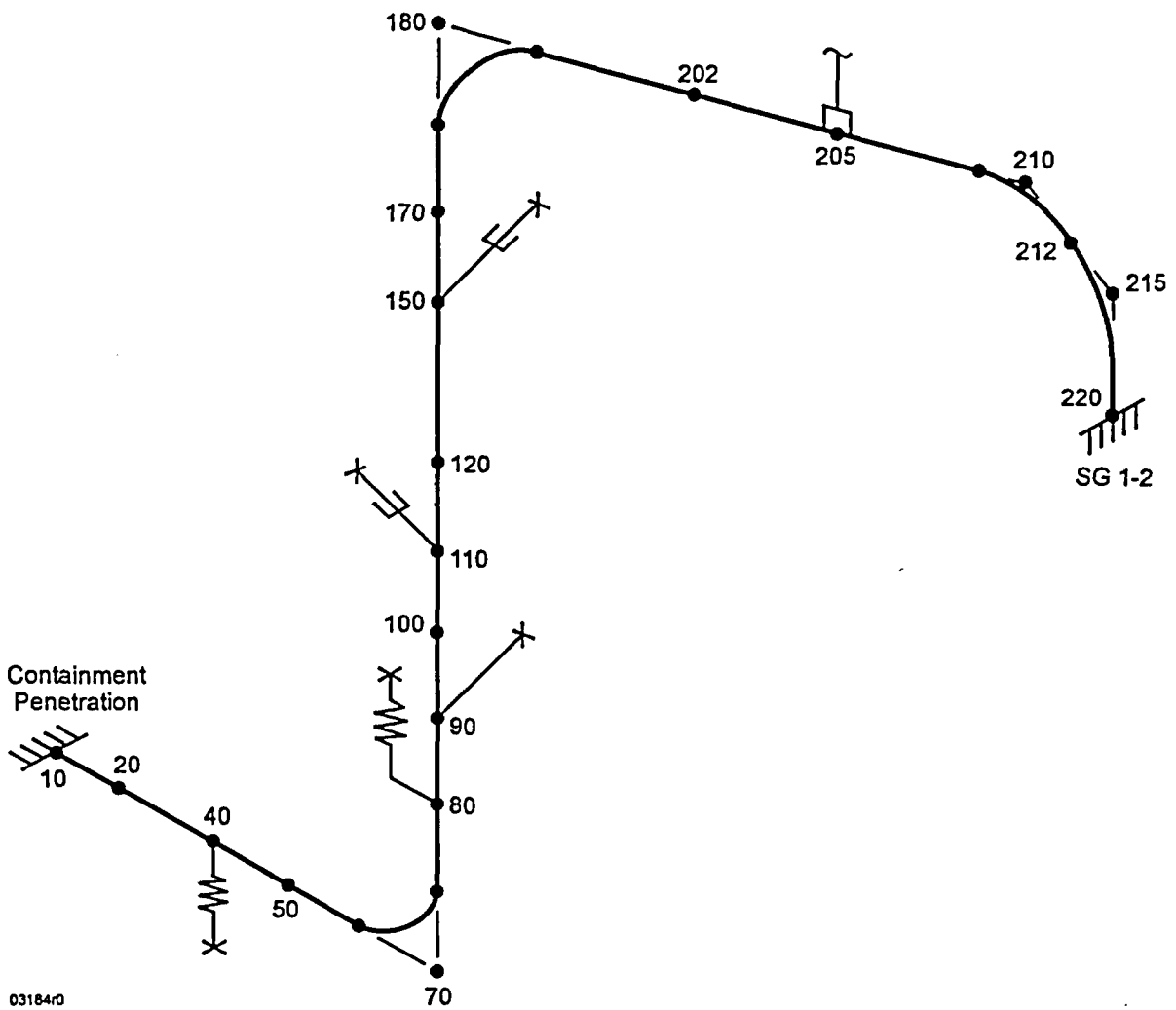


Figure 4-2. Schematic of Piping Model and Selected Node Points Unit 1, Points for Main Steam Piping Inside Containment Unit 1, Steam Generator 1-2

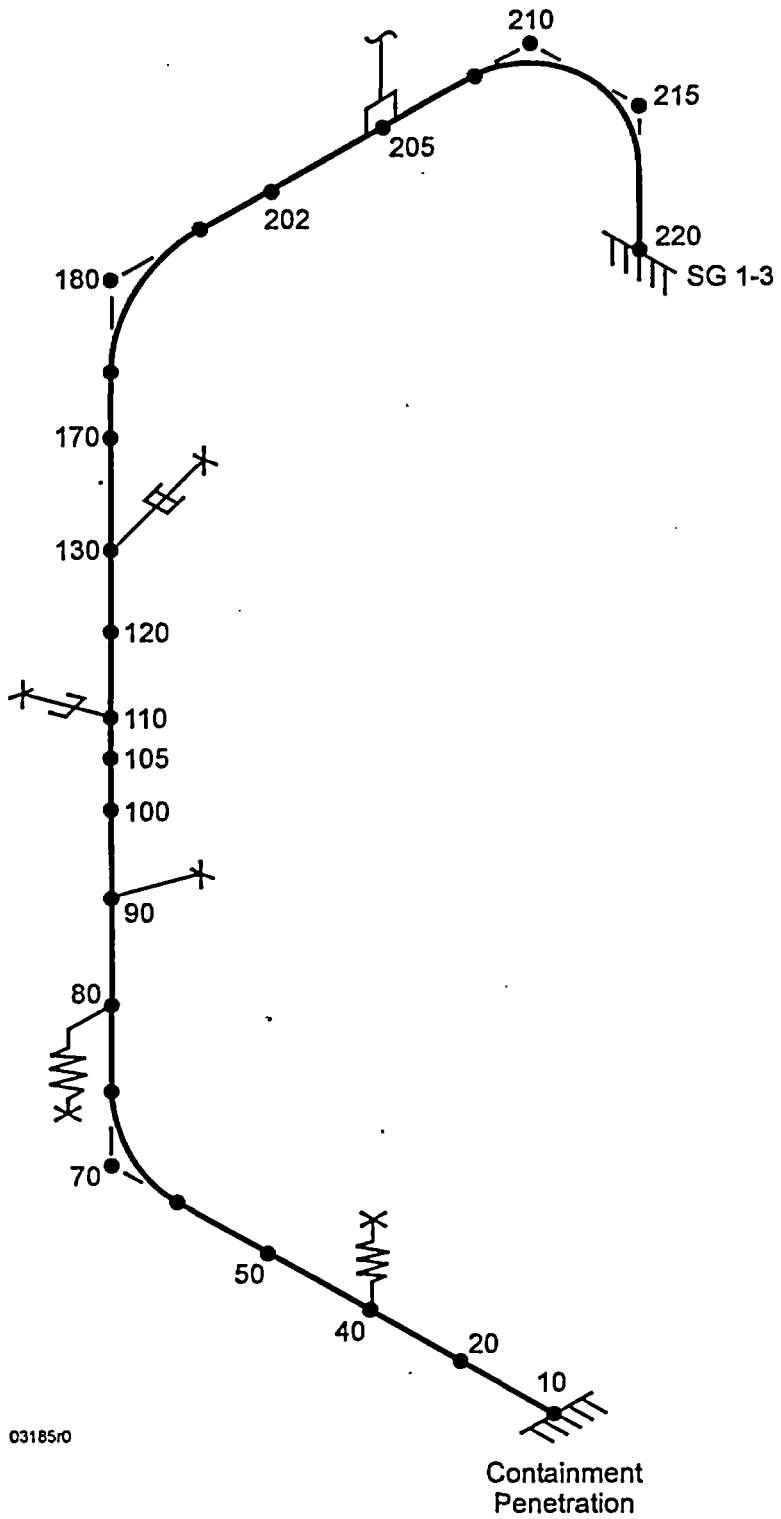


Figure 4-3. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 1, Steam Generator 1-3

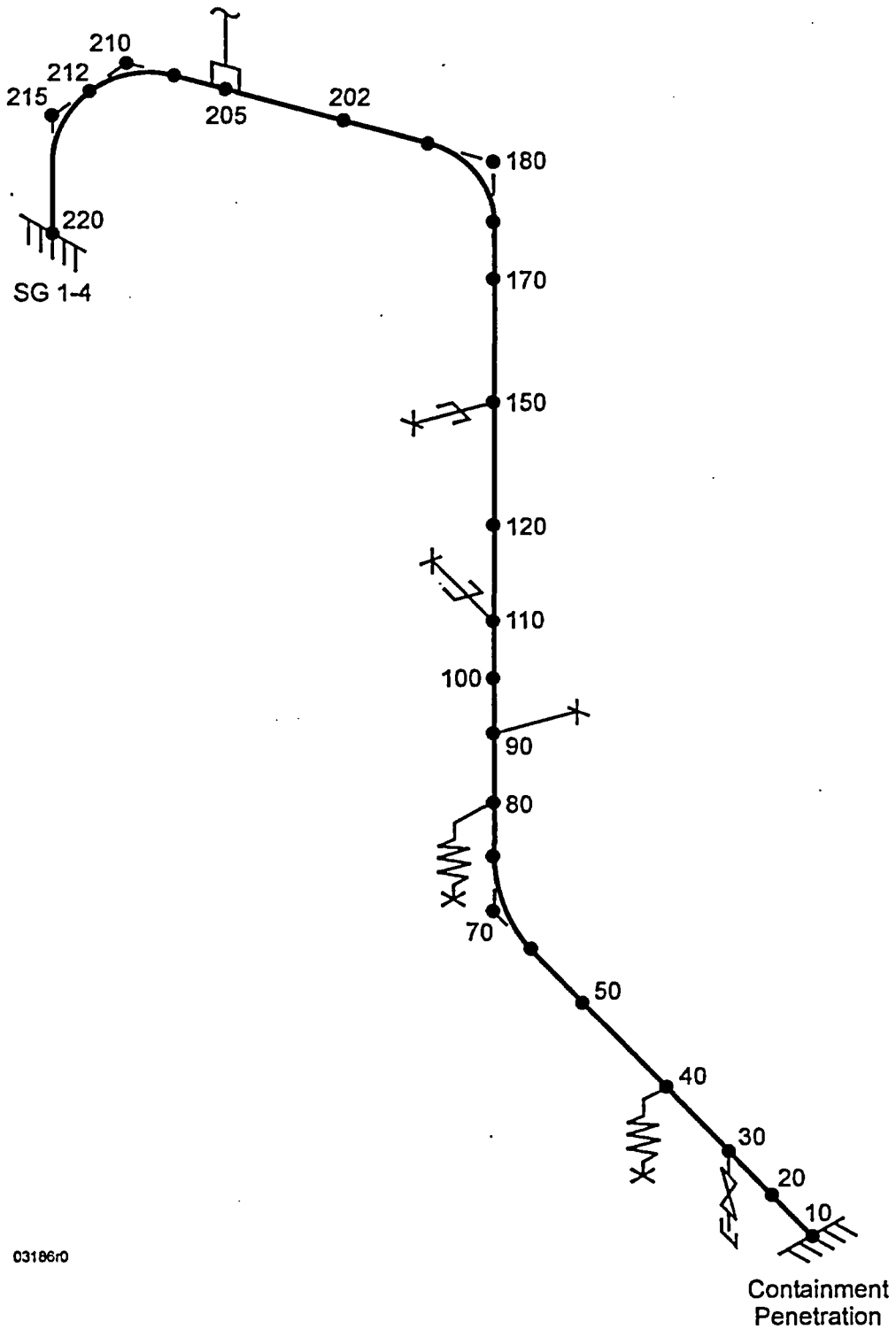


Figure 4-4. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 1, Steam Generator 1-4

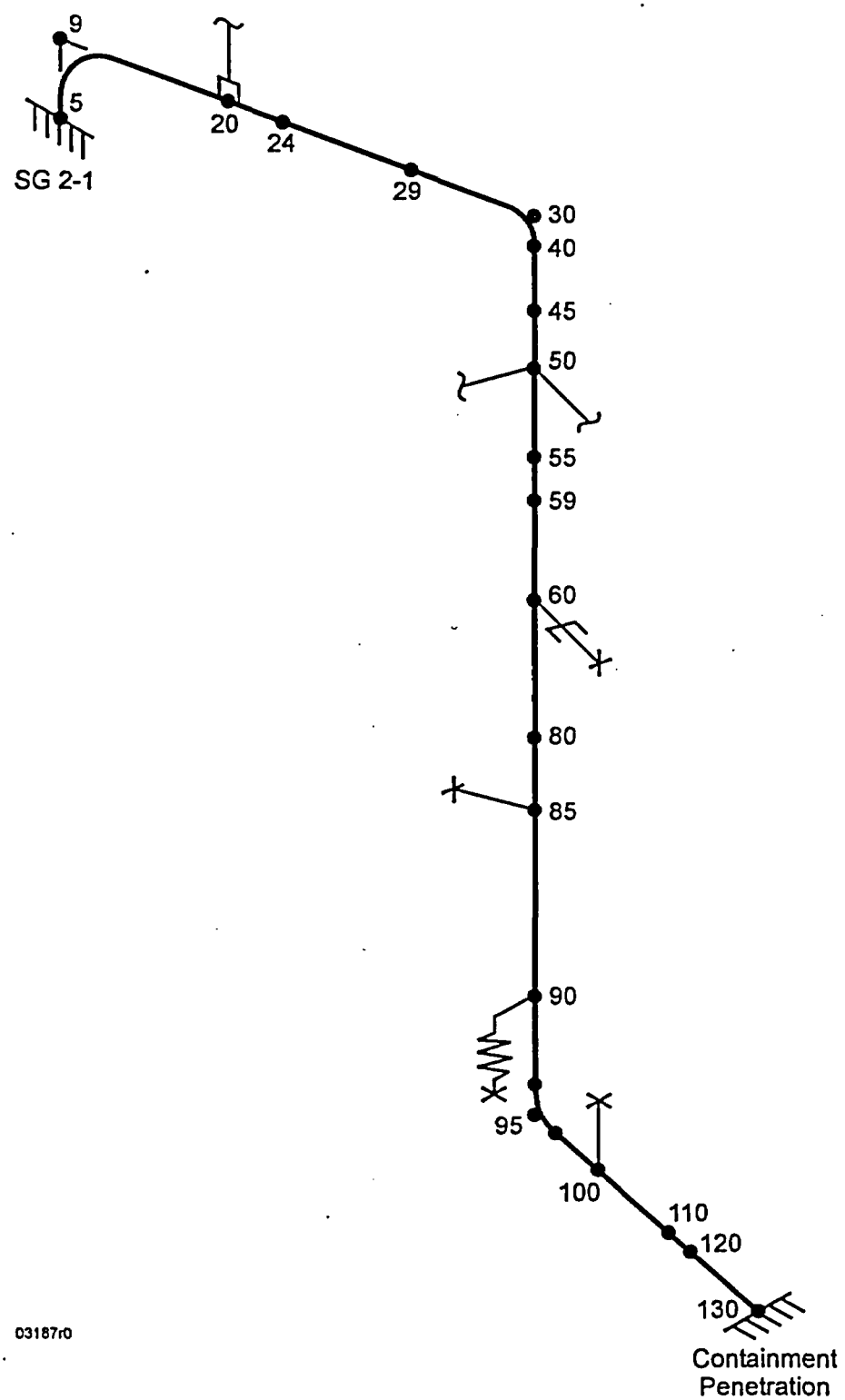


Figure 4-5. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 2, Steam Generator 2-1

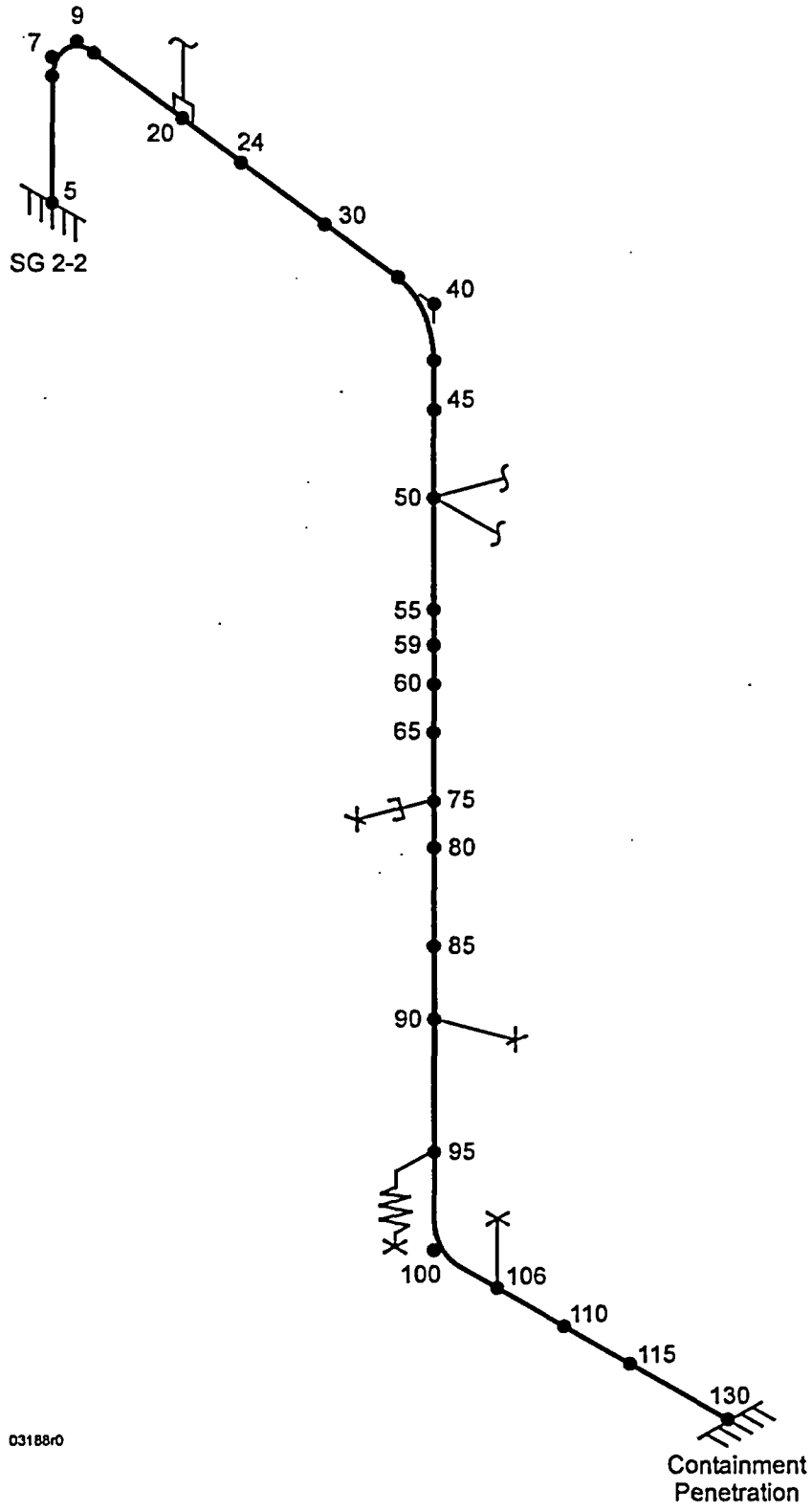


Figure 4-6. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 2, Steam Generator 2-2

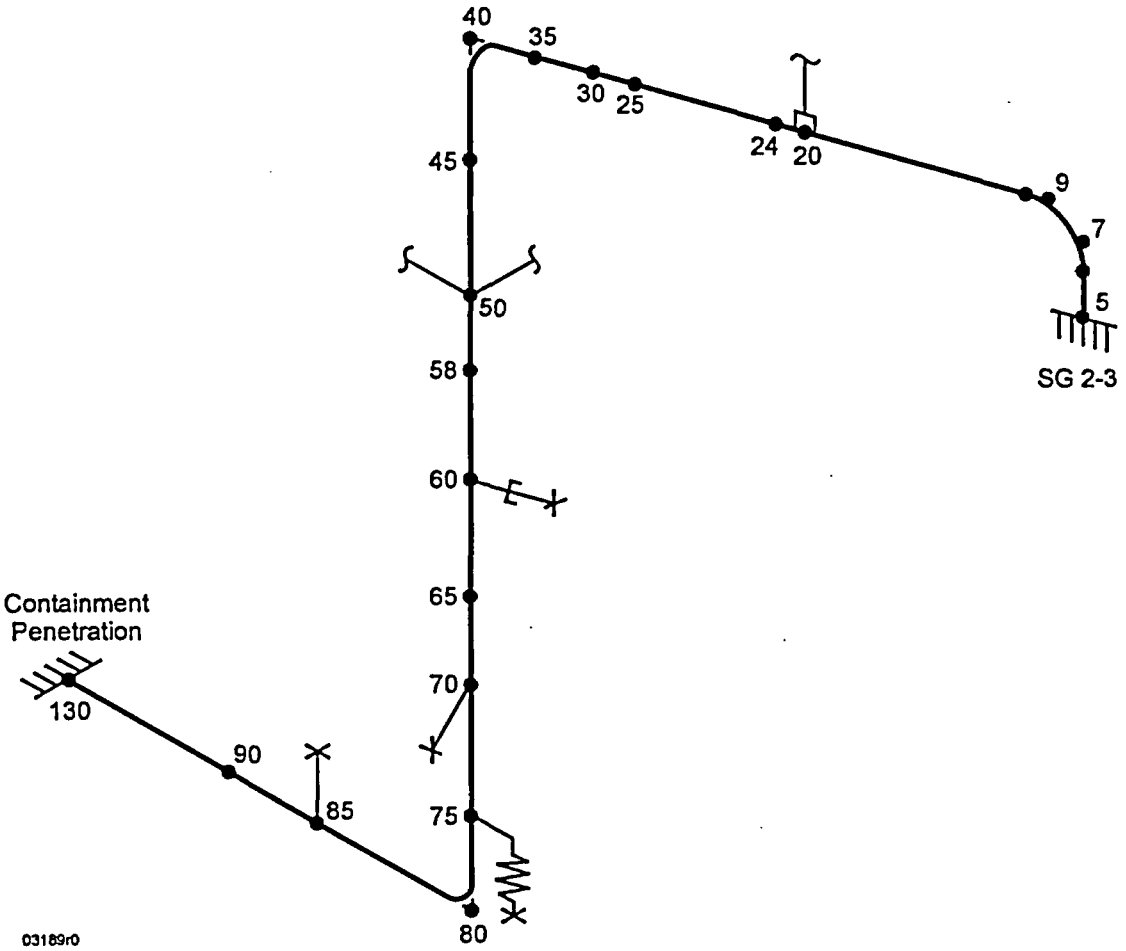


Figure 4-7. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 2, Steam Generator 2-3

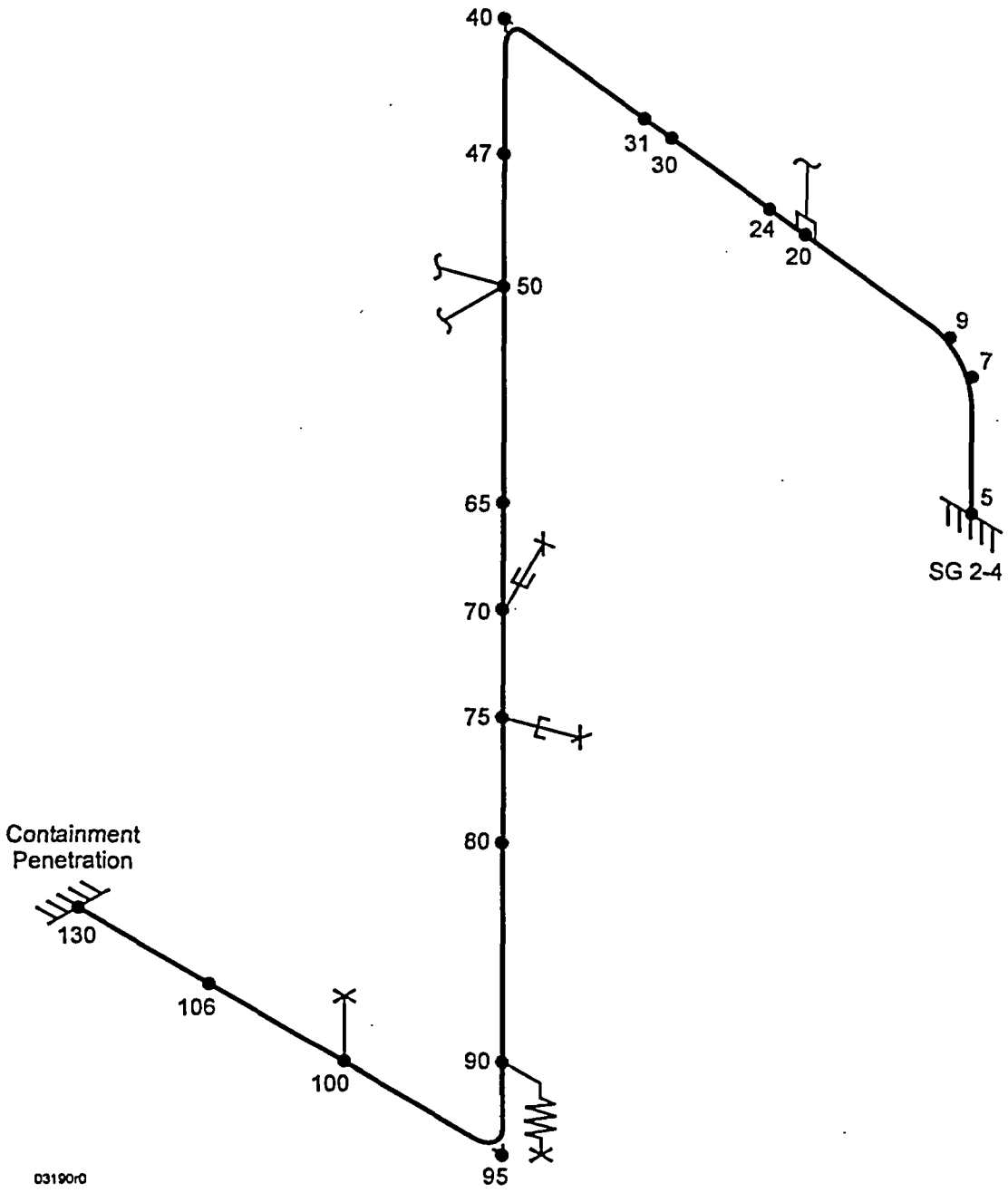


Figure 4-8. Schematic of Piping Model and Selected Node Points for Main Steam Piping Inside Containment Unit 2, Steam Generator 2-4

5.0 LEAK-BEFORE-BREAK EVALUATION

The LBB approach involves the determination of critical flaw sizes and leakage through flaws. The critical flaw length for a through-wall flaw is that length for which, under a given set of applied stresses, the flaw would become marginally unstable. Similarly, the critical stress is that stress at which a given flaw size becomes marginally unstable. NUREG-1061, Vol. 3 [5] defines required margins of safety on both flaw length and applied stress. Both of these criteria have been examined in this evaluation. Circumferential flaws are more restrictive than postulated axial flaws because the critical flaw sizes for axial flaws are very long, since they are affected by only pressure stress, and result in large crack opening areas due to out of plane displacements. However, in this evaluation, both axial and circumferential flaws are considered for completeness, especially since the piping and reducing elbows are seam welded. The LBB evaluation is reported for the 28 NPS pipe. The results at the 32-inch end of the reducing elbow were found to be enveloped by the results of the 28-inch pipe. The leakage rate is at least 15 gpm at the 32-inch end of the reducing elbows for the worst combination of NOP + DYN loads for determination of critical flaw size and NOP loads for calculation of leakage.

5.1 Evaluation of Critical Flaw Sizes

Critical flaw sizes may be determined using either limit load/net section collapse criterion (NSCC) approach or J-Integral/Tearing Modulus (J/T) methodology. In this evaluation, the more conservative J/T methodology was used to determine the critical flaw sizes since the main steam piping material is carbon steel which is semi-ductile to ductile.

5.1.1 Circumferential Flaws

A fracture mechanics analysis for determining the stability of through-wall circumferential flaws in cylindrical geometries such as pipes using the J/T approach is presented in References 27 and 28. This procedure was used for the determination of critical stresses and flaw sizes in the main steam piping at Diablo Canyon, using computer program, pc-CRACK™ [31] which has been verified under SI's Quality Assurance program.

The expression for the J-integral for a through-wall circumferential crack under tension loading [27] which is applied in this analysis is:

$$J = f_1\left(a_e, \frac{R}{t}\right)\frac{P^2}{E} + \alpha\sigma_o\varepsilon_o c\left(\frac{a}{b}\right)h_1\left(\frac{a}{b}, n, \frac{R}{t}\right)\left[\frac{P}{P_o}\right]^{n+1} \tag{5-1}$$

where

$$f_1\left(a_e, \frac{R}{t}\right) = \frac{a_e F^2\left(\frac{a}{b}, \frac{R}{t}\right)}{4\pi R^2 t^2} \tag{5-2}$$

a_e	=	effective crack length including small scale yielding correction
R	=	nominal pipe radius
t	=	pipe wall thickness
F	=	elasticity factor [27, 28]
P	=	applied load = σ_∞ ($2\pi Rt$); where σ_∞ is the remote tension stress in the uncracked section
α	=	Ramberg-Osgood material coefficient
E	=	elastic modulus
σ_o	=	yield stress
ε_o	=	yield strain
2a	=	total crack length
2b	=	$2\pi R$
c	=	b-a
h_1	=	plasticity factor [27, 28]
P_o	=	limit load corresponding to a perfectly plastic material
n	=	Ramberg-Osgood strain hardening exponent.

Similarly, the expression for the J-integral for a through-wall crack under bending loading [28] is given by :

$$J = f_1\left(a_e, \frac{R}{t}\right)\frac{M^2}{E} + \alpha\sigma_o\varepsilon_o c\left(\frac{a}{b}\right)h_1\left(\frac{a}{b}, n, \frac{R}{t}\right)\left[\frac{M}{M_o}\right]^{n+1} \tag{5-3}$$

The parameters in the above equations are the same as the tension loading case except

M	=	applied moment = $\sigma_\infty(\pi R^2 t)$
σ_∞	=	remote bending stress in the uncracked section
I	=	moment of inertia of the uncracked cylinder about the neutral axis
M_o	=	limit moment for a cracked pipe under pure bending corresponding to $n = \infty$ (elastic-perfectly plastic case)
	=	$M_o^{'}\left[\mathrm{Cos}\left(\frac{\gamma}{2}\right) - \frac{1}{2}\mathrm{Sin}(\gamma)\right]$ (5-4)
$M_o^{'}$	=	limit moment of the uncracked cylinder = $4\sigma_o R^2 t$

The Tearing Modulus (T) is defined by the expression:

$$T = \frac{dJ}{da}\frac{E}{\sigma_f^{\,2}} \tag{5-5}$$

Hence, in calculating T, J from the above expressions is determined as a function of crack size (a) and the slope of the J versus crack size (a) curve is calculated in order to determine T. (The flow stress, σ_f, is taken as the mean of the yield and ultimate tensile strengths.) The material resistance J-R curve can also be transformed into J-T space in the same manner. The intersection of the applied and the material J-T curves is the point at which instability occurs and the crack size associated with this instability point is the critical crack size.

The piping stresses consist of both tension and bending stresses. The tension stress is due to internal pressure while the bending stress is caused by deadweight, thermal and seismic or other dynamic loads. Because a fracture mechanics model for combined tension and bending loads is not readily available, the critical flaw length under such loading conditions is determined using the tension and bending models separately. For the first case, the stress combination is assumed to be entirely due to tension and the critical flaw length is determined using the tension model. For the second case, the stress combination is assumed to be entirely due to bending and the critical flaw length is determined as such. The half critical flaw sizes (lengths) obtained with the tension model (a_t) and the bending model (a_b) are combined to determine the actual half critical flaw size (a_c) due to a combined tension and bending stress using linear interpolation, as described by the following equation:

$$a_c = a_t \frac{\sigma_t}{\sigma_b + \sigma_t} + a_b \frac{\sigma_b}{\sigma_b + \sigma_t} \tag{5-6}$$

Where σ_t and σ_b are the piping tensile and bending stresses respectively. This scheme was shown in a previous submittal [3] to provide conservative results.

The critical flaw sizes are determined as a function of applied moment for constant pressure stress and are presented in Tables 5-1 and 5-2. This was done so that the relationship between stress and critical flaw size can be used on a generic basis for the main steam piping line at DCPP. In these tables, the critical flaw length is the minimum value determined by two approaches as required by NUREG-1061, Vol. 3. In the first approach, the half critical flaw length is determined with a factor of unity on the NOP + DYN stress combination. The leakage flaw total length in this case (ℓ_1) is equal to the half critical flaw length (a_c). In the second approach, critical flaw length is determined with a factor of $\sqrt{2}$ on the NOP + DYN stresses. The leakage flaw length in this case (ℓ_2) is the total flaw length ($2a_c$). The final leakage flaw length is the minimum of ℓ_1 and ℓ_2. It was determined that the leakage flaw size based on a factor of unity on the stresses was controlling for all cases and as such are used in subsequent evaluations to determine leakage. The relationship between the critical flaw size and applied moment is shown graphically in Figure 5-2. A typical J-T curve for the determination of the critical circumferential through-wall length is shown in Figure 5-3.

The fracture mechanics models used in the determination of the critical flaw sizes (lengths) are limited to flaw sizes of half the circumference of the pipe. For cases where the piping moments/stresses are relatively low, the critical flaw sizes are much greater than half the circumference of the pipe. As can be seen in Figure 5-2, an extrapolation scheme was used to determine the critical flaw sizes for conditions with very low NOP + DYN moments.

5.1.2 Axial Flaws

Axial flaws are considered in this evaluation since the main steam piping and the reducing elbows at the nozzle connections are seam-welded. As such, the possibility of an axial flaw along the seam welds was considered. The critical flaw size for an axial flaw was determined using the expression for the J-integral and Tearing Modulus given by Zahoor in Reference 30.

The applied tearing modulus (T_a) for an axial through-wall crack in a pipe under specified internal pressure is:

$$T_a = (J/c) \bullet \left(E/\sigma_f^{\,2}\right) + H_0 \bullet (\sigma/\sigma_f) \bullet \tan(M\pi\sigma/2\sigma_f) \tag{5-7}$$

where

$$T_a = (\partial J/\partial c)_p \bullet E/\sigma_f^{\,2} \tag{5-8}$$

$$J = \left(8c\,\sigma_f^{\,2}/\pi E\right) \bullet \ln\left[\sec(M\pi\sigma/2\sigma_f)\right] \tag{5-9}$$

$$M = \left[1 + 1.2987\lambda^2 - 0.026905\lambda^4 + 5.3549\text{x}10^{-4}\lambda^6\right]^{0.5} \tag{5-10}$$

$$H_0 = 4\left[1.2987\lambda^2 - 0.05381\lambda^4 + 1.60645\text{x}10^{-3}\lambda^6\right]/M \tag{5-11}$$

$$\lambda = c/(Rt)^{0.5} \tag{5-12}$$

$$\sigma = pR/t \tag{5-13}$$

where:

J is the J-integral

p is the internal pressure = 806 psia

R and t are the pipe mean radius and wall thickness, respectively

c is the crack half-length

σ_f is a reference flow stress, defined as the average of yield and ultimate strengths.

The applied J versus T curve derived from Equations 5-7 through 5-13 is shown in Figure 5-4. The material J-T curve derived from the J-Resistance curve, whose parameters are shown in Table 4-4, is also plotted in Figure 5-4. The through-wall flaw size corresponding to the intersection of these curves corresponds to the critical axial through-wall length. The half critical through-wall length was calculated as 11.5 inches, resulting in a total critical length of 23 inches.

The above calculation for the critical through-wall axial flaw considered a straight pipe section. However, the applicability of the Zahoor method to the seam-welded reducing elbows was not apparent. A limited amount of data presented in Reference 31 indicated that the straight-pipe analysis techniques under-predicted the experimental failure moments for elbows in the majority of cases. Hence, the use of the straight-pipe solution to the DCPP reducing elbow is acceptable, especially considering the relatively large critical flaw size. The effect of the elbow on the crack opening area will be discussed in Section 5.2.2.

5.2 Leak Rate Determination

The determination of leak rate is performed using the EPRI program, PICEP [32]. The flow rate equations in PICEP are based on a modification of Henry's homogeneous non-equilibrium critical flow model [33]. The program accounts for non-equilibrium mass transfer between liquid and vapor phases, fluid friction due to surface roughness and convergent flow paths. The model was validated for steam and water leakage conditions [32].

In the determination of leak rates using PICEP, the following assumptions are made:

- A plastic zone correction is included in calculating the crack opening displacement. This is consistent with fracture mechanics principles for ductile materials.

- The crack is assumed to be elliptical in shape. This is the most appropriate representation for a crack that has the maximum crack opening displacement at the center of the crack that is available in PICEP for calculations of leakage.
- Crack roughness is taken as 0.000197 inches [34].
- There are no turning losses included since there are no mechanisms to cause intergranular cracking in the piping.
- The cracks are assumed to have a constant through wall depth and include a sharp-edged entrance loss factor of 0.61 is used (PICEP default).
- The default friction factors of PICEP are utilized.
- The crack opening area at the inlet and outlet are the same.
- The stress combinations included those for NOP conditions.

5.2.1 Circumferential Flaws

The leakage was calculated for the normal operating pressure of 806 psia and a temperature of 519°F. The material properties listed in Table 4-3 were used to perform the evaluations. The evaluation was performed on a generic basis with respect to the normal operating moments such that the leakage was calculated as a function of through-wall flaw length for a given moment. The results of the evaluation are shown in Figure 5-5.

Figure 5-5 can be combined with Figure 5-2 for any particular leakage rate to determine the combinations of NOP moments and NOP + SSE or NOP + MSIV moments that will result in that particular leakage rate. This relationship is shown in Figure 5-6. The actual piping moments can be plotted in Figure 5-6 to determine the leakage for each node. The leakage rate for intermediate points between the curves may be determined by interpolation.

5.2.2 Axial Flaws

The leakage through an axial flaw is calculated with an internal pressure of 806 psia and a temperature of 519°F. The evaluation was performed assuming a straight pipe, since it has been previously shown that the elbow does not have a profound effect on the crack opening area

calculated for the main steam piping at DCPP. The results of the evaluation are shown in Figure 5-7. As can be seen from this figure, at half the critical flaw size (11.5 inches), the leakage is at least 15 gpm.

In order to determine the effect of the elbow on the crack opening area, a finite element analysis was performed to compare the crack opening area of a straight pipe with that of the reducing elbow when subjected to an internal pressure equal to that of the main steam piping at DCPP.

Two three-dimensional finite element models were developed using the ANSYS computer program [35]. One is a straight pipe and the other a reducing elbow, as shown in Figure 5-8. For the straight pipe, a 32-inch outside diameter was used. The reducing elbow had an outside diameter of 32 inches on the nozzle end, gradually reduced to 28 inches on the pipe end. The thickness for both were maintained at 1 inch. Taking advantage of symmetry, only one half of the configurations were modeled, as shown in Figure 5-8. Because of the relatively small thickness-to-radius ratio, shell elements were used for the evaluation. Various through-wall flaw lengths were simulated in the straight pipe and the elbow. The crack was simulated at several locations on the elbow, both at the intrados and extrados, as shown in Figure 5-9. The evaluation was performed to determine the equivalent axial through-wall crack length in the reducing elbow that would yield the same crack opening area to an axial through-wall crack in the straight pipe when subjected to the main steam piping operating pressure.

The analysis results are summarized in Figure 5-10. It can be seen that for smaller crack lengths, the elbow can have a significant effect on the critical crack length that produces the same crack opening area in a straight pipe (up to 20%). However, as the crack length increases, this effect decreases. At half the critical flaw length and beyond (11.5 inches and greater), this effect is almost negligible (at most 5%). Hence, the critical flaw length calculated for the straight pipe can be used to represent the reducing elbow as well.

5.3 LBB Evaluation Results and Discussions

The NOP moments versus the NOP + SSE or NOP + MSIV moments for the various locations on the main steam piping at DCPP Units 1 and 2 are plotted on Figures 5-11 and 5-12, respectively, to determine the leakage rate at all points in the piping system. It is seen that for Unit 1, a significant number of these locations will meet 5 gpm leakage rate in order to qualify for LBB. Only a few points are below this 5 gpm leakage. The limiting location has a leakage of approximately 2 gpm. Similarly for Unit 2, the majority of points will qualify for LBB based on a leakage of 5 gpm. Only seven points are below this leakage. The limiting leakage in this case is 3.5 gpm. As shown above, the leakage through the leakage flaw size for an axial flaw is 15 gpm, which is much greater than the limiting circumferential flaw. Hence, an axial flaw is not limiting.

The leakage and critical crack size analyses conducted herein were based on the steam line nominal operating pressure of 806 psia. The minimum pressure in the line may be as low as 750 psia [38]. It is judged that this difference will not have a significant effect on the final results, as although the leakage for a given crack size may be slightly reduced, the critical flaw size at the lower pressure will be slightly greater, resulting in a compensating increase in leakage.

Table 5-1

Leakage Flaw Size Versus Stress Determined by J/T Analysis
(No safety factor on loads)

Stress (ksi)	Moment (in-kip)	Leakage Flaw Length (1)		
		Tension a_t (in)	Bending a_b (in)	Combined a_c (in)
5.03	0.00	21.30	21.30	21.30
10.00	2751	14.74	19.71	17.21
11.00	3304	13.76	18.13	16.13
12.00	3858	12.95	16.72	15.14
13.00	4412	12.25	15.51	14.25
14.00	4966	11.65	14.48	13.46
15.00	5520	11.12	13.58	12.76
16.00	6074	10.66	12.80	12.13
17.00	6628	10.27	12.11	11.57
18.00	7181	9.78	11.50	11.02
19.00	7735	9.33	10.94	10.51
20.00	8289	8.91	10.52	10.12
25.00	11058	6.80	8.30	8.00

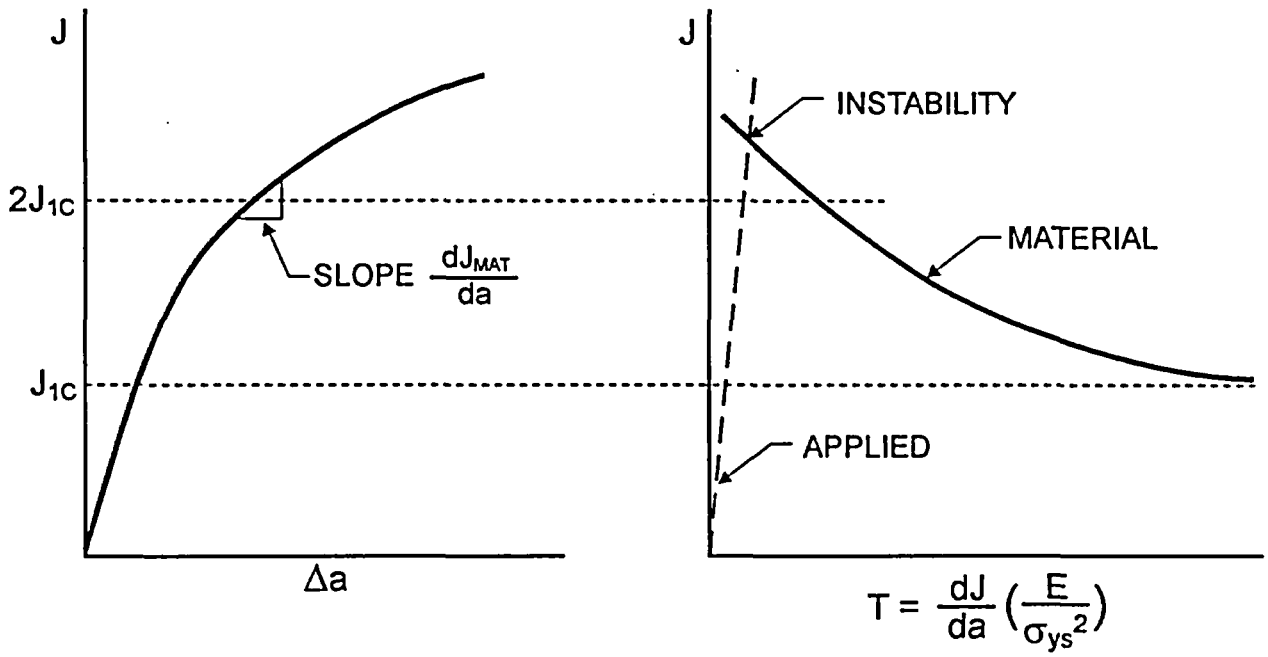
Note: (1) Leakage flaw length is equal to half the critical flaw length

Table 5-2

Leakage Flaw Size Versus Stress Determined by J/T Analysis
(1.414 safety factor on loads)

Stress (ksi)	Moment (in-kip)	Leakage Flaw Length (1)		
		Tension $2a_t$ (in)	Bending $2a_b$ (in)	Combined $2a_c$ (in)
7.12	0.00	42.60	42.60	42.60
10.00	1596	29.48	34.41	31.93
11.00	2150	27.53	32.26	30.09
12.00	2704	25.89	30.27	28.44
13.00	3258	24.50	28.50	26.95
14.00	3812	23.30	26.92	25.62
15.00	4366	22.24	25.51	24.41
16.00	4919	21.32	24.26	23.33
17.00	5473	20.55	23.13	22.37
18.00	6027	19.57	22.03	21.34
19.00	6581	18.66	21.03	20.40
20.00	7135	17.81	20.23	19.62
25.00	9904	13.59	15.99	15.51

Note: (1) Leakage flaw length is equal to the critical flaw length



93220r0

Note: Linear extrapolation used to determine $T_{material}$ for J values greater than 2 J_{IC}

Figure 5-1. J-Integral/Tearing Modulus Concept for Determination of Instability During Ductile Tearing

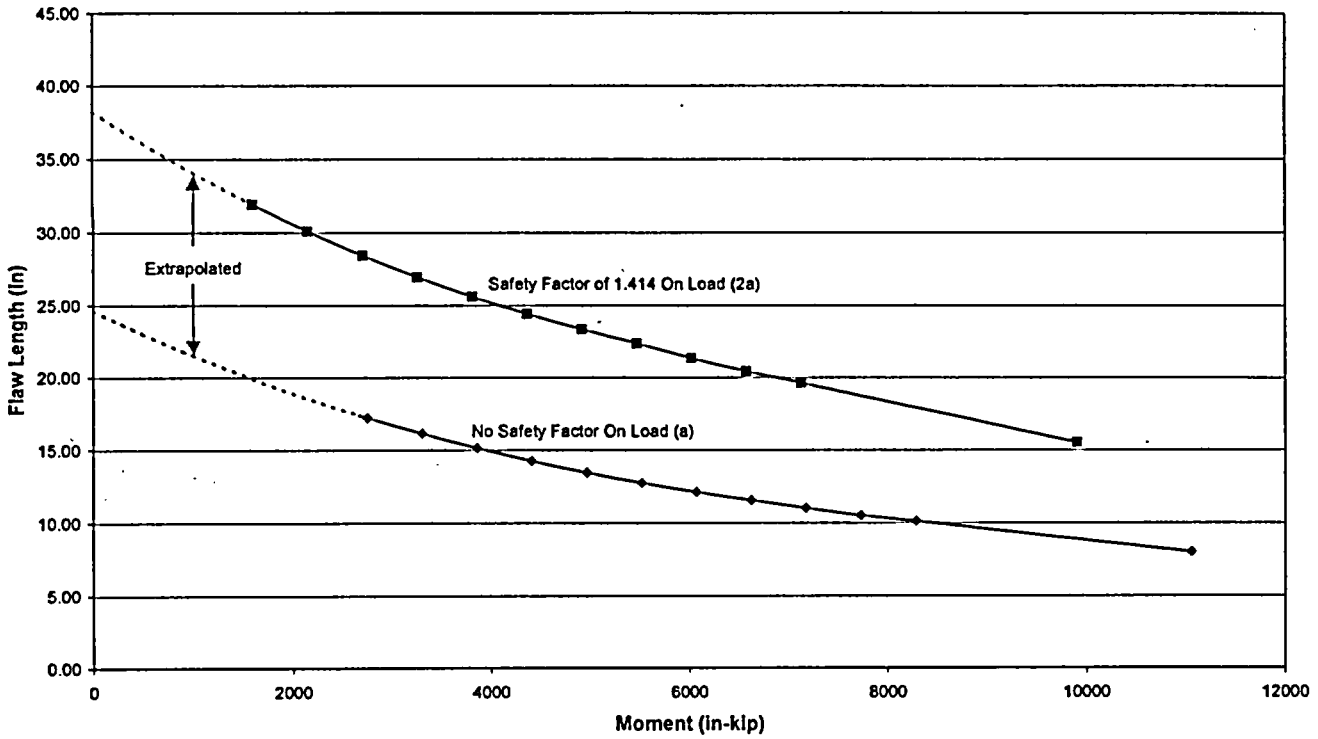


Figure 5-2. Leakage Flaw Size Versus Moment

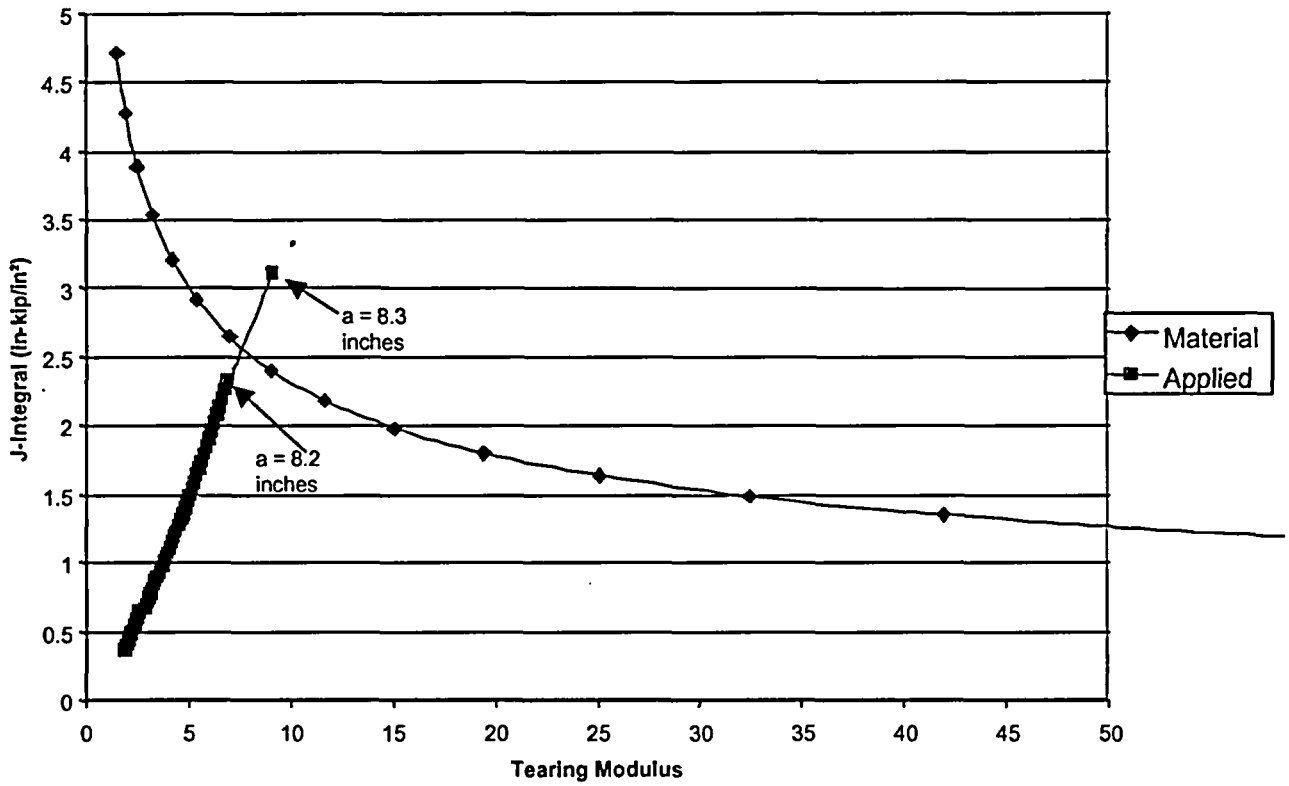


Figure 5-3. Typical J-T Analysis Results for Critical Circumferential Through-Wall Flaw

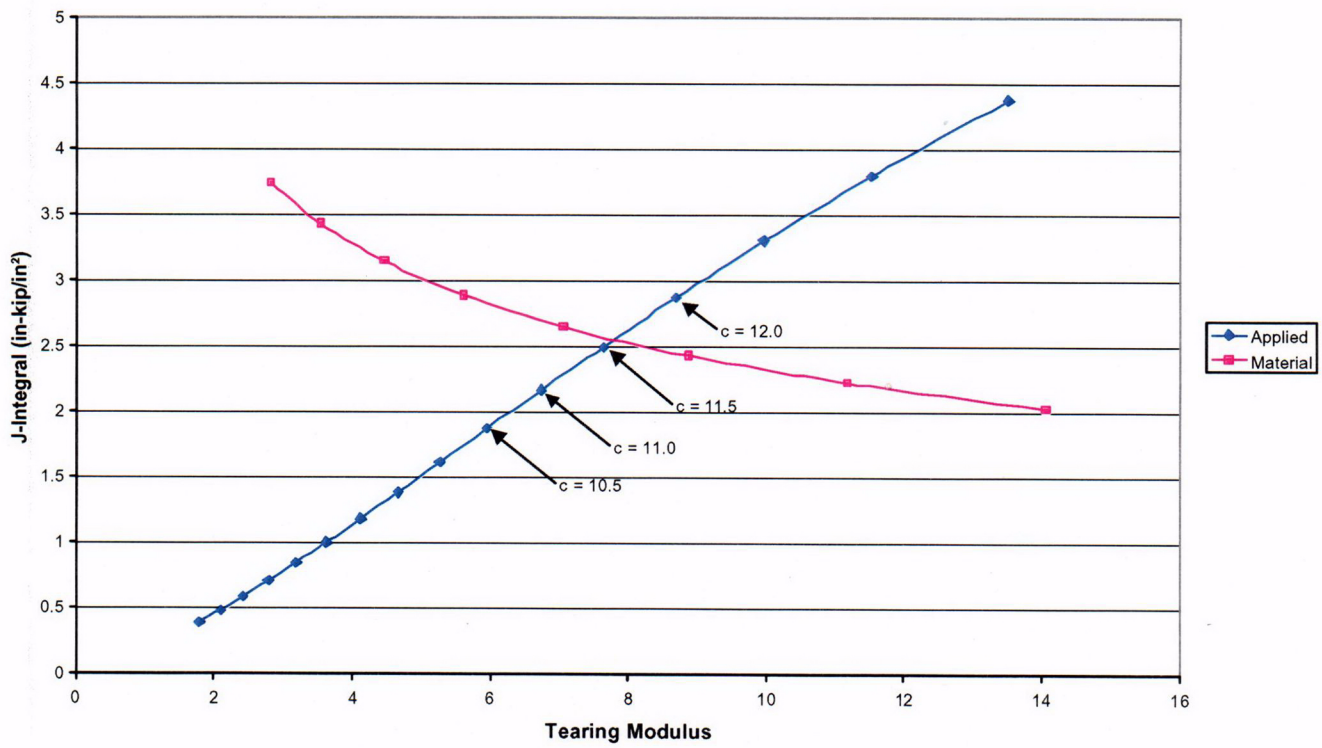


Figure 5-4. J-T Analysis Results for Critical Axial Through-wall Flaw in a Straight Pipe

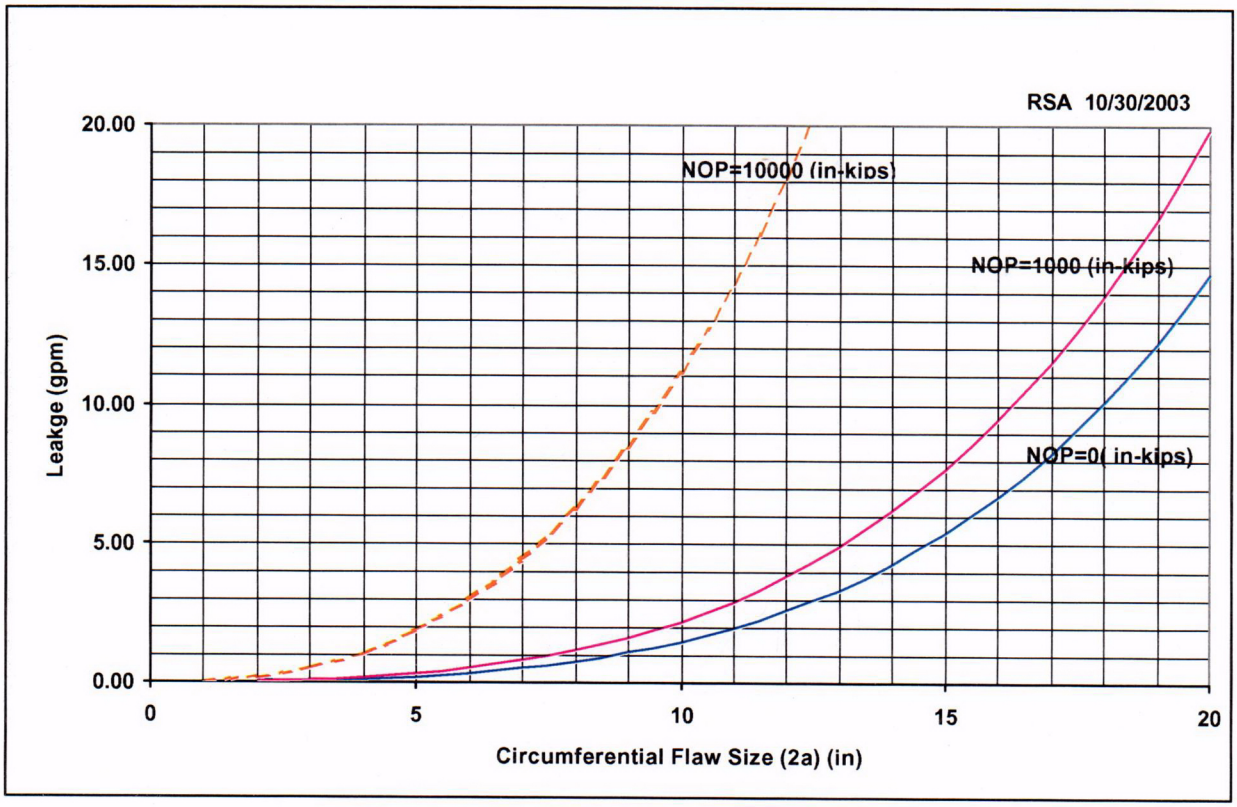


Figure 5-5. Leakage versus Flaw Size for Circumferential Flaws

C02

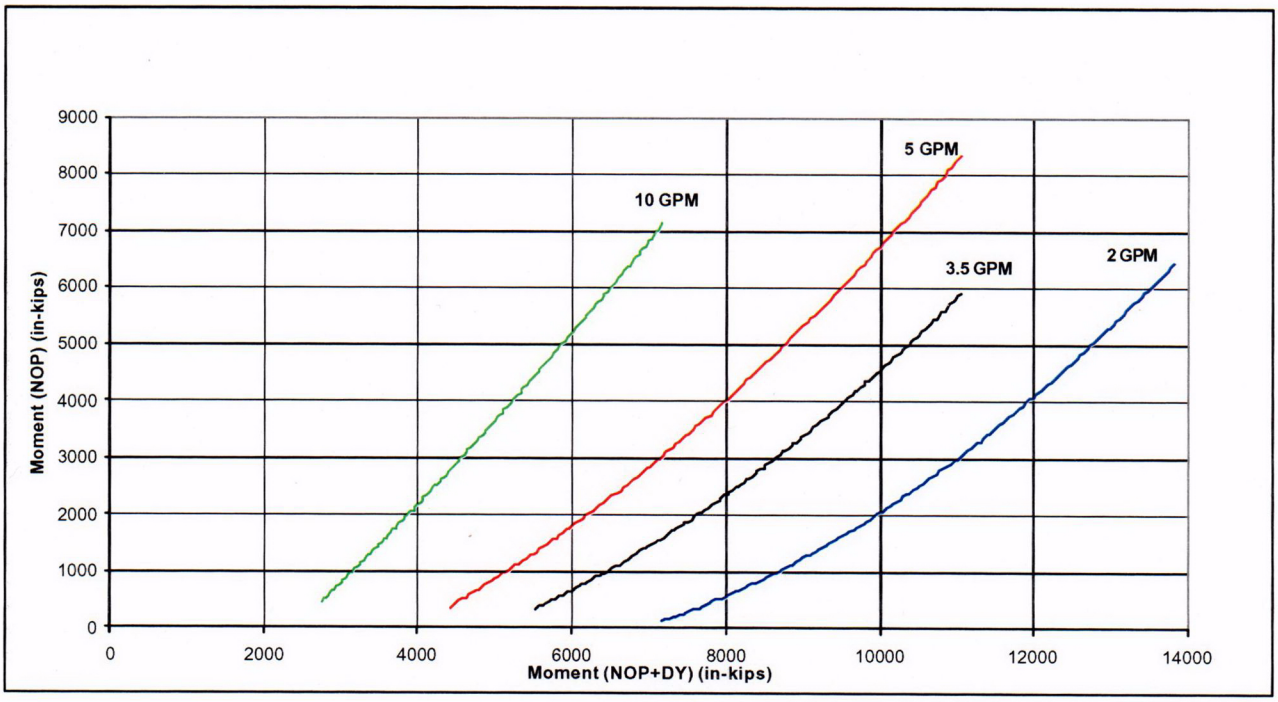


Figure 5-6. Leakage as a Function of NOP Moments versus NOP + Dynamic Moments

C03

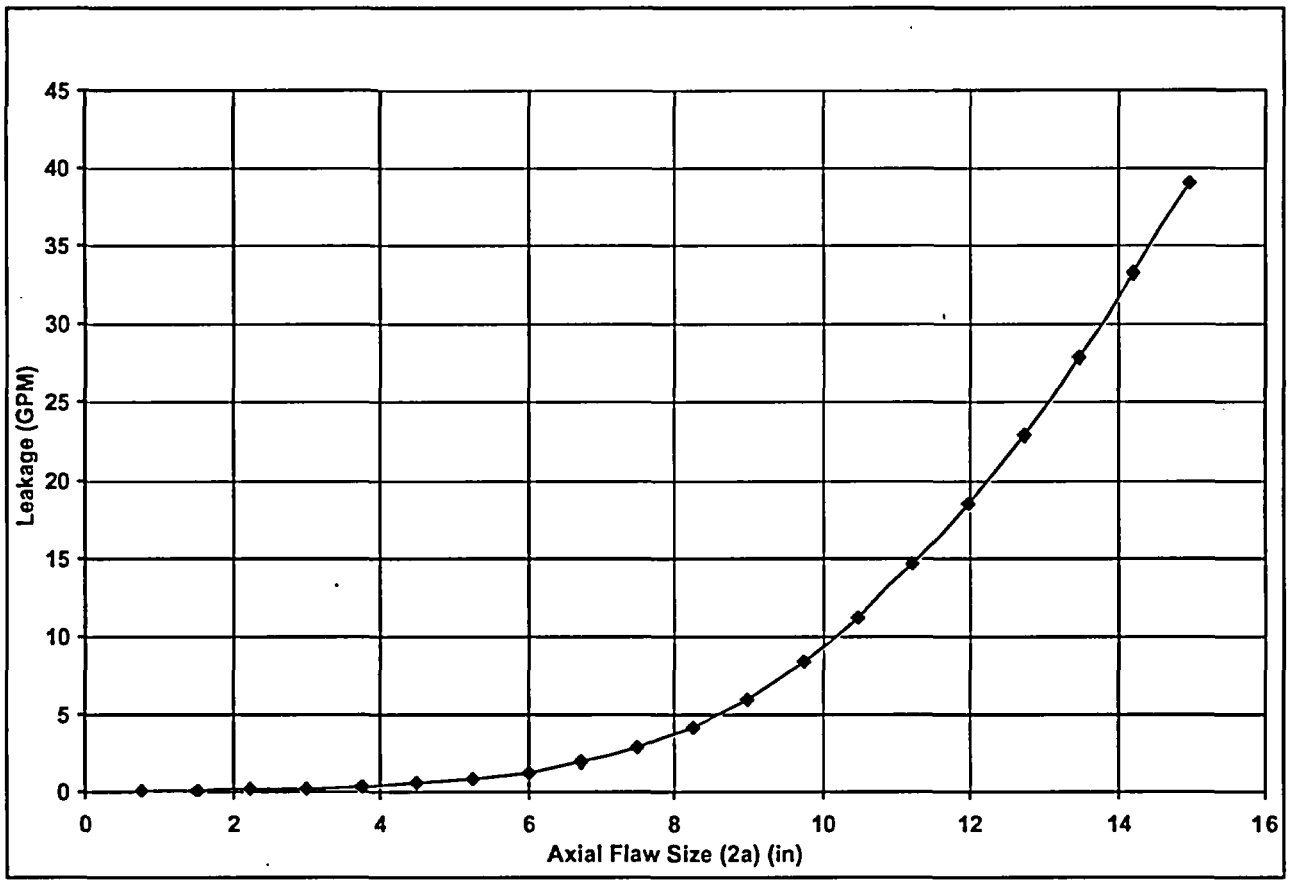


Figure 5-7. Leakage versus Flaw Size for Axial Flaws

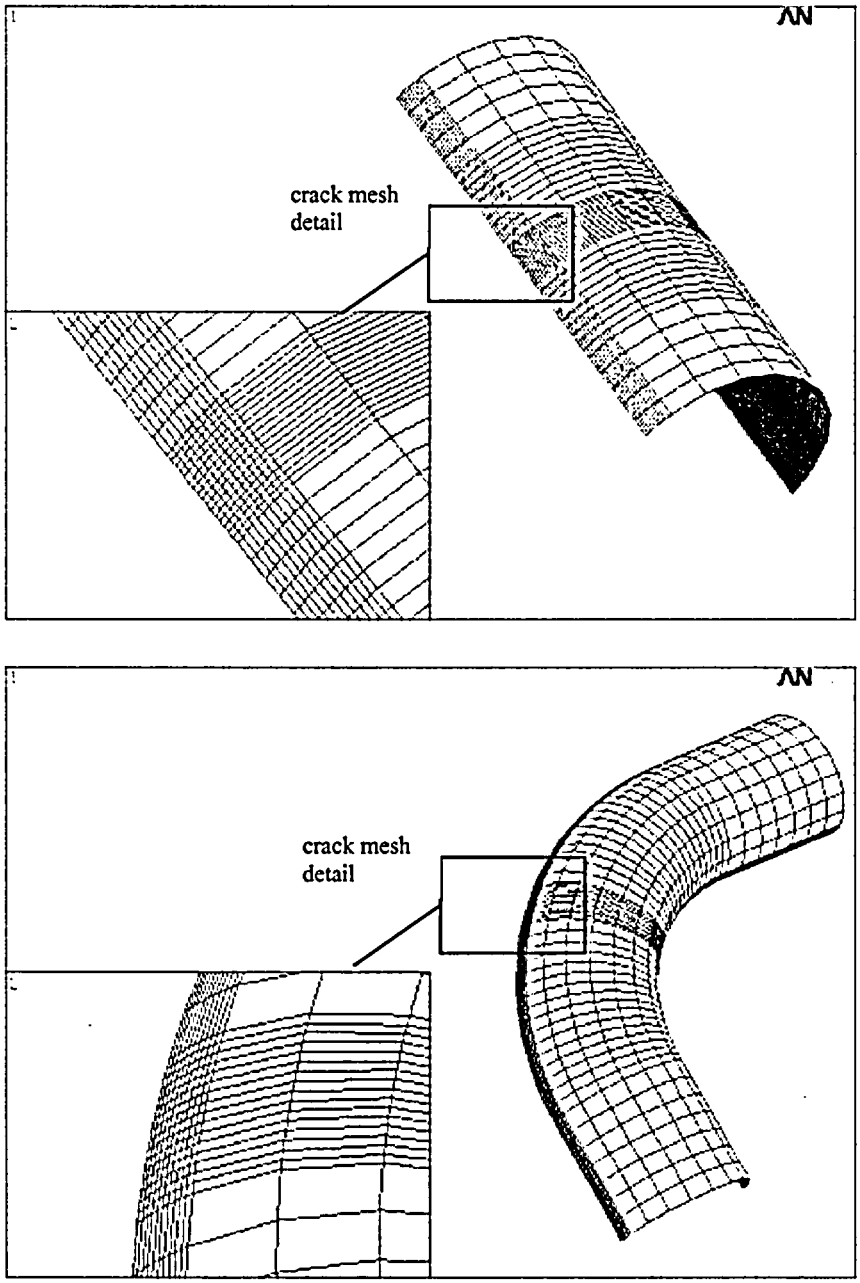


Figure 5-8. Finite Element Model of Straight Pipe and Reducing Elbow with Axial Through-wall Flaw

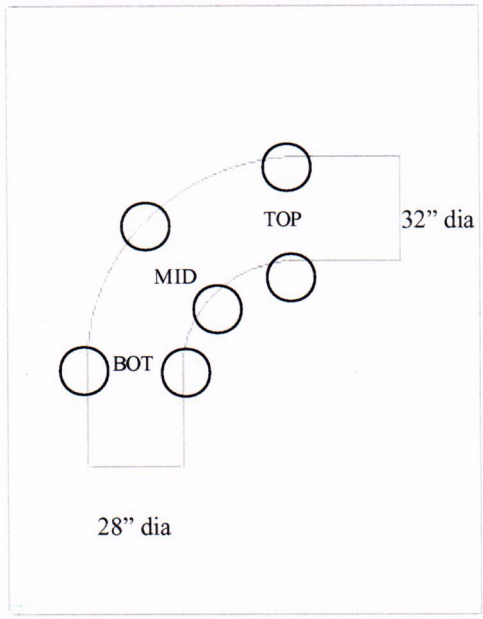


Figure 5-9. Location of Axial Flaws in the Reducing Elbow

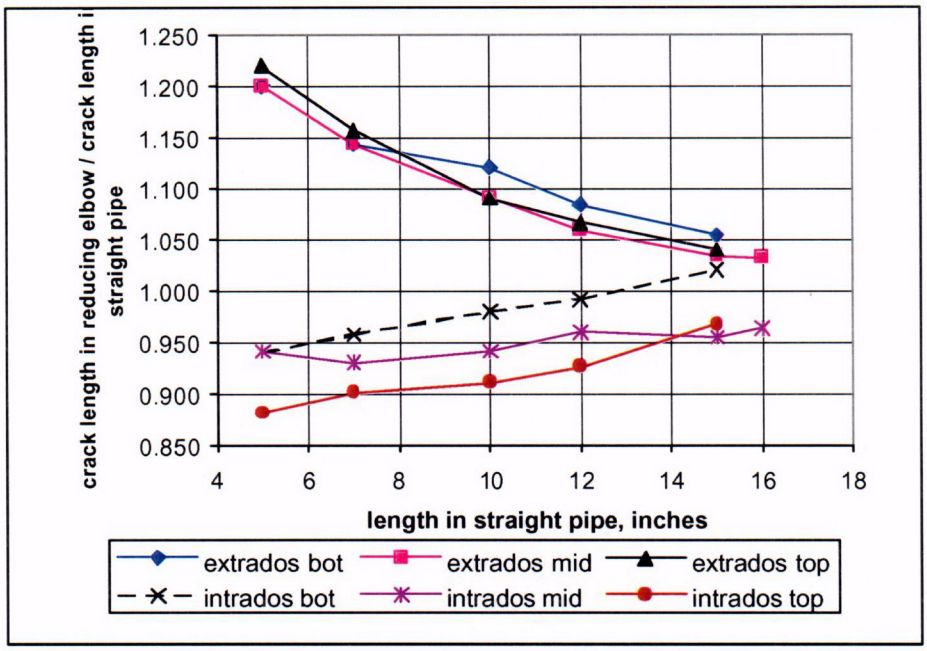


Figure 5-10. Ratio of Reducing Elbow Equivalent Flaw Length to Straight Pipe Flaw Length

C04

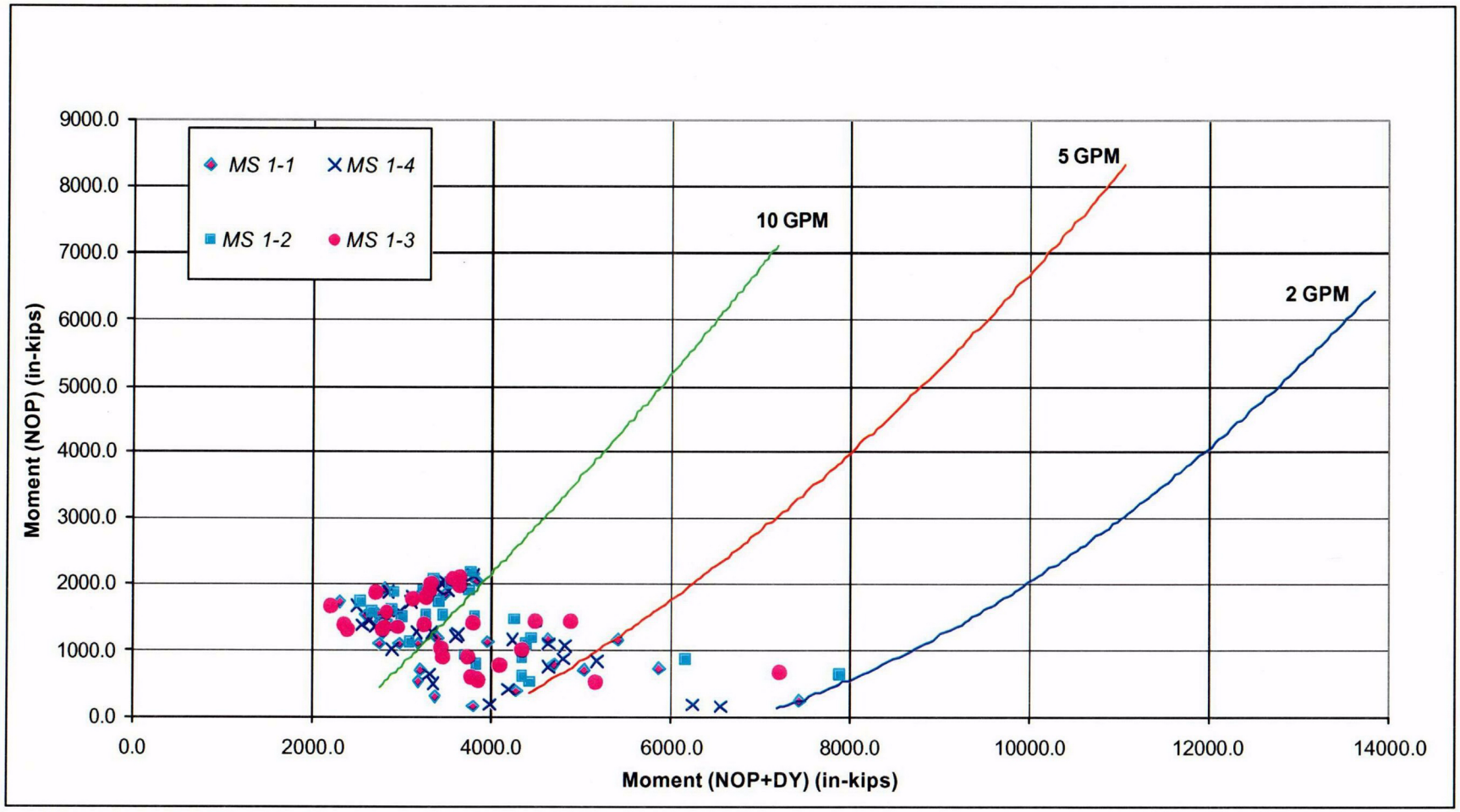


Figure 5-11. Leak-Before-Break Evaluation Results for Diablo Canyon Unit 1

C05

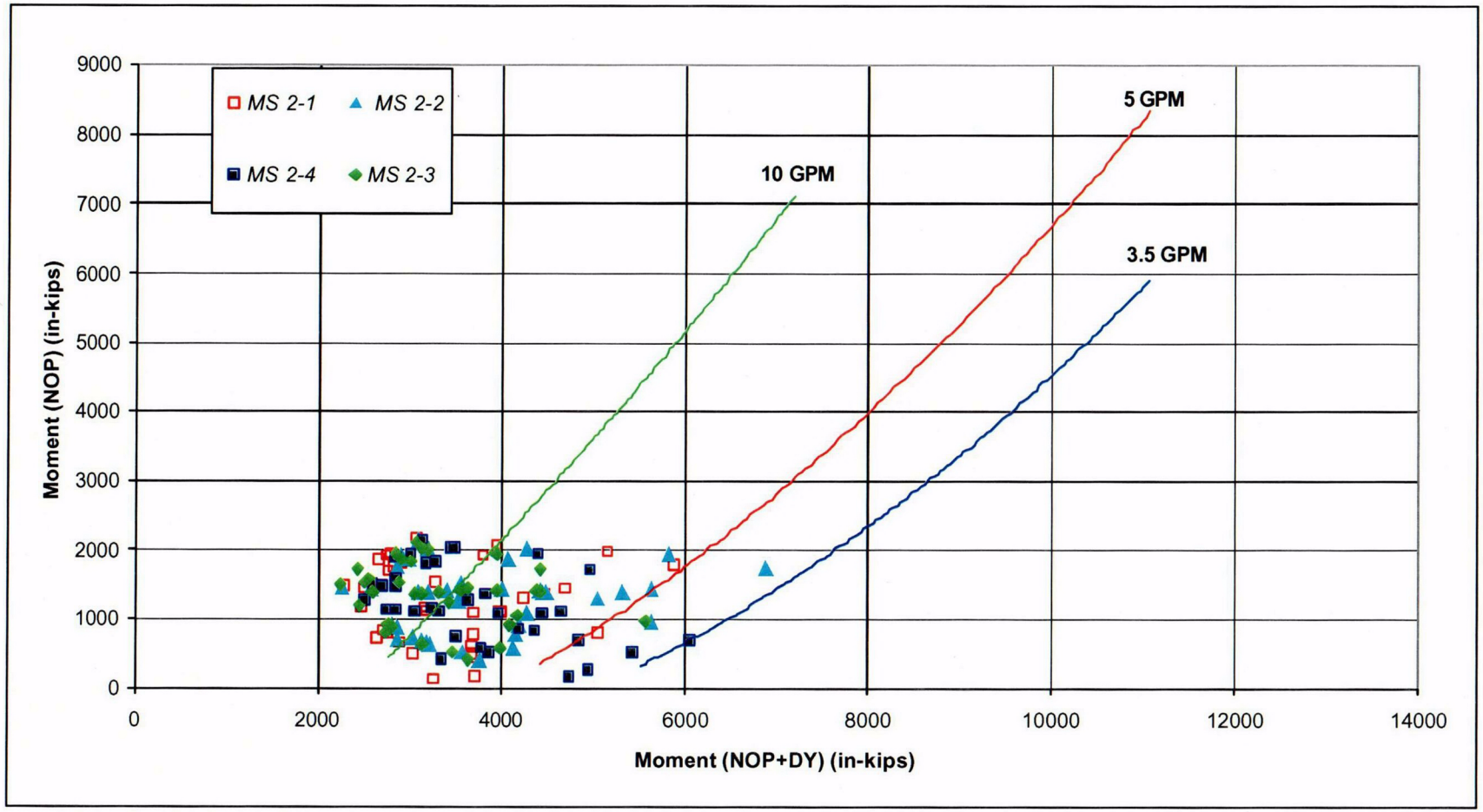


Figure 5-12. Leak-Before-Break Evaluation Results for Diablo Canyon Unit 2

C06

6.0 EVALUATION OF FATIGUE CRACK GROWTH OF SURFACE FLAWS

In accordance with the NRC criteria [5] set forth in Section 2 of this report, the growth of postulated surface cracks by fatigue is evaluated to demonstrate that such growth is insignificant for the plant life, when initial flaw sizes meeting ASME Code Section XI IWB-3514 acceptance standards [36] are postulated. The crack growth analysis is performed for the locations with the maximum stresses. The evaluation is performed for the maximum stress location which corresponds to the flued head (Node 10) for main steam lead 1-2 in Unit 1.

6.1 Plant Transients

Since the main steam piping at DCPP was designed to the requirements of ANSI B31.1, no line-specific transients are defined or analyzed in the design basis. Hence, transient information specific only to this LBB evaluation is developed to perform the crack growth evaluation. The plant transients used in this evaluation are presented in Table 6-1 [37]. These are consistent with the FSAR and the design of the steam generators. The number of rapid MSIV actuation cycles was conservatively assumed to be 500 for plant life. These rapid actuations only occur during events that cause high-high containment pressure, low steam line pressure, or high steam pressure rate, which to date have been very few. The pressure change due to normal fluctuations is assumed for those events with no significant pressure change defined.

The most severe seismic case, Hosgri, was used in this evaluation. The number of Hosgri cycles was conservatively taken as the number of OBE events, 20, times the number of cycles per event, 20, for a total of 400 cycles. The Hosgri event is postulated to occur only once in the plant life.

For crack growth analysis, the design basis transients are combined into load set pairs to give the largest pressure and temperature ranges. The combined transients and the associated number of cycles are shown in Table 6-2. For purposes of this analysis, the test events in Table 6-1 transients are treated as stand-alone events and they are not combined with the normal system transients.

6.2 Stresses for Crack Growth Evaluation

The axial stresses due to pressure and thermal loads are calculated as described below. For pressure loads, P, the axial stress is calculated as:

$$\sigma_p = P\frac{D_i^2}{D_o^2 - D_i^2}$$

where D_o is the outside diameter and D_i is the inside diameter of the pipe.

Bending stress is given by $\sigma_b = D_o(M)/2I$,

where

M = bending moment

I = moment of inertia

$= (\pi/64)*(D_o^4 - D_i^4)$

For thermal expansion moments, the maximum operating thermal moments ($M_{max\ oper}$), from Section 4, are scaled by the ratio of the transient temperature range (ΔT) to the operating temperature range (ΔT_{oper}):

$$M_t = M_{max\ oper}\ (\Delta T/\Delta T_{oper}),$$

where ΔT_{oper} is based on the temperatures at which the thermal expansion moments were calculated. $\Delta T_{oper} = 519 - 70 = 449°$. Table 6-3 gives the bounding non-scaled moments, based on the Section 4 tables. The operating conditions used for this evaluation have been provided in Section 4.1.

Non-cyclic stresses were also considered as they affect crack growth rate. The dead weight stresses are computed from the dead weight moments presented in Table 6-3. In addition, weld

residual stresses are considered in the evaluation. The weld residual stress is conservatively represented by a pure through-wall bending stress approximately equal to the base metal material yield stress at the operating temperature. Thus, $S_y = 30.2$ ksi at 519°F was used.

The calculated maximum and minimum stresses for each of the load conditions considered, are presented in Table 6-4.

The axial pressure, thermal, dead weight and residual stresses were combined to obtain the stress ranges corresponding to each load group. Within a load group, the maximum stresses were used. The resulting stress ranges are shown in Table 6-5, where the pressure stresses are taken as uniform tension across the pipe thickness and the other stresses are considered to have a linear through-wall distribution.

6.3 Model for Stress Intensity Factor

The stress intensity factors, K, corresponding to the point of the maximum depth of a semi-elliptical crack are calculated using fracture mechanics solutions presented in Reference 30. The stress intensity factors are determined for a conservative aspect ratio (a/ℓ) of 0.1.

The stress intensity factor for the deepest point on the semi-elliptical flaw from Reference 30 is given as:

$$K_I = (\pi t)^{0.5} \cdot \left[\sum_{i=0}^{3} \sigma_i (a/t)^i G_i \right]$$

where σ_i are the coefficients of the stress polynomial describing the axial stress (σ) variation through the cylinder wall and are defined below.

$$\sigma = \sigma_o + \sigma_1 (z/t) + \sigma_2 (z/t)^2 + \sigma_3 (z/t)^3,$$

z is the distance measured from the inner surface of the cylinder wall and t is the cylinder wall thickness. The G_i are the influence coefficients associated with the coefficients of the stress polynomial σ_i and are expressed by the following general form:

$$G_i = A_1\alpha_i + A_2\alpha_i^2 + A_3\alpha_i^3 + A_4\alpha_i^4 + A_5\alpha_i^5 + A_6\alpha_i(R/t-5)$$

$$\alpha_i = (a/t)/(a/c)^m$$

The values of A_1 through A_6 and m are provided in Reference 30 for each G_i. The constant R is the mean radius of the cylinder. The parameters 2c and *a* are the flaw length measured at the cylinder inner surface and flaw depth at the deepest point of the flaw, respectively.

6.4 Allowable Flaw Size

At the operating temperature of 519°F, the SA-516, Grade 70 carbon steel material is expected to behave in a ductile manner; hence, the net section plastic collapse methodology in Appendix H of ASME Code Section XI [36] can be used to determine the allowable flaw size. The load combination used for determining the allowable flaw size is pressure deadweight and seismic, or MSIV actuation loads. The total stress for this load combination is 21.02 ksi. The design stress intensity, S_m, for SA-516, Grade 70 at 519°F is 20.16 ksi. The stress ratio $(P_m+P_b)/S_m = 1.04$. With an aspect ratio of 1 to10 and a thickness of 1.008 inch, starting with the maximum allowable flaw depth-to-thickness ratio of 0.75, the maximum possible flaw length is 7.56 inches. The ratio of this flaw length to the pipe circumference is 0.086. Using Table H-5310-2 for emergency and faulted conditions (Service Level C/D), the allowable end-of-evaluation period flaw depth-to- thickness ratio is determined to be 0.75. Since the OBE loads are generally about half the SSE/MSIV loads, and the safety factor for Service Level A/B is twice that for Level C/D, the allowable flaw size will not be less than 0.75 inches for normal operating and upset (Service Level A/B) conditions.

6.5 Fatigue Crack Growth Analysis

6.5.1 Depth Direction Crack Growth

Fatigue crack growth analysis requires the use of an appropriate fatigue crack growth law for the ferritic steel piping. The ASME Code Section XI fatigue crack growth for ferritic steels in water environment is used for the evaluation.

The stresses are cycled between maximum and the minimum stress conditions shown in Table 6-4, with the stress ranges presented in Table 6-5. For each location, the actual K values for the fatigue crack growth are calculated based on the stresses.

Based on the guidelines of ASME Code Section XI, IWB-3514, an initial flaw size equal to the allowable depth of 15% of wall thickness is postulated. For the crack growth analysis an aspect ratio, a/l, of 0.1 has been conservatively used.

The results of the fatigue crack growth analysis are presented in Table 6-6. The results show that crack growth is very minimal. At the end of the design plant life, the crack growth for a postulated circumferential flaw of 15% of pipe wall and a/l = 0.1 is 0.262 inches, which is equivalent to a final flaw depth-to-thickness ratio, a/t, of 41%. This result bounds the rest of the main steam piping locations at DCPP since the most highly stressed location was used in the evaluation.

6.5.2 Length Direction Crack Growth

NUREG-1061, Section 5.2 (g) [5] requires that an evaluation be performed to show that the leakage flaw size is stable during an SSE event. A very simple approach is taken to determine the crack growth of a through-wall leakage size flaw to demonstrate stability. The initial through-wall flaw is assumed to correspond to the leakage flaw length (half critical flaw length) for the most limiting location, Node 10 of Steam Generator 1-2. The total NOP+SSE moment at this location is 9441 in-kips (stress = 22.1 ksi, including internal pressure) and the leakage flaw

size is 9.24 inches for this load combination. The stress intensity factor K, can be calculated as $K = \sigma\sqrt{\pi a} = 84.2$ ksi $\sqrt{in}$. Using the most conservative R ratio in ASME Code Section XI crack growth curve for carbon steels in water environment (Figure A-4300-2), the crack growth per cycle is 10^{-3} inches. For 400 SSE cycles, this translates into 0.4 inches. This crack growth is insignificant compared to the total circumference of 88 inches. In fact, this crack growth is less than 1% of the leakage flaw size.

Table 6-1

Plant Design Transients at Diablo Canyon

Conditions	Design Transients	Occurrences	ΔP (psi)	ΔT (°F)
Normal	RCS heatup and cooldown at ≤100°F/hr	250 (ea.)	1005	477
	Unit loading and unloading at 5% of full power / min	18,300 (ea.)	235	31
	Step load increase and decrease of 10% of full power	2,500 (ea.)	137	16
	Large step load decrease	250	313	40
	Steady state fluctuations	infinite	25	3
	T_{avg} coastdown from nominal to reduced temperature	50	*	*
Upset	Loss of load (above 15% full power), w/o immediate turbine or reactor trip	100	358	45
	Loss of all offsite power	50	386	48
	Partial loss of flow	100	192	26
	Reactor trip from full power	500	252	33
	Design earthquake	20	_	_
Faulted	Main reactor coolant pipe break	1	1005	335
	Steam pipe break	1	1005	335
	Double design earthquake	1	_	_
	7.5M Hosgri earthquake	1	_	_
Test	Turbine roll test	10	470	70
	Hydrostatic test conditions			
	a. Primary side	10	—	—
	b. Secondary side (each generator)	10	1356	0
	c. Primary side leak test	60	—	—

*Enveloped by RCS heatup and cooldown.

Table 6-2

Plant Design Transients used for LBB Evaluations

Conditions	Design Transients	Occurrences [1]	ΔP (psi)	ΔT (°F)	Group
Normal	RCS heatup and cooldown at ≤100°F/hr	250 (ea.)	1005	477	1
	Unit loading and unloading at 5% of full power / min	18,300 (ea.)	235	31	2
	Step load increase and decrease of 10% of full power	2,500 (ea.)	137	16	
	Large step load decrease	250	313	40	
	Steady state fluctuations	infinite	25	3	3
	T_{avg} coastdown from nominal to reduced temperature	50	– [2]	– [2]	– [2]
Upset	Loss of load (above 15% full power), w/o immediate turbine or reactor trip	100	358	45	4
	Loss of all offsite power	50	386	48	
	Partial loss of flow	100	192	26	
	Reactor trip from full power	500	252	33	
	Design earthquake	20	– [3]	– [3]	– [3]
Faulted	Main reactor coolant pipe break	1	1005	335	5
	Steam pipe break	1	1005	335	
	Double design earthquake	1	–	–	7
	7.5M Hosgri earthquake	1	–	–	
Test	Turbine roll test	10	470	70	6
	Hydrostatic test conditions a. Primary side b. Secondary side (each generator) c. Primary side leak test	 10 10 60	 — 1356 —	 — 0 —	
MSIV	Main steam isolation valve fast closure	500	—	—	8

Notes
1. The above event counts reflect the 40-year design life.
2. Enveloped by RCS heatup and cooldown
3. Conservatively grouped with 7.5 M Hosgri Earthquake

Table 6-3

Bounding Moments

Loads (ft-lb)	Plant Unit	Unit 1				Unit 2			
	Line No.	1-106	1-119	1-120	1-121	G-028-01	G-029-01	G-030-01	G-031-01
	Node No.	10	10	10	10	130	130	130	130
DW	MA (Torsion)	26	-29	39	-37	24	-25	-259	25
	MB	32	26	-59	151	-97	74	690	52
	MC	-7766	-4429	2315	1569	-10824	-10076	9951	10226
Thermal	MA (Torsion)	9826	-8868	6236	-9623	8878	-7515	-8651	7059
	MB	4283	44517	51198	5525	-4488	-52534	-2747	-52461
	MC	32346	-18152	-34542	-10070	-65874	-65426	58254	64292
SSE HS	MA (Torsion)	19602	27968	25358	21830	40738	41300	24517	42504
	MB	175351	236010	224782	204043	237214	251913	406130	259430
	MC	458882	532182	515018	459985	31141	31164	34098	33697
SAM HS	MA (Torsion)	31518	43351	30009	44826	39596	40892	45251	40059
	MB	136817	140762	122179	146247	190973	188295	103227	177100
	MC	77104	93045	69415	94131	235120	249850	254028	243585
MSIV	MA (Torsion)	-308	1528	421	-740	-367	-3986	840	2392
	MB	2144	3059	6682	-4522	1543	19289	-9145	-17227
	MC	630746	653882	595812	570446	103329	-198624	125365	-103467

Table 6-4

Maximum and Minimum Transient Stresses

Group	Maximum Stresses (ksi)				Minimum Stresses (ksi)			
	Pressure	Thermal	DW	Total	Pressure	Thermal	DW	Total
1	6.277	1.125	0.096	7.498	0.000	0.000	0.096	0.096
2	7.744	1.198	0.096	9.039	4.809	1.052	0.096	5.957
	7.132	1.163	0.096	8.391	5.421	1.088	0.096	6.604
	8.231	1.220	0.096	9.547	6.277	1.125	0.096	7.498
3	6.433	1.132	0.096	7.661	6.120	1.118	0.096	7.335
4	8.512	1.231	0.096	9.840	6.277	1.125	0.096	7.498
	8.687	1.238	0.096	10.022	6.277	1.125	0.096	7.498
	7.476	1.187	0.096	8.758	6.277	1.125	0.096	7.498
	7.850	1.203	0.096	9.149	6.277	1.125	0.096	7.498
5	6.277	0.790	0.096	7.163	0.000	0.000	0.096	0.096
	6.277	0.790	0.0960	7.163	0.000	0.000	0.096	0.096
6	2.935	0.165	0.0960	3.196	0.000	0.000	0.096	0.096
	8.469	0	0.0960	8.565	0.000	0.000	0.096	0.096

Table 6-5

Stress Ranges for Fatigue Crack Growth Evaluation

Group	Cyclic Stresses (ksi)				DW + Residual	Total Stress Ranges (ksi)			
	Maximum		Minimum			Maximum		Minimum	
	Uniform	Linear	Uniform	Linear	(ksi)	Uniform	Linear	Uniform	Linear
1	6.277	1.125	0.000	0.000	30.296	6.277	31.421	0.000	30.296
2	8.231	1.220	6.277	1.125	30.296	8.231	31.516	6.277	31.421
3	6.433	1.132	6.120	1.118	30.296	6.433	31.428	6.120	31.414
4	8.687	1.238	6.277	1.125	30.296	8.687	31.534	6.277	31.421
5	6.277	0.790	0.000	0.000	30.296	6.277	31.086	0.000	30.296
6	8.469	0.000	0.000	0.000	30.296	8.469	30.296	0.000	30.296
7	0.000	15.891	0.000	-15.891	30.296	0.000	46.187	0.000	14.405
8	0.000	14.168	0.000	-14.168	30.296	0.000	44.464	0.000	16.128

Table 6-6

Results of Fatigue Crack Growth Analysis

Assumed Initial a/t	Initial Depth a (in)	Final Depth a (in)	Final a/t
15%	0.151	0.413	41%

7.0 SUMMARY AND CONCLUSIONS

Leak-before-break (LBB) evaluations are performed for the main steam piping at Diablo Canyon Units 1 and 2 in accordance with the requirements of NUREG-1061. The evaluation included all the four main steam lines in both units. The approach taken is consistent with that used by SI in other recent LBB submittals for other plants [1, 2, 3]. The analysis was performed using conservative lower bound material properties for the base metals and weldments and location specific stresses consisting of pressure, deadweight, thermal and dynamic (envelope of SSE seismic and MSIV) loads. In the evaluations, both circumferential and axial flaws have been considered. Critical flaw sizes and leakage flaw sizes were calculated on a location specific basis using both elastic-plastic J-Integral/Tearing modulus methodology. The leakage flaw size is defined as the minimum of one half the critical flaw size with a factor of one on the stresses or the full critical flaw size with a factor of $\sqrt{2}$ on the stresses. Leakage was then calculated through the leakage flaw size. Fatigue crack growth analysis was also performed to determine the extent of growth of any pre-existing flaws.

Based on these evaluations, the following conclusions can be made.

- The lowest predicted leakage for the Unit 1 main steam piping is 2.0 gpm while that for Unit 2 is 3.5 gpm. A significant portion of the main steam piping at DCPP Units 1 and 2 will meet a 5 gpm leakage limit. NUREG-1061 requires that the Diablo Canyon leak detection systems be capable of detecting leaks of 1/10 of these amounts.

- Fatigue crack growth of an assumed subsurface flaw of 15% of pipe wall shows that fatigue crack growth is insignificant for the most limiting locations for all the main steam piping inside containment at Diablo Canyon and therefore does not invalidate the application of leak-before-break evaluation of these lines.

- The effect of degradation mechanisms that could invalidate the LBB evaluations was considered in the evaluation. It was determined that there is no potential for water hammer, intergranular

stress corrosion cracking (IGSCC) and erosion-corrosion for portions of the main steam system considered in the LBB evaluations.

- In conjunction with the application of leak-before-break methodology, the inservice inspection plan for the main steam piping inside containment is being augmented. The limiting weld location on each line, the containment penetration flued head-to-pipe weld, will be inspected according to ASME Section XI frequency requirements.

- The LBB evaluation performed for the main steam inside containment at DCPP contains several conservative assumptions:

  - The SSE loads are based on a conservative envelope of building response spectra from multiple elevations. The highest seismic loads are calculated to occur at the elevation with the lowest acceleration input. Use of the multiple level spectral method would likely result in reduced seismic loads at the limiting location. Lower seismic loads would result in larger critical flaw sizes and larger leak rates.
  - The MSIV loads used in the evaluation were conservatively calculated. The loads were developed nearly twenty-five years ago using limited computation capabilities. Use of currently available software and methodologies, along with more realistic assumptions, would likely reduce these loads. Reduced loads will result in larger critical flaw sizes and therefore, higher leakage rates.
  - Lower bound ASME Code minimum material properties were used for the stress-strain parameters in the fracture mechanics evaluation.
  - Lower bound fracture toughness properties, which formed the basis for the flaw acceptance in ASME Code Section XI, was used to determine the critical flaw sizes.

In addition to the conservative assumptions used in the evaluation, there are added conservatisms in the LBB evaluation requirements in NUREG-1061, Vol. 3, and NUREG-0800, SRP 3.63.

- There is a requirement of a safety factor of 2 between the critical flaw size and the leakage flaw size. If this safety factor is reduced to 1.5, the calculated leakage will increase considerably. Reduction of this safety factor will still allow a significant amount of time to detect leakage before the critical flaw size is reached, since crack growth is very minimal.

- NUREG-1061 recommends an additional safety factor of 10 between the calculated leakage and the detectable leakage. While this factor was reasonable some time ago due to uncertainties in the calculation methods and material properties, the analytical techniques and material property characterization have improved over the years such that this safety factor is judged to be too conservative.

8.0 REFERENCES

1. Letter from G. S. Vissing (USNRC) to R. C. McCredy (RG&E) including Safety Evaluation Report, "Staff Review of the Submittal by Rochester Gas & Electric to Apply Leak Before Break Status to portions of R. E. Ginna Nuclear Power Plant Residual Heat Removal System Piping (TAC No. MA039)", dated February 25, 1999, Docket No. 50-244.

2. Letter from R. B. Eaton (USNRC) to R. P. Necci (Northeast Nuclear Energy Company) including Safety Evaluation Report, "Staff Review of the Submittal by Northeast Nuclear Energy Company to Apply Leak Before Break Status to the Pressurizer Surge Line, Millstone Nuclear Power Station Unit 2 (TAC No. MA4146)", dated May 4, 1999, Docket No. 50-336.

3. Letter from J. G. Lamb (USNRC) to T. Contu (Nuclear Management Company, LLC) including Safety Evaluation Report, "Kewaunee Nuclear Power Plant - Review of the Leak Before Break Evaluation for the Residual Heat Removal, Accumulator Injection Line, and Safety Injection System (TAC No. MB1301)", dated September 5, 2002, Docket No. 50-305.

4. Stello, Jr., V., "Final Broad Scope Rule to Modify General Design Criterion 4 of Appendix A, 10 CFR Part 50," NRC SECY-87-213, Rulemaking Issue (Affirmation), August 21, 1987.

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Proprietary Notice and Application for Withholding for Westinghouse Electric LLC WCAP 16170-P, Revision 0, "Diablo Canyon SG Alternate Repair Criteria Based on Limited Tube Support Plate Displacement," dated November 2003 (proprietary)

Westinghouse

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Our ref: CAW-03-1741

November 20, 2003

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: WCAP-16170-P, "Diablo Canyon SG Alternate Repair Criteria Based on Limited Tube Support Plate Displacement" (Proprietary)

The proprietary information for which withholding is being requested in the above-referenced report is further identified in Affidavit CAW-03-1741 signed by the owner of the proprietary information, Westinghouse Electric Company LLC. The affidavit, which accompanies this letter, sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10 CFR Section 2.790 of the Commission's regulations.

Accordingly, this letter authorizes the utilization of the accompanying affidavit by Pacific Gas and Electric Company.

Correspondence with respect to the proprietary aspects of the application for withholding or the Westinghouse affidavit should reference this letter, CAW-03-1741, and should be addressed to J. S. Galembush, Acting Manager, Regulatory Compliance and Plant Licensing, Westinghouse Electric Company LLC, P.O. Box 355, Pittsburgh, Pennsylvania 15230-0355.

Very truly yours,

J. S. Galembush, Acting Manager
Regulatory Compliance and Plant Licensing

Enclosures

cc: D. Holland
B. Benney
E. Peyton

CAW-03-1741

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared J. S. Galembush, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC (Westinghouse), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

J. S. Galembush, Acting Manager
Regulatory Compliance and Plant Licensing

Sworn to and subscribed
before me this 21st day
of November, 2003

Sharon L. Fiori
Notary Public

SHARON L. FIORI
COMMONWEALTH OF PENNSYLVANIA
NOTARY PUBLIC

Notarial Seal
Sharon L. Fiori, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires January 29, 2007
Member, Pennsylvania Association Of Notaries

(1) I am Acting Manager, Regulatory Compliance and Plant Licensing, in Nuclear Services, Westinghouse Electric Company LLC (Westinghouse), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rule making proceedings, and am authorized to apply for its withholding on behalf of Westinghouse.

(2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse "Application for Withholding" accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by Westinghouse in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of

Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information that is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in WCAP-16170-P, "Diablo Canyon SG Alternate Repair Criteria Based on Limited Tube Support Plate Displacement," (Proprietary) dated November 2003. The information is provided in support of a submittal to the Commission, being transmitted by Pacific Gas and Electric Company letter and Application for Withholding Proprietary Information from Public Disclosure, to the Document Control Desk. The proprietary information as submitted for use by Westinghouse for Diablo Canyon Units 1and 2 is expected to be applicable for other licensee submittals in support of implementing alternate repair criteria (ARC) for axial outside diameter stress corrosion cracking (ODSCC) based upon tube expansion at the tube support plate (TSP) intersections.

This information is part of that which will enable Westinghouse to:

(a) Establish a 4.0 volt alternate repair criterion at the intersections of hot leg TSPs 1 through 4 in the Diablo Canyon Units 1 and 2 steam generators.

(b) Discuss the hydraulic loads used to determine the tube locations requiring expansion to limit TSP displacements to acceptable levels.

(c) Discuss analysis and testing programs used in support of the development of the 4.0 volt alternate plugging criterion.

(d) Discuss the sleeve stabilizer which is used to implement the required tube expansions at the TSP intersections.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of meeting NRC requirements for licensing documentation.

(b) Westinghouse can sell support and defense of this information to its customers in the licensing process.

(c) The information requested to be withheld reveals the distinguishing aspects of a methodology which was developed by Westinghouse.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar licensing support documentation and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended.

Further the deponent sayeth not.

PROPRIETARY INFORMATION NOTICE

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

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