MPR ASSOCIATES, INC.

SUSQUEHANNA STEAM ELECTRIC STATION

LEAK BEFORE BREAK EVALUATION OF POSTULATED RECIRCULATION SYSTEM PIPE CRACKS

MPR-949
Revision 1

Prepared for:

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1. INTRODUCTION

Current practice in the design of high energy piping in nuclear power plants is to assume that instantaneous, double-ended pipe ruptures can occur and to design for the dynamic effects associated with these postulated pipe breaks. Such effects include pipe whip and leakage jet impingement on nearby equipment. In some specific applications, the unrealistic assumption of a double-ended guillotine pipe break results in the need for pipe supports and/or jet impingement barriers which may not be practical or advisable. For these reasons, Pennsylvania Power and Light (PP&L) requested that MPR evaluate the reasonableness of the double-ended pipe break assumption for postulated breaks in the recirculation system piping at and near its connections to the reactor pressure vessel nozzles. The purpose of this report is to present the results of an evaluation performed in accordance with the recommended criteria of NUREG 1061, Volume 3, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, Evaluation of Potential for Pipe Breaks". The evaluation was performed to determine if postulated through-wall flaws in the recirculation piping which are readily detectable by existing leak detection equipment can be accommodated with substantial safety margin against unstable rupture or plastic collapse of the piping. Demonstration of adequate margin against unstable pipe rupture in the presence of detectable size flaws provides assurance that any such flaws would be detected and corrective action taken well before there is any risk of an instantaneous, double-ended pipe rupture.

The methodology used to evaluate the potential of the recirculation piping to fail unstably in the presence of large through-wall flaws is well established and is outlined in NUREG 1061. This "leak-before-break" analysis approach has been utilized in the case of numerous operating BWR and PWR nuclear power plants and provides a realistic approach for the evaluation of failure mechanisms in such piping.

The specific portions of concern in the recirculation piping system at the Susquehanna Steam Electric Station (SSES) Units 1 & 2 are the pipe-to-safe end welds at the following reactor vessel inlet and outlet nozzles.

Unit 1	Unit 2
N1A	N1A
N2A	N2A
N2B	N2E
N2E	N2J
N2K	N2K

The leak-before-break (LBB) approach consists of determining postulated through-wall flaw sizes which result in leak rates substantially greater than the existing leak detection capability and to evaluate the capability of the piping to accommodate these flaws without catastrophic rupture for severe loadings (normal operating pressure, deadweight, and thermal loads in combination with the maximum calculated loads for the design safe shutdown earthquake). The specific steps in the evaluation and the recommended acceptance criteria given in NUREG 1061 are as follows:

- Evaluate the plant leakage detection capabilities for leakage from the postulated flaws to determine the detectable leak rate.
- Calculate the expected leakage from through-wall flaws under normal operating pressure and determine the crack size which leaks at a rate ten times that detectable by the leakage detection system. This is the postulated flaw for fracture mechanics analyses.
- Identify and calculate the applied loads on the piping system for normal operating conditions plus safe shutdown earthquake (SSE) loads.
- For the calculated applied loading, show that the postulated flaw is stable and calculated crack growth is minimal.

- Demonstrate that a margin of safety in terms of postulated crack length exists which is at least 2.0. That is, show that the crack size which corresponds to unstable pipe failure for the applied loads is at least twice as long as the postulated flaw.

- Demonstrate that a margin of safety in terms of applied load exists which is at least 1.41. That is, show that the load which corresponds to unstable pipe failure for the postulated crack size is at least 1.41 times the applied load.

As an alternative, if the above mentioned crack length and applied load margin acceptance criteria cannot be satisfied, NUREG 1061 allows a limit load evaluation in which it must be shown that the limit load for the postulated cracked section is, as a minimum, three times the applied load.

The analyses described in this report are based upon the method described above for demonstrating margin against unstable pipe rupture. Input used in the analyses which was received from PP&L included descriptions of the SSES leakage detection systems and their capabilities, the original General Electric Co. design stress analyses for the recirculation system piping, piping and nozzle safe end drawings, and descripitions of the In-Service Inspection (ISI) history for all welds in question.

The remainder of this report contains the following main sections:

- Summary & Conclusions - a summary of the results and conclusions of the LBB evaluation.

- Leak Detection Capability - describes the leakage detection capability of SSES Units 1 & 2.

- Leak Rate Modeling - describes the model used for predicting the leakage rate from through-wall pipe cracks.

- Applicability of Leak-Before Break Methodology - addresses the applicability of limitations imposed upon LBB analyses by NUREG 1061.

- Fracture Mechanics Analyses - describes methodology and results of analyses performed as part of the evaluation.
- References.
- Appendices - include detailed methods and calculations used as part of the evaluation.

2. SUMMARY & CONCLUSIONS

Analyses have been performed to determine if large through-wall flaws which would leak at a rate well beyond the limit of existing detection capability can be accomodated in the Susquehanna Steam Electric Station (SSES) recirculation system piping without significant growth, unstable growth or tearing, or plastic section collapse with safety margins greater than those recommended in NUREG 1061, Volume 3 (Reference 1). Specifically, evaluations have been performed in accordance with the recommended criteria of NUREG 1061 to determine the leak detection capability of the SSES leak detection systems, to establish postulated circumferential through-wall flaw sizes which can be readily detected by these systems, and to determine whether such postulated flaws can result in an unstable double-ended pipe rupture. Results of these evaluations and analyses are summarized below. The analyses were performed for postulated cracks at the pipe-to-safe end welds at the following reactor vessel nozzles.

Unit 1	Unit 2
N1A	N1A
N2A	N2A
N2B	N2E
N2E	N2J
N2K	N2K

2.1 Leak Detection Capability

The primary method used to monitor and detect unidentified leakage inside the primary containment at SSES is an operator log of sump pump run times and level recorders. There are two 150 gallon sumps in each containment. Every four hours, the operators log the percent change in sump level during the previous four hours. If the sump pump was activated during the four hour period, this information is also

logged. With knowledge of the sump capacity, the level change is used to calculate the net flow into and/or out of the sump during the period.

Over the four hour surveillance period required by SSES Technical Specifications, the containment leak detection sensitivity is at least 0.5 gallons per minute (gpm). This leakage rate, 0.5 gpm, is the assumed detectable leakage rate for fracture mechanics analyses. This value is considered very conservative because actual operational data indicates a sensitivity significantly better than 0.5 gpm.

2.2 Determination of Detectable Flaw Sizes

The leakage rate of high energy reactor coolant from postulated through-wall cracks in the recirculation system piping was predicted using a specialized computer program developed specifically for this purpose. The flow model uses an fL/D loss mechanism through the crack to predict pressure drop and a homogeneous choking model based on the crack exit plane stagnation pressure to evaluate critical flow. The crack opening area due to internal pressure is determined using formulae presented in Reference 6. Conservative estimates of flow from the cracks are obtained by the use of an appropriate friction factor which is based on comparisons of model predictions to measurements of leakage through representative through-wall cracks.

There are two pipe-to-safe end geometries of interest in this evaluation, those for the 28" recirculation discharge nozzles (designated N1), and those for the 12" recirculation inlet nozzles (designated N2). The relationship between crack size and leakage rate

for each nozzle type is shown in Figure 2.1. Although cracks are postulated at the weld heat affected zone of each side of the pipe-to-safe end weld (in the safe end and in the pipe), conservative crack size-leakage correlations were determined by using only the thicker safe end cross sections in the leakage calculation. A thicker pipe wall results in lower leakage rates for a particular crack size, requiring a larger crack to obtain a particular detectable leak rate. Consequently, use of a thicker pipe wall is conservative for a leak-before-break analysis.

NUREG 1061 recommends that the leakage rate for the postulated flaw sizes for fracture mechanics analyses be ten times the detectable rate. For SSES, this corresponds to a five gpm leak rate. In addition, as specified in the SSES Technical Specifications, this also is the largest unidentified leakage rate which can exist at SSES without forcing the unit to shut down. Based on the results of the crack size-leakage analyses, the postulated circumferential, through-wall flaw sizes chosen for fracture mechanics analyses were 9.8 inches for the N1 type nozzle safe ends and 10.1 inches for the N2 type nozzle safe ends. These crack lengths correspond to approximately 39 degree and 85 degree circumferential cracks, respectively.

2.3 Applicability of Analysis Method

The guidelines presented in NUREG 1061 do not recommend the application of leak-before-break analyses to piping susceptible to failure from intergranular stress corrosion cracking (IGSCC), waterhammer or fatigue. Pennsylvania Power & Light (PP&L) has already taken measures to mitigate any IGSCC at the recirculation system welds. These actions include induction heating stress improvement (IHSI) of the N1 nozzle safe end to pipe welds and replacement of the N2 nozzle safe ends with those fabricated from IGSCC resistant material, in combination with applying corrosion resistant cladding on the inside diameter of the attached piping near the N2 safe ends. Further, in-service inspections (ISI) of

the N1 safe end to pipe welds shows that at the present time, no cracks are present in the N1 welds. Preservice inspections of the N2 safe end to pipe welds indicate that these welds are also defect free. Further, IGSCC is not expected in the N2 safe end to pipe welds because of the use of low carbon 316L safe end material and the presence of corrosion resistant cladding on the pipe ID near the safe end to pipe weld.

It is concluded that, because of the results of these inspections and the mitigating actions taken by PP&L, there is reasonable assurance that the pipe-to-safe end welds at the N1 and N2 nozzles will not be subject to significant IGSCC. Planned future in-service inspections of these areas will provide an additional check on this conclusion.

A review of waterhammer loadings and fatigue usage for the recirculation system indicates that these areas are not significant concerns for the SSES recirculation piping. For these reasons, the leak-before-break analysis approach described in NUREG 1061 is applicable and valid for the portions of the SSES recirculation piping evaluated in this report.

2.4 Fracture Mechanics Analyses

The objectives of fracture mechanics analyses were to determine if the postulated flaws whose size is determined by leak detection capabilities will grow significantly or result in unstable failure under normal operating condition plus design safe shutdown earthquake (SSE) loads. The margins to unstable failure in terms of crack length should be at least 2.0 and the margins to unstable failure in terms of load should be at least 1.41. These acceptance criteria are recommended in NUREG 1061.

The applied loads at the safe end locations evaluated in this report were obtained from the original General Electric Co. design stress analyses for the SESS recirculation piping system. The forces and moments on the postulated crack locations due to deadweight, thermal

expansion and SSE loading were obtained from these stress analyses. The stress due to internal pressure was determined by hand calculation.

The recirculation system piping and nozzle safe ends are forged austenitic (300-series) stainless steel. The pertinent material properties selected for fracture mechanics analyses are values based on conservative data obtained for stainless steel casting material at operating temperature (550^{o}F). A considerable amount of published research has demonstrated that some forms of stainless steel weld metal or casting material have lower crack initiation and tearing resistance than forged stainless steel base metal. Accordingly, such lower bound data were used in this analysis.

The results of crack extension analyses are shown in Table 2.1. This table lists the calculated J-integral (crack driving potential) for each nozzle safe end location. The initiation of crack growth is predicted if the calculated value of J reaches the crack growth initiation point, J_{IC}. As can be seen, the calculated J for each location is less than J_{IC}, predicting no growth of cracks even under normal operating plus safe shutdown earthquake loads.

The results of tearing stability analyses are shown in Table 2.2. This table lists the calculated tearing modulus, T, for each nozzle safe end location. Unstable crack growth (tearing) is predicted if the calculated value of T is greater than the material tearing resistance, T_{MAT}. As can be seen, the calculated T for each location is less than T_{MAT}, predicting no unstable tearing. The margins to unstable crack growth or tearing in terms of applied load and postulated crack length are all well over 1.41 and 2.0, respectively, and therefore satisfy the criteria recommended in NUREG 1061.

The criteria presented in NUREG 1061 allow for a limit load analysis to be performed if the recommended fracture mechanics acceptance criteria

described above cannot be met. The objective of the limit load analysis is to demonstrate that the load required for plastic collapse of the postulated cracked section is at least three times the applied load. This factor provides substantial margin against failure. Although not required, limit load analyses were performed as part of this evaluation to further demonstrate the safety margins present against unstable crack growth leading to failure. The results of these analyses, shown in Table 2.3, indicate that the margin against plastic collapse is approximately three or greater in all cases.

Conclusions

It is concluded that sufficient mitigating actions have been taken at SSES to eliminate concerns with IGSCC at the safe end to pipe welds covered in this analysis. Further, since no waterhammer or fatigue concern exists for these welds, use of NUREG-1061 methods for leak-before-break analysis is appropriate and valid.

Fracture mechanics analyses were performed that included the following conservatisms: (1) use of lower bound material properties, (2) use of maximum section thickness and a conservative roughness factor to predict lower bound leak rates, (3) use of pipe minimum wall geometry for fracture mechanics analyses, (4) use of larger than recommended through-wall crack sizes, and (5) use of conservative EPRI estimates of J-integral values. Results of the analyses show that, even with these conservatisms, there is still considerable margin against double-ended ruptures of the recirculation piping at the reactor inlet and outlet nozzle areas. Therefore, jet loads resulting from double-ended breaks are extremely unlikely to occur and need not be postulated at these locations.

TABLE 2.1
CRACK EXTENSION RESULTS

Unit	Nozzle	Crack Angle	$J^{(1)}$ (in-lb/in^2)	$J_{IC}^{(2)}$ (in-lb/in^2)
1	N1A	45°	57	992
1	N2A	90°	217	992
1	N2B	90°	224	992
1	N2E	90°	103	992
1	N2K	90°	90	992
2	N1A	45°	80	992
2	N2A	90°	235	992
2	N2E	90°	89	992
2	N2J	90°	363	992
2	N2K	90°	83	992

(1) Calculated value of J-integral.

(2) The value of the J-integral at which the crack would start to grow. (NOTE: This does not imply unstable growth of the crack.)

TABLE 2.2
UNSTABLE CRACK GROWTH OR TEARING RESULTS

Unit	Nozzle	Crack Angle	L/R	$T^{(1)}$	$T_{MAT}^{(2)}$	Load(3,5) Margin	Recommended Load Margin	Crack Length(4) Margin	Recommended Crack Length Margin
1	N1A	45^0	53	0.2	182	7.37	1.41	> 4.0	2.0
1	N2A	90^0	35	2.0	182	3.57	1.41	> 2.0	2.0
1	N2B	90^0	35	2.1	182	3.53	1.41	> 2.0	2.0
1	N2E	90^0	35	0.8	182	4.92	1.41	> 2.0	2.0
1	N2K	90^0	35	0.7	182	5.23	1.41	> 2.0	2.0
2	N1A	45^0	53	0.3	182	6.30	1.41	> 4.0	2.0
2	N2A	90^0	35	2.2	182	3.46	1.41	> 2.0	2.0
2	N2E	90^0	35	0.7	182	5.27	1.41	> 2.0	2.0
2	N2J	90^0	35	3.5	182	2.95	1.41	> 2.0	2.0
2	N2K	90^0	35	0.6	182	5.43	1.41	> 2.0	2.0

(1) Calculated applied tearing modulus.

(2) The value of T corresponding to unstable crack growth or tearing.

(3) The load corresponding to unstable crack growth or tearing for the postulated crack length divided by the applied load.

(4) The crack length corresponding to unstable crack growth or tearing for the applied load divided by the postulated crack length.

(5) For the given system compliance and crack length, failure is controlled by plastic collapse rather than unstable crack growth or tearing. Load margin is plastic collapse load for postulated crack length divided by applied load.

TABLE 2.3
MARGINS TO PLASTIC COLLAPSE

Unit	Nozzle	Applied Moment (in-Kip)	No Crack Collapse Moment (in-Kip)	No Crack Margin	Postulated Crack[1] Collapse Moment (in-Kip)	Postulated Crack[1] Margin
1	N1A	4979.6	46496.6	9.34	26518.3	7.37
1	N2A	701.5	4396.0	6.27	2507.2	3.57
1	N2B	711.4	4396.0	6.18	2507.2	3.53
1	N2E	509.6	4396.0	8.63	2507.2	4.92
1	N2K	479.4	4396.0	9.17	2507.2	5.23
2	N1A	5830.5	46496.6	7.97	26518.3	6.30
2	N2E	724.0	4396.0	6.07	2507.2	3.46
2	N2A	467.0	4396.0	9.24	2507.2	5.27
2	N2E	851.6	4396.0	5.16	2507.2	2.95[2]
2	N2K	461.5	4396.0	9.53	2507.2	5.93

(1) 45° circumferential through-wall cracks in N1 nozzle safe ends
90° circumferential through-wall cracks in N2 nozzle safe ends

(2) For a 85°, five gpm leakage through-wall crack, margin = 3.07

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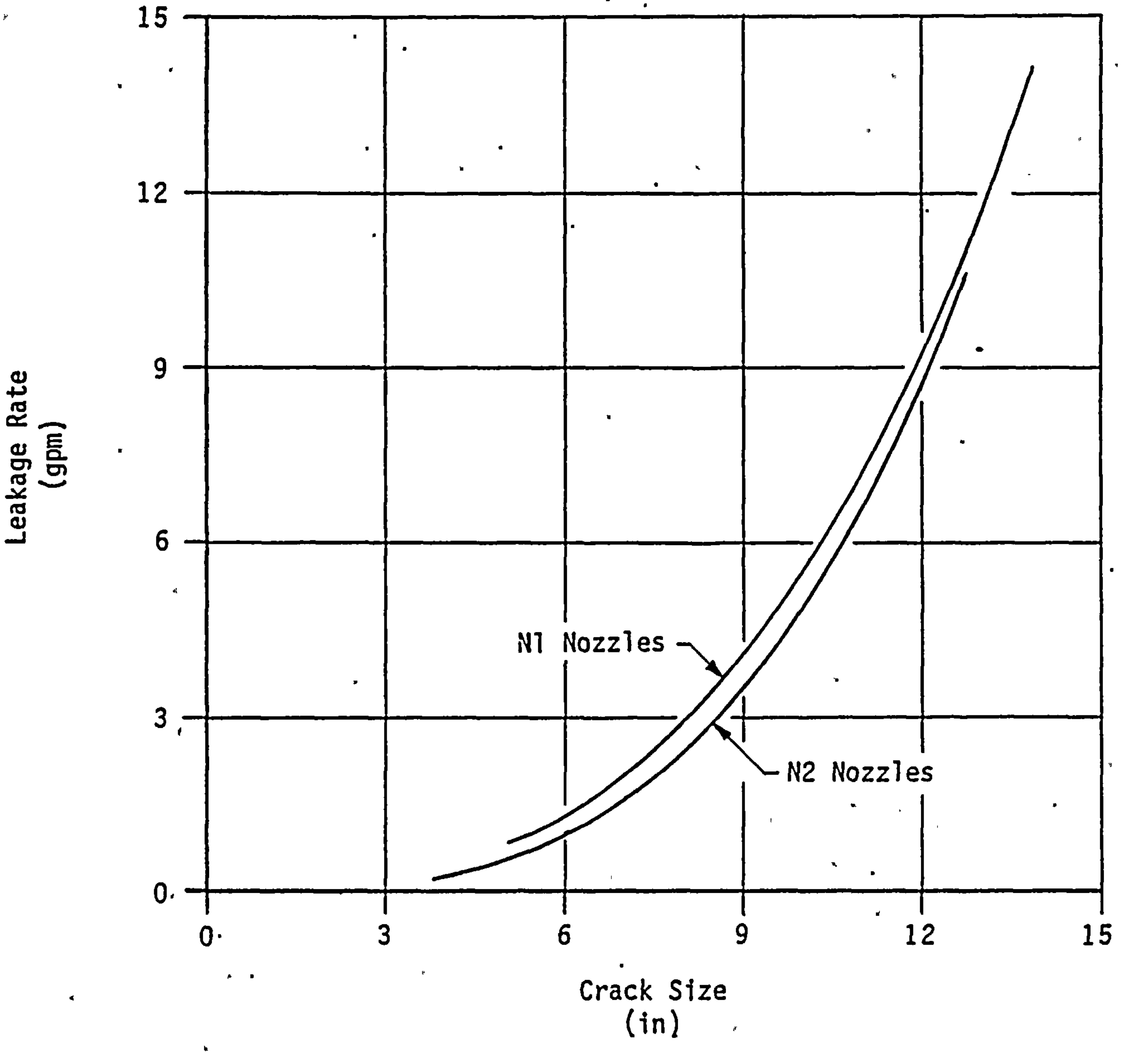

CALCULATED SAFE END LEAKAGE RATES

FIGURE 2.1

3. LEAK DETECTION CAPABILITY

There are two containment sump pumps for each unit at SSES that collect unidentified leakage inside containment. Each sump has a capacity of 150 gallons. Currently, the total level change of each sump is logged by an operator every four hours. From this level change and the sump capacity, the total flow pumped out of the sump (and thus an estimate of the leakage into the sump) during the four hour period can be calculated. This total flow and average flow rate during the period are also logged every four hours. A leak inside containment, such as is postulated at the reactor vessel nozzle safe ends, would cause a noticeable change in the run times of the pumps and the sump level.

Leakage from any single source inside containment can collect in either or both sumps. Since leakage measurement is based on rate of change in sump level, the measurement sensitivity is worst when leakage is equally divided between the two sumps, generating the slowest change in sump level. Using this worst case assumption, the average leakage detection sensitivity inside containment over the four hour surveillance period required by SSES Technical Specifications is at least 0.5 gallons per minute (gpm). A review of actual operational data indicates a sensitivity significantly better than 0.5 gpm. For purposes of this analysis, however, the detectable containment leakage rate was conservatively assumed to be 0.5 gpm.

The SSES Technical Specifications require a unit to shut down if the unidentified leakage rate, as detected by the sump pump level indicators, increases over a four hour span by greater than two gpm or if the total unidentified leakage at any time is greater than five gpm. Thus, if a through-wall crack develops which leaks greater than five gpm or increases in leakage more than two gpm in four hours, the

unit must shut down. This analysis conservatively assumed the flawed piping leak rate is five gpm, a value which is at least ten times the actual sensitivity and is also the largest flaw which can exist without the unit shutting down. Fracture Mechanics analyses were performed for through-wall crack sizes corresponding to five gpm leak rates. This is consistent with the guidelines presented in NUREG 1061.

4. LEAK RATE MODELING

The correlation between pipe through-wall crack size and leak rate was calculated using CIRFLO, a specialized computer code developed specifically for this purpose. The computer model assumes that the pressure loss through the crack can be described by a typical fL/D loss mechanism. Choking (critical flow) is evaluated using a homogeneous choking model which depends on local stagnation pressure and stagnation enthalpy at the choke point. Conservative, i.e., lower bound, estimates of flow through tight cracks were obtained by using a friction factor based on a relative roughness of 0.1. The crack opening flow area as a function of internal pressure was determined from formulae given in Reference 6. CIRFLO results compare favorably to measured flows through small slits reported in Reference 13 and the LEAKS 01 model developed for EPRI in Reference 14. A more detailed description of CIRFLO and its technical basis is provided in Appendix A.

There are two pipe-to-safe end geometries of concern as part of this evaluation, those on N1 designated nozzles and N2 designated nozzles. Cracks are postulated on either side of the pipe-to-safe end weld. In each instance, the safe end cross section has a larger diameter and thicker wall than the pipe. Thus, for a given internal pressure and crack length, the flow out of a safe end crack will be less than a pipe crack. To determine the crack lengths required for detectable leaks as part of this evaluation, the cross section properties of the safe end were conservatively assumed for both safe end cracks and pipe cracks.

The relationship between through-wall crack length and safe end leakage is shown in Table 4.1 and also in Figure 4.1. These data were used to interpolate the crack sizes required for a leakage rate of 5 gpm. As recommended in NUREG 1061, the postulated flaw for fracture mechanics evaluations was chosen to be the crack size which leaks at a rate ten

times the detectable leakage rate of 0.5 gpm. For the N1 nozzle safe ends, a 5 gpm leakage rate corresponds to a 9.8" through-wall crack (approximately a 39^{0} circumferential crack). The five gpm leakage rate for the N2 nozzles is 10.1" (approximately an 85^{0} circumferential crack).

TABLE 4.1
CRACK LEAKAGE RATES

	N1 Nozzles		N2 Nozzles	
Crack length (inches)	Crack Angle	Leakage(1) (GPM)	Crack Angle	Leakage(1) (GPM)
4.0			33.9^{0}	0.3
5.0	20.2^{0}	0.8	42.4^{0}	0.6
6.0	24.2^{0}	1.3	50.8^{0}	1.0
7.0	28.3^{0}	2.0	59.3^{0}	1.6
8.0	32.3^{0}	2.9	67.8^{0}	2.5
9.0	36.4^{0}	4.0	76.2^{0}	3.5
10.0	40.4^{0}	5.3	84.7^{0}	4.9
11.0	44.4^{0}	7.0	93.2^{0}	6.5
12.0	48.5^{0}	9.0	101.6^{0}	8.6
13.0	52.5^{0}	11.3	110.1^{0}	11.1
14.0	56.5^{0}	14.1		

(1) Equivalent leak rate of condensed water in the containment sump.

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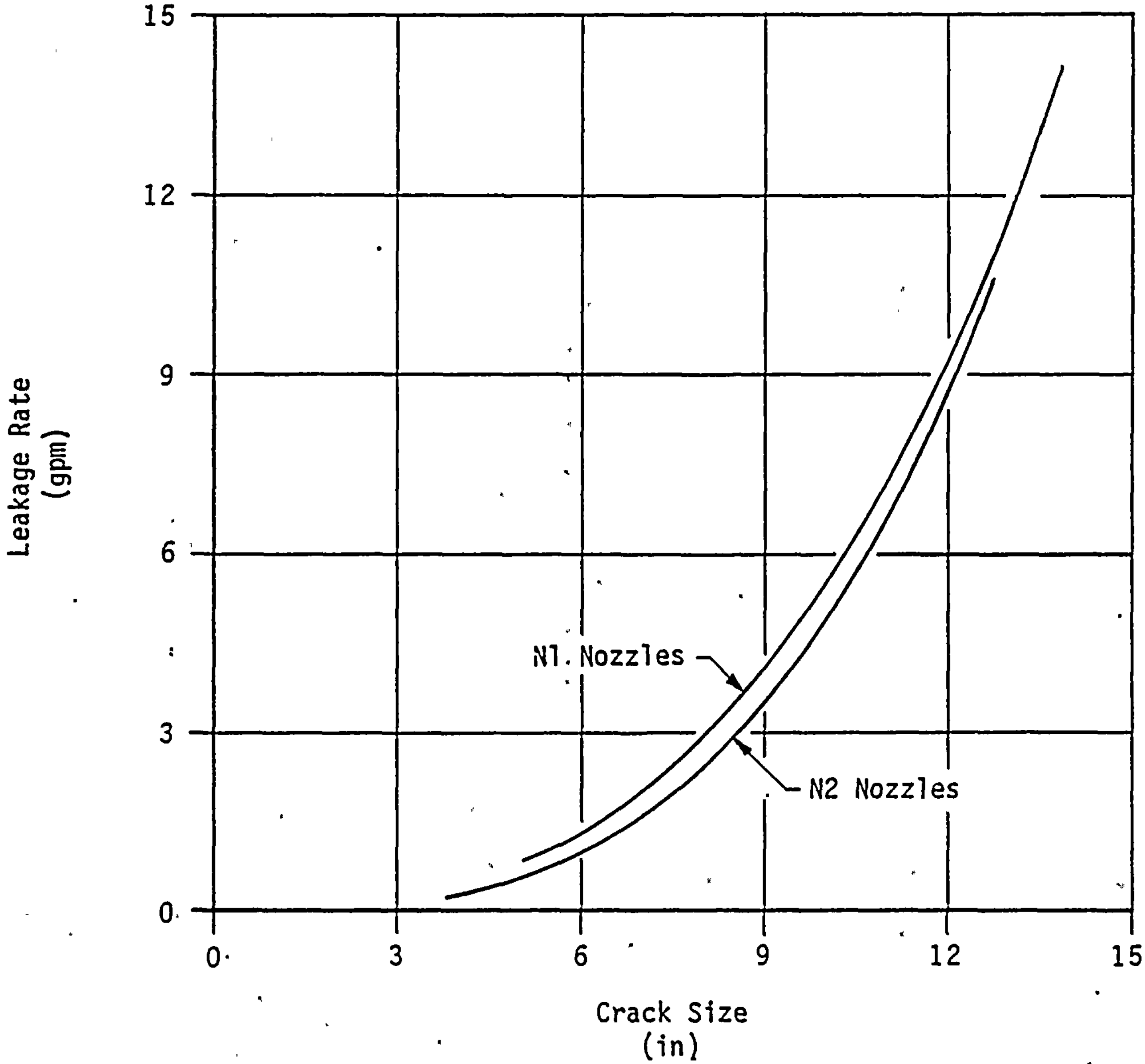

CALCULATED SAFE END LEAKAGE RATES

FIGURE 4.1

5. APPLICABILITY OF LEAK-BEFORE-BREAK METHODOLOGY

NUREG 1061 recommends that leak-before-break (LBB) analyses of high energy piping be subject to several limitations. These limitations do not recommend the application of a LBB evaluation for piping systems which are susceptible to failure from the effects of intergranular stress corrosion cracking (IGSCC), waterhammer or fatigue. The susceptibility of the Susquehanna Units 1 & 2 recirculation piping and associated welds to each of these failure mechanisms is discussed below.

5.1. INTERGRANULAR STRESS CORROSION CRACKING

The Susquehanna Units 1 & 2 recirculation piping is Type 304 stainless steel. This type of stainless steel in the sensitized as-welded condition in a typical BWR environment is susceptible to degradation due to IGSCC. However, at Susquehanna steps have been taken to greatly reduce the possibility of IGSCC at the reactor vessel nozzle safe ends in the recirculation system.

Induction Heating Stress Improvement (IHSI) has been performed on the 28 inch N1 nozzle pipe-to-safe end welds (see Figure 5.1). The effect of IHSI is to cause a redistribution of the residual stresses in the weld (or pipe) wall. Prior to IHSI, the residual stresses near the inside diameter are predominently tensile, contributing to the possibility of crack initiation and growth. This is a result of the original welding process. During IHSI, the outside diameter of the pipe is heated while the inside diameter is kept relatively cool by reactor coolant inside the pipe. When the pipe cools, the outer thickness of the pipe wall compresses in against the inner wall material. The effect of this procedure is to cause residual compressive stresses on the pipe inside diameter and residual tensile on the pipe outside diameter. Extensive experimental data and field experience at other utilities both in the U.S. and abroad using IHSI on BWR recirculation system piping welds

supports the expected result that these residual compressive stresses preclude flaw growth. Recent in-service inspection (ISI) of these welds using EPRI qualified ultrasonic test procedures and personnel indicates no flaws are present in the N1A safe end to pipe welds.

The measures taken to eliminate IGSCC at the N2 nozzle safe ends include the application of corrosion resistant cladding on the pipe inside diameter and safe end replacement. The original design N2 nozzle safe ends were Type 304 stainless steel. Like the recirculation system piping, the original safe ends were susceptible to IGSCC in the high purity BWR reactor coolant environment. This design was changed and new nozzle safe ends, made of Type 316L stainless steel, were installed. This new material has a very low carbon content which reduces the amount of excess carbon available to form chromium carbides at the material grain boundaries. Without chromium carbides at the grain boundaries the material cannot be sensitized, thereby eliminating the possibility of IGSCC. In order to protect the piping side of the pipe to safe end weld, the pipe inside diameter was overlayed with a corrosion resistant cladding. This arrangement can be seen in Figure 5.2. The cladding is used to eliminate the possibility of corrosive reactor coolant contacting the sensitized weld heat affected zone in the pipe. As an additional precaution, when the safe ends were replaced, the nozzle thermal sleeves were also replaced with a new design. Originally, the nozzle thermal sleeves were welded to the nozzle safe ends near the safe end-pipe weld, creating another potential site for crack initiation. The new design includes a "tuning fork" design in which the thermal sleeve and safe end are one piece, eliminating the additional weld. Pre-service ultrasonic and radiographic inspections of the N2 pipe to safe end welds indicated that these joints are defect free.

As a result of the protective measures described above, crack development and crack growth due to the effects of IGSCC are not expected at the recirculation system safe ends. IHSI at the N1 nozzles and the

combination cladding/low carbon material at the N2 nozzles are expected to adequately protect the material in the weld heat affected zones.

-5.2. WATERHAMMER

BWR's, in general, report no evidence or history of waterhammer events in the recirculation system piping. The design of the recirculation piping is relatively simple, with very few valves, elbows or complicated pipe runs. This simple geometry is typically not susceptible to waterhammer, which usually occurs in piping systems containing many elbows and long lengths of pipe. For these reasons, no waterhammer events are expected to occur in the recirculation system piping.

5.3. FATIGUE

The recirculation system is designated as Class 1 piping and has been analyzed for fatigue usage as part of the design stress analysis of the system. A review of the design stress analyses for the recirculation piping performed by General Electric (References 2-5) was made to determine the fatigue usage factors calculated for the system. These stress analyses calculated fatigue life usage factors for the piping system including all expected operational transients (start-ups, shut-downs, scrams, etc.) for the design life of the unit. For the recirculation piping at the reactor vessel nozzle safe ends, the piping stress analyses show the fatigue usage factors listed in Table 5.1. As can be seen, all usage factors are less than 0.0002.

TABLE 5.1
DESIGN FATIGUE USAGE FACTORS

Unit	Nozzle	Usage Factor
1	N1A	0.0002
1	N2A	0.0
1	N2B	0.0
1	N2E	0.0
1	N2K	0.0
2	N1A	0.0001
2	N2A	0.0
2	N2E	0.0
2	N2J	0.0
2	N2K	0.0

As a result of these very low usage factors, piping degradation due to the effects of fatigue or fatigue crack growth is not expected in the SSES recirculation piping.

As descibed above, it can be seen that IGSCC, waterhammer and fatigue are not concerns in the Susquehanna recirculation system. Thus, the LBB analysis of the reactor vessel pipe-to-safe end welds is applicable to evaluate the probability of unstable ruptures.

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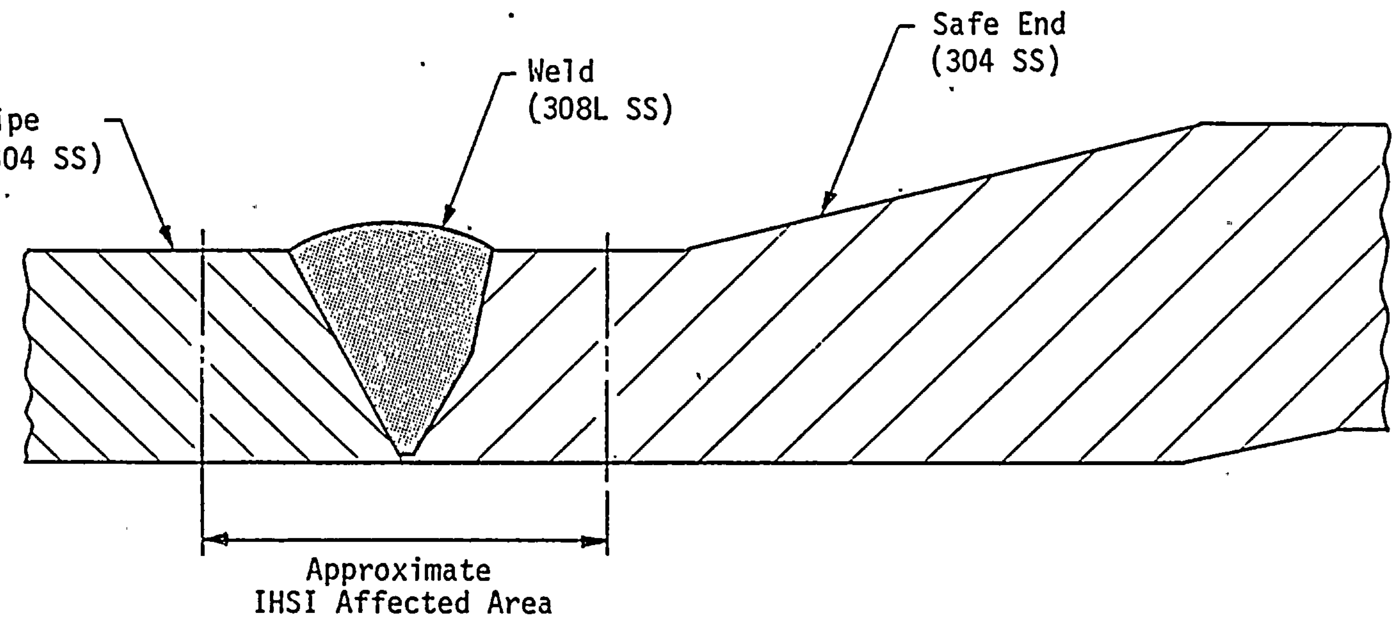

N1 NOZZLE PIPE-TO-SAFE END WELD

FIGURE 5.1

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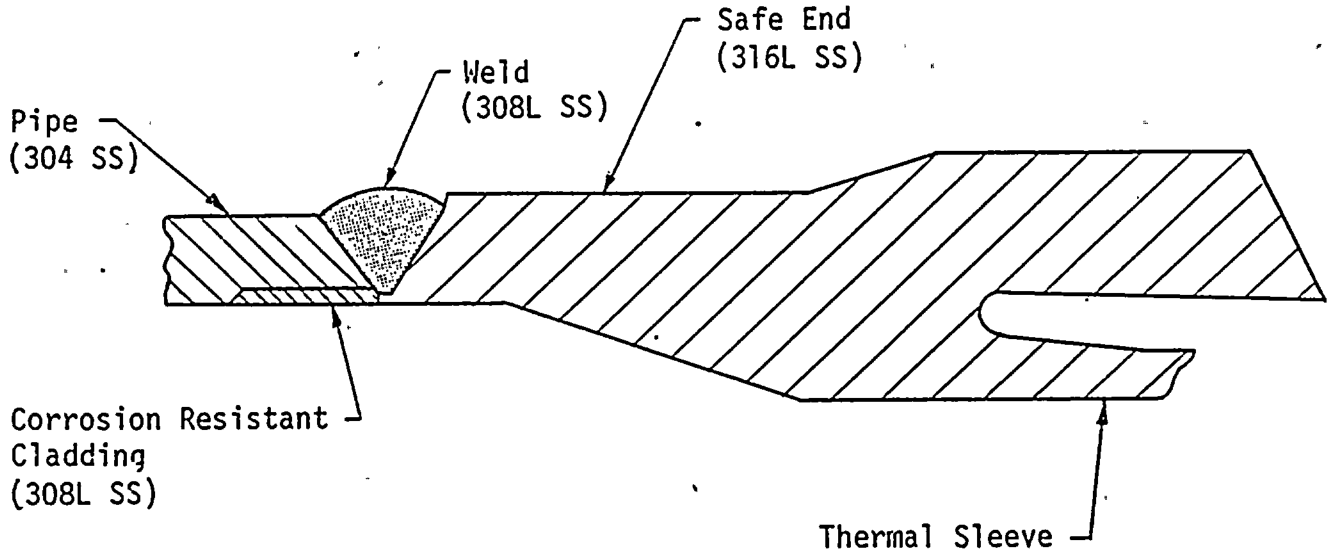

N2 NOZZLE PIPE-TO-SAFE END WELD

FIGURE 5.2

6. FRACTURE MECHANICS ANALYSES

Analyses have been performed to evaluate the likelihood of unstable double-ended rupture at the recirculation system pipe-to-safe end welds which have been identified by PP&L. This section describes the Leak-Before-Break (LBB) fracture mechanics analyses performed to show that postulated double-ended breaks at the pipe-to-safe end welds are not credible. The guidelines used for this analysis are taken from NUREG 1061, Vol. 3 (Reference 1).

A total of ten pipe-to-safe end welds specified by PP&L were evaluated. All analyses performed as part of this evaluation were performed for each safe end at the reactor vessel nozzles listed below.

Unit 1	Unit 2
N1A	N1A
N2A	N2A
N2B	N2E
N2E	N2J
N2K	N2K

The objective of the fracture mechanics evaluations, using the guidelines presented in NUREG 1061 are:

- Identify the applied loads at the postulated crack locations. The loading combination considered is normal operating condition plus safe shutdown earthquake (SSE) loads.
- For the postulated flaw size determined from leak detection capabilities, show that no unstable failure or significant growth is predicted for the assumed loading conditions.
- Demonstrate that a margin of safety in terms of crack length exists against unstable crack growth or tearing which is at least 2.0. That is, show that the critical crack length corresponding to unstable crack growth or tearing of the cracked pipe cross section for the applied load is at least 2 times the postulated crack length.

- Demonstrate that a margin of safety in terms of load exists against unstable crack growth or tearing which is at least 1.41. That is, show that the load corresponding to unstable crack growth or tearing of the cracked pipe cross section for the postulated flaw is at least 1.41 times the applied load.
- If the above mentioned margins cannot be met, NUREG 1061 allows for a limit load analysis. It must be shown that the limit load for the postulated cracked cross section is at least three times the applied load.

6.1 SAFE END LOADS

As recommended in NUREG 1061, fracture mechanics analyses were performed using normal operating condition loads (deadweight, pressure and thermal expansion) plus loads due to the design safe shutdown earthquake (SSE). The loads at the pipe-to-safe end welds for deadweight, thermal and SSE conditions were obtained from the design stress analyses for the recirculation piping performed by General Electric (References 2-5). These finite element analyses were performed as part of the original design analyses of the recirculation piping for both units. The pressure stress was determined by a hand calculation using the normal reactor operating pressure.

The fracture mechanics methodology described below requires the cracked section load to be expressed in terms of an equivalent applied moment rather than individual stress components. This moment (detailed in Appendix B) was obtained by combining the axial stresses and bending stresses resulting from deadweight, thermal and safe shutdown earthquake loads along with the longitudinal pressure stress to obtain a total stress at the cracked section. The equivalent moment used in fracture mechanics evaluations was chosen as the bending moment which would result in this total stress if only bending stresses were present. Table 6.1 lists the nozzle safe ends included in this analysis, the total applied stress and the calculated equivalent moments for each.

Although cracks can be postulated on each side of the pipe-to-safe end weld, the fracture mechanics analyses of the leak-before-break evaluation, including the determination of applied loads, were performed using the minimum pipe cross section properties. This is conservative since minimum pipe cross section properties will lead to less margin in the fracture mechanics analyses.

TABLE 6.1
APPLIED LOAD EQUIVALENT MOMENTS

Unit	Nozzle	Stress (ksi)	Equivalent Moment (in-kips)
1	N1A	7.2	4979.6
1	N2A	10.8	701.5
1	N2B	10.9	711.4
1	N2E	7.8	509.6
1	N2K	7.4	479.4
2	N1A	8.5	5830.5
2	N2A	11.1	724.0
2	N2E	7.3	476.0
2	N2J	13.1	851.6
2	N2K	7.1	461.5

6.2 FRACTURE MECHANICS METHODOLOGY

Elastic and elastic-plastic fracture mechanics analyses were performed for normal operating conditions plus SSE loading conditions to evaluate the margin available both for crack extension and for unstable crack growth or tearing at each nozzle safe end. The methodologies used are discussed below and are described in more detail in Appendix C.

6.2.1 Crack Extension

Using the NUREG 1061 guidelines, it should be shown that the postulated crack (determined from leakage detection capabilities) will not grow significantly as a result of the applied loading conditions. The

determination of whether cracks will grow is evaluated by comparing the crack driving potential, or J-integral, for a particular flaw size and a particular load combination to J_{IC}, the value of J where cracks will start to grow as recommended in NUREG 1061. Calculated values of J greater than J_{IC} indicate that crack growth will occur. If the calculated J is less than J_{IC}, the crack tip may blunt, but crack extension will not occur. If the value of J exceeds J_{IC}, crack extension is expected and a tearing stability analysis would be required to determine whether the crack will grow in a stable or unstable manner.

When stresses are low, the value of J is related to the more traditional linear-elastic fracture mechanics stress intensity factor by the relation

$$J = K^2/E$$

Traditional elastic K_I solutions are available in Reference 6. Suitable plastic zone corrections for ductile materials were applied to calculate an effective crack length as outlined in Reference 7.

As the loading at the postulated cracked section increases, the uncracked net section can become plastic before J_{IC} is reached. In this case, the more generalized expression for J was used

$$J = J_e + J_p$$

where J_e is the elastic value of J discussed above (with a plastic zone correction) and J_p is the purely plastic contribution to J. The plastic contribution to J has been studied in detail by General Electric Co. for EPRI (Reference 8) and can be expressed in the form

$$J_p = \alpha\, \varepsilon_o \sigma_o \; \frac{a}{b} \; c\, h_1(a/b,\ n,\ R/t) \; \left(\frac{M}{Mo}\right)^{n+1}$$

where

α,n are the strain hardening fitting coefficient and exponent for the material

σ_o is the material yield strength

ε_o is the material yield strain

c is half the remaining uncracked length on the pipe circumference

a is half the crack length

b is half the pipe circumference (c=b-a)

h_1 is a tabulated function of a/b,n and R/t given in Reference 8

M is half the effective applied moment on the cracked section

Mo is half the moment at which the remaining uncracked section becomes fully plastic

Due to the applied load and the presence of a crack, the pipe tends to "kink" at the cracked section, forming a hinge angle. The plastic contribution to the cracked section hinge angle, ϕ_p, is calculated in a similar manner to J.

$$\phi_p = \alpha\varepsilon_o h_4 (a/b, n, R/t) \left(\frac{M}{Mo}\right)^n$$

where

h_4 is a tabulated function of a/b, n and R/t given in Reference 8

This function is needed for tearing stability analyses described below.

6.2.2 Tearing Stability

An important criteria of the NUREG 1061 guidelines is that the postulated cracked section should not tear unstably under the applied

load. The cracked section resistance to unstable growth or tearing is determined by examining the moment carried by the crack and mathematically perturbing the assumed flaw size. Paris, in Reference 9, states that stability is assured if the moment lost from the cracked section due to an increase in crack length is less than the moment that is picked up by the piping system via the increase in cracked section hinge angle. A stable condition is represented by:

$$\left|\frac{dM}{d\phi}\right|_{\text{crack}} < \left|\frac{dM}{d\phi}\right|_{\text{system}}$$

The expression on the right is a function of the piping geometry and can be evaluated directly from stiffness calculations of the piping system or by a finite element model of the piping system by inserting a ball and socket joint at the crack location, applying a moment couple on the joint, and determining the resulting rotations. In Paris' notation, this is the piping system compliance. This system compliance is often equated to the stiffness of a cantilever beam of length L with the same area moment of inertia, I, and radius, R, of the pipe. The ratio, L/R, of the equivalent cantilevered pipe is used to report system compliances in this analysis.

The expression on the left is evaluated in terms of the partial derivatives of J and ϕ with respect to crack size, a, and applied moment, M, and a material property called the tearing modulus which is defined as

$$T_{mat} = \frac{E}{\sigma_o^2} \frac{dJ}{da}$$

T_{MAT} is determined directly from the slope of J vs Δa obtained from test data for the material of interest. In terms of these parameters, the stability criterion becomes (see Appendix C)

$$T_{mat} > \frac{E}{\sigma_o^2} \left\{ \frac{\partial J}{\partial a}\right)_M - t \left. \frac{\partial J}{\partial M}\right)_a^2 \left[C_s + \left.\frac{\partial \phi}{\partial M}\right)_a\right]^{-1} \right\}$$

Since the expressions on the right side of the above inequality are all functions of the ratio M/Mo, actual margins to tearing instability can be directly calculated in terms of applied moment.

6.3 MATERIAL PROPERTIES

The nozzle safe ends are Type 304 and Type 316L stainless steel and the recirculation system piping is Type 304 stainless steel. For this analysis, lower bound tensile properties applicable to both Type 304 and 316L stainless steel were used.

Large strain stress-strain data for Type 304 stainless steel at elevated temperatures are available in Reference 10. The material strain hardening exponent and coefficient for a Ramberg-Osgood power law strain hardening model, α and n, were determined from these data. The data base used to define J_{IC} and T_{MAT} was obtained from cast stainless steel material test data at 550^{o} F in Reference 11. This cast material, which is similar to stainless steel weld metal, has lower crack initiation and growth resistance than base material, thus providing a conservative lower bound estimate for material properties. Appendix D describes in greater detail the determination of material properties.

The material property values used in the fracture mechanics analyses are presented in Table 6.2. The tensile properties are based upon ASME Code minimum values except for yield strength, where the value taken is that of the material in Reference 10 whose strain hardening behavior was quantified. The flow stress used in limit load analyses was chosen as three times the material design stress intensity value from the ASME Code as recommended in Reference 12.

TABLE 6.2
MATERIAL PROPERTIES*

Elastic Modulus, E	25600.0 ksi
Yield Stress, σ_o	23.0 ksi
Flow Stress, σ_f	50.7 ksi
J_{IC}	992.0 in-lb/in^2
T_{MAT}	182.0
α	2.13
n	3.79

*Values taken at 550^{o}F.

6.4 SYSTEM COMPLIANCE

The methodology developed above to evaluate the stability of postulated pipe cracks requires the knowledge of the piping system compliance at the cracked section. The compliance is a measure of how much load is picked up by the piping system as the cracked section sheds moment. In a very compliant system, as the crack grows, the system picks up very little of the moment on the cracked section, so the load on the section changes very little. In a very noncompliant system, the system can pick up a large portion of the monent, so as the crack grows, the load on the cracked section reduces.

The compliance of the piping system at the safe ends was determined using a finite element model of the piping arrangement. The translational degrees of freedom at the safe end location of the model were fixed and the rotational degrees of freedom allowed to change. A moment was then applied at this location and the resulting rotations determined. This procedure represents the insertion of half a ball and socket joint into the model at the postulated crack location. The other "half" of the joint is not modeled because the nozzle is assumed rigid compared to the system piping so the resulting rotations would be zero. A second analysis was also performed, applying a moment about an

axis perpendicular to the first moment. These analyses are used to obtain the compliance at the safe ends about two axes. The maximum (conservative) compliance about any axis was obtained using these compliances and a Mohr's Circle approach as recommended in Reference 9. The calculated system compliance at the nozzle safe ends for the two cases being examined are L/R = 53 for N1 nozzles and L/R = 35 for the N2 nozzles. These compliance values describe a piping system which is fairly rigid.

It is conservative to assume the cracked section is dead loaded, that is, it is infinitely compliant, and as the crack grows, the applied load on the section never reduces. This corresponds to a pipe length which is infinitely long, or $L/R = \infty$. In addition to analyses performed for the calculated system compliance, fracture mechanics analyses were also performed for the conservative infinite system compliance to determine the sensitivity of the analysis results to the system compliance.

6.5 FRACTURE MECHANICS RESULTS

6.5.1 Fracture Mechanics Analyses Assumed Flaws

Fracture mechanics analyses were performed to determine if assumed initial flaws are likely to grow or fail unstably under the normal operating condition plus SSE loads calculated for the safe end locations. Analyses were performed for initial crack sizes for each nozzle safe end location corresponding to a five gpm leakage rate. The five gpm leak rate is ten times the detectable leak rate and is also the largest crack which can exist without the unit having to shut down due to Technical Specification requirements.

It should be noted that all fracture mechanics analyses were performed using the conservative minimum cross section pipe properties. Analyses were not performed for the safe end cross sections because those analyses would be bounded by the results of analyses on the thinner pipe cross section.

The methods used to calculate the applied J integral require the knowledge of tabular functions from Reference 8. These functions are only specified for discrete points, so interpolation may be required. For convenience, rather than interpolating these tabular functions, the crack lengths used for fracture mechanics analyses were conservatively rounded up to a 45^{o} circumferential crack for the N1 nozzles and a 90^{o} circumferential crack for the N2 nozzles. These flaws correspond to leakage rates of 7.0 gpm at the N1 nozzles and 5.9 gpm at the N2 nozzles.

6.5.2 Crack Extension Calculations

Crack extension analyses were performed to demonstrate that the calculated J-integral for the applied loads and assumed flaw size is less than J_{IC}, the value corresponding to initiation of crack growth. The results of these analyses are shown in Table 6.3. As can be seen in Table 6.3, all calculated values of J are less than J_{IC} for the normal operating condition plus SSE loads assumed. These results demonstrate that no crack growth will occur.

Although not explicity required by the NUREG 1061 guidelines, Table 6.3 also includes margins to the point where crack growth would begin in terms of both applied load and postulated crack size to demonstrate the large margins calculated for this analysis. The margin to initiation of crack growth in terms of applied load was determined by holding constant the postulated flaw size and finding that load at which the crack would start to grow. As shown in Table 6.3, in the worst case, the load required for the initiation of crack growth is 1.5 times the applied load, with most margins greater than 2.5. The margin to the initiation of crack growth in terms of crack length was determined by holding constant the applied load and finding the crack length at which the crack wold start to grow. Table 6.3 shows that the worst case margin in terms of crack length is 1.49. The method used to calculate J requires

the knowledge of tabular functions which are a function of crack size. However, these functions have not been tabulated and published for crack lengths greater than 180°. When determing margins in terms of crack length, there were instances in which a crack size of 180° still did not correspond to the initiation of crack growth. In these instances, the margin is specified as being greater than the margin appropriate for the 180° flaw.

6.5.3 Tearing Stability Calculations

Tearing stability calculations were performed to demonstrate sufficient margin against unstable growth or tearing of the postulated cracks under the applied loads. Calculations were carried out using two values of piping system compliance, the actual calculated L/R for the piping arrangements and also, for comparison, a conservative L/R of infinity. The results of these analyses, shown in Tables 6.4 and 6.5, show that all assumed cracks under the applied load are stable, even for the very conservative infinite L/R. All calculated values of T_{APP} are less than T_{MAT}.

As recommended by NUREG 1061, the margins to instability in terms of crack length and applied load were determined for each crack length and L/R combination. The margin to instability in terms of crack length is the ratio of the crack size corresponding to T_{MAT} for the applied load to the postulated crack length and must be at least 2.0. The margin in terms of load is the ratio of the load corresponding to T_{MAT} for the postulated crack length to the applied load and must be at least 1.41.

As can be seen in Tables 6.4 and 6.5, the margins in terms of load are all greater than 2.1 even for the conservative L/R of infinity. It should be noted that in some instances, as the applied load is increased, plastic collapse of the cracked pipe section is controlling rather than unstable growth or tearing. In these cases, which are noted in Table 6.4, the margin to instability in terms of applied load is

simply the ratio of the limit moment corresponding to plastic collapse for the cracked section to the applied moment.

Due to the method used to perform the fracture mechanics analyses, crack lengths greater than 180° are not solvable at this time. The method requires tabular functions based on crack size which have only been calculated and published for crack lengths up to 180°. In determining the margins to instability in terms of crack length, if the crack size corresponding to unstable growth or tearing was greater than 180°, the margin was conservatively specified as greater than the margin corresponding to the 180° flaw. As shown in Table 6.4, for the actual system compliance calculated for the recirculation system piping, the margins in terms of crack length are all greater than the recommended criteria of 2.0. Even if a very conservative system compliance is assumed (L/R = infinity), only one postulated flaw with a margin of 1.84 does not meet the recommended criteria demonstrating that significant margin against unstable growth or tearing exists.

6.6 PLASTIC SECTION COLLAPSE

Because the fracture mechanics evaluations described above meet all of the specified acceptance criteria, NUREG 1061 does not require evaluation of margins against net section plastic collapse. Nevertheless, these evaluations have been performed to verify that all margins to plastic collapse (the ratio of limit load to applied load) were greater the 3.0, the recommended criteria in NUREG 1061.

The margin to plastic collapse of the postulated cracked section was evaluated by calculating the plastic collapse moment for the cracked cross section for the postulated crack size and comparing this value to the applied load (The equivalent applied moment described in 6.1 was used for the applied moment). Plastic collapse of the cross section occurs when the stress across the entire section reaches the material flow stress, a value typically three times the material design stress

[illegible]

intensity value. The expression used for plastic collapse moment was taken from NUREG 1061 and the material properties in 6.3 were used. The limit moment, M_L, is calculated as

$$M_L = 4\sigma_f R^2 t \, [\cos(\gamma/2) - 1/2 \sin(\gamma)]$$

where σ_f is the flow stress, R is the average radius, t is the wall thickness, and γ is half the crack angle.

Table 6.6 summarizes the plastic collapse analysis results. The applied moment, plastic collapse moment and margin to plastic collapse for both no crack and the postulated cracks used in the fracture mechanics analyses (45^o for N1 nozzles and 90^o for N2 nozzles) are presented. The calculated margins to plastic collapse are approximately three or greater for all cases.

TABLE 6.3
CRACK EXTENSION RESULTS

Unit	Nozzle	Crack Angle	$J^{(1)}$ (in-lb/in^2)	$J_{IC}^{(2)}$ (in-lb/in^2)	Load Margin (3)	Crack Length Margin (4)
1	N1A	45°	57	992	3.33	3.84
1	N2A	90°	217	992	1.82	1.70
1	N2B	90°	224	992	1.80	1.69
1	N2E	90°	103	992	2.51	>2.0
1	N2K	90°	90	992	2.67	>2.0
2	N1A	45°	80	992	2.85	3.51
2	N2A	90°	235	992	1.77	1.67
2	N2E	90°	89	992	2.69	>2.0
2	N2J	90°	363	992	1.50	1.49
2	N2K	90°	83	992	2.77	>2.0

(1) Calculated value of J-integral.

(2) The value of the J-integral corresponding to the initiation of crack growth.

(3) The load corresponding to the initiation of crack growth for the postulated crack length divided by the applied load.

(4) The crack length corresponding to the initiation of crack growth for the applied load divided by the postulated crack length.

(NOTE: The initiation of crack growth does not indicate unstable crack growth or tearing.)

TABLE 6.4
UNSTABLE CRACK GROWTH OR TEARING RESULTS

Unit	Nozzle	Crack Angle	L/R	T[1]	T_{MAT}[2]	Load[3,5] Margin	Recommended Load Margin	Crack Length[4] Margin	Recommended Crack Length Margin
1	N1A	45°	53	0.2	182	7.37	1.41	>4.0	2.0
1	N2A	90°	35	2.0	182	3.57	1.41	>2.0	2.0
1	N2B	90°	35	2.1	182	3.53	1.41	>2.0	2.0
1	N2E	90°	35	0.8	182	4.92	1.41	>2.0	2.0
1	N2K	90°	35	0.7	182	5.23	1.41	>2.0	2.0
2	N1A	45°	53	0.3	182	6.30	1.41	>4.0	2.0
2	N2A	90°	35	2.2	182	3.46	1.41	>2.0	2.0
2	N2E	90°	35	0.7	182	5.27	1.41	>2.0	2.0
2	N2J	90°	35	3.5	182	2.95	1.41	>2.0	2.0
2	N2K	90°	35	0.6	182	5.43	1.41	>2.0	2.0

(1) Calculated applied tearing modulus.

(2) The value of T corresponding to unstable crack growth or tearing.

(3) The load corresponding to unstable crack growth or tearing for the postulated crack length divided by the applied load.

(4) The crack length corresponding to unstable crack growth or tearing for the applied load divided by the postulated crack length.

(5) For the given system compliance and crack length, failure is controlled by plastic collapse rather than unstable crack growth or tearing. Load margin is plastic collapse load for postulated crack length divided by applied load.

TABLE 6.5
UNSTABLE CRACK GROWTH OR TEARING RESULTS
FOR CONSERVATIVE ASSUMPTION OF INFINITE SYSTEM COMPLIANCE

Unit	Nozzle	Crack Angle	L/R	$T^{(1)}$	$T_{MAT}^{(2)}$	Load Margin(3)	Recommended Load Margin	Crack Length Margin(4)	Recommended Crack Length Margin
1	N1A	45^o	∞	0.2	182	5.62	1.41	> 4.0	2.0
1	N2A	90^o	∞	2.8	182	2.64	1.41	> 2.0	2.0
1	N2B	90^o	∞	3.0	182	2.60	1.41	> 2.0	2.0
1	N2E	90^o	∞	1.0	182	3.63	1.41	> 2.0	2.0
1	N2K	90^o	∞	0.8	182	3.86	1.41	> 2.0	2.0
2	N1A	45^o	∞	0.4	182	4.80	1.41	> 4.0	2.0
2	N2A	90^o	∞	3.2	182	2.56	1.41	2.0	2.0
2	N2E	90^o	∞	0.8	182	3.89	1.41	> 2.0	2.0
2	N2J	90^o	∞	5.9	182	2.17	1.41	1.84	2.0
2	N2K	90^o	∞	0.7	182	4.01	1.41	> 2.0	2.0

(1) Calculated applied tearing modulus.

(2) The value of T corresponding to unstable crack growth or tearing.

(3) The load corresponding to unstable crack growth or tearing for the postulated crack length divided by the applied load.

(4) The crack length corresponding to unstable crack growth or tearing for the applied load divided by the postulated crack length.

TABLE 6.6
MARGINS TO PLASTIC COLLAPSE

Unit	Nozzle	Applied Moment (in-Kip)	No Crack Collapse Moment (in-Kip)	No Crack Margin	Postulated Crack[1] Collapse Moment (in-Kip)	Postulated Crack[1] Margin
1	N1A	4979.6	46496.6	9.34	26518.3	7.37
1	N2A	701.5	4396.0	6.27	2507.2	3.57
1	N2B	711.4	4396.0	6.18	2507.2	3.53
1	N2E	509.6	4396.0	8.63	2507.2	4.92
1	N2K	479.4	4396.0	9.17	2507.2	5.23
2	N1A	5830.5	46496.6	7.97	26518.3	6.30
2	N2E	724.0	4396.0	6.07	2507.2	3.46
2	N2A	467.0	4396.0	9.24	2507.2	5.27
2	N2E	851.6	4396.0	5.16	2507.2	2.95[2]
2	N2K	461.5	4396.0	9.53	2507.2	5.93

(1) 45° circumferential through-wall cracks in N1 nozzle safe ends
90° circumferential through-wall cracks in N2 nozzle safe ends

(2) For a 85°, five gpm leakage through-wall crack, margin = 3.07

7. References

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Appendix A

CALCULATION OF LEAKAGE FLOW THROUGH PIPE CRACKS

This appendix describes the method used to calculate the leakage rate from through-wall circumferential pipe cracks. It is conservatively assumed that the only force acting to open the crack is the pipe internal pressure. The crack opening flow area is defined (from Reference 1) as

$$A = \sigma(2\pi Rt)G/E \tag{1}$$

where,

A is the flow area

σ is the stress across the crack tip = $PR/2t$

R is the pipe inside radius

t is the pipe wall thickness

E is the pipe material modulus of elasticity defining,

a is the crack length

$G = \lambda^2 + 0.16\lambda^4$ for $0 \leq \lambda \leq 1$

$G = 0.02 + 0.81\lambda^2 + 0.30\lambda^3 + 0.03\lambda^4$ for $1 \leq \lambda \leq 5$

$$\lambda = a/(2\sqrt{Rt})$$

To determine the leakage flow through the crack, the crack is divided into a number of control volumes through the wall thickness of the pipe, as shown in Figure 1, and an initial guess for the mass flow rate through the crack is assumed. The pressure loss through the crack is described by an fL/D loss model and the stagnation pressure drop between control volumes in the crack is

$$\Delta P_o = -\left(\frac{f\Delta L}{D} + K\right)\frac{W^2}{\rho A^2} \tag{2}$$

where,

P_o is the stagnation pressure

f is the friction factor

ΔL is the length of pipe wall thickness between the two control volumes

K is the K factor describing entrance or exit losses for the control volumes at the inside and outside of the wall thickness

D is the crack hydraulic diameter
$D=2A/L$ (L is crack length)

W is the crack leakage mass flow rate

ρ is the local density at the control volume

A. is the crack flow area

The stagnation enthalpy is assumed constant through the crack,

$$ho = \text{constant} \qquad (3)$$

where ho is the stagnation enthalpy.

From the known conditions inside the pipe and the assumed mass flow rate, equations 2 and 3 are used to define the stagnation pressure and enthalpy at the center of each control volume assuming homogeneous equilibrium flow. For each control volume, the assumed mass flow out of the control volume (note that the mass flow out of each control volume is constant through the crack) is compared to the critical mass flow rate for the control volume stagnation conditions. The critical flow is expressed as

$$W_c = A\, G_c(Po,ho)$$

where,

W_c is the critical mass flow

A is the flow area

G_c is the critical mass flux as a function of stagnation pressure and enthalpy

If the assumed flow is greater than the critical flow for any control volume conditions, the assumed flow is too great and must be reduced. If the assumed flow is less than the critical flow for all control volumes, the calculated exit static pressure (leaving the crack) is compared to the pressure outside the pipe. If the exit static pressure is greater than the outside pressure, the assumed flow was too low (the pressure losses were not great enough) and the flow is increased. If the exit static pressure is less than the outside pressure, the assumed flow was too great (pressure losses were too high) and the flow is decreased. This iterative procedure (assume flow, calculate pressures, assume flow, calculate pressures....) is continued until one of two conditions is reached; the critical flow out of the last control volume which chokes is equal to the assumed flow or, with no critical flow, the calculated exit static pressure is equal to the outside pressure.

As described in Reference 2, this method yields satisfactory, conservative results for the fluid conditions of interest (approximately 1000 psia up to approximately 60^{o}F subcooling) when a relative surface roughnesses of 0.1 is used. It should be noted that for leak-before-break analyses, it is conservative to underpredict the mass flow rate, thus overpredicting the crack size for a given leakage rate. Figure 2 compares results obtained using the procedure described above to test data obtained from References 3 and 4 and demonstrates that the method used provides conservative predictions of leakage flow.

A computer program, CIRFLO, is used to perform the iterative procedure detailed above. A listing of this program is attached as Listing 1.

References

1. "Estimation of Stress Intensity Factors and the Crack Opening Area of a Circumferential and a Longitudinal Through-Crack in a Pipe," H. Tada and P. Paris, included in NRC letter L505-81-12-015, dated December 4, 1981, to Consumers Power Corporation.

2. "Method for Calculation of Leak Flow Rate Which Can Pass Through a Crack in a Pipe," H.D. Giesecke, April 24, 1984.

3. "Critical Discharge of Initially Subcooled Water Through Slits," NUREG/CR-3475, C.N. Amos and V.E. Schrock, September 1983.

4. "A Calculation of Leak Rate Through Cracks in Pipes and Tubes," EPRI NP-3395, S. Levy Inc., December 1983.

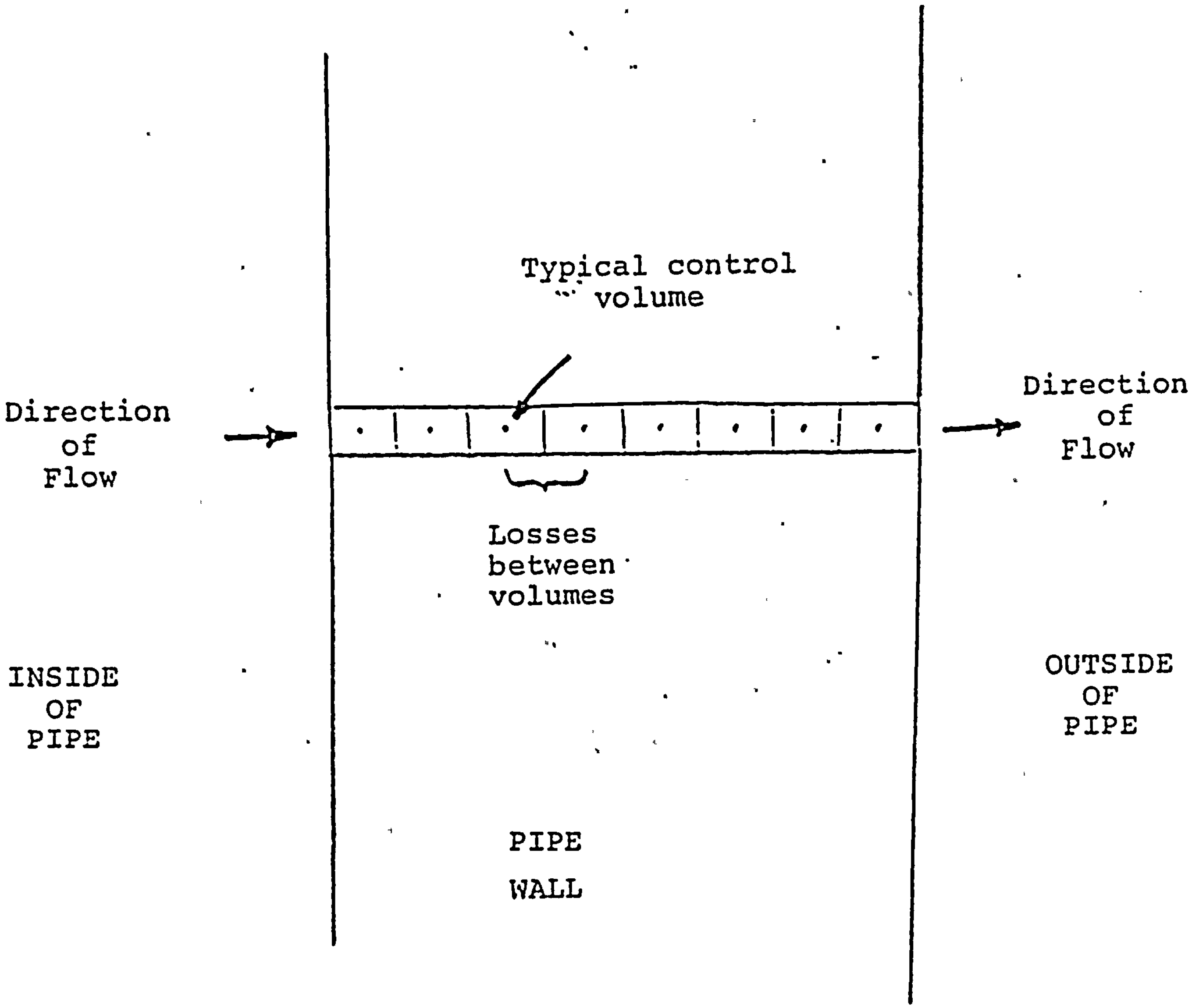

FIGURE 1

SCHEMATIC OF CRACK DIVIDED
INTO CONTROL VOLUMES

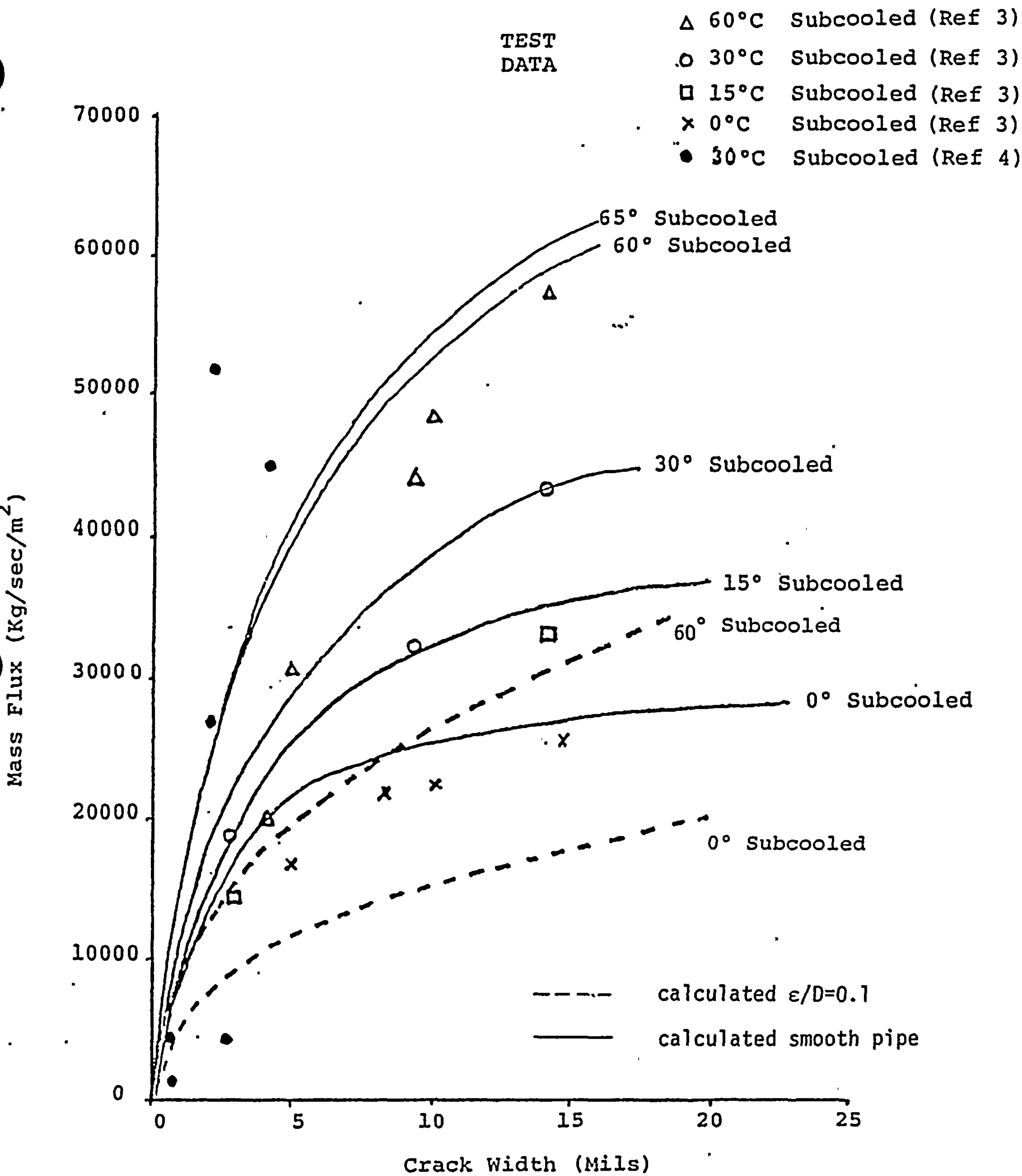

FIGURE 2

COMPARISON OF LEAK RATE CALCULATIONS WITH TEST DATA

Listing 1

Computer Program CIRFLO

```
      PROGRAM CIRFLO
C*****************************************************************************
C     CALCULATES FLOW THROUGH CIRCUMFERENTIAL CRACKS IN PIPES
C*****************************************************************************
      CHARACTER*1 FF,DASH
      CHARACTER*5 BLNK
      CHARACTER*10 TITLE
      COMMON/TITE/ TITLE(8)
      COMMON/FRICR/ROUGH
      DIMENSION PSC(20),TSC(20),VOIDC(20)
      DATA PI,DEG,FACT,GRAV,GALPP/3.1415926,180.0,144.0,32.2,448.831/
      DATA DASH,BLNK/'-','     '/
      DATA PEX/14.7/
      DATA RHOW/62.4/
      DATA LPP/60/
      DATA IFT/0/
      FF=CHAR(12)
      OPEN(5,FILE='CIRFLO.INP',STATUS='OLD')
      OPEN(6,FILE='CIRFLO.OUT',STATUS='NEW')
      WRITE(*,3000)
      WRITE(6,1500) FF
      READ(5,1000) TITLE
      WRITE(6,2000) TITLE
      READ(5,1010) NITER,NUMEL,NCRAK,ROUGH
      NN=NITER
      WRITE(6,2010) NITER,NUMEL,NCRAK,ROUGH
C
C     READ INPUT DATA FOR NEXT PIPE CONFIGURATION
C
   40 READ(5,1020,END=260) DO,THICK,PO,TO,VOIDO,GALMIN,GALMAX,E
      CRLMIN=GALMIN
      CRLMAX=GALMAX
      R=DO/2.0
      ROT=R/THICK
C
C     DETERMINE INLET THERMODYNAMIC PROPERTIES
C
      XO=VOIDO
      HSSAT=HSV(PO,TSAT,SS,VSSAT)
      HLSAT=HSL(TSAT)
      VLSAT=VSL(TSAT)
      IF(VOIDO.LE.0.0) GO TO 80
      IF(VOIDO.GE.1.0) GO TO 100
      TO=TSAT
      VO=1.0/(VOIDO/VSSAT+(1.0-VOIDO)/VLSAT)
      XO=VO*VOIDO/VSSAT
      HO=XO*HSSAT+(1.0-XO)*HLSAT
      GO TO 120
   80 CONTINUE
      IF(TO.GT.TSAT) TO=TSAT
      HO=HCL(PO,TO,SO)
      VO=VCL(PO,TO)
      GO TO 120
  100 CONTINUE
      IF(TO.LT.TSAT) TO=TSAT
      HO=HSS(PO,TO,SO,VO)
  120 CONTINUE
      GO=GCTAB(PO,HO,PCRIT)
      POM=PO/145.0
      TSP=(TO-TSL(PO))/1.8
```

```
      GOG=GO*(39.37/12.0)**2/2.2
      WRITE(6,2120)
      IF(NCRAK.EQ.0) WRITE(6,2030)
      IF(NCRAK.EQ.0) WRITE(6,2040)
      IF(NCRAK.EQ.1) WRITE(6,2035)
      IF(NCRAK.EQ.1) WRITE(6,2045)
      WRITE(6,2135) (DASH,K=1,79)
      WRITE(6,2050) DO,THICK,PO,TO,VOIDO,GALMIN,GALMAX,E
      WRITE(6,2120)
C
C     DETERMINE APPROXIMATE CRACK LENGTH RANGE
C
      SIGC=PO*R/(2.0*THICK)
      CAREA=CRACKC(1.0,R,THICK,SIGC,E)
      IF(NCRAK.EQ.1) GOTO 154
      GALC=GALPP*CAREA*GO/(RHOW*FACT)
      CCL1=SQRT(GALMIN/GALC)
      CCL2=SQRT(GALMAX/GALC)
      GOTO 158
  154 CCL1=CRLMIN
      CCL2=CRLMAX
C
C     DETERMINE FLOW THROUGH CRACK
C
  158 CONTINUE
      WRITE(6,2060)
      WRITE(6,2070)
      WRITE(6,2130) (DASH,K=1,69)
      WRITE(*,3030)
      DO 240 I=1,NN
      CCL=CCL1+(CCL2-CCL1)*FLOAT(I-1)/FLOAT(NN-1)
      CANGLE=CCL/(PI*DO)*360.0
      CAREA=CRACKC(CCL,R,THICK,SIGC,E)
      WC=FLOW(PO,HO,VO,CCL,CAREA,THICK,PEX,NUMEL,PSC,TSC,VOIDC,WCC)
      GC=0.0
      IF(CAREA.NE.0.0) GC=FACT*WC/CAREA
C******* NOTE GPM IS BASED ON ATMOSPHERIC WATER FOR MAKEUP OF SUMP FLOW
      GALC=GALPP*WC/RHOW
      GCG=GC*(39.37/12.0)**2/2.2
      WRITE(*,3020) CCL,CANGLE,GALC
      WRITE(6,2080) I,CCL,CANGLE,CAREA,WC,PSC(NUMEL),GCG,GALC
  240 CONTINUE
      WRITE(*,*)
      WRITE(6,2120)
      GO TO 40
  260 CONTINUE
      CLOSE(5)
      CLOSE(6)
      STOP
C
C     FORMATS
C
 1000 FORMAT(8A10)
 1010 FORMAT(3I5,F10.2)
 1020 FORMAT(8F10.2)
 1500 FORMAT(A1,51HCIRFLO- CALCULATION OF FLOW THROUGH CIRCUMFERENTIAL,
     1       12H PIPE CRACKS,/)
 2000 FORMAT(8A10)
 2010 FORMAT(/1X,30HNUMBER OF CRACKS EACH CASE ---,I5,/1X,
     1             30HNUMBER OF ELEMENTS IN CRACK --,I5,/1X,
```

```
     2           30HCRACK FLOW (0) OR LENGTH (1) -,I5,/1X,
     3           30HRELATIVE ROUGHNESS -----------,F10.5,/)
 2020 FORMAT(A1)
 2030 FORMAT(8X,2HDO,5X,5HTHICK,8X,2HPO,8X,2HTO,5X,4HVOID,2X,
     18HMIN LEAK,2X,8HMAX LEAK,9X,1HE)
 2035 FORMAT(8X,2HDO,5X,5HTHICK,8X,2HPO,8X,2HTO,5X,4HVOID,2X,
     18HMIN CRAK,2X,8HMAX CRAK,9X,1HE)
 2040 FORMAT(2X,8H(INCHES),2X,8H(INCHES),4X,6H(PSIA),3X,7H(DEG F),10X,
     19H(GAL/MIN),1X,9H(GAL/MIN),5X,5H(PSI))
 2045 FORMAT(2X,8H(INCHES),2X,8H(INCHES),4X,6H(PSIA),3X,7H(DEG F),11X,
     18H(INCHES),2X,8H(INCHES),5X,5H(PSI))
 2050 FORMAT(F10.4,F10.6,2F10.2,F9.4,2F10.4,F10.0,10X,F10.4,F10.2,F10.1)
 2060 FORMAT(2X,4HITER,5X,5HCRACK,5X,5HANGLE,6X,4HAREA,6X,4HFLOW,4X,
     1 6HEXIT-P,6X,4HFLUX,6X,4HFLOW)
 2070 FORMAT(6X,2X,8H(INCHES),2X,8H(DEGREE),3X,7H(SQ IN),2X,8H(LB/SEC),
     1 4X,6H(PSIA),1X,9H(KG/S/M2),1X,9H(GAL/MIN))
 2080 FORMAT(I6,2F10.2,F10.3,2F10.2,F10.1,F10.2)
 2120 FORMAT(1X)
 2130 FORMAT(6X,70A1)
 2135 FORMAT(79A1)
 3000 FORMAT(52H CIRFLO- CALCULATION OF FLOW THROUGH CIRCUMFERENTIAL,
     1        12H PIPE CRACKS,/)
 3020 FORMAT(F10.2,6X,F10.2,8X,F10.2)
 3030 FORMAT(47H CRACK LENGTH    CRACK ANGLE      LEAKAGE (GPM))
      END
      FUNCTION CRACKC(CL,R,T,SIG,E)
C*********************************************************************
C     DETERMINES CRACK AREA FROM GEOMETRY AND STRESS
C     CIRCUMFERENTIAL CRACK
C*********************************************************************
      DATA PI/3.1415926/
      XL=CL/SQRT(R*T)/2.0
      IF(XL.LE.1.0) GP=XL**2+0.16*XL**4
      IF(XL.GT.1.0) GP=0.02+0.81*XL**2+0.3*XL**3+0.03*XL**4
      CRACKC=SIG*(2.0*PI*R*T)*GP/E
      RETURN
      END
      FUNCTION FLOW(PO,HO,VO,CL,CAREA,THICK,PEX,NUMEL,PS,TS,VOIDS,WC)
C*********************************************************************
C     DETERMINES THE FLOW THROUGH CRACK INCLUDING FRICTION EFFECTS
C*********************************************************************
      COMMON/FRICR/ROUGH
      DIMENSION PS(1),TS(1),VOIDS(1)
      DATA GRAV,FACT,FTI/32.2,144.0,12.0/
      DATA CRIT/1.0E-3/
      IF(CAREA.EQ.0.0) GO TO 180
      DX=THICK/(FTI*FLOAT(NUMEL))
      DH=2.0*CAREA/(CL*FTI)
      A=CAREA/FACT
      FIN=0.5/(2.0*GRAV*FACT*A**2)
      FOUT=1.0/(2.0*GRAV*FACT*A**2)
      FINT=DX/(2.0*GRAV*FACT*A**2*DH)
C
C     SET LIMITS AND SUPPLY FIRST FLOW GUESS
C
      WMIN=0.0
      WMAX=A*GCTAB(PO,HO,PCRIT)
      W=(WMIN+WMAX)/2.0
C
C     BEGIN ITERATIVE LOOP TO OBTAIN FLOW
```

```
C
      DO 140 ITER=1,20
      P=PO-FIN*VO*W**2
C
C     DETERMINE FRICTION PRESSURE DROP ON NODE BY NODE BASIS
C
      DO 80 I=1,NUMEL
      HS=HSV(P,TSAT,S,VS)
      IF(HO.GT.HS) GO TO 40
      HL=HSL(TSAT)
      IF(HO.LT.HL) GO TO 20
      T=TSAT
      HL=HSL(TSAT)
      VL=VSL(TSAT)
      X=(HO-HL)/(HS-HL)
      V=X*VS+(1.0-X)*VL
      VOID=X*VS/V
      VISC=VOID*VISV(P,T)+(1.0-VOID)*VISL(P,T)
      GO TO 60
   20 S=SSSICL(P,HO,T)
      V=VCL(P,T)
      VOID=0.0
      VISC=VISL(P,T)
      GO TO 60
   40 S=SSSISS(P,HO,T,V,X)
      VOID=1.0
      VISC=VISV(P,T)
   60 RE=DH*ABS(W)/(A*VISC)
C****** NOTE FOR SMALL CRACK USE RELATIVE ROUGHNESS OF 0.1 *************
      F=FRICTF(RE,1.0,ROUGH)
      P=P-F*FINT*V*W**2
      PS(I)=P
      TS(I)=T
      VOIDS(I)=VOID
      IF(P.LT.PEX) GO TO 120
   80 CONTINUE
C
C     CHECK FOR NARROW WMIN TO WMAX
C
      IF(WMIN.EQ.0.0) GO TO 100
      IF(ABS((WMAX-WMIN)/WMIN).LT.CRIT) GO TO 160
C
C     CHECK FOR CRITICAL FLOW OR CRITICAL FLOW CONVERGENCE
C
  100 WC=A*GCTAB(P,HO,PCRIT)
      IF(ABS((WC-W)/WC).LT.CRIT) GO TO 160
      IF(WC.LT.W) GO TO 120
C
C     CHECK FOR NON-CRITICAL OUTLET
C
      P=P-FOUT*V*W**2
      IF(ABS((P-PEX)/PEX).LT.CRIT) GO TO 160
      IF(P.LT.PEX) GO TO 120
C
C     FLOW IS TOO LOW - ADJUST ACCORDINGLY
C
      WMIN=W
      W=(W+WMAX)/2.0
      GO TO 140
C
```

```
C      FLOW TOO HIGH - ADJUST ACCORDINGLY
C
  120 WMAX=W
      W=(W+WMIN)/2.0
  140 CONTINUE
C
C     TOO MANY ITERATIONS WITHOUT CONVERGENCE - PRINT ERROR AND STOP
C
      WRITE(6,1000) W,WMIN,WMAX,P
      STOP
C
C     CONVERGED SOLUTION
C
  160 FLOW=W
      RETURN
  180 FLOW=0.0
      RETURN
C
C     FORMATS
C
 1000 FORMAT(//1X,45HNO CONVERGENCE IN FLOW - EXECUTION TERMINATED,/1X,
     111X,1HW,8X,4HWMIN,8X,4HWMAX,11X,1HP,/1X,4E12.5)
      END
```

Appendix B

APPLIED LOADS FOR FRACTURE MECHANICS ANALYSES

The applied load on the postulated cracked cross section must be known to perform fracture mechanics analyses to evaluate the potential for through-wall cracks to fail unstably. In particular, the applied load must be specified as an applied moment. This appendix documents the method used to calculate the equivalent applied moment on the Susquehanna Steam Electric Station (SSES) recirculation system reactor vessel nozzle pipe-to-safe end welds. A total of ten nozzle safe ends are evaluated in fracture mechanics evaluations. These nozzle safe ends are listed below.

Unit 1	Unit 2
N1A	N1A
N2A	N2A
N2B	N2E
N2E	N2J
N2K	N2K

The applied load was determined for the loading conditions resulting from normal plant operation plus the loads due to the design safe shutdown earthquake (SSE). The loads on the pipe-to-safe end weld locations for deadweight, thermal expansion, and SSE were obtained from the original system design stress analyses performed by General Electric Co. These finite element analyses (References 1 through 4) were performed as part of the plant licensing. The information in these stress analysis reports includes the forces and moments on each finite element node point for each loading condition and were used to calculate the equivalent applied moment for fracture mechanics analyses. The loads on the piping due to the normal internal pressure of 1050 psig were determined by a hand calculation.

A review of the node point locations used in the finite element analyses revealed that in each model, the locations of the pipe-to-safe end welds did not exactly coincide with node point locations. For this reason, the node point closest to the pipe-to-safe end weld was chosen as representative of the load on the pipe-to-safe end weld. This assumption is considered acceptable for two reasons. First, in each instance, the location difference is small, and second, in each instance, the node chosen was the terminal node of the piping model. During the stress analyses, the nodal displacements of the terminal nodes were fixed in all degrees of freedom. The result of this procedure is usually to produce higher loads and stresses at the terminal end. Listed below are the finite element model node points used to obtain applied loads at the pipe-to-safe end weld locations.

Unit	Nozzle	Node	Ref(1)
1	N1A	005	1
1	N2A	224	2
1	N2B	254	2
1	N2E	164	2
1	N2K	164	1
2	N1A	001	3
2	N2A	350	4
2	N2E	250	4
2	N2J	330	3
2	N2K	350	3

(1) Reference number of finite element stress analyses.

The resultant forces and moments at the node points identified above for the different loading conditions are listed in Table C2-1 of References 1 through 4. The axial force and all three bending moments are used to calculate the equivalent moment. In the coordinate system used in References 1 through 4, the 'A' direction is the pipe axial direction and the 'B' and 'C' directions are perpendicular to 'A'. Thus, the

following values are needed (using nomenclature from References 1 through 4) F_A, M_A, M_B, M_C.

A review of References 1 through 4 shows that the load cases of interest are labeled as follows:

THERMAL 1 - normal operating thermal expansion loads

WEIGHT 1 - normal deadweight loads

SSEI 1 - inertial loads due to SSE in global 'X' direction

SSEI 2 - inertial loads due to SSE in global 'Y' direction

SSEI 3 - inertial loads due to SSE in global 'Z' direction

The forces and moments for each node and each loading were read from the appropriate reference table.

The procedure used to calculate a total stress and equivalent moment for each pipe-to-safe end weld location is described below.

1. The equivalent total moments and axial force due to the design SSE were obtained by a square root sum of the squares (SRSS) combination of the three coordinate direction (X, Y, and Z) results.

2. The forces and moments due to deadweight, thermal expansion and SSE were absolute summed to obtain the total axial force and bending moment in each local system direction (A, B, and C).

3. The three coordinate direction moments (torsion and two perpendicular) were SRSS combined to yield a total moment, M_{tot}.

4. The applied stress was calculated as the absolute sum of the axial force stress, the bending stress and the axial pressure stress.

5. The equivalent applied moment for fracture mechanics analyses, M_{eq}, was calculated as the moment which would produce the applied stress if only bending stresses were present.

In each instance the applied stresses and equivalent bending moments were calculated using minimum specified cross section properties for the recirculation piping at the nozzle safe end. This procedure yields conservative stresses and moments. The pipe cross section properties used in this analysis are (from reference 5)

nozzle safe end type	outside diameter	wall thickness
N1	28.0"	1.285"
N2	12.75"	0.586"

The results of the calculation of applied stresses and equivalent bending moments are tabulated below for each safe end location.

Unit	Nozzle	F_A (kip)	M_{tot} (in-kip)	Stress (ksi)	M_{eq} (in-kip)
1	N1A	4.2	1546.7	7.2	4979.6
1	N2A	2.1	374.0	10.8	701.5
1	N2B	0.5	388.6	10.9	711.4
1	N2E	1.6	183.6	7.8	509.6
1	N2K	1.2	154.5	7.4	479.4
2	N1A	6.0	2386.1	8.5	5830.5
2	N2A	2.3	395.9	11.1	724.0
2	N2E	1.6	150.0	7.3	476.0
2	N2J	0.5	528.8	13.1	851.6
2	N2K	1.3	136.4	7.1	461.5

References

1. General Electric Co. Stress Report 22A5693, Rev 1, (Susquehanna Unit 1, Loop A).

2. General Electric Co. Stress Report 22A5624, Rev 2, (Susquehanna Unit 1, Loop B).

3. General Electric Co. Stress Report 23A1897, Rev 0, (Susquehanna Unit 2, Loop A).

4. General Electric Co. Stress Report 23A1898, Rev 0, (Susquehanna Unit 2, Loop B).

5. Pennsylvania Power & Light Company Drawing FC1-P49-950, Rev. 16, 6/27/82.

Appendix C

FRACTURE MECHANICS METHODOLOGIES

C.1 Calculation of J-Integral

C.2 Tearing Stability Theory

CALCULATION OF J-INTEGRAL

The recommended leak-before-break (LBB) analysis guidelines presented in NUREG 1061, Volume 3 contain the criteria that postulated through-wall flaws should not experience unstable growth when subject to normal operating condition loads (pressure, deadweight and thermal expansion) plus the loads resulting from the design safe shutdown earthquake (SSE). The onset of flaw growth is calculated by means of the crack driving potential, or J-integral. The calculated value of J for the postulated cracked section is compared to the critical value of J for the material, J_{IC}. J_{IC} corresponds to the value of J at which crack growth initiation occurs.

If the calculated J is less than J_{IC}, crack extension is not predicted. If the calculated value of J is greater than J_{IC}, the crack will grow. During J controlled crack growth, the slope of the J vs Δa curve (dJ/da) for a cracked section is a straight line. Thus, if the calculated J is greater than J_{IC}, the amount of crack growth can be determined from

$$\Delta a = (J_{APP} - J_{IC}) / \frac{dJ}{da}$$

Described below are two methodologies used to calculate the applied J-integral for circumferential through-wall cracks. One method is appropriate when stresses at the cracked section are low and is based upon linear-elastic fracture mechanics methods. The other method is appropriate when the stresses at the cracked section are high, approaching plastic loads. In this instance, a method based upon elastic-plastic fracture mechanics is used.

Elastic Loads

In the linear elastic range, the calculated J-integral, J_{app}, is related to K, the stress intensity factor from linear-elastic fracture mechanics (LEFM), by the relation, $J = K^2/E$, where E is the material elastic modulus. The stress intensity factor for circumferential through-wall flaws is expressed as

$$K = \Sigma \sigma_i f_i \sqrt{\pi(a + r_y)}$$

where the summation is over all stresses acting on the cracked section (tension, bending and pressure) and f_i is a geometry factor dependent upon the type of stress. These values for f_i are available from Reference 1. In the expression for K above, r_y is a plastic zone correction used to account for plasticity near the crack tip. For large loads on the cracked section, the plastic zone near the crack tip may no longer be negligible compared to the crack size. The plastic zone correction used in this methodology is one which accounts realisticly for large scale plasticity effects. This correction factor model is taken from Reference 2 and can be expressed as

$$r_y = \frac{K^2}{\beta \pi \sigma_y{}^2}$$

where σ_y is the material yield stress and β varies according to the initial crack length. In this approach, r_y is no longer an estimate of the actual plastic zone size, but rather it can be thought of as an index representing the compliance of the cracked section. It is possible to adjust β so that the point of 'compliance instability' occurs at the limit load of the pipe, that is, the load required to make the entire cross-section plastic. This determination of r_y allows calculation of K (and thus J) up to the limit moment. The calculation of J using this method was expedited by using the computer program ELASJC, attached as Listing 1.

Plastic Loads

When applied loads exceed the limit moment load discussed above, no solution for J is possible using plastic zone corrected LEFM methods. In this case, it is necessary to use elastic-plastic fracture mechanics (EPFM) methods which are developed specifically for plastic cross-sections. The method used to calculate J_{app} is taken from Reference 3. Using this approach, the calculated J-integral is expressed as the sum of an elastic contribution and a plastic contribution, $J=J_e+J_p$. These contributions to the J-integral are expressed as

$$J = \frac{\pi R^2 F^2 aeM^2}{I^2 E} + \alpha \varepsilon_o \sigma_o \frac{a}{b} \; c \; h_1(a/b, \eta, R/t) \left(\frac{M}{Mo}\right)^{n+1}$$

where the following are defined for the pipe cross-section,

- ae = pseudo-plastic zone corrected crack length determined using the methods presented in Reference 3.
- M = one-half the moment applied to the pipe.
- F = a tabulated geometry correction factor.
- α ,n= strain hardening coefficients for a Ramberg-Osgood fit of the material stress-strain curve.
- σ_o, ε_o = material yield stress and yield strain.
- a = one-half the circumferential crack length.
- b = one-half the pipe circumference.
- c = b-a
- h_1 = a tabulated function based on detailed finite element J-integral modeling of cracked bodies.
- M_o = one-half the moment required to make the cracked cross-section fully plastic assuming elastic-perfectly plastic behavior.

The calculation of J using this elastic-plastic approach was performed using the computer program JGE, attached as Listing 2.

References

1. H. Tada, "The Effects of Shell Corrections on Stress Intensity Factors and the Crack Opening Area of a Circumferential and a Longitudinal Through Crack in a Pipe," NUREG/CR-3464, September 1983.

2. H. Tada and P. Paris, "Estimation Procedures for Load-Development Relation and J-integral for Entire Range of Elastic-Plastic Loading of Circumferentially Cracked Pipes," NUREG/CR-3464.

3. EPRI NP-3607, "Advances in Elastic-Plastic Fracture Analysis," August 1984.

Listing 1

Computer Program ELASJC

```
5 OPEN "ELASJC.OUT" FOR OUTPUT AS #1
7 KEY OFF
10 DEF FNF(T)=1+8*(T/PI)^2.5
20 DEF FNG(T)=T*FNF(T)^2
30 DEF FNGP(T)=(FNG(T*1.01)-FNG(T))/(.01*T)
100 GOSUB 6000
250 GOSUB 3000
260 GOSUB 4000
265 IF CONVERG=1 THEN 280
270 GOSUB 5000
280 GOSUB 7000
290 GOSUB 8000
295 IF Q=1 OR Q1=1 THEN 100
300 CLOSE #1
305 PRINT :PRINT :PRINT :PRINT
306 PRINT "More complete printout is contained in file ELASJC.OUT"
308 SYSTEM
310 END
3000 REM
3010 REM
3020 REM
3030 DELTA=PI/8
3040 THETAE=THETA0+DELTA
3050 IF ABS(THETAE-THETAE0)<.0001 THEN GOTO 3090
3060 DELTA=FNG(THETAE)/FNGP(THETAE)
3070 THETAE0=THETAE
3080 GOTO 3040
3090 SP=(COS(THETA0/2)-SIN(THETA0)/2)*4/PI
3100 ALPHA=FNGP(THETAE)*SP^2
3110 RETURN
4000 REM
4010 REM
4020 THETA=THETA0
4030 SIGMA=SIGB+SIGT+SIGP
4040 KP=SIGMA*FNF(THETA)*SQR(PI*R*THETA)
4050 IF ABS(KP-KP0)< 10 THEN RETURN
4060 THETA=THETA0+KP^2/(PI*R*ALPHA*SIGY^2)
4065 IF THETA>2*PI THEN CONVERG=1:RETURN
4070 KP0=KP
4080 GOTO 4040
5000 REM
5010 REM
5020 REM
5030 REM
5040 TP=THETA/PI
5050 FT=1+7.5*TP^1.5-15*TP^2.5+33*TP^3.5
5060 FB=1+6.8*TP^1.5-13.6*TP^2.5+20*TP^3.5
5065 LAMBDA=R*THETA/SQR(R*T)
5070 IF LAMBDA<1 THEN FP=SQR(1+.3225*LAMBDA^2) ELSE FP=.9+.25*LAMBDA
5080 K=(SIGB*FB+SIGT*FT+SIGP*FP)*SQR(R*PI*THETA)
5090 J=K*K/E
5100 RETURN
6000 REM
6001 CLS
6002 IF Q=1 THEN 6120
6003 IF Q1=1 THEN 6065
6005 PRINT "This program will solve for the J-integral for circumferential"
6006 PRINT "flaws in pipe. The necessary inputs will appear on the screen"
6007 PRINT "and simply need to be input. The results will appear on the screen
6008 PRINT "for J for each crack length analyzed. More complete printout"
```

```
6009 PRINT "information is written onto file ELASJC.OUT and may be examined"
6010 PRINT "after completion of the program.":PRINT :PRINT :PRINT
6011 PRINT "            press any key to continue...."
6012 T$=INKEY$
6013 IF T$="" THEN 6012
6019 THETAE0=0
6020 KP0=0
6030 PI=3.1415
6040 B$=" "
6060 CLS
6065 INPUT "TITLE: ";TITLE$:PRINT
6066 TITLE$=TITLE$+"  (CIRCUM FLAW)"
6067 INPUT "PIPE MATERIAL: ";M$:PRINT
6070 INPUT "PIPE DIAMETER  (IN) :  ";D:PRINT
6080 INPUT "WALL THICKNESS  (IN) : ";T:PRINT
6090 INPUT "BENDING STRESS  (PSI) : ";SIGB:PRINT
6100 INPUT "AXIAL STRESS  (PSI) : ";SIGT:PRINT
6110 INPUT "SYSTEM PRESSURE  (PSI) : ";P:PRINT
6114 IF LEFT$(M$,1)="C" THEN SIGY=27100:E=2.7E+07:M$="CARBON STEEL":GOTO 6116
6115 SIGY=23000:E=2.56E+07:M$="STAINLESS STEEL"
6116 R=(D-T)/2
6117 SIGP=P*(R-T/2)^2/(2*R*T)
6120 INPUT "INITIAL CRACK LENGTH  (IN) : ";A0:PRINT
6160 THETA0=A0/(2*R)
6180 RETURN
7000 REM
7010 REM
7020 CLS
7025 PRINT #1,CHR$(12)
7030 PRINT #1,TITLE$:PRINT #1,B$
7040 PRINT #1,M$:PRINT #1,B$
7050 PRINT #1,"PIPE DIAMETER=  ";:PRINT #1,USING "##.### ";D;:PRINT #1," in"
7060 PRINT #1,"WALL THICKNESS= ";:PRINT #1,USING " #.### ";T;:PRINT #1," in"
7070 PRINT #1,B$
7080 PRINT #1,"BENDING  STRESS= ";:PRINT #1,USING "#####.#";SIGB;:PRINT #1," psi
7090 PRINT #1,"AXIAL  STRESS=   ";:PRINT #1,USING "#####.#";SIGT;:PRINT #1," psi
7100 PRINT #1,"PRESSURE STRESS= ";:PRINT #1,USING "#####.#";SIGP;:PRINT #1," psi
7110 PRINT #1,B$:A=2*R*THETA
7120 PRINT #1,"INITAL  CRACK  LENGTH=  ";:PRINT #1,USING "##.##";A0;:PRINT #1," i
7123 PRINT "INITAL  CRACK  LENGTH=  ";:PRINT USING "##.##";A0;:PRINT " in"
7124 PRINT
7125 IF CONVERG=1 THEN 7170
7130 PRINT #1,"EFFECTIVE CRACK LENGTH= ";:PRINT #1,USING "##.##";A;:PRINT #1," in
7140 PRINT #1,B$
7148 PRINT "J= ";:PRINT USING "#####.#";J;:PRINT " in-lb/in^2"
7149 PRINT #1,"J= ";:PRINT #1,USING "#####.#";J;:PRINT #1," in-lb/in^2"
7150 FOR I=1 TO 5 :PRINT #1,B$ :NEXT I
7155 PRINT :PRINT :PRINT :PRINT
7160 RETURN
7170 PRINT #1,B$:PRINT #1,B$:PRINT #1,B$
7180 PRINT #1,"For the above conditions, this problem has no solution"
7185 PRINT  "This initial crack length does not converge for this situation"
7190 PRINT :PRINT :PRINT:CONVERG=0
7195 FOR I=1 TO 5 :PRINT #1,B$ :NEXT I
7200 RETURN
8000 REM
8010 REM
8020 INPUT "another crack length";Q$
8030 IF Q$="Y" THEN Q=1:RETURN
8033 Q=0
```

```
8035 PRINT:PRINT:INPUT "start again from beginning";Q1$
8040 IF Q1$="Y" THEN Q1=1:ELSE Q1=0
8050 RETURN
```

Listing 2

Computer Program JGE

```
$STORAGE:2
      PROGRAM JGE
C*********************************************************************
C
C*********************************************************************
      CHARACTER*50 TITLE
      CHARACTER*35 MLABEL
      DATA PI/3.14159/
   20 CONTINUE
      WRITE(*,*)
      WRITE(*,2000)
      WRITE(*,*)
      WRITE(*,2020)
      READ(*,1000) TITLE
      WRITE(*,*)
      CALL GETMAT(MLABEL,E,SIG0,E0,SIGFLO,AL,XN)
      CALL GEOM(R,T)
      ROT=R/T
      D=2*R
      WRITE(*,*)
      WRITE(*,2040)
      READ(*,1020) AOB
      WRITE(*,*)
      WRITE(*,2080)
      READ(*,1020) XM
   40 CONTINUE
      XI=PI*(R**4-(R-T)**4)/4.0
      B=PI*R
      A=B*AOB
      C=B-A
      GAMMA=PI*AOB
      CALL GEPROP(AOB,XN,ROT,H1,H4,F1,V3)
      TRIG=COS(GAMMA/2.0)-SIN(GAMMA)/2.0
      XM0=2.0*SIG0*R*R*T*TRIG
      IF(XM.LT.0.0) THEN
        XMM0=-XM
        XM=XMM0*XM0
       ELSE
        XMM0=XM/XM0
       ENDIF
C **** calc J ****
      XJE=PI*A*R*R*F1*F1*XM*XM/(XI*XI*E)
      XKE=SQRT(XJE*E)
      PHI=1.0/(1.0+XMM0*XMM0)
      RY=1.0/(2.0*PI)*(XN-1.0)/(XN+1.0)*(XKE/SIG0)**2.0
      AE=A+PHI*RY
      XJE=PI*AE*R*R*F1*F1*XM*XM/(XI*XI*E)
      XJP=AL*SIG0*E0*C*A*H1*XMM0**(XN+1)/B
      XJ=XJE+XJP
      CALL OUTPUT(TITLE,MLABEL,AOB,D,T,XM,XMM0,XJ,2.0*A,2.0*AE)
      WRITE(*,*)
      WRITE(*,2100)
      READ(*,1040) NCH
      IF(NCH.EQ.0) STOP
      IF(NCH.EQ.1) THEN
        WRITE(*,2040)
        READ(*,1020) AOB
        GOTO 40
       ENDIF
      IF(NCH.EQ.2) THEN
```

```
         WRITE(*,2080)
         READ(*,1020) XM
         GOTO 40
        ENDIF
       GOTO 20
       STOP
 1000  FORMAT(A)
 1020  FORMAT(F12.4)
 1040  FORMAT(I2)
 2000  FORMAT(' JGE- Program to Calculate J')
 2020  FORMAT('   Enter Problem Title: ',\)
 2040  FORMAT('   Enter Crack Length (a/b): ',\)
 2080  FORMAT('   Enter Applied Moment (in-lb): ',\)
 2100  FORMAT('   Enter:',/,
     1        '     0 to quit',/,
     2        '     1 to change a/b',/,
     3        '     2 to change M      ',\)
       END
       SUBROUTINE OUTPUT(TITLE,MLABEL,AOB,D,T,XM,XMM0,XJ,A,AE)
C**********************************************************************
C
C**********************************************************************
       CHARACTER*50 TITLE
       CHARACTER*35 MLABEL
       DO 40 I=1,24
         WRITE(*,*)
   40  CONTINUE
       WRITE(*,1500)
       WRITE(*,2000) TITLE
       WRITE(*,*)
       WRITE(*,2020) MLABEL
       WRITE(*,2040) AOB
       WRITE(*,2050) A
       WRITE(*,2055) AE
       WRITE(*,*)
       WRITE(*,2060) D
       WRITE(*,2080) T
       WRITE(*,*)
       WRITE(*,2110) XM
       WRITE(*,2120) XMM0
       WRITE(*,*)
       WRITE(*,2160) XJ
       WRITE(*,*)
       RETURN
 1500  FORMAT(' JGE: Calculation of J',/)
 2000  FORMAT(A50)
 2020  FORMAT(A35)
 2040  FORMAT(' Crack Length (a/b): ',F5.3)
 2050  FORMAT(' Crack Length (in) : ',F7.3)
 2055  FORMAT(' Effective Crack Length (in) : ',F7.3)
 2060  FORMAT(' Pipe Diameter: ',F6.3,' inches')
 2080  FORMAT(' Pipe Wall Thickness: ',F6.3,' inches')
 2110  FORMAT(' Applied Moment: ',F12.1,' in-lb')
 2120  FORMAT(' Applied Load/Yield Load: ',F4.2)
 2160  FORMAT(' J-integral: ',F10.1,' in-lb/in²')
       END
       SUBROUTINE GEOM(R,T)
C**********************************************************************
C
C**********************************************************************
```

```
      WRITE(*,*)
      WRITE(*,2000)
      READ(*,1000) D
      WRITE(*,2020)
      READ(*,1000) T
      R=D/2.0
      RETURN
 1000 FORMAT(F12.4)
 2000 FORMAT('  Enter Pipe Diameter: ',\)
 2020 FORMAT('  Enter Pipe Wall Thickness: ',\)
      END
      SUBROUTINE GETMAT(MLAB,E,SIG0,E0,SIGFLO,AL,XN)
C***********************************************************************
C
C***********************************************************************
      CHARACTER*35 MLABEL(3),MLAB
      DATA MLABEL/' A106 Gr B Carbon Steel Base Metal',
     1            ' 304 Stainless Steel Weld Metal   ',
     2            ' GE EPRI Report Pipe Properties   '/
      DATA NMAT/3/
   20 CONTINUE
      WRITE(*,2000)
      DO 40 I=1,NMAT
        WRITE(*,2020) I,MLABEL(I)
   40  CONTINUE
      WRITE(*,*)
      WRITE(*,2030)
      READ(*,1000) MAT
      IF(MAT.LT.1.OR.MAT.GT.NMAT) GOTO 20
      WRITE(*,*)
      MLAB=MLABEL(MAT)
      CALL MATPROP(MAT,E,SIG0,E0,SIGFLO,AL,XN)
      RETURN
 1000 FORMAT(I1)
 2000 FORMAT('  Allowable Materials:')
 2020 FORMAT(I4,'. ',A35)
 2030 FORMAT('  Select Pipe Material... ',\)
      END
      SUBROUTINE MATPROP(MAT,E,SIG0,E0,SIGFLO,AL,XN)
C***********************************************************************
C
C***********************************************************************
      IF(MAT.EQ.1) THEN
        SIG0=27100.0
        SIGFLO=43600.0
        E=27.0E6
        AL=1.94
        XN=4.42
        GOTO 100
       ENDIF
      IF(MAT.EQ.2) THEN
        SIG0=23000.0
        SIGFLO=42000.0
        E=25.6E6
        AL=2.13
        XN=3.79
        GOTO 100
       ENDIF
      IF(MAT.EQ.3) THEN
        SIG0=30000.0
```

```
         SIGFLO=42000.0
         E=30.0E6
         AL=1.69
         XN=5.42
         GOTO 100
        ENDIF
  100 CONTINUE
      E0=SIG0/E
      RETURN
      END
      SUBROUTINE GEPROP(AOB,XN,ROT,H1,H4,F1,V3)
C*********************************************************************
C
C*********************************************************************
      H1=H1VAL(AOB,XN,ROT)
      H4=H4VAL(AOB,XN,ROT)
      F1=F1VAL(AOB,ROT)
      V3=V3VAL(AOB,ROT)
      RETURN
      END
      FUNCTION H1VAL(AB,XN,ROT)
C*********************************************************************
C
C*********************************************************************
      DIMENSION H1(5,4),ABVAL(4),XNVAL(5),ROTVAL(3)
      DATA H1/4.987,6.018,6.743,7.620,7.969,
     1        5.361,5.987,6.281,6.311,5.996,
     2        5.620,5.312,4.886,3.969,3.240,
     3        3.646,2.682,2.105,1.424,1.035/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA XNVAL/1.0,2.0,3.0,5.0,7.0/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NXN,NROT/4,5,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      DO 40 I=2,NAB
        IF(AOB.LE.ABVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
         ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NXN
        IF(XN.LE.XNVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
         ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACA=(AOB-ABVAL(I1))/(ABVAL(I2)-ABVAL(I1))
      FRACN=(XN-XNVAL(J1))/(XNVAL(J2)-XNVAL(J1))
      VAL1=H1(J1,I1)+FRACN*(H1(J2,I1)-H1(J1,I1))
      VAL2=H1(J1,I2)+FRACN*(H1(J2,I2)-H1(J1,I2))
      H1VAL=VAL1+FRACA*(VAL2-VAL1)
      RETURN
      END
      FUNCTION H4VAL(AB,XN,ROT)
C*********************************************************************
```

```
C
C*********************************************************************
      DIMENSION H4(5,4),ABVAL(4),XNVAL(5),ROTVAL(3)
      DATA H4/-.194,0.078,0.144,0.288,0.429,
     1        0.136,0.565,0.783,1.119,1.317,
     2        1.459,2.098,2.334,2.308,2.049,
     3        5.384,4.283,3.232,2.049,1.400/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA XNVAL/1.0,2.0,3.0,5.0,7.0/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NXN,NROT/4,5,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      DO 40 I=2,NAB
        IF(AOB.LE.ABVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
        ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NXN
        IF(XN.LE.XNVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
        ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACA=(AOB-ABVAL(I1))/(ABVAL(I2)-ABVAL(I1))
      FRACN=(XN-XNVAL(J1))/(XNVAL(J2)-XNVAL(J1))
      VAL1=H4(J1,I1)+FRACN*(H4(J2,I1)-H4(J1,I1))
      VAL2=H4(J1,I2)+FRACN*(H4(J2,I2)-H4(J1,I2))
      H4VAL=VAL1+FRACA*(VAL2-VAL1)
      RETURN
      END
      FUNCTION F1VAL(AB,ROT)
C*********************************************************************
C
C*********************************************************************
      DIMENSION F1(4,3),ABVAL(4),ROTVAL(3)
      DATA F1/1.046,1.143,1.423,2.555,
     1        1.070,1.219,1.599,2.896,
     2        1.118,1.343,1.836,3.337/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NROT/4,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      RT=ROT
      RT=10.0
      DO 40 I=2,NROT
        IF(RT.LE.ROTVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
        ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NAB
```

```
         IF(AOB.LE.ABVAL(J)) THEN
           J1=J-1
           J2=J
           GOTO 100
         ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACR=(RT-ROTVAL(I1))/(ROTVAL(I2)-ROTVAL(I1))
      FRACA=(AOB-ABVAL(J1))/(ABVAL(J2)-ABVAL(J1))
      VAL1=F1(J1,I1)+FRACA*(F1(J2,I1)-F1(J1,I1))
      VAL2=F1(J1,I2)+FRACA*(F1(J2,I2)-F1(J1,I2))
      F1VAL=VAL1+FRACR*(VAL2-VAL1)
      RETURN
      END
      FUNCTION V3VAL(AB,ROT)
C***********************************************************************
C
C***********************************************************************
      DIMENSION V3(4,3),ABVAL(4),ROTVAL(3)
      DATA V3/-.065,0.003,0.389,3.925,
     1        -.043,0.034,0.504,5.117,
     2        -.070,0.020,0.626,6.795/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NROT/4,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      RT=ROT
      RT=10.0
      DO 40 I=2,NROT
        IF(RT.LE.ROTVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
        ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NAB
        IF(AOB.LE.ABVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
        ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACR=(RT-ROTVAL(I1))/(ROTVAL(I2)-ROTVAL(I1))
      FRACA=(AOB-ABVAL(J1))/(ABVAL(J2)-ABVAL(J1))
      VAL1=V3(J1,I1)+FRACA*(V3(J2,I1)-V3(J1,I1))
      VAL2=V3(J1,I2)+FRACA*(V3(J2,I2)-V3(J1,I2))
      V3VAL=VAL1+FRACR*(VAL2-VAL1)
      RETURN
      END
```

TEARING STABILITY THEORY

The criteria for the stability of a cracked pipe under large loads were discussed by Paris and Tada in Reference 1. These general criteria involve only considerations of simple moment balance at the cracked section of pipe and the concept of rebound compliance as defined by Kaiser and Carlsson (2).

Consider the pipe system geometry in Figure 1. A cracked pipe section or plastic hinge is embedded in a statically indeterminant piping system, actually a frame, and is carrying a moment, M, and has a hinge angle, ϕ . The details of the piping system are unimportant here; however, it is assumed to behave elastically to changes in moment at the cracked section. That is, a change in moment at the cracked section causes a proportional change in angle ϕ due to the stiffness of the attached piping system:

$$dM = K_s \, d\phi \tag{1}$$

The small, plastically deformed cracked section has its own compliance properties, which are generally different from that of the piping system and may not even be linear. Under conditions of extreme loading, the moment-carrying capability of the hinge decreases with increasing angle due to crack growth and reduction of net moment- carrying section.

Figure 2 shows a hypothetical $M - \phi$ curve for a short cracked section loaded as illustrated. The rebound compliance, C_r, (2) is the non-constant decending slope of the $M - \phi$ curve. The rebound <u>stiffness</u>, K_r (= $1/C_r$), is a measure of the rate a which moment is shed from the cracked section with increasing hinge angle:

$$\frac{dM}{d\phi} = K_r \tag{2}$$

In general, K_r is a function of ϕ and is less than zero. The stability condition developed by Paris (1) and Kaiser and Carlsson (2) states that the moment shed by the cracked section during a perturbation or variation in hinge angle can be picked up by the attached piping system. That is

$$dM_{crack} < dM_{system} \tag{3}$$

or

$$\left.\frac{dM}{d\phi}\right|_{crack} d\phi < \left.\frac{dM}{d\phi}\right|_{system} d\phi \tag{4}$$

From (1), this becomes

$$\left.\frac{dM}{d\phi}\right|_{crack} < K_s \quad \text{(Stable)} \tag{5}$$

and

$$\left.\frac{dM}{d\phi}\right|_{crack} > K_s \quad \text{(Unstable)} \tag{6}$$

The quantity, K_s, can be calculated directly from the finite element model of the piping system. However, short of actually obtaining rebound stiffness data from full-sized cracked pipe sections, the criteria of equations 5 and 6 provide little practical use for determining stability in a given case. What is desired is a method for determining fracture parameters from small test specimens and applying these parameters to the pipe geometry of interest. One commonly used parameter is the (dimensionless) material tearing modulus, T_{MAT}, which was proposed by Paris, et. al (3,4) to explain stable versus unstable crack growth. In general, T_{MAT} has the form

$$T_{mat} = \frac{E}{\sigma_o^2} \frac{dJ}{da} \tag{7}$$

where E is Young's modulus, 2a is the crack length, σ_f is the flow stress and J is the Rice J-integral (5).

The tearing modulus can be determined from test data, such as J-R curves developed from small specimens, and it is considered to be a material property, at least under certain restrictions relating to the applicability of J-controlled crack growth. The tearing modulus concept has been extensively developed and applied to the stability of crack growth of test specimens in relatively simple test machines (6). Constant displacement boundary conditions are normally assumed in these analyses (7), but these are not applicable to the pipe crack situation discussed here. The material tearing modulus concept itself, however, is useful, and will be used here to develop the stability conditions equations 5 and 6 in terms of T_{MAT}, rather than $dM/d\phi|_{crack}$

The following system equations will be used to transform Eqs 5 and 6:

$$M = M(a, \phi) \tag{8}$$

$$J = J(a, \phi) \tag{9}$$

$$\frac{dJ}{da} = \frac{\sigma_o^{\,2}}{E} T_{mat} \tag{10}$$

We let J have the usual deformation theory form (8), as

$$J = \frac{1}{t} \int_0^M \frac{\partial \phi}{\partial a} \Big)_M dM = \frac{-1}{t} \int_0^\phi \frac{\partial M}{\partial a} \Big)_\phi d\phi \qquad (11)$$

where t is the pipe wall thickness. In all equations we consider only the crack growth and J integral at one crack front rather than both crack fronts. On this basis, M is half the moment applied to the pipe. See Figure 3.

From equations 5 and 6, it is apparent that the total derivative of M with respect to ϕ is desired:

$$dM = \frac{\partial M}{\partial a} \Big)_\phi da + \frac{\partial M}{\partial \phi} \Big)_a d\phi \qquad (12)$$

or

$$\frac{dM}{d\phi} = \frac{\partial M}{\partial a} \Big)_\phi \frac{da}{d\phi} + \frac{\partial M}{\partial \phi} \Big)_a \qquad (13)$$

The expression, $da/d\phi$, can be eliminated by using equations 9 and 11:

$$dJ = \frac{\partial J}{\partial a} \Big)_\phi da - \frac{1}{t} \frac{\partial M}{\partial a} \Big)_\phi d\phi$$

or

$$\frac{dJ}{da} = \frac{\sigma_o^2}{E} T_{mat} = \frac{\partial J}{\partial a} \Big)_\phi - \frac{1}{t} \frac{\partial M}{\partial a} \Big)_\phi \frac{d\phi}{da}$$

Solving for $da/d\phi$

$$\frac{da}{d\phi} = \frac{1}{t}\frac{\partial M}{\partial a}\Big)_\phi \left[\frac{\partial J}{\partial a}\Big)_\phi - \frac{\sigma_o^2}{E} T_{mat} \right]^{-1} \tag{14}$$

Substituting equation 14 into equation 13, we find

$$\frac{dM}{d\phi} = \frac{1}{t}\frac{\partial M}{\partial a}\Big)_\phi^2 \left[\frac{\partial J}{\partial a}\Big)_\phi - \frac{\sigma_o^2}{E} T_{mat} \right]^{-1} + \frac{\partial M}{\partial \phi}\Big)_a \tag{15}$$

The stability criterion, equation 5 can now be evaluated with equation 15

$$-\frac{1}{t} \frac{\partial M}{\partial a}\Big)_\phi^2 \left[\frac{\partial J}{\partial a}\Big)_\phi - \frac{\sigma_o^2}{E} T_{mat} \right]^{-1} - \frac{\partial M}{\partial \phi}\Big)_a < K_s$$

or, in terms of T_{MAT}

$$T_{mat} > \frac{E}{\sigma_o^2}\frac{1}{t} \frac{\partial M}{\partial a}\Big)_\phi^2 \left[K_s + \frac{\partial M}{\partial \phi}\Big)_a \right]^{-1} + \frac{E}{\sigma_o^2}\frac{\partial J}{\partial a}\Big)_\phi \tag{16}$$

This expression is the general stability criterion equation 5 expressed in terms of the material tearing modulus and system stiffness, K_s.

It is interesting to note that equation 16 is identical to the tearing modulus stability criterion developed by McCabe and Ernst (9) for a cracked specimen embedded in a compliant structure under displacement controlled boundary conditions. The geometry for this case is shown in Figure 4. Further, McCabe and Ernst point out that the stability conditions equations 5 and 6 are implied by the Paris et al (3,4) stability conditions

$$T_{mat} > T_{app} \quad \text{(Stable)} \tag{17}$$

$$T_{mat} < T_{app} \quad \text{(Unstable)} \tag{17a}$$

where

$$T_{app} = \frac{E}{\sigma_o^2} \frac{dJ}{\partial a})_{\phi_t} \tag{18}$$

with

$$\phi_t = \phi + K_s M = \text{constant} \tag{19}$$

The ability to derive equation 16 from equations 5 and 6 directly shows that, rather than being only a consequence of equation 17, equations 5 and 6 are exactly equivalent to equation 17, and no assumption regarding total displacements of the cracked body and surrounding system, equation 19, are needed to perform the stability analysis.

Thus far, the stability condition equation 16 has been discussed in terms of crack size, a, and hinge angle, ϕ , as independent variables (see equations 8 and 9). Useful expressions have been developed for J and ϕ as functions of a and M, however, (10), and in anticipation of the use of these expressions, it is necessary to reformulate equation 16 in terms of J and ϕ as functions of a and M. This can be done directly with some algebraic manipulation and use of equation 11. The result is

$$T_{mat} > \frac{E}{\sigma_o^2} \left\{ \left(\frac{\partial J}{\partial a}\right)_M - t \left(\frac{\partial J}{\partial M}\right)_a^2 \left[C_s + \left(\frac{\partial \phi}{\partial M}\right)_a\right]^{-1} \right\} \tag{20}$$

where

Equation 20 was initially derived from equations 17 and 18 by Hutchinson and Paris (7) for displacement controlled boudary conditions in the "a, M" independent variable system. However, it has been shown here that this equation is also valid for the piping stability problem discussed above, without references to constant displacement boudary conditions.

Application of Tearing Stability Theory to Strain Hardening Pipes

In order to apply the tearing stability expression, Equation 20, it is necessary to evaluate in detail the various terms that appear in the expression. Expressions for the J-integral and crack plastic hinge angle have been developed by General Electric Co. for the case of pure moment loading on a pipe cross-section (11). These expressions are used as the basis for the development of the necessary derivatives appearing in the tearing instability expression. All derivatives are taken explicitly to improve accuracy.

For strain hardening materials which obey a Ramberg-Osgood power hardening law,

$$\varepsilon/\varepsilon_o = \sigma/\sigma_o + \alpha(\sigma/\sigma_o)^n \quad \text{, where}$$

where α and n are material constants, the J-integral and crack hinge angle can be expressed as (11)

$$J = \frac{\pi R^2 F^2 a M^2}{I^2 E} + \alpha \varepsilon_o \sigma_o \frac{a}{b} c\, h_1(a/b, n, R/t) \left(\frac{M}{Mo}\right)^{n+1} \tag{21}$$

$$\phi = \frac{4RV_3M}{EI} + \alpha\, \varepsilon_o\, h_4\, (a/b,\, n,\, R/t)\, \left(\frac{M}{Mo}\right)^n \qquad (22)$$

where,

a = one-half the crack length.

M = one-half the applied moment on the cracked section.

F, V_3 = tabulated geometry factors from Reference 11.

b = one-half the pipe circumference.

c = b-a

σ_o, ε_o = material yield stress and yield strain.

h_1, h_4 = tabulated functions based on detailed finite element J-integral modeling of cracked bodies.

M_O = one-half the moment required to make the cracked cross-section fully plastic assuming elastic-perfectly plastic behavior.

$$M_O = 2\sigma_f R_M^2 t \, [\cos(\gamma/2) - \tfrac{1}{2} \sin(\gamma)]$$

R_m is the pipe mean radius.

σ_f is the material flow stress.

γ is one-half the crack angle.

Neglecting C_s, three other terms appearing in the tearing instability expression must be evaluated. The evaluation of these terms is made convenient if the expressions for the J-integral and hinge angle presented above (equations 21 and 22) are rewritten as

$$J = J_e + J_p$$

$$\phi = \phi_e + \phi_p$$

where J_e is the elastic contribution to the J-integral and corresponds to the first term in equation 21 and J_p is the plastic contribution

corresponding to the second term. The definitions of ϕ_e and ϕ_p are similar. All derivatives can now be expressed as the sum of an elastic part and a plastic part. The necessary derivatives are taken algebraically to yield the following expressions

$$\frac{\partial J}{\partial a}\Big)_M = J_e \left[\frac{2}{F}\frac{dF}{da} + \frac{1}{a}\right] + J_p \left[-\frac{(n+1)}{Mo}\frac{dMo}{da} + \frac{1}{h_1}\frac{dh_1}{da} + \frac{1}{a} - \frac{1}{c}\right]$$

$$\frac{\partial J}{\partial M}\Big)_a = \frac{2J_e}{M} + \frac{(n+1)}{M} J_p$$

$$\frac{\partial \phi}{\partial M}\Big)_a = \frac{\phi_e}{M} + \frac{n\phi_p}{M}$$

The derivatives of tabular functions are obtained numerically from the tables in Reference 11. The other expression needed is the derivative of M_0 with respect to crack length. This expression is

$$\frac{dMo}{da} = -\sigma_f R_m t \left[\sin(\gamma/2) + \cos(\gamma)\right]$$

The evaluation of piping system cracked section stability using equation 20 and the terms derived above was performed using the computer program TEAR, attached as Listing 1.

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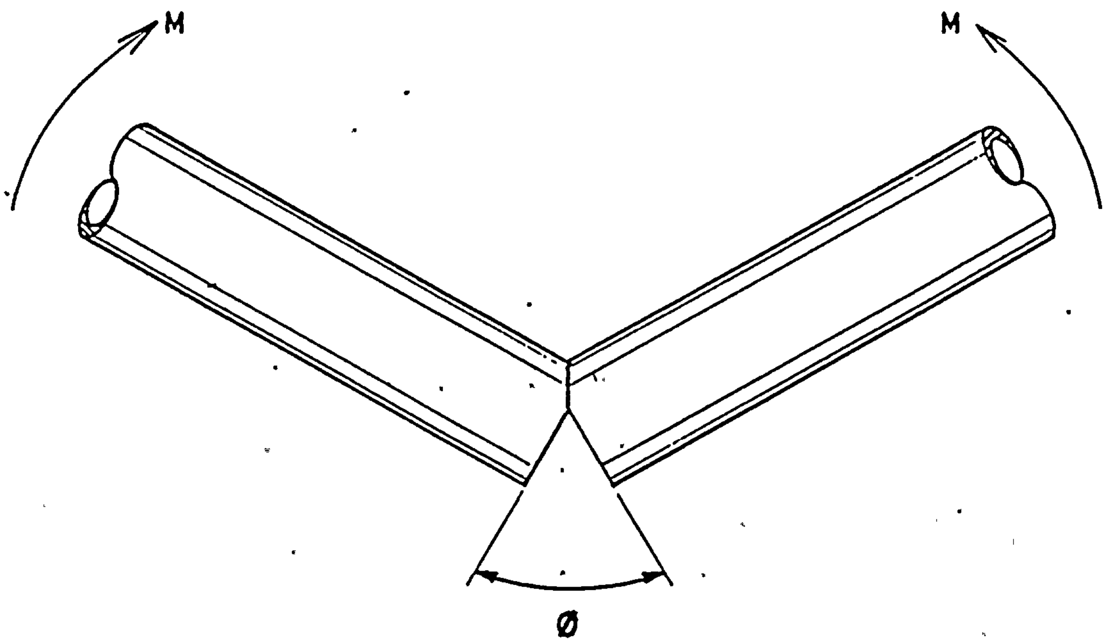
11. V. Kumar et al, "Advances in Elastic-Plastic Fracture Analysis," EPRI NP-3607, August 1984.

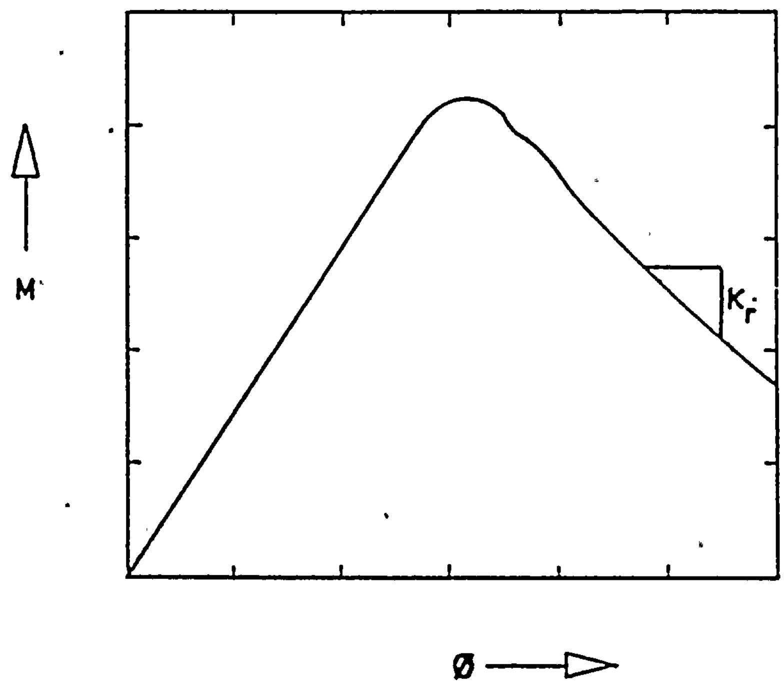
MPR ASSOCIATES
F-109-14-5
9/12/86



APPLIED LOAD AND HINGE ANGLE FOR A CRACK
AND RESULTING PLASTIC HINGE IN A PIPING SYSTEM

FIGURE 1

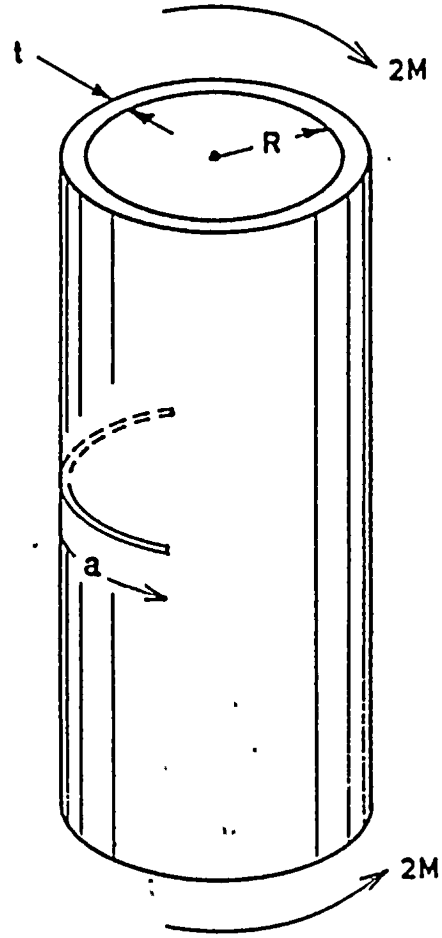
MPR ASSOCIATES
F-109-14-6
9/12/86



A LOAD DISPLACEMENT CURVE FOR A SHORT PIPE
WITH EMBEDDED THROUGH-WALL FLAW
UNDER CONDITIONS OF LARGE MOMENT LOADING.
THE STIFFNESS, K_r, FOR THE CRACKED SECTION IS SHOWN

FIGURE 2

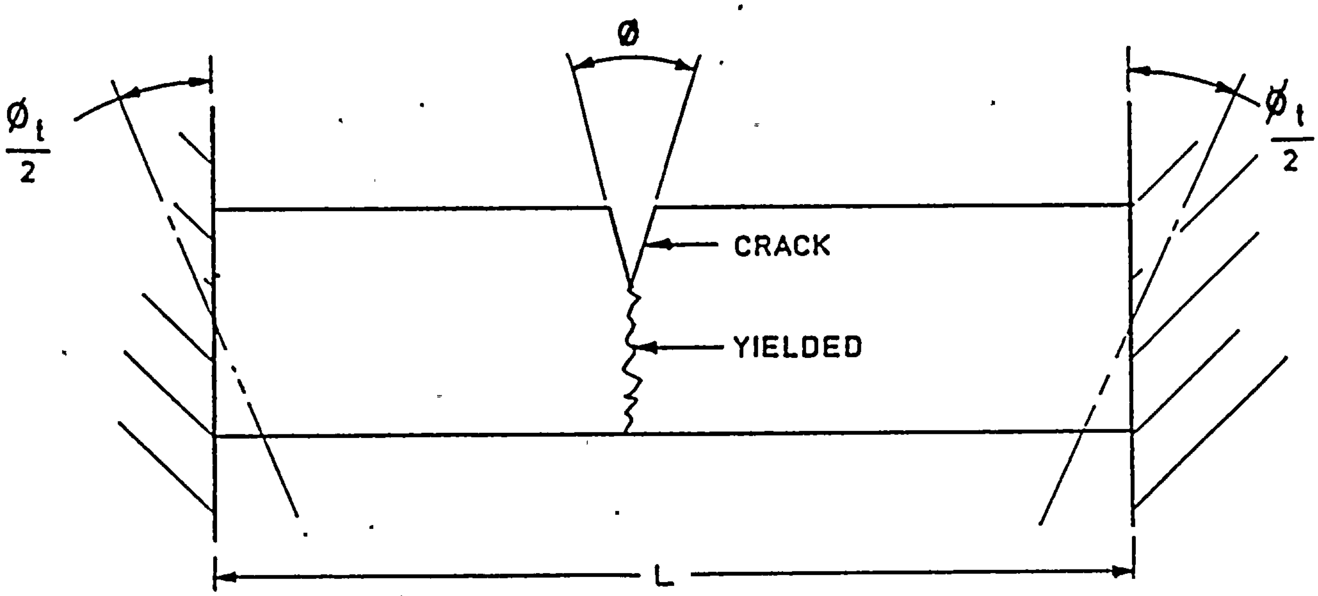
MPR ASSOCIATES
F-109-14-7
9/12/86



THE MOMENT LOADING AND FLAW SIZE
FOR THE FULL PIPE SECTION

FIGURE 3

MPR ASSOCIATES
F-109-14-8
9/12/86



EQUIVALENT CRACKED PIPE SECTION
SHOWING CONSTANT DISPLACEMENT BOUNDARY CONDITIONS

FIGURE 4

Listing 1

Computer Program TEAR

```
$STORAGE:2
      PROGRAM TEAR
C*******************************************************************
C
C*******************************************************************
      CHARACTER*50 TITLE
      CHARACTER*35 MLABEL
      DATA PI/3.14159/
   20 CONTINUE
      WRITE(*,*)
      WRITE(*,2000)
      WRITE(*,*)
      WRITE(*,2020)
      READ(*,1000) TITLE
      WRITE(*,*)
      CALL GETMAT(MLABEL,E,SIG0,E0,SIGFLO,AL,XN)
      CALL GEOM(R,T)
      ROT=R/T
      D=2*R
      WRITE(*,*)
      WRITE(*,2040)
      READ(*,1020) AOB
      WRITE(*,*)
      WRITE(*,2060)
      READ(*,1020) XLR
      WRITE(*,2080)
      READ(*,1020) XM
   40 CONTINUE
      XI=PI*(R**4-(R-T)**4)/4.0
      B=PI*R
      A=B*AOB
      C=B-A
      GAMMA=PI*AOB
      CALL GEPROP(AOB,XN,ROT,H1,H4,F1,V3,H1P,F1P,V3P)
      DH1DA=H1P/B
      DF1DA=F1P/B
      DV3DA=V3P/B
      TRIG=COS(GAMMA/2.0)-SIN(GAMMA)/2.0
      XM0=2.0*SIG0*R*R*T*TRIG
      DM0DA=-SIG0*R*T*(SIN(GAMMA/2.0)+COS(GAMMA))
      IF(XM.LT.0.0) THEN
        XMM0=-XM
        XM=XMM0*XM0
       ELSE
        XMM0=XM/XM0
       ENDIF
C **** calc J ****
      XJE=PI*A*R*R*F1*F1*XM*XM/(XI*XI*E)
      XJP=AL*SIG0*E0*C*A*H1*XMM0**(XN+1)/B
      XJ=XJE+XJP
C **** calc FC ****
      FCE=4.0*R*XM*V3/(XI*E)
      FCP=AL*E0*H4*XMM0**XN
      FC=FCE+FCP
C **** djda at m ****
      DJEDA=XJE*(2.0*DF1DA/F1+1.0/A)
      DJPDA=XJP*(-(XN+1.0)*DM0DA/XM0+DH1DA/H1+1.0/A-1.0/C)
      DJDA=DJEDA+DJPDA
C **** djdm at a ****
      DJEDM=2.0*XJE/XM
```

```
      DJPDM=XJP*(XN+1.0)/XM
      DJDM=DJEDM+DJPDM
C **** dfcda at m ****
      DFCDA=T*DJDM
C **** dfcdm at a ****
      DFCEDM=FCE/XM
      DFCPDM=XN*FCP/XM
      DFCDM=DFCEDM+DFCPDM
C **** calc TEAR ****
      XLEFF=R*XLR
      CEFF=XLEFF/(E*XI)
      TEARV=(DJDA-DJDM*DFCDA/(CEFF+DFCDM))*E/SIG0**2
      COLOAD=SIGFLO/SIG0
      FC=FC*180.0/PI
      CALL OUTPUT(TITLE,MLABEL,AOB,D,T,COLOAD,XM,XMM0,XLR,XJ,TEARV,FC)
      WRITE(*,*)
      WRITE(*,2100)
      READ(*,1040) NCH
      IF(NCH.EQ.0) STOP
      IF(NCH.EQ.1) THEN
        WRITE(*,2060)
        READ(*,1020) XLR
        GOTO 40
       ENDIF
      IF(NCH.EQ.2) THEN
        WRITE(*,2080)
        READ(*,1020) XM
        GOTO 40
       ENDIF
      IF(NCH.EQ.3) THEN
        WRITE(*,2040)
        READ(*,1020) AOB
        GOTO 40
       ENDIF
      GOTO 20
      STOP
 1000 FORMAT(A)
 1020 FORMAT(F12.4)
 1040 FORMAT(I2)
 2000 FORMAT(' TEAR- Program to Calculate Tearing Modulus')
 2020 FORMAT('  Enter Problem Title: ',\)
 2040 FORMAT('  Enter Crack Length (a/b): ',\)
 2060 FORMAT('  Enter System Compliance (L/R): ',\)
 2080 FORMAT('  Enter Applied Moment (in-lb): ',\)
 2100 FORMAT('  Enter:',/,
     1       '    0 to quit',/,
     2       '    1 to change L/R',/,
     3       '    2 to change M      ',/,
     4       '    3 to change a/b    ',\)
      END
      SUBROUTINE OUTPUT(TITLE,MLABEL,AOB,D,T,COLOAD,XM,XMM0,XLR,XJ,
     1 TEARV,FC)
C***********************************************************************
C
C***********************************************************************
      CHARACTER*50 TITLE
      CHARACTER*35 MLABEL
      DO 40 I=1,24
        WRITE(*,*)
   40  CONTINUE
```

```
      WRITE(*,1500)
      WRITE(*,2000) TITLE
      WRITE(*,*)
      WRITE(*,2020) MLABEL
      WRITE(*,2040) AOB
      WRITE(*,*)
      WRITE(*,2060) D
      WRITE(*,2080) T
      WRITE(*,*)
      WRITE(*,2110) XM
      WRITE(*,2120) XMM0
      WRITE(*,2100) COLOAD
      WRITE(*,2140) XLR
      WRITE(*,*)
      WRITE(*,2160) XJ
      WRITE(*,2180) TEARV
      WRITE(*,2200) FC
      WRITE(*,*)
      RETURN
 1500 FORMAT(' TEAR: Calculation of Tearing Modulus',/)
 2000 FORMAT(A50)
 2020 FORMAT(A35)
 2040 FORMAT(' Crack Length (a/b): ',F5.3)
 2060 FORMAT(' Pipe Diameter: ',F6.3,' inches')
 2080 FORMAT(' Pipe Wall Thickness: ',F6.3,' inches')
 2100 FORMAT(' Plastic Collapse/Yield Load: ',F4.2)
 2110 FORMAT(' Applied Moment: ',F12.1,' in-lb')
 2120 FORMAT(' Applied Load/Yield Load: ',F4.2)
 2140 FORMAT(' System Compliance (L/R): ',F10.0)
 2160 FORMAT(' J-integral: ',F10.1,' in-lb/in²')
 2180 FORMAT(' Tearing Modulus: ',F10.1)
 2200 FORMAT(' Hinge Angle: ',F6.1,' degrees')
      END
      SUBROUTINE GEOM(R,T)
C*********************************************************************
C
C*********************************************************************
      WRITE(*,*)
      WRITE(*,2000)
      READ(*,1000) D
      WRITE(*,2020)
      READ(*,1000) T
      R=D/2.0
      RETURN
 1000 FORMAT(F12.4)
 2000 FORMAT('  Enter Pipe Diameter: ',\)
 2020 FORMAT('  Enter Pipe Wall Thickness: ',\)
      END
      SUBROUTINE GETMAT(MLAB,E,SIG0,E0,SIGFLO,AL,XN)
C*********************************************************************
C
C*********************************************************************
      CHARACTER*35 MLABEL(3),MLAB
      DATA MLABEL/' A106 Gr B Carbon Steel Base Metal',
     1           ' 304 Stainless Steel Weld Metal   ',
     2           ' GE EPRI Report Pipe Properties   '/
      DATA NMAT/3/
      WRITE(*,2000)
      DO 40 I=1,NMAT
        WRITE(*,2020) I,MLABEL(I)
```

```
   40  CONTINUE
      WRITE(*,*)
      WRITE(*,2030)
      READ(*,1000) MAT
      WRITE(*,*)
      MLAB=MLABEL(MAT)
      CALL MATPROP(MAT,E,SIG0,E0,SIGFLO,AL,XN)
      RETURN
 1000 FORMAT(I1)
 2000 FORMAT('  Allowable Materials:')
 2020 FORMAT(I4,'. ',A35)
 2030 FORMAT('  Select Pipe Material... ',\)
      END
      SUBROUTINE MATPROP(MAT,E,SIG0,E0,SIGFLO,AL,XN)
C**************************************************************************
C
C**************************************************************************
      IF(MAT.EQ.1) THEN
        SIG0=27100.0
        SIGFLO=43600.0
        E=27.0E6
        AL=1.94
        XN=4.42
        GOTO 100
       ENDIF
      IF(MAT.EQ.2) THEN
        SIG0=23000.0
        SIGFLO=42000.0
        E=25.6E6
        AL=2.13
        XN=3.79
        GOTO 100
       ENDIF
      IF(MAT.EQ.3) THEN
        SIG0=30000.0
        SIGFLO=42000.0
        E=30.0E6
        AL=1.69
        XN=5.42
        GOTO 100
       ENDIF
  100 CONTINUE
      E0=SIG0/E
      RETURN
      END
      SUBROUTINE GEPROP(AOB,XN,ROT,H1,H4,F1,V3,H1P,F1P,V3P)
C**************************************************************************
C
C**************************************************************************
      H1=H1VAL(AOB,XN,ROT)
      H4=H4VAL(AOB,XN,ROT)
      F1=F1VAL(AOB,ROT)
      V3=V3VAL(AOB,ROT)
      H1P=DH1(AOB,XN,ROT)
      F1P=DF1(AOB,ROT)
      V3P=DV3(AOB,ROT)
      RETURN
      END
      FUNCTION DH1(AOB,XN,ROT)
C**************************************************************************
```

```
C
C***********************************************************************
      DATA DEL/0.05/
      IF(AOB.LT.0.125) THEN
        A1=0.0625
        A2=0.125
       ENDIF
      IF(AOB.GE.0.125.AND.AOB.LT.0.25) THEN
        A1=0.125
        A2=0.25
       ENDIF
      IF(AOB.GE.0.25) THEN
        A1=0.25
        A2=0.5
       ENDIF
      DH1=(H1VAL(A2,XN,ROT)-H1VAL(A1,XN,ROT))/(A2-A1)
      RETURN
      END
      FUNCTION DF1(AOB,ROT)
C***********************************************************************
C
C***********************************************************************
      DATA DEL/0.05/
      IF(AOB.LT.0.125) THEN
        A1=0.0625
        A2=0.125
       ENDIF
      IF(AOB.GE.0.125.AND.AOB.LT.0.25) THEN
        A1=0.125
        A2=0.25
       ENDIF
      IF(AOB.GE.0.25) THEN
        A1=0.25
        A2=0.5
       ENDIF
      DF1=(F1VAL(A2,ROT)-F1VAL(A1,ROT))/(A2-A1)
      RETURN
      END
      FUNCTION DV3(AOB,ROT)
C***********************************************************************
C
C***********************************************************************
      DATA DEL/0.05/
      IF(AOB.LT.0.125) THEN
        A1=0.0625
        A2=0.125
       ENDIF
      IF(AOB.GE.0.125.AND.AOB.LT.0.25) THEN
        A1=0.125
        A2=0.25
       ENDIF
      IF(AOB.GE.0.25) THEN
        A1=0.25
        A2=0.5
       ENDIF
      DV3=(V3VAL(A2,ROT)-V3VAL(A1,ROT))/(A2-A1)
      RETURN
      END
      FUNCTION H1VAL(AB,XN,ROT)
C***********************************************************************
```

```
C
C**********************************************************************
      DIMENSION H1(5,4),ABVAL(4),XNVAL(5),ROTVAL(3)
      DATA H1/4.987,6.018,6.743,7.620,7.969,
     1        5.361,5.987,6.281,6.311,5.996,
     2        5.620,5.312,4.886,3.969,3.240,
     3        3.646,2.682,2.105,1.424,1.035/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA XNVAL/1.0,2.0,3.0,5.0,7.0/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NXN,NROT/4,5,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      DO 40 I=2,NAB
        IF(AOB.LE.ABVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
         ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NXN
        IF(XN.LE.XNVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
         ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACA=(AOB-ABVAL(I1))/(ABVAL(I2)-ABVAL(I1))
      FRACN=(XN-XNVAL(J1))/(XNVAL(J2)-XNVAL(J1))
      VAL1=H1(J1,I1)+FRACN*(H1(J2,I1)-H1(J1,I1))
      VAL2=H1(J1,I2)+FRACN*(H1(J2,I2)-H1(J1,I2))
      H1VAL=VAL1+FRACA*(VAL2-VAL1)
      RETURN
      END
      FUNCTION H4VAL(AB,XN,ROT)
C**********************************************************************
C
C**********************************************************************
      DIMENSION H4(5,4),ABVAL(4),XNVAL(5),ROTVAL(3)
      DATA H4/-.194,0.078,0.144,0.288,0.429,
     1        0.136,0.565,0.783,1.119,1.317,
     2        1.459,2.098,2.334,2.308,2.049,
     3        5.384,4.283,3.232,2.049,1.400/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA XNVAL/1.0,2.0,3.0,5.0,7.0/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NXN,NROT/4,5,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      DO 40 I=2,NAB
        IF(AOB.LE.ABVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
         ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NXN
```

```
        IF(XN.LE.XNVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
         ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACA=(AOB-ABVAL(I1))/(ABVAL(I2)-ABVAL(I1))
      FRACN=(XN-XNVAL(J1))/(XNVAL(J2)-XNVAL(J1))
      VAL1=H4(J1,I1)+FRACN*(H4(J2,I1)-H4(J1,I1))
      VAL2=H4(J1,I2)+FRACN*(H4(J2,I2)-H4(J1,I2))
      H4VAL=VAL1+FRACA*(VAL2-VAL1)
      RETURN
      END
      FUNCTION F1VAL(AB,ROT)
C***********************************************************************
C
C***********************************************************************
      DIMENSION F1(4,3),ABVAL(4),ROTVAL(3)
      DATA F1/1.046,1.143,1.423,2.555,
     1        1.070,1.219,1.599,2.896,
     2        1.118,1.343,1.836,3.337/
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NROT/4,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      RT=ROT
      RT=10.0
      DO 40 I=2,NROT
        IF(RT.LE.ROTVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
         ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NAB
        IF(AOB.LE.ABVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
         ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACR=(RT-ROTVAL(I1))/(ROTVAL(I2)-ROTVAL(I1))
      FRACA=(AOB-ABVAL(J1))/(ABVAL(J2)-ABVAL(J1))
      VAL1=F1(J1,I1)+FRACA*(F1(J2,I1)-F1(J1,I1))
      VAL2=F1(J1,I2)+FRACA*(F1(J2,I2)-F1(J1,I2))
      F1VAL=VAL1+FRACR*(VAL2-VAL1)
      RETURN
      END
      FUNCTION V3VAL(AB,ROT)
C***********************************************************************
C
C***********************************************************************
      DIMENSION V3(4,3),ABVAL(4),ROTVAL(3)
      DATA V3/-.065,0.003,0.389,3.925,
     1        -.043,0.034,0.504,5.117,
     2        -.070,0.020,0.626,6.795/
```

```
      DATA ABVAL/0.0625,0.125,0.25,0.5/
      DATA ROTVAL/5.0,10.0,20.0/
      DATA NAB,NROT/4,3/
      AOB=AB
      IF(AOB.GT.ABVAL(NAB)) AOB=ABVAL(NAB)
      RT=ROT
      RT=10.0
      DO 40 I=2,NROT
        IF(RT.LE.ROTVAL(I)) THEN
          I1=I-1
          I2=I
          GOTO 60
         ENDIF
   40  CONTINUE
   60 CONTINUE
      DO 80 J=2,NAB
        IF(AOB.LE.ABVAL(J)) THEN
          J1=J-1
          J2=J
          GOTO 100
         ENDIF
   80  CONTINUE
  100 CONTINUE
      FRACR=(RT-ROTVAL(I1))/(ROTVAL(I2)-ROTVAL(I1))
      FRACA=(AOB-ABVAL(J1))/(ABVAL(J2)-ABVAL(J1))
      VAL1=V3(J1,I1)+FRACA*(V3(J2,I1)-V3(J1,I1))
      VAL2=V3(J1,I2)+FRACA*(V3(J2,I2)-V3(J1,I2))
      V3VAL=VAL1+FRACR*(VAL2-VAL1)
      RETURN
      END
```

Appendix D

DETERMINATION OF MATERIAL PROPERTIES

The Susquehanna Steam Electric Station (SSES) recirculation system piping and outlet nozzle safe ends are Type 304 stainless steel. The recirculation system reactor inlet nozzle safe ends are Type 316L stainless steel. This latter material is low carbon compared to the standard Type 304 stainless steel and has much greater resistance to intergranular stress corrosion cracking (IGSCC).

Fracture mechanics analyses were performed for the recirculation piping geometric cross section and nominal tensile properties for 304 stainless steel at 550^{o}F. Results of the analyses conservatively bound possible fracture mechanics analyses of the thicker safe end cross section since stresses are higher in the pipe side of the weld. Required material properties for the analyses can be broken into three groups, as follows:

Stress-Strain Coefficients

The tearing stability theory used in fracture mechanics analyses accounts for strain hardening effects. Large strain stress-strain data for Type 304 stainless steel was obtained from Reference 1. This data was used to fit the strain hardening coefficients α and n as $\alpha = 2.13$ and n = 3.79 at 550^{o}F.

Tensile Properties

Material properties which fall under the grouping of tensile properties include the material modulus of elasticity, the yield stress, and the flow stress. The modulus of elasticity was obtained as the ASME Boiler and Pressure Vessel Code specified minimum value, E=25600 ksi. The yield stress was chosen as the yield strength of the material used to describe the material stress-strain curve, 23.0 ksi. The flow stress is three times the material design stress intensity from the ASME Code as recommended in Reference 2, 50.7 ksi.

Fracture Properties

The fracture mechanics analysis methodology requires two material fracture properties, the material crack initiation potential, J_{IC}, and the material tearing modulus, T_{MAT}. Both J_{IC} and T_{MAT} can be obtained from J-resistance curves available in the literature. J_{IC} is the value of the crack driving potential (the J-integral) at which crack initiation is observed. The material tearing modulus is obtained from the slope of the J resistance curve as

$$T_{mat} = \frac{E}{\sigma_o^2} \frac{dJ}{da}$$

The data used to define J_{IC} and T_{MAT} was obtained from Reference 3 for cast stainless steel at 550°F. J_{IC} and T_{MAT} were determined for cast stainless steel since this represents lower bound material performance for these alloys and is representative of weld metal. J_{IC} was obtained from the lower bound J-R curves for cast stainless steel at 550°F. The lower bound values for J_{IC} was found to be 992 in-lb/m^2. Lower bound material tearing resistance was obtained by measuring the slope of the J-resistance curve at significant crack extensions (greater than 60 mils). The modulus of elasticity and yield stress listed above were used to translate the material tearing resistance, dJ/da, to the dimensionless form of T_{MAT}=182.

References

1. Aerospace Structural Metals Handbook, Volume 2, Code 1303, p. 13.
2. EPRI NP-2472-SY, Volume 1, "The Growth and Stability of Stress Corrosion Cracks in Large Diameter BWR Piping," July 1982.
3. J. P. Gudas and D. R. Anderson, "J-R Curve Characteristics of Piping Material and Welds," 9th Water Reactor Safety Research Information Meeting, October 29, 1981.

ATTACHMENT 1

8610210344

OCT 24 '84 C205532

CALCULATION SHEET

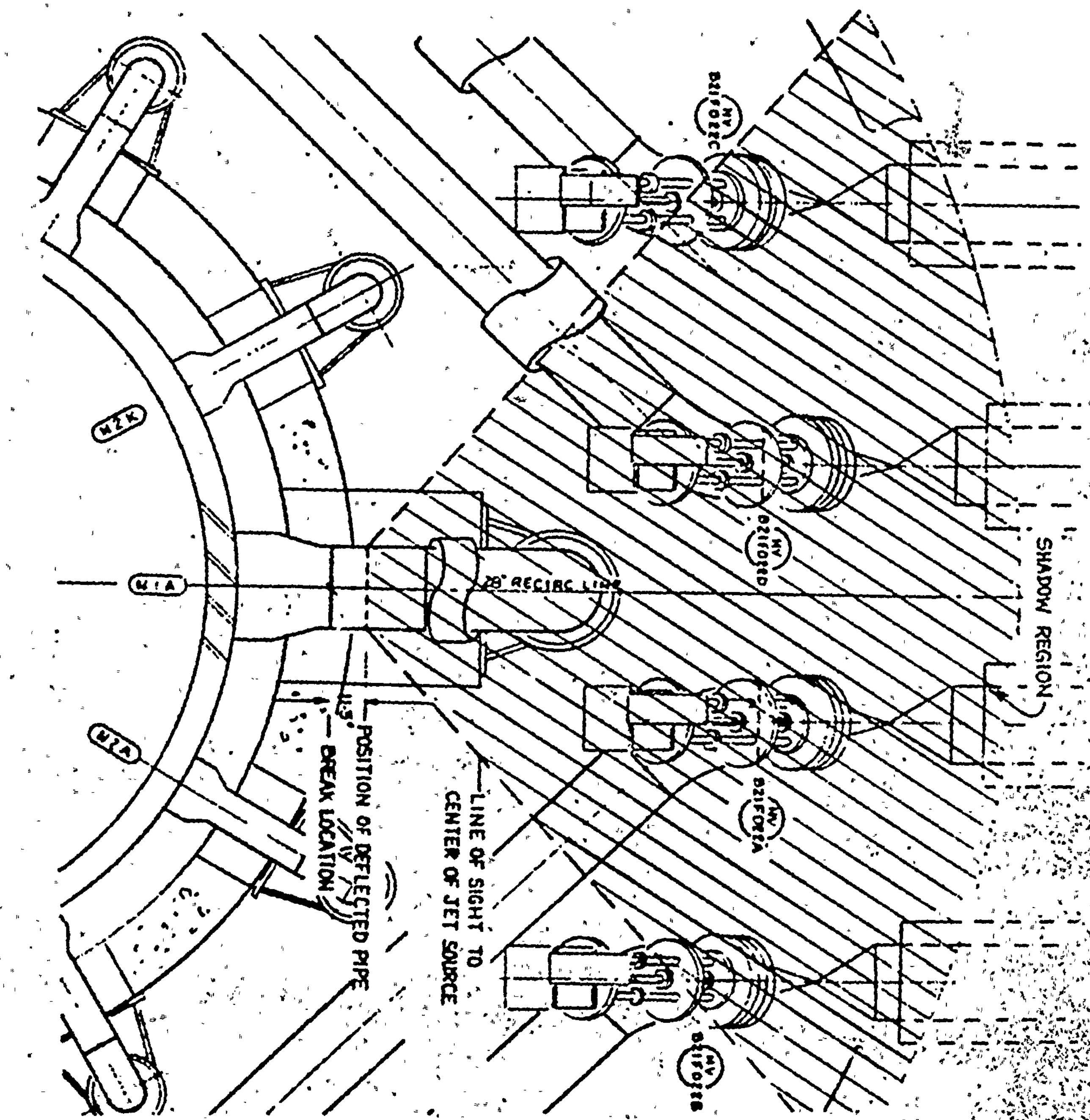
CALC. NO. MISC-047 REV. NO. 0

ORIGINATOR Timoth L. DATE 10-25-84 CHECKED RKH DATE 11/4/84

PROJECT SSES JOB NO. 8856

SUBJECT SEE COVER SHEET SHEET NO. 3

SKETCH SHOWING THE SHADOW REGION FOR 28" RECIRC. LINE BREAK.
REF. DWG M-26-4 REV. 26. NOTE THAT ONLY BREAK LOCATION AND MSIV ARE SHOWN, OTHER MATERIAL ON THE DWG IS REMOVED FOR CLARITY.



NOTE THAT MSIV C & B ARE NOT WITHIN THE JET ZONE OF INFLUENCE PER MECHANICAL CALC MISC-026 REV 3.

ATTACHMENT 2

OCT 24 '84 C205562

CALCULATION SHEET

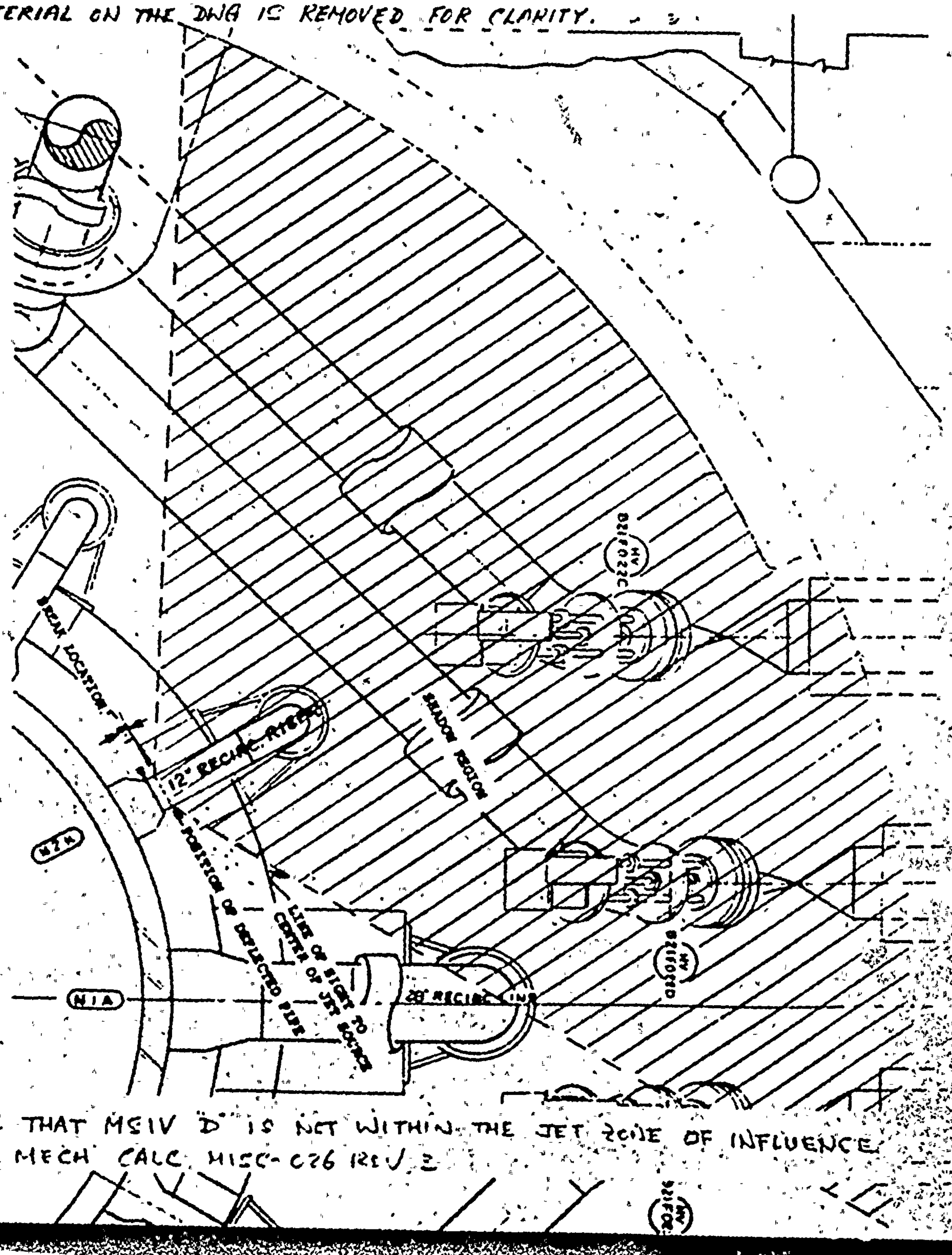
CALC. NO. MISC-027 REV. NO. 0

ORIGINATOR Simon L. DATE 10-5-84 CHECKED RKH DATE 10/4/84

PROJECT SSES JOB NO. [illegible]

SUBJECT JET COVER SHEET SHEET NO. 4

SKETCH SHOWING THE SHADOW REGION FOR 12" RECIRC. NOZZLE (N2K) BREAK. REF. DWG. M-26-4 REV 26. NOTE THAT ONLY BREAK LOCATION AND MSIV ARE SHOWN. OTHER MATERIAL ON THE DWG IS REMOVED FOR CLARITY.



NOTE THAT MSIV 'D' IS NOT WITHIN THE JET ZONE OF INFLUENCE PER MECH CALC MISC-026 REV 2

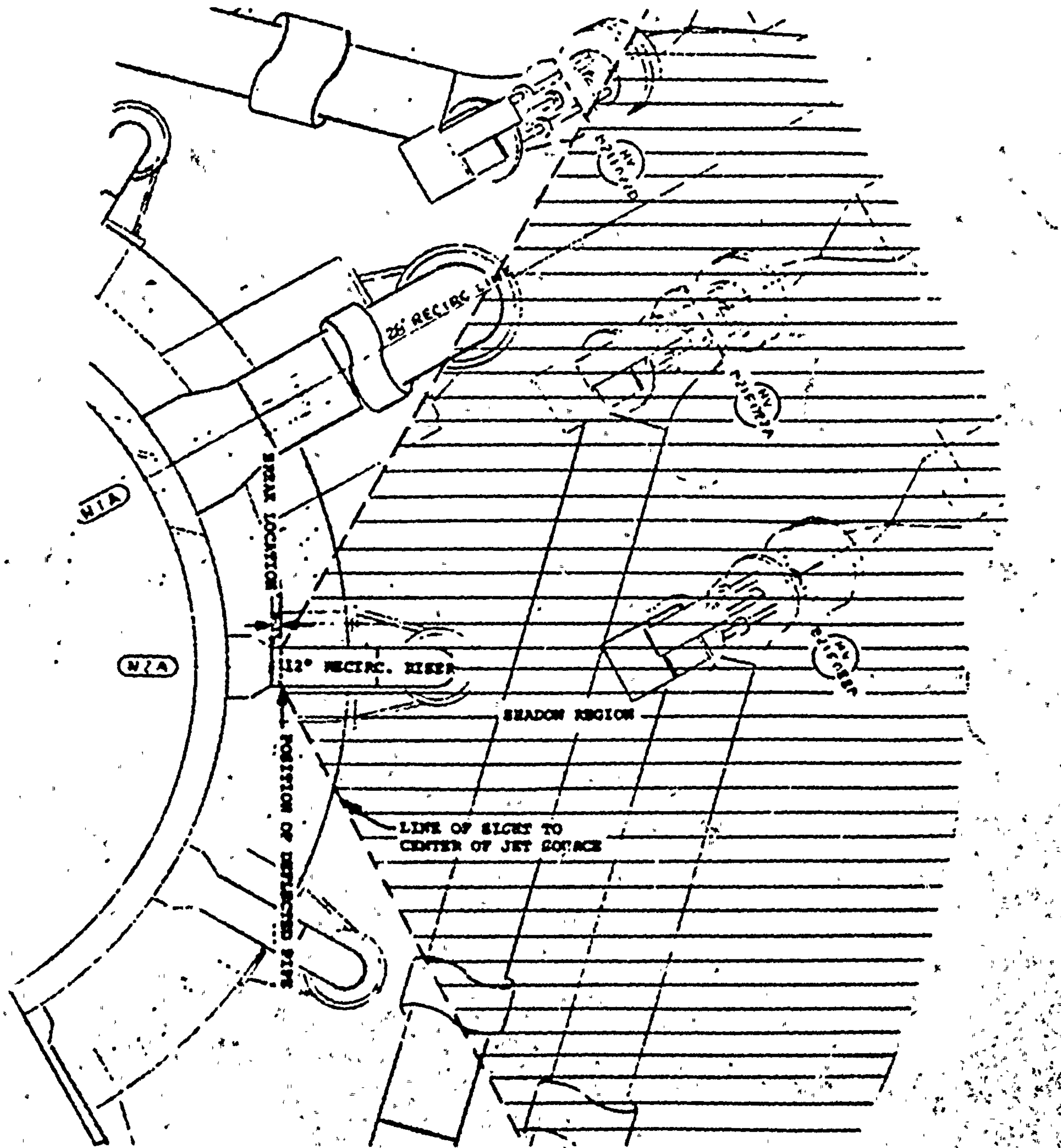
ATTACHMENT 3

CALCULATION SHEET

OCT 24 '84 0205532

CALC. NO.	MISC-047	REV. NO.	0
ORIGINATOR	Simon Li	DATE	10.5.84
CHECKED	RKH	DATE	10/4/84
PROJECT	SSES	JOB NO.	8856
SUBJECT	SEE COVER SHEET	SHEET NO.	5

SKETCH SHOWING THE SHADOW REGION FOR 12" RECIRC NOZZLE (N2A) BREAK. REF. DWG. M-26-4 REV. 26. NOTE THAT ONLY BREAK LOCATION AND MSIV ARE SHOWN. OTHER MATERIAL ON THE DWG IS REMOVED FOR CLARITY.



NOTE THAT MSIV "A & D" ARE NOT WITHIN THE JET ZONE OF INFLUENCE PER MECH. CALC MISC-026 REV 3.

ATTACHMENT 4

PP&L Form 2454 (10/83)
Cat. #973401

Dept. ______ PENNSYLVANIA POWER & LIGHT COMPANY CALCULATION SHEET ER No. ______

Date 8/28 19 85

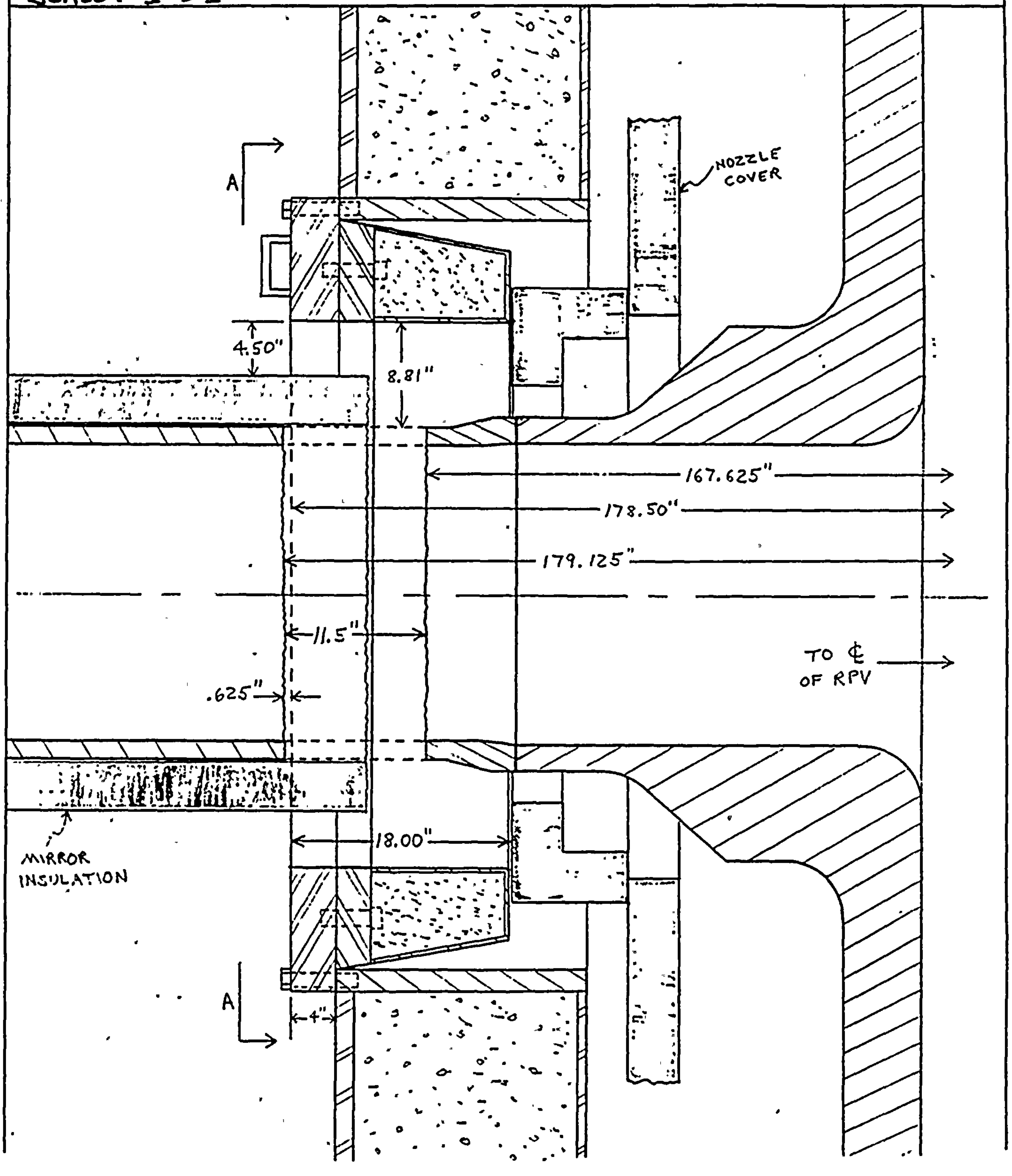
Designed by J. WEIK PROJECT ______ Sht. No. ____ of ____

Approved by ______

LOOP A RECIRC. OUTLET

0° AZIMUTH

SCALE: 1" = 1'



[illegible]

ATTACHMENT 5

PP&L Form 2454 (10/83)
Cat. #973401

Dept. ________
Date 9/3 19 85
Designed by J. WEIK
Approved by ________

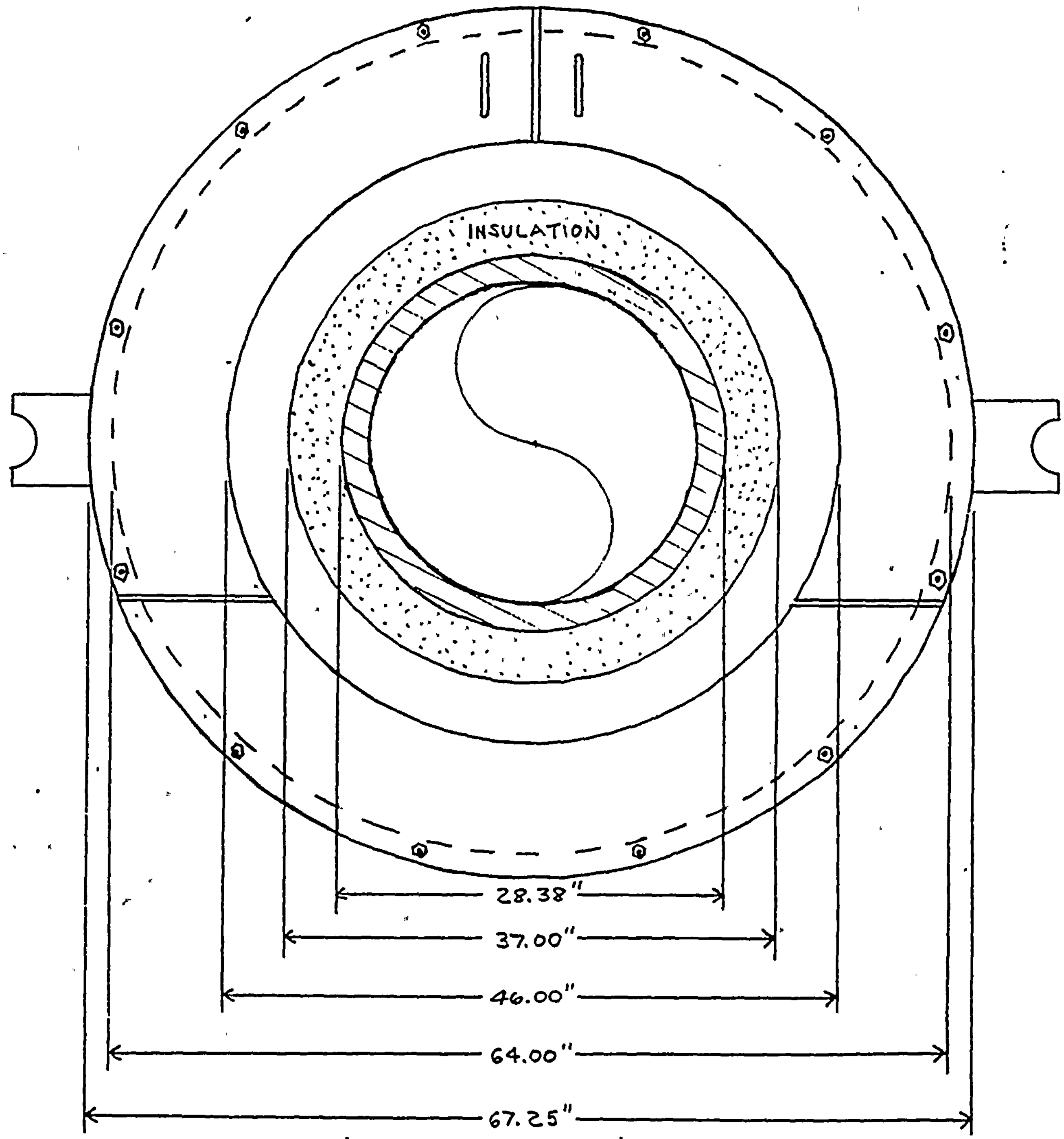
PENNSYLVANIA POWER & LIGHT COMPANY
CALCULATION SHEET

PROJECT ________
LOOP A RECIRC OUTLET
SECTION A-A

ER No. ________

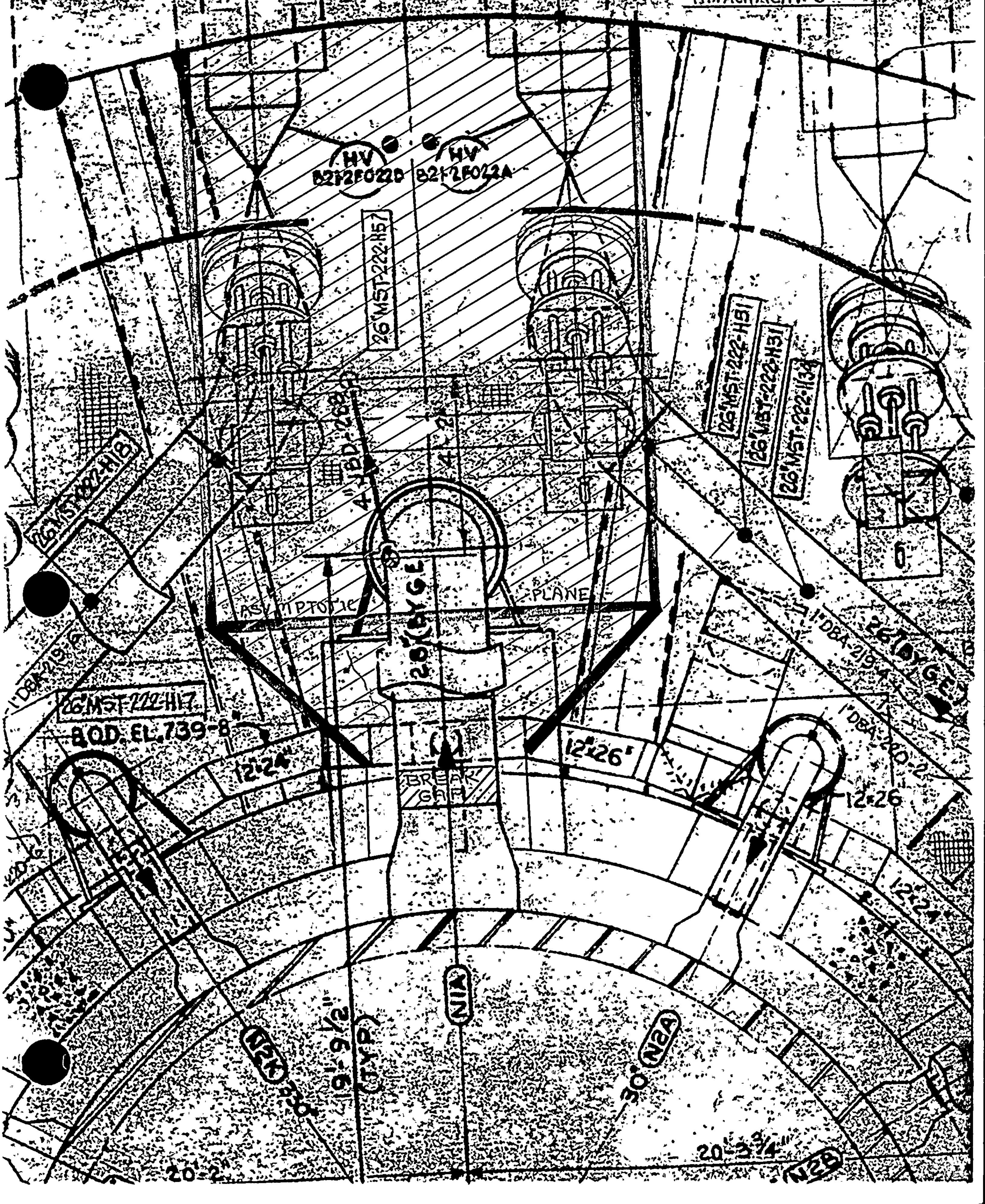
Sht. No. ____ of ____

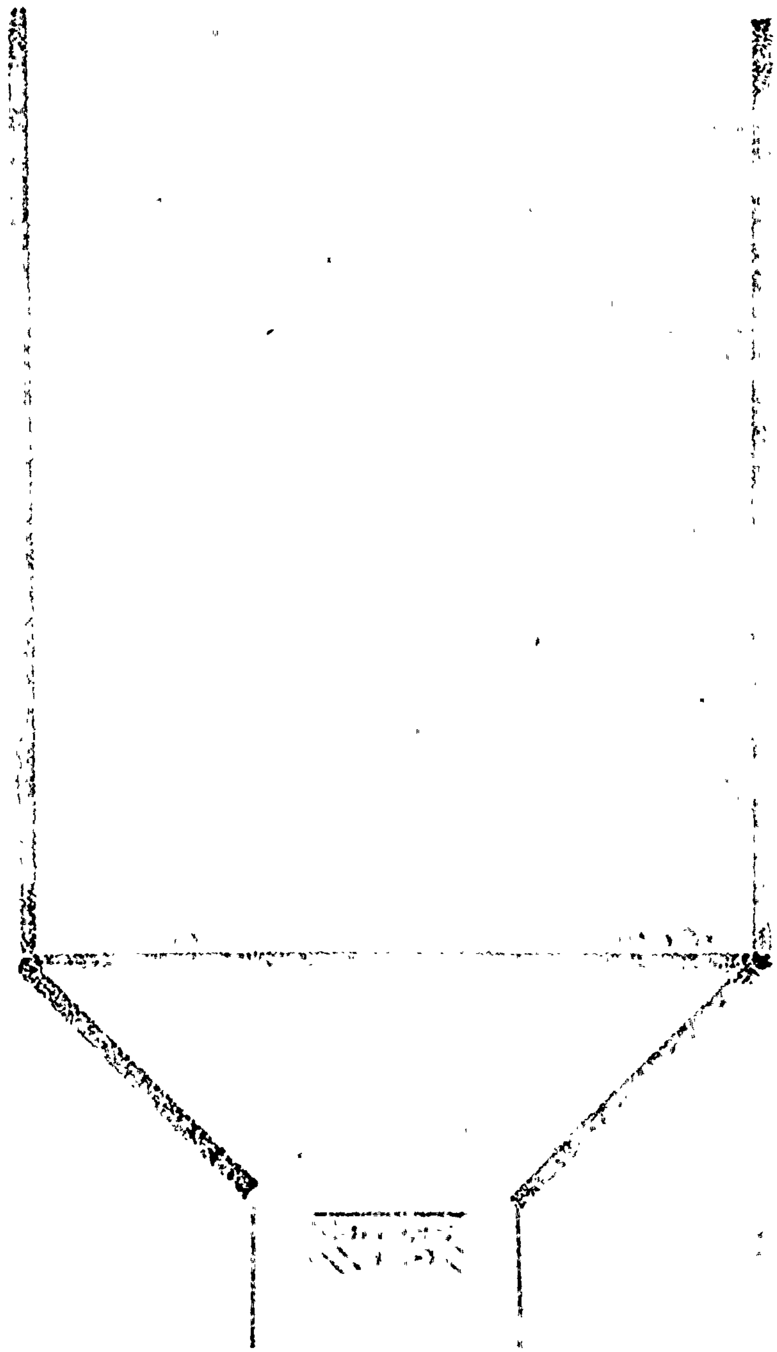
SCALE: 1" = 1'

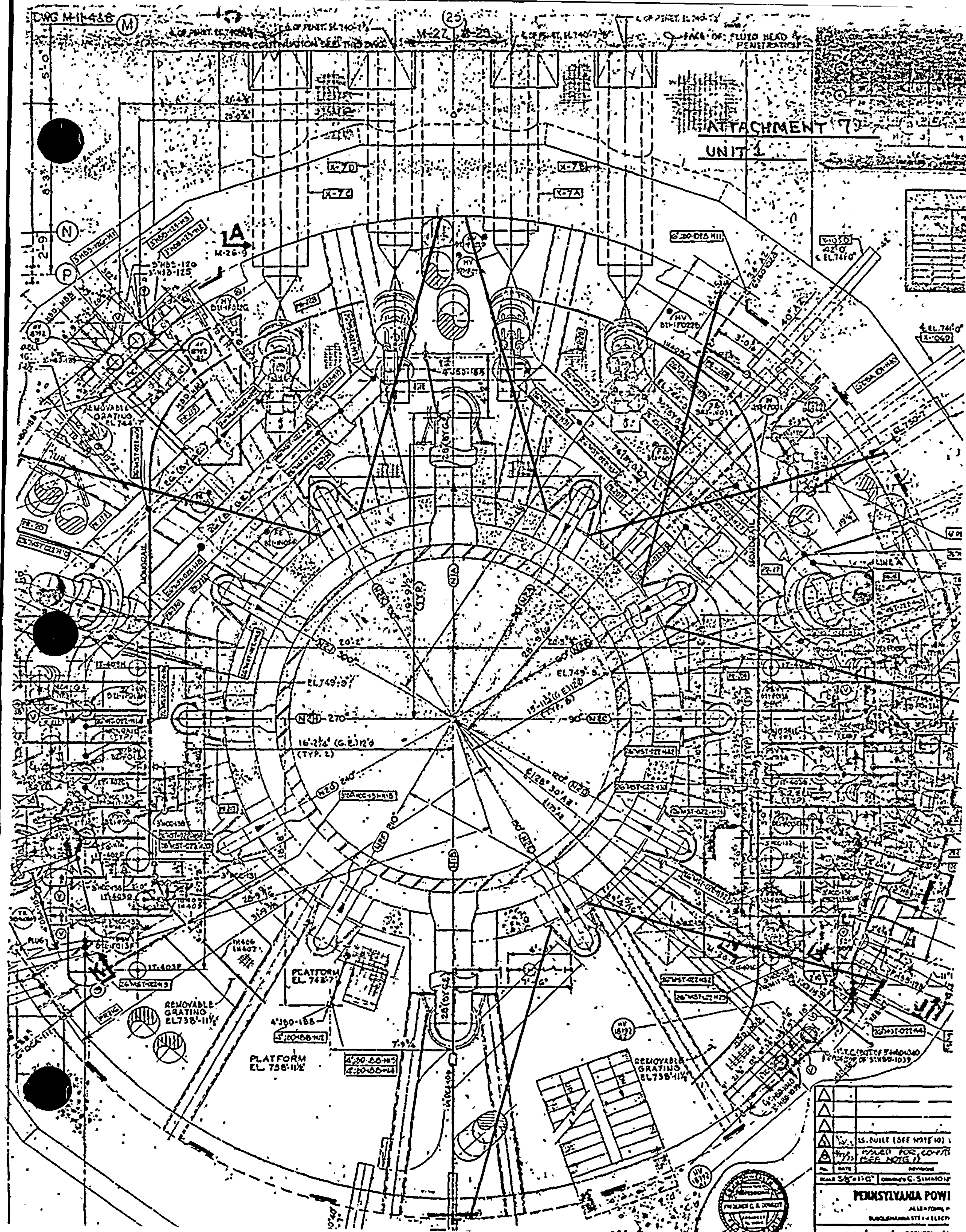


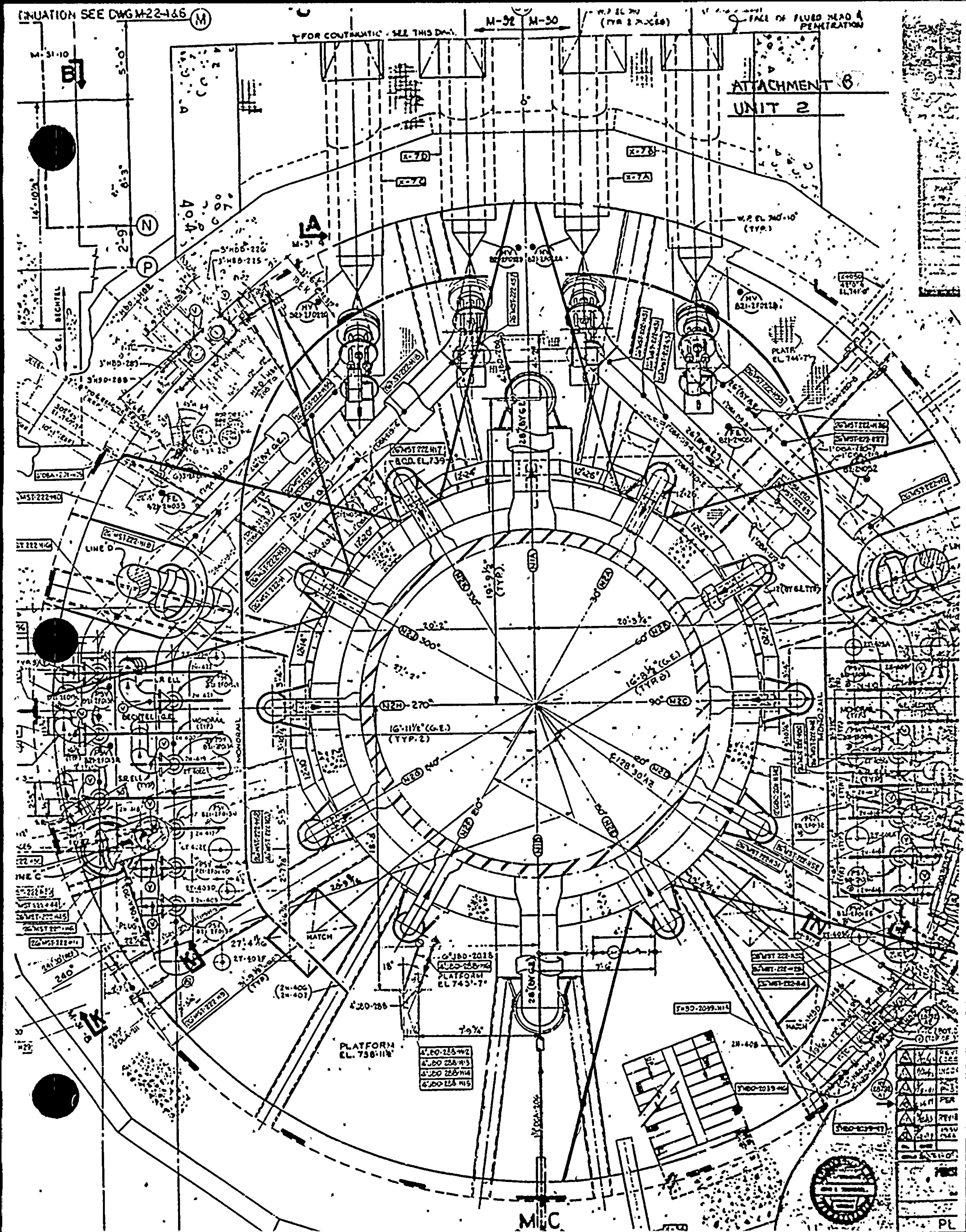
X-7

ATTACHMENT 6






DWG M-11-488
ATTACHMENT 7
UNIT 1
REMOVABLE GRATING EL 744'
EL 749'-9"
PLATFORM EL 743'-7"
REMOVABLE GRATING EL 738'-11½"
PLATFORM EL 738'-11½"
PENNSYLVANIA POWE



ATTACHMENT 6
UNIT 2
NUATION SEE DWG M-22-166
FOR CONTINUATION SEE THIS DWG.
M-32
M-30
FACE OF FLUED HEAD & PENETRATION
LINE "D"
LINE "C"
MONORAIL
BECHTEL
G.E.
HATCH
PLATFORM EL. 738'-11"
PLATFORM EL. 743'-7"
B.C.D. EL. 739'
N2A
N2B
N2C
N2D
N2E
N2F
N2G
N2H
N2J
N2K
270°
90°
300°
60°
30°
330°
240°
210°
150°
120°
16'-11 1/2" (G.E.) (TYP. 2)
16'-8 1/2" (G.E.) (TYP. 8)
28" (BY G.E.)
26" (BY G.E.)
4"-DD-228
M-C

PSI/ISI EXAMINATION HISTORY

WELD ID: VRRB311-FW-A1
DESCRIPTION: N1A SAFE-END TO PIPE (UNIT #1)
MATERIAL UPSTREAM: SA336 CL F8
MATERIAL DOWNSTREAM: SA 358 TP304 CL1
IGSCC COUNTERMEASURES: IHSI (FIRST REFUEL - SPRING 1985)

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB311-FW-A1	ASME XI 80W80	SUR	SWRI-NDT-200-1	04/85	
	ASME XI 80W80	VOL	SWRI-NDT-600-31	04/85	INSPECTION PERSONNEL QUALIFIED TO EPRI IGSCC QUALIFICATION PROGRAM
	NUREG 0313	VOL	SWRI-NDT-600-31	03/86	INSPECTION PERSONNEL QUALIFIED TO EPRI IGSCC REQUALIFICATION PROGRAM
	ASME XI 74S75	VOL	NES 80A2771	09/81	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

WELD ID: VRRB311-FW-A19M
DESCRIPTION: PIPE TO N2K SAFE-END (UNIT #1)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB311-FW-A19M	ASME XI 80W80	SUR			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 80W80	VOL			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 74S75	VOL	NES 80A2787	06/82	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

ATTACHMENT 10
SHEET 1 OF 5

PSI/ISI EXAMINATION HISTORY

WELD ID: VRRB312-FW-B15M
DESCRIPTION: PIPE TO N2A SAFE-END (UNIT #1)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB312-FW-B15M	ASME XI 80W80	SUR			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 80W80	VOL			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 74S75	VOL	NES 80A2787	06/82	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

WELD ID: VRRB312-FW-B16M
DESCRIPTION: PIPE TO N2B SAFE-END (UNIT #1)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB312-FW-B16M	ASME XI 80W80	SUR			NO EXAM SCHEDULED
	ASME XI 80W80	VOL			NO EXAM SCHEDULED
	ASME XI 74S75	VOL	80A2787	06/82	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

2. TO 5 [illegible]

PSI/ISI EXAMINATION HISTORY

WELD ID: VRRB312-FW-B19M
DESCRIPTION: PIPE TO N2E SAFE-END (UNIT #1)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB312-FW-B19M	ASME XI 80W80	SUR			NO EXAM SCHEDULED
	ASME XI 80W80	VOL			NO EXAM SCHEDULED
	ASME 74S75	VOL	NES 80A2787	06/82	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

WELD ID: VRRB313-FW-A-1
DESCRIPTION: N1A SAFE-END TO PIPE (UNIT #2)
MATERIAL UPSTREAM: SA336 CL F8
MATERIAL DOWNSTREAM: SA 358 TP304 CL1
IGSCC COUNTERMEASURES: IHSI (PRE-COMMERCIAL OPERATION)

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB313-FW-A-1	ASME XI 80W81	SUR			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 80W81	VOL			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	NUREG 0313	VOL		09/86	INSPECTION PERSONNEL QUALIFIED TO EPRI IGSCC REQUALIFICATION
	ASME XI 74S75	VOL	NES 80A2771	06/83	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

PSI/ISI EXAMINATION HISTORY

WELD ID: VRRB313-FW-A-18
DESCRIPTION: PIPE TO N2J SAFE-END (UNIT #2)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB313-FW-A-18	ASME XI 80W81	SUR			NO EXAM SCHEDULED
	ASME XI 80W81	VOL			NO EXAM SCHEDULED
	ASME XI 74S75	VOL	NES 80A2787	04/83	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

WELD ID: VRRB313-FW-A-19
DESCRIPTION: PIPE TO N2K SAFE-END (UNIT #2)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB313-FW-A-19	ASME XI 80W81	SUR			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 80W81	VOL			TO BE EXAMINED FOR SECTION XI CREDIT DURING THE FIRST INTERVAL
	ASME XI 74S75	VOL	NES 80A2787	04/83	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

WELD ID: VRRB314-FW-B-15
DESCRIPTION: PIPE TO N2A SAFE-END (UNIT #2)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB314-FW-B-15	ASME XI 80W81	SUR			NO EXAM SCHEDULED
	ASME XI 80W81	VOL			NO EXAM SCHEDULED
	ASME XI 74S75	VOL	NES 80A2787	04/83	INSPECTION PERSONNEL QUALI FIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE

WELD ID: VRRB314-FW-B-19
DESCRIPTION: PIPE TO N2E SAFE-END (UNIT #2)
MATERIAL UPSTREAM: SA376 TP304 SMLS
MATERIAL DOWNSTREAM: SA-182 GR F316L FORGED
IGSCC COUNTERMEASURES: CORROSION RESISTANT CLADDING

	EXAMINATION REQUIREMENT	TYPE OF EXAMINATION	NDE PROCEDURE	EXAM DATE	REMARKS
VRRB314-FW-B-19	ASME XI 80W81	SUR			NO EXAM SCHEDULED
	ASME XI 80W81	VOL			NO EXAM SCHEDULED
	ASME XI 74S75	VOL	NES 80A2787	04/83	INSPECTION PERSONNEL QUALIFIED TO ASNT-TC-1A
	ASME III	RT/PT			CONSTRUCTION CODE NDE