MPR ASSOCIATES, INC.

OYSTER CREEK NUCLEAR GENERATING STATION

LEAK BEFORE BREAK EVALUATION OF ISOLATION CONDENSER SYSTEM PIPING OUTSIDE CONTAINMENT

MPR - 1226

Volume 1

Prepared for:

General Public Utilities Nuclear
Parsippany, NJ

April, 1991

TABLE OF CONTENTS

Volume I

Volume II

Section 1

INTRODUCTION

This report summarizes the results of a leak-before-break evaluation of the isolation condenser system (ICS) steam supply and condensate return piping outside of the drywell at Oyster Creek Nuclear Generating Station. The purpose of the evaluation is to show that the likelihood of a double-ended guillotine type pipe break in this system is very small. Consequently, the dynamic effects of such a break need not be considered in the licensing basis for this system. Consideration of such effects would otherwise be required by General Design Criterion 4 of Title 10, Code of Federal Regulations, Part 50.

The methodology used to evaluate the potential of the ICS piping to fail unstably in the presence of large through-wall flaws is outlined in the draft version of Standard Review Plan (SRP) Section 3.6.3 (Reference 1). The approach consists of determining postulated through-wall flaw sizes which result in leak rates substantially greater than the existing leak detection capability and evaluating the capability of the piping to accommodate these flaws without catastrophic rupture under severe loads (pressure, deadweight, and operating 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 SRP 3.6.3 (Draft) are as follows:

- Demonstrate that the piping system is not susceptible to failure mechanisms such as waterhammer, fatigue, intergranular stress corrosion cracking (IGSCC), wall thinning, or creep.

- Evaluate the plant leak detection capabilities to determine the detectable leak rate.

- Calculate the expected leakage from through-wall flaws under normal operating pressure and determine the crack size which is predicted to leak at a rate ten times the detectable rate. This is the postulated flaw for fracture mechanics analyses.

- Calculate the applied loads and resulting stresses in the piping system for normal operating conditions plus safe shutdown earthquake (SSE).

- For the loading condition noted above, determine the highest stress locations in the piping. These are the locations for postulated through-wall flaws.

- For the calculated loading, show that the postulated flaws are stable.

- Demonstrate a factor of safety of at least 2 times the postulated crack length. 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 a factor of safety which is at least 1.41 times the applied load. 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.

The analyses described in this report are based upon the methods described above for demonstrating margin against unstable pipe rupture. 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 at Oyster Creek.

- 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 limitations imposed on the applicability of LBB analyses by SRP 3.6.3 (Draft).

- 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.

Section 2

SUMMARY AND 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 accommodated in the Oyster Creek ICS piping without unstable tearing or plastic section collapse. Specifically, evaluations have been performed to determine the leak detection capability for this piping at Oyster Creek, 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. The analyses were performed for postulated cracks in each of the four piping systems which make up the ICS piping: steam supply to condenser A, steam supply to condenser B, condensate return from condenser A and condensate return from condenser B.

The analyses of the ICS piping meet all of the SRP 3.6.3 (Draft) analysis criteria with one exception. SRP 3.6.3 (Draft) recommends a safety margin of two in terms of critical crack size. This margin is intended to account for uncertainties in the fracture mechanics analysis methodology and leak detection capability (Reference 21). Although the margins on crack size for the ICS piping are greater than two in most locations, in a few cases the margin is as low as 1.75. As described in this report, a factor of 10 has already been applied on the calculated leak rate over the leak detection capability to account for the leak detection and leak calculation uncertainty. Further, in all cases examined, the critical crack size is limited by plastic collapse rather than unstable tearing. Plastic collapse can be predicted relatively precisely compared to unstable tearing failure. Thus, the recommended margin of two is very conservative for the ICS piping. Considering the basis for the recommended margin of two, the calculated margins are considered to provide adequate safety margin against failure. More detailed summaries of the evaluations performed for the ICS piping are provided below.

2.1 Applicability of Analysis Method

The SRP 3.6.3 guidelines do not provide for a leak-before-break evaluation on a system where piping is subject to significant environmental degradation mechanisms such as intergranular stress corrosion cracking (IGSCC), creep or erosion/corrosion wall thinning. The methodology is also considered to be inappropriate for piping subject to high fatigue usage or waterhammer type loads. Each of these concerns was addressed in this evaluation.

IGSCC - The ICS piping outside the drywell has been recently replaced with Type 316NG material which is more resistant to IGSCC in BWR reactor coolant environments than traditional stainless steels. Further, the isolation valves (which lie outside the drywell) have also been replaced with valves with bodies fabricated from low carbon cast stainless steel with controlled ferrite content. By the criteria of NUREG 0313, Rev 2 (Reference 2), the ICS piping and valves are made from IGSCC "resistant" materials.

Pipe-to-pipe welds have been made with controlled weld metal chemistry and ferrite content, as well as controlled joint geometry and heat input to reduce residual stress and heat affected zone sensitization to IGSCC. Welds between the new pipe and the existing isolation condenser nozzles (which are non-resistant, high carbon stainless steel) have been made with the nozzle side protected by specially applied corrosion resistant cladding.

It is planned to apply a stress improvement treatment (induction heating or mechanical stress improvement) to all appropriate ICS weld joints outside the drywell during the next refueling outage in order to add a second IGSCC mitigator to those weld joints. All pipe-to-pipe welds will have at least two corrosion mitigators: low carbon material or corrosion resistant clad plus a stress improvement treatment within 24 months of operation of the new piping. Thus, these joints can be considered "Category A" resistant welds as defined in NUREG 0313, Rev 2. Possible exceptions are the welds between pipe and valves and the welds at the isolation condenser nozzles where a stress improvement treatment may be impossible to apply effectively.

Because of the special care taken to fabricate and install the replacement ICS pipe and fittings, it is considered that the ICS piping outside the drywell is highly resistant to IGSCC.

Fatigue - As part of this fracture mechanics based leak-before-break evaluation, a full ASME Code Section III, Class 1 fatigue evaluation was performed on the ICS system outside the drywell. A conservative number of system actuations was assumed (10 per year) during which the condensate return piping was conservatively assumed to undergo a step change in temperature from 70°F to 575°F (the system design temperature). In addition, conservative stress intensity factors were assumed for weld joints and discontinuities between pipe and fittings and within fittings. The calculated usage factors for 40 years of operation were all found to fall below 0.2, with a Code allowable of 1.0. Therefore, fatigue failure of the piping is not considered to be a concern.

Waterhammer - A review of waterhammer events in isolation condenser systems nationwide shows that waterhammer has only been a serious concern at one BWR, Millstone 1. Based on the information provided in References 3 to 5, it appears that the frequent waterhammer events reported early on at Millstone 1 were due to faulty feedwater regulator valve control after SCRAM combined with poor ICS steam supply line routing. Modification of the valve control logic eliminated the waterhammer events. A single waterhammer event was reported at Nine Mile Point Unit 1 during plant startup testing. This was due to poor steam supply line routing. After the addition of drains, ICS waterhammer has not been observed at Nine Mile Point Unit 1.

Oyster Creek has never reported an ICS waterhammer event. Post SCRAM water level control in the vessel has been adequate and the steam supply lines are well drained. The newly installed pipe maintains the good steam supply drain features of the original piping. GPUN has also implemented operating procedures which preclude operating the isolation condenser system when the reactor vessel level is in a range which could lead to a waterhammer event. Based on the good history at Oyster Creek, ICS waterhammer is not expected to be of concern.

Creep and Wall Thinning - Neither of these degradation mechanisms are considered to be possible in a relatively low temperature (550°F), low flow velocity system fabricated from stainless steel.

Based on the above considerations, it is concluded that the leak-before-break analysis methodology is applicable to the Oyster Creek ICS in accordance with the guidelines of SRP 3.6.3 (Draft).

2.2 Leak Detection Capability

The primary methods for detecting leakage from the ICS piping outside the drywell are visual inspections of the piping conducted at least daily and daily reactor building sump inleakage reports which, by administrative limits, require investigation of inleakage to the sump exceeding 260 gallons per day. Secondary methods for detecting leaks include area temperature alarms in the vicinity of the steam supply and condensate return isolation valves, and reactor building air particulate radiation monitors.

Based on an evaluation of these leak detection methods, it is concluded that daily inspections of the system, all of which is accessible, combined with daily sump inleakage reports, support a leak detection sensitivity for the isolation condenser piping of 0.2 gallons per minute (gpm).

2.3 Determination of Detectable Flaw Sizes

The leak rate of reactor coolant from postulated through-wall cracks in the ICS piping was predicted using a specialized computer program developed 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 is used to evaluate critical flow. Estimates of flow from the cracks were obtained from the model and were confirmed to be conservative based on comparisons of model predictions to reported measurements of leakage from through-wall cracks in test specimens.

The steam supply piping contains six sizes of pipe: 10" diameter schedules 80 and 100, 12" diameter schedules 80 and 100 and 16" diameter schedules 80 and 100. The condensate return piping contains four sizes of piping: 8" diameter schedules 80 and 100 and 10" diameter schedules 80 and 100. Thus, there are a total of ten combinations of pipe size and fluid (steam in the steam supply lines and subcooled liquid in the condensate return lines). Calculated leakage rate as a function of through-wall crack size is shown in Figures 2.1 and 2.2 for each pipe size/fluid combination.

SRP 3.6.3 (Draft) recommends that the leak rate for the postulated flaws used in fracture mechanics analyses be ten times the detectable rate. For the Oyster Creek ICS piping, this corresponds to a two gpm leak rate. Based on the results of the crack size leakage analyses, the postulated circumferential, through-wall flaw sizes chosen for fracture mechanics analyses are shown in Table 2.1. These crack lengths range from about 64° to 106° of pipe circumference.

2.4 Fracture Mechanics Analyses

The portion of the isolation condenser piping considered for leak before break analysis was that piping which lies outside containment between the containment penetrations and the isolation condenser nozzles. Piping inside the containment, while included in the stress analysis model, was not considered in the leak before break analysis. This is acceptable and in accordance with the intent of SRP 3.6.3 (Draft), since: (1) the components which are critical to this evaluation are the steam line isolation valves, all of which lie outside the drywell and would not be subject to jet loads resulting from breaks inside the drywell; and (2) the portion of piping outside the drywell is mechanically isolated from pipe reaction loads resulting from a postulated break inside the drywell. The isolation is due to the high stiffness of the drywell penetration which acts like an anchor point.

The applied loads on the ICS piping due to deadweight, thermal expansion and SSE were obtained from the ANSI/ASME B31.1 design stress analyses for the ICS piping (References 6 to 9). The locations selected for fracture mechanics analyses are the highest loaded points in each system for each pipe size, or a total of 20 locations. In general, these locations correspond to terminal ends of the piping, such as a condenser nozzle or drywell penetration, or change in pipe cross section, such as from schedule 100 to 80. These locations are identified in Figures 6.1 to 6.4.

The replacement ICS piping is Type 316NG stainless steel. The pertinent tearing modulus selected for fracture mechanics analyses is based on conservative data obtained for stainless steel casting material at operating temperature (550°). This value is 181.

The results of tearing stability analyses are shown in Table 2.2. This table lists the calculated applied tearing modulus, T, for each fracture mechanics analysis location. Unstable crack growth (tearing) is predicted if the calculated value of the applied tearing modulus is greater than the material tearing modulus, T_{MAT}. As can be seen, the calculated applied tearing modulus for each location is less than T_{MAT}. No unstable tearing is predicted for the assumed through wall flaws under normal operating plus earthquake loads.

The calculated safety factors on applied load are shown in Table 2 3. The safety factors are all greater than 1.41 and therefore satisfy the criteria recommended in SRP 3.6.3 (Draft).

Table 2.3 also shows the safety factors in terms of crack size. In each case the limiting failure mode is plastic collapse rather than tearing instability, since tearing instability becomes unlikely for the very large crack sizes evaluated here. As shown in Table 2.3, some of the analysis locations do not quite meet the SRP 3.6.3 recommended criteria of a margin of two on crack size (the worst case is 1.75). However, as described above, considering the basis for the recommended margin of two, the calculated margins (minimum of 1.75) are considered to provide adequate safety margin against failure.

Conclusion

It is concluded that sufficient mitigating actions have been taken at Oyster Creek to eliminate concerns with IGSCC in the ICS piping. Further, since no waterhammer or fatigue concerns exist for this system, use of SRP 3.6.3 (Draft) 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 tearing modulus (2) use of lower bound leak rates, (3) use of pipe minimum wall geometry for fracture mechanics analyses, and (4) use of conservative GE/EPRI estimates of J-integral values. Results of the analyses show that, even with these conservatisms, there is considerable margin against double-ended ruptures of the ICS piping.

Table 2.1

2 GPM LEAKAGE CIRCUMFERENTIAL CRACK SIZES

Piping	Fluid	Pipe Size	θ_{2GPM}	a_{2GPM}
Condensate Return	1035 psia, 549°F Saturated Liquid	8" Schedule 80	76°	5.72"
		8" Schedule 100	86°	6.47"
		10" Schedule 80	64°	6.00"
		10" Schedule 100	73°	6.85"
Steam Supply	1035 psia, 549°F Saturated Steam	10" Schedule 80	93°	8.72"
		10" Schedule 100	106°	9.94"
		12" Schedule 80	82°	9.12"
		12" Schedule 100	94°	10.46"
		16" Schedule 80	70°	9.77"
		16" Schedule 100	80°	11.17"

Table 2.2

CALCULATED APPLIED TEARING MODULUS RESULTS

System	Location (Node)	Pipe Size	Applied Tearing Modulus*
A - Condensate	D04N	8" Schedule 80	1.8
	D03A	8" Schedule 100	2.3
	B08	10" Schedule 80	0.7
	B01	10" Schedule 100	0.7
A - Steam	B09	10" Schedule 80	2.8
	B01	10" Schedule 100	3.5
	D12	12" Schedule 80	3.6
	D10A	12" Schedule 100	4.4
	B19	16" Schedule 80	0.4
	B11	16" Schedule 100	0.5
B - Condensate	C28	8" Schedule 80	8.9
	C26A	8" Schedule 100	11.9
	C05	10" Schedule 80	0.8
	B20	10" Schedule 100	1.4
B - Steam	B09	10" Schedule 80	5.9
	B01	10" Schedule 100	4.6
	D17	12" Schedule 80	4.7
	D04	12" Schedule 100	5.1
	B15N	16" Schedule 80	0.9
	B13	16" Schedule 100	1.2

* To be compared with T_{MAT} = 181.

Table 2.3

SAFETY FACTORS

System	Location (Node)	Pipe Size	Safety Factor on Applied Load	Safety Factor on Crack Length
A - Condensate	D04N	8" Schedule 80	3.83	2.56
	D03A	8" Schedule 100	3.54	2.26
	B08	10" Schedule 80	5.05	3.20
	B01	10" Schedule 100	5.12	2.86
A - Steam	B09	10" Schedule 80	3.23	2.07
	B01	10" Schedule 100	2.90	1.82
	D12	12" Schedule 80	3.10	2.24
	D10A	12" Schedule 100	3.11	2.02
	B19	16" Schedule 80	6.53	3.16
	B11	16" Schedule 100	5.95	2.75
B - Condensate	C28	8" Schedule 80	2.32	2.10
	C26A	8" Schedule 100	2.28	1.91
	C05	10" Schedule 80	4.91	3.17
	B20	10" Schedule 100	4.03	2.68
B - Steam	B09	10" Schedule 80	2.47	1.87
	B01	[illegible] Schedule 100	2.57	1.75
	D17	12" Schedule 80	2.92	2.19
	D04	12" Schedule 100	2.93	1.98
	B15N	16" Schedule 80	4.69	2.91
	B13	16" Schedule 100	4.30	2.54

Calculated Leakage Rates - 8" Piping

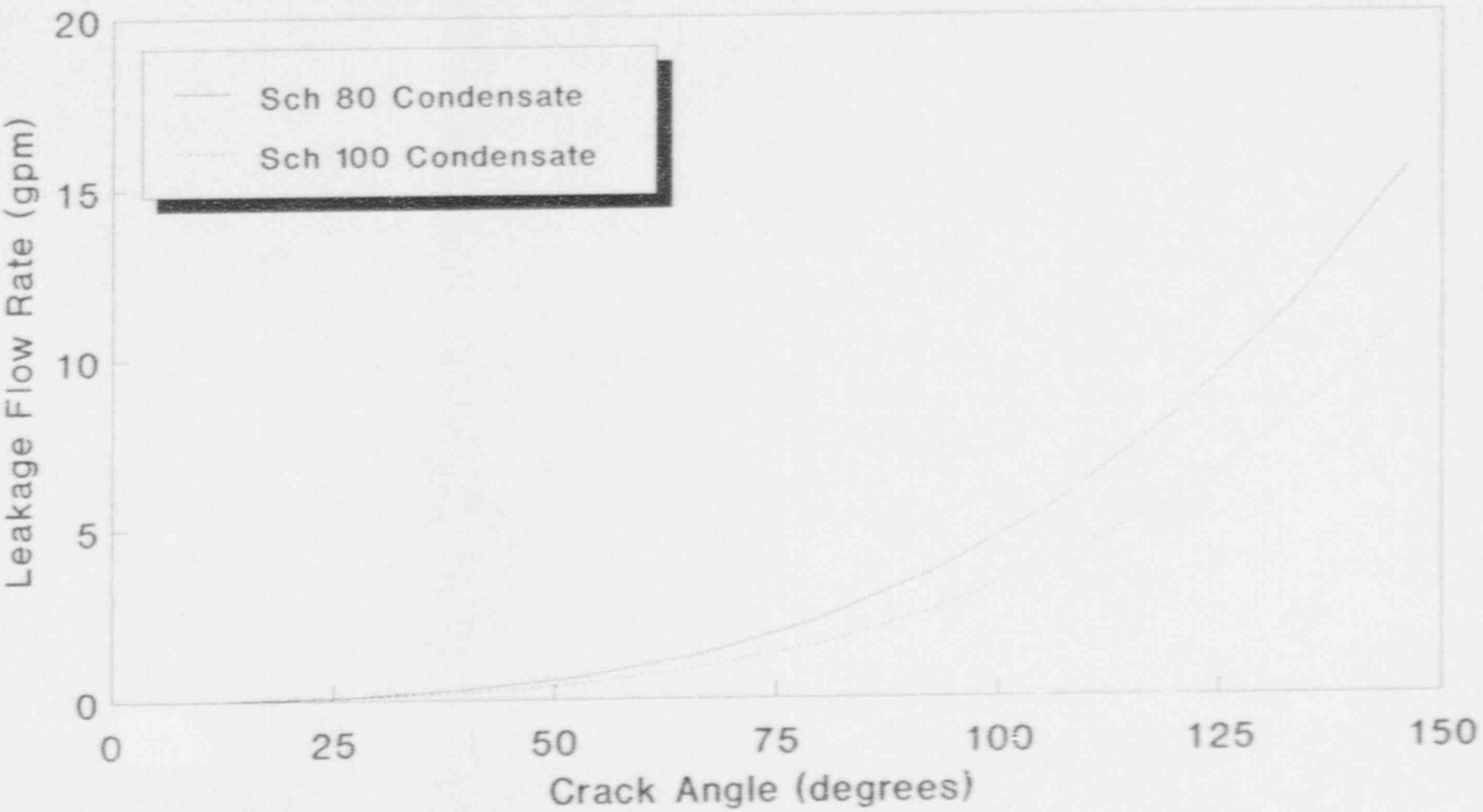


Figure 2-1

Calculated Leakage Rates - 10" Piping

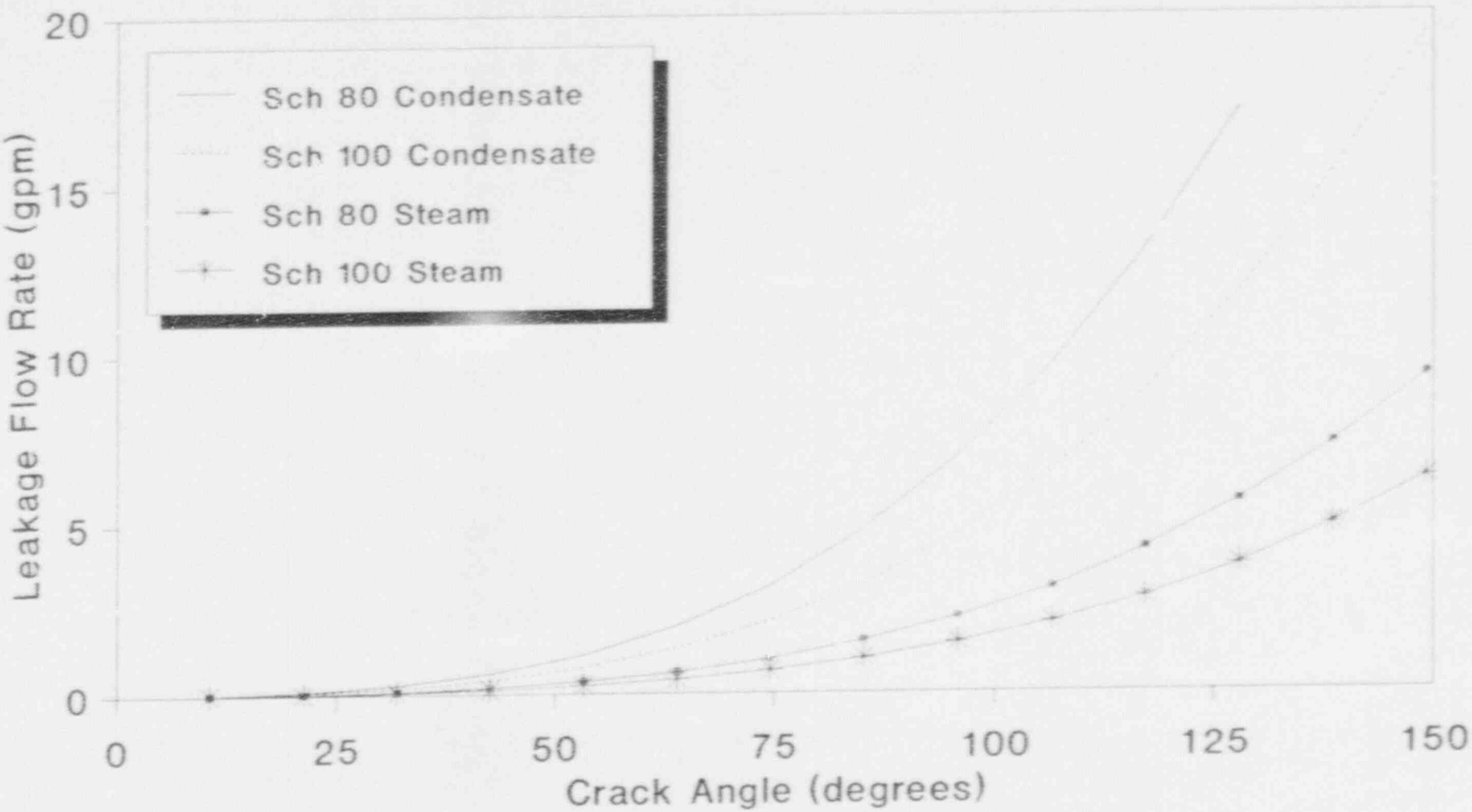


Figure 2-2

Calculated Leakage Rates - 12" Piping

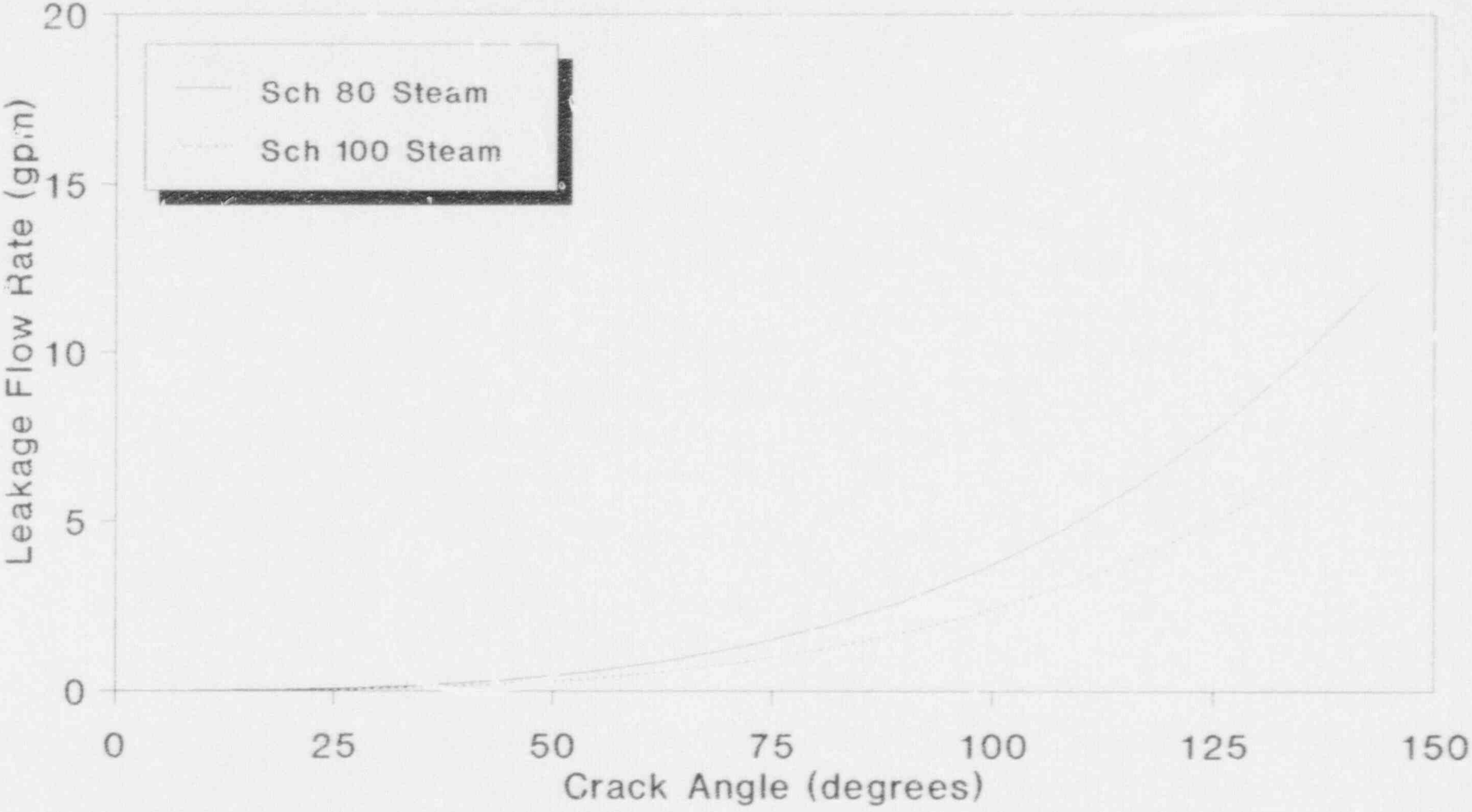


Figure 2-3

Calculated Leakage Rates - 16" Piping

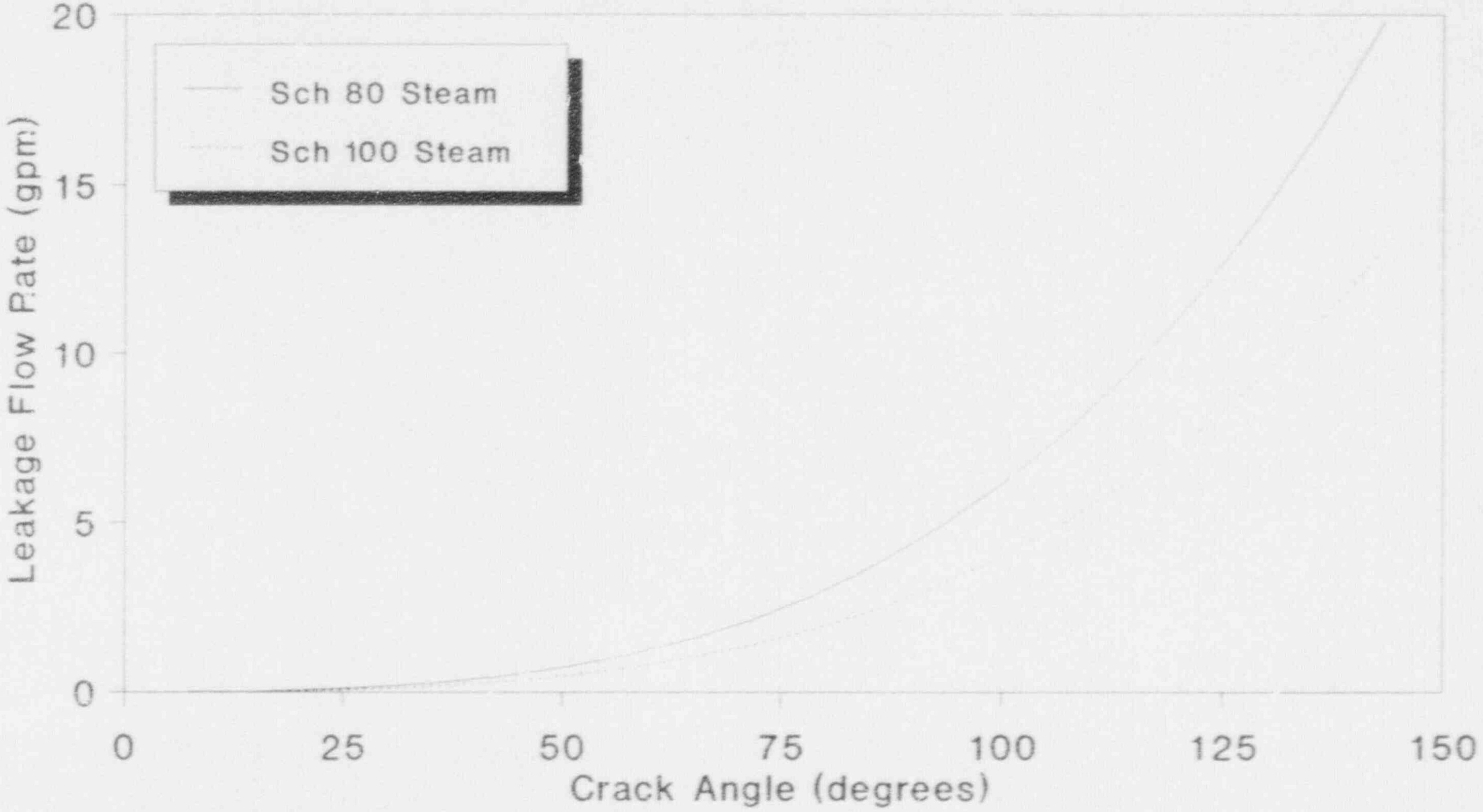


Figure 2-4

Section 3

APPLICABILITY OF LEAK-BEFORE-BREAK METHODOLOGY

SRP 3.6.3 (Draft) recommends that the application of 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. It must also be shown that wall thinning and creep are not concerns. The susceptibility of the Oyster Creek ICS piping outside containment to each of these pipe degradation mechanisms is discussed below.

3.1 Intergranular Stress Corrosion Cracking

The Oyster Creek ICS piping is Type 316NG stainless steel. This type of stainless steel in the as-welded condition in a typical BWR environment has shown superior resistance to IGSCC in comparison to other austenitic stainless steels such as 304 or 316. Further, the isolation valves have also been replaced with valves made from low carbon cast stainless steel with controlled ferrite content. Both the piping and the valves are made from IGSCC resistant materials as described by NUREG-0313, Rev.2. In addition, other steps have been taken or are planned by GPUN to further reduce the possibility of IGSCC occurring in the ICS piping. These steps, which include tight control of the welding process, stress improvement and application of corrosion resistant cladding, are described below.

The pipe to pipe welds have been made with controlled weld metal chemistry and ferrite content, as well as controlled weld joint geometry and heat input. This weld process control reduces the welding residual stresses in the weld and also reduces the potential for heat affected zone sensitization and the potential for IGSCC.

Welds between the new low carbon pipe and the existing isolation condenser nozzles (which are non-resistant, high carbon stainless steel) were made with the nozzle side inside diameter protected by specially applied corrosion resistant cladding. The cladding prevents the corrosive reactor coolant from contacting the sensitized weld heat affected zone in the high carbon material.

It is planned to apply a stress improvement treatment (induction heating stress improvement or mechanical stress improvement) to all appropriate ICS weld joints outside the drywell during the next refueling outage. This procedure, which leaves the weld joint with favorable residual stresses to resist IGSCC, will add a second mitigator to those welds.

As a result of the protective measures described above, crack development and crack growth due to the effects of IGSCC are not expected in the ICS piping. All of the welds outside containment, with the possible exception of the welds to valves and the condensers, will have two IGSCC mitigators (resistant material and stress improvement) and will meet the NUREG-0313, Rev.2 requirements for Category A welds. The valve and condenser welds may not have stress improvement due to the difficulty in applying stress improvement to these joints. However, they will still be fabricated from resistant material.

3.2 Waterhammer

There is documented evidence of ICS piping waterhammer events at only two U.S. BWRs (References 3 to 5). These events occurred at Millstone and at Nine Mile Point Unit 1. The waterhammer events at NMP-1 occurred during start-up testing and were caused by condensate forming in the low points in the steam supply piping when the system was not operational. This water then became entrained in the steam on system actuation. System modifications were made to install drains in the piping low points and no waterhammer events have occurred since. Waterhammer events occurred at Millstone when the reactor vessel water level increased above the ICS steam supply nozzle, allowing water to enter the steam supply piping. The

Millstone operating procedures were revised to keep the water level lower and no waterhammer events have been reported since.

After the waterhammer events at Millstone, procedure changes were implemented at Oyster Creek to assure that waterhammer events would not occur in the ICS piping. GPUN Safety Evaluation SE-315403-005 and Oyster Creek Operating Procedure OP-307 (References 19 and 20) describe the precautions taken at Oyster Creek to prevent waterhammer. In summary, the operators are precluded from using the ICS system when the reactor water level is above 180" TAF (top of active fuel). When the water level is above 180" TAF, the possibility exists for reactor coolant in the reactor vessel to enter the ICS steam supply nozzles.

It should be noted that on more than one occurrence, the Oyster Creek reactor vessel level has risen above the ICS steam supply nozzle and there have been no reported instances of waterhammer in the ICS piping. In addition, the steam supply piping is sloped to allow gravity draining. These design features combine to produce a system with essentially no dead legs or locations where water can be trapped. Therefore, waterhammer is not expected.

Since there have been no reported waterhammer events in the Oyster Creek ICS piping and no events occurred at other plants after system modifications were made, it is assumed that waterhammer is not a concern for the Oyster Creek ICS piping.

3.3 Fatigue

A detailed ASME Code, Section III, Class 1 piping fatigue analysis was performed to demonstrate that fatigue is not a concern for the ICS piping. Details of this calculation are included in Appendix B.

The fatigue analysis considered the stresses in the piping resulting from plant startup and shutdowns (pressure and thermal loads), earthquakes, and also the stresses due to the thermal transient associated with system activation. During normal plant operation, the ICS system is not in operation and sections of the piping, in particular the condensate return piping and the steam supply piping near the condensers, can cool and fill with condensate. For the thermal transient evaluation, these sections of piping were assumed to undergo a step change in temperature from 70° to 575°F (the system design temperature) on system initiation. The maximum stresses in the pipe wall during this step change transient were used to calculate fatigue usage. In addition, conservative stress intensification factors were used at all locations.

The ICS system is actuated each plant startup and shutdown, so the stress range used to calculate fatigue usage was the maximum stress range from cold shutdown to hot operation including the effects of system actuation. A total of 400 cycles (10 cycles/year for 40 years) was assumed. The stresses due to earthquake events were also included by assuming 5 occurrences of the Operating Basis Earthquake (OBE) with each occurrence contributing 10 cycles of peak stress. The maximum fatigue usage factors are listed in Table 3.1. As is shown, the usage factors are all very low; the maximum usage factor is less than 0.2. Thus, fatigue is not a concern for the ICS piping.

3.4 Wall Thinning

There are two potential concerns with regard to wall thinning of piping and fittings. These are fabrication wall thinning and service induced wall thinning due to erosion. Fabrication wall thinning can occur during the fabrication of elbows if straight pipe is bent to produce the curved elbow. This is not a concern for the ICS piping because, to allow for this effect, the elbow piping was ordered thicker than the remainder of the piping, schedule 100 rather than schedule 80. Erosion can also occur in power plant piping which contains liquids or wet steam moving at high velocity. The ICS piping usually contains saturated steam, saturated liquid, or slightly subcooled liquid traveling at relatively slow velocities associated with gravity feed. Further, the piping is high chromium stainless steel which is quite resistant to erosion or erosion/corrosion thinning. Therefore, wall thinning is not a concern.

3.5 Creep

The normal operating temperature of the ICS piping is about 550°F. As stated in SRP 3.6.3 (Draft), creep is not a concern for austenitic stainless steel operating under 600°F.

Table 3.1

MAXIMUM CALCULATED FATIGUE USAGE

System	Location (Node)	Description	Usage
A - Condensate	C03	8" Pipe Connection to Concentric Reducer	0.095
	D02N	8" by 10" 45° Lateral Connection to 8" 45° Bend	0.103
	B09	Center of 8" by 10" Lateral	0.093
A - Steam		None Calculated (Bounded by B-Steam)	
B - Condensate	B20	Flued Collar Connection to 10" Pipe (With Thermal Gradient)	0.134
	C28	8" Pipe Connection to Condenser Nozzles	0.174
	C01	10" Pipe Connection to Valve (With Thermal Gradient)	0.133
	D08	8" Butt Weld	0.125
	C11	Center of 8" by 10" Tee	0.143
B - Steam	A11	Flued Collar Connection to 10" Pipe (Without Thermal Gradient)	0.001
	B01	10" Pipe Connection to Valve (Without Thermal Gradient)	0.001
	B05	Valve Connection to Valve	0.128
	B09	10" Valve Connection to Eccentric Reducer	0.002
	D17	12" Pipe Connection to Condenser Nozzle	0.098

Section 4

LEAK DETECTION CAPABILITY

Several methods are available for detecting leaks in the ICS piping outside containment at Oyster Creek. These include (1) visual inspection during system walkdowns, (2) reactor building sump monitoring, (3) area temperature monitors, (4) area radiation monitors, and (5) building ventilation radiation monitoring. Taken together, these methods provide a high degree of assurance that significant leaks (more than a tenth of a gallon per minute) would be quickly detected, and action could be taken before potentially unstable flaws could develop in the piping.

Since the ICS piping is generally accessible, it is possible to walk the system down to observe possible leakage. According to studies performed by Wyle Laboratories (Reference 10), visual observations are capable of detecting small leaks. Leaks as small as 0.1 gpm were seen in the Wyle tests, even with insulated pipe. Currently, operators perform system walkdowns of the ICS piping at least once each day.

Leakage from the ICS piping would condense and would eventually flow into the floor drains. The reactor building floor drains discharge into a single sump (sump #1-7). A daily sump inleakage report is kept by the operators. This is a log of the volume of water (in gallons) pumped out of the reactor building and other sumps each day. A review of this log for January through May 1990 indicates that the total flow each day is usually less than 250 gallons. A plot of the sump inleakage data for January to May 1990 is shown in Figure 4-1. From this figure it can be seen that over a typical two day period less than about five hundred gallons are pumped out of the reactor building sump. The pump only actuates when a certain sump level is reached, so it does not necessarily actuate each day. When it does actuate, it typically pumps 400-450 gallons each time. Typically, the pump actuates every two or three days. The daily log alarm set point is 260 gallons per day, which, if exceeded, requires the operators to identify and document the source of leakage. For example, a copy of the report for May 20, 1990 is shown in Figure 4-2. This report shows that the high inleakage for that day, 5,335 gallons, was due to the draining of a water filled line for maintenance.

Based on a review of the inleakage report data, it can be concluded that a leak from the ICS piping exceeding 0.18 gallons per minute (260 gallons per day) would require a daily special leakage evaluation based on the requirements of the daily inleakage report. Such a leak (0.18 gpm) in the ICS could not go undetected for many days, since all of the isolation condenser piping is accessible for visual inspection.

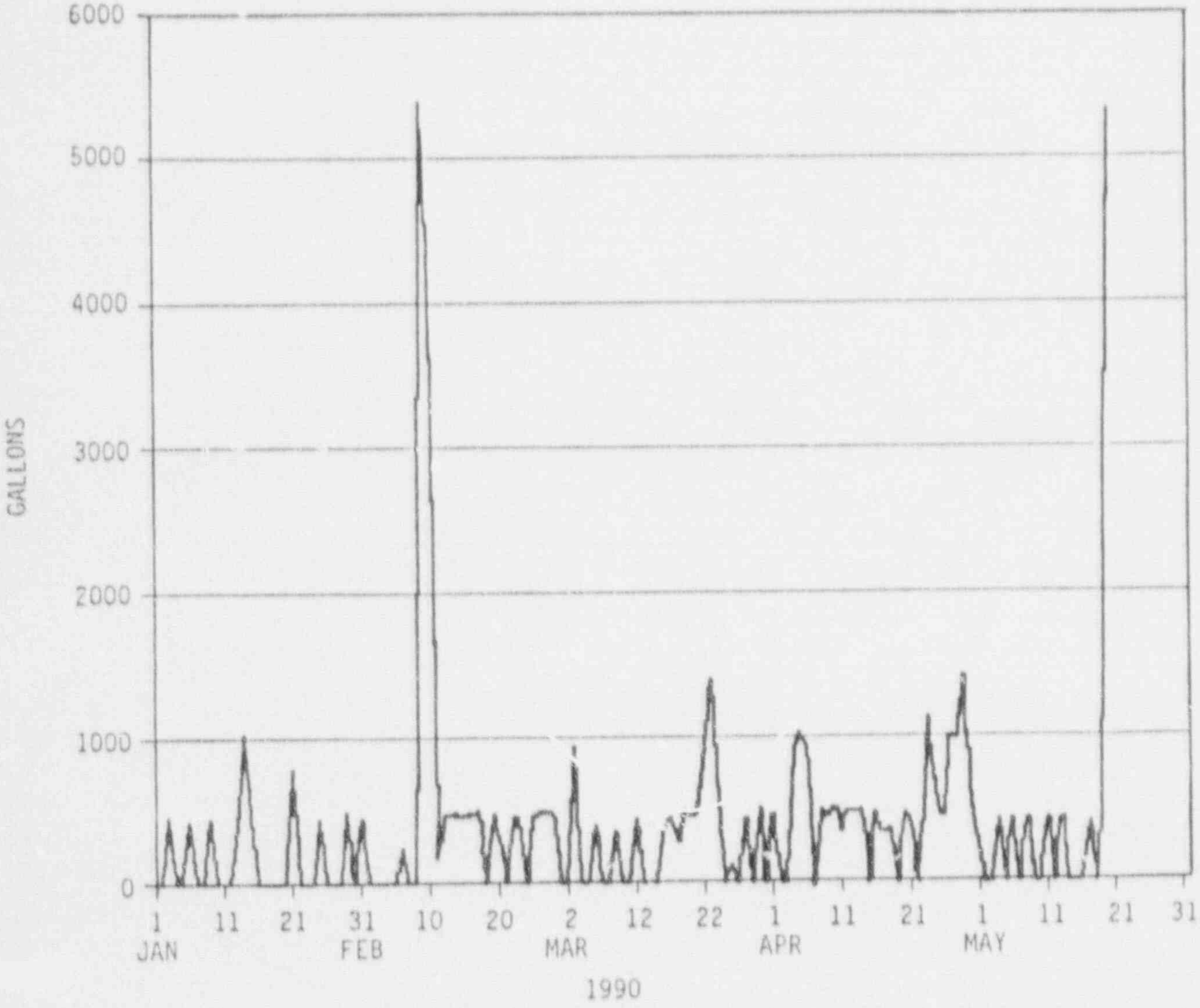
In addition to the inleakeage report, the reactor building sump has a level switch with a high level setpoint which alarms in the main control room. If a reactor coolant leak were present in the reactor building which exceeded the sump pump capacity, the sump level would increase and an alarm would occur, indicating to the operators that a problem might exist and appropriate action should be taken.

An area temperature monitor (ATM) is installed near the EC system isolation valves outside containment. This monitor, which has a setpoint of 160°F is capable of detecting leakage in the piping which lies immediately outside containment. Procedure 2000-RAP-3024.01 requires the operators to investigate an ATM alarm and take appropriate actions, including system isolation.

A radiation monitor is included on the reactor building ventilation exhaust, with an alarm setpoint at 13 mR/hr. If a leak developed which contributed to the airborne radiation level in the building atmosphere, this monitor would be able to detect it and the appropriate operator actions could be taken in accordance with procedure EMG-3200.11.

In summary, several redundant methods are available for detecting leakage in the reactor building from the ICS and that operating procedures are in place to address this leakage if it is discovered. Based on sump monitoring and system walkdowns, there are bases to support a detectable leak rate from the ICS piping of 0.2 gpm.

MPR ASSOCIATES
F-83-133-2
4/3/91



1-7 SUMP DISCHARGE

FIGURE 4-1

```
                    DAILY INLEAKAGE REPORT 5/20/90

 WCSUMPS  PERIOD1  PERIOD2  PERIOD3  PERIOD4  PERIOD5  PERIOD6  TOTAL
********  *******  *******  *******  *******  *******  *******  *****
1-2             0        0        0       22       11        0     33
1-3             0        0        0        0        0        0      0
1-4             0      375        0        0        0        0    375
1-7           940     3270        0     1125        0        0   5335
1-8           423      360      429      412      364      433   2421
1-9             0        0        0        0        0        0      0
1-10            0        0        0        0        0        0      0
1-12          800      424     1154      800      447      593   4219
NRW 1         150        0        0      150        0      150    450
NRW 2         900      900     1200      900     1200      900   6000
NRW 3           0        0        0        0        0        0      0
CHEM LAB        0        0        0        0        0        0      0
LAUNDRY         0        0        0        0        0        0      0
HI COND         0        0        0        0        0        0      0
TOTAL        3213     5328     2783     3409     2023     2076  18833
TANK INC     3500     3780     1120      700     -680        0   8420

 HPSUMPS  PERIOD1  PERIOD2  PERIOD3  PERIOD4  PERIOD5  PERIOD6  TOTAL
********  *******  *******  *******  *******  *******  *******  *****
1-11                     0        0        0        0        0      0
RBEDT                  228        0        0      236        0    464
DWEDT                 1132      923      921     1107      915   5901
LOW COND        0        0        0        0        0        0      0
TOTAL         903     1360      923      921     1343      915   6365
TANK INC     2188     1360     4494     1194     3792     2236  15264

     INVESTIGATE 1-7 SUMP HIGH RUN TIME.    NOTE 1

     INVESTIGATE 1-12 SUMP HIGH RUN TIME.   NOTE 2

     INVESTIGATE NRW 1 SUMP HIGH RUN TIME.  NOTE 3

     INVESTIGATE NRW 2 SUMP HIGH RUN TIME.  NOTE 4


     NOTE 1:  1-7 SUMP-- DRAINING CONDENSATE LINE

     NOTE 2:  1-12 SUMP-- CONDENSATE RETURN TANK OVERFLOW

     NOTE 3:  NRW 1 SUMP-- CONTACTED GPSS. UNABLE TO IDENTIFY SOURCE

     NOTE 4:  NRW 2 SUMP--  EVAPORATOR AND SUSPECT FLOAT HANGING UP
```

Figure 4-2

Section 5

LEAK RATE MODELING

The correlation between pipe through-wall crack size and leak rate was calculated using CIRFLO, a specialized computer code developed by MPR 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 11. CIRFLO results compare favorably to measured flows through small slits reported in Reference 12 and the LEAKS 01 model developed for EPRI in Reference 13. A more detailed description of CIRFLO, including its technical basis and results of comparisons to test data, is provided in Appendix A.

The ICS steam supply piping normally contains saturated steam at essentially reactor vessel conditions of 1035 psia, 549°F. The conditions of the fluid in the ICS condensate return piping vary along the length of the pipe from saturated liquid at reactor vessel conditions to subcooled liquid at reactor vessel pressure. For the purpose of calculating leak rates from postulated through-wall cracks, the steam supply and condensate return piping were assumed to contain saturated steam and saturated liquid at normal reactor vessel conditions. This approach, which could underpredict the leakage flow if the steam supply piping contains water or the condensate return piping is subcooled, is conservative for leak-before-break types of analyses.

The steam supply piping contains six different cross section geometries: 10" diameter schedules 80 and 100, 12" diameter schedules 80 and 100, and 16" diameter schedules 80 and 100. The condensate return piping contains four different cross section geometries: 8" diameter schedules 80 and 100 and 10" diameter schedules 80 and 100. Thus, there are a total of ten pipe size/fluid combinations in the ICS piping. The relationship between through-wall crack length and calculated leakage rate is shown in Figures 4.1 and 4.2. These data were used to interpolate the crack sizes required for a leak rate of 2 gpm. The 2 gpm crack sizes are shown in Table 5.1. They range from about 64° to 106° of pipe circumference. The detailed calculation of the crack sizes is provided in Appendix A.

Table 5.1

2 GPM LEAKAGE CIRCUMFERENTIAL CRACK SIZES

Piping	Fluid	Pipe Size	θ_{2GPM}	a_{2GPM}
Condensate Return	1035 psia, 549°F Saturated Liquid	8" Schedule 80	76°	5.72"
		8" Schedule 100	86°	6.47"
		10" Schedule 80	64°	6.00"
		10" Schedule 100	73°	6.85"
Steam Supply	1035 psia, 549°F Saturated Steam	10" Schedule 80	93°	8.72"
		10" Schedule 100	106°	9.94"
		12" Schedule 80	82°	9.12"
		12" Schedule 100	94°	10.46"
		16" Schedule 80	70°	9.77"
		16" Schedule 100	80°	11.17"

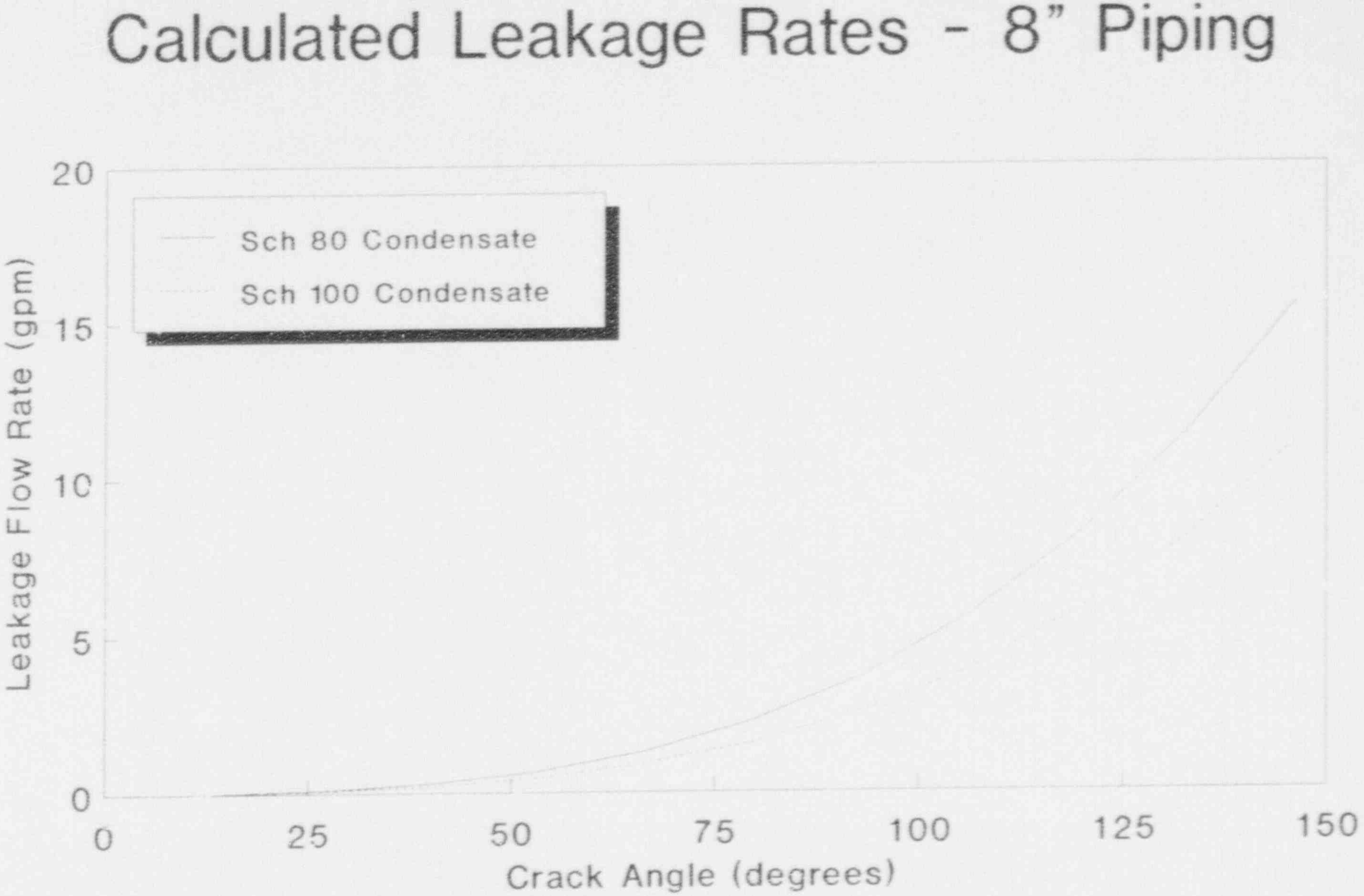
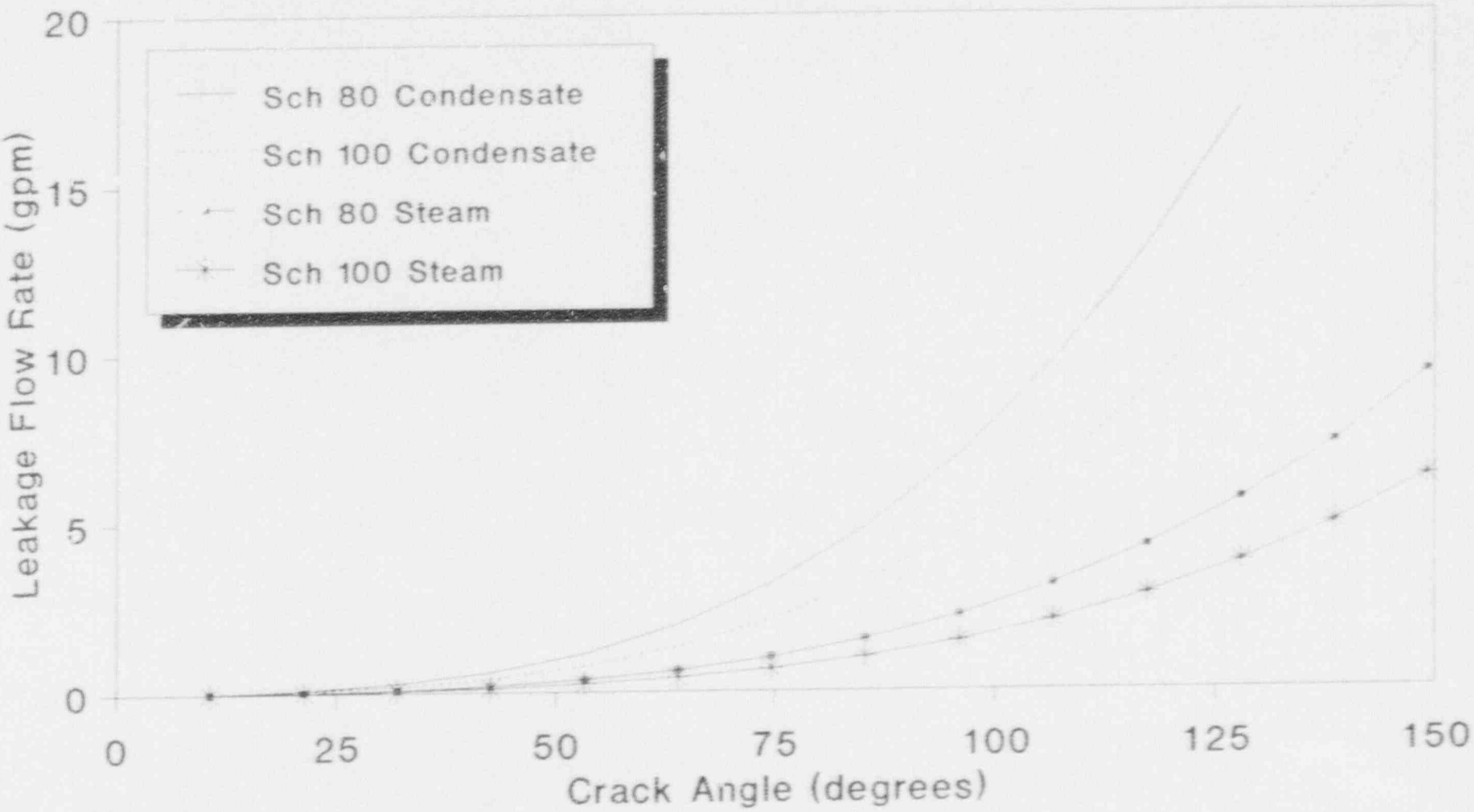

Calculated Leakage Rates - 8” Piping
Sch 80 Condensate
Sch 100 Condensate
Leakage Flow Rate (gpm)
20
15
10
5
0
0
25
50
75
100
125
150
Crack Angle (degrees)

Figure 5-1



Calculated Leakage Rates - 10" Piping

Figure 5-2

Calculated Leakage Rates - 12" Piping

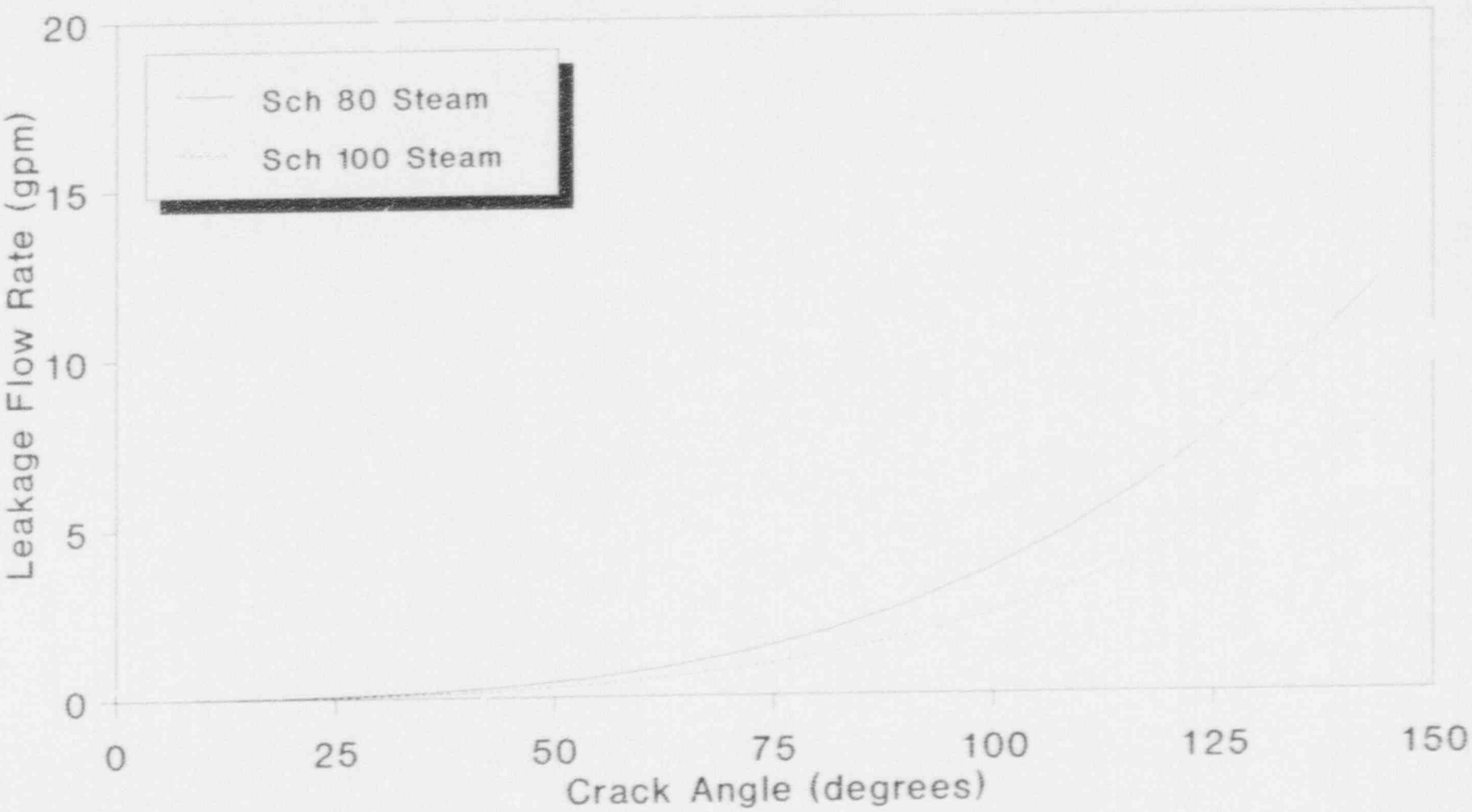


Figure 5-3

Calculated Leakage Rates - 16” Piping

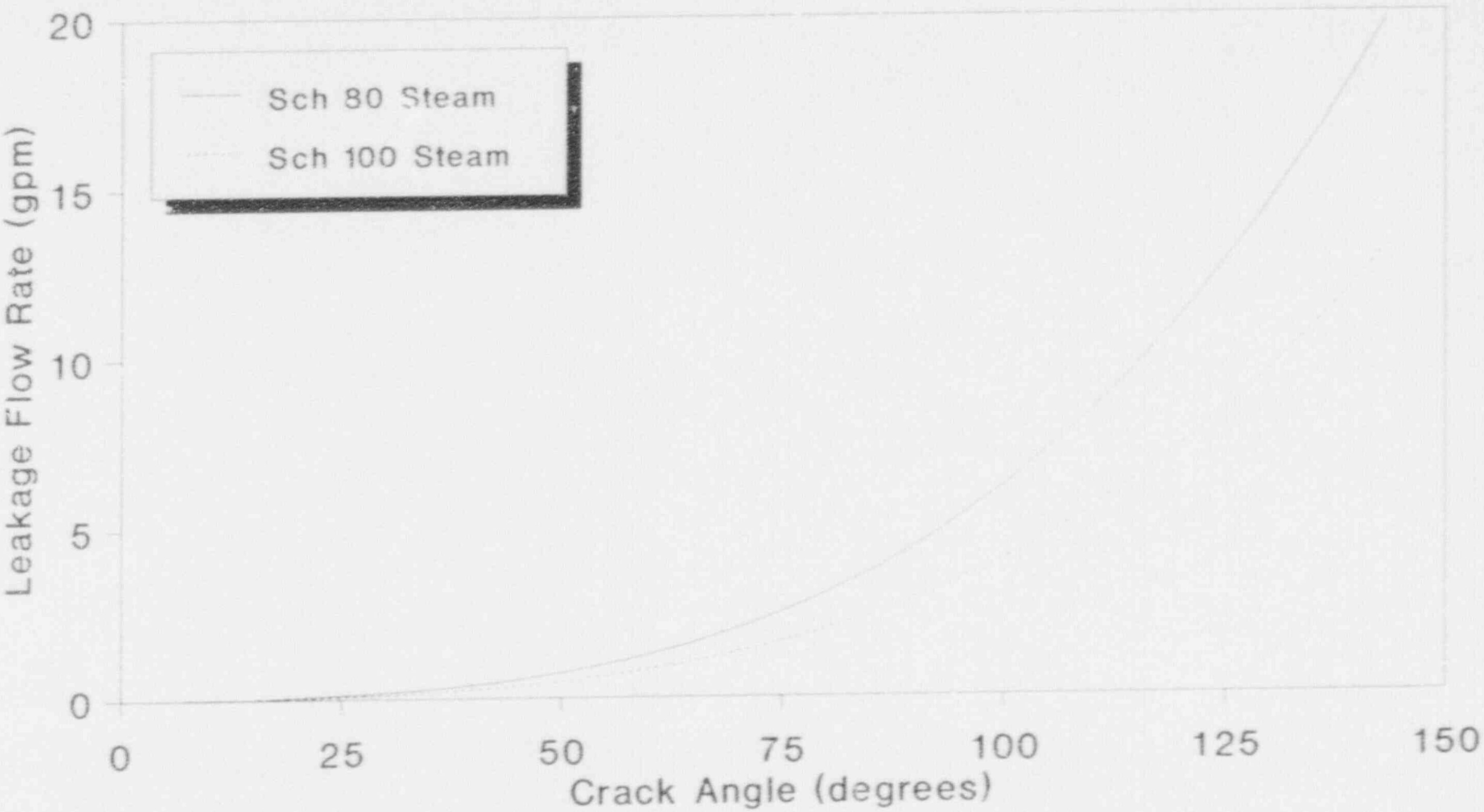


Figure 5-4

Section 6

FRACTURE MECHANICS ANALYSES

Analyses were performed to evaluate the likelihood of unstable double-ended pipe rupture in the Oyster Creek ICS piping. This section describes the Leak-Before-Break (LBB) fracture mechanics analyses performed to show that the probability of postulated double-ended breaks in the piping is very low. The guidelines used for this analysis are taken from SRP 3.6.3 (Draft), Reference 1.

The objectives of the fracture mechanics evaluations, using the guidelines and recommended acceptance criteria presented in SRP 3.6.3 (Draft) are:

- Identify the highest loaded locations in the piping system. These are the postulated crack locations. The loading combination considered is normal operating conditions plus safe shutdown earthquake (SSE) loads.
- For the postulated flaw size determined from leak detection capabilities, show that no unstable failure is predicted for the assumed loading conditions.
- Demonstrate a factor of safety in terms of crack length of at least 2. 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 a factor of safety in terms of load of 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.

The ICS piping contains both schedule 80 and schedule 100 thickness for each pipe diameter in the system. However, the installation procedures for the piping allowed the installer to counterbore the schedule 100 piping to schedule 80 dimensions where necessary to meet fit-up requirements. Consequently, all fracture mechanics calculations used the schedule 80 wall thickness for the schedule 100 piping. The only exception to this approach was the 10" piping in the steam supply lines. The installer was not permitted to machine the 10" schedule 100 steam supply piping below schedule 100 limits. For this piping, the actual schedule 100 wall thickness was used.

6.1 Applied Loads

SRP 3.6.3 (Draft) recommends that the loading combination used in the analyses include pipe deadweight, normal pipe internal pressure, normal thermal expansion loads, and safe shutdown earthquake (SSE). While the ANSI/ASME B3.1 stress analysis models included all of the ICS piping inside and outside containment, the fracture mechanics analyses considered only the piping between the containment penetrations and condenser nozzles. This is because the stiffness of the penetrations was found by analysis to be very high; the penetrations are essentially fixed anchors. The portion of the piping outside containment represents the analyzable portion of the system and is evaluated in accordance with the guidance in SRP 3.6.3 (Draft).

The loads on the ICS piping due to the deadweight plus thermal plus SSE combination are documented in the design stress analysis reports for the piping (References 6 to 9). These loads were calculated using the AUTOPIPE finite element program as part of the ANSI/ASME B31.1 evaluation of the piping. The stresses due to internal pressure were determined by hand calculation.

The fracture mechanics methodology described below requires the postulated load on the cracked section to be expressed in terms of an equivalent applied bending moment rather than individual stress components. Fracture mechanics evaluations are required to be performed at the locations of highest loading in the ICS piping. These locations were determined by calculating the equivalent moment at each node point in the finite element models of the piping and selecting the highest loaded node for each pipe size in each of the four piping runs (condenser A steam supply and condensate return and condenser B steam supply and condensate return). The method used to determine the equivalent moments is described in detail in Appendix C and is summarized below.

- The loads calculated by AUTOPIPE at each node point are forces and moments about three axes. The forces and moments at each node point for the deadweight plus thermal plus SSE load combination were combined using square-root-sum-of-squares (SRSS) to determine the maximum force and moment. The calculations in References 6 to 9 provide two sets of results for this load combination: deadweight plus thermal plus SSE and deadweight plus thermal minus SSE. The combination which yields the highest equivalent moment is used.

- The SRSS force is divided by the cross sectional area to calculate an axial stress. The SRSS moment, pipe radius and area moment of inertia are used to calculate a bending stress.

- The axial stress and bending stress from the AUTOPIPE results are summed along with the axial internal pressure stress to determine a total equivalent stress at each node point.

- The equivalent moment used in fracture mechanics evaluations is calculated as the bending moment which would result in the total equivalent stress if only bending stresses were present.

- The location of highest equivalent moment for each pipe size for each piping system are selected as postulated crack locations.

The points of highest equivalent stress in each system along with the equivalent stresses and moments are shown in Table 6.1. The locations of these points within the system are also listed in Table 6.1 and are shown on system isometrics in Figures 6.1 to 6.4. As expected, most of the highest stressed locations are either terminal ends of piping, reducers, or drywell penetration attachments.

6.2 Fracture Mechanics Methodology

Elastic-plastic fracture mechanics analyses were performed for the normal operating conditions plus SSE load combination described above to evaluate the margins available for unstable crack growth or tearing at each postulated crack location. The methodology used is discussed below and described in detail in Reference 14.

An important criteria of the SRP 3.6.3 (Draft) 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 15, 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 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 (inverse of stiffness) in this analysis.

For the widely applicable case where the crack growth and hinge angle are controlled by the J-integral, the expression on the left of the stability equation can be evaluated in terms of the partial derivatives of the J-integral, J, and hinge angle, 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 (as shown in Reference 14).

$$T_{MAT} > \frac{E}{\sigma_o^2} \left\{ \frac{\partial J}{\partial a}\bigg|_M - t \; \frac{\partial J}{\partial M}\bigg|_a^2 \left[C_s + \frac{\partial \phi}{\partial M}\bigg|_a \right]^{-1} \right\},$$

where C_s is the system compliance. The expression on the right side of the inequality is commonly referred to as the applied tearing modulus.

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 and assumed crack size. The application of this stability criterion to cracked pipes is described in Appendix D.

6.3 Material Properties

The ICS pipe material is Type 316NG stainless steel. For this analysis, lower bound tensile properties for Type 304 stainless steel, which is similar to 316NG, were used. Large strain stress-strain data for Type 304 stainless steel at elevated temperatures are available in Reference 16. 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 T_{MAT} was obtained from cast stainless steel material test data at 550°F reported in Reference 17. Cast material, which is similar to stainless steel weld metal, has lower crack initiation and growth resistance than the pipe base material, thus providing a conservative lower bound estimate for T_{MAT}. Appendix E 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 16 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 18.

6.4 System Compliance

The methodology developed above to evaluate the stability of postulated pipe cracks requires knowledge of the piping system compliance at each postulated 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 moment, so as the crack grows, the load on the cracked section reduces.

The compliance of the piping system at the postulated crack locations was determined using the AUTOPIPE finite element models of the piping arrangement. For each postulated crack location, a node is added to the system model coincident with the node at the postulated crack location. The translational degrees of freedom of the two nodes were coupled but the rotational degrees of freedom were uncoupled. Equal and opposite moments were applied on each of the coincident nodes and the resulting rotations determined. This procedure represents the insertion of a ball and socket joint into the model at the postulated crack location. A second analysis was also performed, applying the moments about an axis perpendicular to the first moment to obtain the compliance 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 15. The calculated system compliances for each postulated crack location are shown in Table 6.3 and range from L/R = 38 to 151. Typically, L/R values less than 100 describe a piping system which is fairly rigid; L/R valves over about 150-200 describe a fairly flexible system. Since local counterboring of the pipe wall (for fit-up) would not significantly affect the overall stiffness of the piping system, all compliance calculations used the actual pipe minimum wall thicknesses (i.e., schedule 100 thicknesses were used for schedule 100 piping). Compliance calculations for the ICS piping are described in more detail in Appendix F.

6.5 Fracture Mechanics Results

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 the piping system compliance at the postulated crack locations. The results of these analyses, shown in Table 6.4, show that all postulated cracks are stable under the applied load. All calculated values of the applied tearing modulus are less than T_{MAT}. The tearing modulus calculations are described in detail in Appendix G.

As recommended by SRP 3.6.3 (Draft), safety margins in terms of crack size and applied load were determined for each postulated crack location. The safety margin in terms of crack size is the ratio of the crack size corresponding to failure for the applied load to the postulated crack size and is recommended to be at least 2.0. The margin in terms of load is the ratio of the load corresponding to failure for the postulated crack length to the applied load and is recommended to be at least 1.41. The failure mode is limited by either unstable tearing or plastic collapse of the remaining cross section. Which mode of failure is actually limiting is dependent on crack size, applied loads, complaince and other factors. In this analysis, margins are reported for each analysis location for whichever failure mode is limiting, unstable tearing or plastic collapse.

As can be seen in Table 6.5, the safety margins in terms of load are all greater than 1.41. It should be noted that in each case evaluated, as the applied load is increased, plastic collapse of the cracked pipe section is controlling rather than unstable growth or tearing. Thus, the safety margin 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.

Table 6.5 also shows safety margin in terms of crack size. In each case, the limiting failure mode is also plastic collapse. As shown in Table 6.5, some of the analysis locations do not quite meet the SRP 3.6.3 recommended criteria of a margin of two on crack size (the worst case is 1.75). The safety margin of two on crack size is recommended to account for uncertainties in the fracture mechanics analyses methodology and leak detection capability (Reference 21). However, a factor of 10 has already been applied on the leakage detection capability (when determining crack size) to account for the leak detection and leak calculation uncertainty. Further, in each case, critical crack size is limited by plastic collapse, which can be calculated relatively precisely compared to a tearing instability limit crack size. Thus, the recommended factor of two is very conservative for the ICS piping. Considering the basis for the recommended margin of two, the calculated margins (minimum of 1.75) are considered to provide adequate safety margin again.. failure.

Table 6.1

HIGHEST LOADED LOCATIONS

System	Location (Node)	Description	Pipe Size	Equivalent Stress (Ksi)	Equivalent Moment (in-Kip)
A-Condensate	D04N	Elbow	8" Schedule 80	11.6	284
	D03A	[illegible]	8" Schedule 100	11.6	284
	D08	Pipe Weld	10" Schedule 80	9.6	437
	B01	Pipe to Valve	10" Schedule 100	8.9	404
A-Steam	B09	Valve to Eccentric Reducer	10" Schedule 80	12.0	546
	B01	Pipe to Valve	10" Schedule 100	12.0	640
	D12	Condenser Nozzle	12" Schedule 80	13.6	1017
	D10A	Elbow	12" Schedule 100	12.3	919
	B19	Pipe Weld	16" Schedule 8	7.1	1025
	B11	Snubber Attachment	16" Schedule 100	7.2	1043
B-Condensate	C[illegible]	Condenser Nozzle	8" Schedule 80	19.2	470
	C26A	Elbow	8" Schedule 100	18.0	441
	C05	Valve to Pipe	10" Schedule 80	9.8	449
	B20	Flued Collar Connection	10" Schedule 100	11.3	513
B-Steam	B09	Valve to Eccentric Reducer	10" Schedule 80	15.7	715
	B01	Pipe to Valve	10" Schedule 100	13.6	724
	D17	Condenser Nozzle	12" Schedule 80	14.4	1077
	D04	Pipe Weld	12" Schedule 100	13.1	976
	[illegible]15N	Elbow	16" Schedule 80	9.9	1429
	B13	Snubber Attachment	16" Schedule 100	10.0	1444

Table 6.2

MATERIAL PROPERTIES

Property	Value @ 550°F
Elastic Modulus, E	25600.0 ksi
Yield Stress, σ_y	23.0 ksi
Flow Stress, σ_f	50.7 ksi
T_{MAT}	182
α	2.13
n	3.79

Table 6.3

CALCULATED SYSTEM COMPLIANCE

System	Location (Node)	Pipe Size	L/R
A - Condensate	D04N	8" Schedule 80	127
	D03A	8" Schedule 100	146
	B08	10" Schedule 80	127
	B01	10" Schedule 100	73
A - Steam	B09	10" Schedule 80	38
	B01	10" Schedule 100	44
	D12	12" Schedule 80	88
	D10A	12" Schedule 100	151
	B19	16" Schedule 80	135
	B11	16" Schedule 100	133
B - Condensate	C28	8" Schedule 80	65
	C26A	8" Schedule 100	150
	C05	10" Schedule 80	66
	B20	10" Schedule 100	65
B - Steam	B09	10" Schedule 80	39
	B01	10" Schedule 100	41
	D17	12" Schedule 80	124
	D04	12" Schedule 100	104
	B15N	16" Schedule 80	104
	B13	16" Schedule 100	127

Table 6.4

CALCULATED APPLIED TEARING MODULUS RESULTS

System	Location (Node)	Pipe Size	Applied Tearing Modulus*
A - Condensate	D04N	8" Schedule 80	1.8
	D03A	8" Schedule 100	2.3
	B08	10" Schedule 80	0.7
	B01	10" Schedule 100	0.7
A - Steam	B09	10" Schedule 80	2.8
	B01	10" Schedule 100	3.5
	D12	12" Schedule 80	3.6
	D10A	12" Schedule 100	4.4
	B19	16" Schedule 80	0.4
	B11	16" Schedule 100	0.5
B - Condensate	C28	8" Schedule 80	8.9
	C26A	8" Schedule 100	11.9
	C05	10" Schedule 80	0.8
	B20	10" Schedule 100	1.4
B - Steam	B09	10" Schedule 80	5.9
	B01	10" Schedule 100	4.6
	D17	12" Schedule 80	4.7
	D04	12" Schedule 100	5.1
	B15N	16" Schedule 80	0.9
	B13	16" Schedule 100	1.2

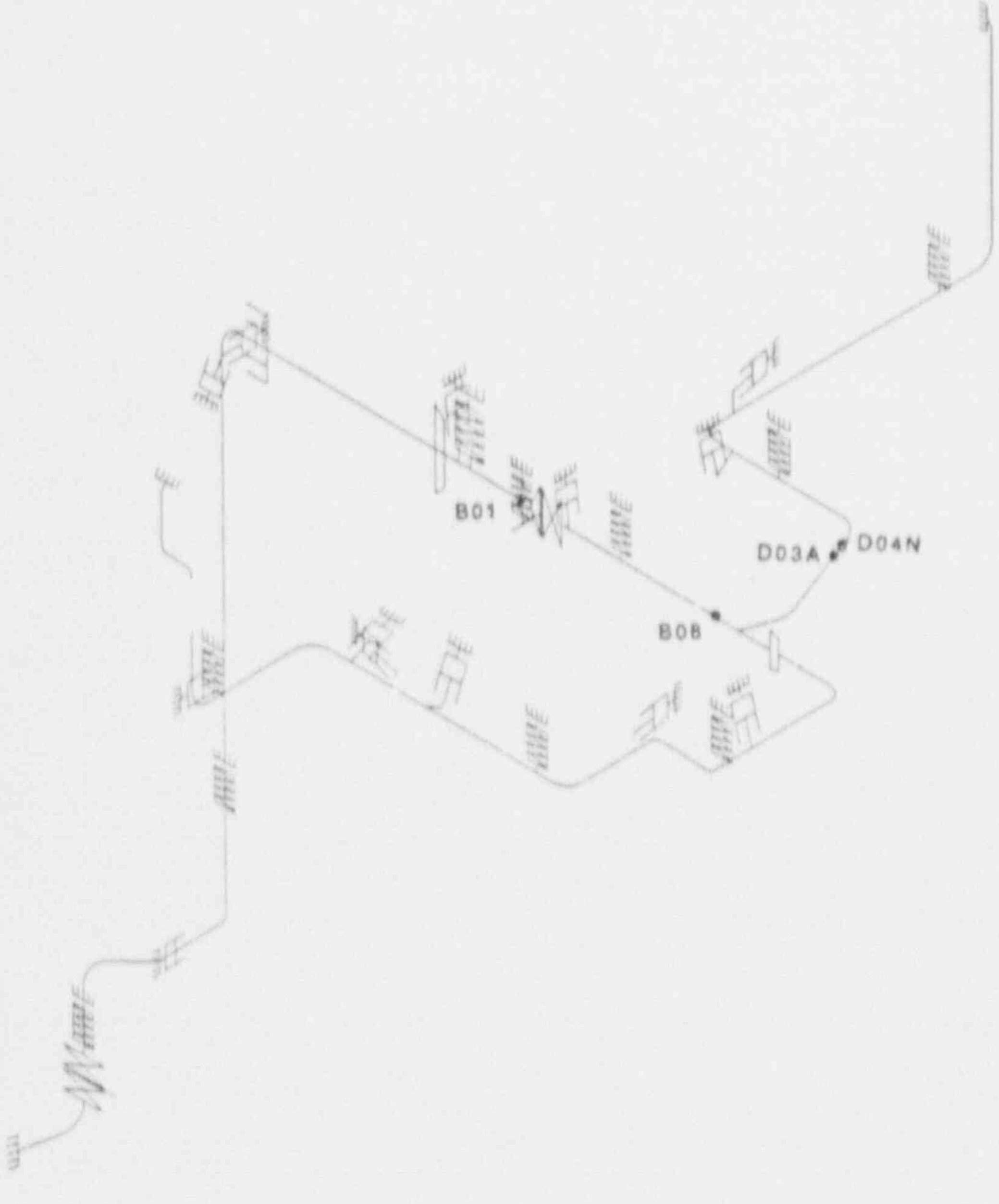
* To be compared to the limiting tearing modulus. $T_{MAT} = 181$.

Table 6.5

SAFETY FACTORS

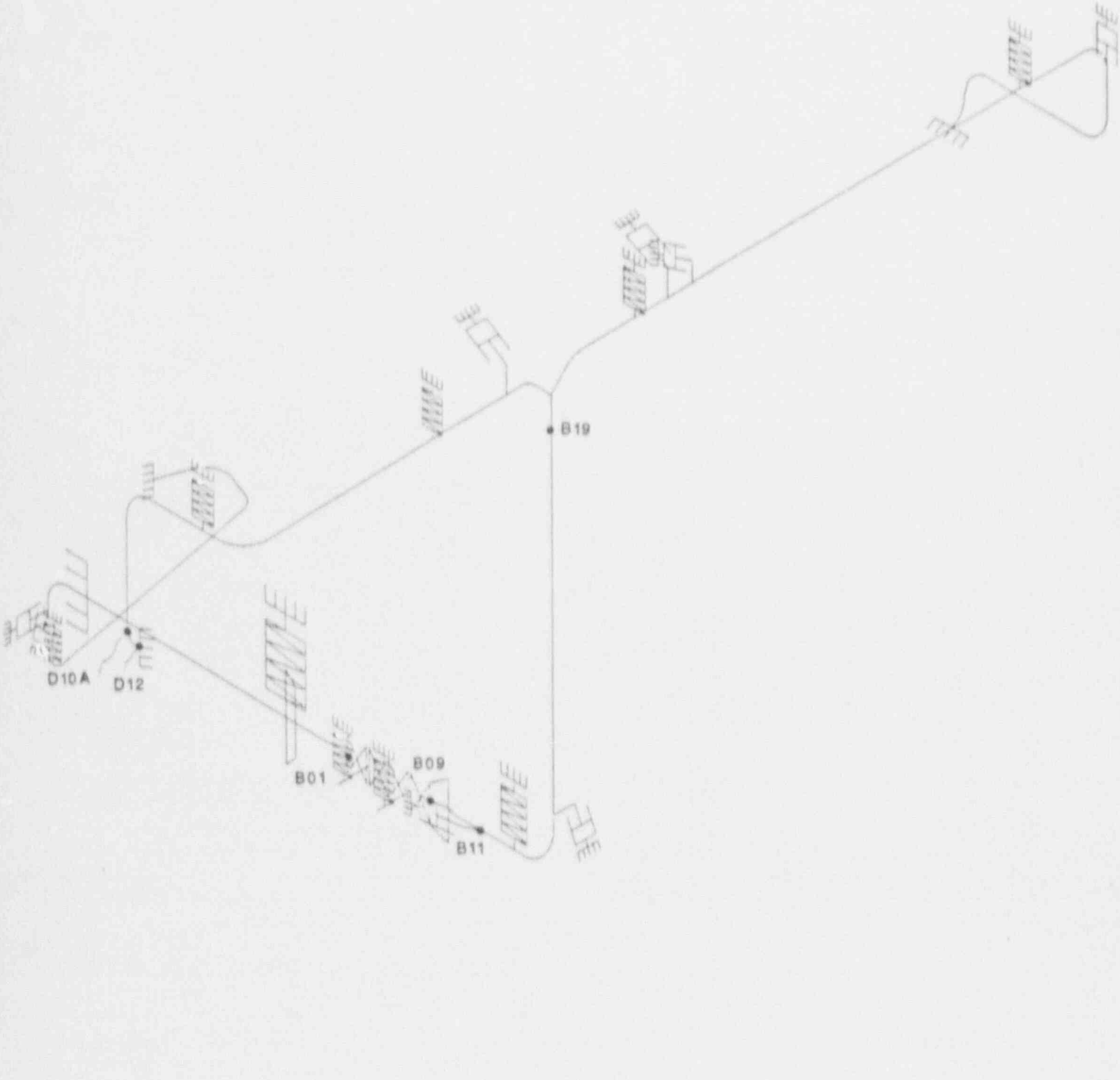
System	Location (Node)	Pipe Size	Safety Factor on Applied Load	Safety Factor on Crack Length
A - Condensate	D04N	8" Schedule 80	3.83	2.56
	D03A	8" Schedule 100	3.54	2.26
	B08	10" Schedule 80	5.05	3.20
	B01	10" Schedule 100	5.12	2.86
A - Steam	B09	10" Schedule 80	3.23	2.07
	B01	10" Schedule 100	2.90	1.82
	D12	12" Schedule 80	3.10	2.24
	D10A	12" Schedule 100	3.11	2.02
	B19	16" Schedule 80	6.53	3.16
	B11	16" Schedule 100	5.95	2.75
B - Condensate	C20	8" Schedule 80	2.32	2.10
	C26A	8" Schedule 100	2.28	1.91
	C05	10" Schedule 80	4.91	3.17
	B20	10" Schedule 100	4.03	2.68
B - Steam	B09	10" Schedule 80	2.47	1.87
	B01	10" Schedule 100	2.57	1.75
	D17	12" Schedule 80	2.92	2.19
	D04	12" Schedule 100	2.93	1.98
	B15N	16" Schedule 80	4.69	2.91
	B13	16" Schedule 100	4.30	2.54

MPR ASSOCIATES
F-83-133-3
4/3/91



A CONDENSATE SYSTEM

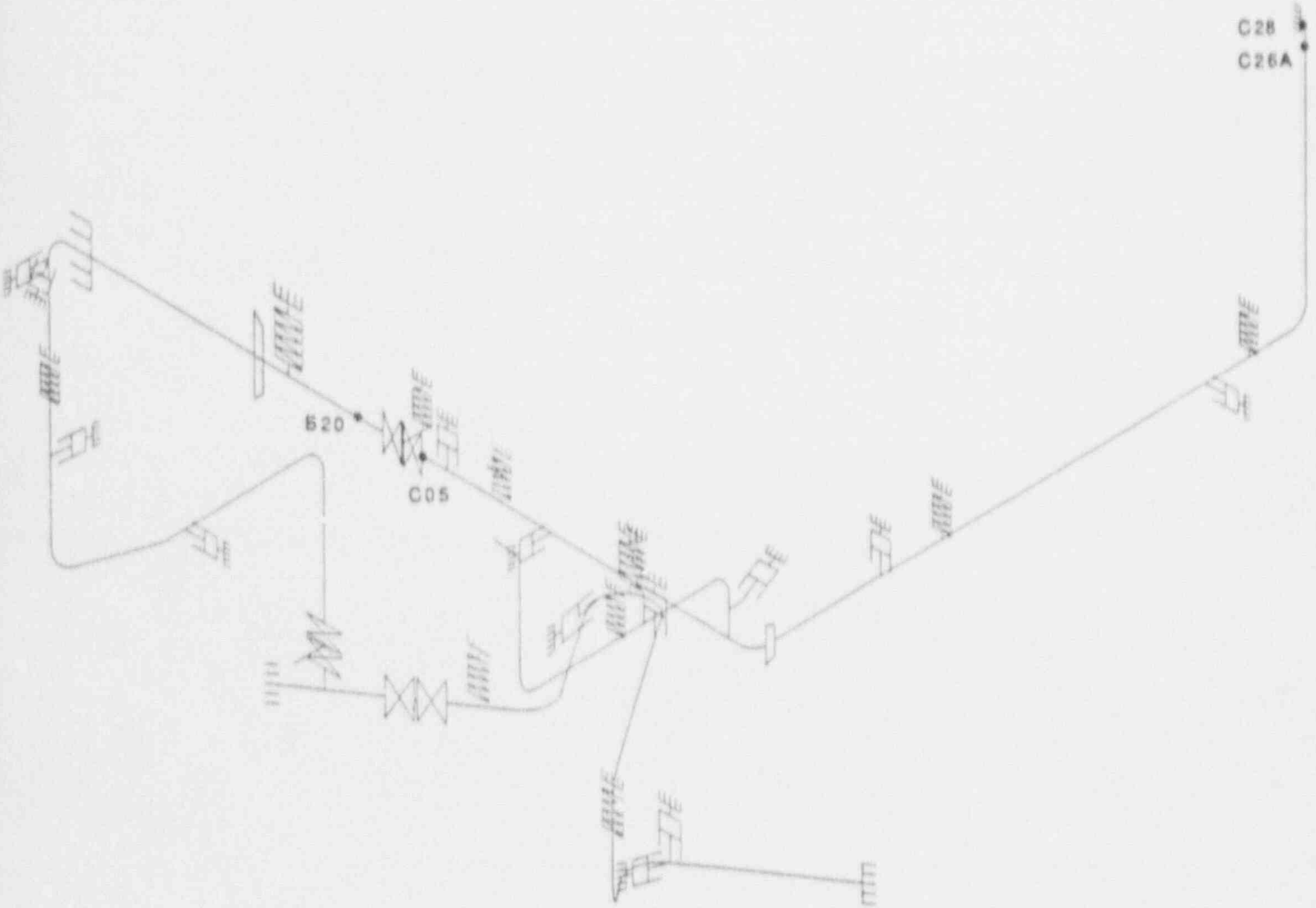
FIGURE 6-1



A STEAM SYSTEM

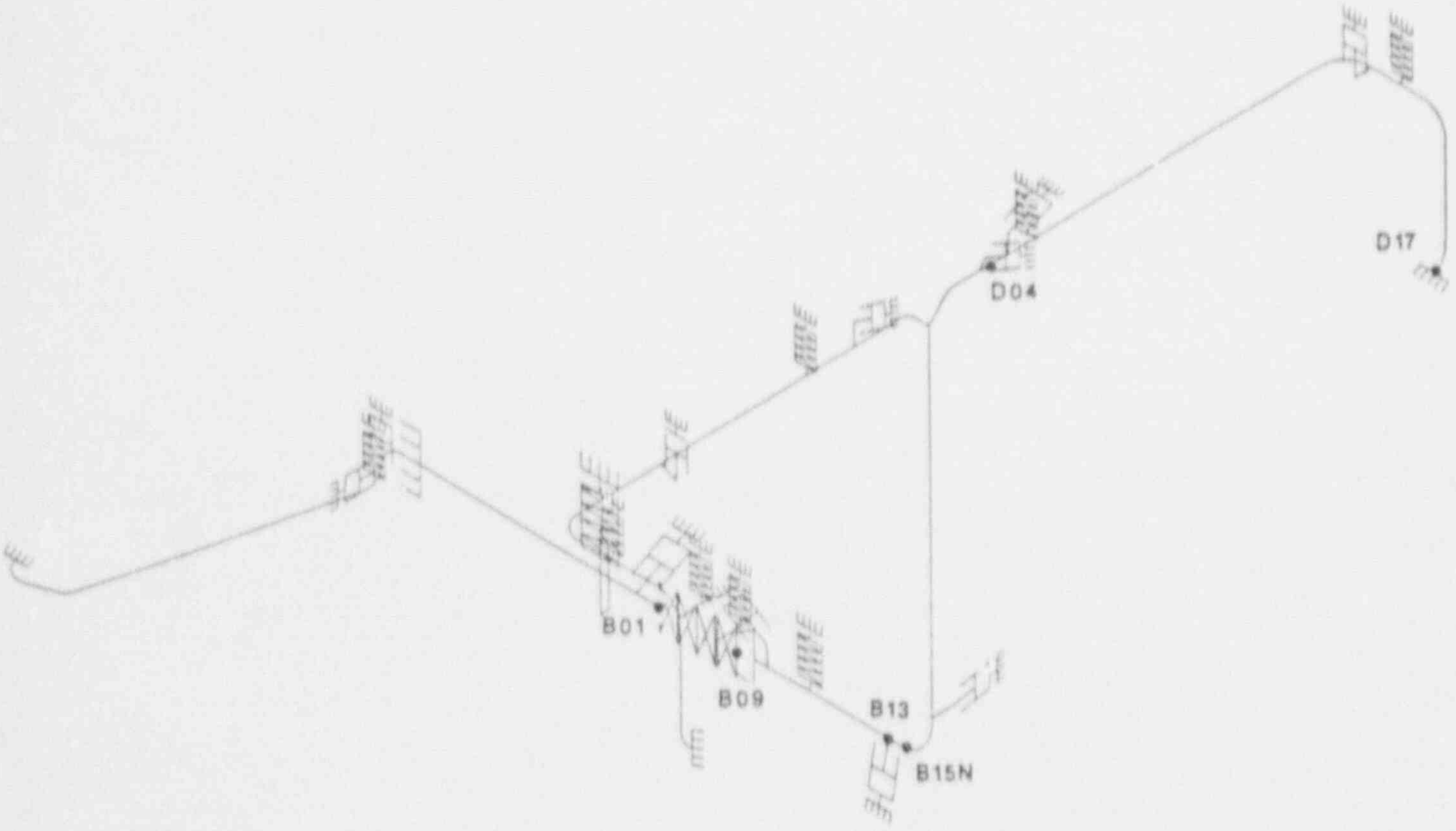
FIGURE 6-2

MPR ASSOCIATES
I-83-133-5
4/3/91



B CONDENSATE SYSTEM

FIGURE 6-3



B STEAM SYSTEM

FIGURE 6-4

Section 7

REFERENCES

1. Standard Review Plan 3.6.3 (Draft), published in Federal Register, Volume 52, Number 167, 8/28/87.

2. USNRC NUREG-0313, Rev. 2, "Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping," January 1988.

3. USNRC NUREG/CR-2059, "Compilation of Data Concerning known and Suspected Waterhammer Events in Nuclear Power Plants," EG&G Idaho, May 1982.

4. USNRC NUREG/CR-2781, "Evaluation of Waterhammer Events in Light Water Reactor Plants," EG&G Idaho, July 1982.

5. USNRC NUREG-0927, Rev.1, "Evaluation of Water Hammer Occurrence in Nuclear Power Plants," March 1984.

6. MPR - 1177, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line to Condenser NE-01-A," Rev. 1, February 1991.

7. MPR - 1178, "Isolation Condenser System, Analysis of Modified Piping Configuration, Condensate Line From Condenser NE-01-A," Rev. 1, February 1991.

8. MPR - 1179, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line to Condenser NE-01-B," Rev. 1, February 1991.

9. MPR - 1180, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line From Condenser NE-01-B," Rev. 1, February 1991.

10. NSAC-110, "Leak Detection in Nuclear Piping Outside Containment," Wyle Laboratories, March 1987.

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

12. USNRC NUREG/CR-3475, "Critical Discharge of Initially Subcooled Water through Slits," September 1983.

13. EPRI NP-3395, "Calculation of Leak Rates Through Cracks in Pipes and Tubes," December 1983.

14. J.E. Nestell and R.N. Coward, "Crack Growth Instability in Piping Systems with Complex Loading," Nonlinear Fracture Mechanics: Volume II - Elastic Plastic Fracture, ASTM STP-995, American Society for Testing and Materials, 1989.

15. Paul C. Paris, Hiroshi Tada, and Richard Marcek, "Fracture Proof Design and Analysis of Nuclear Piping," NUREG/CR-3464, September 1983.

16. Aerospace Structural Metals Handbook, Volume 2, Code 1303, p. 13.

17. 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.

18. EPRI NP-2472-SY, Volume 1, "The Growth and Stability of Stress Corrosion Cracks in Large-Diameter BWR Piping," July 1982.

19. GPUN Safety-Environmental Determination and 50.59 Review, SE-315403-005, "Oyster Creek - Prevention of Isolation Condenser Waterhammer in Oyster Creek Emergency and Abnormal Procedures," October 29, 1986.

20. GPUN Oyster Creek Nuclear Generating Station Procedure, OP-307, Rev. 40, "Isolation Condenser System," October 28, 1990.

21. USNRC NUREG-1061, Volume 3, "Report of the USNRC Piping Review Committee - Evaluation of Potential for Pipe Breaks," November, 1984.

MPR ASSOCIATES, INC.

OYSTER CREEK NUCLEAR GENERATING STATION

LEAK BEFORE BREAK EVALUATION OF ISOLATION CONDENSER SYSTEM PIPING OUTSIDE CONTAINMENT

MPR - 1226

Volume II

Prepared for:

General Public Utilities Nuclear
Parsippany, NJ

April, 1991

TABLE OF CONTENTS

Volume I

Volume II

Section 8

APPENDICES

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPUN	PAGE 1 OF 16
PROJECT ICS Piping LBB	TASK NO. 83-133
CALCULATION TITLE Leakage Flow Rates	CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
4/1/9		4-17-91	0

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 2

Purpose - This calculation determines the leakage rate as a function of circumferential throughwall crack length, for postulated cracks in the Oyster Creek Isolation Condenser System (ICS) piping outside the drywell. The cracks are postulated as part of a leak-before-break analysis of the ICS piping outside the drywell. The leakage flow rate is determined for each size pipe (diameter, wall thickness) in both the steam supply and condensate return piping.

Results - Leakage flow rates as a function of circumferential crack length are shown in Figures 1 and 2. Figures 3 and 4 show flow rates in the 1 to 5 GPM range.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3

Method - The leakage flow rate is determined using the CIRFLO computer program documented in Reference 2. CIRFLO uses a control volume approach to obtain the leakage flow through the crack by solving the mass, momentum and energy conservation equations for a series of control volumes inside the crack.

The input required by CIRFLO is listed below:

- The number of control volumes representing the crack [NUMEL]
- The relative surface roughness of the flow path (crack) [ROUGH]
- The pipe outside diameter and wall thickness [DO, THICK]
- The pipe fluid conditions - stagnation pressure, fluid temperature, void fraction [PO, TO, VOIDO]
- The minimum and maximum crack sizes to evaluate [GALMIN, GALMAX]
- The pipe modulus of elasticity [E]

The input used for the ICS piping is shown on the following page.

- The crack is modeled using 15 control volumes, NUMEL= 15

- The relative surface roughness is 0.1, ROUGH=0.1. As discussed in Reference 1, this value will underpredict the flow rate, which is conservative for leak-before-break analyses.

- The ICS piping is composed of several different sizes of pipe as listed below: (Dimensions from Reference 2)

		DO (in)	THICK (in)
Condensate Return	8", Sch. 80	8.625	0.5
	8", Sch. 100	8.625	0.594
	10", Sch. 80	10.75	0.594
	10", Sch. 100	10.75	0.719
Steam Supply	10", Sch. 80	10.75	0.594
	10", Sch. 100	10.75	0.719
	12", Sch. 80	12.75	0.688
	12", Sch. 100	12.75	0.844
	16", Sch. 80	16.00	0.844
	16", Sch 100	16.00	1.031

- The fluid in the steam supply piping is normally saturated steam at reactor vessel pressure of 1035 psia and vessel temperature of 547°F (Ref 3). A void fraction VOIDO = 0.999999 is used (essentially all steam). It is possible that some sections of pipe away from the reactor vessel may have smaller void fractions (wetter steam), however assuming saturated steam is conservative because smaller flow rates are calculated

- The fluid in the condensate return piping is subcooled liquid at reactor vessel pressure, 1035 psia. The amount of subcooling likely varies as a function of distance from the reactor vessel. To ensure conservative flow rates are calculated for all portions of the piping, it is assumed the fluid is saturated water at reactor vessel pressure and temperature, 1035 psia, 547°F, VOIDO = 0.000001. (Flowrate increases as the amount of subcooling increases.)
- For each case, the flowrate is determined for 20 crack sizes: 1", 2", … 19", 20".
- The piping will be Type 316 stainless steel, from Reference 4. $E = 25.6 \times 10^6$ psi @ 550°F.

The CIRFLO output is included on the following pages. Graphs of the CIRFLO results are shown in Figures 1 to 4.

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 6

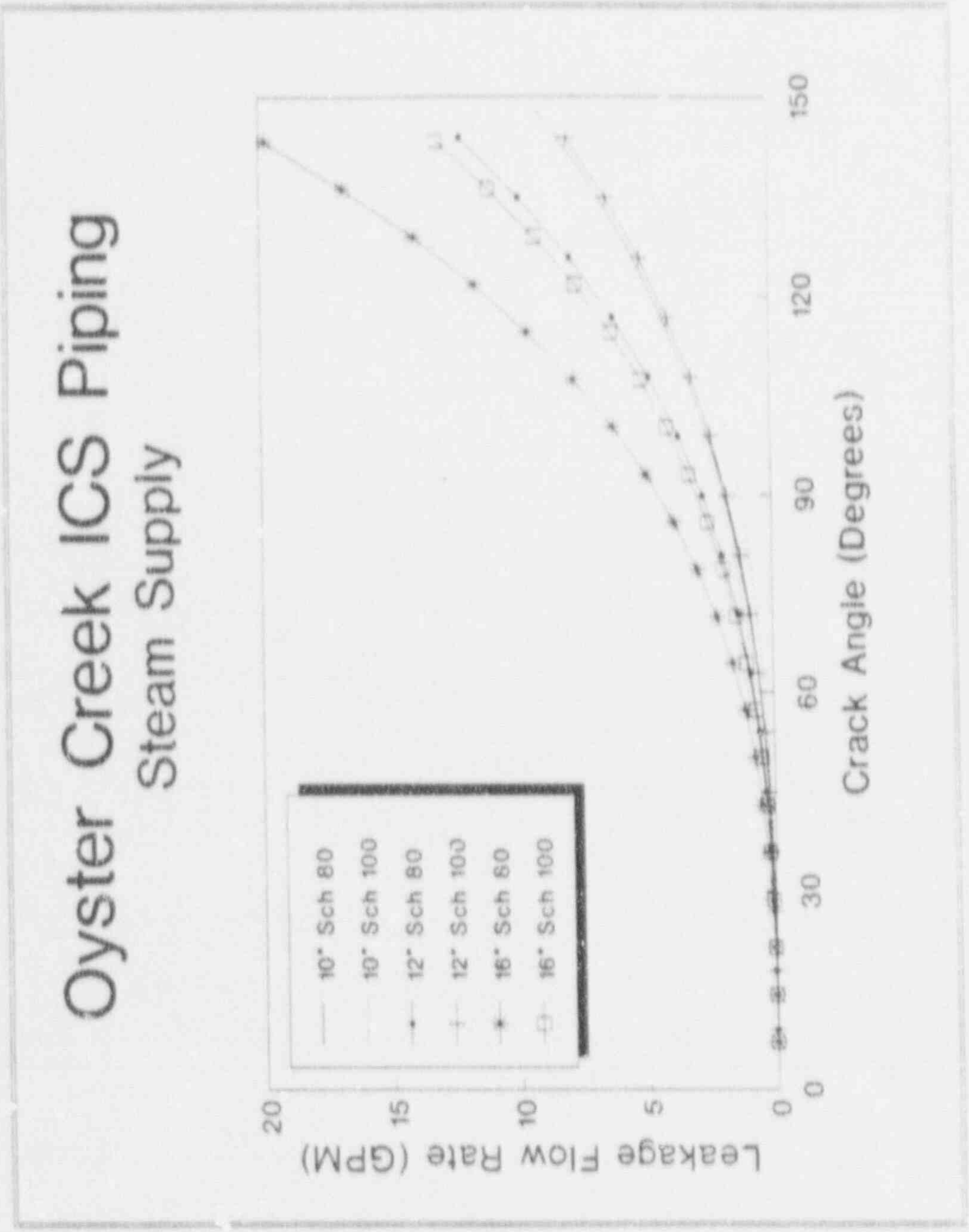


Figure 1

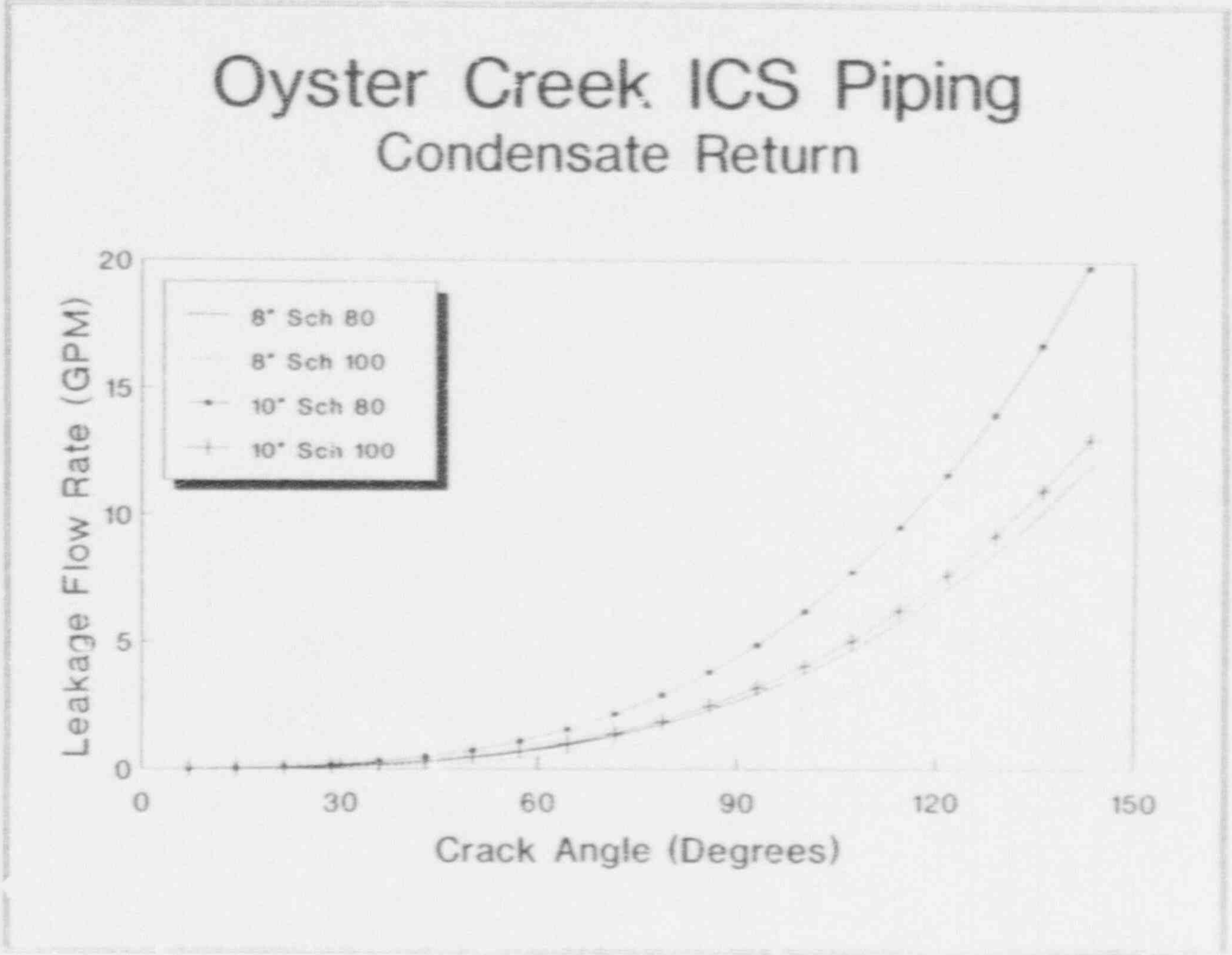

Oyster Creek ICS Piping
Condensate Return
8" Sch 80
8" Sch 100
10" Sch 80
10" Sch 100
Leakage Flow Rate (GPM)
0
5
10
15
20
Crack Angle (Degrees)
0
30
60
90
120
150

Figure 2

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 8

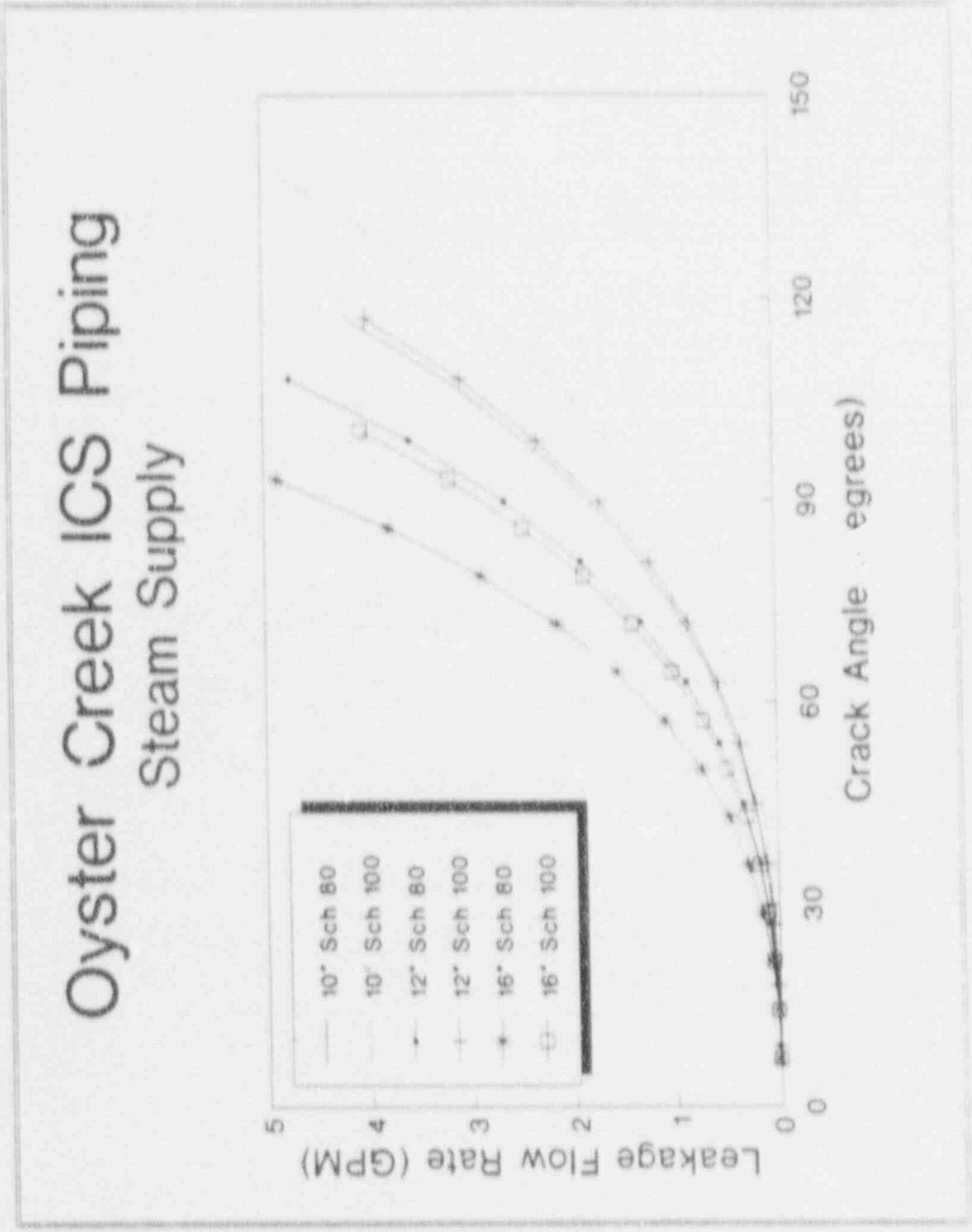


Figure 3

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 9

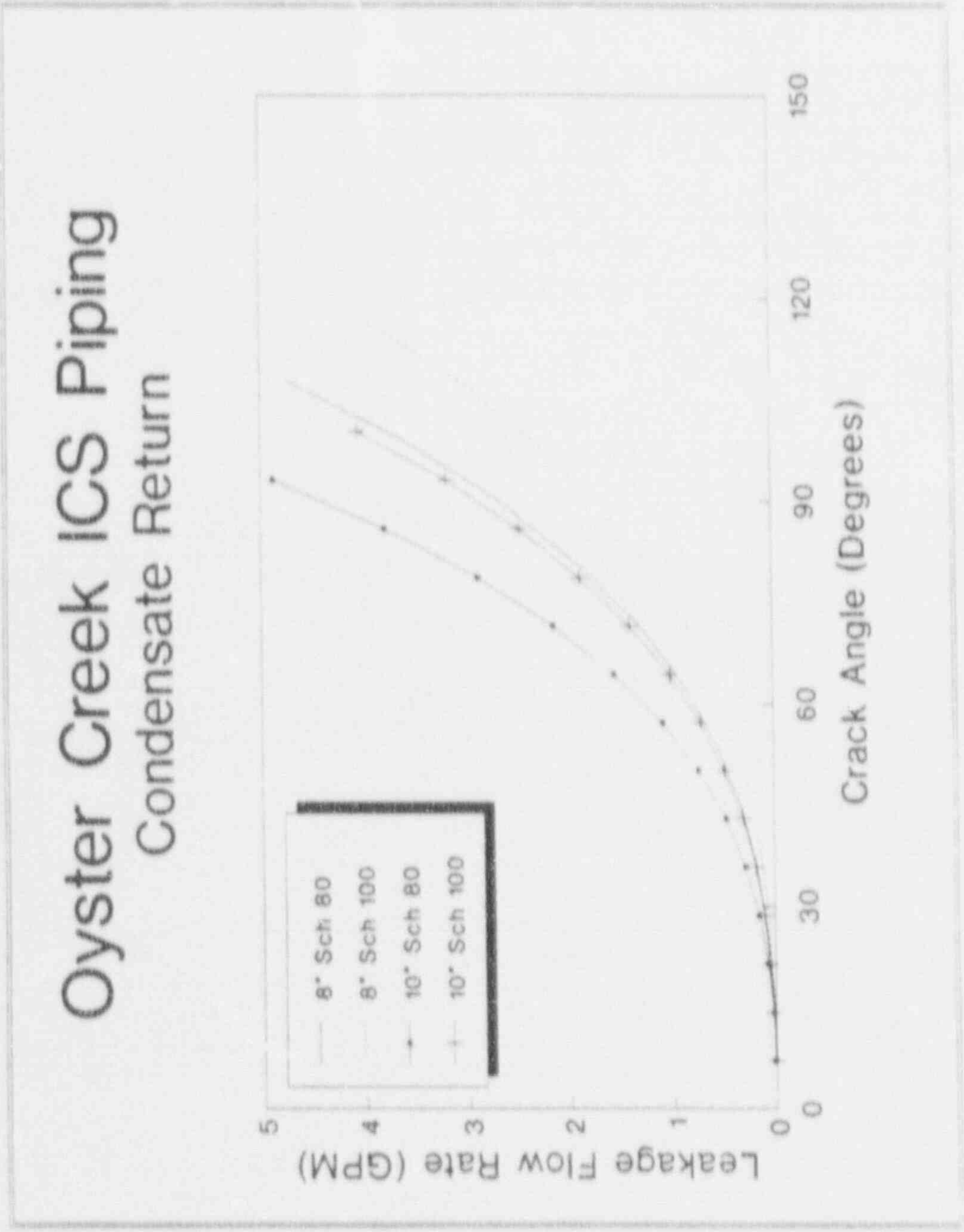


Figure 4

```
CIRFLO: CALCULATION OF FLOW THROUGH CIRCUMFERENTIAL PIPE CRACKS
  VERSION 2.0
 TODAY'S DATE:  04/01/91

OYSTER CREEK ICS PIPING

 NUMBER OF CRACKS EACH CASE ---    20
 NUMBER OF ELEMENTS IN CRACK --    15
 CRACK FLOW (0) OR LENGTH (1) -     1
 RELATIVE ROUGHNESS -----------      .10000

      DO     THICK        PO         TO      VOID  MIN CRAK  MAX CRAK         E
  (INCHES) (INCHES)    (PSIA)   (DEG F)          (INCHES)  (INCHES)     (PSI)
*******************************************************************************
    8.6250   .500000   1035.00    548.77    .0000    1.0000   20.0000 25600000.

   ITER     CRACK     ANGLE       AREA      FLOW     EXIT-P      FLUX      FLOW
          (INCHES)  (DEGREE)   (SQ IN)  (LB/SEC)    (PSIA) (KG/S/M2) (GAL/MIN)
       **********************************************************************
     1      1.00     13.29      .000       00     320.94     7271.2       .02
     2      2.00     26.57      .001      .01     383.56     7800.2       .09
     3      3.00     39.86      .003      .04     472.43     9750.3       .29
     4      4.00     53.14      .006      .09     542.89    11479.1       .66
     5      5.00     66.43      .010      .18     602.32    13023.7      1.29
     6      6.00     79.72      .015      .31     647.56    14465.0      2.26
     7      7.00     93.00      .023      .51     688.30    15762.6      3.67
     8      8.00    106.29      .032      .78     726.76    16890.6      5.60
     9      9.00    119.57      .045     1.13     761.95    17856.4      8.14
    10     10.00    132.86      .060     1.58     794.14    18652.7     11.37
    11     11.00    146.15      .078     2.15     819.34    19404.7     15.47
    12     12.00    159.43      .100     2.86     840.10    20097.7     20.54
    13     13.00    172.7       .126     3.71     858.27    20702.3     26.67
    14     14.00    186.        .157     4.73     874.07    21233.1     34.01
    15     15.00    199.29      .193     5.93     887.70    21704.9     42.68
    16     16.00    212.58      .234     7.34     899.64    22117.8     52.81
    17     17.00    225.86      .281     8.97     910.19    22471.7     64.50
    18     18.00    239.15      .335    10.84     919.33    22796.1     77.98
    19     19.00    252.43      .396    12.98     927.28    23091.0     93.39
    20     20.00    265.72      .465    15.40     934.48    23326.9    110.74
```

```
       DO      THICK        PO         TO       VOID    N CRAK  MAX CRAK          E
 (INCHES)  (INCHES)    (PSIA)    (DEG F)             (INCHES)  (INCHES)      (PSI)
***********************************************************************************
   8.6250   .594000   1035.00     548.77      .0000    1.0000   20.0000 25600000.

  ITER     CRACK      ANGLE        AREA        FLOW     EXIT-P       FLUX       FLOW
         (INCHES)  (DEGREE)     (SQ IN)   (LB/SEC)     (PSIA)  (KG/S/M2)  (GAL/MIN)
         *************************************************************************
     1      1.00      13.29        .000         .00     300.55     6113.7        .01
     2      2.00      26.57        .001         .01     346.64     7105.3        .07
     3      3.00      39.86        .002         .03     409.27     8268.4        .26
     4      4.00      53.14        .005         .06     473.58     9[illegible]8.2        .46
     5      5.00      66.43        .008         .12     530.80    11187.9        .90
     6      6.00      79.72        .012         .22     581.59    12463.4       1.57
     7      7.00      93.00        .018         .3[illegible]     622.74    13668.8       2.54
     8      8.00     106.29        .026  [illegible]     [illegible]57.99    14804.2       3.90
     9      9.00     119.57        .035         .79     691.59    15836.3       5.[illegible]
    10     10.00     132.86        .047        1.12     722.65    16772.7       8.06
    11     11.00     146.15        .061        1.53     752.35    17591.0      11.01
    12     12.00     159.43        .078        2.03     779.28    18313.5      14.63
    13     13.00     172.72        .098        2.64     804.51    18918.1      19.00
    14     14.00     186.00        .122        3.38     823.39    19552.1      24.32
    15     15.00     199.29        .149        4.26     840.57    20112.5      30.63
    16     16.00     212.58        .181        5.28     855.92    20613.8      38.00
    17     17.00     225.06        .217        6.48     869.12    21085.6      46.61
    18     18.00     239.15        .257        7.85     881.44    21483.8      56.46
    19     19.00     252.43        .304        9.42     892.20    21852.4      67.73
    20     20.00     265.72        .356       11.19     901.96    22176.8      80.51

       DO      THICK        PO         TO       VOID  MIN CRAK  MAX CRAK          E
 (INCHES)  (INCHES)    (PSIA)    (DEG F)             (INCHES)  (INCHES)      (PSI)
***********************************************************************************
  10.7500   .594000   1035.00     548.77      .0000    1.0000   20.0000 25600000.

  ITER     CRACK      ANGLE        AREA        FLOW     EXIT-P       FLUX       FLOW
         (INCHES)  (DEGREE)     (SQ IN)   (LB/SEC)     (PSIA)  (KG/S/M2)  (GAL/MIN)
         *************************************************************************
     1      1.00      10.66        .000         .00     438.94     6862.0        .02
     2      2.00      21.32        .001         .01     356.45     7297.0        .09
     3      3.00      31.98        .003         .04     442.06     9046.2        .27
     4      4.00      42.64        .006         .08     507.01    10601.8        .60
     5      5.00      53.30        .009         .16     563.53    12006.3       1.14
     6      6.00      63.96        .015         .27     611.11    13292.8       1.97
     7      7.00      74.62        .021         .44     648.63    14509.3       3.17
     8      8.00      85.28        .030         .67     [illegible]83.52    15615.2       4.80
     9      9.00      95.94        .041         .96     716.38    16603.1       6.94
    10     10.00     106.60        .054        1.34     747.02    17473.1       9.67
    11     11.00     117.26        .070        1.82     776.02    18210.3      13.06
    12     12.00     127.92        .089        2.39     802.00    18844.4      17.17
    13     13.00     138.58        .112        3.09     821.69    19493.2      22.22
    14     14.00     149.24        .138        3.93     839.38    20068.2      28.23
    15     15.00     159.90        .168        4.91     855.04    20584.3      35.31
    16     16.00     170.55        .203        6.06     868.73    21056.2      43.57
    17     17.00     181.21        .242        7.38     881.11    21469.0      53.09
    18     18.00     191.87        .287        8.90     891.88    21852.4      64.03
    19     19.00     202.53        .337       10.62     901.84    22176.8      76.41
    20     20.00     213.19        .394       12.59     910.27    22501.2      90.54
```

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 12

```
       DO      THICK          PO          TO       VOID   MIN CRAK  MAX CRAK          E
 (INCHES)  (INCHES)      (PSIA)     (DEG F)              (INCHES)  (INCHES)      (PSI)
***************************************************************************************
  10.7500   .719000    1035.00      548.77     .0000     1.0000   20.0000 25600000.

  ITER      CRACK       ANGLE        AREA        FLOW     EXIT-P       FLUX        FLOW
         (INCHES)   (DEGREE)     (SQ IN)   (LB/SEC)     (PSIA)  (KG/S/M2)  (GAL/MIN)
       ************************************************************************
     1       1.00       10.66        .000         .00     212.22     5645.6         .01
     2       2.00       21.32        .001         .01     437.42     6703.5         .07
     3       3.00       31.98        .002         .03     368.30     7545.9         .18
     4       4.00       42.64        .004         .06     435.19     8865.6         .40
     5       5.00       53.30        .007         .11     486.45    10100.5         .77
     6       6.00       63.96        .012         .18     533.31    11243.2        1.32
     7       7.00       74.62        .017         .29     575.41    12308.6        2.11
     8       8.00       85.28        .024         .44     611.40    '3318.6        3.20
     9       9.00       95.94        .032         .65     641.74    '4288.1        4.65
    10      10.00      106.60        .042         .91     670.15    15194.9        6.52
    11      11.00      117.26        .0[illegible]        1.23     697.54    16028.0        8.87
    12      12.00      127.92        .069        1.64     723.16    16794.8       11.76
    13      13.00      138.58        .086        2.12     747.42    17487.8       15.27
    14      14.00      149.24        .105        2.70     770.93    18092.4       19.42
    15      15.00      159.90        .128        3.38     792.78    18623.2       24.30
    16      16.00      170.55        .154        4.17     811.05    19139.3       30.03
    17      17.00      181.21        .183        5.10     826.56    19640.6       36.71
    18      18.00      191.87        .216        6.18     840.31    20112.5       44.43
    19      19.00      202.53        .254        7.39     853.32    20525.3       53.17
    20      20.00      213.19        .296        8.77     864.97    20908.7       63.10

       DO      THICK          PO          TO       VOID   MIN CRAK  MAX CRAK          E
 (INCHES)  (INCHES)      (PSIA)     (DEG F)              (INCHES)  (INCHES)      (PSI)
***************************************************************************************
  10.7500   .594000    1035.00      548.77    1.0000     1.0000   20.0000 25600000.

  ITER      CRACK       ANGLE        AREA        FLOW     EXIT-P       FLUX        FLOW
         (INCHES)   (DEGREE)     (SQ IN)   (LB/SEC)     (PSIA)  (KG/S/M2)  (GAL/MIN)
       ************************************************************************
     1       1.00       10.66        .000         .00     100.27     2412.8         .01
     2       2.00       21.32        .001         .00     225.69     2238.4         .03
     3       3.00       31.98        .003         .01     281.75     2794.7         .08
     4       4.00       42.64        .006         .03     332.71     3290.6         .19
     5       5.00       53.30        .009         .05     379.13     3747.9         .36
     6       6.00       63.96        .015         .09     422.45     4170.3         .62
     7       7.00       74.62        .021         .14     462.42     4562.8        1.00
     8       8.00       85.28        .030         .21     499.81     4926.6        1.51
     9       9.00       95.94        .041         .31     534.12     5265.5        2.20
    10      10.00      106.60        .054         .43     565.99     5579.5        3.09
    11      11.00      117.26        .070         .59     595.28     5871.0        4.21
    12      12.00      127.92        .089         .78     622.85     6137.7        5.59
    13      13.00      138.58        .112        1.01     648.05     6384.4        7.28
    14      14.00      149.24        .138        1.29     670.92     6613.6        9.30
    15      15.00      159.90        .168        1.63     692.16     6822.9       11.70
    16      16.00      170.55        .203        2.02     711.42     7017.3       14.52
    17      17.00      181.21        .242        2.47     729.51     7191.8       17.78
    18      18.00      191.87        .287        3.00     746.14     7356.2       21.55
    19      19.00      202.53        .337        3.60     760.97     7505.7       25.86
    20      20.00      213.19        .394        4.27     775.17     7635.3       30.72
```

```
       DO      THICK          PO          TD       VOID  MIN CRAK  MAX CRAK         E
 (INCHES)  (INCHES)      (PSIA)    (DEG F)              (INCHES)  (INCHES)     (PSI)
**************************************************************************************
  10.7500   .719000   1035.00     548.77   1.0000    1.0000   20.0000 25600000.

 ITER     CRACK     ANGLE       AREA        FLOW     EXIT-P       FLUX       FLOW
        (INCHES)  (DEGREE)    (SQ IN)   (LB/SEC)    (PSIA)  (KG/S/M2)  (GAL/MIN)
      ****************************************************************************
    1      1.00      10.66       .000        .00     188.87     1882.0        .00
    2      2.00      21.32       .001        .00     185.75     1847.2        .02
    3      3.00      31.98       .002        .01     233.39     2316.3        .06
    4      4.00      42.64       .004        .02     276.25     2737.4        .12
    5      5.00      53.30       .007        .03     316.00     3129.9        .24
    6      6.00      63.96       .012        .06     353.69     3498.7        .41
    7      7.00      74.62       .017        .09     389.17     3847.6        .66
    8      8.00      85.28       .024        .14     423.01     4177.7       1.00
    9      9.00      95.94       .032        .20     455.16     4490.5       1.46
   10     10.00     106.60       .042        .29     485.50     4787.0       2.05
   11     11.00     117.26       .054        .39     513.90     5068.6       2.80
   12     12.00     127.92       .069        .52     541.29     5332.8       3.74
   13     13.00     138.58       .086        .68     567.03     5582.0       4.87
   14     14.00     149.24       .105        .87     590.26     5821.2       6.25
   15     15.00     159.90       .128       1.10     613.28     6040.5       7.88
   16     16.00     170.55       .154       1.36     634.20     6249.8       9.81
   17     17.00     181.21       .183       1.67     654.12     6444.2      12.05
   18     18.00     191.87       .216       2.04     672.39     6628.6      14.64
   19     19.00     202.53       .254       2.45     689.88     6798.0      17.61
   20     20.00     213.19       .296       2.92     706.05     6957.5      21.00

       DO      THICK          PO          TD       VOID  MIN CRAK  MAX CRAK         E
 (INCHES)  (INCHES)      (PSIA)    (DEG F)              (INCHES)  (INCHES)     (PSI)
**************************************************************************************
  12.7500   .688000   1035.00     548.77   1.0000    1.0000   20.0000 25600000.

 ITER     CRACK     ANGLE       AREA        FLOW     EXIT-P       FLUX       FLOW
        (INCHES)  (DEGREE)    (SQ IN)   (LB/SEC)    (PSIA)  (KG/S/M2)  (GAL/MIN)
      ****************************************************************************
    1      1.00       8.99       .000        .00     196.04     2324.4        .01
    2      2.00      17.98       .001        .00     210.31     2098.8        .03
    3      3.00      26.96       .003        .01     263.39     2607.8        .08
    4      4.00      35.95       .005        .02     308.82     3055.1        .17
    5      5.00      44.94       .009        .04     350.77     3471.3        .32
    6      6.00      53.93       .014        .08     390.67     3857.5        .55
    7      7.00      62.91       .020        .12     427.76     4218.9        .87
    8      8.00      71.90       .028        .18     462.32     4557.8       1.31
    9      9.00      80.89       .038        .26     494.32     4876.7       1.90
   10     10.00      89.88       .050        .37     525.10     5173.3       2.64
   11     11.00      98.86       .064        .50     553.45     5452.4       3.58
   12     12.00     107.85       .081        .66     579.83     5714.0       4.74
   13     13.00     116.84       .101        .85     605.02     5955.7       6.14
   14     14.00     125.83       .124       1.09     627.77     6185.0       7.83
   15     15.00     134.81       .150       1.37     648.90     6399.3       9.82
   16     16.00     143.80       .180       1.69     669.35     6593.7      12.14
   17     17.00     152.79       .215       2.06     687.80     6778.1      14.85
   18     18.00     161.78       .253       2.50     705.18     6947.5      17.95
   19     19.00     170.76       .296       2.99     721.65     7107.0      21.49
   20     20.00     179.75       .345       3.55     736.14     7256.5      25.52
```

```
       DO      THICK         PO          TO      VOID  MIN CRAK  MAX CRAK         E
 (INCHES)  (INCHES)     (PSIA)    (DEG F)            (INCHES)  (INCHES)       (PSI)
-----------------------------------------------------------------------------------
  12.7500   .844000    1035.00     548.77    1.0000    1.0000   20.0000 25600000.

 ITER     CRACK      ANGLE      AREA       FLOW     EXIT-P      FLUX      FLOW
       (INCHES)  (DEGREE)   (SQ IN)  (LB/SEC)    (PSIA)  (KG/S/M2)  (GAL/MIN)
 --------------------------------------------------------------------------
    1      1.00       8.99      .000        .00    165.10     1650.3       .00
    2      2.00      17.98      .001        .00    169.80     1707.6       .02
    3      3.00      26.96      .002        .01    215.03     2132.5       .05
    4      4.00      35.95      .004        .02    252.03     2508.1       .11
    5      5.00      44.94      .007        .03    288.47     2855.8       .21
    6      6.00      53.93      .011        .05    321.91     3186.0       .35
    7      7.00      62.91      .016        .08    353.46     3499.9       .56
    8      8.00      71.90      .022        .12    384.53     3797.7       .85
    9      9.00      80.89      .029        .17    413.53     4083.1      1.22
   10     10.00      89.88      .038        .24    441.15     4355.9      1.71
   11     11.00      98.86      .049        .32    468.14     4615.1      2.32
   12     12.00     107.85      .062        .43    493.20     4864.3      3.07
   13     13.00     116.84      .077        .55    517.42     5101.0      3.99
   14     14.00     125.83      .094        .71    540.14     5327.8      5.09
   15     15.00     134.81      .113        .89    562.14     5542.1      6.40
   16     16.00     143.80      .135       1.10    582.87     5746.4      7.94
   17     17.00     152.79      .160       1.35    602.46     5940.8      9.73
   18     18.00     161.78      .189       1.64    621.01     6125.2     11.79
   19     19.00     170.76      .220       1.97    638.62     6299.6     14.16
   20     20.00     179.75      .255       2.34    655.37     6464.1     16.85

       DO      THICK         PO          TO      VOID  MIN CRAK  MAX CRAK         E
 (INCHES)  (INCHES)     (PSIA)    (DEG F)            (INCHES)  (INCHES)       (PSI)
-----------------------------------------------------------------------------------
  16.0000   .844000    1035.00     548.77    1.0000    1.0000   20.0000 25600000.

 ITER     CRACK      ANGLE      AREA       FLOW     EXIT-P      FLUX      FLOW
       (INCHES)  (DEGREE)   (SQ IN)  (LB/SEC)    (PSIA)  (KG/S/M2)  (GAL/MIN)
 --------------------------------------------------------------------------
    1      1.00       7.16      .000        .00    222.17     2206.6       .01
    2      2.00      14.32      .001        .00    191.87     1911.9       .02
    3      3.00      21.49      .003        .01    238.40     2368.0       .07
    4      4.00      28.65      .005        .02    278.59     2758.6       .15
    5      5.00      35.81      .009        .04    314.71     3118.7       .28
    6      6.00      42.97      .013        .06    349.74     3457.6       .46
    7      7.00      50.13      .019        .10    382.19     3777.8       .73
    8      8.00      57.30      .026        .15    412.92     4080.6      1.08
    9      9.00      64.46      .035        .22    442.69     4365.9      1.55
   10     10.00      71.62      .045        .30    470.37     4637.5      2.14
   11     11.00      78.78      .058        .40    496.50     4895.4      2.88
   12     12.00      85.94      .072        .53    521.74     5138.4      3.79
   13     13.00      93.11      .089        .68    545.17     5370.1      4.88
   14     14.00     100.27      .108        .86    567.40     5589.4      6.19
   15     15.00     107.43      .131       1.07    588.56     5796.3      7.73
   16     16.00     114.59      .156       1.32    608.28     5993.1      9.52
   17     17.00     121.75      .184       1.61    626.76     6180.0     11.60
   18     18.00     128.92      .216       1.94    644.54     6354.5     13.99
   19     19.00     136.08      .251       2.32    661.31     6518.9     16.70
   20     20.00     143.24      .290       2.75    677.16     6673.4     19.77
```

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 15

```
       DO     THICK        PO        TO      VOID  MIN CRAK  MAX CRAK          E
 (INCHES)  (INCHES)    (PSIA)   (DEG F)            (INCHES)  (INCHES)      (PSI)
**********************************************************************************
  16.0000  1.031000   1035.00    548.77    1.0000    1.0000   20.0000  25600000.

    ITER     CRACK     ANGLE       AREA      FLOW    EXIT-P      FLUX      FLOW
          (INCHES)  (DEGREE)    (SQ IN)  (LB/SEC)    (PSIA) (KG/S/M2) (GAL/MIN)
          ***************************************************************
       1      1.00      7.16       .000       .00    144.10    1434.7       .00
       2      2.00     14.32       .001       .00    155.01    1560.6       .02
       3      3.00     21.49       .002       .01    194.68    1943.1       .05
       4      4.00     28.65       .004       .01    228.23    2273.3       .10
       5      5.00     35.81       .007       .03    259.76    2572.9       .18
       6      6.00     42.97       .010       .04    287.75    2859.5       .30
       7      7.00     50.13       .015       .07    317.12    3131.1       .48
       8      8.00     57.30       .020       .10    343.63    3392.8       .71
       9      9.00     64.46       .027       .14    368.79    3644.5      1.01
      10     10.00     71.62       .035       .19    393.27    3886.2      1.40
      11     11.00     78.78       .045       .26    417.30    4117.9      1.88
      12     12.00     85.94       .056       .34    439.87    4342.2      2.47
      13     13.00  9[illegible]   .069       .44    461.79    4557.8      3.19
      14     14.00  100.[illegible] .083      .56    483.10    4764.6      4.05
      15     15.00    107.43       .100       .70    503.43    4964.0      5.06
      16     16.00    114.59       .119       .87    522.88    5155.8      6.25
      17     17.00    121.75       .140      1.06    541.55    5340.2      7.62
      18     18.00    128.92       .163      1.28    559.48    5517.2      9.20
      19     19.00    136.08       .190      1.53    576.72    5686.6     11.01
      20     20.00    143.24       .219      1.82    593.81    5846.1     13.06
```

References

1) MPR Calculation, "CIRFLO (Versi[illegible] Documentation", by R. Coward, [illegible]/90.

2) Crane Technical Paper, No. 410, "Flow of Fluids Through Valves, Fittings, and Pipe".

3) CE Power Systems Steam Tables

4) 1993 ASME Boiler + Pressure Vessel Code, Section III, Appendices

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT MPR	PAGE 1 OF 17
PROJECT Leakage Rates Out of Pipe Cracks	TASK NO. 10-13
CALCULATION TITLE CIRFLO Documentation (Version 2.0)	CALCULATION NO. (OPTIONAL) RNC10-13-01

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
10/4/90	10-12-90	H.D. 12-17-90	0

Purpose - This calculation documents the CIRFLO computer program (Version 2.0). The CIRFLO program calculates the leakage out of circumferential throughwall cracks in pipes. The program theory is discussed, the required input listed, a program listing supplied and a comparison is made to published test data.

<u>Method</u>. The method used to calculate the leakage from circumferential pipe cracks is the same as the method used in Reference 1.

This method uses a control volume approach to obtain the leakage flow through the crack by solving the mass, momentum, and energy conservation equations for a series of control volumes inside the crack. The effects of friction and critical flow are included in the analytic model and comparison of calculated results obtained from the model to emperial data have been used to demonstrate that the model gives conservative results.

The crack opening area is defined as (from reference 2)

$$A = \frac{\sigma}{E}\left(2\pi R t\right) G \qquad (1)$$

A is the flow area

σ is the stress across the crack tip $= \frac{PR}{2t}$

R is the inside radius

t is the wall thickness

if $\lambda = \frac{a}{2\sqrt{Rt}}$ (a is crack length)

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

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

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4

The crack is divided into a number of control volumes through the wall thickness of the pipe (see Figure 1) and an initial guess for the mass flow rate through the crack is assumed. Conservation of mass requires that the flow through each control volume is the same, thus only one flow rate is required in the analysis. The pressure loss through the crack is described by a typical fL/D loss model, so the stagnation pressure drop between control volumes in the crack can be expressed as

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

P_o is the stagnation pressure

f is the friction factor

ΔL is the length of pipe wall thickness between the two control volumes (see Figure 1)

K is the K factor describing entrance or exit losses

D_h is the crack hydraulic diameter

$$D_h = \frac{2A}{L}$$

W is the mass flow rate (leak rate)

ρ is the local density

A is the crack flow area

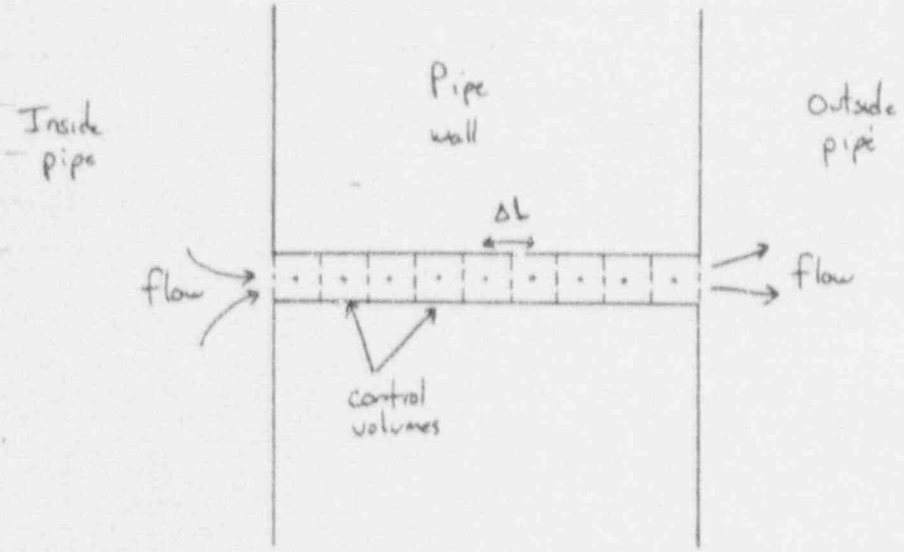


Figure 1

The flow in the crack is considered to be isenthalpic, or

$$h_0 = \text{stagnation enthalpy} = \text{constant} \qquad (3)$$

Equations 2 and 3 are used to calculate the stagnation pressure and enthalpy at the center of each control volume. [Homogeneous equilibrium flow is assumed since this tends to underpredict the flow rate, which is conservative for a leak-before-break analysis]. At each control volume, the critical flow rate based on the stagnation pressure in that control volume is compared to the assumed flow. The critical flow is

$$W_{crit} = A\, G_{crit}(P_0, h_0)$$

W_{crit} is the critical flow out of the control volume

G_{crit} is the critical mass flux, which is a function of the control volume stagnation conditions

A is the flow area

If the assumed flow is greater than the critical flow for any control volume, the assumed flow is too great and is reduced. If the assumed flow is less than the critical flow for all control volumes, the calculated exit pressure (leaving the crack) is compared to the pressure outside the pipe. If the exit static pressure is greater than the outside pressure, the flow was too low (pressure losses were not great enough) and it is increased. If the exit static pressure is less than the outside pressure, the flow was too high (pressure losses were too great) and the flow is reduced. This iterative procedure (assume flow, calculate pressures, assume flow, calculate pressures . . .) is continued until one of two conditions is reached;

① the critical flow out of the last control volume is equal to the assumed flow, or ② with no critical flow, the exit static pressure is equal to the outside pressure. Either of these conditions is an acceptable solution.

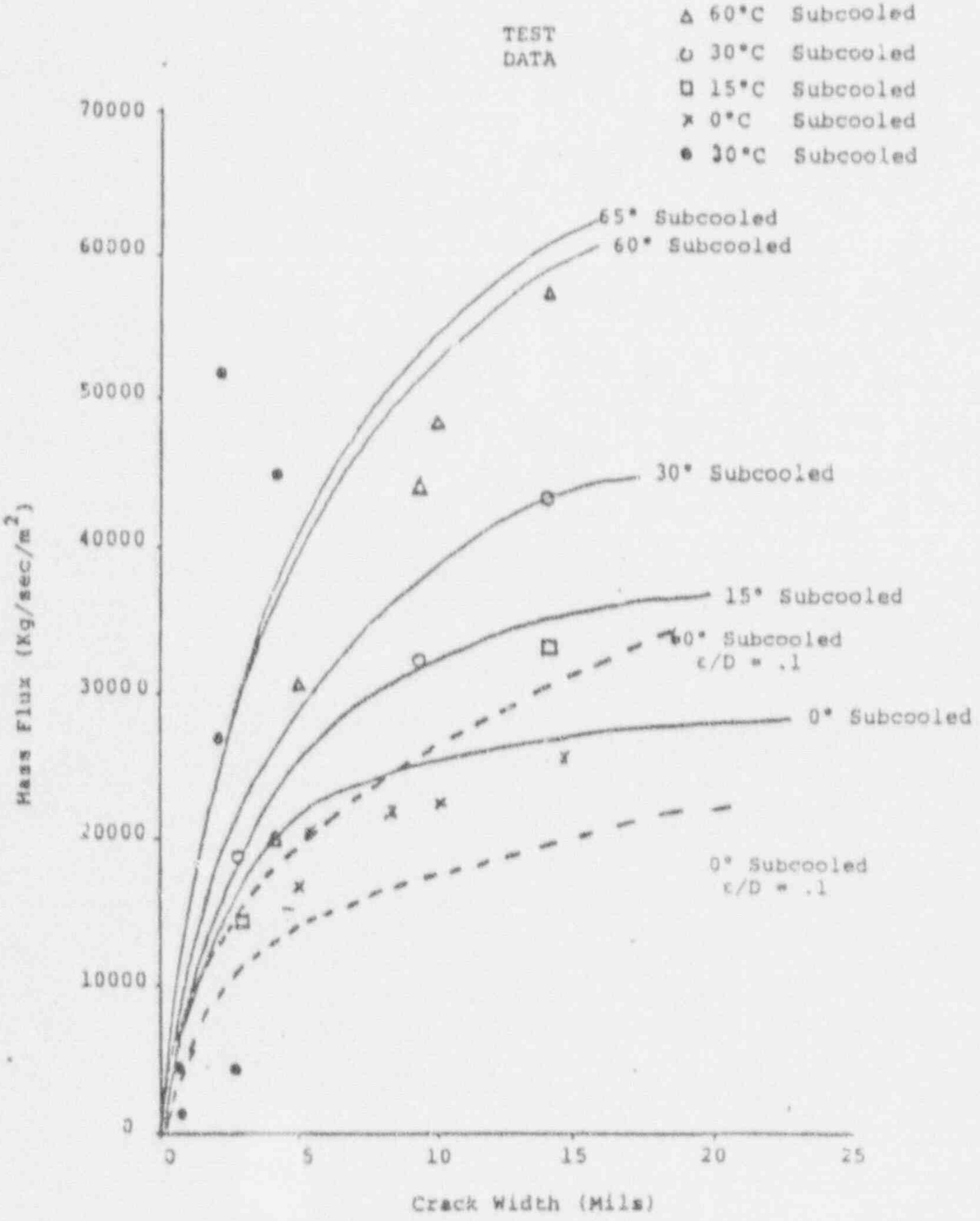
The solution method described above has been compared to test data and has shown to provide conservative results for the fluid conditions of interest (≈ 1000 psia, up to about 60° of subcooling). Figure 2 (from Reference 1) compares results using the above described method to test data. This calculation uses the same relative surface roughness, 0.1, as Reference 1. This value is recommended for small cracks.

It should be noted that the gallons/minute output of CIRFLO is in terms of gallons of water at atmospheric conditions, <u>not</u> the pipe conditions.

Figure 2

Comparison of Leakage Model with Test Data

Test Data from References 3 + 4



The data used to construct the $\varepsilon/D = 0.1$ case results in Figure 2 is shown below:

$OD = 28.0''$

$t = 1.05''$

$P = 1045$ psia ($T_{SAT} = 549.9°F$)

$E = 25.5 \times 10^6$ psi

Case 1 - 0°F Subcooling $T = 549.9°F$

Case 2 - 60°F Subcooling $T = 489.9°F$

The CIRFLO Output is on the following page. The data used in Figure 2 is shown below assuming rectangular crack openings (Area = Length * width)

Length	Area	Width	Flux 0° Subcooled	Flux 60° Subcooled
6.0"	0.017 in^2	2.8 mils	11369	16428
10.5"	0.054 in^2	5.4 mils	14648	21343
15.0"	0.146 in^2	9.7 mils	17665	27054
20.0"	0.309 in^2	15.5 mils	19682	31902

```
CIRFLO- CALCULATION OF FLOW THROUGH CIRCUMFERENTIAL PIPE CRACKS
  VERSION 2.0
 TODAY'S DATE:  10/05/90

CIRFLO TEST DATA COMPARISON - ROUGHNESS=0.1

 NUMBER OF CRACKS EACH CASE ---    15
 NUMBER OF ELEMENTS IN CRACK --    15
 CRACK FLOW (0) OR LENGTH (1) -     1
 RELATIVE ROUGHNESS -----------    .10000

      DO      THICK          PO         TO      VOID  MIN CRAK  MAX CRAK         E
 (INCHES)  (INCHES)     (PSIA)    (DEG F)             (INCHES)  (INCHES)     (PSI)
***********************************************************************************
  28.0000  1.050000    1045.00     549.90     .0000    6.0000   20.0000 25500000.

  ITER      CRACK     ANGLE       AREA       FLOW    EXIT-P      FLUX       FLOW
          (INCHES)  (DEGREE)    (SQ IN)  (LB/SEC)    (PSIA) (KG/S/M2)  (GAL/MIN)
        **************************************************************************
     1       6.00     24.56       .017        .27    540.07   11368.5       1.97
     2       7.00     28.65       .024        .41    574.58   12251.8       2.98
     3       8.00     32.74       .032        .60    605.78   13082.0       4.31
     4       9.00     36.83       .042        .83    630.77   13889.4       6.00
     5      10.00     40.93       .054       1.13    654.17   14647.5       8.11
     6      11.00     45.02       .068       1.48    677.37   15345.0      10.67
     7      12.00     49.11       .084       1.91    699.01   15997.1      13.74
     8      13.00     53.20       .102       2.41    719.35   16603.6      17.36
     9      14.00     57.30       .123       3.00    738.57   17164.6      21.57
    10      15.00     61.39       .146       3.67    757.58   17665.0      26.41
    11      16.00     65.48       .173       4.44    775.49   18119.9      31.93
    12      17.00     69.57       .202       5.30    793.02   18514.1      38.13
    13      18.00     73.67       .234       6.28    807.79   18908.4      45.18
    14      19.00     77.76       .270       7.39    819.88   19317.8      53.19
    15      20.00     81.85       .309       8.63    831.72   19681.7      62.07

      DO      THICK          PO         TO      VOID  MIN CRAK  MAX CRAK         E
 (INCHES)  (INCHES)     (PSIA)    (DEG F)             (INCHES)  (INCHES)     (PSI)
***********************************************************************************
  28.0000  1.050000    1045.00     489.90     .0000    6.0000   20.0000 25500000.

  ITER      CRACK     ANGLE       AREA       FLOW    EXIT-P      FLUX       FLOW
          (INCHES)  (DEGREE)    (SQ IN)  (LB/SEC)    (PSIA. (KG/S/M2)  (GAL/MIN)
        **************************************************************************
     1       6.00     24.56       .017        .40    559.41   16428.2       2.84
     2       7.00     28.65       .024        .59    588.11   17575.4       4.28
     3       8.00     32.74       .032        .86    603.34   18772.7       6.18
     4       9.00     36.83       .042       1.21    609.83   20079.0       8.68
     5      10.00     40.93       .054       1.64    616.12   21343.3      11.82
     6      11.00     45.02       .068       2.18    622.70   22557.4      15.69
     7      12.00     49.11       .084       2.83    629.02   23738.0      20.38
     8      13.00     53.20       .102       3.62    635.46   24876.8      26.00
     9      14.00     57.30       .123       4.54    641.80   25982.1      32.66
    10      15.00     61.39       .146       5.62    648.07   27053.8      40.45
    11      16.00     65.48       .173       6.88    654.30   28092.1      49.50
    12      17.00     69.57       .202       8.33    660.52   29096.9      59.93
    13      18.00     73.67       .234       9.99    666.93   30059.8      71.82

    14      19.00     77.76       .270      11.87    673.12   30997.6      85.34
    15      20.00     81.85       .309      13.99    679.31   31901.9     100.60
```

A program listing of CIRFLO is included on the following pages. The required input is described below:

line 1: a problem title (80 characters max)
line 2: NITER, NUMEL, NCRAK, ROUGH [3I5, F10 format]

NITER is the number of crack lengths to be evaluated for each data set
NUMEL is the number of control volumes representing the crack (at least 10 recommended)
NCRAK - if NCRAK=0, enter range of crack sizes by specifying an approximate range of leakage rates (see below)
if NCRAK=1, enter range of crack sizes by specifying minimum and maximum crack sizes (see below)
ROUGH is the relative roughness

line 3: DO, THICK, PO, TO, VOIDO, GALMIN, GALMAX, E [8F10 format]

DO is the pipe diameter (inches)
THICK is the pipe wall thickness (inches)
PO is the pipe fluid stagnation pressure (psia)
TO is the pipe fluid temperature (°F)
VOIDO is the pipe fluid void fraction
GALMIN - if NCRAK=0, GALMIN is an approximate leakage rate (GPM) for the minimum crack size. if NCRAK=1, it is the minimum crack size (inches)
GALMAX - same as GALMIN but maximum crack
E - pipe modulus of elasticity (psi)

[Note: line 3 cards may be repeated to evaluate several data sets]

```
$STORAGE:2
      PROGRAM CIRFLO
C***********************************************************************
C     CALCULATES FLOW THROUGH CIRCUMFERENTIAL CRACKS IN PIPES
C     VERSION 2.0 - 10/4/90
C***********************************************************************
      CHARACTER*1 FF,DASH
      CHARACTER*10 TITLE,ADATE
      COMMON/TITE/ TITLE(8)
      COMMON/FRICK/ROUGH
      DIMENSION PSC(20),TSC(20),VOIDC(20)
      DATA PI,FACT,GALPP/3.1415926,144.0,448.831/
      DATA DASH/'-'/
      DATA PEX/14.7/
      DATA RHOW/62.4/
      FF=CHAR(12)
      CALL DATE(ADATE)
      OPEN(5,FILE='CIRFLO.INP',STATUS='OLD')
      OPEN(6,FILE='CIRFLO.OUT',STATUS='UNKNOWN')
      WRITE(*,3000)
      WRITE(6,1500) FF,ADATE
      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)
      PON=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,[illegible]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,/1X,12H VERSION 2.0,/,1X,14HTODAY'S DATE: ,A10,/)
 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,[illegible],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
```

References

① "Method for Calculation of Leak Flow Rate which Can Pass Through a Crack in a Pipe", H. Giesecke, April 24, 1984.

② "Estimation of Stress Intensity Factors and the Crack Opening Area of a Circumferential and a Longitudinal Through-Crack in a Pipe", by H. Tada and P. Paris. (Included by NRC with Guidelines for Leak Before Break Analyses of High Energy Piping in SWP plants)

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

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

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPUN	PAGE 1 OF 5
PROJECT ICS Piping LBB	TASK NO. 83-133
CALCULATION TITLE Fracture Mechanics Crack Sizes	CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
R. Carl 4/1/91	J C Hall 4/2/91	J S Nestell 4-17-91	0

Purpose - This calculation documents the pipe cross-section geometries and through-wall crack lengths to be used in leak-before-break fracture mechanics evaluations of the Oyster Creek Isolation Condenser System (ICS) piping outside the drywell.

Results - The ICS condensate return and steam supply piping contain different sizes of pipe. These are listed below along with the crack size corresponding to a 2.0 GPM leakage rate (and the percentage of the pipe circumference). The labeling convention used is DDSSSF where DD is the nominal pipe diameter, SSS is the pipe schedule and F is the fluid, C for condensate, S for steam.

Pipe	OD (in)	t (in)	θ (deg)	a/b
08080C	8.625	0.50	76	0.211
08100C	8.625	0.594	86	0.239
10080C	10.75	0.594	64	0.178
10100C	10.75	0.719	73	0.203
10080S	10.75	0.594	93	0.258
10100S	10.75	0.719	106	0.294
12080S	12.75	0.688	82	0.228
12100S	12.75	0.844	94	0.261
16080S	16.00	0.844	70	0.194
16100S	16.00	1.031	80	0.222

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3
		A.C. Hall	

Calculation. Leak-before-break fracture mechanics analyses are to be performed as part of an evaluation to demonstrate that the probability of unstable pipe rupture in the ICS piping outside the drywell is insignificantly small. As part of this evaluation, conservative estimates of through-wall crack leakage rate as a function of crack size were calculated for each pipe size in the ICS piping (Reference 1).

The leakage detection capabilities for the ICS piping have been evaluated with the determination that leak rates as low as 0.2 GPM can easily be detected. From Reference 2, the postulated through-wall crack sizes for leak-before-break evaluations are the crack sizes corresponding to a leak rate of 10 times the detectable rate or, in this case, 2.0 GPM.

The crack sizes corresponding to 2.0 GPM are determined by interpolating the leak rate results in Reference 1 and are shown on the following page. The pipe cross section dimensions for each case are also listed. The labeling scheme used is DDSSSF where DD is the pipe diameter, SSS is the pipe schedule and F indicates the fluid, condensate or steam.

For convenience in performing fracture mechanics calculations, the postulated crack sizes are also expressed in terms of percentage of the pipe circumference (a/b). (Pipe Dimensions from Ref 1)

Pipe	OD (in)	t (in)	θ_{2GPM} (deg)	a (in)	$\theta/360$
08080C	8.625"	0.50"	76	5.72	0.211
08100C	8.625"	0.594"	86	6.47	0.239
10080C	10.75"	0.594"	64	6.00	0.178
10100C	10.75"	0.719"	73	6.85	0.203
10080S	10.75"	0.594"	93	8.72	0.258
10100S	10.75"	0.719"	106	9.94	0.294
12080S	12.75"	0.688"	82	9.12	0.228
12100S	12.75"	0.844"	94	10.46	0.261
16080S	16.00"	0.844"	70	9.77	0.194
16100S	16.00"	1.031"	80	11.17	0.222

References

1) MPR Calculation, "Leakage Flow Rates", by R. Conrad,

2) USNRC Standard Review Plan Section 3.6.3 (For Comment), 8/28/87

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPU Nuclear	PAGE 1 OF 46
PROJECT Oyster Creek Isolation Condenser System Leak Before Break	TASK NO. 83-133
CALCULATION TITLE Isolation Condenser System Fatigue Usage	CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
D. Jacobs 3/21/91	E. Schiman 4/3/91	4/3/91	0

A. Purpose: To assess the fatigue usage of the Oyster Creek Nuclear Generating Station Isolation Condenser System (ICS) piping outside the drywell.

B. Results: The largest usage factors in the isolation condenser system occur in the B-Condensate line. They are:

Description	Node #	Usage Factor
8-inch pipe connection to condenser nozzle	C28	0.1740
flued collar connection to 10-inch pipe	B20	0.1336
10-inch pipe connection to valve (end of valve towards reactor pressure vessel)	C01	0.1336
center of 8-inch by 10-inch tee	C11	0.1429

Table of Contents:

C. Background:

The Oyster Creek ICS consists of two condensers, NE-01-A and NE-01-B. A steam line goes to each condenser from the reactor pressure vessel, and a condensate return line goes from each condenser back to the reactor pressure vessel (through the reactor recirculation piping or shutdown cooling piping). In this calculation, each line is treated as a separate piping system. The systems are called A-Steam, A-Condensate (condenser NE-01-A), and B-Steam, B-Condensate (condenser NE-01-B).

Isolation valves are located in the steam and condensate lines as shown below. During startup and normal operation, the three valves outside the drywell are opened and the one valve inside the drywell is closed. e ICS does not operate during startup , normal plant operation, reduction of power, or during a change from plant operating to hot standby.

During a SCRAM and during a change from plant operating (or hot standby) to shutdown, the normally closed valve in the return line is opened and the ICS operates.

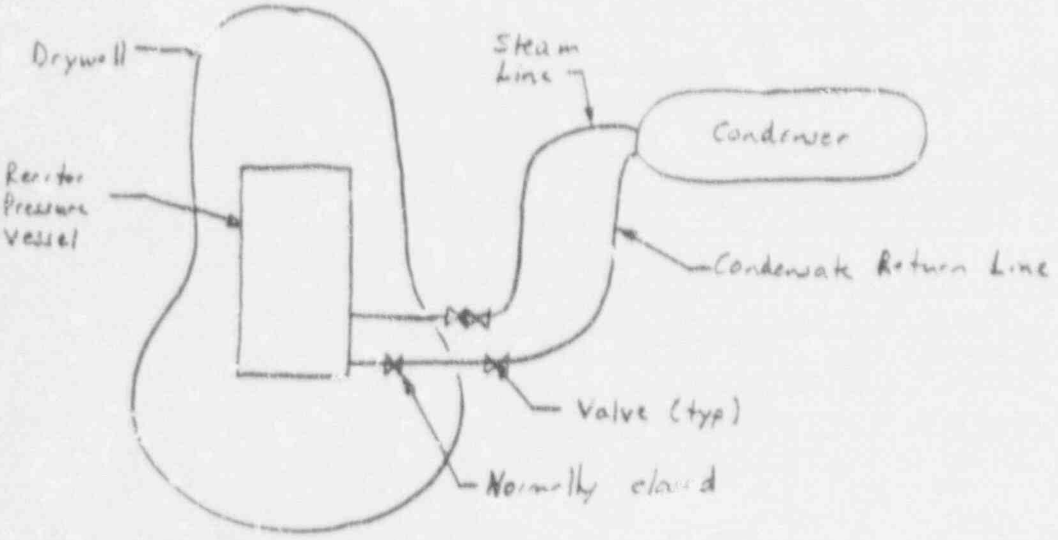


Figure 1. Isolation Valve Locations in ICS Piping

D. Calculation: Operating Conditions

Note: Cold = 0 psi, 70°F } For steam and
Hot = 1250 psi, 575°F } condensate lines
(Ref 2, App C)

a. Heatup from Cold to Plant Operating:

Since the valves in the steam lines are opened, the steam line piping heats and pressurizes at the same rate as the reactor pressure vessel (< 100°F/hr). The stress range in the steam lines during heatup is due to internal pressure, thermal expansion of the piping, and anchor motions.

Since the valves in the condensate lines are closed, the condensate lines stay relatively cold during plant heatup and during normal plant operation; however, they are pressurized at the same rate as the reactor pressure vessel. The stress range in the condensate lines during heatup is due to internal pressure and anchor motions (of drywell and condensers).

b. Reduction in Power:

A reduction in plant power does not significantly change the pressure or temperature the ICS piping. It is assumed that there are no cyclic stresses in the ICS piping during a reduction in power.

c. Change from Plant Operating to Hot Standby:

A change from plant operating to hot standby does not significantly change the pressure or temperature in the ICS piping. It is assumed that there are no cyclic stresses in the ICS piping during a change from plant operating to hot standby.

d. Plant Operating (or Hot Standby) to Cold Shutdown (including SCRAM):

The steam line piping cools down and depressurizes at the same rate as the reactor pressure vessel (less than 100°F/hr.). The stress range in the steam lines during shutdown is the same as that for heatup.

The condensate line piping experiences a sudden

perature jump from cold to hot when the hot condensate begins flowing upon ICS activation. This causes thermal gradients through the pipe wall. As the ICS operates, the condensate lines cool down and depressurize at the same rate as the reactor pressure vessel. The stress range in the condensate lines during shutdown is due to internal pressure, thermal expansion, anchor motions and thermal gradients through the pipe wall.

Note: The steam lines are configured as shown below.

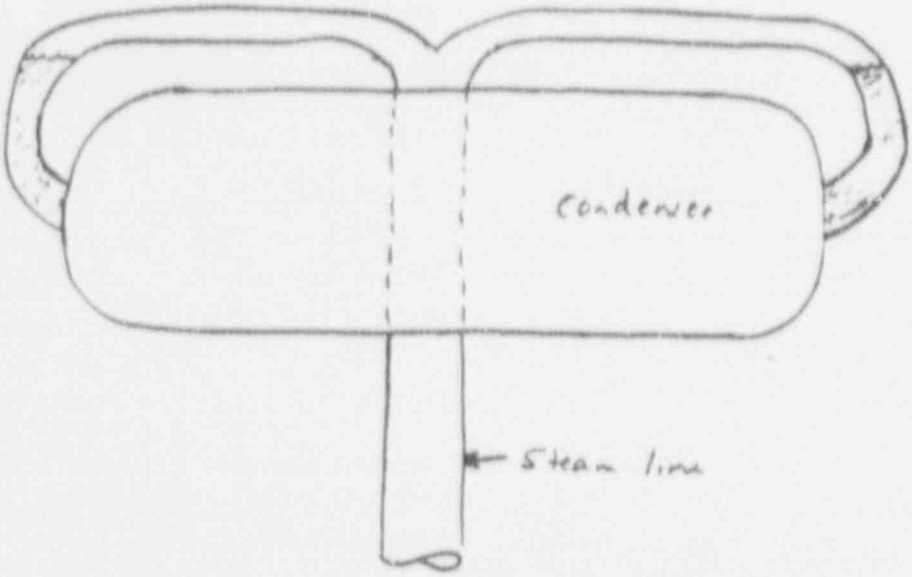


Figure 2. Steam Line Configuration (Ref 2, App A)

During plant operation, the steam near the condenser condenses and becomes trapped in the vertical run of pipe as shown. It is conservatively assumed that this condensate is at ambient temperature. Therefore, through-wall gradients occur in these vertical runs upon ICS activation, and these local vertical runs in the steam supply lines are treated as condensate return lines in this calculation.

Fatigue Cycles

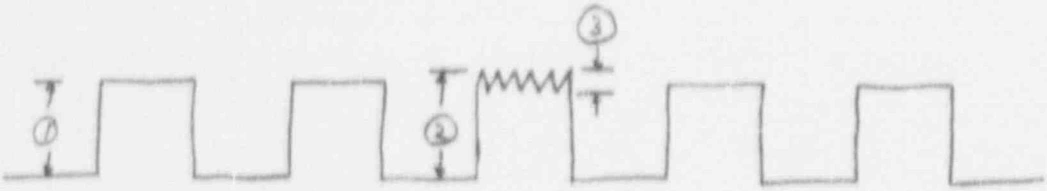


Figure 3. Cycle Definitions

Assume 400 cycles of cold to hot to cold (10 cycles/year for 40 years; Ref 7) and 5 Operating Basis Earthquakes (OBE) with each earthquake contributing 10 cycles peak stress. See Tables I and II on the next page for a description of the cycle types, number of cycles, and stresses which contribute to each cycle type.

Table I. Steam Line Cycles

Cycle Type	Description	Contributing Stresses	# Cycles
①	Heatup from cold to plant operating	a. Internal pressure b. Moment due to thermal expansion and anchor motions	395
②	Heatup from cold to plant operating plus OBE	a. Internal pressure b. Moment due to thermal expansion, anchor motions, and seismic effects	5
③	OBE	a. Moment due to seismic effects	50

Table II. Condensate Line Cycles

Cycle Type	Description	Contributing Stresses	# Cycles
①	Plant operating to cold shutdown	a. Internal pressure b. Moment due to thermal expansion and anchor motions c. Stress due to thermal gradient through pipe wall	395
②	Plant operating to cold shutdown plus OBE	a. Internal pressure b. Moment due to thermal expansion, anchor motions, and seismic effects c. Stress due to thermal gradient through pipe wall	5
③	OBE	a. Moment due to seismic effects	50

Analysis Locations

Locations at which to perform a fatigue analysis were chosen based on the following procedure:

1. The highly stressed and moderately stressed locations were identified in each piping system (A, B-Steam; A, B-Condensate).
2. The stress intensification factors (SIF) were determined for selected fittings and weld transition geometries present in the ICS system which engineering judgement identified as having the potential for large stress intensification factors.
3. Locations were chosen based on high stress, high stress plus high SIF, or moderate stress plus high SIF.
4. Another factor in location selection was the presence or nonpresence of stresses due to a thermal gradient through the pipe wall. Stresses due to a thermal gradient typically constitute a significant portion of the total peak stress.

Analysis locations are shown in Table III.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schrimer	12

Table III. Analysis Locations

Description	Pipe System	Node #	Rationale
8-inch pipe connection to concentric reducer	A-Condensate	C03	Moderate stress, High SIF, Thermal gradient
8-inch by 10-inch 45° lateral connection to 8-inch 45° bend	A-Condensate	D02N	Moderate stress, High SIF, Thermal gradient
flued collar connection to 10-inch pipe (no thermal gradient)	B-Steam	A11 (seg B)	High stress
10-inch pipe connection to valve (no thermal gradient)	B-Steam	B01-	High stress
valve connection to valve (10-inch)	B-Steam	B05	High stress, High SIF
10-inch valve connection to eccentric reducer	B-Steam	B09+	High stress, High SIF
flued collar connection to 10-inch pipe (with thermal gradient)	B-Condensate	B20 (seg C)	Moderate stress, Thermal gradient
8-inch and 12-inch pipe connection to condenser nozzles	B-Steam B-Condensate	D17 C28	High stress, High SIF, Thermal gradient

Table III. Analysis Locations (Continued)

Description	Pipe System	Node #	Rationale
10-inch pipe connection to valve, sch 100 (with Thermal gradient)	B-Condensate	C01 -	Moderate stress, Thermal gradient
butt weld (8-inch)	B-Condensate	D08 +	High stress, Thermal Gradient
center of 8-inch by 10-inch tee	B-Condensate	C11 - (seg C) C11 (seg D)	High stress, High SIF, Thermal gradient
center of 8-inch by 10-inch lateral	A-Condensate	B09 (seg B) B09 (seg D)	Moderate stress, High SIF, Thermal gradient

<u>Conclusions and notes concerning the selected locations</u>:

1. No locations on the A-Steam line were chosen because the B-Steam line stresses are consistently higher and the geometry is similar.

2. No locations were chosen on 16-inch pipe (located in the steam lines) because the stresses are low compared to the stresses in other pipe sizes. Also, there are no stresses present due to thermal gradient through the pipe wall.

3. The 10-inch pipe connection to valve and the 10-inch pipe connection to flued collar configurations were chosen twice each:

   - B-Steam line: high stress but no thermal gradient
   - B-Condensate line: moderate stress <u>with</u> a thermal gradient

4. The 16" X 12" X 12" reducing wyes (located in the steam lines) were not chosen because the stresses are enveloped by the 8" X 10" tee (B-condensate),

i.e. the SIF's are similar, the stresses are similar, the wall thickness of the wyes is larger, and there is no thermal gradient in the wyes (there *is* a thermal gradient in the tee).

5. The locations chosen are typically connection points to fittings, although one straight butt weld was chosen based on high stress.

6. On the condensate line valves, the joint closest to the drywell will be schedule 100 while the joint farthest from the drywell will be schedule 80. Only the schedule 100 joint was chosen as an analysis location because the stresses are higher than in the schedule 80 joint.

Peak Stress Intensity (S_p), Alternating Stress Intensity (S_{alt}), and Usage Factor Equations

Equation (11) from Section NB-3653.2 of the ASME Boiler and Pressure Vessel Code, 1989 Edition is used to determine the peak stress intensity range for the selected locations in the ICS piping systems (Ref 3).

Equation (11):

$$\boxed{S_p = K_1 C_1 \left(\frac{P_o D_o}{2t} \right) + K_2 C_2 \left(\frac{M_i D_o}{2I} \right) + \frac{1}{2(1-\nu)} K_3 E \alpha |\Delta T_1| + K_3 C_3 E_{ab} |\alpha_a T_a - \alpha_b T_b| + \frac{1}{(1-\nu)} E \alpha |\Delta T_2|}$$

Where: S_p = peak stress intensity range

K_1, K_2, K_3 = local stress indices

C_1, C_2, C_3 = secondary stress indices

P_o = range of service pressure

D_o = outside diameter of pipe

t = nominal wall thickness of product

M_i = resultant range of moment when the system goes from one load set to another

I = moment of inertia = $\frac{\pi}{64}(D_o^4 - D_i^4)$

ν = Poisson's ratio

E = modulus of elasticity at room temperature

α = mean coefficient of thermal expansion at room temperature

$|\Delta T_1|$ = absolute value of the range of temperature difference between the temperature of the outside surface and inside surface of the piping product (linear portion)

$|\Delta T_2|$ = nonlinear portion of $|\Delta T_1|$

E_{ab} = average modulus of elasticity of the two sides of a gross material or structural discontinuity

$\alpha_{a,b}$ = coefficient of thermal expansion on side a(b) of a gross structural or material discontinuity at room temperature

The alternating stress intensity range is found using $S_{alt} = S_p/2$ (Ref 3). The allowable number of cycles is then detetermined from Figure I-9.2.1, "Design Fatigue Curve for Austenitic Steels..." (Ref 5). Finally a usage factor is calculated using $U = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3}$ where n_i is the actual number of cycles and N_i is the allowable number of cycles. The usage factor must be less than 1.0.

The fourth term in Equation (11), $k_3 C_3 E_{ab} |\alpha_a T_a - \alpha_b T_b|$, accounts for gross structural or material discontinuities. There are no gross structural or material discontinuities in the ICS piping systems (Ref 2), so the fourth term is always zero and is dropped from Equation (11) for the remainder of this calculation.

The third and fifth terms in Equation (11) (those containing $|\Delta T_1|$ and $|\Delta T_2|$) account for thermal gradients through the pipe wall. The third and fifth terms are zero for the majority of the two steam lines (since through-wall gradients are not developed), but are relevant for the two condensate lines.

The first and second terms in Equation (11) account for pressure loadings and moment loadings due to thermal expansion, thermal anchor motions, and seismic loads. The first and second terms are relevant to both the steam and condensate lines.

For branch connections or tees, the pressure and moment terms of Equation (11) are discussed in Attachment 1.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 20
	D. Jacobs	Ed Schumer	

Material Properties (E, ν, α)

All replacement piping in the ICS piping systems is SA-376 TP 316(NG). All replacement fittings (wyes, reducers, tees, laterals) are SA-403 TP316 (NG) (Ref 2). Material properties for TP 316 (NG) are not listed in the ASME B&PV code; however, TP 316 (NG) meets or exceeds the yield strength, tensile strength, and elongation requirements for TP 316 (Ref 2, App B). Therefore the material properties for SA-376 TP316 and SA-403 TP316 are used in this calculation.

At 70°F:

$E = 28.3 \times 10^6$ psi
$\nu = 0.3$
} (Ref 2, App B)

$\alpha = 8.42 \times 10^{-6}$ in/in/°F (Ref 5, Table I-5.0 for 18 Cr - 13 Ni - 3 Mo Alloy Steel*)

* SA-376 and SA-403 TP316 are 16 to 18 Cr - 11 to 14 Ni - 2 to 3 Mo per Ref 6.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 21
	D. Jacobs	Ed Schuren	

Pressure Range (Po)

For type ① and ② cycles, the pressure changes from zero to 1250 psi; the pressure range is 1250 psi. For type ③ cycles the pressure range is zero.

Moments (Mi)

Moments are taken from an analysis of the piping systems to ANSI B31.1 Code requirements (Ref. 2).

For type ① cycles, moments are due to thermal expansion and thermal anchor motions. For type ② cycles, moments are due to thermal expansion, thermal anchor motions, and OBE. For type ③ cycles, moments are due to OBE. Moment calculations are shown in Attachment 3 for each location analyzed.

Pipe Outside Diameter, Wall Thickness, Moment of Inertia (D_o, t, I)

Pipe dimensions are taken from Reference 2, Appendix B.

Fitting dimensions are taken from Reference 4. Common pipe dimensions are shown in Table IV. Weld preparation dimensions are listed in Reference 10.

Table IV. Pipe Dimensions

Pipe Size		D_o (in)	t (in)	I (in^4)
8-inch	sch 80	8.625	0.500	105.7
	sch 100	8.625	0.594	121.3
10-inch	sch 80	10.750	0.594	244.8
	sch 100	10.750	0.719	286.1
12-inch	sch 80	12.750	0.688	475.1
	sch 100	12.750	0.844	561.6
16-inch	sch 80	16.000	0.844	1155.8
	sch 100	16.000	1.031	1364.5

NOTE:
Field change request no. C084320, 2/11/91, to Reference 10 allows the installation contractor for the ICS replacement piping to counterbore all weld preparations to nominal schedule 80 requirements (with some exceptions in the valve area).
Therefore, all joints are assumed to be schedule 80 in this calculation.

Temperature Gradient Through Pipe Wall (ΔT_1, ΔT_2)

The stresses in the pipe due to a temperature gradient through the pipe wall (which is caused by a sudden change in fluid temperature) are determined using the parameters ΔT_1 and ΔT_2. In this section of the calculation, ΔT_1 and ΔT_2 are determined for the two pipe sizes present in the ICS condensate lines (8-inch and 10-inch) and for the 12-inch piping present in the vertical runs of the steam lines near the condensers. The methods of Reference 9 are used.

The results are shown in Table V below.

Table V. ΔT_1 and ΔT_2 Values

Pipe Size	ΔT_1	ΔT_2
8-inch	379°F	86°F
10-inch	354°F	126°F
12-inch	343°F	86°F
10-inch by 8-inch tee and lateral	333°F	182°F

From Reference 9,

$$\Delta T_1 = (T_f - T_0)\, L_1$$

$$\Delta T_2 = (T_f - T_0)\, N_1$$

where: T_f = temperature of the fluid in the pipe after the temperature change = 575°F

T_0 = initial uniform temperature of the pipe wall = 70°F

L_1 = coefficient for linear variation of temperature through a pipe wall

N_1 = coefficient for nonlinear variation of temperature through a pipe wall

L_1 and N_1 are determined from the charts shown in Figures 4 and 5. The charts are for a step change in fluid temperature and depend on the log (base 10) of the Fourier number (N_F) and the Biot number (N_B):

$$N_B = \frac{ht}{k} \text{ (dimensionless)} \qquad N_F = \frac{\epsilon\theta}{t^2} \text{ (dimensionless)}$$

where: h = heat transfer coefficient
t = pipe wall thickness
k = pipe wall thermal conductivity

where: ϵ = thermal diffusivity of pipe material
t = pipe wall thickness
θ = time from start

The Biot numbers for the ICS condensate lines are shown in Reference 8 to be 6.4 for 8-inch pipe, 9.0 for 10-inch pipe, 4.5 for 12-inch pipe, and 17.2 for the 8-inch by 10-inch tee and lateral in the condensate lines. Schedule 100 pipe was used for the Biot number calculations in Reference 8 to conservatively obtain the largest Biot number for each pipe size. For ease of reading the charts shown in Figures 4 and 5, and to again be conservative, Biot numbers of 8.0 for 8-inch pipe, 10.0 for 10-inch pipe, 6.0 for 12-inch pipe and 20.0 for the tee and lateral are used in this calculation

Note: A fluid temperature of 550°F (vs. 575°F) was used in Reference 8 to calculate the Biot numbers. The difference is considered to be negligible.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 26
	D. Jacobs	Ed Schmi	

For this calculation, the Fourier number, N_F, goes from zero to infinity (i.e. time goes from zero to a very large number); therefore $\log_{10} N_F$ can = any value along the horizontal axis of Figures 4 and 5. To be conservative, the values of L_1 and N_1 used are those which maximize the value of S_p for a given Biot number (L_{max}, N_{max}) as shown below:

To maximize the value of S_p, it is necessary to maximize the following two terms in Equation (11):

$$\frac{1}{2(1-\nu)} k_3 E\alpha |\Delta T_1| + \frac{1}{(1-\nu)} E\alpha |\Delta T_2| .$$

Simplifying yields: $\frac{1}{(1-\nu)} E\alpha \left[\frac{k_3}{2} |\Delta T_1| + |\Delta T_2| \right]$ where: $\Delta T_1 = (T_f - T_o) L_1$
$\Delta T_2 = (T_f - T_o) N_1$

Thus: $\frac{1}{(1-\nu)} E\alpha (T_f - T_o) \left[\frac{k_3}{2} L_1 + N_1 \right]$

Therefore, to maximize the value of S_p, it is necessary to maximize the value of $\frac{k_3}{2} L_1 + N_1$

From pages 31 through 42 of this calculation:

$k_3 = 1.0$ or 1.7 for 8, 10, 12 inch pipe

$k_3 = 1.0$ for the tee and lateral in the condensate lines.

From the charts on the following pages:

- For N_B = 8, the maximum value of $\frac{k_1}{2}L_1 + N_1$ is 0.81 and is obtained at $\text{Log}_{10} N_F = -1.0$ using $k_3 = 1.7$.

The corresponding L_{max} and N_{max} values are 0.75 and 0.17 respectively, and ΔT_1 and ΔT_2 are:

$$\Delta T_1 = (575° - 70°)(.75) = 379°F$$

$$\Delta T_2 = (575° - 70°)(.17) = 86°F$$

- For N_B = 10, the maximum value of $\frac{k_1}{2}L_1 + N_1$ is 0.85 and is obtained at $\text{Log}_{10} N_F = -1.25$ using $k_3 = 1.7$.

The corresponding L_{max} and N_{max} values are 0.70 and 0.25 respectively, and ΔT_1 and ΔT_2 are:

$$\Delta T_1 = (575° - 70°)(.70) = 354°F$$

$$\Delta T_2 = (575° - 70°)(.25) = 126°F$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 28
	D. Jacobs	Ed Schimmer	

- For $N_B = \underline{6}$ the maximum value of $\frac{k_3}{2}L_1 + N_1$ is 0.75 and is obtained at $\text{Log}_{10} N_F = -1.0$ using $k_3 = 1.7$.
  The corresponding L_{max} and N_{max} values are 0.68 and 0.17 respectively, and ΔT_1 and ΔT_2 are:

$$\Delta T_1 = (575° - 70°)(.68) = 343° F$$

$$\Delta T_2 = (575° - 70°)(.17) = 86° F$$

- For $N_B = \underline{20}$ the maximum value of $\frac{k_3}{2}L_1 + N_1$ is 0.69 and is obtained at $\text{Log}_{10} N_F = -1.5$.
  The corresponding L_{max} and N_{max} values are 0.66 and 0.36 respectively, and ΔT_1 and ΔT_2 are:

$$\Delta T_1 = (575° - 70°)(.66) = 333° F$$

$$\Delta T_2 = (575° - 70°)(.36) = 182° F$$

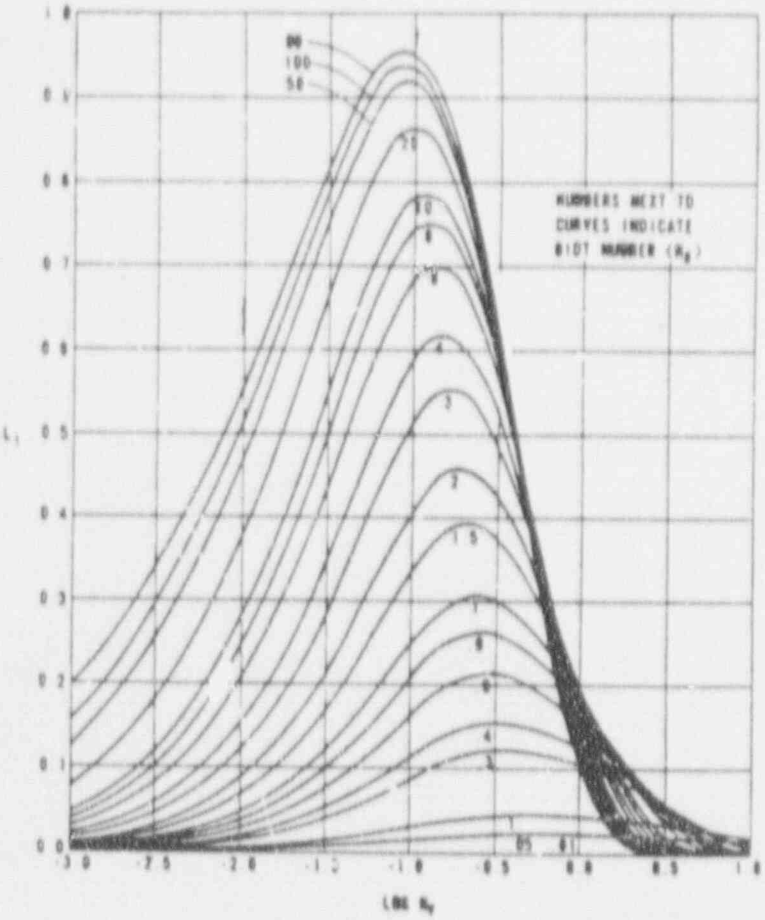


Figure 4

Coefficient L_1 for a Step Change in Fluid Temperature as a Function of the Common Logarithm of the Fourier Number for a Varying Biot Number (Ref 9).

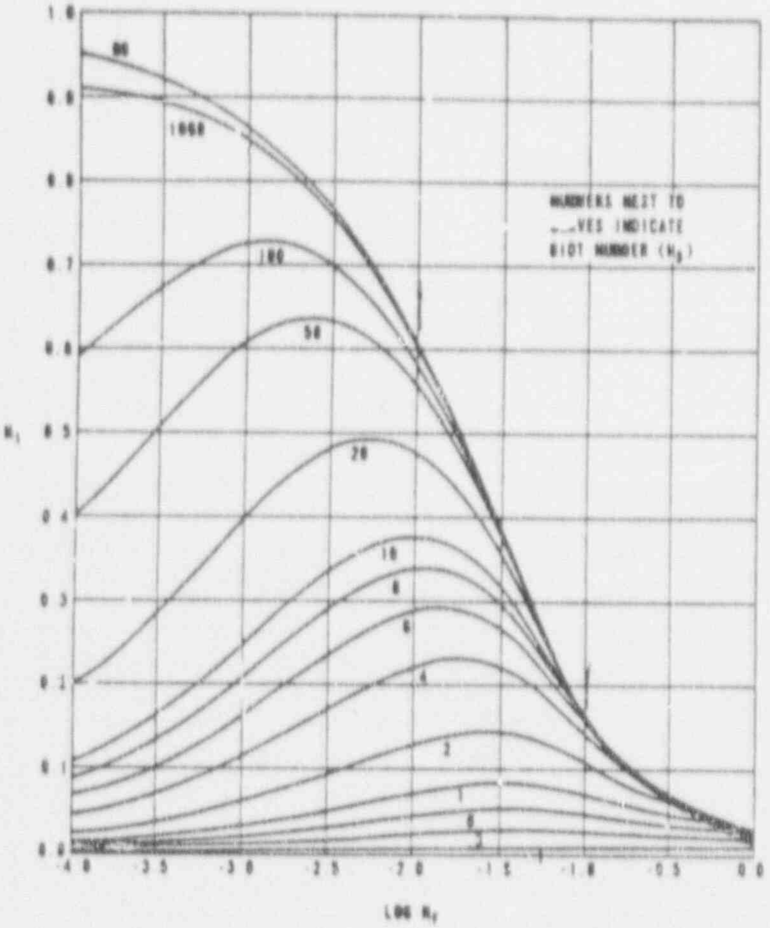


Figure 5

Coefficient N_1 for a Step Change in Fluid Temperature as a Function of the Common Logarithm of the Fourier Number for Varying Biot Number (Ref 9).

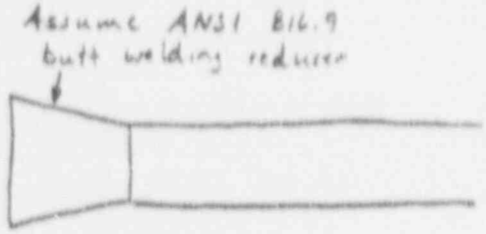
CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed [illegible]	31

Stress Indices (K_1, K_2, K_3, C_1, C_2)

Stress indices are taken from Table NB-3681(a)-1 of Reference 3 or calculated in accordance with section NB-3680 of Reference 3. Stress indices are tabulated on the following pages for each location analyzed. When stress indices were calculated in accordance with Reference 3 (NB-3680), the calculations are shown in Attachment 2.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	E.L. Schriner	32

A-Cond, Node C03: 8-inch Pipe Connection to Conc. Reducer



The reducer is assumed to be a ANSI B16.9 butt welding reducer. The joint is assumed to be as-welded with a transition within a 1:3 slope envelope. The stress indices are shown in Table VI. The set of indices which gives the largest value of S_p is used in this calculation.

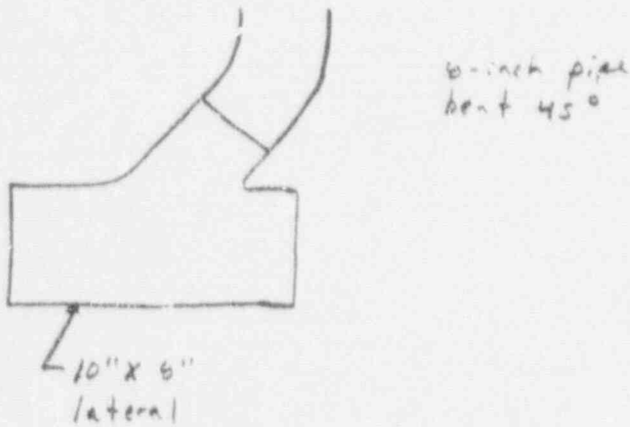
Table VI. Stress Indices, 8-inch Pipe Connection to Concentric Reducer

Index	Pipe Configuration	
	B16.9 Reducer	1:3 Slope
k_1	1.0 +	1.2 #
k_2	1.0 +	1.8 #
k_3	1.0 #	1.7 #
C_1	2.1 +	1.0 +
C_2	3.4 +	1.0 +

from Ref 3, Table NB-3681(a)-1   + calculated in attachment 2

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 33
	D. Jacobs	Ed Schummer	

Node : Connection of 8"x10" Lateral to 8-inch 45° bend



The bend is assumed to have the stress indices of curved pipe. The joint is assumed to have the stress indices of a transition with a 1:3 slope (as-welded). The stress indices are shown below. The set of indices which gives the largest value of Sp is used in this calculation.

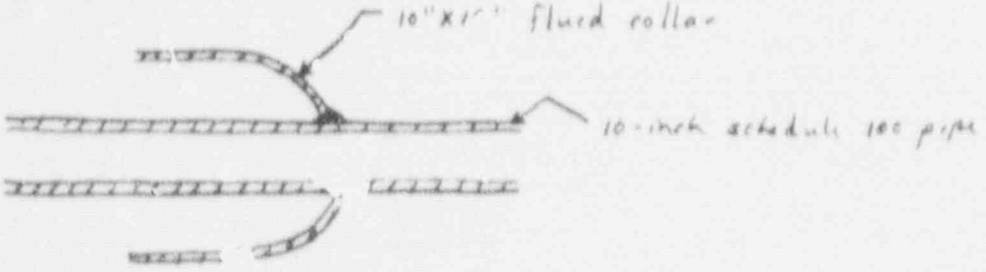
Table VII . Stress Indices 8"x10' Lateral to 8-inch 45° Bend

Index	Pipe Configuration		
		Curved Pipe	1:3 Slope
k_1		1.0*	1.2*
k_2		1.0*	1.8*
k_3		1.0*	1.7*
C_1		1.3+	1.0+
C_2		3.0+	1.0+

* from Ref 3, Table NB-3681(a)-1 + calculated in attachment 2

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 34
	D. Jacobs		

B-Steam, Node A11 }
B-Condensate, Node B2C } Flued Collar Connection to Pipe



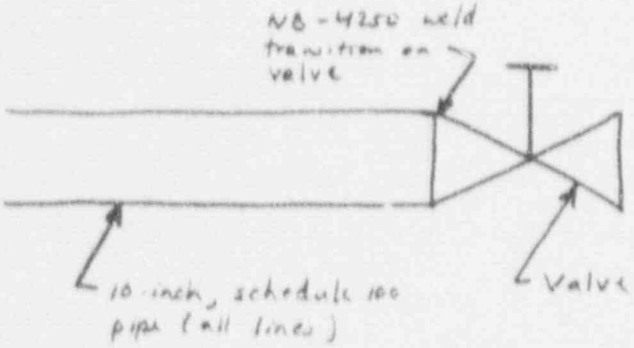
The set of stress indices used in this calculation for the + Flued collar to pipe joint is the set listed below which gives the largest value of Sp. As-welded conditions are assumed.

Table VIII. Stress Indices, Flued Collar Connection to Pipe

Index	Pipe Configuration		
	NB-4250 trans.	1:3 slope	butt weld
k_1	1.2*	1.2*	1.2*
k_2	1.8*	1.8*	1.8*
k_3	1.7*	1.7*	1.7*
C_1	1.2+	1.0+	1.0*
C_2	1.7+	1.5+	1.0*

* From Ref 3, Table NB-3681(a)-1
\+ calculated in attachment 2

<u>B-Steam, Node B01 -</u>
<u>B-Condensate, Node C01 -</u> } Pipe Connection to Valve



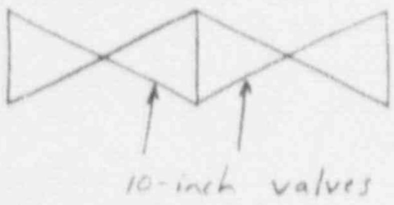
The joint is assumed to have the stress indices of an <u>NB-4250 weld transition</u> (as-welded). The stress indices are shown below.

Table IX. Stress Indices, Pipe Connection to Valve (Condensate and Steam Lines)

Index	NB-4250 transition
k_1	1.2 *
k_2	1.8 *
k_3	1.7 *
C_1	1.2 +
C_2	1.7 +

* from Ref 3, Table NB-3681(a)-1 + calculated in attachment 2

<u>B-Steam, Node B05:</u> Valve Connection to Valve



The joint is assumed to have stress indices that are <u>twice the value of a single NB-4250 transition</u> connected to 10-inch schedule 100 pipe.

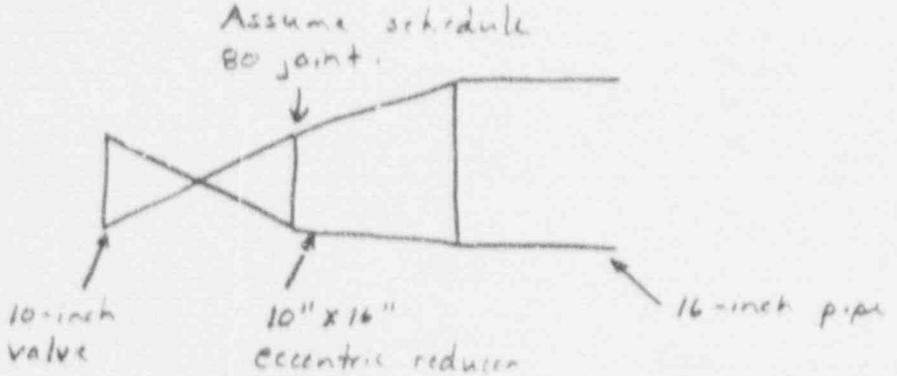
Table X . Stress Indices, Valve Connection to Valve

Index	NB-4250 transition X 2
k_1	2.4 *
k_2	3.6 *
k_3	3.4 *
C_1	2.4 +
C_2	3.4 +

* From Ref 3, Table NB-3681(a)-1
\+ calculated in attachment 2

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schrimmer	37

B-Steam, Node B09+ : 10-inch Valve Connection to Eccentric Reducer



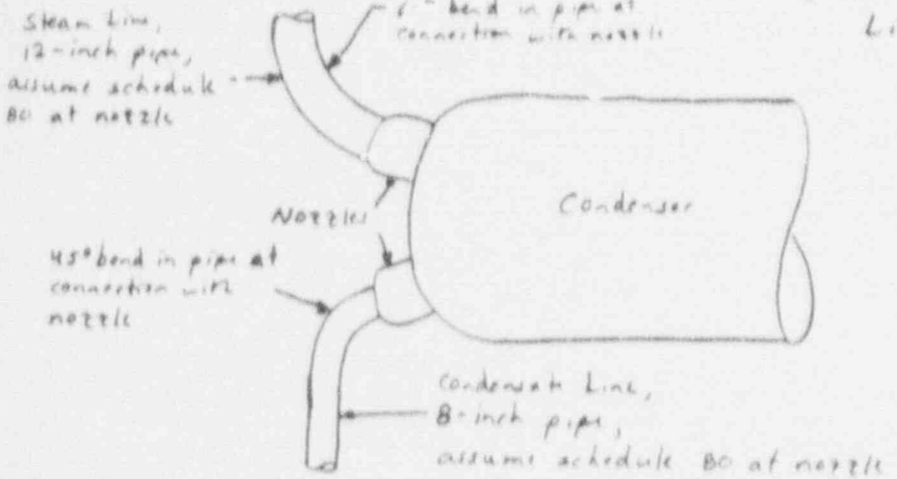
The reducer is assumed to be a ANSI B16.9 butt welding reducer. The joint is assumed to be as-welded with a NB-4250 transition. The stress indices are shown in Table XI. The set of indices which gives the largest value of Sp is used in this calculation.

Table XI. Stress Indices, 10-inch Valve Connection to Eccentric Reducer

Index	Pipe Configuration	
	B16.9 Reducer	NB-4250
k_1	1.0+	1.2*
k_2	1.1+	1.8*
k_3	1.0*	1.7*
C_1	2.2+	1.3+
C_2	3.4+	1.7+

* From Ref 3, Table NB-3681(a)-1   + calculated in attachment 2

<u>B-Steam, Node 017:</u>
<u>B-Cond, Node C28:</u> } Pipe Connection to Condenser Nozzles (Steam and Condensate Lines)



The bent pipe is assumed to have the stress indices of <u>curved pipe</u> in accordance with ANSI B16.9. The joints are assumed to have the stress indices of a <u>transition within a 1:3 slope envelope</u> (as-welded). The stress indices are shown in Tables XII and XIII. The set of indices which gives the largest value of S_p is used in this calculation.

Table XII. Stress Indices, Pipe Connection to Condenser Nozzles (Condensate Lines)

Index	Pipe Configuration	
	1:3 Slope	Curved Pipe
k_1	1.2*	1.0*
k_2	1.8*	1.0*
k_3	1.7*	1.0*
C_1	1.0+	1.3+
C_2	1.3+	3.9+

* from Ref 3, Table NB-3681(a)-1 + calculated in attachment 2

Pipe Connection to Condenser Nozzles, Cont'd:

Table XIII. Stress Indices, Pipe Connection to Condenser Nozzles (Steam Lines)

Index	Pipe Configuration	
	1:3 Slope	Curved Pipe
k_1	1.2^{*}	1.0^{+}
k_2	1.8^{*}	1.0^{+}
k_3	1.7^{*}	1.0^{+}
C_1	1.0^{+}	1.3^{+}
C_2	1.0^{+}	4.0^{+}

* From Ref 3, Table NB-3681(a)-1

\+ calculated in attachment 2

B-Cond, Node D08+: Butt Weld

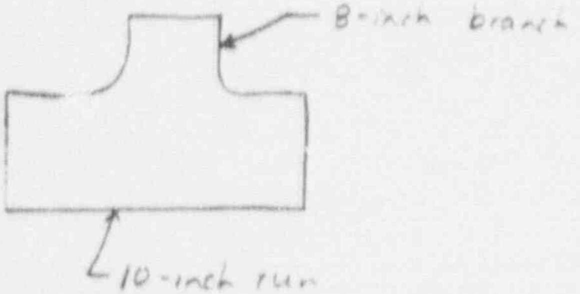
Butt welds are assumed to be as-welded. The stress indices are listed below.

Table XIV. Stress Indices, As-welded Butt Weld

Index	Pipe Butt weld *
K_1	1.2
K_2	1.8
K_3	1.7
C_1	1.0
C_2	1.0

* from Ref 3, Table NB-3681(a)-1

<u>B-Cond, Node C11-(seg C)</u>
<u>and Node C11 (seg D)</u> : Center of 8-inch by 10-inch tee



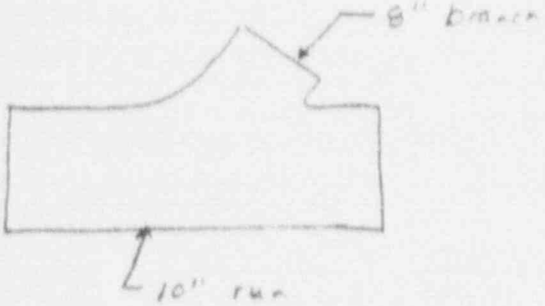
The tee is assumed to have the stress indices of a <u>ANSI B16.9 butt welding tee</u>. The stress indices are shown below.

Table XV . Stress Indices, Center of 8-inch by 10-inch Tee

Index	ANSI B16.9 Butt-welding Tee
k_1	4.0^*
k_2	$k_{2b} = k_{2r} = 1.0^+$
k_3	1.0^*
C_1	1.5^*
C_2	$C_{2b} = C_{2r} = 1.8^+$

* From Ref 3, table NB-3681(a)-1
\+ calculated in attachment 2

<u>A-Cond, Node B09 (seg A)</u>
<u>and Node B04 (seg D)</u> : Center of 8"x10" Lateral



The lateral is assumed to have the stress indices of a <u>ANSI B16.9 butt welding tee</u>. The stress indices are shown below.

Table XVI. Stress Indices, 8"x10" Lateral

Index	ANSI B16.9 Butt Welding Tee
k_1	4.0*
k_2	$k_{2b} = k_{2r} = 1.0$†
k_3	1.0*
C_1	1.5*
C_2	$C_{2b} = C_{2r} = 1.7$†

* from Ref 3, Table NB-3691(a)-1
† calculated in attachment 2

E. Conclusions

The peak stress intensity range, alternating stress intensity range, and usage factor for each location analyzed are calculated in Attachment 4. The usage factor for each location is tabulated below.

Table XVII Usage Factors

Description	Pipe System	Node #	Usage
8-inch pipe connection to concentric reducer	A-Condensate	C03	0.0953
8-inch by 10-inch 45° lateral connection to 8-inch 45° bend	A-Condensate	D02 N	0.1026
Flued collar connection to 10-inch pipe (no thermal gradient)	B-Steam	A11 (seg B)	0.0005
10-inch pipe connection to valve (no thermal gradient)	B-Steam	B01 -	0.0005
valve connection to valve (10-inch)	B-Steam	B05	0.1278

Table XVII. Usage Factors, Continued

Description	Pipe System	Node #	Usage
10-inch valve connection to eccentric reducer	B-Steam	D09 +	0.023
Flued collar connection to 10-inch pipe (with thermal gradient)	B-Condensate	B20 (seg C)	0.1336
8-inch and 12-inch pipe connection to condenser nozzles	B-Steam (12-inch) B-Condensate (8-inch)	D17 C28	0.0976 0.1740
10-inch pipe connection to valve, sch 100 (with thermal gradient)	B-Condensate	C01 -	0.1336
butt weld (8-inch)	B-Condensate	D09 +	0.1251
center of 8-inch by 12-inch tee	B-Condensate	C11 - (seg C) C11 (seg D)	0.1429
center of 8-inch by 10-inch lateral	A-Condensate	B09 (seg B) B09 (seg D)	0.0931

F. <u>References</u>:

1. MPR Drawing 1083-131-09, Rev D, "Oyster Creek Nuclear Generating Station Isolation Condenser Piping, Drywell Penetration, 10X16 Flued Collar".

2. MPR-1177 through 1180, "Oyster Creek Nuclear Generating Station Isolation Condenser System, Analysis of Modified Piping Configuration," Rev. 1, February 1991.

3. ASME Boiler and Pressure Vessel Code, Class I Components, Section III, Subsection NB, 1989 Ed.

4. Mannesman Spool Piece Drawings, Attachment 1 to GPU Nuclear Letter 5512-89-126, from Mr. J. A Sergentanis to Mr. B R Bernier, September 26, 1989.

5. ASME Boiler and Pressure Vessel Code, Section III, Appendices, 1989

6. ASTM Specifications, 1988.

7. MPR Calculation, "Oyster Creek Nuclear Generating Station Average Startups/Shutdowns per Year," Rev 0.

8. MPR Calculation, "Biot Number for Flow through the Condensate Return Lines in the O.C. ICS," May 31, 1990, D Jacobs.

9. ORNL-TM-3645, "Nuclear Piping Design," Oak Ridge National Laboratory, Oak Ridge, Tennessee, Feb 1972, Distributed by NTIS.

10. MPR Associates Drawing 1083-131-15, "Oyster Creek Nuclear Generating Station Isolation Condenser Piping Replacement, Counterbore Dimensions for Butt Weld Ends," Rev B.

Attachment 1

Modifications to Equation (11)
for Branch Connections and Tees

For branch connections or tees, the pressure term of Equation (11) shall be replaced with (Ref 3):

$$k_1 C_1 \left(\frac{P_o D_o}{2 T_r} \right)$$

and the moment term of Equation (11) shall be replaced with

$$C_{2b} K_{2b} \left(\frac{M_b}{Z_b} \right) + C_{2r} K_{2r} \left(\frac{M_r}{Z_r} \right)$$

where: (see next page)

M_b = resultant moment on the branch

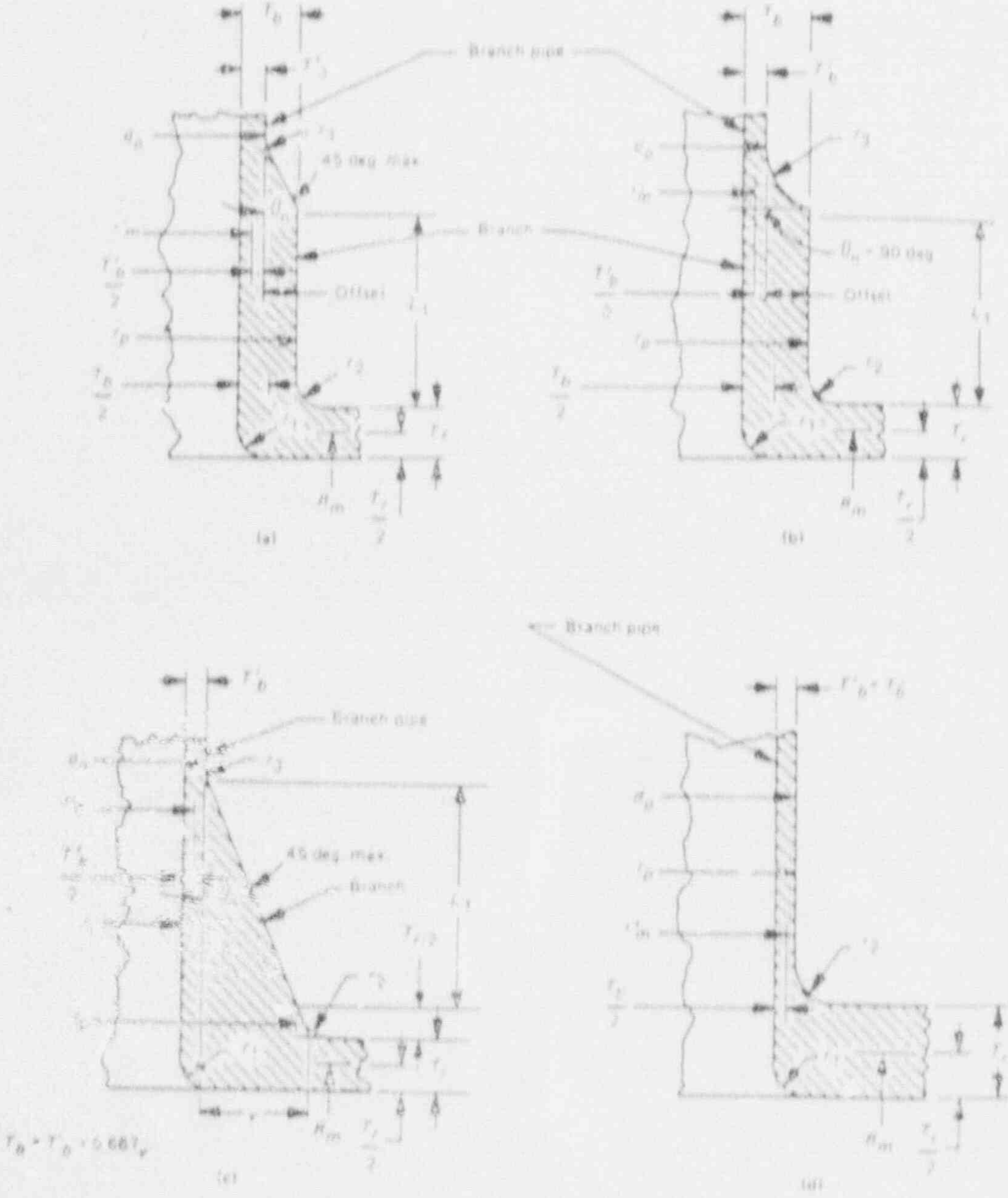
M_r = resultant moment on the run

$Z_b = \pi (r'_m)^2 T'_b$

$Z_r = \pi (R_m)^2 T_r$

r'_m, R_m = mean radius of branch and run, respectively

T'_b, T_r = nominal wall thickness of branch and run, respectively



GENERAL NOTE
If L_1 equals or exceeds $0.5\sqrt{r_i T_b}$, then r_m can be taken as the radius to the center of T_b.

Figure 1-1
TEE AND BRANCH CONNECTION NOMENCLATURE
[FIG NB-3643.3(a)-1 from Ref 3]

Attachment 2

Stress Index Calculations

Contents:

1. Transitions within a 1:3 Slope Envelope
2. NB-4250 Transitions
3. B16.9 Butt Welding Reducer
4. Curved Pipe
5. B16.9 Butt Welding Tee

Transitions within a 1:3 Slope Envelope:

$C_1 = 1.0 + 1.5\,(\delta/t)$ but not > 1.8

$C_2 = t_{max}/t + 3\,(\delta/t)$ but not > the smaller of

$[1.33 + 0.04\sqrt{D_o/t} + 3\,(\delta/t)]$ or 2.1

where: $\delta = 0$ for flush welded joints and for as-welded joints with $t > .237$ in. (Ref 3, NB 3683.5)

t_{max} = max wall thickness within a distance $\sqrt{D_o t}$ from welding end

t = nominal wall thickness of pipe

D_o = outside diameter of pipe

a. Connection of pipe to condenser nozzles (condensate lines):

$\delta = 0$
t_{max}: .625 in (Ref 10)
t = .500 in } assume schedule 80
D_o: 8.625 in

$C_1 = 1.0 + 1.5\,(0/t) = \underline{1.0}$

$C_2 = \frac{.625}{.500} + 3\,(0/t) = \underline{1.3}$

Note that:
$1.33 + 0.04\sqrt{8.625/.500} + 3\,(0/t)$
$= 1.5$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 2-3
	D. Jacobs	Ed Schummer	

Transitions with a 1:3 Slope Envelope (Continued):

b. Connection of 8" pipe to concentric reducer and lateral

$\delta = 0$
$t_{max} = 0.500$ in (Ref 4, spool pieces 05-08, 03-02, 04-02)
$t = 0.500$ in } assume schedule 80
$D_o = 8.625$ in

$C_1 = 1.0 + 1.5(0/t) = \underline{1.0}$

$C_2 = \frac{.5}{.5} + 3(0/t) = \underline{1.0}$

Note that:
$1.33 + 0.04\sqrt{D_o/t} + 3\,\delta/t$
$= 1.5$ as above

c. Connection of 10" sch 100 pipe to flued collar

$\delta = 0$
$t_{max} =$ in (Ref 1)
$t = 0.719$
$D_o = 10.75$ in

$C_1 = 1.0 + 1.5(0/t) = \underline{1.0}$

$C_2 = \frac{1.5}{.719} + 3(0/t) = 2.1$

Note that:
$1.33 + 0.04\sqrt{10.75/.719} + 3(0/t)$
$= \underline{1.5}$

Transitions with a 1:3 slope envelope (continued):

d. Connection of 12" pipe to condenser nozzles (steam lines):

$\delta = 0$

$t_{max} = .688$ (Ref 10)

$t = .688$ } assume schedule 80

$D_o : 12.75$ }

$C_1 = 1.0 + 1.5(\delta/t) = \underline{1.0}$

$C_2 = \frac{.6875}{.688} + 3(\delta/t) = \underline{1.0}$

Note that:

$1.33 + 0.04\sqrt{12.75/.688} + 3(\delta/t) = 1.5$

<u>NB-4250 Transitions</u>:

$C_1 = 0.5 + .33\left(D_o/t\right)^{0.3} + 1.5\left(\delta/t\right)$ but not > 1.8

$C_2 = 1.7 + 3.0\left(\delta/t\right)$ but not > 2.1

where: $\delta = 0$ for flush welded joints and for as-welded joints with $t > .237$ (Ref 3, NB 3683.5)

D_o outside diameter of pipe

$t =$ nominal wall thickness of pipe

a. Connection of 10" Sch 100 pipe to valve and flued collar

$\delta = 0$
$D_o = 10.75$ in
$t = .719$ in

$C_1 = 0.5 + .33\left(10.75/.719\right)^{.3} + 1.5\left(0/t\right) = \underline{1.2}$

$C_2 = 1.7 + 3.0\left(0/t\right) = \underline{1.7}$

b. Connection of 10" X 16" eccentric reducer to valve
(schedule 80 joint)

$\delta = 0$

$D_o = 10.75$ in

$t = 0.594$ in

$$C_1 = 0.5 + .33\left(\frac{10.75}{.594}\right)^{.3} + 1.5\left(0/t\right) = \underline{1.3}$$

$$C_2 = 1.7 + 3.0\left(0/t\right) = \underline{1.7}$$

B16.9 Butt Welding Reducer

- for r_1 and/or r_2 < $0.1 D_1$:

$$C_1 = 1.0 + 0.00465 \alpha^{1.285} \left(D_n / t_n \right)^{0.39}$$

$$C_2 = 1.0 + 0.0185 \alpha \sqrt{D_n / t_n}$$

where: α : cone angle

D_n / t_n = the larger of D_1/t_1 and D_2/t_2

$D_{1,2}$ = nominal outside diameter at large, small end of reducer, respectively

$t_{1,2}$: nominal wall thickness at large, small end of reducer, respectively

r_1 and r_2 are defined in Figure 3683.6-1

- For t_1 or t_2 > 3/16 in, and δ_1/t_1 or $\delta_2/t_2 \leq 0.1$:

$$K_1 = 1.2 - 0.2 L_m / \sqrt{D_m t_m} \quad \text{but not} < 1.0$$

$$K_2 = 1.8 - 0.8 L_m / \sqrt{D_m t_m} \quad \text{but not} < 1.0$$

B16.9 Butt Welding Reducer, Continued

where: $L_m/\sqrt{D_m t_m}$ = the smaller of $L_1/\sqrt{D_1 t_1}$ or $L_2/\sqrt{D_2 t_2}$

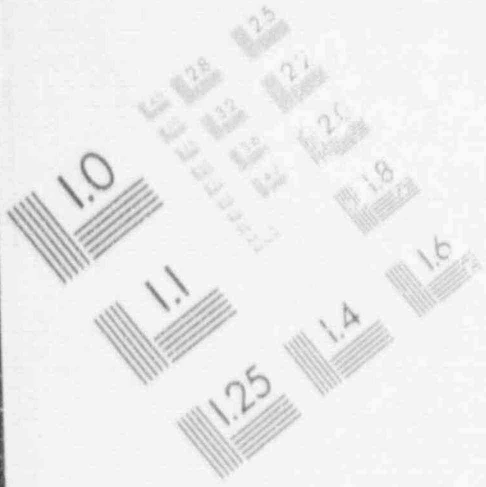
$L_{1,2}$ = length of cylindrical portion at the large, small end of a reducer, respectively

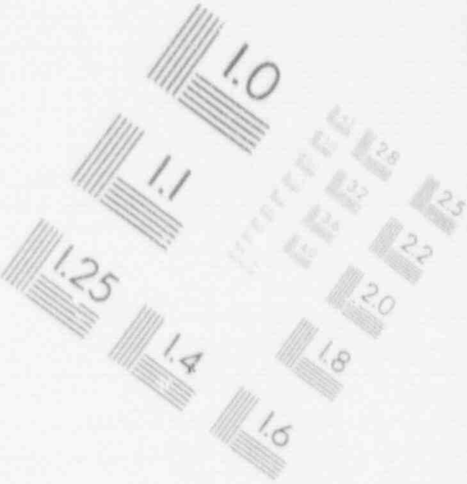
$D_{1,2}$ and $t_{1,2}$ are defined above

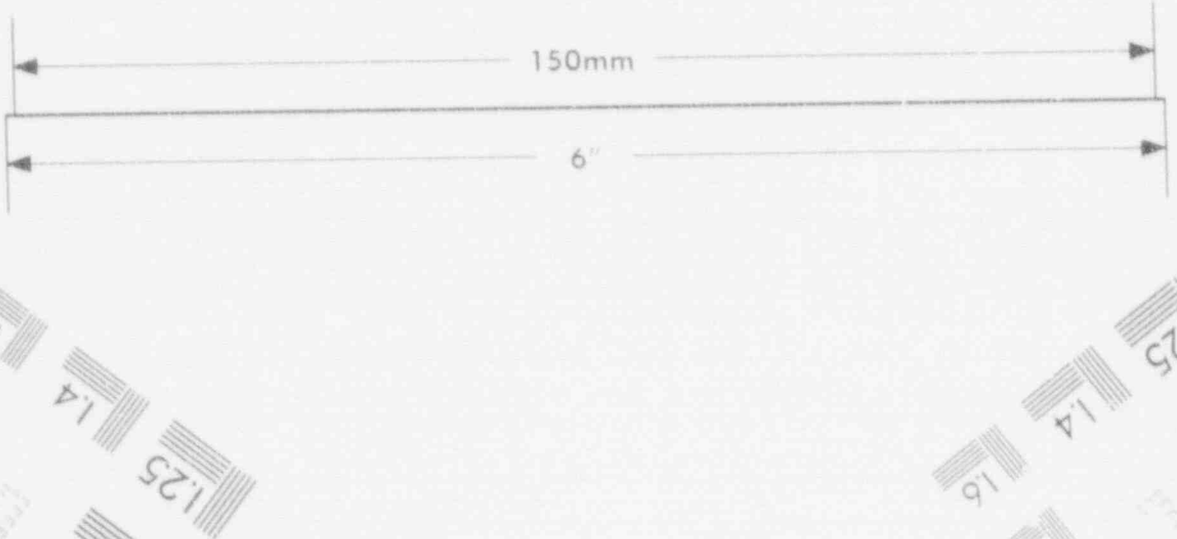
$\delta_1 = \delta_2 = 0$ for flush welded joints and for as-welded joints with $t > 0.237$ in (Ref 3, NB 3683.5)

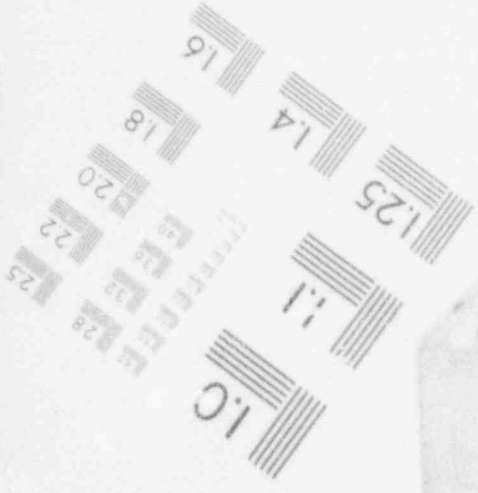
1

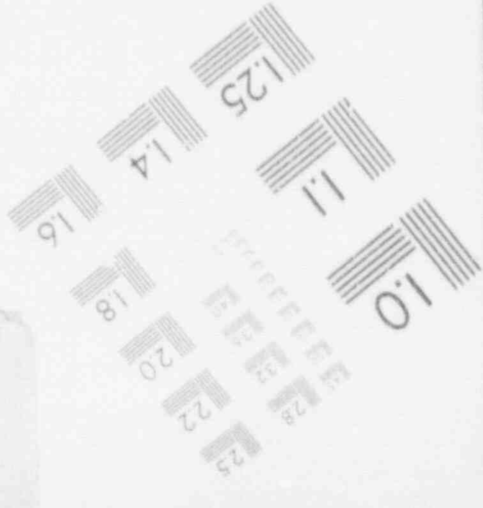
IMAGE EVALUATION
TEST TARGET (MT-3)





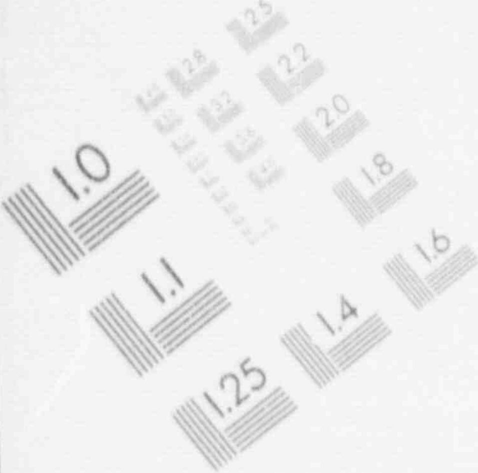


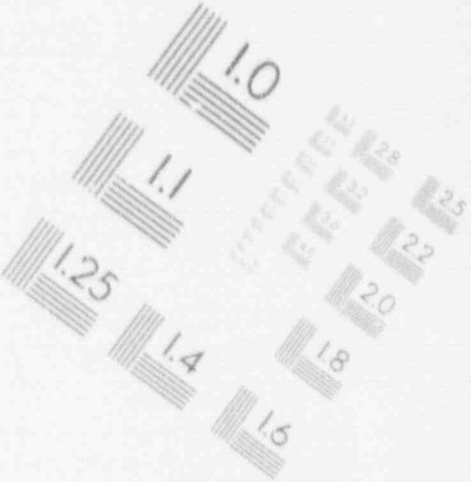


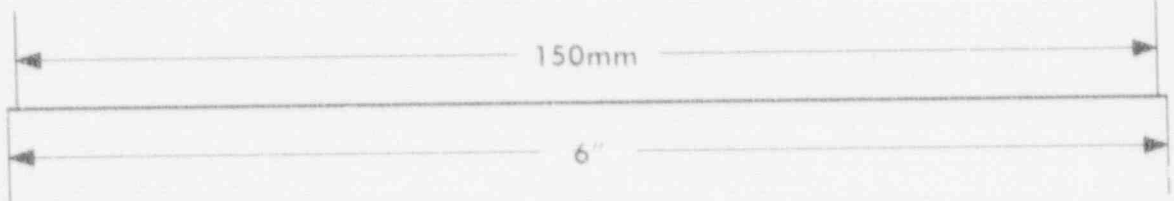


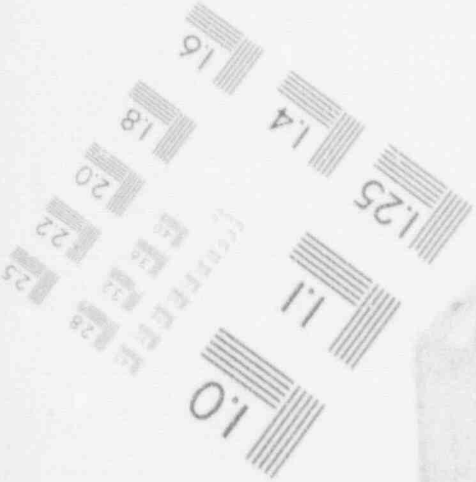
1

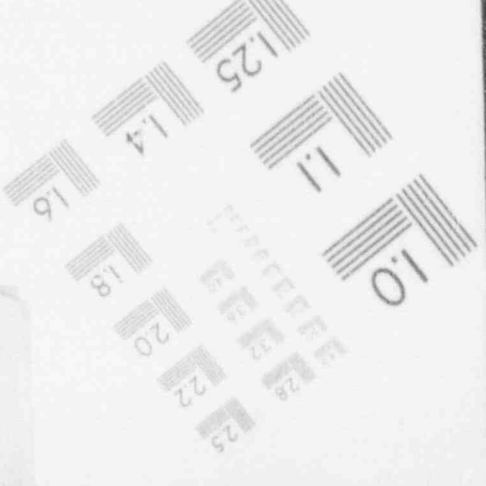
IMAGE EVALUATION
TEST TARGET (MT-3)





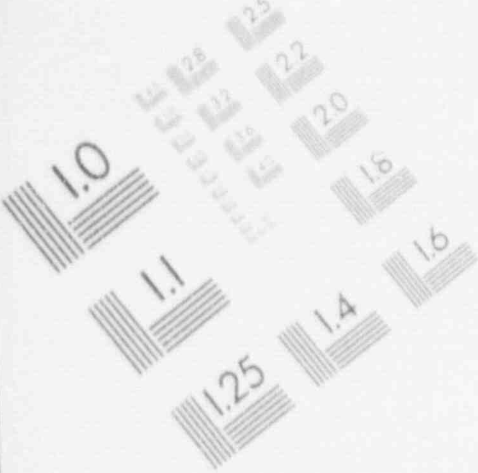


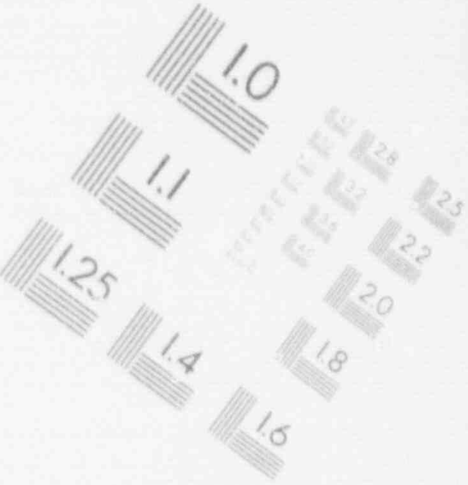


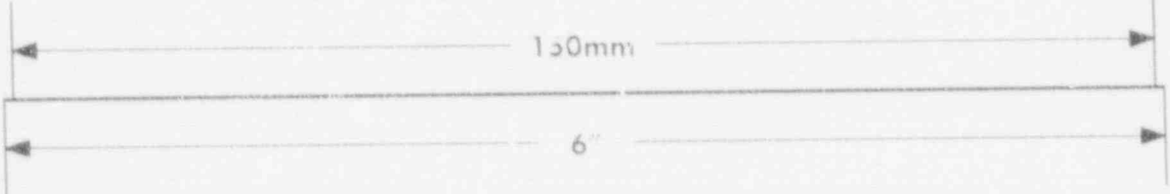


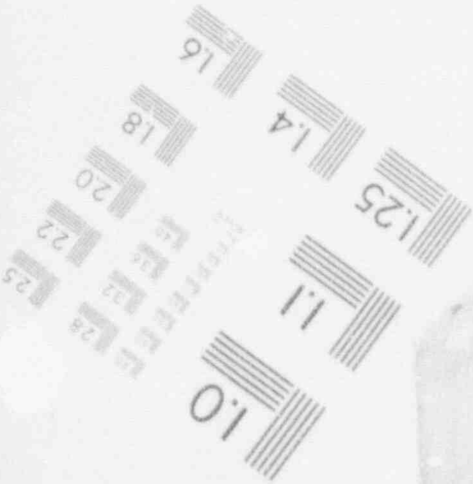
1

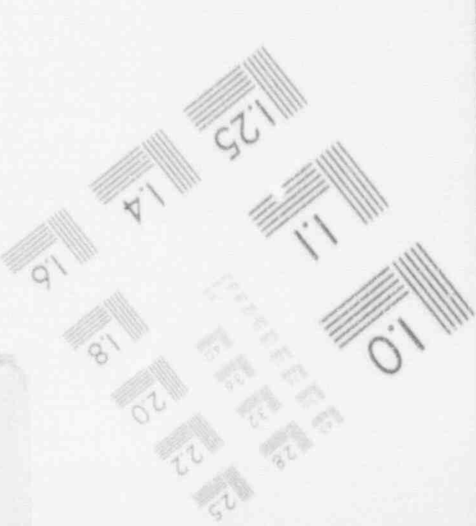
IMAGE EVALUATION
TEST TARGET (MT-3)











B16.9 Butt Welding Reducer, Continued

a. 8" x 10" concentric reducer (schedule 80)

$D_1 = 10.75$ in
$t_1 = 0.593$ in
$D_2 = 8.625$ in
$t_2 = 0.500$ in
$\alpha = 30°$

$L_1 = 3.00$ in
$L_2 = 2.16$ in

Dimensions are from Ref. 4, spool piece 03-08

$$\left.\begin{aligned} \frac{D_1}{t_1} &= \frac{10.75}{0.593} = 18.13 \\ \frac{D_2}{t_2} &= \frac{8.625}{0.500} = 17.25 \end{aligned}\right\} \text{ So } \frac{D_n}{t_n} = 18.13$$

$$C_1 = 1.0 + 0.00465(30)^{1.285}(18.13)^{.39} = \underline{2.1}$$

$$C_2 = 1.0 + 0.0185(30)\sqrt{18.13} = \underline{3.4}$$

$$\left.\begin{aligned} \frac{L_1}{\sqrt{D_1 t_1}} &= \frac{3.00}{\sqrt{(10.75)(.593)}} = 1.19 \\ \frac{L_2}{\sqrt{D_2 t_2}} &= \frac{2.16}{\sqrt{(8.625)(.5)}} = 1.04 \end{aligned}\right\} \text{ So } \frac{L_m}{\sqrt{D_m t_m}} = 1.04$$

$$k_1 = 1.2 - 0.2(1.04) = \underline{1.0}$$

$$k_2 = 1.8 - 0.8(1.04) = \underline{1.0}$$

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schumer	2-10

B16.9 Butt Welding Reducer, cont'd

b. 10" x 16" eccentric reducer

D_1 = 16.00 in L_1 = 3.09 in

t_1 = 0.843 in L_2 = 2.25 in

D_2 = 10.75 in

t_2 = 0.593 in Dimensions are from Ref. 4,

α = 30° spool piece 02-01

$$\left.\begin{aligned}\frac{D_1}{t_1} &= \frac{16.00}{0.843} = 18.98 \\ \frac{D_2}{t_2} &= \frac{10.75}{0.593} = 18.13\end{aligned}\right\} \text{ So } \frac{D_n}{t_n} = 18.98$$

$$C_1 = 1.0 + 0.00465 (30)^{1.285} (18.98)^{0.39} = \underline{2.2}$$

$$C_2 = 1.0 + 0.0185 (30) \sqrt{18.98} = \underline{3.4}$$

$$\left.\begin{aligned}\frac{L_1}{\sqrt{D_1 t_1}} &= \frac{3.09}{\sqrt{(16)(.843)}} = 0.84 \\ \frac{L_2}{\sqrt{D_2 t_2}} &= \frac{2.25}{\sqrt{(10.75)(.593)}} = 0.89\end{aligned}\right\} \text{ So } \frac{L_m}{\sqrt{D_m t_m}} = .84$$

$$K_1 = 1.2 - .2 (.84) = \underline{1.0}$$

$$K_2 = 1.8 - .8 (.84) = \underline{1.1}$$

Curved Pipe:

$$C_1 = \frac{(2R - r_m)}{2(R - r_m)}$$

$$C_2 = \frac{1.95}{h^{2/3}} \quad \text{but not} < 1.5$$

$$h = \frac{tR}{r_m^2}$$

where: R = nominal bend radius of curve
r_m = mean pipe radius
t = nominal wall thickness of pipe

a. Connection of 8" pipe to condenser nozzles (condensate lines):

$R = 12$ in (Ref 4, spool piece 04-07)
$r_m = \frac{8.625 - .5}{2} = 4.06$ in (assume sch 80)

$t = .500$ in

$$C_1 = \frac{(2(12) - 4.06)}{2(12 - 4.06)} = \underline{1.3}$$

$$h = \frac{(.500)(12)}{(4.06)^2} = .36$$

$$C_2 = 1.95 / .36^{2/3} = \underline{3.9}$$

Curved Pipe (continued):

b. Connection of pipe to condenser nozzles (steam lines):

$R = 18$ in (Ref 4)

$r_m = \frac{12.75 - .688}{2} = 6.03$ (assume sch 80)

$t = .688$ in

$$C_1 = \frac{(2(18) - 6.03)}{2(18 - 6.03)} = \underline{1.3}$$

$$h = \frac{(.688)(18)}{(6.03)^2} = .34$$

$$C_2 = \frac{1.95}{(.34)^{2/3}} = \underline{4.0}$$

c. Connection of 45° bend (8-inch pipe) to lateral:

$R = 12$ in (Ref 4)

$r_m = \frac{8.625 - .5}{2} = 4.06$ (assume sch 80)

$t = .5$

$$C_1 = \frac{(2(12) - 4.06)}{2(12 - 4.06)} = \underline{1.3}$$

$$h = \frac{(.500)(12)}{(4.06)^2} = .36 \qquad C_2 = \frac{1.95}{.36^{2/3}} = \underline{3.9}$$

Butt Welding Tee

$$C_{2b} = 0.67\left(R_m/T_r\right)^{2/3} \quad \text{but not} < 2$$

$$C_{2r} = 0.67\left(R_m/T_r\right)^{2/3} \quad \text{but not} < 2$$

$$k_{2b} = k_{2r} = 1$$

where: R_m = mean radius of run pipe
T_r = nominal wall thickness of run pipe

a. 8-inch by 10-inch 45° lateral

$$R_m = \frac{9.564 + 12.32}{4} = 5.471 \quad \text{(Ref 4)}$$

$$T_r = 1.38$$

$$C_{2b} = C_{2r} = .67\left(\frac{5.471}{1.38}\right)^{2/3} = \underline{1.7}$$

b. 8-inch by 10-inch tee

$$R_m = \frac{9.566 + 11.926}{4} = 5.37\text{ in} \quad \text{(Ref 4)}$$

$$T_r = 1.18 \text{ in}$$

$$C_{2b} = C_{2r} = .67\left(\frac{5.37}{1.18}\right)^{2/3} = \underline{1.8}$$

Attachment 3

Moment Calculations

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3-2
	D. Jacobs	Ed Schmiser	

Moment Calculation Worksheet   Piping System A-Condensate   Node C03

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(3168 ft-lbs)(12 in/ft) = 38,016 in-lbs

Cycle ②: X, y, and z moments for loads T1, R1 and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-1468	-258	-2795
R1	621	1631	770
2R1	1242	3262	1540
Sum of absolute values of T1 and R1	2089 (a)	1889 (b)	3565 (c)

SRSS of (a), (b), and (c) 4543 ft-lbs A

SRSS of 2R1 moments 3815 ft-lbs B

(4543 ft-lb)(12 in/ft) = 54,516 in-lbs
The greater of A and B

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(3815 ft-lbs)(12 in/ft) = 45,780 in-lbs

Moment Calculation Worksheet Piping System A-Condensate Node D02N

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(10196 ft-lbs)(12 in/ft) = $\boxed{122,352}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	2815	-8214	-5344
R1	461	1993	839
2R1	922	3986	1678
Sum of absolute values of T1 and R1	3276 (a)	10207 (b)	6183 (c)

SRSS of (a), (b), and (c) 12375 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 4422 ft-lbs $\boxed{B}$

(12375 ft-lb)(12 in/ft) = $\boxed{148,500}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(4422 ft-lbs)(12 in/ft) = $\boxed{53,064}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schumann	3-4

Moment Calculation Worksheet   Piping System B-Steam   Node All (seg B)

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(30678 ft-lbs)(12 in/ft) = 368,136 in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-4492	10092	-28620
R1	1711	9364	11930
2R1	3422	18728	23860
Sum of absolute values of T1 and R1	6203 (a)	19456 (b)	40550 (c)

SRSS of (a), (b), and (c) 45402 ft-lbs A

SRSS of 2R1 moments 30525 ft-lbs B

(45402 ft-lb)(12 in/ft) = 544824 in-lbs
The greater of A and B

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(30525 ft-lbs)(12 in/ft) = 366,300 in-lbs

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3-5
	B. Jacobs	Ed Schriner	

<u>Moment Calculation Worksheet</u>   Piping System <u>B-Steam</u>   Node <u>601-</u>

<u>Cycle ①</u>: Resultant moment for load T1 from Ref 2, App C:

(<u>30944</u> ft-lbs)(12 in/ft) = $\boxed{371,328}$ in-lbs

<u>Cycle ②</u>: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-4492	10043	-28923
R1	1711	9582	11942
2R1	3422	19164	23884
Sum of absolute values of T1 and R1	6203 (a)	19625 (b)	40865 (c)

SRSS of (a), (b), and (c) <u>45756</u> ft-lbs $\boxed{A}$

SRSS of 2R1 moments <u>30813</u> ft-lbs $\boxed{B}$

(<u>45756</u> ft-lb)(12 in/ft) = $\boxed{549,072}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

<u>Cycle ③</u>: Resultant moment for load 2R1 from Ref 2, App C:

(<u>30813</u> ft-lbs)(12 in/ft) = $\boxed{369,756}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schuiner	3-6

Moment Calculation Worksheet   Piping System B-Steam   Node B#5

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(39115 ft-lbs)(12 in/ft) = $\boxed{469,380}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-5108	8529	-37830
R1	876	14391	11213
2R1	1752	28782	22426
Sum of absolute values of T1 and R1	5984 (a)	22920 (b)	49043 (c)

SRSS of (a), (b), and (c) 54464 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 36529 ft-lbs $\boxed{B}$

(54464 ft-lb)(12 in/ft) = $\boxed{653,568}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(36529 ft-lbs)(12 in/ft) = $\boxed{438,348}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schriner	3-7

Moment Calculation Worksheet   Piping System B-Steam   Node B09+

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(46667 ft-lbs)(12 in/ft) = $\boxed{560,004}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1 and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-5655	7015	-45789
R1	2451	14781	8276
2R1	4902	29562	16552
Sum of absolute values of T1 and R1	8106 (a)	21796 (b)	54065 (c)

SRSS of (a), (b), and (c) 58854 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 34233 ft-lbs $\boxed{B}$

(58854 ft-lb)(12 in/ft) = $\boxed{706,248}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(34233 ft-lbs)(12 in/ft) = $\boxed{410,796}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3-8
	D. Jacobs	Ed Schrimer	

Moment Calculation Worksheet   Piping System B-Condensate Node B20 (seg C)

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(7023 ft-lbs)(12 in/ft) = $\boxed{34276}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	1604	236	6833
R1	2875	7291	7479
2R1	5750	14582	14958
Sum of absolute values of T1 and R1	4479 (a)	7527 (b)	14312 (c)

SRSS of (a), (b), and (c) 16779 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 21667 ft-lbs $\boxed{B}$

(21667 ft-lb)(12 in/ft) = $\boxed{260,004}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(21667 ft-lbs)(12 in/ft) = $\boxed{260,004}$ in-lbs

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed	3-9

Moment Calculation Worksheet   Piping System B-Steam   Node D17

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(48211 ft-lbs)(12 in/ft) = $\boxed{578{,}532}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-44930	-16386	-6091
R1	2615	1009	3934
2R1	5230	2018	7868
Sum of absolute values of T1 and R1	47545 (a)	17395 (b)	10025 (c)

SRSS of (a), (b), and (c) 51610 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 9661 ft-lbs $\boxed{B}$

(51610 ft-lbs)(12 in/ft) = $\boxed{619{,}320}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(9661 ft-lbs)(12 in/ft) = $\boxed{115{,}932}$ in-lbs

Moment Calculation Worksheet Piping System B-Condensate Node C28

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(25182 ft-lbs)(12 in/ft) = $\boxed{302,184}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	24449	4488	4033
R1	476	459	633
2R1	952	918	1266
Sum of absolute values of T1 and R1	24925 (a)	4947 (b)	4666 (c)

SRSS of (a), (b), and (c) 25836 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 1831 ft-lbs $\boxed{B}$

(25836 ft-lb)(12 in/ft) = $\boxed{310,032}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(1831 ft-lbs)(12 in/ft) = $\boxed{21,972}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3-11
	D. Jacobs	Ed Schriner	

Moment Calculation Worksheet   Piping System B-Condensate   Node C01 -

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(6958 ft-lbs)(12 in/ft) = 83496 in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	1604	267	6765
R1	2875	7277	7436
2R1	5750	14554	14872
Sum of absolute values of T1 and R1	4479 (a)	7544 (b)	14201 (c)

SRSS of (a), (b), and (c) 16693 ft-lbs A

SRSS of 2R1 moments 21588 ft-lbs B

(21588 ft-lb)(12 in/ft) = 259056 in-lbs
The greater of A and B

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(21588 ft-lbs)(12 in/ft) = 259056 in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schriner	3-12

Moment Calculation Worksheet   Piping System B-Condensate   Node D084

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(17773 ft-lbs)(12 in/ft) = 213,276 in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	15336	-7495	-4950
R1	434	364	394
2R1	868	728	788
Sum of absolute values of T1 and R1	15770 (a)	7859 (b)	5344 (c)

SRSS of (a), (b), and (c) 18412 ft-lbs A

SRSS of 2R1 moments 1380 ft-lbs B

(18412 ft-lb)(12 in/ft) = 220944 in-lbs
The greater of A and B

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(1380 ft-lbs)(12 in/ft) = 16,560 in-lbs

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schriner	3-13

Moment Calculation Worksheet   Piping System B-Condensate   Node C11-
(Run of 10" x 8" tee) (Seg C)

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(16981 ft-lbs)(12 in/ft) = 203,772 in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	21	8674	-14556
R1	05	1512	512
2R1	1210	3024	1024
Sum of absolute values of T1 and R1	1726 (a)	10186 (b)	15068 (c)

SRSS of (a), (b), and (c) 18270 ft-lbs A

SRSS of 2R1 moments 3414 ft-lbs B

(18270 ft-lb)(12 in/ft) = 219,240 in-lbs
The greater of A and B

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(3414 ft-lbs)(12 in/ft) = 40,968 in-lbs

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 3-14
	B. Jacobs	Ed Schummer	

Moment Calculation Worksheet   Piping System B-Condensate Node C11
(Branch of 10" x 8" tee)

Cycle ①: Resultant moment for load T1 from Ref 2, App C: (seg 4)

(19699 ft-lbs)(12 in/ft) = $\boxed{236,388}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	-3951	14446	-12796
R1	383	893	329
2R1	766	1786	658
Sum of absolute values of T1 and R1	4334 (a)	15339 (b)	13125 (c)

SRSS of (a), (b), and (c) 20648 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 2052 ft-lbs $\boxed{B}$

(20648 ft-lb)(12 in/ft) = $\boxed{247,776}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(2052 ft-lbs)(12 in/ft) = $\boxed{24,624}$ in-lbs

CALCULATION NO.	PREPARED BY D. Jacobs	CHECKED BY Ed Schummer	PAGE 3-15

Moment Calculation Worksheet   Piping System A-Condensate   Node B09
(Run of 8"x 10" lateral) (Seg B)

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(10835 ft-lbs)(12 in/ft) = $\boxed{130,020}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	1267	-8314	-6831
R1	822	1424	729
2R1	1644	2848	1458
Sum of absolute values of T1 and R1	2089 (a)	9739 (b)	7560 (c)

SRSS of (a), (b), and (c) 12504 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 3597 ft-lbs $\boxed{B}$

(12504 ft-lb)(12 in/ft) = $\boxed{150,048}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(3597 ft-lbs)(12 in/ft) = $\boxed{43,164}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schimmer	3-16

Moment Calculation Worksheet   Piping System A-Condensate Node B09
(Branch of 8" x 10" lateral) (seg D)

Cycle ①: Resultant moment for load T1 from Ref 2, App C:

(8326 ft-lbs)(12 in/ft) = $\boxed{99,912}$ in-lbs

Cycle ②: X, y, and z moments for loads T1, R1, and 2R1 from Ref 2, App C.

	x (ft-lbs)	y (ft-lbs)	z (ft-lbs)
T1	2735	-6490	-4441
R1	667	2378	1262
2R1	334	4756	2524
Sum of absolute values of T1 and R1	3402 (a)	8868 (b)	5703 (c)

SRSS of (a), (b), and (c) 11079 ft-lbs $\boxed{A}$

SRSS of 2R1 moments 5547 ft-lbs $\boxed{B}$

(11,079 ft-lb)(12 in/ft) = $\boxed{132948}$ in-lbs
The greater of $\boxed{A}$ and $\boxed{B}$

Cycle ③: Resultant moment for load 2R1 from Ref 2, App C:

(5547 ft-lbs)(12 in/ft) = $\boxed{66,564}$ in-lbs

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schimmer	4-1

Attachment 4

Peak Stress Intensity Range,
Alternating Stress Intensity Range,
and Usage Factor Calculations

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW–Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4-2
	D. Jacobs	Ed Schimmer	

Piping System: A-Condensate
Location: C03
Description: <u>8-inch pipe connection to concentric reducer</u>

<u>Inputs to Equation (11)</u>

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 38,016 in-lbs for cycle type ①
54,516 in-lbs for cycle type ②
45,780 in-lbs for cycle type ③

k_1 = 1.0 for B16.9 reducer, 1.2 for 1:3 slope transition
k_2 = 1.0 ", 1.8 "
k_3 = 1.0 ", 1.7 "

C_1 = 2.1 ", 1.0 "
C_2 = 3.4 ", 1.0 "

D_o = 8.625 in
t = 0.50 in
I = 105.7 in^4

$\left.\begin{array}{l}\Delta T_1 = 379°F \\ \Delta T_2 = 86°F\end{array}\right\}$ ① and ②
$\Delta T_1 = \Delta T_2 = 0$ ③

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4.3
	D. Jacobs	Ed Schimmer	

Piping System: A-Condensate
Location: C03
Description: 8-inch pipe connection to concentric reducer (continued)

Results

S_p = 121,700 psi for cycle ①, B16.9 reducer
154,700 psi for cycle ①, 1:3 slope transition

124,000 psi for cycle ②, B16.9 reducer
155,900 psi for cycle ②, 1:3 slope transition

6400 psi for cycle ③, B16.9 reducer
3400 psi for cycle ③, 1:3 slope transition

The larger values of S_p are used to calculate S_{alt} and the usage factor:

S_{alt} = 77,350 psi ①
77,950 psi ②
1,700 psi ③

$N_1 = 4.2 \times 10^3$ $n_1 = 395$
$N_2 = 4.2 \times 10^3$ $n_2 = 5$
$N_3 = 1 \times 10^6$ $n_3 = 50$

$$U = \frac{395}{4.2\times10^3} + \frac{5}{4.2\times10^3} + \frac{50}{1\times10^6} = \boxed{0.0953}$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4-4
	D. Jacobs	Ed Schimmer	

Piping System: A-Condensate
Location: D02N
Description: 8-inch by 10-inch 45° lateral connection to 8-inch 45° bend

Input: to Equation (11)

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 122,352 in-lbs ①
148,500 in-lbs ②
53,064 in-lbs ③

k_1 = 1.0 for curved pipe , 1.2 for 1:3 slope transition
k_2 = 1.0 " , 1.8 "
k_3 = 1.0 " , 1.7 "

C_1 = 1.3 " , 1.0 "
C_2 = 3.9 " , 1.0 "

D_o : 8.625 in
t = 0.50 in
I = 105.7 in^4

$$\left.\begin{array}{l}\Delta T_1 = 379°F \\ \Delta T_2 = 86°F\end{array}\right\} ① \text{ and } ②$$
$\Delta T_1 = \Delta T_2 = 0$ ③

Piping System: A-Condensate
Location: D02N
Description: 3-inch by 10-inch 45° lateral connection to 8-inch 45° bend (continued)

Results

$S_p =$ 127,300 psi for cycle ①, curved pipe
160,900 psi for cycle ①, 1:3 slope transition

131,400 psi for cycle ②, curved pipe
162,800 psi for cycle ②, 1:3 slope transition

8400 psi for cycle ③, curved pipe
3900 psi for cycle ③, 1:3 slope transition

The larger values of S_p are used to calculate S_{alt} and the usage factor:

$S_{alt} =$ 80,450 psi ①
81,400 psi ②
1,950 psi ③

$N_1 = 3.9 \times 10^3$	$n_1 = 395$
$N_2 = 3.9 \times 10^3$	$n_2 = 5$
$N_3 = 1 \times 10^6$	$n_3 = 50$

$$U = \frac{395}{3.9 \times 10^3} + \frac{5}{3.9 \times 10^3} + \frac{50}{1 \times 10^6} = \boxed{0.1026}$$

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4-6
	B. Jacobs	Ed Schuimer	

Piping System: B-Steam
Location: All (segment B)
Description: Flued collar connection to 10-inch pipe (no thermal gradient)

Inputs to Equation (11)

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 368,136 in-lbs ①
544,824 in-lbs ②
366,300 in-lbs ③

	NB-4250 trans.	1:3 slope	butt weld
k_1 =	1.2	1.2	1.2
k_2 =	1.8	1.8	1.8
k_3 =	1.7	1.7	1.7
C_1 =	1.2	1.0	1.0
C_2 =	1.7	1.5	1.0

D_o = 10.75 in
t = 0.719 in
I = 286.1 in^4

ΔT_1 = 0 ① ② ③
ΔT_2 = 0 ① ② ③

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4-7
	D. Jacobs	Ed Schminer	

Piping System: B-Steam
Location: All (segment B)
Description: Flued collar connection to 10-inch pipe (no thermal gradient) continued

Results

S_p = 34,600 psi for cycle ①, NB-4250 transition
29,900 psi for cycle ①, 1:3 slope transition
23,700 psi for cycle ①, butt weld

44,800 psi for cycle ②, NB-4250 transition
38,900 psi for cycle ②, 1:3 slope transition
29,600 psi for cycle ②, butt weld

21,100 psi for cycle ③, NB-4250 transition
18,600 psi for cycle ③, 1:3 slope transition
12,400 psi for cycle ③, butt weld

The larger values of S_p are used to calculate S_{alt} and the usage factor:

S_{alt} = 17,300 psi ①
22,400 psi ②
10,550 psi ③

$N_1 = 1 \times 10^6$ $n_1 = 395$
$N_2 = 1 \times 10^6$ $n_2 = 5$
$N_3 = 1 \times 10^6$ $n_3 = 50$

$$U = \frac{395}{1 \times 10^6} + \frac{5}{1 \times 10^6} + \frac{50}{1 \times 10^6} = \boxed{0.0005}$$

CALCULATION NO.	PREPARED BY D. Jacobs	CHECKED BY Ed Schmiser	PAGE 4-8

Piping System: B-Steam
Location: B01-
Description: <u>10-inch pipe connection to valve (no thermal gradient)</u>

Inputs to Equation (11)

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 371,328 in-lbs ①
549,072 in-lbs ②
369,756 in-lbs ③

K_1 = 1.2
K_2 = 1.8
K_3 = 1.7

C_1 = 1.2
C_2 = 1.7

D_o = 10.75 in
t = 0.719 in
I = 286.1 in^4

ΔT_1 = 0 ① ② ③
ΔT_2 = 0 ① ② ③

Piping System: B-Steam
Location: B01-
Description: 10-inch pipe connection to valve (no thermal gradient) continued

Results

S_p = 34,800 psi for cycle ①
45,000 psi for cycle ②
21,300 psi for cycle ③

S_{alt} = 17,400 psi ①
22,500 psi ②
10,650 psi ③

$N_1 = 1X10^6$ $n_1 = 395$
$N_2 = 1X10^6$ $n_2 = 5$
$N_3 = 1X10^6$ $n_3 = 50$

$$U = \frac{395}{1X10^6} + \frac{5}{1X10^6} + \frac{50}{1X10^6} = \boxed{0.0005}$$

Piping System: B-Steam
Location: B05
Description: Valve connection to valve

Inputs to Equation (11)

P_o: 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 469,390 in-lbs ①
653,568 in-lbs ②
438,348 in-lbs ③

k_1 = 2.4
k_2 = 3.6
k_3 = 3.4

C_1 = 2.4
C_2 = 3.4

D_o = 10.75 in
t = 0.719 in
I = 286.1 in⁴

ΔT_1 = 0 ① ② ③
ΔT_2 = 0 ① ② ③

Piping System: B-Steam
Location: B05
Description: Valve connection to valve (continued)

Results

S_p = 161,800 psi for cycle ①
204,100 psi for cycle ②
100.800 psi for cycle ③

S_{alt} = 80,900 psi ①
102,050 psi ②
50,400 psi ③

N_1 :	3.2×10^3	n_1 :	395
N_2 :	1.8×10^3	n_2 :	5
N_3 :	3.2×10^4	n_3 :	50

$$U = \frac{395}{3.2\times10^3} + \frac{5}{1.8\times10^3} + \frac{50}{3.2\times10^4} = \boxed{0.1278}$$

Piping System: B-Steam
Location: B09+
Description: 10-inch valve connection to eccentric reducer

Inputs to Equation (11)

P_0 = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 560 004 in-lbs ①
706,240 in-lbs ②
410,796 in-lbs ③

k_1 = 1.0 for B16.9 reducer, 1.2 for NB-4250 transition
k_2 = 1.1 ", 1.8 "
k_3 = 1.0 " 1.7 "

C_1 = 2.2 ", 1.3 "
C_2 = 3.4 ", 1.7 "

D_0 = 10.75 in
t = 0.594 in
I = 244.8 in^4

$\Delta T_1 = 0$ ① ② ③
$\Delta T_2 = 0$ ① ② ③

Piping System: B-Steam
Location: B09 +
Description: <u>10-inch valve connection to eccentric reducer (continued)</u>

<u>Results</u>

S_p = 70,900 psi for cycle ①, B16.9 reducer
55,300 psi for cycle ①, NB-4250 transition

82,900 psi for cycle ②, B16.9 reducer
65,100 psi for cycle ②, NB-4250 transition

33,700 psi for cycle ③, B16.9 reducer
27,600 psi for cycle ③, NB-4250 transition

The larger values of S_p are used to calculate S_{alt} and the usage factor:

S_{alt} = 35,450 psi ①
41,450 psi ②
16,850 psi ③

$N_1 = 1.8 \times 10^5$ $n_1 = 395$
$N_2 = 9.0 \times 10^4$ $n_2 = 5$
$N_3 = 1 \times 10^6$ $n_3 = 50$

$$U = \frac{395}{1.8 \times 10^5} + \frac{5}{9.0 \times 10^4} + \frac{50}{1 \times 10^6} = \boxed{0.0023}$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schriner	4-14

Piping System: B-Condensate
Location: B20 (segment C)
Description: Flued collar connection to 10-inch pipe (with thermal gradient)

Inputs to Equation (11)

P_o = 1250 psi for cycle types ① and ⑤
0 psi for cycle type ③

M_i = 84,276 in-lbs ①
260,004 in-lbs ②
260,004 in-lbs ③

	NB-4250 trans.	1:3 slope	butt weld
k_1	1.2	1.2	1.2
k_2	1.8	1.8	1.8
k_3	1.7	1.7	1.7
C_1	1.2	1.0	1.0
C_2	1.7	1.5	1.0

D_o = 10.75 in
t = 0.719 in
I = 286.1 in^4

$$\left.\begin{array}{l}\Delta T_1 = 354°F \\ \Delta T_2 = 126°F\end{array}\right\}\ ①\text{ and }②$$

$\Delta T_1 = \Delta T_2 = 0$ ③

Piping System: B-Condensate
Location: B20 (segment C)
Description: Flued collar connection to 10-inch pipe (with thermal gradient) continued

Results

S_p = 163,600 psi for cycle ①, NB-4250 transition
160,800 psi for cycle ①, 1:3 slope transition
159,400 psi for cycle ①, butt weld

173,700 psi for cycle ②, NB-4250 transition
169,700 psi for cycle ②, 1:3 slope transition
165,300 psi for cycle ②, butt weld

14,900 psi for cycle ③, NB-4250 transition
13,200 psi for cycle ③, 1:3 slope transition
5,800 psi for cycle ③, butt weld

The larger values of S_p are used to calculate S_{alt} and the usage factor:

S_{alt} = 81,800 psi ①
86,850 psi ②
7,450 psi ③

N_1 = 3.0×10^3 n_1 = 395
N_2 = 2.6×10^3 n_2 = 5
N_3 = 1×10^6 n_3 = 50

$$U = \frac{395}{3.0 \times 10^3} + \frac{5}{2.6 \times 10^3} + \frac{50}{1 \times 10^6} = \boxed{0.1336}$$

Piping System: B-Steam
Location: D17
Description: <u>12-inch pipe connection to condenser nozzles</u>

<u>Inputs to Equation (11)</u>

P_o : 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 578,532 in-lbs ①
619,320 in-lbs ②
115,932 in-lbs ③

k_1 = 1.2 for 1:3 slope transition , 1.0 for curved pipe
k_2 = 1.8 " , 1.0 "
k_3 = 1.7 " , 1.0 "

C_1 = 1.0 " , 1.3 "
C_2 = 1.0 " , 4.0 "

D_o = 12.75 in
t = 0.688 in
I = 475.1 in^4

$$\left.\begin{array}{l}\Delta T_1 = 343^\circ F \\ \Delta T_2 = 86^\circ F\end{array}\right\}$$ ① and ②
$\Delta T_1 = \Delta T_2 = 0$ ③

Piping System: B-Steam
Location: D17
Description: 12-inch pipe connection to condenser nozzles (continued)

Results

S_p = 156,400 psi for cycle ①, 1:3 slope transition
133,800 psi for cycle ①, curved pipe

157,400 psi for cycle ②, 1:3 slope transition
136,000 psi for cycle ②, curved pipe

2,800 psi for cycle ③, 1:3 slope transition
6,200 psi for cycle ③, curved pipe

The larger values of Sp are used to calculate Salt and the usage factor:

S_{alt} = 78,200 psi ①
78,700 psi ②
1,400 psi ③

$N_1 = 4.1 \times 10^3$ $n_1 = 395$
$N_2 = 4.1 \times 10^3$ $n_2 = 5$
$N_3 = 1 \times 10^6$ $n_3 = 50$

$$U = \frac{395}{4.1 \times 10^3} + \frac{5}{4.1 \times 10^3} + \frac{50}{1 \times 10^6} = \boxed{0.0976}$$

Piping System : B-Condensate
Location : C28
Description : 8-inch pipe connection to condenser nozzle

Inputs to Equation (11):

P_0 = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 302,184 for cycle type ①
310,032 for cycle type ②
21,972 for cycle type ③

k_1 = 1.2 for 1:3 slope transition , 1.0 for curved pipe
k_2 = 1.8 for 1:3 slope transition , 1.0 for curved pipe
k_3 = 1.7 for 1:3 slope transition , 1.0 for curved pipe

C_1 = 1.0 for 1.3 slope transition , 1.3 for curved pipe
C_2 = 1.3 for 1:3 slope transition , 3.9 for curved pipe

D_0 = 8.625 in
t = 0.500 in
I = 105.7 in^4

$$\left.\begin{array}{l}\Delta T_1 = 379°F \\ \Delta T_2 = 86°F\end{array}\right\}\text{ for cycles ① and ②}$$

$\Delta T_1 = \Delta T_2 = 0$ for cycle ③

Piping System : B-Condensate
Location : C2B
Description : 8-inch pipe connection to condenser nozzle (continued)

Results:

S_p = 180,700 psi for cycle ①, 1:3 slope transition
155,900 psi for cycle ①, curved pipe

181,500 psi for cycle ②, 1:3 slope transition
157,100 psi for cycle ②, curved pipe

2,100 psi for cycle ③, 1:3 slope transition
3,500 psi for cycle ③, curved pipe

The larger values of S_p are used to calculate S_{alt} and the usage factor:

S_{alt} = 90,350 psi ①
90,750 psi ②
1,050 psi ③

$N_1 = 2.3 \times 10^{3}$ $n_1 = 395$
$N_2 = 2.3 \times 10^{3}$ $n_2 = 5$
$N_3 = 1 \times 10^{6}$ $n_3 = 50$

$$U = \frac{395}{2.3 \times 10^{3}} + \frac{5}{2.3 \times 10^{3}} + \frac{50}{1 \times 10^{6}} = \boxed{0.174}$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs		4-20

Piping System: B-Condensate
Location: C01-
Description: <u>10-inch pipe connection to valve, schedule 100 (with thermal gradient)</u>

<u>Inputs to Equation (11)</u>

P_0 = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 83496 in-lbs ①
259,056 in-lbs ②
259,056 in-lbs ③

k_1 = 1.2
k_2 = 1.8
k_3 = 1.7

C_1 = 1.2
C_2 = 1.7

D_0 = 10.75 in
t = 0.719 in
I = 286.1 in^4

$$\left.\begin{array}{l}\Delta T_1 = 354°F \\ \Delta T_2 = 126°F\end{array}\right\} \text{① and ②}$$
$\Delta T_1 = \Delta T_2 = 0$ ③

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed	4.21

Piping System: B-Condensate
Location: C01 -
Description: 10-inch pipe connection to valve, schedule 100 (with thermal gradient), cont'd

Results:

S_p = 163,600 psi for cycle ①
173,700 psi for cycle ②
14,900 psi for cycle ③

S_{alt} = 81,800 psi ①
86,850 psi ②
7,450 psi ③

$N_1 = 3.0 \times 10^3$	$n_1 = 395$
$N_2 = 2.6 \times 10^3$	$n_2 = 5$
$N_3 = 1 \times 10^6$	$n_3 = 50$

$$U = \frac{395}{3.0 \times 10^3} + \frac{5}{2.6 \times 10^3} + \frac{50}{1 \times 10^6} = \boxed{0.1336}$$

Piping System : B-Condensate
Location : D08+
Description : <u>8-inch butt weld</u>

<u>Inputs to Equation (11)</u>

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_i = 213,276 in-lbs ①
220,944 in-lbs ②
16,560 in-lbs ③

k_1 = 1.2
k_2 = 1.8
k_3 = 1.7

C_1 = 1.0
C_2 = 1.0

D_o = 8.625 in
t = 0.500 in
I = 105.7 in^4

$\left.\begin{array}{l}\Delta T_1 = 379°F \\ \Delta T_2 = 86°F\end{array}\right\}$ ① and ②
$\Delta T_1 = \Delta T_2 = 0$ ③

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed	4-23

Piping System: B-Condensate
Location: DWB+
Description: 8-inch butt weld (continued)

Results

S_p = 167,500 psi for cycle ①
168,100 psi for cycle ②
1,200 psi for cycle ③

S_{alt} = 83,750 psi ①
84,050 psi ②
600 psi ③

$N_1 = 3.2\times10^3$		$n_1 = 395$	
$N_2 = 3.2\times10^3$		$n_2 = 5$	
$N_3 = 1\times10^6$		$n_3 = 50$	

$$U = \frac{395}{3.2\times10^3} + \frac{5}{3.2\times10^3} + \frac{50}{1\times10^6} = \boxed{0.1251}$$

Piping System : B-Condensate
Location : C11-(segment C), C11 (segment D)
Description : <u>Center of 8-inch by 10-inch tee</u>

<u>Inputs to Equation (11)</u>:

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle types ③

M_b = 236,388 in-lbs for cycle ① M_r = 203,772 ①
247,776 in lbs for cycle ② 219,240 ②
24,624 in-lbs for cycle ③ 40,968 ③

k_1 = 4.0
$k_{2b} = k_{2r}$ = 1.0
k_3 = 1.0

ΔT_1 = 333° F } For cycles ① and ②
ΔT_2 = 182° F }
$\Delta T_1 = \Delta T_2 = 0$ for cycle ③

C_1 = 1.5
$C_{2b} = C_{2r}$ = 1.8

D_o = 10.75
T_r = 1.18 in (Ref 4)
T'_b = 0.50 in

$$\left.\begin{aligned} R_m &= \frac{11.926 + 9.564}{4} = 5.37 \text{ in} \\ r'_m &= \frac{8.625 + 7.625}{4} = 4.06 \text{ in} \end{aligned}\right\} \text{(Ref 4)}$$

$Z_r = \pi (5.37)^2 (1.18) = 106.9 \text{ in}^3$

$Z_b = \pi (4.06)^2 (0.5) = 25.9 \text{ in}^3$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	B. Jacobs		4.25

Piping System: B-Condensate
Location: C11+ (segment C), C11 (segment D)
Description: Center of 8-inch by 10-inch tee (continued)

Results:

$S_p =$ 172,700 psi for cycle ① $S_{alt} =$ 86,350 ①
173,700 psi for cycle ② 86,850 ②
2,400 psi for cycle ③ 1,200 ③

$N_1 = 2.8 \times 10^3$ $n_1 = 395$
$N_2 = 2.8 \times 10^3$ $n_2 = 5$
$N_3 = 1 \times 10^6$ $n_3 = 50$

$$U = \frac{395}{2.8 \times 10^3} + \frac{5}{2.8 \times 10^3} + \frac{50}{1 \times 10^6} = \boxed{0.1429}$$

Piping System: A Condensate
Location: B09 (segment B) and B09 (segment D)
Description: <u>Center of 8-inch by 10-inch lateral</u>

Inputs to Equation (11)

P_o = 1250 psi for cycle types ① and ②
0 psi for cycle type ③

M_b = 99,912 in-lbs ①
182,948 in-lbs ②
66,564 in-lbs ③

M_r = 130,020 in-lbs ①
150,048 in-lbs ②
43,164 in-lbs ③

$k_1 = 4.0$
$k_{2b} = k_{2r} = 1.0$
$k_3 = 1.0$

$\Delta T_1 = 333°F$
$\Delta T_2 = 182°F$ } ① and ②
$\Delta T_1 = \Delta T_2 = 0$ ③

$C_1 = 1.5$
$C_{2b} = C_{2r} = 1.7$

$D_o = 10.75$ in
$T_r = 1.38$ in (Ref 4)
$T'_b = 0.787$ in (Ref 4)

$$R_m = \frac{9.564 + 12.32}{4} = 5.47 \text{ in}$$

$$r'_m = \frac{7.625 + 9.197}{4} = 4.21 \text{ in}$$

} (Ref 4)

$$Z_r = \pi(5.47)^2(1.38) = 129.7 \text{ in}^4$$

$$Z_b = \pi(4.21)^2(0.787) = 43.8 \text{ in}^4$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	Ed Schimmer	4-27

Piping System: A-Condensate
Location: B09 (segment B) and B09 (segment D)
Description: Center of 8-inch by 10-inch lateral (cont'd)

Results

S_p = 153,400 psi for cycle ①
155,000 psi for cycle ②
3,100 psi for cycle ③

S_{alt} = 76,700 psi ①
77,500 psi ②
1,550 psi ③

$N_1 = 4.3 \times 10^3$	$n_1 = 395$
$N_2 = 4.3 \times 10^3$	$n_2 = 5$
$N_3 = 1 \times 10^6$	$n_3 = 50$

$$U = \frac{395}{4.3 \times 10^3} + \frac{5}{4.3 \times 10^3} + \frac{50}{1 \times 10^6} = \boxed{0.0931}$$

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPU Nuclear	PAGE 1 OF 8
PROJECT Oyster Creek ICS Leak Before Break	TASK NO. 83-133
CALCULATION TITLE Biot Number for Flow Through the Condensate Return Lines in the Oyster Creek ICS.	CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
D. Jacobs 5/31/90	S A Carmody 6/1/90	J E Katell 6-4-90	0
D. Jacobs 3/18/91	G M Haas 3/18/91	J E Katen 3-28-91	1

Purpose: To determine the Biot number for flow through the condensate return lines in the Oyster Creek
Rev. 1 Isolation Condenser System and through the vertical runs of 12-inch steam line pipe near the condensers (where the steam condenses and forms a column of standing water when the Iso Condenser system is not operating).

Results: The Biot number for 8-inch, schedule 100 pipe in the condensate return lines is 6.4. The Biot number for 10-inch, schedule 100 pipe in the
Rev. 1 condensate return lines is 9.0. The Biot number for water flowing through the 12-inch schedule 100 steam lines is 4.5. The Biot number for the 8"x 10" tee and lateral in the condensate return lines is 17.2.

REV	PREPARED BY	CHECKED BY
1	D. Jacobs	G. M. Haus

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	S. A. Carmody	3

REV	PREPARED BY	CHECKED BY
1	D. Jacobs	J. W. How

Calculation:

1. Velocity of Condensate in the Lines:

Maximum mass flow rate in a condenser is 330,000 lbm/hr. (Ref 1, Table 6.3-1).

Pipe sizes of the condensate lines, wall thicknesses, inside diameters, and internal cross-sectional areas are (Ref 2 and 3).

	Pipe Size	Wall Thickness, t (in)	Inside Diameter, D (in)	Area, A (ft²)
	8-inch, sch 100	0.594	7.437	.3018
Rev.1	10-inch run of tee and lateral (Ref 7)	1.378 (The largest t is used to get the largest N_b)	9.312 (sch 100 I.D. is used to get largest velocity; therefore largest N_b)	.4732
	10-inch, sch 100	0.719	9.312	.4732
Rev.1	12-inch, sch 100	0.844	11.062	.6677

ρ of water at 550°F is 45.9 lbm/ft³ (Ref 4)

$$V = \left(\frac{330{,}000\ \text{lbm}}{\text{hr}}\right)\left(\frac{1}{45.9\ \frac{\text{lbm}}{\text{ft}^3}}\right)\left(\frac{1}{.6036\ \text{ft}^2}\right)^{*}\left(\frac{1\ \text{hr}}{3600\ \text{sec}}\right) = 3.3\ \text{ft/s} \quad \begin{bmatrix}\text{8-inch,}\\ \text{sch 100}\end{bmatrix}$$

$$V = \left(\frac{330{,}000\ \text{lbm}}{\text{hr}}\right)\left(\frac{1}{45.9\ \text{lbm/ft}^3}\right)\left(\frac{1}{.4732\ \text{ft}^2}\right)\left(\frac{1\ \text{hr}}{3600\ \text{sec}}\right) = 4.2\ \text{ft/s} \quad \begin{bmatrix}\text{10-inch,}\\ \text{sch 100;}\\ \text{tee and}\\ \text{lateral}\end{bmatrix}$$

Rev. 1 →

* Note: In the ICS condensate lines, two 8-inch pipes lead into one 10-inch pipe. (Ref 2)

CALCULATION NO.	PREPARED BY Rev. 1 B. Jacobs	CHECKED BY Rev. 1	PAGE 3A

$$V = \left(\frac{330{,}000\ \text{lbm}}{\text{hr}}\right)\left(\frac{1}{45.9\ \text{lbm}/\text{ft}^3}\right)\left(\frac{1}{1.3354\ \text{ft}^2}\right)^{*}\left(\frac{1\ \text{hr}}{3600\ \text{sec}}\right) = 1.5\ \text{ft}/\text{s}\ \left[\begin{matrix}\text{12-inch}\\ \text{sch 100}\end{matrix}\right]$$

* Note: Two 12-inch pipes lead into one 16-inch pipe.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D. Jacobs	S. Carmody	4

REV	PREPARED BY	CHECKED BY
1	D. Jacobs	

2. Reynolds Number:

ν = kinematic viscosity = $.139 \times 10^{-5}\ ft^2/s$ (Ref 4)

$$Re = \frac{VD}{\nu} = \frac{(3.3\ ft/s)(7.437\ in)\left(\frac{1\ ft}{12\ in}\right)}{.139 \times 10^{-5}\ ft^2/s} = 1.5 \times 10^6 \quad \left[\begin{array}{c}\text{8-inch}\\ \text{sch 100}\end{array}\right]$$

$$Re = \frac{(4.2)(9.312)\left(\frac{1}{12}\right)}{.139 \times 10^{-5}} = 2.3 \times 10^6 \quad \left[\begin{array}{c}\text{10-inch}\\ \text{sch 100;}\\ \text{tee and}\\ \text{lateral}\end{array}\right]$$

Rev. 1 →

From a Moody Diagram, the flow in the 8-inch, 10-inch, and 12-inch pipes is in the transition stage between laminar and turbulent. Full turbulence is assumed for the remainder of this calculation; this assumption is conservative because the heat transfer coefficient for turbulent flow is larger than that for laminar flow.

Rev. 1

Rev. 1

$$Re = \frac{(1.5)(11.062)\left(\frac{1}{12}\right)}{.139 \times 10^{-5}} = 1.0 \times 10^6 \quad \left[\begin{array}{c}\text{12-inch}\\ \text{sch 100}\end{array}\right]$$

3. Convective Heat Transfer Coefficient, $\bar{h}_c$:

$$\bar{h}_c = 0.023\, C_p G \left(\frac{\mu_f}{D_H G}\right)^{.2} Pr_f^{-2/3} \quad Eqn(1)$$

$$G = \rho V \quad Eqn(2)$$

$$Pr_f = \frac{C_p \mu_f}{K_f} \quad Eqn(3)$$

(Ref 4, page 347)

where*: C_p = specific heat = 1.03 Btu/lbm-°F at 310°F
= 1.31 Btu/lbm-°F at 550°F
μ = absolute viscosity = .122 x10⁻³ lbm/ft-sec at 310°F
ρ = density = 45.9 lbm/ft³ at 550°F
V = velocity = 1.5 ft/s (12-inch pipe), 3.3 ft/s (8-inch pipe), and 4.2 ft/s (10-inch)
D_H = hydraulic diameter = D = 7.437 in (8-inch) and 9.312 in (10-inch) 11.062 (12-inch)
k = thermal conductivity of the water at mean film temperature = .394 Btu/hr-ft-°F at 310°F

Rev. 1

The subscript f in Eqn's (1) and (3) above indicates that the property should be evaluated at T_f where $T_f = .5\,(T_s + T_b)$.

T_s = pipe wall temperature, T_b = bulk fluid temperature.

$$T_f = .5\,(70° + 550°) = 310°F \quad (Ref\ 2)$$

* all properties listed above are for the condensate

REV	PREPARED BY	CHECKED BY
1	D. Jacobs	G. Hovee

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D Jacobs		6

REV	PREPARED BY	CHECKED BY
1	D. Jacobs	

8-inch pipe

$$\bar{h}_c = 0.023\left(1.31\,\frac{Btu}{lbm\text{-}^\circ F}\right)\left(45.9\,\frac{lbm}{ft^3}\right)\left(3.3\,\frac{ft}{s}\right)\left(\frac{3600\,s}{hr}\right)\times$$

$$\left(\frac{.122\times10^{-3}\,\frac{lbm}{ft\text{-}sec}}{\left(\frac{7.437\,in}{12\,in/ft}\right)\left(45.9\,\frac{lbm}{ft^3}\right)\left(3.3\,\frac{ft}{s}\right)}\right)^{.2}\times\left(\frac{\left(1.03\,\frac{Btu}{lbm\text{-}^\circ F}\right)\left(.122\times10^{-3}\,\frac{lbm}{ft\text{-}sec}\right)}{\left(.394\,\frac{Btu}{hr\text{-}ft\text{-}^\circ F}\right)\left(\frac{1\,hr}{3600\,sec}\right)}\right)^{-2/3}$$

$$\bar{h}_c = 996\ \frac{Btu}{hr\text{-}ft^2\text{-}^\circ F}$$

10-inch pipe, tee, and lateral ← Rev. 1

$$\bar{h}_c = 0.023\,(1.31)(45.9)(4.2)(3600)\quad\times$$

$$\left(\frac{.122\times10^{-3}}{\left(\frac{9.312}{12}\right)(45.9)(4.2)}\right)^{.2}\times\left(\frac{(1.03)(.122\times10^{-3})}{(.394)\left(\frac{1}{3600}\right)}\right)^{-2/3}$$

$$\bar{h}_c = 1155\ \frac{Btu}{hr\text{-}ft^2\text{-}^\circ F}$$

12-inch pipe

Rev. 1

$$\bar{h}_c = 0.023\,(1.31)(45.9)(1.5)(3600)\quad\times$$

$$\left(\frac{.122\times10^{-3}}{\left(\frac{11.062}{12}\right)(45.9)(1.5)}\right)^{.2}\times\left(\frac{(1.03)(.122\times10^{-3})}{(.394)\left(\frac{1}{3600}\right)}\right)^{-2/3}$$

$$\bar{h}_c = 490\ \frac{Btu}{hr\text{-}ft^2\text{-}^\circ F}$$

REV	PREPARED BY	CHECKED BY
1	D. Jacobs	

4. <u>Biot Number, N_B</u>

$$N_B = \frac{ht}{k}$$

where k = thermal conductivity at the pipe wall
$= 7.7 \frac{\text{Btu}}{\text{hr-ft-°F}}$ at 70°F for
16Cr-12Ni-2Mo*
(Ref 5)

<u>8-inch pipe</u>

$$N_B = \frac{\left(996 \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}\right)(.594 \text{ in})\left(\frac{1 \text{ ft}}{12 \text{ in}}\right)}{\left(7.7 \frac{\text{Btu}}{\text{hr-ft-°F}}\right)} = \boxed{6.4}$$

<u>10-inch pipe</u>

$$N_B = \frac{(1155)(.719)\left(\frac{1}{12}\right)}{7.7} = \boxed{9.0}$$

* SA-376 and SA-403 TP 316 are 16Cr-12Ni-2Mo (Ref 6)

Rev. 1

<u>12-inch pipe</u>

$$N_B = \frac{(440)(.844)\left(\frac{1}{12}\right)}{7.7} = \boxed{4.5}$$

<u>10-inch x 8-inch tee and lateral</u>

$$N_B = \frac{(1155)(1.378)\left(\frac{1}{12}\right)}{7.7} = \boxed{17.2}$$

References:

1. Oyster Creek Nuclear Generating Station, Updated Final Safety Analysis Report, Volume 5.

2. MPR-1177 through 1180, "Oyster Creek Nuclear Generating Station Isolation Condenser System, Analysis of Modified Piping Configuration," April, 1990.

3. Crane Technical Bulletin No. 410, Flow of Fluids through Valves, Pipe, and Fittings.

4. Kreith, [illegible] k, <u>Principles of Heat Transfer</u>, International Textbook Company, Scranton, PA, 1963.

5. ASME Boiler and Pressure Vessel Code, Section III, Appendices, 1989.

6. ASTM Standards, 1988, Volume 01.01.

7. Mannesman Spool Piece Drawings, Attachment 1 to GPU Nuclear Letter 5512-89-126, from Mr. J. A. Sergentanis to Mr. B.R. Bernier, September 26, 1989.

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPU Nuclear	PAGE 1 OF 3
PROJECT ICS Pipe Leak Before Break	TASK NO. 83-133
CALCULATION TITLE Oyster Creek Nuclear Generating Station Average Startups / Shutdowns per Year	CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
D. Jacobs 6/1/90	C Dobson 6/1/90	J S Kester 6-4-90	0

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D Jacobs	C. Dobson	2

Purpose: To determine the average number of startups and shutdowns per year over the life of the Oyster Creek Nuclear Generating Station.

Results: The average number of startups and shutdowns per year is 8.1.

Calculation: (Ref 1, Sect 5)

Years of operation: Dec. 23, 1969 to present (outage data available up to March 31, 1986)
= 16.25 years of outage data

Number of outages: 131 (see next page)

Average number of outages (startups and shutdowns) per year =
$\boxed{8.1}$

Reference:
"Oyster Creek Nuclear Generating Station Important Dates, Facts, and Statistics", Topical Report 026, Rev 2, August 14, 1986.

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	D Jacobs	C. Dokos	3

NUMBER AND
LENGTH OF OUTAGES
(Beginning December 23, 1969)
(Refueling/Maintenance Outages Not Included)
(Ref 1)

	X (Hours) Outage Time 2X (Hours					
	O.T. 24 Number	24<O.T.<48 Number	48 O.T. 96 Number	96 O.T. 192 Number	O.T.≥192 Number	
1969	1	-	-	-	-	
1970	9	9	-	1	3	
1971	1	1	1	2	-	
1972	4	1	3	1	-	
1973	3	2	-	1	2	
1974	-	1	2	2	1	
1975	2	2	1	3	1	
1976	-	1	-	1	-	
1977	1	1	1	-	-	
1978	-	2	1	1	-	
1979	1	1	2	-	2	
1980	1	-	1	3	-	
1981	2	-	2	2	3	
1982	-	2	-	1	3	
1983	-	-	1	-	-	
1984	3	-	1	-	1	
1985	3	2	1	2	2	
(A)1986	-	-	1	1	-	
	31	25	18	21	18	= 113

(A) INCLUDES DATA ONLY UP TO MARCH 31, 1986

Refueling/Maintenance Outages : 18 (Ref 1)

Total # Outages = 131

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPUN	PAGE 1 OF 16
PROJECT ICS Piping LBB	TASK NO. 83-133
CALCULATION TITLE Applied Piping Loads	CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV NO.
4/9/91	4/11/91	4-17-91	0

__Purpose__ - This calculation documents the postulated crack locations to be evaluated as part of a leak-before-break evaluation of the Oyster Creek Isolation Condenser System (ICS) piping outside the drywell. The loads on the piping at these locations are also determined.

<u>Calculation</u> - Reference 1 requires that leak-before-break evaluations perform fracture mechanics for postulated through-wall cracks at the locations of highest stress in the piping system. For this analysis of the Oyster Creek ICS piping outside containment, cracks will be postulated at the highest loaded point of each pipe size and fluid type. This corresponds to a total of 4 points in each condensate return line (the highest loaded 8"-sch 80, 8"-Sch 100, 10"-Sch 80 and 10"-Sch 100 pipes) and 6 points in each steam supply line (the highest loaded 10"-sch 80, 10"-Sch 100, 12"-Sch 80, 12"-Sch 100, 16"-Sch 80 and 16"-Sch 100 pipes), for a total of 20 locations.

It is possible that to meet fit-up requirements, some of the schedule 100 piping may be machined back to schedule 80 thicknesses. To account for this possibility, all fracture mechanics analyses will use the schedule 80 wall thicknesses for the schedule 100 piping. The exception to this is the 10" schedule 100 piping at the containment penetrations which will not be machined. It will be evaluated using the schedule 100 thickness.

The piping loads due to deadweight, thermal expansion and safe shutdown earthquake (SSE) are obtained from Reference 2 to 5. The ICS piping is subjected to axial and shear forces, bending and torsional moments, and internal pressure. However, the method used for fracture mechanics analyses (Reference 6), require the applied loads to be expressed only as an overturning bending moment. The method used to calculate the piping loads (an equivalent bending moment) for the ICS piping is listed below:

1. Loads are calculated at each node in the AUTOPIPE finite element models. If an AUTOPIPE model node is the junction of two different pipe sizes, the loads are calculated for each size.
2. The AUTOPIPE printout of the forces and moments at each node point include the SRSS sums of the three coordinate direction forces and moments at the node. These SRSS forces and moments are used to calculate the equivalent bending moment.

3. For each node, the longitudinal pressure stress, S_p is calculated from $S_p = \frac{PR_o}{2t}$. The system operating pressure of 1050 psi is used.

4. The stress analysis results in References 2 to 5 include forces and moments for the load combinations GR+T2+R2 and GR+T2-R2. GR is deadweight, T2 is operating thermal expansion and R2 is SSE. The worst case of these two combinations (+R2 or -R2) is used. The force is F_t and the moment is M_t.

5. A total stress at the node is calculated from

$$I = \frac{\pi (R_o^4 - R_i^4)}{4}$$

$$A = \pi (R_o^2 - R_i^2) \qquad S_T = S_p + S_A + S_B$$

$$S_A = \frac{F_T}{A}$$

$$S_B = \frac{12 M_t R_o}{I}$$ (AUTOPIPE moments are in ft-lbs)

6. The equivalent bending moment which would produce this same stress is calculated from

$$M_{eq} = \frac{S_T I}{R_o}$$

The results of these calculations for the ICS piping are shown on the following pages. The pipe dimensions used are listed below.

		OD	t	
8"	sch. 80	8.625	0.50	
8"	sch. 100	8.625	0.50	*
10"	sch. 80	10.75	0.594	
10"	sch. 100	10.75	0.594	*
10"	sch. 100	10.75	0.719	**
12"	sch. 80	12.75	0.688	
12"	sch. 100	12.75	0.688	*
16"	sch. 80	16.00	0.844	
16"	sch 100	16.00	0.844	*

* Fracture mechanics analyses of the schedule 100 piping assume schedule 80 section properties (to allow for machining of the pipe).

** The 10" sch. 100 pipe in the steam supply lines will not be machined, so the schedule 100 section properties are used for these lines.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	R. C. T	A. C. Hall	7

A-CONDENSATE LINE
8" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
C03A	1277	8455	4528	100	4139	8767	214915
C04 N	1276	8454	4528	100	4138	8766	214901
C04 F	1327	7646	4528	104	3743	8375	205303
C07A	1052	8153	4528	82	3991	8602	210859
C08 N	1049	8153	4528	82	3991	8601	210853
C08 F	1020	8154	4528	80	3992	8600	210809
C09A	945	10250	4528	74	5018	9620	235817
C10 N	954	10250	4528	75	5018	9620	235834
C10 F	961	10666	4528	75	5221	9825	240840
C11A +	1238	12501	4528	97	6119	10745	263392
C12 N	1255	12502	4528	98	6120	10746	263436
C12 F	1305	11816	4528	102	5784	10415	255301
C17A	1766	10873	4528	138	5323	9989	244870
C18 N	1762	10875	4528	138	5324	9990	244886
C18 F	1714	11760	4528	134	5757	10419	255414
C20A	2303	11727	4528	180	5741	10449	256149
C21 N	2301	11729	4528	180	5742	10450	256170
C21 F	2225	11193	4528	174	5479	10182	249592
C23A	1969	5222	4528	154	2556	7239	177448
C24 N	1971	5221	4528	154	2556	7238	177440
C24 F	1947	4934	4528	153	2415	7096	173950
C24A +	1875	4259	4528	147	2085	6760	165711
C25 N	1878	4259	4528	147	2085	6760	165717
C25 F	1860	4299	4523	146	2104	6778	166163
C25A +	1159	6547	4528	91	3205	7824	191792
C26 N	1163	6551	4528	91	3206	7826	191836
C26 F	1159	7847	4528	91	3841	8460	207392
C27	1158	7857	4528	91	3846	8465	207510
D01 +	2614	11225	4528	205	5495	10228	250723
D02 N	2616	11229	4528	205	5497	10230	250775
D02 F	2618	11957	4528	205	5853	10586	259514
D03A	2607	14016	4528	204	6861	11593	284201
D04 N	2610	14017	4528	205	6862	11594	284219 ←
D04 F	2619	12735	4528	205	6234	10967	268852
D06A	2234	11018	4528	175	5394	10097	247509
D07 N	2218	11023	4528	174	5396	10098	247538
D07 F	2103	12501	4528	165	6119	10812	265053
D12A	2509	12795	4528	197	6263	10988	269361
D13 N	2486	12799	4528	195	6265	10988	269365
D13 F	2412	12818	4528	189	6275	10992	269451
D15A	2291	8960	4528	180	4386	9094	222922
D16 N	2298	8964	4528	180	4388	9096	222984
D16 F	2298	10440	4528	180	5111	9819	240696
D17	2297	10449	4528	180	5115	9823	240802

A-CONDENSATE LINE
10" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
B05 +	3407	16410	4751	180	4317	9247	421826
B10 -	3427	16420	4751	181	4320	9251	421994
B10 +	3155	16420	4751	166	4320	9237	421339
B06 -	3249	16621	4751	171	4372	9294	423978
B06 +	3382	16621	4751	178	4372	9301	424298
B07	3248	16556	4751	171	4355	9277	423195
B08 -	3139	17732	4751	166	4665	9581	437045 ←
C02 +	1204	12822	4751	64	3373	8187	373467
C03	1198	11954	4751	63	3145	7959	363037

A-CONDENSATE LINE
10" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
A26	3999	14704	4751	211	3868	8830	402779
B01 -	4000	14802	4751	211	3894	8856	403957 ←

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 8

A-CONDENSATE LINE
8" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
C03	1198	11954	4528	94	5852	10474	256751
C03A	1277	8455	4528	100	4139	8767	214915
C04 F	1327	7446	4528	104	3743	8375	205303
C05 -	1412	6977	4528	111	3415	8054	197438
C05 +	1398	6977	4528	110	3415	8053	197411
C06 -	1540	7407	4528	121	3626	8275	202844
C06 +	1293	7407	4528	101	3626	8255	202369
C07 -	1398	8265	4528	110	4046	8684	212867
C07 +	1068	8265	4528	84	4046	8658	212233
C07A	1052	8153	4528	82	3991	8602	210859
C08 F	1020	8154	4528	80	3992	8600	210809
C09 -	947	8897	4528	74	4355	8958	219585
C09 +	984	8897	4528	77	4355	8960	219656
C09A	945	10250	4528	74	5018	9620	235817
C10 F	961	10666	4528	75	5221	9825	240840
C11 -	939	10944	4528	74	5357	9959	244133
C11 +	1177	11262	4528	92	5513	10133	248407
C11A -	1200	12501	4528	94	6119	10742	263319
C12 F	1305	11816	4528	102	5784	10415	255301
C13 -	1467	10896	4528	115	5334	9977	244572
C13 +	2384	10896	4528	187	5334	10049	246333
C14	2154	5364	4528	169	2626	7323	179507
C15 -	1948	5713	4528	153	2797	7477	183300
C15 +	2369	5897	4528	186	2887	7600	186316
C16 -	2280	6690	4528	179	3275	7982	195661
C16 +	2235	6805	4528	175	3331	8034	196955
C17 -	2105	9185	4528	165	4496	9189	225265
C17 +	1829	9185	4528	143	4496	9168	224735
C17A	1766	10873	4528	138	5323	9989	244870
C18 F	1714	11760	4528	134	5757	10419	255414
C19 -	1697	11703	4528	133	5729	10390	254697
C19 +	1712	11703	4528	134	5729	10391	254726
C20 -	1557	11519	4528	122	5639	10289	252221
C20 +	2322	11519	4528	182	5639	10349	253690
C20A	2303	11727	4528	180	5741	10449	256149
C21 F	2225	11193	4528	174	5479	10182	249592
C22 -	2198	10540	4528	172	5160	9860	241704
C22 +	2207	10540	4528	173	5160	9861	241721
C23	2077	7062	4528	163	3457	8148	199735
C23A	1969	5222	4528	154	2556	7239	177448
C24 F	1947	4934	4528	153	2415	7096	173950
C24A -	1870	4259	4528	147	2085	6760	165702
C25 F	1860	4299	4528	146	2104	6778	166163
C25A -	1149	6547	4528	90	3205	7823	191773
D02 F	2618	11957	4528	205	5853	10586	259514
D03 -	2605	12621	4528	204	6178	10910	267457
D03 +	2615	12621	4528	205	6178	10911	267477
D03A	2607	4016	4528	204	6861	11593	284201 ←
D04 F	2619	12735	4528	205	6234	10967	268852
D05 -	2626	6382	4528	206	3124	7858	192630
D05 +	3006	6382	4528	236	3124	7888	193360
D06 -	2068	8978	4528	162	4395	9085	222710
D06 +	2300	8932	4528	180	4372	9081	222604
D06A	2734	11018	4528	175	5394	10097	247509
D07 F	2103	12501	4528	165	6119	10812	265053
D08 -	2046	11653	4528	160	5704	10393	254768
D08 +	1786	11649	4528	140	5702	10370	254220
D09	1632	9671	4528	128	4734	9390	230189
D10 -	1492	8490	4528	117	4156	8801	215748
D10 +	1615	8490	4528	127	4156	8811	215984
D11	1696	8336	4528	133	4081	8742	214292
D12 -	1581	9276	4528	124	4541	9193	225351
D12 +	2658	9276	4528	208	4541	9277	227419
D12A	2509	12795	4528	197	6263	10988	269361
D13 F	2412	12818	4528	189	6275	10992	269451
D14 -	2396	11884	4528	188	5817	10533	258212
D14 +	2357	11884	4528	185	5817	10530	258137
D15	2228	1844	4528	175	903	5605	137409
D15A	2291	8960	4528	180	4386	9094	222922

A-STEAM LINE
10" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
B09 +	6635	26146	4751	350	6878	11979	546427 ←
B10 -	6618	24668	4751	349	6489	11589	528650

A-STEAM LINE
10" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
A13	7020	34453	3925	310	7758	11992	639107
B01 -	7021	34504	3925	310	7769	12004	639721 ←

A-STEAM LINE
12" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
C01A	4911	28482	4865	188	4581	9634	718824
C02 N	4887	28490	4865	187	4582	9634	718851
C02 F	4770	31013	4865	183	4988	10035	748792
C09A	6087	29764	4865	233	4787	9885	737573
C10 N	6096	29764	4865	234	4787	9885	737599
C10 F	6138	24966	4865	235	4015	9115	680143
C11A	6176	23521	4865	237	3783	8884	662912
C12 N	6204	23524	4865	238	3783	8886	663028
C12 F	6270	19959	4865	240	3210	8315	620437
C13A	5336	24847	4865	205	3996	9065	676420
C14 N	5305	24847	4865	203	3996	9064	676355
C14 F-	5318	36820	4865	204	5921	10990	820044
C14 F+	5290	36820	4865	203	5921	10989	819964
C15 N	5272	36850	4865	202	5926	10993	820273
C15 F	6806	42504	4865	261	6836	11961	892511
C16	6806	42515	4865	261	6837	11963	892643
D01A	5574	39484	4865	214	6350	11428	852745
D02 N	5580	39491	4865	214	6351	11430	852846
D02 F	5598	41835	4865	215	6728	11807	881026
D06A	7908	27487	4865	303	4421	9588	715461
D07 N	7947	27487	4865	305	4421	9590	715573
D07 F	5263	21274	4865	202	3421	8488	633335
D08A	5458	25417	4865	209	4088	9162	683609
D09 N	5432	25428	4865	208	4089	9162	683667
D09 F	5339	30220	4865	205	4860	9929	740905
D10A	8393	44361	4865	322	7134	12321	919337
D11 N	8403	44375	4865	322	7136	12323	919534
D11 F	8364	52462	4865	321	8437	13622	1016466
D12	8364	52468	4865	321	8438	13623	1016538 ←

A-STEAM LINE
16" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
B12A	8291	18379	4976	206	1524	6707	970373
B13 N	8326	18367	4976	207	1523	6707	970355
B13 F	7922	12648	4976	197	1049	6222	900272
B16 +	1086	17965	4976	27	1490	6493	939465
B17	769	20587	4976	19	1708	6703	969787
B18	1178	22812	4976	29	1892	6898	997960
B19 -	1751	24919	4976	44	2067	7087	1025307 ←

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	A. C. C	A. C. Hall	10

A-STEAM LINE
12" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
C01 +	4923	27515	4865	189	4425	9478	707254
C01A	4911	28482	4865	188	4581	9634	718824
C02 F	4770	31013	4865	183	4988	10035	748792
C0[illegible] -	4732	33454	4865	182	5380	10426	777975
C03 +	5461	33454	4865	209	5380	10454	780062
C04 -	5342	32025	4865	205	5150	10220	762573
C04 +	5340	32031	4865	205	5151	10221	762639
C05 -	5246	32235	4865	201	5184	10250	764818
C05 +	4907	34194	4865	188	5499	10552	787356
C06	4946	31614	4865	190	5084	10139	756508
C07 -	4867	30247	4865	187	4864	9916	739878
C07 +	5119	30247	4865	196	4864	9925	740599
C08	5388	30303	4865	207	4873	9945	742041
C09 -	5410	32832	4865	208	5280	10352	772452
C09 +	5905	32832	4865	226	5280	10371	773869
C09A	6087	29764	4865	233	4787	9885	737573
C10 F	6138	24966	4865	235	4015	9115	680143
C11 -	6147	23451	4865	236	37[illegible]	8872	661989
C11 +	6146	23334	4865	236	3753	8853	660582
C11A	6176	23521	4865	237	3783	8884	662912
C12 F	6270	19959	4865	240	3210	8315	620437
C13 -	6287	15531	4865	241	2498	7604	567350
C13 +	6413	15531	4865	246	[illegible]	7608	567710
C13A	5336	24847	4865	205	3996	9065	676420
D01 +	5570	38541	4865	214	6198	11277	841418
D01A	5574	39484	4865	214	6350	11428	852745
D02 F	5599	41835	4865	215	6728	11807	881026
D03 -	5606	41928	4865	215	6743	11823	882165
D03 +	5528	42004	4865	212	6755	11832	882854
D04 -	5588	43055	4865	214	6924	12003	895637
D04 +	5910	43055	4865	227	6924	12016	896559
D05 -	5807	37966	4865	223	6106	11193	835196
D05 +	5751	37966	4865	221	6106	11191	835036
D06	5496	30646	4865	211	4929	10004	746466
D06A	7908	27487	4865	303	4421	9588	715461
D07 F	5263	21274	4865	202	3421	8488	633335
D08 -	5250	19853	4865	201	3193	8259	616246
D08 +	5631	19853	4865	216	3193	8273	617336
D08A	5458	25417	4865	209	4088	9162	683609
D09 F	5339	30220	4865	205	4860	9929	740905
D10 -	5323	29668	4865	204	4771	9840	734235
D10 +	5273	29668	4865	202	4771	9838	734092
D10A	8393	44361	4865	322	7134	12321	919337 ←

A-STEAM LINE
16" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
B10 +	6674	24668	4976	166	2046	7188	1040019
B11 -	6612	22424	4976	165	1860	7001	1012868
B11 +	3697	25834	4976	92	2143	7211	1043293 ←
B12 -	3488	21613	4976	87	1793	6856	991889
B12 +	8367	21613	4976	208	1793	6977	1009454
B12A	8291	18379	4976	206	1524	6707	970373
B13 F	7922	12648	4976	197	1049	6222	900272
B14	7856	12723	4976	195	1055	6227	900934
B15 -	7792	12813	4976	194	1063	6233	901784
B15 +	5494	17403	4976	137	1443	6556	948591
B16 -	1196	17965	4976	30	1490	6496	939861

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	R.C.C.	A.C. Hel	11

B-CONDENSATE LINE
8" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
C14	3920	9466	4528	307	4634	9469	232123
C15	3838	7299	4528	301	3573	8402	205962
C16 -	3854	6827	4528	302	3342	8172	200328
C16 +	3772	6827	4528	296	3342	8166	200171
C17 -	3808	6840	4528	298	3348	8175	200396
C17 +	3837	6840	4528	301	3348	8177	200452
C18	3717	6460	4528	291	3162	7982	195661
C19 -	3662	8762	4528	287	4289	9104	223180
C22A	3398	18648	4528	266	9129	13923	341305
C23 N	3378	18652	4528	265	9131	13923	341314
C23 F	3328	17548	4528	261	8590	13379	327970
C26A	3065	27013	4528	240	13223	17992	441045
C27 N	3063	27020	4528	240	13227	17995	441125
C27 F	3042	29459	4528	238	14421	19187	470353
C28	3042	29467	4528	238	14425	19191	470449 ←
D02A	4765	17297	4528	373	8467	13369	327718
D03 N	4736	17300	4528	371	8469	13368	327699
D03 F	3681	16720	4528	288	8185	13001	318712
D06A	5159	20507	4528	404	10039	14971	366995
D07 N	5162	20514	4528	404	10042	14975	367085
D07 F	5104	20542	4528	400	10056	14984	367309
D09A	4128	6915	4528	323	3385	8237	201911
D10 N	4116	6917	4528	323	3386	8237	201912
D10 F	4061	7817	4528	318	3827	8673	212606
D11A	4960	9842	4528	389	4818	9735	238633
D12 N	4973	9843	4528	390	4818	9736	238670
D12 F	4975	11326	4528	390	5544	10462	256470
D13A	4942	17187	4528	387	8413	13329	326738
D14 N	4954	17193	4528	388	8416	13333	326833
D14 F	4938	19666	4528	387	9627	14542	356479
D15	4938	19675	4528	387	9631	14546	356587

B-CONDENSATE LINE
10" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
C05 +	4357	18482	4751	230	4862	9642	448976 ←
C06 -	4267	14058	4751	225	3698	8674	395672
C06 +	3566	14058	4751	188	3698	8637	393985
C07 -	3639	15228	4751	192	4006	8949	408200
C07 +	3755	15228	4751	198	4006	8955	408479
C08 -	3657	15051	4751	193	3959	8903	406120
C08 +	2874	15051	4751	152	3959	8862	404235
C09 -	2718	13312	4751	143	3502	8396	382992
C09 +	4685	13312	4751	247	3502	8500	387726
C10 -	4281	13771	4751	226	3623	8599	392262
C10 +	4208	13771	4751	222	3623	8595	392086
C11 -	4155	15246	4751	219	4011	8981	409658
C11 +	4055	6196	4751	214	1630	6595	300818
C12 N-	4049	8189	4751	214	2154	7119	324719
C12 N+	4014	8189	4751	212	2154	7117	324635
C12 F	3984	9919	4751	210	2609	7570	345323
C13	3974	9917	4751	210	2609	7569	345275
C14	3920	9466	4751	207	2490	7448	339733

B-CONDENSATE LINE
8" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
C19 +	3574	8762	4528	280	4289	9097	223011
C20	3373	11786	4528	264	5769	10562	258913
C21 -	3344	13181	4528	262	6452	11242	275597
C21 +	3244	13181	4528	254	6452	11235	275405
C22 -	3249	13206	4528	255	6465	11247	275714
C22 +	3520	13206	4528	276	6465	11269	276235
C22A	3398	18648	4528	266	9129	13923	341305
C23 F	3328	17548	4528	261	8590	13379	327970
C24 -	3316	16049	4528	260	7856	12644	309959
C24 +	3287	16049	4528	258	7856	12642	309903
C25	3379	4320	4528	265	2115	6908	169332
C26	3203	14288	4528	251	6994	11773	288610
C26A	3065	27013	4528	240	13223	17992	441045 ←
C11	5490	16048	4528	430	7856	12814	314123
D01 -	5465	15962	4528	428	7814	12770	313043
D01 +	5474	15962	4528	429	7814	12771	313060
D02 -	5443	16030	4528	426	7847	12802	313817
D02 +	4815	16258	4528	377	7959	12864	315346
D02A	4765	17297	4528	373	8467	13369	327718
D03 F	3681	16720	4528	288	8185	13001	318712
D04 -	3526	8878	4528	276	4346	9150	224310
D04 +	3610	8878	4528	283	4346	9157	224472
D05 -	3553	7170	4528	278	3510	8316	203866
D05 +	4823	7170	4528	378	3510	8416	206306
D06	5263	13099	4528	412	6412	11353	278299
D06A	5159	20507	4528	404	10039	14971	366995
D07 F	5104	20542	4528	400	10056	14984	367309
D08 -	5080	18825	4528	398	9215	14141	346659
D08 +	5114	18825	4528	401	9215	14144	346725
D09	5048	9455	4528	396	4628	9552	234158
D09A	4128	6915	4528	323	3385	8237	201911
D10 F	4061	7817	4528	318	3827	8673	212606
D11 -	4025	8682	4528	315	4250	9093	222917
D11 +	3993	8682	4528	313	4250	9091	222855
D11A	4960	9842	4528	389	4818	9735	238633
D12 F	4975	11326	4528	390	5544	10462	256470
D13 -	4930	14069	4528	386	6887	11801	289299
D13 +	4968	14069	4528	389	6887	11804	289372
D13A	4942	17187	4528	387	8413	13329	326738

B-CONDENSATE LINE
10" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
B20	4021	23898	4751	212	6287	11250	513160 ←
C01 -	4020	23874	4751	212	6280	11243	512869

```
B-STEAM LINE
10" SCH 80
  Node        FT     MT     SP     SA     SB     ST      MEQ
B09  +       3945  40758  4751    208  10722  15681   715297 ←
B10  -       4021  36680  4751    212   9649  14612   666544

B-STEAM LINE
10" SCH 100
  Node        FT     MT     SP     SA     SB     ST      MEQ
A11          3780  42016  3925    167   9461  13552   722242
B01  -       3779  42155  3925    167   9492  13584   723908 ←


B-STEAM LINE
12" SCH 80
  Node        FT     MT     SP     SA     SB     ST      MEQ
C01A         5895  30870  4865    226   4965  10055   750296
C02 N        5914  30880  4865    227   4966  10058   750470
C02 F        6019  34234  4865    231   5506  10601   791019
C08A         7102  41138  4865    272   6616  11753   876966
C09 N        7123  41140  4865    273   6616  11754   877051
C09 F        7151  33932  4865    274   5457  10596   790635
C11A         8437  21745  4865    324   3497   8685   648071
C12 N        8520  21751  4865    327   3498   8689   648381
C12 F        8553  24466  4865    328   3935   9127   681055
C13A         8701  46230  4865    334   7435  12633   942647
C14 N        8726  46244  4865    335   7437  12636   942886
C14 F        8717  55012  4865    334   8847  14046  1048077
C15          8717  55020  4865    334   8848  14047  1048173
D01A         6032  40650  4865    231   6537  11633   868048
D02 N        6011  40660  4865    231   6539  11634   868108
D02 F        5938  44243  4865    228   7115  12208   910895
D09A         7759  40285  4865    298   6479  11641   868611
D10 N        7755  40288  4865    297   6479  11641   868635
D10 F        7723  33452  4865    296   5380  10541   786512
D13A         8134  25828  4865    312   4154   9330   696200
D14 N        8121  25832  4865    311   4154   9330   696211
D14 F        8036  22586  4865    308   3632   8805   657016
D15A         8759  46538  4865    336   7484  12685   946509
D16 N        8762  46554  4865    336   7487  12688   946709
D16 F        8761  57431  4865    336   9236  14437  1077231
D17          8761  57441  4865    336   9238  14438  1077351 ←


B-STEAM LINE
16" SCH 100
  Node        FT     MT     SP     SA     SB     ST      MEQ
B10  +       4097  36680  4976    102   3042   8121  1174885
B23  -       4247  35143  4976    106   2915   7997  1156981
B23  +       3149  35540  4976     78   2948   8002  1157792
B11  -       3402  34092  4976     85   2828   7889  1141327
B11  +       4553  34092  4976    113   2828   7917  1145471
B12          4244  48068  4976    106   3987   9069  1312070
B13  -       4007  59047  4976    100   4897   9973  1442965
B13  +       4343  59047  4976    108   4897   9982  1444175 ←
B14          4397  58345  4976    109   4839   9925  1435945
B14A         4439  57706  4976    110   4786   9873  1428428
B15 F        4714  53976  4976    117   4477   9570  1384658
B16  -       4743  52673  4976    118   4369   9463  1369127
B16  +       3404  52558  4976     85   4359   9420  1362926
B17          3627  42510  4976     90   3526   8592  1243153
```

B-STEAM LINE
12" SCH 100

Node	FT	MT	SP	SA	SB	ST	MEQ
C01 +	5884	29668	4865	226	4771	9862	735840
C01A	5895	30870	4865	226	4965	10055	750296
C02 F	6019	34234	4865	231	5506	10601	791019
C03 -	6103	37567	4865	234	6042	11140	831255
C03 +	6115	37100	4865	235	5966	11066	825686
C04 -	6177	39740	4865	237	6391	11493	857543
C04 +	6483	39740	4865	249	6391	11504	858419
C05	6616	36789	4865	254	5916	11035	823387
C06 -	6536	34479	4865	251	5545	10660	795439
C06 +	6803	34479	4865	261	5545	10671	796203
C07 -	6761	36254	4865	259	5830	10954	817382
C07 +	6960	36402	4865	267	5854	10986	819728
C08	7066	38879	4865	271	6253	11388	849755
C08A	7102	41138	4865	272	6616	11753	876966
C09 F	7151	33932	4865	274	5457	10596	790635
C10 -	7825	31102	4865	300	5002	10167	758604
C10 +	7843	31102	4865	301	5002	10167	758655
C11 -	7834	24550	4865	300	3948	9113	680005
C11 +	8437	24550	4865	324	3948	9136	681731
C11A	8437	21745	4865	324	3497	8685	648071
C12 F	8553	24466	4865	328	3935	9127	681055
C13 -	8539	24243	4865	328	3899	9091	678339
C13 +	8747	24243	4865	336	3899	9099	678935
C13A	8701	46230	4865	334	7435	12633	942647
D01 +	6045	39470	4865	232	6348	11444	853925
D01A	6032	40650	4865	231	6537	11633	868048
D02 F	5938	44243	4865	228	7115	12208	910895
D03 -	5908	46[illegible]97	4865	227	7462	12553	936657
D03 +	5697	46256	4865	219	7439	12522	934361
D04 -	5672	49715	4865	218	7995	13077	975798 ←
D04 +	6956	46753	4865	267	7519	12650	943929
D05 -	6965	47940	4865	267	7710	12842	958198
D05 +	7604	47940	4865	292	7710	12866	960027
D06	7600	39697	4865	292	6384	11540	861100
D07 -	7472	35161	4865	287	5655	10806	806301
D07 +	7715	35161	4865	296	5655	10815	806997
D08	7805	33922	4865	299	5455	10619	792387
D09	7797	36421	4865	299	5857	11021	822352
D09A	7759	40285	4865	298	6479	11641	868611
D10 F	7723	33452	4865	296	5380	10541	786512
D11 -	7720	32112	4865	296	5164	10325	770423
D11 +	7726	31977	4865	296	5143	10304	768820
D12 -	7709	26330	4865	296	4234	9395	701008
D12 +	7699	26330	4865	295	4234	9394	700979
D13 -	7695	25703	4865	295	4134	9293	693444
D13 +	8199	25703	4865	314	4134	9313	694886
D13A	8134	25828	4865	312	4154	9330	696200
D14 F	8036	22586	4865	308	3632	8805	657016
D15 -	8697	22023	4865	334	3542	8740	652151
D15 +	8772	22023	4865	336	3542	8743	652366
D15A	8759	46538	4865	336	7484	12685	946509

B-STEAM LINE
16" SCH 80

Node	FT	MT	SP	SA	SB	ST	MEQ
B14A	4439	57706	4976	110	4786	9873	1428428
B15 N	4496	57704	4976	112	4786	9874	1428610 ←
B15 F	4714	53976	4976	117	4477	9570	1384658
B17 +	3580	42510	4976	89	3526	8591	1242984
B18	3825	29106	4976	95	2414	7486	1083018
B19	3916	14947	4976	97	1240	6313	913437
B20	5589	16924	4976	139	1404	6519	943185
B21 -	5188	28443	4976	129	2359	7465	1079969

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 15
	R. Cul	A C. Hell	

The maximum loads for each line are tabulated below. One-half of the equivalent moment is also included since the fracture mechanics analysis methods require ½ the applied moment.

	Meq (in-lb)	Meq/2 (in-lb)
A - Condensate		
8" Sch 80 - D04N	284219	142110
8" Sch 100 - D03A	284201	142101
10" Sch 80 - B08	437045	218523
10" Sch 100 - B01	403957	201979
A - Steam		
10" Sch 80 - B09	546427	273214
10" Sch 100 - B01	639721	319861
12" Sch 80 - D12	1016538	508269
12" Sch 100 - D10A	919337	459669
16" Sch 80 - B19	1025307	512654
16" Sch 100 - B11	1043293	521647
B - Condensate		
8" Sch 80 - C28	470449	235225
8" Sch 100 - C26A	441045	220523
10" Sch 80 - C05	448976	224488
10" Sch 100 - B20	513160	256580
B - Steam		
10" Sch 80 - B09	715287	357644
10" Sch 100 - B01	723908	361954
12" Sch 80 - D17	1077351	538676
12" Sch 100 - D04	975798	487899
16" Sch 80 - B15N	1428610	714305
16" Sch 100 - B13	1444175	722088

References

1) USNRC Standard Review Plan 3.6.3 (Draft), 8/28/87

2) MPR-1177, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line to Condenser NE-01-A"

3) MPR-1178, "Isolation Condenser System Analysis of Modified Piping Configuration, Condensate Line From Condenser NE-01-A

4) MPR-1179, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line to Condenser NE-01-B"

5) MPR-1180, "Isolation Condenser System, Analysis of Modified Piping Configuration, Condensate Line From Condenser NE-01-B"

6) MPR Calculation, "TBAR Documentation" (Version 2.0), by R. Cowan, [illegible]/90.

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT
MPR

PAGE 1 OF 21 (A1-A8)

PROJECT
Tearing Modulus Calculation Methodology

TASK NO.
10-13

CALCULATION TITLE
TEAR Documentation (Version 2.0)

CALCULATION NO. (OPTIONAL)
RNC 10-13-02

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
10/5/90	10/16/90	12-17-90	0

Purpose - This calculation documents a method for evaluating the tearing stability of pipe cracks and a computer program, TEAR (Version 2.0), which performs the necessary calculations. The method and all necessary equations are presented along with a program listing and verification problems.

Method

The tearing stability of a circumferential pipe crack can be evaluated using the expression below (from reference 1):

$$T_{MAT} > T_{APP} \qquad \text{stable}$$

$$T_{MAT} < T_{APP} \qquad \text{unstable}$$

where

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

E is the material modulus of elasticity

σ_o is the material flow stress

J is the J-integral

a is half the crack length

t is the pipe wall thickness

M is half the applied bending moment on the pipe cross section

C_s is the piping system compliance (inverse of stiffness) at the crack location

ϕ is the crack hinge angle

This calculation will derive the terms appearing in equation ① so the stability of pipe cracks can be evaluated.

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4

A strain hardening material model is assumed and the J-integral expressions presented in Reference ② are used. The J-integral is assumed to be the sum of an elastic component and a plastic component.

$$J_e = f_1\left(a, \frac{R}{t}\right) \frac{M^2}{E}$$

$$J_p = \alpha \sigma_0 \epsilon_0 c \frac{a}{b} h_1\left(\frac{a}{b}, n, \frac{R}{t}\right) \left[\frac{M}{M_0}\right]^{n+1}$$

$$J = J_e + J_p$$

where,

$$f_1 = \frac{\pi a R^2 \bar{F}^2}{I^2}$$

α, n are strain hardening coefficients from a power law hardening fit of the material stress strain behavior:

$$\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n$$

σ_0, ϵ_0 are yield stress and yield strain

c is the remaining ligament ahead of the crack

$b = a + c$

h_1, $\bar{F}$ are tabulated functions

M_0 is half the fully plastic moment for the pipe cross section containing the through wall crack,

$$M_0 = 2\sigma_0 R^2 t \left[\cos\left(\frac{a}{2R}\right) - \frac{1}{2}\sin\left(\frac{a}{R}\right)\right]$$

R is the pipe mean radius

M is half the applied moment on the pipe.

Using the expressions for J_e and J_p,

$$\boxed{J_e = \frac{\pi a R^2 F^2 M^2}{E I^2}}$$

$$\boxed{J_p = \alpha \sigma_0 \epsilon_0 c \frac{a}{b} h_1 \left(\frac{M}{M_0}\right)^{n+1}}$$

the following can be derived;

$$\left.\frac{\partial J_e}{\partial a}\right)_M = \frac{\pi R^2 M^2}{E I^2}\left[a 2F \frac{dF}{da} + F^2\right]$$

$$= \frac{a \pi R^2 M^2 F^2}{E I^2}\left[\frac{2}{F}\frac{dF}{da} + \frac{1}{a}\right]$$

$$\boxed{\left.\frac{\partial J_e}{\partial a}\right)_M = J_e\left[\frac{2}{F}\frac{dF}{da} + \frac{1}{a}\right]}$$

$$\boxed{\left.\frac{\partial J_e}{\partial M}\right)_a = \frac{2 J_e}{M}}$$

$$\left.\frac{\partial J_p}{\partial a}\right) = \frac{\alpha \sigma_0 \epsilon_0 M^{n+1}}{b}\left[-c a h_1 (n+1)\left(\frac{1}{M_0}\right)^{n+2}\frac{dM_0}{da} + c a \frac{dh_1}{da}\left(\frac{1}{M_0}\right)^{n+1} - a h_1 \left(\frac{1}{M_0}\right)^{n+1} + c h_1 \left(\frac{1}{M_0}\right)^{n+1}\right]$$

$$= \frac{\alpha \sigma_0 \epsilon_0}{b}\left(\frac{M}{M_0}\right)^{n+1}\left[-a c h_1 (n+1)\left(\frac{1}{M_0}\right)\frac{dM_0}{da} + a c \frac{dh_1}{da} + c h_1 - a h_1\right]$$

$$\boxed{\left.\frac{\partial J_p}{\partial a}\right)_M = J_p\left[\frac{-(n+1)}{M_0}\frac{dM_0}{da} + \frac{1}{h_1}\frac{dh_1}{da} + \frac{1}{a} - \frac{1}{c}\right]}$$

$$\boxed{\left.\frac{\partial J_p}{\partial M}\right)_a = \frac{(n+1) J_p}{M}}$$

Reference ② also presents the following expression for crack hinge angle:

$$\phi_e = f_4 \left(a, \frac{R}{t}\right) \frac{M}{E}$$

$$\phi_p = \alpha \epsilon_0 h_4 \left(\frac{a}{b}, n, \frac{R}{t}\right) \left[\frac{M}{M_0}\right]^n$$

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

$$f_4 = \frac{4RV_3}{I}$$

V_3 and h_4 are tabulated functions

using the expressions for ϕ_e and ϕ_p,

$$\boxed{\phi_e = \frac{4RV_3M}{EI}}$$

$$\boxed{\phi_p = \alpha \epsilon_0 h_4 \left(\frac{M}{M_0}\right)^n}$$

the following can be derived;

$$\boxed{\left.\frac{\partial \phi_e}{\partial M}\right)_a = \frac{\phi_e}{M}}$$

$$\boxed{\left.\frac{\partial \phi_p}{\partial M}\right)_a = \frac{n\phi_p}{M}}$$

The following additional expression are used in the expressions above:

$$M_0 = 2\sigma_0 R^2 t \left[\cos\left(\frac{a}{2R}\right) - \frac{1}{2}\sin\left(\frac{a}{R}\right)\right]$$

$$M_0 = 2\sigma_0 R^2 t\, \overline{\underline{X}}$$

$$\frac{dM_0}{da} = 2\sigma_0 R^2 t \frac{d\overline{\underline{X}}}{da}$$

$$\frac{d\overline{\underline{X}}}{da} = \frac{-1}{2R}\sin\left(\frac{a}{2R}\right) - \frac{1}{2R}\cos\left(\frac{a}{R}\right)$$

$$= \frac{-1}{2R}\left[\sin\left(\frac{a}{2R}\right) + \cos\left(\frac{a}{R}\right)\right]$$

$$\boxed{\frac{dM_0}{da} = -\sigma_0 R t\left[\sin\left(\frac{a}{2R}\right) + \cos\left(\frac{a}{R}\right)\right]}$$

$$\boxed{\frac{dh_1}{da} = \frac{dh_1(a/b)}{d(a/b)}\left(\frac{1}{b}\right)}$$

$$\boxed{\frac{dF}{da} = \frac{dF(a/b)}{d(a/b)}\left(\frac{1}{b}\right)}$$

$$\boxed{\frac{dV_3}{da} = \frac{dV_3(a/b)}{d(a/b)}\left(\frac{1}{b}\right)}$$

The values of h_1, h_4, F and V_3 are obtained from tables in reference ②.

Typically, the stiffness of a piping system is expressed in terms of a dimensionless length $\frac{L}{R}$. The smaller the piping $\frac{L}{R}$, the stiffer the system. The compliance, C_s, can be evaluated in terms of $\frac{L}{R}$;

$$K = \frac{EI}{L} \quad \text{(rotational stiffness)}$$

$$C_s = \frac{1}{K} = \frac{L}{EI} = \frac{R}{EI}\left(\frac{L}{R}\right)$$

Program TEAR

The program TEAR (a listing is included in Appendix A) performs the calculations listed above. The program is used interactively and requires the following input:

- a title
- the pipe material (see material properties, below)
- the pipe diameter (inches) and wall thickness (inches)
- the postulated crack length in terms of percentage of cracking, a/b.
- the system compliance, L/R
- $\underline{1/2}$ the applied moment (in-lb)

and calculates the J-integral, Tearing Modulus, and Hinge Angle.

Material Properties

Three materials are built into the TEAR program. These materials, along with the material properties used are listed below.

Material	E	σ_y	σ_f	α	n	
A106 Gr. B	27×10^6 psi	27.1×10^3 psi	43.6×10^3 psi	1.94	4.42	Ref ③
304 SS Weld Metal	25.6×10^6 psi	23×10^3 psi	42.0×10^3 psi	2.13	3.79	
Ref. 2 Material	30.0×10^6 psi	30×10^3 psi	42.0×10^3 psi	1.69	5.42	

Tabulated Function

All tabulated functions are taken from Reference 2. It should be noted that all tabulated functions assume the pipe $R/t = 10.0$. This should be an acceptable approximation for most cases; most power plant piping has dimensions of $R/t \approx 10$. [Tabulated functions are available only at a limited number of R/t values. $R/t = 10.0$ was selected as applicable to the most combinations expected.] For R/t less than 10 TEAR is slightly conservative; for $R/t > 10$ it is slightly unconservative.

Verification Problem #1

Calculate T_{APP} and J for Type 304 SS $[\alpha = 2.13,\ n = 3.79,\ \sigma_0 = 23000\ psi,\ E = 25.6 \cdot 10^{6}\ psi]$

$D = 13.53"$ $a/b = 0.25$ $L/R = 50.0$

$t = 1.012"$ $M/M_0 = 0.75$

The expressions and below are from the calculation this Appendix accompanies

$$J_{tb} = \frac{\pi a R^2 F^2 M^2}{E I^2}$$

$a = .25b = .25\pi R$

$R = \frac{13.53}{2} = 6.765"$ $a = .25\pi(6.765") = 5.31"$

assume, $R/t = 10$, $F = 1.599$

Table 6-5

F, V_1, V_2, V_3 FOR BENDING (R/t = 5, 10, 20)

		a/b = 1/16	a/b = 1/8	a/b = 1/4	a/b = 1/2
R/t = 5	F	1.046	1.143	1.423	2.555
	V_1	1.052	1.194	1.732	4.958
	V_2	0.052	0.117	0.326	1.677
	V_3	-0.065	0.003	0.389	3.925
R/t = 10	F	1.070	1.219	1.599	2.896
	V_1	1.081	1.304	2.116	6.510
	V_2	0.053	0.127	0.390	2.150
	V_3	-0.043	0.034	0.504	5.117
R/t = 20	F	1.118	1.343	1.836	3.337
	V_1	1.141	1.510	2.753	8.727
	V_2	0.059	0.153	0.514	2.886
	V_3	-0.070	0.020	0.626	6.795

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 11
	R. C.		

$$M_0 = 2\sigma_0 R^2 t \left[\cos\left(\frac{a}{2R}\right) - \frac{1}{2}\sin\left(\frac{a}{R}\right)\right]$$

$$= 2(23000)(6.765)^2(1.012)\left[0.924 - 0.354\right]$$

$$= 1215059 \text{ in-lb}$$

$$M = .75 M_0 = 911294 \text{ in-lb}$$

$$I = \frac{\pi}{4}\left[R^4 - (R-t)^4\right] = 784.6 \text{ in}^4$$

$$J_e = \frac{\pi(5.31)(6.765)^3(1.544)^2(911294)^2}{(25.666)(784.6)^2} = 102.9 \ \frac{\text{in-lb}}{\text{in}^2}$$

$$J_p = \alpha\sigma_0\epsilon_0 c \frac{a}{b} h_1 \left(\frac{M}{M_0}\right)^{n+1}$$

$$b = \pi R = 21.25''$$

$$c = b - a = 15.94''$$

$$\epsilon_0 = \frac{\sigma_0}{E} = 0.0008484$$

$h_1 = 4.524$ (see following page)

$$J_p = (2.13)(23000)(0.0008484)(15.94)(0.25)(4.524)(0.75)^{4.79}$$

$$J_p = 200.0 \ \frac{\text{in-lb}}{\text{in}^2}$$

$$\boxed{J = 302.9 \ \frac{\text{in-lb}}{\text{in}^2}}$$

Table 6-7

h-FUNCTION FOR THROUGH-CRACKS IN BENDING (R/t = 10)

		n = 1	n = 2	n = 3	n = 5	n = 7
a/b = 1/16	h_1	4.987	6.018	6.743	7.620	7.969
	h_2	4.931	6.111	6.906	7.867	8.260
	h_3	0.244	3.077	0.388	0.511	0.503
	h_4	-0.194	0.078	0.144	0.288	0.429
	h_5	0.159	0.133	0.265	0.897	1.894
a/b = 1/8	h_1	5.361	5.987	6.281	6.311	5.996
	h_2	5.229	6.007	6.349	6.412	6.097
	h_3	0.510	0.560	0.572	0.588	0.596
	h_4	0.136	0.565	0.783	1.119	1.317
	h_5	0.214	0.172	0.305	0.872	1.627
a/b = 1/4	h_1	5.620	5.312	4.886	3.969	3.240
	h_2	6.131	5.929	5.453	4.385	3.535
	h_3	1.131	1.088	1.029	0.897	0.769
	h_4	1.459	2.098	2.334	2.308	2.049
	h_5	0.120	0.132	0.220	0.541	0.886
a/b = 1/2	h_1	3.646	2.682	2.105	1.424	1.035
	h_2	6.849	4.564	3.331	2.076	1.446
	h_3	2.262	1.583	1.205	0.789	0.563
	h_4	5.384	4.283	3.232	2.049	1.400
	h_5	0.030	0.075	0.109	0.219	0.251

$$\left.\frac{\partial \bar{J}_e}{da}\right)_M = J_e \left[\frac{2}{F}\frac{dF}{da} + \frac{1}{a}\right]$$

$$\frac{dF}{da} = \frac{1}{b}\,\frac{dF(a/b)}{d(a/b)}$$

$$= \frac{1}{21.25}\left[\frac{(2.896 - 1.549)}{(0.50 - 0.25)}\right] = 0.244 = \frac{dF}{da}$$

$$\left.\frac{\partial \bar{J}_e}{da}\right)_M = (102.9)\left[\frac{2}{1.549}(0.249) + \frac{1}{5.31}\right] = 50.9\ \frac{in\cdot lb/}{in^2/in} = \left.\frac{\partial \bar{J}_e}{da}\right)_M$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 13
	R. Cud		

$$\left.\frac{dJ_e}{dM}\right)_a = \frac{2J_e}{M} = \frac{2(102.9)}{911294} = 0.000\,2258 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in-lb}$$

$$\left.\frac{\partial J_p}{\partial a}\right)_M = J_p\left[\frac{-(n+1)}{M_o}\frac{dM_o}{da} + \frac{1}{h_1}\frac{dh_1}{da} + \frac{1}{a} - \frac{1}{c}\right]$$

$$\frac{dM_o}{da} = -\sigma_o R t\left[\sin\left(\frac{a}{2R}\right) + \cos\left(\frac{a}{R}\right)\right]$$

$$= -(23000)(6.765)(1.012)[0.382 + 0.707]$$

$$\frac{dM_o}{da} = -171976 \ \text{in-lb}/\text{in}$$

$$\frac{dh_1}{da} = \frac{1}{b}\,\frac{dh_1(a/b)}{d(a/b)}$$

$$= \frac{1}{21.25}\left[\frac{(1.836 - 4.524)}{(0.50 - 0.25)}\right] = -0.506 = \frac{dh_1}{da}$$

$$\left.\frac{dJ_p}{da}\right)_M = (200.0)\left[\frac{-(4.79)}{1215059}(-171976) + \frac{1}{4.524}(-0.506) + \frac{1}{5.31} - \frac{1}{15.94}\right]$$

$$\left.\frac{\partial J_p}{da}\right)_M = 137.9 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in}$$

$$\left.\frac{dJ_p}{dM}\right)_a = \frac{(n+1)J_p}{M} = \frac{(4.79)(200)}{911294}$$

$$\left.\frac{dJ_p}{dM}\right)_a = 0.001051 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in-lb}$$

$$\phi_e = \frac{4RV_3M}{EI}$$

$$V_3 = 0.504$$

$$\phi_e = \frac{4(6.765)(.504)(911294)}{(25.666)(784.6)} = 0.006188 \ \text{rad}$$

$$\phi_p = \alpha \varepsilon_0 h_4 \left(\frac{M}{M_0}\right)^n$$

$$h_4 = 2.329$$

$$\phi_p = (2.13)(0.0008984)(2.329)(0.75)^{3.79}$$

$$\phi_p = 0.001495 \text{ rad}$$

$$\left.\frac{\partial \phi_e}{\partial M}\right)_a = \frac{\phi_e}{M} = \frac{0.0006188}{911294} = 6.790\text{E-}10 \ \text{rad/in-lb}$$

$$\left.\frac{\partial \phi_p}{\partial M}\right)_a = \frac{n\phi_p}{M} = \frac{(3.79)(0.001495)}{911294} = 6.218\text{E-}9 \ \text{rad/in-lb}$$

$$\left.\frac{\partial J}{\partial a}\right)_M = \left.\frac{\partial J_e}{\partial a}\right)_M + \left.\frac{\partial J_p}{\partial a}\right)_M = 188.7 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in}$$

$$\left.\frac{\partial J}{\partial M}\right)_a = \left.\frac{\partial J_e}{\partial M}\right)_a + \left.\frac{\partial J_p}{\partial M}\right)_a = 0.001277 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in-lb}$$

$$\phi = \phi_e + \phi_p = 0.002114 \text{ rad} = \boxed{0.12 \text{ degrees} = \phi}$$

$$\left.\frac{\partial \phi}{\partial M}\right)_a = \left.\frac{\partial \phi_e}{\partial M}\right)_a + \left.\frac{\partial \phi_p}{\partial M}\right)_a = 6.897\text{E-}9 \ \text{rad/in-lb}$$

$$C_s = \frac{R}{EI}\left(\frac{L}{R}\right) = \frac{6.765}{(25.6\text{E}6)(759.6)}(50) = 1.684\text{E-}8 \ \text{rad/in-lb}$$

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

$$= \frac{25.6\text{E}6}{(23000)^2}\left\{ 188.7 - (1.012)(.001277)^2 \left[1.684\text{E-}8 + 6.897\text{E-}9\right]^{-1} \right\}$$

$$\boxed{T_{APP} = 5.8}$$

```
TEAR: Calculation of Tearing Modulus - Version 2.0
 Today's Date:  10/05/90

Verification Problem #1

 304 Stainless Steel Weld Metal
Crack Length (a/b):  .250

Pipe Diameter: 13.530 inches
Pipe Wall Thickness:  1.012 inches

Applied Moment:      911294.4 in-lb
Applied Load/Yield Load:  .75
Plastic Collapse/Yield Load: 1.83
System Compliance (L/R):          50.

Hinge Angle:      .1 degrees
J-integral:      302.9 in-lb/in²
Tearing Modulus:         5.8
```

Verification Problem #2

Calculate T_{APP} and J for A106 Gr B Steel [$\alpha = 1.99$, $n = 4.92$, $\sigma_0 = 27100$ psi, $E = 27.086$]

$D = 20''$ $a/b = 0.125$ $Y/R = 500.0$

$t = 1''$ $M/M_0 = 1.0$ $R = 10''$

$$J_e = \frac{\pi a R^2 F^2 M^2}{E I^2}$$

$a = .125 b = .125 \pi R = 3.93''$

$F = 1.219$

$M_0 = 2\sigma_0 R^2 t \left[\cos\left(\frac{a}{2R}\right) - \frac{1}{2}\sin\left(\frac{a}{R}\right)\right]$

$= 2(27100 \text{ psi})(10)^2(1)[0.789]$

$M_0 = 4278794$ in-lb

$M = M_0 = 4278794$ in-lb

$I = \frac{\pi}{4}\left(R^4 - (R-t)^4\right) = 2701.0 \text{ in}^4$

$$J_c = \frac{\pi(3.93)(10)^2(1.219)^2(4278794)^2}{(27.086)(2701)^2} = 170.5 \ \frac{\text{in-lb}}{\text{in}^2}$$

$J_p = \alpha \sigma_0 \epsilon_0 c \frac{a}{b} h_1 \left(\frac{M}{M_0}\right)^{n+1}$

$\epsilon_0 = \frac{\sigma_0}{E} = \frac{27100}{27.086} = 0.001004$

$c = b - a = \pi r - a = \pi(10) - 3.93 = 27.49''$

$h_1 = 6.302$

$$J_p = (1.94)(27100)(0.001009)(27.99)(.125)(6.302)(1)^{5.92}$$

$$J_p = 1143.1 \ \text{in-lb/in}$$

$$\boxed{J = 1313.6 \ \text{in-lb/in}}$$

$$\left.\frac{\partial J_e}{\partial a}\right)_M = J_e\left[\frac{2}{F}\frac{dF}{da} + \frac{1}{a}\right]$$

$$\frac{dF}{da} = \frac{1}{b}\,\frac{dF(a/b)}{d(a/b)}$$

$$= \frac{1}{31.92}\left[\frac{1.549 - 1.219}{0.25 - 0.125}\right] = 0.0968 = \frac{dF}{da}$$

$$\left.\frac{\partial J_e}{\partial a}\right)_M = (170.5)\left[\frac{2}{1.219}(0.0960) + \frac{1}{3.93}\right] = 70.5 \ \frac{\text{in-lb}}{\text{in}^2/\text{in}} = \left.\frac{\partial J_e}{\partial a}\right)_M$$

$$\left.\frac{\partial J_e}{\partial M}\right)_a = \frac{2J_e}{M} = \frac{2(170.5)}{4278784} = 0.00007970 \ \frac{\text{in-lb}}{\text{in}^2/\text{in-lb}}$$

$$\left.\frac{\partial J_p}{\partial a}\right)_M = J_p\left[\frac{-(n+1)}{M_o}\frac{dM_o}{da} + \frac{1}{h_1}\frac{dh_1}{da} + \frac{1}{a} - \frac{1}{c}\right]$$

$$\frac{dM_o}{da} = -\sigma_o R t\left[\sin\left(\frac{a}{2R}\right) + \cos\left(\frac{a}{R}\right)\right]$$

$$= -(27100)(10)(1)\left[0.1952 + 0.9238\right]$$

$$\frac{dM_o}{da} = -303249.6 \ \text{in-lb/in}$$

$$\frac{dh_1}{da} = \frac{1}{b}\,\frac{dh_1(a/b)}{d(a/b)}$$

$$= \frac{1}{31.42}\left[\frac{4.235 - 6.302}{.25 - .125}\right] = -0.526 = \frac{dh_1}{da}$$

$$\frac{\partial J_p}{\partial a}\Big)_M = (1143.1)\left[\frac{-(5.42)(-303299.6)}{4278784} + \frac{1}{6.392}(-0.546) + \frac{1}{3.93} - \frac{1}{27.99}\right]$$

$$\frac{\partial J_p}{\partial a}\Big)_M = 593.0 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in}$$

$$\frac{\partial J_p}{\partial M}\Big)_a = \frac{(n+1)J_p}{M} = \frac{(5.42)(1143.1)}{4278784} = 0.001448 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in-lb}$$

$$\phi_e = \frac{4RV_3M}{EI}$$

$$V_3 = 0.034$$

$$\phi_e = \frac{4(10)(.034)(4278784)}{(2766)(2701)} = 0.00007979 \ \text{rad}$$

$$\phi_p = \alpha\,\varepsilon_0\,h_4\left(\frac{M}{M_0}\right)^n$$

$$h_4 = 1.022$$

$$\phi_p = (1.94)(0.001004)(1.022)(1)^{4.42}$$

$$\phi_p = 0.001991 \ \text{rad}$$

$$\frac{\partial \phi_e}{\partial M}\Big)_a = \frac{\phi_e}{M} = \frac{0.00007979}{4278784} = 1.865\text{E-}11 \ \text{rad}/\text{in-lb}$$

$$\frac{\partial \phi_p}{\partial M}\Big)_a = \frac{n\phi_p}{M} = \frac{(4.42)(0.001991)}{4278784} = 2.057\text{E-}9 \ \text{rad}/\text{in-lb}$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 19

$$\left.\frac{\partial J}{\partial a}\right)_M = \left.\frac{\partial J_e}{\partial a}\right)_M + \left.\frac{\partial J_p}{\partial a}\right)_M = 663.5 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in}$$

$$\left.\frac{\partial J}{\partial M}\right)_a = \left.\frac{\partial J_e}{\partial M}\right)_a + \left.\frac{\partial J_p}{\partial M}\right)_a = 0.001528 \ \frac{\text{in-lb}}{\text{in}^2}/\text{in-lb}$$

$$\phi = \phi_e + \phi_p = 0.002071 \text{ rad} = \boxed{0.119 \text{ degrees} = \phi}$$

$$\left.\frac{\partial \phi}{\partial M}\right)_a = \left.\frac{\partial \phi_e}{\partial M}\right)_a + \left.\frac{\partial \phi_p}{\partial M}\right)_a = 2.076E\text{-}9 \ \text{rad}/\text{in-lb}$$

$$C_S = \frac{R}{EI}\left(\frac{L}{R}\right) = \frac{10}{(2766)(2701)}(500.0) = 6.856E\text{-}8 \ \text{rad}/\text{in-lb}$$

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

$$= \frac{2766}{(27100)^2}\left\{663.5 - (1)(0.001528)^2\left[6.856E\text{-}8 + 2.076E\text{-}9\right]^{-1}\right\}$$

$$\boxed{T_{APP} = 23.2}$$

```
TEAR: Calculation of Tearing Modulus - Version 2.0
 Today's Date:  10/05/90

Verification Problem #2

 A106 Gr B Carbon Steel Base Metal
Crack Length (a/b):  .125

Pipe Diameter: 20.000 inches
Pipe Wall Thickness:  1.000 inches

Applied Moment:     4278784.0 in-lb
Applied Load/Yield Load: 1.00
Plastic Collapse/Yield Load: 1.61
System Compliance (L/R):         500.

Hinge Angle:       .1 degrees
J-integral:      1313.1 in-lb/in²
Tearing Modulus:        23.2
```

Verification Problem #3

Same as #2, but $L/R = 0.0$

$$C_S = \frac{R}{EI} \cdot \left(\frac{L}{R}\right) = 0.0$$

$$T_{APP} = \frac{E}{\sigma_0^2} \left\{ \left.\frac{\partial J}{\partial a}\right)_M - t \left.\frac{\partial J}{\partial M}\right)_a^2 \left[C_S + \left.\frac{\partial \phi}{\partial M}\right)_a \right]^{-1} \right\}$$

$$= \frac{27e6}{(27100)^2} \left\{ 6635 - (1)(0.001528)^2 \left[0 + 2.076E\text{-}4 \right]^{-1} \right\}$$

$$\boxed{T_{APP} = -17.0}$$

```
TEAR: Calculation of Tearing Modulus - Version 2.0
 Today's Date:  10/05/90

Verification Problem #3

 A106 Gr B Carbon Steel Base Metal
Crack Length (a/b):  .125

Pipe Diameter: 20.000 inches
Pipe Wall Thickness:  1.000 inches

Applied Moment:     4278784.0 in-lb
Applied Load/Yield Load: 1.00
Plastic Collapse/Yield Load: 1.61
System Compliance (L/R):          0.

Hinge Angle:      .1 degrees
J-Integral:      1313.1 in-lb/in²
Tearing Modulus:       -17.0
```

References

① "Stability Analysis of J-Controlled Crack Growth", in ASTM 668, by JW Hutchinson and P.C. Paris, March 1979.

② EPRI NP-3607, "Advances in Elastic-Plastic Fracture Analysis", Aug. 1984

③ MPR Calculation, "Elastic-Plastic Material Properties for SA106 Gr B and 304SS", R. Cowan, 10/5/90

Appendix A - Program Listing

```
$STORAGE:2
      PROGRAM TEAR
C*****************************************************************************
C
C*****************************************************************************
      CHARACTER*10 ADATE
      CHARACTER*50 TITLE
      CHARACTER*35 MLABEL
      COMMON/DATEINFO/ADATE
      DATA PI/3.14159/
      CALL DATE(ADATE)
   20 CONTINUE
      WRITE(*,*)
      WRITE(*,2000)
      WRITE(*,*)
      WRITE(*,2020)
      READ(*,1000) TITLE
      WRITE(*,*)
      CALL GETMAT(MLABEL,E,SIGO,EO,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
      XMO=2.0*SIGO*R*R*T*TRIG
      DMODA=-SIGO*R*T*(SIN(GAMMA/2.0)+COS(GAMMA))
      IF(XM.LT.0.0) THEN
        XMMO=-XM
        XM=XMMO*XMO
       ELSE
        XMMO=XM/XMO
       ENDIF
C **** calc J ****
      XJE=PI*A*R*R*F1*F1*XM*XM/(XI*XI*E)
      XJP=AL*SIGO*EO*C*A*H1*XMMO**(XN+1)/B
      XJ=XJE+XJP
C **** calc FC ****
      FCE=4.0*R*XM*V3/(XI*E)
      FCP=AL*EO*H4*XMMO**XN
      FC=FCE+FCP
C **** djda at m ****
      DJEDA=XJE*(2.0*DF1DA/F1+1.0/A)
      DJPDA=XJP*(-(XN+1.0)*DMODA/XMO+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/SIGO**2
      COLOAD=SIGFLO/SIGO
      FC=FC*180.0/PI
      CALL OUTPUT(TITLE,MLABEL,AOB,D,T,COLOAD,XM,XMMO,XLR,XJ,TEARV,FC)
      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',/,
     1 '  Version 2.0')
 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,      1 to change L/R',/,
     2        '    2 to change M, 3 to change a/b   ',\)
      END
      SUBROUTINE OUTPUT(TITLE,MLABEL,AOB,D,T,COLOAD,XM,XMMO,XLR,XJ,
     1 TEARV,FC)
C**********************************************************************
C
C**********************************************************************
      CHARACTER*10 ADATE
      CHARACTER*[illegible] TITLE
      CHARACTER*35 MLABEL
      COMMON/DATEINFO/ADATE
      DO 40 I=1,24
```

```
        WRITE(*,*)
   40  CONTINUE
       WRITE(*,1500) ADATE
       WRITE(*,2000) TITLE
       WRITE(*,*)
       WRITE(*,2020) MLABEL
       WRITE(*,2040) AOB
       WRITE(*,*)
       WRITE(*,2060) D
       WRITE(*,2080) T
       WRITE(*,*)
       WRITE(*,2110) XM
       WRITE(*,2120) XMMO
       WRITE(*,2100) COLOAD
       WRITE(*,2140) XLR
       WRITE(*,*)
       WRITE(*,2200) FC
       WRITE(*,2160) XJ
       WRITE(*,2180) TEARV
       WRITE(*,*)
       RETURN
 1500 FORMAT(' TEAR: Calculation of Tearing Modulus - Version 2.0',
     1  /,1X,15H Today's Date: ,A10,/)
 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: ',F6.2)
 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,SIGO,EO,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,SIGO,EO,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,SIGO,EO,SIGFLO,AL,XN)
C**********************************************************************
C
C**********************************************************************
      IF(MAT.EQ.1) THEN
        SIGO=27100.0
        SIGFLO=43600.0
        E=27.0E6
        AL=1.94
        XN=4.42
        GOTO 100
       ENDIF
      IF(MAT.EQ.2) THEN
        SIGO=23000.0
        SIGFLO=42000.0
        E=25.6E6
        AL=2.13
        XN=3.79
        GOTO 100
       ENDIF
      IF(MAT.EQ.3) THEN
        SIGO=30000.0
        SIGFLO=42000.0
        E=30.0E6
        AL=1.69
        XN=5.42
        GOTO 100
       ENDIF
  100 CONTINUE
      EO=SIGO/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
```

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT MPR	PAGE 1 OF 18
PROJECT Tearing Modulus Calculation Methodology	TASK NO. 10-13
CALCULATION TITLE Elastic-Plastic Material Properties for A106 Gr B and 304SS	CALCULATION NO. (OPTIONAL) RNC 10-13-#3

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
10/15/90	10/15/90	12-17-90	0

Purpose - This calculation determines various material properties of Type 304 SS weld metal and A106 GrB steel for use in elastic-plastic fracture mechanics analyses. The properties are determined for 550°F.

Results - The appropriate material properties are listed below

Material	α	n	T_{MAT}
A106 Gr B	1.94	4.42	215
304 SS	2.13	3.79	182

where α, n are strain hardening coefficients for a power law stress-strain curve

$$\frac{\varepsilon}{\varepsilon_0} = \alpha \left(\frac{\sigma}{\sigma_0}\right)^n$$

and T_{MAT} is the material Tearing Modulus.

STRAIN-HARDENING COEFFICIENTS

Type 304 SS

Stress-Strain curves from reference ①, (following page) are used to find α, n as a function of temperature where:

$$\frac{\epsilon}{\epsilon_0} = \alpha \left(\frac{\sigma}{\sigma_0}\right)^n$$

The yield point and two other points on the curves are used to fit α and n. After α and n have been found for the four temperatures

available, α and n are normalized to α_0 and n_0 at 70°F (RT). This gives α/α_0 and n/n_0 as a function of temperature. The values of α/α_0 and n/n_0 at 550°F (estimated from the obtained plots) are used with carefully developed values of $\alpha_0 = 1.69$ and $n_0 = 5.92$, available in reference ②, to yield values of α and n at 550°F.

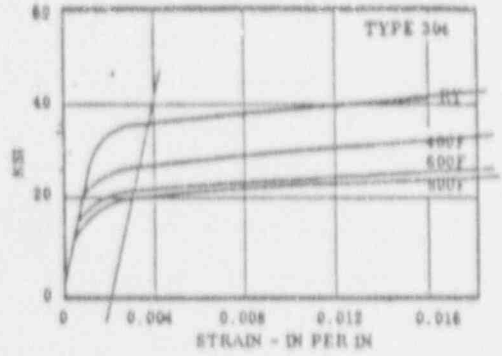


FIG 3.03112 STRESS - STRAIN CURVES AT ROOM AND ELEVATED TEMPERATURES (23)

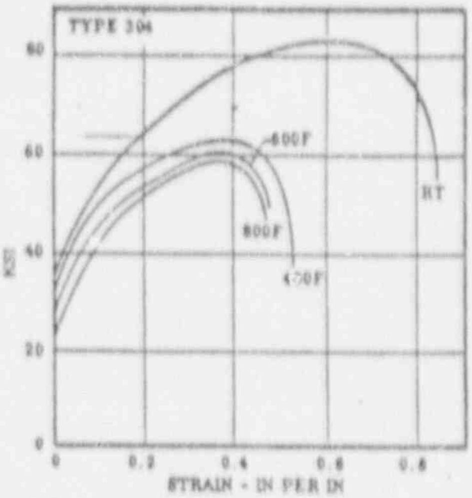


FIG 3.03111 STRESS - STRAIN CURVES TO FAILURE AT ROOM AND ELEVATED TEMPERATURES (23)

The above are obtained from reference ① and are used to determine the temperature dependence of α and n

$$\frac{\epsilon}{\epsilon_0} = \alpha\left(\frac{\sigma}{\sigma_0}\right)^n$$

$$\frac{\epsilon_1}{\epsilon_0} = \alpha\left(\frac{\sigma_1}{\sigma_0}\right)^n \qquad \frac{\epsilon_2}{\epsilon_0} = \alpha\left(\frac{\sigma_2}{\sigma_0}\right)^n$$

$$\ln\epsilon_1 - \ln\epsilon_0 - \ln\alpha = n\left(\ln\sigma_1 - \ln\sigma_0\right)$$

$$\underline{\ln\epsilon_2 - \ln\epsilon_0 - \ln\alpha = n\left(\ln\sigma_2 - \ln\sigma_0\right)}$$

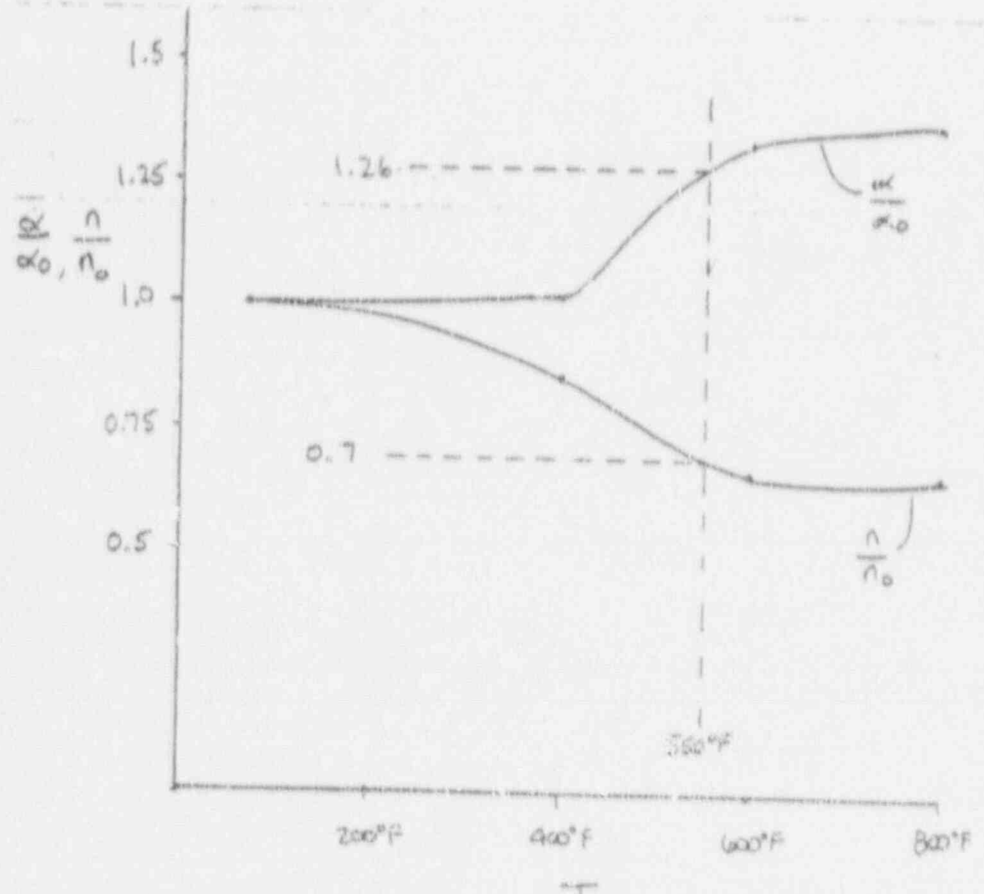
$$\ln\epsilon_1 - \ln\epsilon_2 = n\left[\left(\ln\sigma_1 - \ln\sigma_0\right) - \left(\ln\sigma_2 - \ln\sigma_0\right)\right]$$

$$n = \frac{\ln\epsilon_1 - \ln\epsilon_2}{\ln\sigma_1 - \ln\sigma_2}$$

$$\alpha = \frac{\epsilon_1}{\epsilon_0}\left(\frac{\sigma_0}{\sigma_1}\right)^n$$

T °F	σ_0 (ksi)	ϵ_0	σ_1 (ksi)	ϵ_1	σ_2 (ksi)	ϵ_2	α	n
70	36	3.667E-3	42	0.02	75	0.35	2.55	4.94
400	27	3.33E-3	33	0.02	57	0.20	2.58	4.21
600	22	3.45E-3	26	0.02	53	0.20	3.35	3.23
800	20	2.8E-3	25	0.02	51	0.20	3.43	3.23

(note: these points are used only to determine temperature dependence of α and n)



From reference ②,

$\alpha_0 = 1.69$ } at 70° F
$n_0 = 5.42$

$\alpha = \left(\frac{\alpha}{\alpha_0}\right)_{550} \alpha_0 = (1.26)(1.69) = 2.13$

$n = \left(\frac{n}{n_0}\right)_{550} n_0 = (0.70)(5.42) = 3.79$

A106 Gr B

A. Tabulated Values of "n"

In Reference (3), values of 1/n are tabulated for carbon and manganese steels at room temperature. No data for A106 Grade are shown, but data are shown for similar A201 and A212 material, in several heat treated conditions. We shall focus on the normalized and annealed conditions, since high strength heat treatments (ie normalized and stress relieved) are inappropriate for hot finished pipe:

Steel	Heat Treat*	Yield Strength	Ult. Strength	n
A-201	N	38.6 ksi	60.6 ksi	4.41
A-201	A	34.0	55.1	4.20
A-212	N	50.6	77.8	4.42
A-212	A	35.4	70.6	4.26

* N = normalized
A = annealed

The material properties specified for A106 Grade B pipe are 35 ksi min yield and 60 ksi min ultimate. Heat treatment is not specified since the pipe is "hot finished" with no special effort to control working temperatures. Since a higher value of "n" represents less strain hardening and is conservative, and since the heat treatment of the pipe is not controlled, a value of $n = 4.42$ is chosen as a conservative value from this table.

B. Fitted Values of n and α from Stress / Strain Curve:

A large-strain stress/strain curve for a "mild carbon steel" is shown in Reference (4) and on the following page. We wish to compute α, n from this curve to get a feel for α, n directly, rather than relying on tabulated values for n, as above.

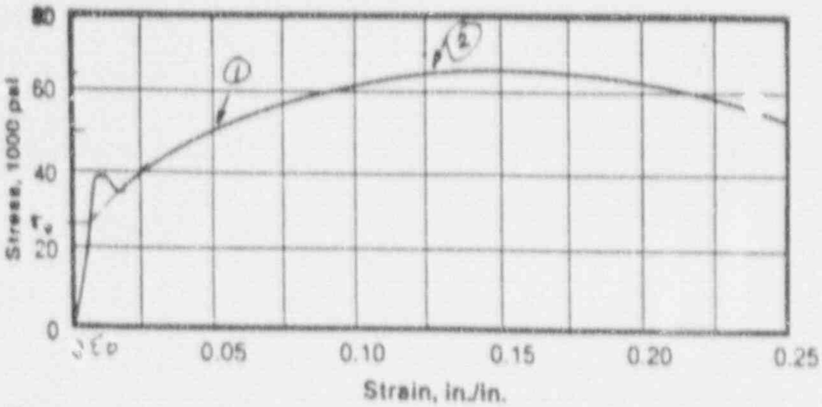


FIGURE 8.9. Sharp yield point in a stress-strain curve. Typical stress-strain curve for a mild carbon steel, showing the sharp yield point at 40000 psi.

Ref (4)

For a two point fit at .050 and .125 strain,

[illegible]

$$n = \frac{\ln(\varepsilon_1/\varepsilon_2)}{\ln(\sigma_1/\sigma_2)} = \frac{\ln\left(\frac{.050}{.125}\right)}{\ln(50/65)} = \underline{\overline{3.49}}$$

$$\alpha = \varepsilon/\varepsilon_0 \Big/ (\sigma/\sigma_0)^n$$

Note, because of the sharp yield point, we must estimate ε_0 as where the power law function intersects the [illegible] response portion of the stress strain curve:

$$\varepsilon_0 = \sigma_0/E + .002 \quad , \quad \sigma_0 = 27,000 \text{ psi}$$

Typically, $E = 27.9 \times 10^6$ psi, and, therefore $\varepsilon_0 \simeq .003$

On this basis, using properties at point ①,

$$\alpha = (.05/.003)/(50/27)^{3.49}$$

$$\boxed{\alpha \simeq 1.94}$$

This material (mild steel) shows considerably more strain hardening behavior than that for A 201 and A 212 reported in Reference (3). We will use the higher value of n reported in Reference (3) and will use a value for α of 1.94, since this is what we get for mild steel and it is a value similar to that used by others for A106 Grade B steel (see Reference (5)).

C. Temperature Effect on "n":

In Reference (3), Pense and Stout demonstrate that for carbon and low alloy steels a relation exists between the strain hardening exponent, n, and the cyclic fatigue behavior of the material. In particular they show that the total cyclic strain range for a 5000 cycle fatigue life is related to the strain hardening exponent thus:

$$\varepsilon_{t,5000} = -.0015 + 5n + 2\,\sigma_o/E$$

They show this relation holds for a wide range of material strengths and alloy contents.

If it is assumed that this relationship also holds at elevated temperatures, then elevated temperature fatigue tests should give an estimate of the behavior of n as a function of temperature. In reference (6), Pease and Stout present fatigue data for several carbon and low alloy steels as a function of temperature. In particular, for A 212 steel, data are presented for $\varepsilon_{t,5000}$ at 70°F, 400°F and 600°F:

A212 (normalized and stress relieved)

$\varepsilon_{t,5000}$	T
1.02%	70°F
1.00%	400°F
0.99%	700°F

We note the following for A 21— in Reference (6),

T	σ_o*	E	$2\sigma_o/E$
70°F	50 ksi	27.9×10^6 psi	.358%
400°F	42.9 ksi	27.0×10^6	.318%
600°F	40.0 ksi	25.7×10^6	.311%

* ASME properties for the similar A516 Gr 70 normalized to 50 ksi

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 13
		W. DaPron	

Since,

$$\frac{1}{n} = \frac{\varepsilon_{t\,5000} + .15 - 2\sigma_0/E}{5} \quad \text{(all in percent)}$$

we can calculate n as a function of temp:

A 212

T	n
70°F	6.16
400°F	6.01
600°F	6.03

We note that the n values are larger than we assume for A106 Gr B, but Reference (6) indicates that this is high strength normalized and stress relieved material. We also note that n is essentially constant over this temperature range.

T_{MAT}

The attached figures show experimental J vs. a results for A106 carbon steel and CF8A stainless steel weld metal obtained from reference ①. As shown in these figures, a straight line fit of the data is used to obtain dJ/da. [fitting the data at large value of Δa will yield minimum values of dJ/da]. These curves represent lower bound data and yield the minimum values for dJ/da. (Minimum values are conservative). The material Tearing modulus ; T_{mat}, is obtained through:

$$T = \frac{E}{\sigma_o^2}\left(\frac{dJ}{da}\right)$$

where E = modulus of Elasticity
σ_o = material yield stress

(The experimental curves used are for tests at 550°F, the approximate temperature of high energy piping at NMP-1)

<u>Carbon Steel A106:</u> (Test FOP-500)

$$\frac{dJ}{da} = \frac{3100-2400}{0.2-0.08} = 5833\ \frac{lb}{in^2}$$

use $E = 27.0E6$ psi (reference ⑧
use $\sigma_0 = 27.1E3$ psi (reference ⑧

$$T_{mat} = \frac{27.0E6}{(27.1E3)^2}\left(5833\right) = \boxed{214.5 = T_{mat}}$$

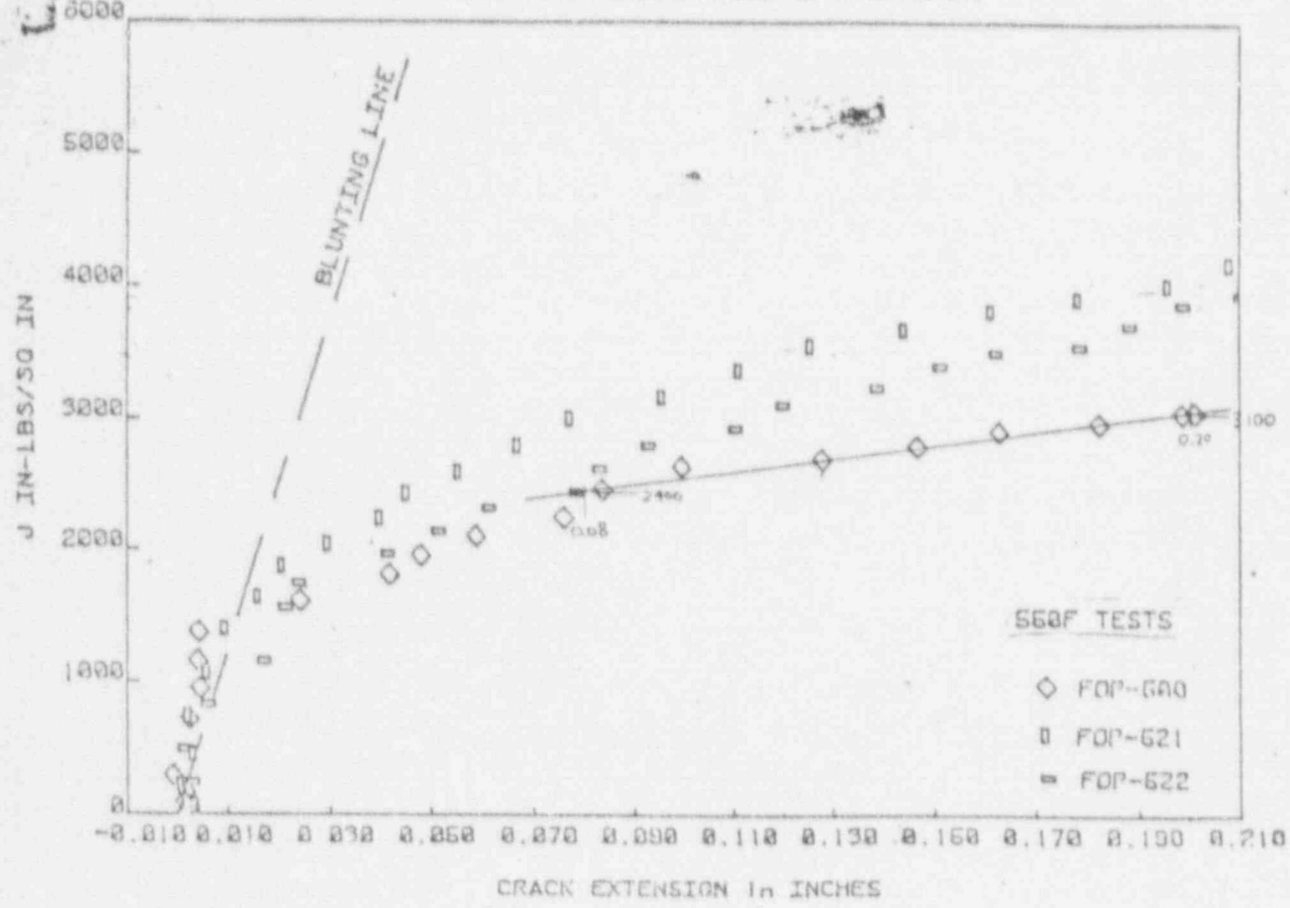
<u>Stainless Steel Weld Metal CF8A:</u> (Test FUC-12)

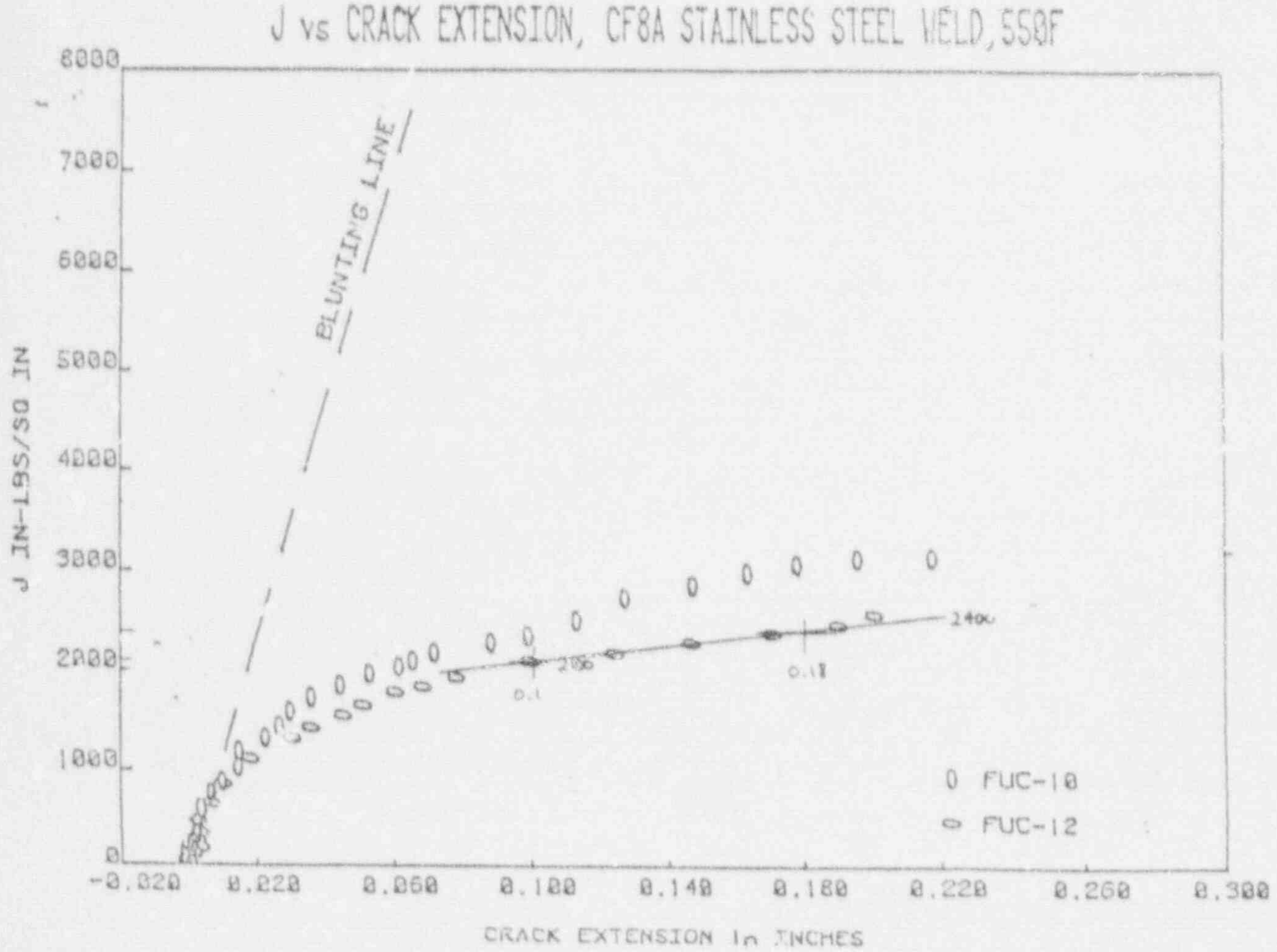
$$\frac{dJ}{da} = \frac{2400-2100}{0.18-0.10} = 3750\ lb/in^2$$

use $E = 25.6E6$ psi (reference ⑧
use $\sigma_0 = 23000$ psi (reference ⑨

$$T_{mat} = \frac{25.6E6}{(23000)^2}(3750) = \boxed{181.5 = T_{mat}}$$

J vs CRACK EXTENSION A106 (L-C Orient.)




J vs CRACK EXTENSION, CF8A STAINLESS STEEL WELD, 550F
J IN-LBS/SQ IN
0
1000
2000
3000
4000
5000
6000
7000
8000
-0.020
0.020
0.060
0.100
0.140
0.180
0.220
0.260
0.300
CRACK EXTENSION In INCHES
BLUNTING LINE
0 FUC-10
⊖ FUC-12
2050
2400
0.1
0.18

References

① Department of Defense Aerospace Structural Metals Handbook

② EPRI NP-2608-LD, Elastic-Plastic Fracture Analysis of Flawed Stainless Steel Pipes, Sept. 1982, p. 2-92.

③ R.D. Stout and A.W. Pense, J. Basic Engr, June 1965, 269

④ G.F. Carter, Principles of Physical and Chemical Metallurgy (American Society for Metals, Metals Park Ohio) 1979 p 221

⑤ Consumers Power Co. letter to Dennis M. Crutchfield, NRC dated Dec 9, 1982

⑥ A.W. Pense and R.D. Stout, Weld Journ, Aug 1975, 247-S

⑦ NUREG/CP-0024, Vol 3
Ninth Water Reactor Safety Research Information Meeting
Oct. 26-30, 1981
"J-R Curve Characteristics of Piping Material and Welds"
J. Gudas NSRDC

⑧ 1980 ASME Code, Section III, Appendices

⑨ DOD Aerospace Structural Metals Handbook, Vol 2, Code 1303, page 15
figure 3.03131

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT GPUN

PAGE 1 OF 33

PROJECT ICS Piping LBB

TASK NO. 83-133

CALCULATION TITLE System Compliance at High Loaded Points

CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
4/9/91	4/11/91	4-17-91	0

Purpose - This calculation determines the system compliance of the Oyster Creek Isolation Condenser System (ICS) piping at the locations of highest loading.

Results - The compliance, in terms of 4/R is listed below for each point of interest in the ICS piping.

A - Steam	4/R	B - Steam	4/R
B09	38	B09	39
B01	44	B01	41
D12	88	D17	124
D10A	151	D04	104
B19	135	B15N	104
B11	133	B13	127

A - Condensate	4/R	B - Condensate	4/R
D04N	127	C28	65
D03A	146	C26A	150
B08	127	C05	66
B01	73	B20	65

Method - The method used to determine the system compliance (the system L/R) is that documented in Reference 1. The equivalent of a ball and socket joint is inserted in a finite element model of the piping system and equal and opposite moments are applied to each side of the joint. The resulting rotations are used to calculate the stiffness (and compliance) at each point of interest.

AUTOPIPE finite element models of each piping system in the ICS are documented in References 2 to 5. These were the models used to perform the B31.1 Code evaluation of the piping. The L/R calculations are performed by modifying these models slightly. The procedure used to calculate L/R at each point of interest is described below:

1) The AUTOPIPE finite element models from the B31.1 evaluation of the piping are used. To eliminate undesired loads, the operating temperature of all the piping is set to 70°F (the reference temperature) and the thermal anchor displacements are set to 0.0.

2) The ball and socket joint is inserted at the location where t/R is to be determined. This is described below.

3) Equal and opposite bending moments are applied on each end of the ball and socket joint. The T1 and T2 load cases are used. The moments are applied about two axes perpendicular to the axis of the pipe.

4) The total rotation in each direction is calculated as the sum of the rotations at each node in the ball and socket joint. (Note that since one moment is oppisite in direction from the other, the sum is actually $\theta_T = \theta_A - \theta_B$).

5) The compliance and stiffness about both axes which had moments applied are determined using the method from Reference 1.

$$C_1 = \frac{\theta_1}{M} \qquad K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2}$$

$$C_2 = \frac{\theta_2}{M} \qquad K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2}$$

$$C_{12} = \frac{\theta_{12}}{M} \qquad K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2}$$

6) The minimum stiffness about any axis is determined using a Mohrs Circle approach

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2}$$

7) The residual stiffness, or L/R, is determined using the pipe cross-section properties:

$$L/R = \frac{EI}{R K_{MIN}}$$

Inserting a Ball and Socket Joint in AUTOPIPE

The determination of compliance requires "installing" the equivalent of a ball and socket joint into the finite element model. Autopipe supports this using a FLEX command to insert a flexible joint. As recommended in the AUTOPIPE documentation, the translational stiffnesses of the FLEX joint are set to RIGID and the rotational stiffnesses are set to 0.0.

The FLEX joint can not have 0.0 length (the two node points can not be coincident) so a new node is inserted in the model at a short offset, 0.0001 ft., from the node being evaluated. Equal and opposite moments are then applied on the new node and the original node. One set of moments is applied in the T1 load case, one in the T2 load case. Typically, the new nodes inserted into the finite element model were labeled with the original label followed by an 'X'. In some instances, FLEX joints are not allowed at the points of interest (for instance at a TEE or the beginning of a segment), in these cases, a second new node was also inserted a short distance from the node being evaluated and was labeled with a 'Z'.

Determination of Y/R

The locations being evaluated using fracture mechanics are determined in Reference 6 and are listed below (Pipe designations from Ref. 7).

A - Steam	B - Steam	Pipe
B09	B09	10080S
B01	B01	10100S
D12	B17	12080S
D10A	D04	12100S
B19	B15N	16080S
B11	B13	16100S
A - Condensate	**B - Condensate**	
D04N	C28	08080C
D03A	C26A	08100C
B08	C05	10080C
B07	B20	10100C

The determination of Y/R for these points is documented on the following pages. There is a special cases: pipe runs which are not parallel to a coordinate system axis. If the piping is not parallel to a coordinate system axis at the point of interest, moments must be applied about all three global axes with magnitudes determined using directional cosines. The resulting rotations must also be transformed to the coordinate system of interest (the local system). These cases are indicated on the following pages where appropriate.

Figures 1 to 4 show the piping models and the locations of the areas where the compliance will be calculated.

The model data listings for the 4/R AutoPipe models are included in Attachment 1. The displacement output results from the 4/R AUTOPIPE analyses are included in Attachment 2.

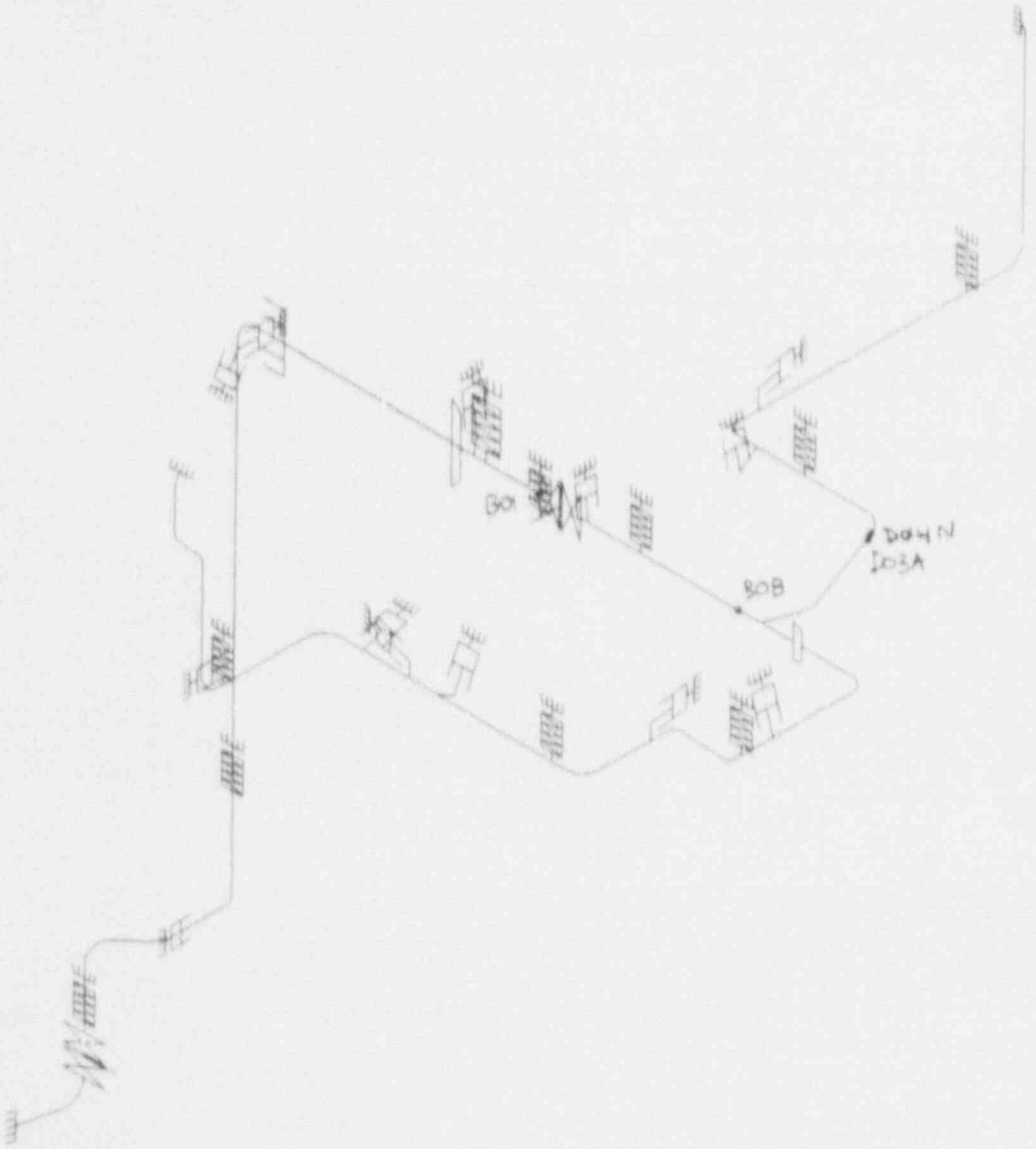


Figure 1

A - Condensate

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 10

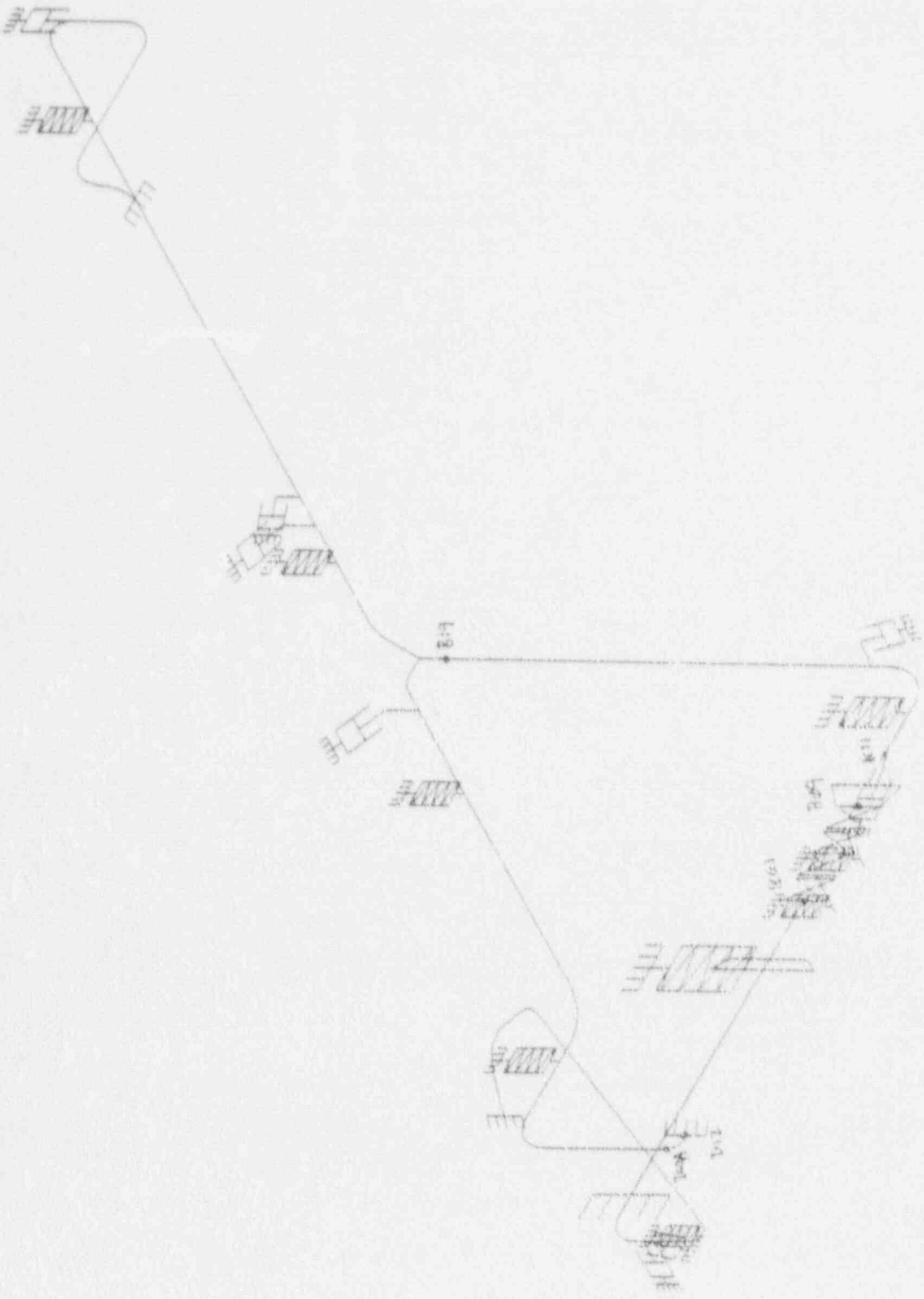


Figure 2
A-Stream

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	A.G.R		11

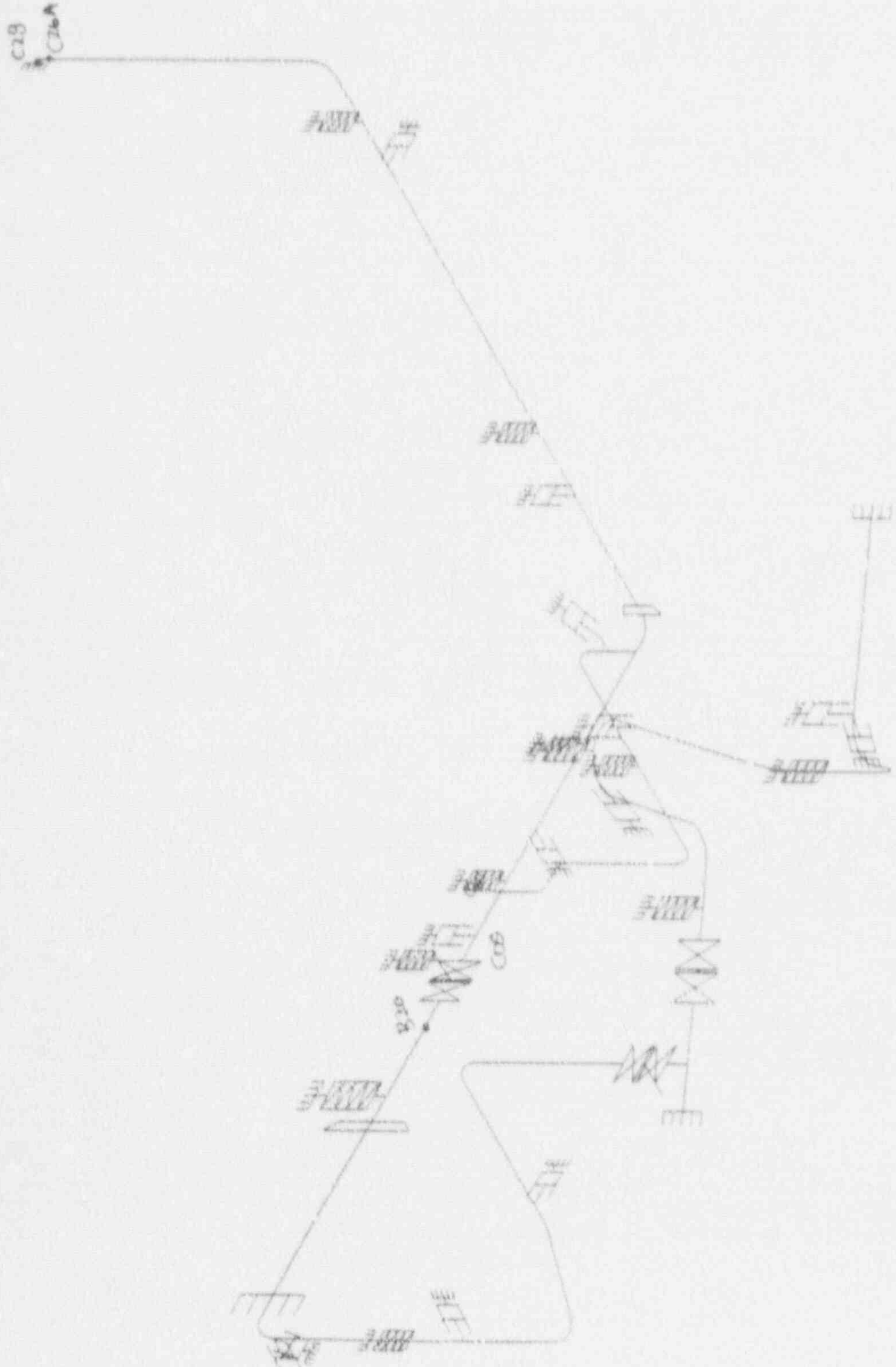


Figure 3
B- Condensate

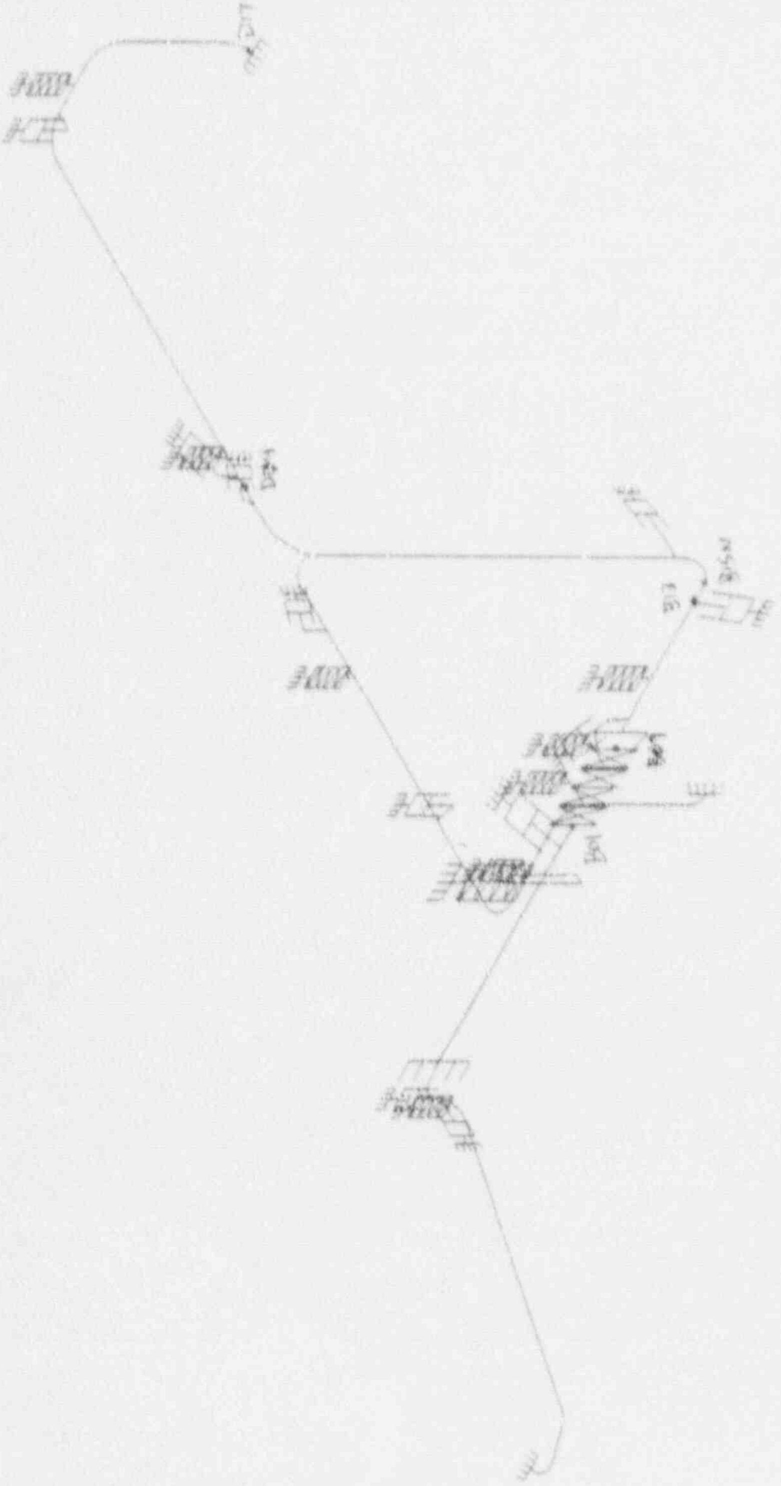


Figure 4
B-Stan

AC DØ4N

	- DØ3A		DØ4X		SUM	
	T1	T2	T1	T2	Deg	Rad
$\theta_{1(x)}$	4.290°	0.016°	-8.556	-1.317	13.126	0.229
θ_2 (Y) (z)	-0.015° 0.701	2.256° 1.365°	0.270 -2.456	-3.671 -3.654	7.642	0.138
* Rotate θ_{12}	⇓ 0.338	⇓ 2.636	⇓ -0.994	⇓ -5.006	1.333	0.023

OD = 8.625
R = 4.313
t = 0.50

$I = \pi/4\,(R_o^4 - R_i^4) = 105.72$
$E = 26.5 \times 10^6$ psi
$M = 100000$ ft-lbs $= 1.2 \times 10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 1.909 \times 10^{-7}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 5.333 \times 10^6$$

$$C_2 = \frac{\theta_2}{M} = 1.111 \times 10^{-7}$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 9.159 \times 10^6$$

$$C_{12} = \frac{\theta_{12}}{M} = 1.939 \times 10^{-8}$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -9.302 \times 10^5$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 5.118 \times 10^6$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 127$$

* The applied moment about the Y axis for case T2 was inadvertently specified as 86000 ft-lb instead of 86600 ft-lb. This small difference is neglected.

* A skewed line: $\theta_z = 60°$
$\theta_y = 30°$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 14
	R. G.	Peter	

AC DØ3A

	Dø3X		DØ3A		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 (x)	4.290	0.02	-3.830	-1.34	13.126	0.229
θ_2 (y)	-0.013	1.235	0.270	-3.702	7.665	0.134
(z)	0.701	1.300	-2.450	-3.545		
* Rslt θ_{12}	0.335	2.038	0.944	-5.029	1.332	0.023

OD = 8.625
R_o = 4.313
t = 0.594

$I = \pi/4\,(R_o^4 - R_i^4) = 121.49$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 1.909\times10^{-7}$$

$$C_2 = \frac{\theta_2}{M} = 1.115\times10^{-7}$$

$$C_{12} = \frac{\theta_{12}}{M} = 1.937\times10^{-8}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 5.332\times10^6$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 9.131\times10^6$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -9.266\times10^5$$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 5.118\times10^6$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 146$$

* Skewed Line : $\theta_x = 60°$
$\theta_y = 30°$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	R.C.C.		15

AC B48

	-309x		309		SUM	
	T1	T2	T1	T2	Deg	Rad
$\theta_1^{(1)}$	1.332	-2.130	-2.606	0.[illegible]	3.990	0.070
$\theta_2^{(2)}$	-0.25	1.86	0.[illegible]	-5.728	7.214	0.126
θ_{12}					-0.301	-0.005

OD = 10.75
R = 5.375
t = 0.394

$I = \pi/4\,(R_o^4 - R_i^4) = 245.19$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$C_1 = \frac{\theta_1}{M} = 5.802\times10^{-8}$

$C_2 = \frac{\theta_2}{M} = 1.049\times10^{-7}$

$C_{12} = \frac{\theta_{12}}{M} = -4.378\times10^{-9}$

$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 1.729\times10^{7}$

$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 9.5[illegible]0\times10^{6}$

$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = 7.213\times10^{5}$

$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 9.444\times10^{6}$

$L/R = \frac{EI}{R\,K_{MIN}} = 127$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 16
	R. C.		

AC_Bϕ1

	− Bϕ1 X		Z			
	T1	T2	T1	T2	SUM Deg.	Rad
θ_1(Y)	1.95	0.009	−2.69	−0.03	3.364	0.059
θ_2(Z)	0.011	0.955	−0.033	−2.617	3.567	0.062
θ_{12}					.022	≈0

OD = 10.75
R = 5.375
t = 0.719

$I = \pi/4\,(R_o^4 - R_i^4) = 286.45$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 4.893\times10^{-8}$$

$$C_2 = \frac{\theta_2}{M} = 5.188\times10^{-8}$$

$$C_{12} = \frac{\theta_{12}}{M} = 3.20\times10^{-10}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 2.044\times10^{7}$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 1.925\times10^{7}$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -1.26\times10^{5}$$

$$K_{MIN} = \frac{k_1+k_2}{2} - \sqrt{\left(\frac{K_1-k_2}{2}\right)^2 + K_{12}^2} = 1.926\times10^{7}$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 73$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 17
	R. C.		

AS B09

	-B09Z		309X		SUM	
	T1	T2	T1	T2	Deg.	Rad
θ_1 (Y)	0.675	0.022	-1.471	-0.085	2.146	0.037
θ_2 (Z)	0.017	0.382	-0.090	-0.926	1.308	0.023
θ_{12}					0.107	0.002

OD = 10.75
R = 5.375
t = 0.594

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 245.19$
$E = 26.5 \times 10^6$ psi
M = 100000 ft-lbs = 1.2×10^6 in-lb

$$C_1 = \frac{\theta_1}{M} = 3.121 \times 10^{-8}$$

$$C_2 = \frac{\theta_2}{M} = 1.902 \times 10^{-8}$$

$$C_{12} = \frac{\theta_{12}}{M} = 1.556 \times 10^{-9}$$

$$K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2} = 3.217 \times 10^7$$

$$K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2} = 5.278 \times 10^7$$

$$K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2} = -2.632 \times 10^6$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}} = 3.184 \times 10^7$$

$$L/R = \frac{E I}{R K_{MIN}} = 38$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 18
	J. C. d		

AS B01

	-30 x		30		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 Y	0.893	[illegible]	-1.301	[illegible]	2.107	0.037
θ_2 (3)	[illegible]	[illegible]	[illegible]	-0.890	1.486	0.026
θ_{12}					0.102	0.002

OD = 10.75
R = 5.375
t = 0.719

$I = \pi/4 (R_o^4 - R_i^4) = 286.45$
$E = 26.5 \times 10^6$ psi
M = 100000 ft-lbs = 1.2×10^6 in-lb

$C_1 = \frac{\theta_1}{M} = 3.066 \times 10^{-8}$

$C_2 = \frac{\theta_2}{M} = 2.161 \times 10^{-8}$

$C_{12} = \frac{\theta_{12}}{M} = 1.484 \times 10^{-9}$

$K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2} = 3.27 \times 10^7$

$K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2} = 4.642 \times 10^7$

$K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2} = -2.247 \times 10^6$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 3.238 \times 10^7$$

$$L/R = \frac{EI}{R K_{MIN}} = 44$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 19

AS D12

	−D12 *		D12		SUM	
	T1	T2	T1	T2	Deg	Rad
Θ_1 *	1.77[illegible]	0.426	−0.088	0.30	2.414	0.042
Θ_2 *	0.8[illegible] −0.340	1.680 1.294	0 0	−0.580 −0.344	2.773	0.048
ROTATED Θ_{12}	0.426	2.095	0	−0.088	0.426	0.007

OD = 12.75
R = 6.375
t = 0.688

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 475.68$
$E = 26.5 \times 10^6$ psi
$M = 100000$ ft-lbs $= 1.2 \times 10^6$ in-lb

$$C_1 = \frac{\Theta_1}{M} = 3.511 \times 10^{-8}$$

$$C_2 = \frac{\Theta_2}{M} = 4.033 \times 10^{-8}$$

$$C_{12} = \frac{\Theta_{12}}{M} = 6.196 \times 10^{-9}$$

$$K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2} = 2.928 \times 10^7$$

$$K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2} = 2.548 \times 10^7$$

$$K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2} = -4.497 \times 10^6$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 2.25 \times 10^7$$

$$L/R = \frac{E I}{R K_{MIN}} = 88$$

* Skewed Line $\Theta_z = 60°$
$\Theta_y = 30°$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 20
	R.-L		

AS D10A

	- D10A		D10A		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 X	1.451	-0.355	-1.02	0.028	2.693	0.047
θ_2 Z	-0.393	3.335	-0.992	-1.048	4.374	0.076
θ_{12}					-0.385	-0.007

OD = 12.75
R = 6.375
t = 0.844

$I = \pi/4\,(R_o^4 - R_i^4) = 562.18$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 3.844\times10^{-8}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 2.685\times10^7$$

$$C_2 = \frac{\theta_2}{M} = 6.362\times10^{-8}$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 1.592\times10^7$$

$$C_{12} = \frac{\theta_{12}}{M} = -5.600\times10^{-9}$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = 2.319\times10^6$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 1.543\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 151$$

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 21
	R. Cd		

AS B19

	- B19X		B19		SUM	
	T1	T2	T1	T2	Deg	Rad
$\theta_1^{(x)}$	0.921	0.001	-0.465	0.114	1.386	0.024
$\theta_2^{(z)}$	-0.013	0.398	0.100	-2.005	2.406	0.042
θ_{12}					-0.113	-0.002

OD = 16.0
R = 8.1
t = 0.84

$I = \pi/4 (R_o^4 - R_i^4) = 1157.45$
$E = 26.5 \times 10^6$ psi
$M = 100000$ ft-lbs $= 1.2 \times 10^6$ in-lb

$C_1 = \frac{\theta_1}{M} = 2.016 \times 10^{-8}$

$C_2 = \frac{\theta_2}{M} = 3.499 \times 10^{-8}$

$C_{12} = \frac{\theta_{12}}{M} = -1.644 \times 10^{-9}$

$K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2} = 4.980 \times 10^7$

$K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2} = 2.869 \times 10^7$

$K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2} = 2.339 \times 10^6$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + C_{12}^2} = 2.843 \times 10^7$$

$$L/R = \frac{EI}{R K_{MIN}} = 135$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 22
	R. C.		

AS B11

	[illegible]		B11		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1	0.533	0.576	[illegible]	-0.584	2.017	0.035
θ_2	5.58	[illegible]	[illegible]	-0.849	1.162	0.020
θ_{12}					0.106	0.002

OD = 16.0

R = 8.0

t = 1.031

$I = \pi/4\,(R_o^4 - R_i^4) = 1364.43$

$E = 26.5\times10^6$ psi

$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$C_1 = \dfrac{\theta_1}{M} = 2.934\times10^{-8}$

$C_2 = \dfrac{\theta_2}{M} = 1.690\times10^{-8}$

$C_{12} = \dfrac{\theta_{12}}{M} = 1.542\times10^{-9}$

$K_1 = \dfrac{C_2}{C_1C_2 - C_{12}^2} = 3.425\times10^{7}$

$K_2 = \dfrac{C_1}{C_1C_2 - C_{12}^2} = 5.945\times10^{7}$

$K_{12} = \dfrac{-C_{12}}{C_1C_2 - C_{12}^2} = -3.125\times10^{6}$

$$K_{MIN} = \frac{k_1+k_2}{2} - \sqrt{\left(\frac{k_1-k_2}{2}\right)^2 + K_{12}^2} = 3.327\times10^{7}$$

$$L/R = \frac{E\,I}{R\,K_{MIN}} = 133$$

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW - Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 23
	1. C L		

BC C28

	- C28x		C28		SUM	
	T1	T2	T1	T2	Deg	Rad
Θ_1 (x)	2.691	-0.172	-0.688	0.00	3.379	0.059
Θ_2 (Y) (Z)	-0.010 -0.233	3.946 4.821	[illegible] [illegible]	-0.486 -.486	6.888	0.120
*Rotate Θ_{12}	-0.172	6.201	[illegible]	-0.687	-0.172	-0.003

OD = 8.625
R = 4.313
t = 0.50

$I = \pi/4\left(R_o^4 - R_i^4\right) = 105.72$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-kips $= 1.2\times10^6$ in-lb

$C_1 = \dfrac{\Theta_1}{M} = 4.915\times10^{-8}$

$C_2 = \dfrac{\Theta_2}{M} = 1.002\times10^{-7}$

$C_{12} = \dfrac{\Theta_{12}}{M} = -2.502\times10^{-9}$

$K_1 = \dfrac{C_2}{C_1C_2 - C_{12}^2} = 2.037\times10^7$

$K_2 = \dfrac{C_1}{C_1C_2 - C_{12}^2} = 9.995\times10^6$

$K_{12} = \dfrac{-C_{12}}{C_1C_2 - C_{12}^2} = 5.087\times10^5$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 9.970\times10^6$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 65$$

* A skewed Line : $\Theta_Y = 45°$
$\Theta_Z = 45°$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 24

BG C26A

	-C26X		C26A		SUM	
	T1	T2	T1	T2	Deg	Rad
$\theta_1(x)$	1.472	-0.227	-1.723	-0.001	3.695	0.064
$\theta_2^{(z)}$	-0.228	12.229	-0.001	-1.564	13.793	0.241
θ_{12}					-0.226	-0.004

OD = 8.625
r = 4.313
t = 0.594

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 121.49$
$E = 26.5\times10^6$ psi
M = 100000 ft-lbs = 1.2×10^6 in-lb

$$C_1 = \frac{\theta_1}{M} = 5.374\times10^{-8}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 1.863\times10^{7}$$

$$C_2 = \frac{\theta_2}{M} = 2.006\times10^{-7}$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 4.990\times10^{6}$$

$$C_{12} = \frac{\theta_{12}}{M} = -3.287\times10^{-9}$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = 3.052\times10^{5}$$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 4.983\times10^{6}$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 150$$

BC CΦ5

	- CΦ5		CΦ5X		SUM	
	T1	T2	T1	T2	Deg	Rad
$\Theta_{1(y)}$	1.350	1.027	-2.401	-0.102	3.751	0.065
$\Theta_2^{(z)}$	0.057	0.995	-0.072	-1.986	2.981	0.052
Θ_{12}					0.129	0.002

OD = 10.75
R = 5.375
t = 0.594

$I = \pi/4\left(R_o^4 - R_i^4\right) = 245.19$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs = 1.2×10^6 in-lb

$$C_1 = \frac{\Theta_1}{M} = 5.456\times10^{-8}$$

$$C_2 = \frac{\Theta_2}{M} = 4.336\times10^{-8}$$

$$C_{12} = \frac{\Theta_{12}}{M} = 1.876\times10^{-9}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 1.836\times10^7$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 2.310\times10^7$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -7.944\times10^5$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 1.823\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 66$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 26
	K. Gd		

BC B20

	- B20 Z		320 X		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 (Y)	1.278	0.030	-1.866	-0.065	3.144	0.055
$\theta_2^{(Z)}$	0.051	0.987	-0.044	-1.446	2.483	0.043
θ_{12}					0.095	0.002

OD = 10.75
R = 5.375
t = 0.719

$I = \pi/4\,(R_o^4 - R_i^4) = 286.45$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 4.573\times10^{-8} \qquad K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 2.189\times10^7$$

$$C_2 = \frac{\theta_2}{M} = 3.611\times10^{-8} \qquad K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 2.772\times10^7$$

$$C_{12} = \frac{\theta_{12}}{M} = 1.382\times10^{-9} \qquad K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -8.377\times10^5$$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 2.178\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 65$$

BS B09

	-B09 Z		B09 X		SUM	
	T1	T2	T1	T2	Deg.	Rad
$\theta_1(y)$	0.809	-0.007	-1.423	-0.009	2.232	0.039
$\theta_2(z)$	-0.003	0.554	-0.006	-0.901	1.455	0.025
θ_{12}					0.002	≈0

OD = 10.75
R = 5.375
t = 0.594

$I = \pi/4\,(R_o^4 - R_i^4) = 245.19$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 3.246\times10^{-8} \qquad K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 3.080\times10^7$$

$$C_2 = \frac{\theta_2}{M} = 2.116\times10^{-8} \qquad K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 4.725\times10^7$$

$$C_{12} = \frac{\theta_{12}}{M} = 2.909\times10^{-11} \qquad K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -4.234\times10^4$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 3.080\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 39$$

BS B&1

	← Bp 1		Bp		SUM	
	T1	T2	T1	T2	Deg	Rad
Θ_1	0.300	−0.02	+1.139	−0.212	1.994	0.035
Θ_2	−0.228	0.0?0	−0.001	−0.752	1.428	0.025
Θ_{12}					0.006	≈0

OD = 10.75
R = 5.375
t = 0.719

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 286.45$
$E = 26.5 \times 10^6$ psi
$M = 100000$ ft-lbs $= 1.2 \times 10^6$ in-lb

$$C_1 = \frac{\Theta_1}{M} = 2.907 \times 10^{-8} \qquad K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2} = 3.4?? \times 10^{7}$$

$$C_2 = \frac{\Theta_2}{M} = 2.077 \times 10^{-8} \qquad K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2} = 4.8? \times 10^{7}$$

$$C_{12} = \frac{\Theta_{12}}{M} = -8.727 \times 10^{-11} \qquad K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2} = 1.445 \times 10^{5}$$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 3.43? \times 10^{7}$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 41$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 29
	L. C.		

BS D17

	- D17X		D17		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 (x)	1.635	-0.772	-0.688	0	2.323	0.041
θ_2 (y) (z)	-0.612 -0.484 ⇓	2.365 2.563 ⇓	0 0 ⇓	-0.596 -0.344 ⇓	4.018	0.070
*rotation θ_{12}	-0.772	3.330	0	-0.688	-0.772	-0.013

$OD = 12.75$

$R = 6.375$

$t = 0.688$

$I = \pi/4\,(R_o^4 - R_i^4) = 475.68$

$E = 26.5\times10^6$ psi

$M = 100000$ ft-kips $= 1.2\times10^6$ in-lb

$C_1 = \frac{\theta_1}{M} = 3.379\times10^{-8}$

$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 3.162\times10^7$

$C_2 = \frac{\theta_2}{M} = 5.844\times10^{-8}$

$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 1.828\times10^7$

$C_{12} = \frac{\theta_{12}}{M} = -1.123\times10^{-8}$

$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = 6.075\times10^6$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 1.593\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 124$$

* A skewed Line: $\theta_y = 30°$
$\theta_z = 60°$

BS D04

	- D04 X		D04		SUM	
	T1	T2	T1	T2	Deg	Rad
$\theta_1 (x)$	1.248	0.223	-1.182	-0.085	2.430	0.042
$\theta_2 (y)$	0.192	1.463	-0.117	-1.430	2.893	0.050
θ_{12}					0.309	0.005

OD = 12.75
R = 6.375
t = 0.844

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 562.18$
$E = 26.5\times10^6$ psi
$M = 100000$ ft-lbs $= 1.2\times10^6$ in-lb

$$C_1 = \frac{\theta_1}{M} = 3.543\times10^{-8}$$

$$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 2.868\times10^7$$

$$C_2 = \frac{\theta_2}{M} = 4.208\times10^{-8}$$

$$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 2.409\times10^7$$

$$C_{12} = \frac{\theta_{12}}{M} = 4.494\times10^{-9}$$

$$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -3.064\times10^6$$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 2.256\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 104$$

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 31
	R. C		

BS B15 N

	- B14A		B15X		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 (Y)	0.539	0.002	-1.323	-0.020	1.562	0.032
θ_2 (Z)	0.004	0.407	-0.018	-0.834	1.241	0.022
θ_{12}					0.022	0.0004

OD = 16.0
R = 8.0
t = 0.841

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 1157.45$
E = 26.5×10^6 psi
M = 100050 ft-lbs = 1.2×10^6 in-lb

$C_1 = \frac{\theta_1}{M} = 2.708\times10^{-8}$

$C_2 = \frac{\theta_2}{M} = 1.805\times10^{-8}$

$C_{12} = \frac{\theta_{12}}{M} = 3.200\times10^{-10}$

$K_1 = \frac{C_2}{C_1C_2 - C_{12}^2} = 3.693\times10^7$

$K_2 = \frac{C_1}{C_1C_2 - C_{12}^2} = 5.541\times10^7$

$K_{12} = \frac{-C_{12}}{C_1C_2 - C_{12}^2} = -6.547\times10^5$

$$K_{MIN} = \frac{K_1+K_2}{2} - \sqrt{\left(\frac{K_1-K_2}{2}\right)^2 + K_{12}^2} = 3.691\times10^7$$

$$L/R = \frac{EI}{R\,K_{MIN}} = 104$$

B5 B13

	- B13		B13X		SUM	
	T1	T2	T1	T2	Deg	Rad
θ_1 (°)	0.568	0.002	-1.363	-0.020	1.931	0.034
θ_2 (°)	0.004	0.423	-0.017	-0.862	1.215	0.022
θ_{12}					0.021	0.0004

OD = 16.0
r = 8.0
t = 1.031

$I = \pi/4 \left(R_o^4 - R_i^4\right) = 1364.43$
$E = 26.5 \times 10^6$ psi
$M = 100000$ ft-lbs $= 1.2 \times 10^6$ in-lb

$C_1 = \frac{\theta_1}{M} = 2.809 \times 10^{-8}$

$C_2 = \frac{\theta_2}{M} = 1.869 \times 10^{-8}$

$C_{12} = \frac{\theta_{12}}{M} = 3.054 \times 10^{-10}$

$K_1 = \frac{C_2}{C_1 C_2 - C_{12}^2} = 3.561 \times 10^7$

$K_2 = \frac{C_1}{C_1 C_2 - C_{12}^2} = 5.352 \times 10^7$

$K_{12} = \frac{-C_{12}}{C_1 C_2 - C_{12}^2} = -5.820 \times 10^5$

$$K_{MIN} = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_1 - K_2}{2}\right)^2 + K_{12}^2} = 3.559 \times 10^7$$

$$L/R = \frac{EI}{R\, K_{MIN}} = 127$$

References

1) P. Paris et al, "Fracture Proof Design and Analysis of Nuclear Piping", in NUREG CR-3464

2) MPR-1177, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line to Condenser NE-01-A"

3) MPR-1178, "Isolation Condenser System, Analysis of Modified Piping Configuration, Condensate Line From Condenser NE-01-A"

4) MPR-1179, "Isolation Condenser System, Analysis of Modified Piping Configuration, Steam Line to Condenser NE-01-B"

5) MPR-1180, "Isolation Condenser System, Analysis of Modified Piping Configuration, Condensate Line From Condenser NE-01-B"

6) MPR Calculation, "Applied Piping Loads", by R. Coward, 4/19/91.

7) MPR Calculation, "Fracture Mechanics Crack Sizes", by R. Coward, 4/1/91

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	R. Card		1-1

Attachment 1

AUTOPIPE MODEL DATA LISTINGS FOR
4/R AUTOPIPE ANALYSES

[AUTOPIPE OUTPUT omitted in Report to reduce Report Size]

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	M. C. A.		2-1

ATTACHMENT 2

DISPLACEMENT OUTPUT RESULTS FOR
4/R AUTOPIPE ANALYSES

[AUTOPIPE OUTPUT omitted in Report to Reduce Report Size]

MPR ASSOCIATES, INC.
1050 Connecticut Ave., NW-Washington, DC 20036

CALCULATION TITLE PAGE

CLIENT
GPUN

PAGE 1 OF 17

PROJECT
ICS Piping LBB

TASK NO.
83-133

CALCULATION TITLE
Tearing Modulus Calculation Results

CALCULATION NO. (OPTIONAL)

PREPARER(S)/DATE	CHECKER(S)/DATE	REVIEWER(S)/DATE	REV. NO.
R.Cu / 4/9/91	4/11/91	JS NaTell 4.17.91	0

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 2
	R.C.		

Purpose - This calculation determines the applied Tearing Modulus for postulated throughwall circumferential cracks in the Oyster Creek Isolation Condenser System (ICS) piping. Margins to Tearing Instability or Plastic Collapse are also determined.

Results - Results for calculation of Tearing Modulus and margins to plastic collapse in terms of crack length, Ra, and applied load, Rm, are shown below.

Point	T	Ra	Rm	Point	T	Ra	Rm
A- Condensate				B- Condensate			
D04N	1.8	2.56	3.33	C28	3.9	2.10	2.32
D03A	2.3	2.26	3.54	C26A	11.9	1.91	2.28
B02	0.9	3.20	5.06	C05	0.5	3.17	4.91
B01	0.7	2.86	5.12	B20	1.4	2.68	4.03
A- Steam				B- Steam			
B09	2.8	2.07	3.23	B09	5.9	1.87	2.47
B01	3.5	1.82	2.90	B01	4.6	1.75	2.57
D12	3.6	2.24	3.10	D17	4.7	2.19	2.92
D10A	4.4	2.02	3.11	D04	5.1	1.98	2.93
B19	0.9	3.16	6.53	B15N	0.9	2.91	4.69
B11	0.5	2.75	5.95	B13	2.	2.54	4.30

This calculation determines the applied Tearing Modulus for postulated throughwall circumferential cracks in the ICS piping. The locations of postulated cracks and the sizes of the cracks are obtained from References 1 and 2. In summary, the locations of interest are the highest loaded points in each piping system for each pipe size and the size of the crack is that corresponding to a 2GPM leakage rate. The loads on the piping are also taken from Reference 1 and include deadweight, thermal expansion, and SSE.

The Tearing Modulus is calculated using the method documented in Reference 3. The information required to calculate T is the relative crack length, a/b (crack length/circumference), one-half the applied moment (see Reference 3), the pipe geometry, the piping compliance, 4/R (taken from Reference 4) and the piping material properties. As discussed in Reference 3, worst case properties for stainless steel are used, including $T_{MAT} = 182$. (Material Properties from Reference 5). The material properties are for 304SS, which is very similar to 316NG SS.

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 4

It is possible that during installation, some of the schedule 100 piping may be machined to the schedule 80 thickness (for fit-up requirements). For this reason, all fracture mechanics calculations will be performed using the schedule 80 wall thickness. The exception to this approach is the 12" schedule 100 piping in the steam supply lines; these will not be machined, so the schedule 100 section properties are used.

All of the required input is shown on the following page for the calculation of T and the margins to tearing instability or plastic collapse

Figures 1 to 4 show the piping system models and the locations for fracture mechanics calculations.

Node	OD	t	a/b	L/R	$M_{eq}/2$
A-Condensate					
D04N	8.625	0.50	0.211	127	142110
D03A	8.625	0.50 *	0.239	46	142101
B08	10.75	0.594	0.178	27	218523
B01	10.75	0.594 *	0.203	73	201979
A-Steam					
B09	10.75	0.594	0.258	38	273214
B01	10.75	0.719	0.294	44	319861
D12	12.75	0.688	0.228	88	508269
D10A	12.75	0.688 *	0.261	151	459669
B19	16.00	0.844	0.194	135	512654
B11	16.00	0.844 *	0.222	133	521647
B-Condensate					
C28	8.625	0.50	0.211	65	235225
C26A	8.625	0.50 *	0.239	150	220523
C05	10.75	0.594	0.178	66	224488
B20	10.75	0.594 *	0.203	65	256580
B-Steam					
B09	10.75	0.594	0.258	39	357649
B01	10.75	0.719	0.294	41	361954
D17	12.75	0.688	0.228	124	538676
D04	12.75	0.688 *	0.261	104	487899
B15N	16.00	0.844	0.194	104	714305
B13	16.00	0.844 *	0.222	127	722088

* Schedule 80 wall thickness

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	A. Gad		6

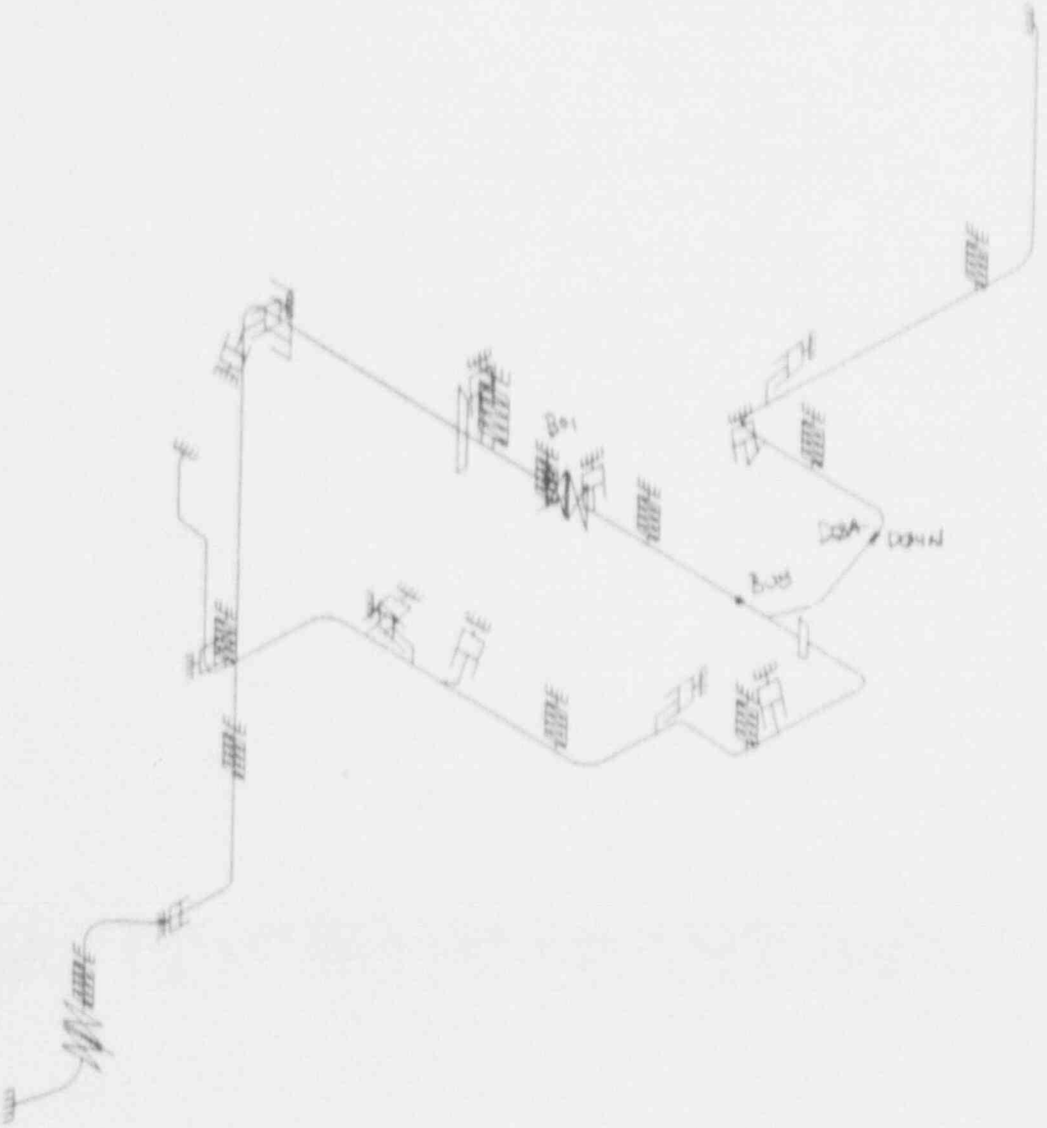


Figure 1

A - Condensate

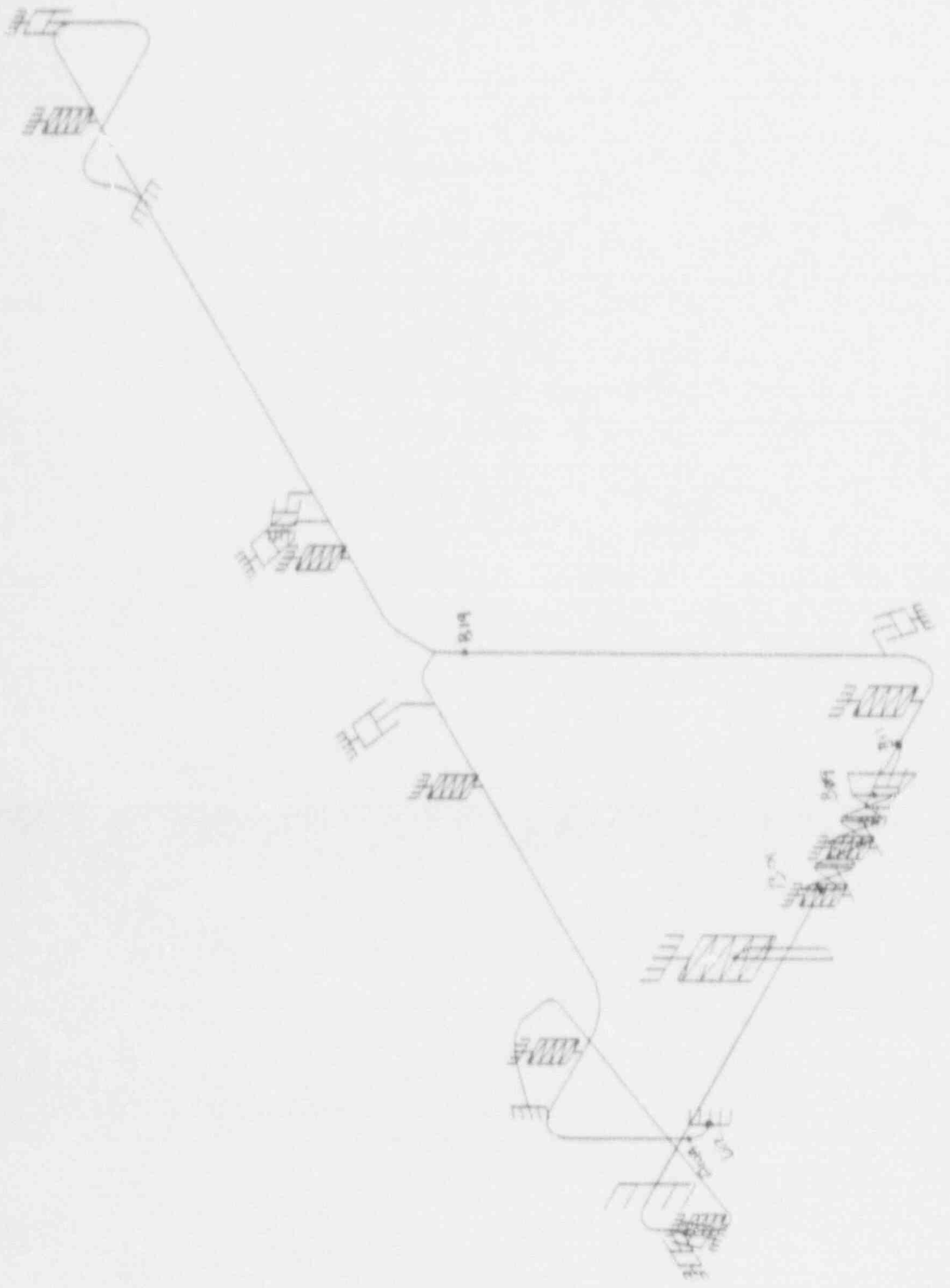


Figure 2
A - Steam

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE 8

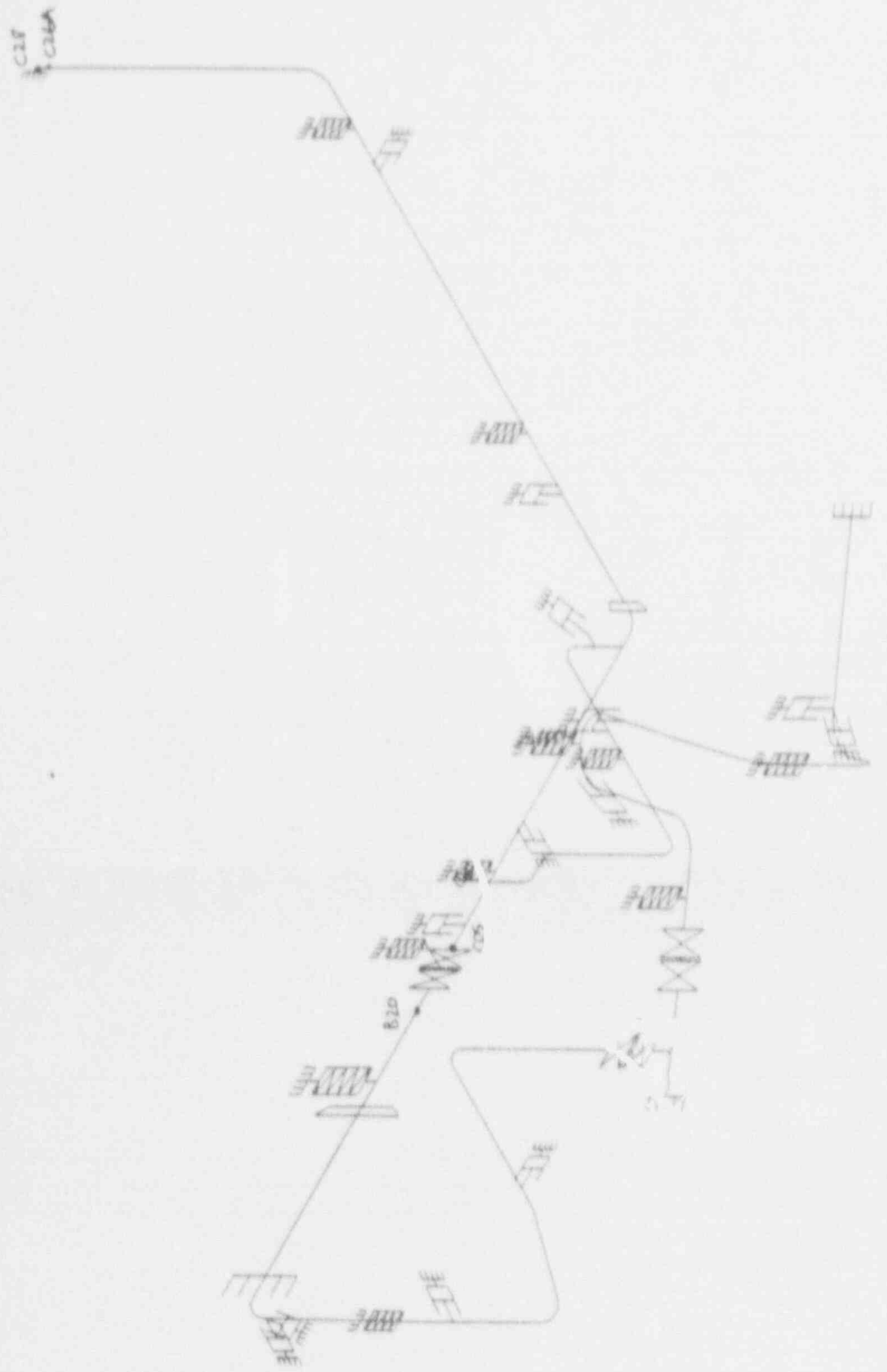


Figure 3
B- Condensate

CALCULATION NO.	PREPARED BY	CHECKED BY	PAGE
	l. G. l		9

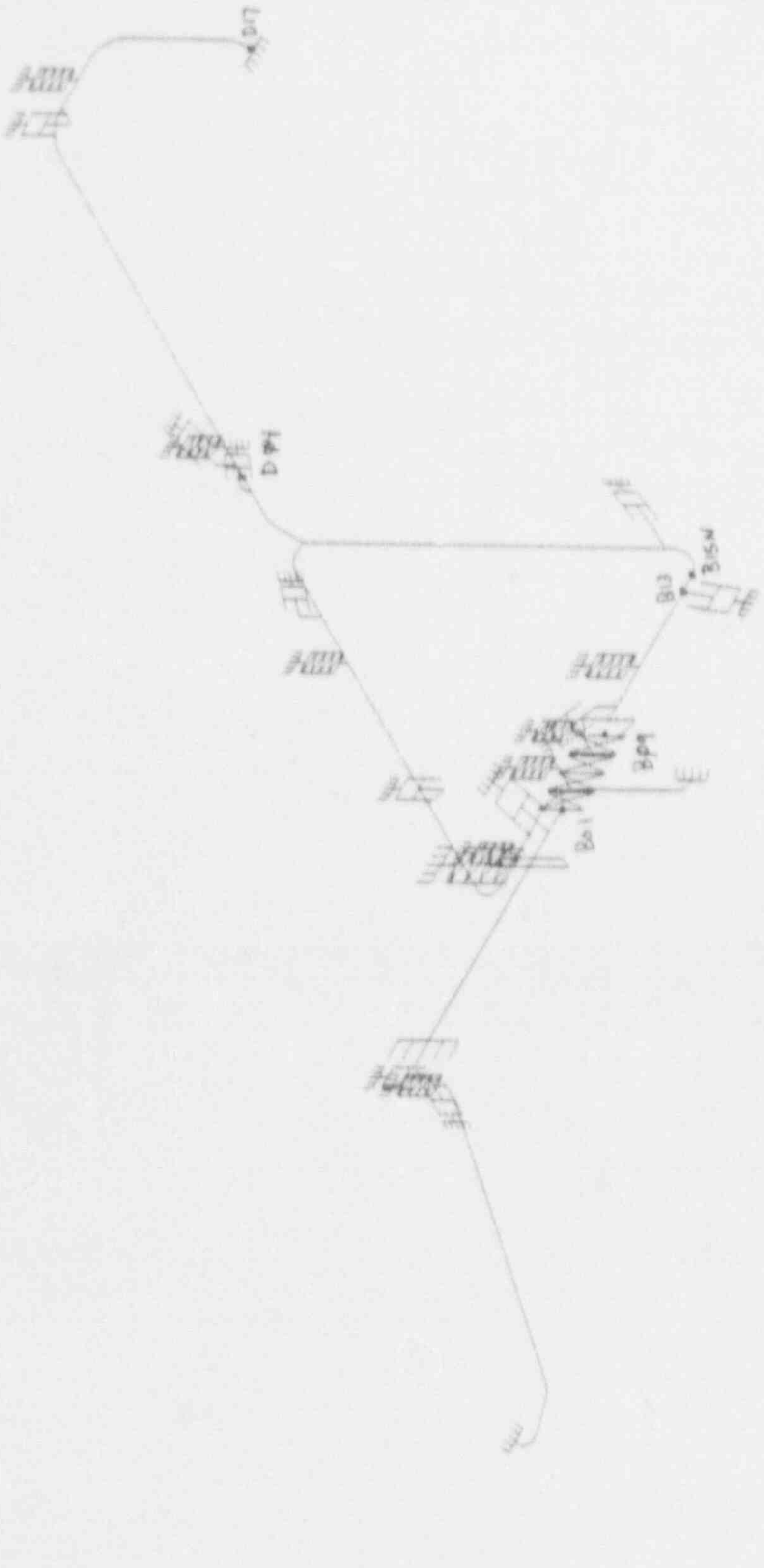


Figure 4
B. Steam

As the postulated crack size or applied moment is increased, the failure mode of the piping could be Tearing Instability or plastic collapse of the remaining uncracked cross section. Each failure mode must be considered and the limiting case selected. The limit moment for a pipe cross section is taken from Reference 6 (with the small plastic zone correction neglected):

$$M_L = 4\sigma_f R_m^2 t \left(\cos \gamma/2 - 1/2 \sin \gamma\right)$$

where

σ_f is the material flow stress

R_m is the mean radius

t is the wall thickness

γ is the half crack angle

From Reference 7, the flow stress is taken as 3 times the material design stress intensity value from the ASME Boiler & Pressure Vessel Code (Reference 8). For 316 stainless steel at 575°F (the design temperature), the flow stress = 3*17.25 = 51.75 ksi.

Shown below are the limit moments for the 2 gpm crack size and the limit crack size for the applied load for plastic collapse failure for each analysis location.

Point	OD	t	a/b_{2gpm}	θ_{2gpm}	M_L	$M_L/2$	$M_{app}/2$	θ_L	a/b_L
A - Condensate									
D04N	8.625		0.211	38.0	1089601	544801	142110	97.0°	0.539
D03A	8.625	.5	0.239	43.0	1006490	503245	142[illegible]1	97.0°	0.539
D08	10.75	0.594	0.178	32.0	2206455	1103228	218520	102.4°	0.569
B01	10.75	0.594	0.203	36.5	2066911	1033455	201979	104.6°	0.581
A - Steam									
B09	10.75	0.594	0.258	46.4	1764985	882492	273214	95.9°	0.533
B01	10.75	0.719	0.294	52.9	1858294	929147	319861	96.1°	0.534
D12	12.75	0.688	0.228	41.0	3150827	1575414	508269	91.8°	0.510
D10A	12.75	0.688	0.261	47.0	2857193	1428596	459669	95.0°	0.528
B19	16.00	0.844	0.194	34.9	6699004	3349502	512654	110.3°	0.613
B11	16.00	0.844	0.222	40.0	6207147	3103573	521647	110.0°	0.611
B - Condensate									
C28	8.625	0.5	0.211	38.0	1089601	882492	235225	79.7°	0.443
C26A	8.625	0.5	0.239	43.0	1006490	929147	220523	82.3°	0.457
C05	10.75	0.594	0.178	32.0	2206455	1575414	224488	101.7°	0.565
B20	10.75	0.594	0.203	36.5	2066911	1428596	[illegible]	97.7°	0.543
B - Steam									
B09	10.75	0.594	0.258	46.4	1764985	3349502	357649	87.1°	0.484
B01	10.75	0.719	0.294	52.9	1858294	929147	361954	92.3°	0.513
D17	12.75	0.688	0.228	41.0	3150827	882492	538676	89.8°	0.499
D04	12.75	0.688	0.261	47.0	2857193	929147	487899	93.1°	0.517
B15N	16.00	0.844	0.194	34.9	6699004	1575414	714305	101.5°	0.564
B13	16.00	0.844	0.222	40.0	6207147	1428596	722498	101.3°	0.563

The results for applied Tearing Moduli are shown on pages Also shown are results of calculations to determine margin to failure (Tearing Instability or plastic collapse). Margins are determined in terms of applied load and crack length. Unstable growth is predicted when $T = T_{MAT} = 182$ (Reference 5); plastic collapse is predicted when the crack size or moment exceeds the limits on the previous page.

The theory used to calculate T does not allow crack lengths greater than $a/b = 0.5$. In cases when $a/b = 0.5$ before tearing instability or plastic collapse is predicted, the margin is calculated using the 0.5 value. The margin to plastic collapse is also calculated for these cases, and this value is used as the margin to failure since in each case, T is much less than T_{MAT} at $a/b = 0.5$.

A - Condensate

Point	Pipe	a/b	Meq/2	L/R	T
D04N	08080C	0.211	142110	127	1.8
D03A	08100C	[illegible]	142101	146	2.3
B08	10080C	0.178	218523	127	0.7
B01	10100C	0.203	201979	73	0.7

Margin in Terms of Crack Length

Point	Pipe	Meq/2	L/R	a/b	T	Margin	Margin FC*
D04N	08080C	142110	127	0.50	1.6	2.37	2.56
D03A	08100C	142101	146	0.50	6.8	2.09	2.26
B08	10080C	218523	127	0.50	8.5	2.81	3.20
B01	10100C	201979	73	0.50	1.3	2.46	2.86

Margin in Terms of Applied Load

Point	Pipe	a/b	L/R	M/2	T	Margin
D04	08080C	0.211	127	544801*	28.6	3.8
D03A	08100C	0.239	146	503245*	52.4	
B08	10080C	0.178	127	1103228*	52.5	5.05
B01	10100C	0.203	73	1033453*	-103.0	5.12

* Plastic Collapse

A - Steam

Point	Pipe	a/b	Meq/2	L/R	T
B09	10080S	0.258	273214	38	2.8
B01	10100S	0.294	319861	44	3.5
D12	12080S	0.228	508269	88	3.6
D10A	12100S	0.261	459669	151	4.4
B19	16080S	0.194	512654	135	0.4
B11	16100S	0.222	521647	133	0.5

Margin in Terms of Crack Length

Point	Pipe	Meq/2	L/R	a/b	T	Margin	Margin-PC*
B09	10080S	273214	38	0.50	-34.3	1.94	2.07
B01	10100S	319861	44	0.50	-26.0	1.70	1.82
D12	12080S	508269	88	0.50	-76.0	2.19	2.24
D10A	12100S	459669	151	0.50	1.1	1.92	2.02
B19	16080S	512654	135	0.50	6.6	2.58	3.16
B11	16100S	521647	133	0.50	6.7	2.25	2.75

Margin in Terms of Applied Load

Point	Pipe	a/b	L/R	M/2	T	Margin
B09	10080S	0.258	38	882492*	-135.7	3.23
B01	10100S	0.294	44	929147*	-149.9	2.90
D12	12080S	0.228	88	157543*	-65	3.10
D10A	12100S	0.261	151	1428590*	75.0	3.11
B19	16080S	0.194	135	3349502*	46.7	6.53
B11	16100S	0.222	133	3103573*	25.9	5.95

* Plastic Collapse

B- Condensate

Point	Pipe	a/b	Meq/2	L/R	T
C28	OB080C	0.211	235225	65	3.9
C26A	OB100C	0.239	220523	150	11.9
C05	10080C	0.178	224488	66	0.8
B20	10100C	0.203	256580	65	1.4

Margin in Terms of Crack Length

Point	Pipe	Meq/2	L/R	a/b	T	Margin	Margin_{pc}*
C28	OB080C	235225	65	0.443*	-148.1	2.10	2.10
C26A	OB100C	220523	150	0.457*	-62.9	1.91	1.91
C05	10080C	224488	66	0.501	-5.6	2.81	3.17
B20	10100C	256580	65	0.500	-14.8	2.46	2.68

Margin in Terms of Applied Load

Point	Pipe	a/b	L/R	M/2	T	Margin
C28	OB080C	0.211	65	544801*	-117.4	2.32
C26A	OB100C	0.239	150	503245*	58.5	2.28
C05	10080C	0.178	66	1103228*	-117.5	4.91
B20	10100C	0.203	65	1033455*	-126.8	4.03

* [illegible] Collapse

B-Steam

Point	Pipe	a/b	Meq/2	L/R	T
B09	100805	0.258	357649	39	5.9
B01	101005	0.294	361954	41	4.6
D17	120805	0.228	538676	124	4.7
D04	121005	0.261	487899	104	5.1
B15N	160805	0.194	714305	104	0.9
B13	161005	0.222	722088	127	1.2

Margin in Terms of Crack Length

Point	Pipe	Meq/2	L/R	a/b	T	Margin	$Margn_{PL}$ *
B09	100805	357649	39	0.484 *	-121.0	1.87	1.87
B01	101005	361954	41	0.500	-55.5	1.70	1.75
D17	120805	538676	124	0.499 *	-48.0	2.19	2.19
D04	121005	487899	104	0.50	-27.1	1.92	1.98
B15N	160805	714205	104	0.50	3.7	2.58	2.91
B13	161005	722088	127	0.50	7.7	2.25	2.54

Margin in Terms of Applied Load

Point	Pipe	a/b	L/R	M/2	T	Margin
B09	100805	0.258	39	882497 *	-133.2	2.47
B01	101005	0.294	41	929147 *	-150.7	2.57
D17	120805	0.228	124	1575413 *	9.7	2.92
D04	121005	0.261	104	1428596 *	-2.2	2.93
B15N	160805	0.194	104	3349502 *	-23.2	4.69
B13	161005	0.222	127	3103573 *	14.1	4.30

* Plastic Collapse

References

1) MPR Calculation, "Applied Piping Loads", by R. Coward, 4/9/91.

2) MPR Calculation, "Fracture Mechanics Crack Sizes", by R. Coward, 4/1/91.

3) MPR Calculation, "TEAR Documentation (Version 2.0)", by R. Coward, 6/5/90.

4) MPR Calculation, "System Compliance at High Loaded Points", by R. Coward, 4/9/91

5) MPR Calculation, "Elastic-Plastic Material Properties for A106 Gr B and 304 SS" by R. Coward, 6/5/91.

6) NUREG-1061, Vol 3, "Report of the USNRC Piping Review Committee (Evaluation of Potential for Pipe Breaks)", p. A-15.

7) EPRI NP-2472-SY, Volume 1, "The growth and stability of Stress Corrosion Cracks in Large Diameter BWR Piping", July, 1982.

8) 1983 ASME Boiler + Pressure Vessel Code, Section III, Appendices.