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August 10, 2000
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File No.: G09.16
10CFR50.55a

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, DC 20555-0001

South Texas Project
Unit 2
Docket No. STN 50-499
Request for Relief from ASME Boiler and Pressure Vessel Code Section XI
Requirements (Dealloying) (Relief Request RR-ENG-35) (Supplement 2)

References: 1) Request for Relief from ASME Boiler and Pressure Vessel Code, Section XI Requirements (Relief Request RR-ENG-35), S. E. Thomas, South Texas Project, to NRC Document Control Desk, dated February 14, 2000 (NOC-AE-00000251)

2) Request for Relief from ASME Boiler and Pressure Vessel Code Section XI Requirements (Relief Request RR-ENG-35) (Supplement), dated May 22, 2000 (NOC-AE-00000855)

This is a supplement to a relief request previously submitted by the South Texas Project in accordance with the provisions of 10CFR50.55a(g)(5)(iii) to obtain relief from IWA-5250 of Section XI of the ASME Boiler and Pressure Vessel Code (References 1 and 2). The relief request was for deferral of code repair of areas of dealuminumization in service water Class 3 piping. Nuclear Regulatory Commission staff reviewers have requested documentation of design activities as assurance that applicable ASME Section XI code requirements are still satisfied.

The attached APTECH report AES-C-1964-1, "Calculation of Critical Bending Stress for Dealloyed Aluminum-Bronze Castings in the ECW System," dated December 1, 1993, applied analysis methods contained in ASME Section XI for flawed piping to calculate critical bending stress for selected large bore piping castings. This was derived from an earlier fracture mechanics model for small bore castings which was submitted to the NRC dated November 1, 1988 (ST-HL-AE-2748). APTECH report AES-C-1964-1 is based on the ASME Code Section XI approach and results in curves of bending stress versus critical crack size for different sizes of castings. Using this basis, safety factors for previous dealloyed flanges that were destructively analyzed were found to exceed ASME Code Section XI requirements.

These fracture mechanics methods were presented to the NRC in 1988 for small bore castings and in 1992 for large bore welds.

A047

If there are any questions, please contact either Mr. P. L. Walker at (361) 972-8392 or me at (361) 972-7902.

T. J. Jordan
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PLW

Attachment: APTECH Report AES-C-1964-1, "Calculation of Critical Bending Stress for Dealloyed Aluminum-Bronze Castings in the ECW System"

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CALCULATION COVER SHEET

ST-7R-HS-090002
PFN: M05.02.02

Document No.: AES-C-1964-1

Title: Calculation of Critical Bending Stress for Dealloyed Aluminum-Bronze Castings in the ECW System

Client: Houston Lighting & Power

Project No.: AES 93061964-1Q

APTECH Office: Sunnyvale

Sheet No. 1 of 44

Purpose: The purpose of this calculation is to perform a fracture mechanics analysis in order to determine the critical bending stress for a circumferential through-wall dealloying in the aluminum-bronze castings. Through-wall cracks are also considered. The analysis methods contained in ASME Section XI for flawed piping are used to calculate critical bending stress for selected large bore piping (3-inch, 4-inch, 6-inch, 8-inch, 10-inch, 14-inch, 24-inch and 30-inch nominal pipe sizes) castings in the essential cooling water system.

Assumptions: See Section 2 for a summary of the major analysis assumptions used in the evaluation. This calculation covers large-bore aluminum-bronze castings (weld region under back-ring) in the ECW system and includes the flanges, tees, valves, and pumps.

Results: The calculated critical bending stresses are presented in graphical form in Section 7. These calculated stresses are the bending stresses required to fail a casting that is dealloyed circumferentially with and without cracks.

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0	RCC 12/1/93	VG 13DEC93	RHC 21JAN94	RCC 1/21/94	Initial Issue

APTECH ENGINEERING SERVICES, INC.

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1.0 INTRODUCTION

The purpose of this calculation is to determine the critical bending stress for failure by plastic collapse or by fracture of aluminum-bronze (Al-Bronze) castings as a function of through-wall dealloying length and/or through-wall crack length. The critical bending stress is the failure stress (i.e., ultimate bending load capacity) without a safety factor. This stress is defined as P_b', σ_b^c, or σ_c as discussed herein.

This calculation covers the weld region of cast flanges, and the same location of other castings, such as tees, valves, and pump casings, where a weld backing ring is present. For simplicity, the word "casting" will mean cast flanges, tees, valves, and pumps. The region of interest is the butt weld (e.g., casting-to-pipe butt weld) at the minimum section at the backing ring where dealloying is known to occur. The dealloy phenomena and the alloys susceptible to dealloying are discussed in Bechtel Report 8804-06FA for small bore castings (1).

Figure 1-1 illustrates the idealized flaw geometry where the dealloyed material or crack angle, 2θ, the mean radius, R, and wall thickness, t, are schematically shown. The flaw model represents the degradation area in an Al-Bronze cast flange region at the weld neck under the backing ring. The piping system covered by this evaluation is the essential cooling water (ECW) system. Analysis methods in ASME Section XI Appendix H (2) are used as guidance in calculating the bending strength of castings containing circumferential through-wall cracks. In particular, both limit load (net-section plastic collapse) and the linear elastic fracture mechanics methods are used to establish the minimum structural capacity of castings.

The sizes that are covered by the scope of this calculation are the 3-inch, 4-inch, 6-inch, 8-inch, 10-inch, 14-inch, 24-inch, and 30-inch nominal pipe sizes (NPS). Other geometry information and design loadings are discussed later in Section 3.

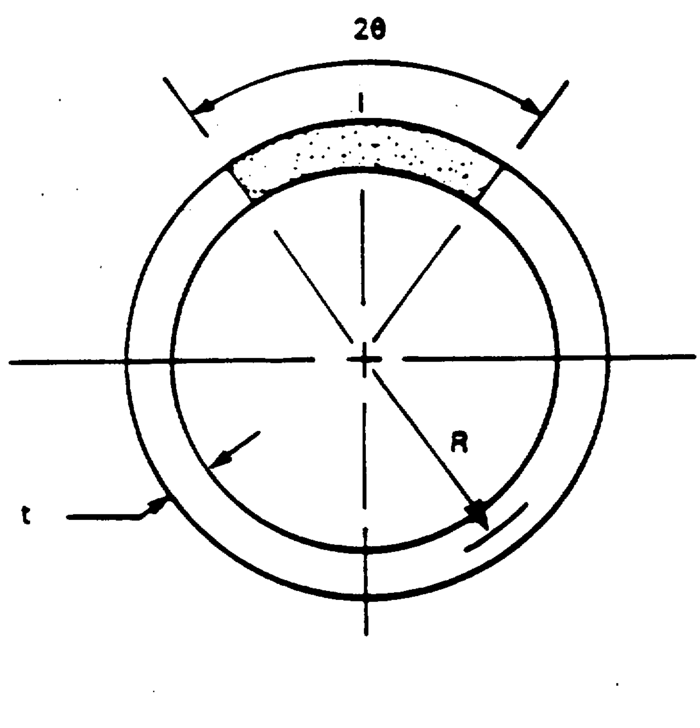

Figure 1-1 - Part-Circumferential Through-Wall Flaw Model.

2.0 ASSUMPTIONS

The following major analysis assumptions are made:

1. Flaw evaluation methods for piping components given in ASME Section XI, Appendix H (2) are generally applicable.

2. When only dealloying is present, the dealloyed region is conservatively modeled as a region not capable of carrying any load. The structural capacity of the casting is determined by a limit load analysis.

3. When cracks are present, the structural capacity is evaluated by both limit load analysis and fracture mechanics to establish the minimum structural capacity.

4. Weld residual stresses are considered as secondary stresses for plastic collapse and are neglected in the evaluation.

5. Weld residual stresses will have a negligible effect on the average stress intensity factor for a through-wall crack because the average residual stress across the wall thickness will be approximately zero.

6. The nominal pipe sizes and corresponding wall thickness covered by this evaluation are given in Section 3.

3.0 PIPING GEOMETRY AND DESIGN CONDITIONS

The piping geometry and design conditions were extracted from the evaluation of ECW pipe welds (3). The division of castings in the ECW system by type and size is given below (4):

Castings	Sizes
Flanges	≤10-inch NPS
Fittings (Tees, etc.)	≤10-inch NPS
Valves	≤30-inch NPS
Pumps	≤30-inch NPS

Flanges and fittings are in sizes 10-inch diameter and less. Valves and pumps are in sizes 30-inch diameter and less. The smallest size of casting considered in this calculation is 3-inch NPS.

The NPS, outside diameter, and wall thicknesses covered by this analysis are listed below:

Nominal Pipe Sizes, NPS (in)	Outside Diameter, D_o (in)	Wall Thickness, t (in)	Mean Radius, R (in)	R/t	σ_m (psi)
3	3.500	0.216	1.642	7.60	486
4	4.500	0.237	2.1315	8.99	570
6	6.625	0.280	3.1725	11.33	710
8	8.625	0.322	4.1515	12.89	804
10	10.75	0.365	5.1925	14.23	884
14	14.00	0.250	6.8750	27.50	1680
24	24.00	0.250	11.8750	47.50	2880
30	30.00	0.250	14.8750	59.50	3600

where R is the mean radius calculated from $R = (D_o - t)/2$.

The design pressure for the ECW system is 120 psig (3). The axial stress, σ_m, for internal pressure is given by:

$$\sigma_m = p\,D_o/4t \qquad (3\text{-}1)$$

The axial stress from Eq. 3-1 is also listed above by NPS with p = 120 psig.

The material properties of the pipe is specified as ASME SB-169 Grade CA-614 (3). The minimum strength properties for the pipe material are (4):

$$S_y = 32 \text{ ksi}$$
$$S_u = 72 \text{ ksi}$$

The castings were supplied to ASME SB-148 specifications in two grades: CA-952 and CA-954 (4). The specified minimum properties of these materials are (5):

	CA-952	CA-954
S_y (ksi)	25	30
S_u (ksi)	65	75

4.0 MATERIAL PROPERTIES

4.1 Fracture Toughness

The fracture toughness of casting Al-Bronze was evaluated in the study of small bore fittings (1). Critical crack tip opening displacement (CTOD) tests of CA-954 alloy material, after conversion to equivalent plane strain fracture toughness (K_{Ic}), gave values in the range of 63.5 to 95.1 ksi in$^{1/2}$. From this range, a conservative value of 65 ksi in$^{1/2}$ was established for evaluation of the 954 alloy. It has been judged that 952 alloy will have better toughness than 954 because it will be less susceptible to dealloying (1). Furthermore, weld metal toughness has significantly higher toughness than the castings (1, 3). Therefore, K_{Ic} = 65 ksi in$^{1/2}$ will be a conservative value for evaluating all castings in the ECW system.

4.2 Flow Stress

For the purpose of calculating the limit load of a pipe component, Article H-5320 of Appendix H to ASME Section XI (2) specifies a definition for flow stress as the average of the specified minimum yield and ultimate strengths:

$$\sigma_f = \frac{S_y + S_u}{2} \tag{4-1}$$

For strength calculations performed in this analysis, the minimum specified strength values will be assumed for the lower strength 952 alloy. Based on Eq. 4-1 and the strength properties of the 952 alloy, the flow stress is:

$$\sigma_f = \frac{(25 + 65)}{2} = 45 \text{ ksi} \tag{4-2}$$

This value for σ_f will be used in the evaluation of all castings.

5.0 LIMIT LOAD ANALYSIS

The limit load evaluation of castings follows the same approach as was performed for the welds (3). For completeness, the method, governing equations, and some numerical results are repeated herein.

5.1 Limit Load Equations

The ability of the castings to tolerate through-wall dealloying and/or cracking was first evaluated based on a net-section plastic collapse. The limit load analysis methods of ASME Code, Section XI, Appendix H (2) was used to calculate the critical bending stress as a function of through-wall crack length. Figure 5-1 is a schematic illustration of the flaw model.

From Appendix H in ASME Section XI (2), the crack dimensions and applied stress level required to cause the remaining weld cross-section to become fully plastic is given by:

$$P_b' = \frac{2\sigma_f}{\pi}\left[2 \sin \beta - (a/t) \sin \theta\right] \quad \textbf{(5-1a)}$$

$$\beta = \frac{\pi}{2}\left[1 - (a/t)(\theta/\pi) - (P_m/\sigma_f)\right] \quad \textbf{(5-1b)}$$

where β is the angular position of the neutral axis for bending about the net section.

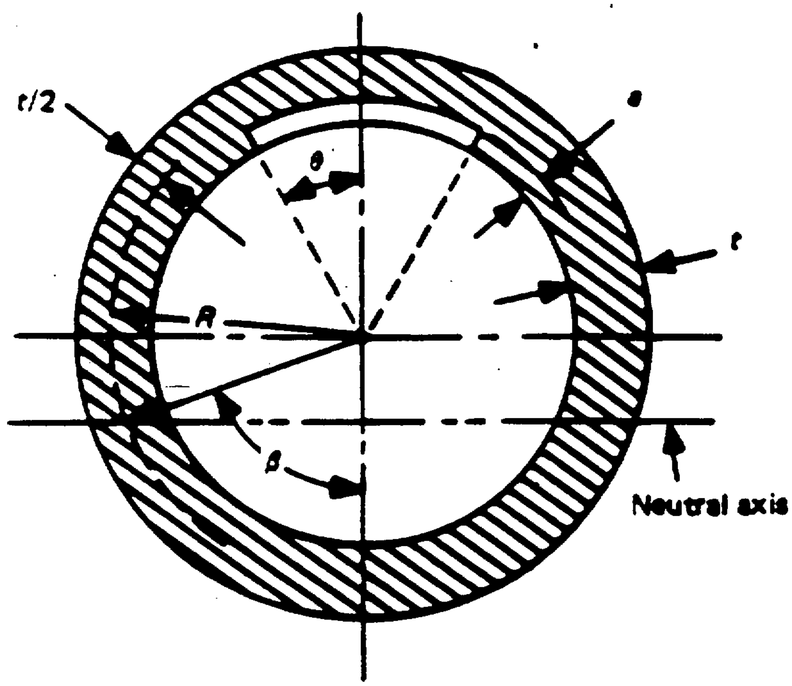

Figure 5-1 - Circumferential Flaw Geometry - Net-Section Collapse Model.

when $(\theta + \beta) \leq \pi$, and

$$P_b' = \frac{2\sigma_f}{\pi}[2 - (a/t)] \sin \beta \tag{5-2a}$$

$$\beta = \frac{\pi}{2 - (a/t)}[1 - (a/t) - (P_m/\sigma_f)] \tag{5-2b}$$

when $(\theta + \beta) > \pi$. In the above equations, P_m is the primary membrane stress as defined in ASME Section III piping design, and P_b' is the critical primary bending stress at incipient plastic collapse. In comparing the ASME Section III derived P_b stress with P_b', P_b is to be redefined as the unconcentrated primary bending stress, that is with the stress intensification factor (SIF) removed from the appropriate code equation.

For a through-wall configuration of the flaw, a/t = 1 in Eqs. 5-1 and 5-2. Therefore, substitution of a/t = 1 yields:

$$P_b' = \frac{2\sigma_f}{\pi}[2 \sin \beta - \sin \theta] \tag{5-3a}$$

$$\beta = \frac{\pi}{2}[1 - (\theta/\pi) - (P_m/\sigma_f)] \tag{5-3b}$$

when $(\theta + \beta) \leq \pi$, and

$$P_b' = \frac{2\sigma_f}{\pi} \sin \beta \tag{5-4a}$$

$$\beta = -\pi \, (P_m/\sigma_f) \tag{5-4b}$$

when $(\theta + \beta) > \pi$. The flow stress, σ_f, for the weld metal is defined in this evaluation as 45 ksi as defined earlier in Section 4.2.

5.2 Applied Membrane Stress

The applied membrane stress, P_m, is calculated from the relationship:

$$P_m = p \, D_o/4t \tag{5-5}$$

where p is the design pressure (120 psig), D_o is the outside diameter, and t is the wall thickness. The use of design pressure will be conservative. The value of P_m was calculated for each pipe size within the scope of this calculation as discussed in Section 3.

5.3 Limit Load Results

The solution of Eqs. 5-3 and 5-4 for P_b' was obtained varying the crack half angle, θ/π. The results for each pipe size are given in Tables 5-1 through 5-8. These results are relevant when through-wall cracks are to be evaluated.

For the case when only dealloying is present (no cracks), the dealloying is conservatively modeled as not having any load carrying capacity. This situation is the same as previously calculated for a through-wall crack. However, a cutoff limit is imposed at the point where the structural strength of a fully dealloyed section is reached. That is,

the minimum strength of a casting without a crack is the case when the casting is fully dealloyed. For the fully dealloyed situation, σ_f = 30 ksi, a/t = 0, and from Eq. 5-1:

$$P_b' = \frac{4\sigma_f}{\pi} \sin\beta \quad (5\text{-}6)$$

$$\beta = \frac{\pi}{2}\left[1 - \frac{P_m}{\sigma_f}\right] \quad (5\text{-}7)$$

From the above equations and the data from Section 3:

NPS (in)	σ_m/σ_f	β	P_b' (ksi)
3	0.016	1.5453	38.18
4	0.019	1.5410	38.18
6	0.024	1.5331	38.17
8	0.027	1.5284	38.16
10	0.029	1.5252	38.16
14	0.056	1.4828	38.05
24	0.096	1.4200	37.76
30	0.120	1.3823	37.52

Based on the above results, the critical bending stress for a fully dealloyed casting without a crack is assumed to be 38 ksi.

Table 5-1

SUMMARY OF LIMIT LOAD RESULTS FOR
3-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 3.5 in
R = Mean radius = 1.642 in
P_R = Mean perimeter = $2\pi R$ = $2\pi(1.642)$ = 10.317 in
P_m = p D_o/4t = 486 psi

t = 0.216 in
R/t = 7.60

Crack Angle (θ/π)	Crack Length (in) L = $(\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0103	0.0031	1.5523	1.5554	57.196
0.005	0.0516	0.0157	1.5460	1.5617	56.828
0.010	0.1032	0.0314	1.5381	1.5695	56.365
0.015	0.1548	0.0471	1.5303	1.5774	55.899
0.020	0.2063	0.0628	1.5224	1.5852	55.430
0.025	0.2579	0.0785	1.5146	1.5931	54.958
0.030	0.3095	0.0942	1.5067	1.6010	54.482
0.040	0.4127	0.1257	1.4910	1.6167	53.523
0.050	0.5158	0.1571	1.4753	1.6324	52.553
0.060	0.6190	0.1885	1.4596	1.6481	51.574
0.070	0.7222	0.2199	1.4439	1.6638	50.586
0.080	0.8254	0.2513	1.4282	1.6795	49.590
0.090	0.9285	0.2827	1.4125	1.6952	48.587
0.100	1.0317	0.3142	1.3967	1.7109	47.577
0.110	1.1349	0.3456	1.3810	1.7266	46.563
0.120	1.2380	0.3770	1.3653	1.7423	45.545
0.130	1.3412	0.4084	1.3496	1.7580	44.523
0.140	1.4444	0.4398	1.3339	1.7737	43.498
0.150	1.5475	0.4712	1.3182	1.7894	42.472
0.200	2.0634	0.6283	1.2397	1.8680	37.344
0.250	2.5792	0.7854	1.1611	1.9465	32.298
0.300	3.0951	0.9425	1.0826	2.0251	27.426
0.350	3.6109	1.0996	1.0040	2.1036	22.812
0.400	4.1268	1.2566	0.9255	2.1821	18.529
0.450	4.6426	1.4137	0.8470	2.2607	14.635
0.500	5.1585	1.5708	0.7684	2.3392	11.173
0.550	5.6743	1.7279	0.6899	2.4178	8.171
0.600	6.1902	1.8850	0.6114	2.4963	5.640
0.700	7.2219	2.1991	0.4543	2.6534	1.965

Table 5-2

SUMMARY OF LIMIT LOAD RESULTS FOR
4-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 4.5 in
R = Mean radius = 2.1315 in
P_R = Mean perimeter = $2\pi R$ = $2\pi(2.1315)$ = 13.393 in
P_m = p D_o/4t = 570 psi

t = 0.237 in
R/t = 8.99

Crack Angle (θ/π)	Crack Length (in) L = (θ/π)P_R	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0134	0.0031	1.5493	1.5525	57.193
0.005	0.0670	0.0157	1.5431	1.5588	56.824
0.010	0.1339	0.0314	1.5352	1.5666	56.360
0.015	0.2009	0.0471	1.5274	1.5745	55.892
0.020	0.2679	0.0628	1.5195	1.5823	55.422
0.025	0.3348	0.0785	1.5116	1.5902	54.948
0.030	0.4018	0.0942	1.5038	1.5980	54.471
0.040	0.5357	0.1257	1.4881	1.6137	53.509
0.050	0.6696	0.1571	1.4724	1.6295	52.537
0.060	0.8036	0.1885	1.4567	1.6452	51.555
0.070	0.9375	0.2199	1.4410	1.6609	50.564
0.080	1.0714	0.2513	1.4252	1.6766	49.566
0.090	1.2053	0.2827	1.4095	1.6923	48.560
0.100	1.3393	0.3142	1.3938	1.7080	47.548
0.110	1.4732	0.3456	1.3781	1.7237	46.531
0.120	1.6071	0.3770	1.3624	1.7394	45.510
0.130	1.7410	0.4084	1.3467	1.7551	44.486
0.140	1.8750	0.4398	1.3310	1.7708	43.459
0.150	2.0089	0.4712	1.3153	1.7865	42.430
0.200	2.6785	0.6283	1.2368	1.8651	37.290
0.250	3.3482	0.7854	1.1582	1.9436	32.231
0.300	4.0178	0.9425	1.0797	2.0222	27.347
0.350	4.6874	1.0996	1.0011	2.1007	22.722
0.400	5.3570	1.2566	0.9226	2.1792	18.429
0.450	6.0267	1.4137	0.8441	2.2578	14.524
0.500	6.6963	1.5708	0.7655	2.3363	11.053
0.550	7.3659	1.7279	0.6870	2.4149	8.042
0.600	8.0356	1.8850	0.6084	2.4934	5.504
0.700	9.3748	2.1991	0.4514	2.6505	1.815

Table 5-3

SUMMARY OF LIMIT LOAD RESULTS FOR 6-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 6.625 in = 0.280 in

R = Mean radius = 3.1725 in

P_R = Mean perimeter = $2\pi R$ = $2\pi(3.1725)$ = 19.933 in

P_m = $p\ D_o/4t$ = 710 psi

t = 0.280 in

R/t = 11.33

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0199	0.0031	1.5444	1.5476	57.186
0.005	0.0997	0.0157	1.5382	1.5539	56.815
0.010	0.1993	0.0314	1.5303	1.5617	56.349
0.015	0.2990	0.0471	1.5225	1.5696	55.879
0.020	0.3987	0.0628	1.5146	1.5774	55.407
0.025	0.4983	0.0785	1.5067	1.5853	54.931
0.030	0.5980	0.0942	1.4989	1.5931	54.452
0.040	0.7973	0.1257	1.4832	1.6089	53.486
0.050	0.9967	0.1571	1.4675	1.6246	52.509
0.060	1.1960	0.1885	1.4518	1.6403	51.522
0.070	1.3953	0.2199	1.4361	1.6560	50.527
0.080	1.5947	0.2513	1.4204	1.6717	49.524
0.090	1.7940	0.2827	1.4046	1.6874	48.514
0.100	1.9933	0.3142	1.3889	1.7031	47.498
0.110	2.1927	0.3456	1.3732	1.7188	46.477
0.120	2.3920	0.3770	1.3575	1.7345	45.452
0.130	2.5913	0.4084	1.3418	1.7502	44.423
0.140	2.7907	0.4398	1.3261	1.7659	43.391
0.150	2.9900	0.4712	1.3104	1.7816	42.358
0.200	3.9867	0.6283	1.2319	1.8602	37.197
0.250	4.9834	0.7854	1.1533	1.9387	32.118
0.300	5.9800	0.9425	1.0748	2.0173	27.214
0.350	6.9767	1.0996	0.9962	2.0958	22.571
0.400	7.9734	1.2566	0.9177	2.1743	18.259
0.450	8.9700	1.4137	0.8392	2.2529	14.338
0.500	9.9667	1.5708	0.7606	2.3314	10.850
0.550	10.9634	1.7279	0.6821	2.4100	7.825
0.600	11.9600	1.8850	0.6035	2.4885	5.273
0.700	13.9534	2.1991	0.4465	2.6456	1.562

Table 5-4

SUMMARY OF LIMIT LOAD RESULTS FOR 8-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 8.625 in
R = Mean radius = 4.1515 in
P_R = Mean perimeter = $2\pi R$ = $2\pi(4.1515)$ = 26.085 in
P_m = $p\ D_o/4t$ = 804 psi

t = 0.322 in
R/t = 12.89

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0261	0.0031	1.5412	1.5443	57.181
0.005	0.1304	0.0157	1.5349	1.5506	56.809
0.010	0.2608	0.0314	1.5270	1.5585	56.341
0.015	0.3913	0.0471	1.5192	1.5663	55.870
0.020	0.5217	0.0628	1.5113	1.5742	55.396
0.025	0.6521	0.0785	1.5035	1.5820	54.918
0.030	0.7825	0.0942	1.4956	1.5899	54.438
0.040	1.0434	0.1257	1.4799	1.6056	53.469
0.050	1.3042	0.1571	1.4642	1.6213	52.489
0.060	1.5651	0.1885	1.4485	1.6370	51.500
0.070	1.8259	0.2199	1.4328	1.6527	50.502
0.080	2.0868	0.2513	1.4171	1.6684	49.496
0.090	2.3476	0.2827	1.4014	1.6841	48.483
0.100	2.6085	0.3142	1.3857	1.6998	47.464
0.110	2.8693	0.3456	1.3700	1.7155	46.440
0.120	3.1302	0.3770	1.3543	1.7312	45.412
0.130	3.3910	0.4084	1.3385	1.7469	44.380
0.140	3.6519	0.4398	1.3228	1.7627	43.346
0.150	3.9127	0.4712	1.3071	1.7784	42.310
0.200	5.2169	0.6283	1.2286	1.8569	37.135
0.250	6.5212	0.7854	1.1500	1.9354	32.042
0.300	7.8254	0.9425	1.0715	2.0140	27.125
0.350	9.1296	1.0996	0.9930	2.0925	22.468
0.400	10.4339	1.2566	0.9144	2.1711	18.145
0.450	11.7381	1.4137	0.8359	2.2496	14.212
0.500	13.0423	1.5708	0.7573	2.3281	10.714
0.550	14.3466	1.7279	0.6788	2.4067	7.679
0.600	15.6508	1.8850	0.6003	2.4852	5.119
0.700	18.2593	2.1991	0.4432	2.6423	1.393

Table 5-5

SUMMARY OF LIMIT LOAD RESULTS FOR
10-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 10.75 in

R = Mean radius = 5.1925 in

P_R = Mean perimeter = $2\pi R$ = $2\pi(5.1925)$ = 32.625 in

P_m = $p D_o/4t$ = 884 psi

t = 0.365 in

R/t = 14.23

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0326	0.0031	1.5384	1.5415	57.176
0.005	0.1631	0.0157	1.5321	1.5478	56.803
0.010	0.3263	0.0314	1.5242	1.5557	56.334
0.015	0.4894	0.0471	1.5164	1.5635	55.862
0.020	0.6525	0.0628	1.5085	1.5714	55.386
0.025	0.8156	0.0785	1.5007	1.5792	54.907
0.030	0.9788	0.0942	1.4928	1.5871	54.426
0.040	1.3050	0.1257	1.4771	1.6028	53.454
0.050	1.6313	0.1571	1.4614	1.6185	52.472
0.060	1.9575	0.1885	1.4457	1.6342	51.480
0.070	2.2838	0.2199	1.4300	1.6499	50.479
0.080	2.6100	0.2513	1.4143	1.6656	49.471
0.090	2.9363	0.2827	1.3986	1.6813	48.456
0.100	3.2625	0.3142	1.3829	1.6970	47.434
0.110	3.5888	0.3456	1.3672	1.7127	46.408
0.120	3.9151	0.3770	1.3515	1.7284	45.377
0.130	4.2413	0.4084	1.3358	1.7442	44.343
0.140	4.5676	0.4398	1.3200	1.7599	43.306
0.150	4.8938	0.4712	1.3043	1.7756	42.268
0.200	6.5251	0.6283	1.2258	1.8541	37.081
0.250	8.1564	0.7854	1.1473	1.9327	31.976
0.300	9.7876	0.9425	1.0687	2.0112	27.048
0.350	11.4189	1.0996	0.9902	2.0897	22.381
0.400	13.0502	1.2566	0.9116	2.1683	18.047
0.450	14.6814	1.4137	0.8331	2.2468	14.105
0.500	16.3127	1.5708	0.7546	2.3254	10.598
0.550	17.9440	1.7279	0.6760	2.4039	7.554
0.600	19.5753	1.8850	0.5975	2.4824	4.986
0.700	22.8378	2.1991	0.4404	2.6395	1.248

Table 5-6

SUMMARY OF LIMIT LOAD RESULTS FOR
14-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 14.00 in
R = Mean radius = 6.875 in
P_R = Mean perimeter = $2\pi R$ = $2\pi(6.875)$ = 43.197 in
P_m = p D_o/4t = 1680 psi

t = 0.250 in
R/t = 27.5

Crack Angle (θ/π)	Crack Length (in) L = $(\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0432	0.0031	1.5106	1.5137	57.102
0.005	0.2160	0.0157	1.5043	1.5200	56.719
0.010	0.4320	0.0314	1.4964	1.5279	56.238
0.015	0.6480	0.0471	1.4886	1.5357	55.753
0.020	0.8639	0.0628	1.4807	1.5436	55.265
0.025	1.0799	0.0785	1.4729	1.5514	54.774
0.030	1.2959	0.0942	1.4650	1.5593	54.280
0.040	1.7279	0.1257	1.4493	1.5750	53.283
0.050	2.1598	0.1571	1.4336	1.5907	52.276
0.060	2.5918	0.1885	1.4179	1.6064	51.259
0.070	3.0238	0.2199	1.4022	1.6221	50.234
0.080	3.4558	0.2513	1.3865	1.6378	49.201
0.090	3.8877	0.2827	1.3708	1.6535	48.161
0.100	4.3197	0.3142	1.3551	1.6692	47.115
0.110	4.7517	0.3456	1.3394	1.6849	46.064
0.120	5.1836	0.3770	1.3237	1.7006	45.009
0.130	5.6156	0.4084	1.3079	1.7164	43.950
0.140	6.0476	0.4398	1.2922	1.7321	42.890
0.150	6.4795	0.4712	1.2765	1.7478	41.827
0.200	8.6394	0.6283	1.1980	1.8263	36.521
0.250	10.7992	0.7854	1.1195	1.9049	31.301
0.300	12.9591	0.9425	1.0409	1.9834	26.262
0.350	15.1189	1.0996	0.9624	2.0619	21.489
0.400	17.2788	1.2566	0.8838	2.1405	17.054
0.450	19.4386	1.4137	0.8053	2.2190	13.017
0.500	21.5984	1.5708	0.7268	2.2976	9.422
0.550	23.7583	1.7279	0.6482	2.3761	6.298
0.600	25.9181	1.8850	0.5697	2.4546	3.657

Table 5-7

SUMMARY OF LIMIT LOAD RESULTS FOR
24-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 24.00 in
R = Mean radius = 11.875 in
P_R = Mean perimeter = $2\pi R$ = $2\pi(11.875)$ = 74.613 in
P_m = $p\ D_o/4t$ = 2880 psi

t = 0.250 in
R/t = 47.5

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0746	0.0031	1.4687	1.4718	56.907
0.005	0.3731	0.0157	1.4624	1.4781	56.510
0.010	0.7461	0.0314	1.4546	1.4860	56.009
0.015	1.1192	0.0471	1.4467	1.4938	55.506
0.020	1.4923	0.0628	1.4388	1.5017	54.999
0.025	1.8653	0.0785	1.4310	1.5095	54.489
0.030	2.2384	0.0942	1.4231	1.5174	53.976
0.040	2.9845	0.1257	1.4074	1.5331	52.942
0.050	3.7306	0.1571	1.3917	1.5488	51.898
0.060	4.4768	0.1885	1.3760	1.5645	50.844
0.070	5.2229	0.2199	1.3603	1.5802	49.782
0.080	5.9690	0.2513	1.3446	1.5959	48.712
0.090	6.7152	0.2827	1.3289	1.6116	47.635
0.100	7.4613	0.3142	1.3132	1.6273	46.552
0.110	8.2074	0.3456	1.2975	1.6431	45.465
0.120	8.9535	0.3770	1.2818	1.6588	44.373
0.130	9.6997	0.4084	1.2661	1.6745	43.279
0.140	10.4458	0.4398	1.2504	1.6902	42.182
0.150	11.1919	0.4712	1.2346	1.7059	41.083
0.200	14.9226	0.6283	1.1561	1.7844	35.601
0.250	18.6532	0.7854	1.0776	1.8630	30.209
0.300	22.3838	0.9425	0.9990	1.9415	25.006
0.350	26.1145	1.0996	0.9205	2.0200	20.076
0.400	29.8451	1.2566	0.8419	2.0986	15.494
0.450	33.5758	1.4137	0.7634	2.1771	11.318
0.500	37.3064	1.5708	0.6849	2.2557	7.596
0.550	41.0371	1.7279	0.6063	2.3342	4.355
0.600	44.7677	1.8850	0.5278	2.4127	1.610

Table 5-8

SUMMARY OF LIMIT LOAD RESULTS FOR
30-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 30.00 in

R = Mean radius = 14.875 in

P_R = Mean perimeter = $2\pi R$ = $2\pi(14.875)$ = 93.462 in

P_m' = p D_o/4t = 3600 psi

t = 0.250 in

R/t = 59.5

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	β	$\theta + \beta$	P_b' (ksi)
0.001	0.0935	0.0031	1.4436	1.4467	56.743
0.005	0.4673	0.0157	1.4373	1.4530	56.336
0.010	0.9346	0.0314	1.4294	1.4608	55.824
0.015	1.4019	0.0471	1.4216	1.4687	55.310
0.020	1.8692	0.0628	1.4137	1.4765	54.792
0.025	2.3366	0.0785	1.4059	1.4844	54.271
0.030	2.8039	0.0942	1.3980	1.4923	53.747
0.040	3.7385	0.1257	1.3823	1.5080	52.690
0.050	4.6731	0.1571	1.3666	1.5237	51.624
0.060	5.6077	0.1885	1.3509	1.5394	50.548
0.070	6.5424	0.2199	1.3352	1.5551	49.463
0.080	7.4770	0.2513	1.3195	1.5708	48.371
0.090	8.4116	0.2827	1.3038	1.5865	47.273
0.100	9.3462	0.3142	1.2881	1.6022	46.168
0.110	10.2809	0.3456	1.2723	1.6179	45.059
0.120	11.2155	0.3770	1.2566	1.6336	43.946
0.130	12.1501	0.4084	1.2409	1.6493	42.829
0.140	13.0847	0.4398	1.2252	1.6650	41.711
0.150	14.0194	0.4712	1.2095	1.6808	40.591
0.200	18.6925	0.6283	1.1310	1.7593	35.004
0.250	23.3656	0.7854	1.0524	1.8378	29.512
0.300	28.0387	0.9425	0.9739	1.9164	24.212
0.350	32.7118	1.0996	0.8954	1.9949	19.190
0.400	37.3850	1.2566	0.8168	2.0735	14.521
0.450	42.0581	1.4137	0.7383	2.1520	10.266
0.500	46.7312	1.5708	0.6597	2.2305	6.469
0.550	51.4043	1.7279	0.5812	2.3091	3.162
0.600	56.0774	1.8850	0.5027	2.3876	0.357

6.0 FRACTURE EVALUATION

The fracture analysis for castings follows the same approach as was performed for the welds (3).

6.1 Fracture Analysis Equations

A linear elastic fracture mechanics analysis was performed for a through-wall circumferential crack in a casting. The same basic flaw model as shown in Figures 1-1 and 5-1 was used in the fracture assessment. The fracture conditions for the casting were evaluated according to: .

$$K_I = K_{Ic} \tag{6-1}$$

where K_I is the applied stress intensity factor and K_{Ic} is the fracture toughness. The stress intensity factor is calculated from:

$$K_I = \left[\sigma_m F_m + \sigma_b F_b\right] (\pi a)^{1/2} \tag{6-2}$$

where,

- a = Half crack length = L/2
- σ_m = Uniform axial stress = $p D_o/4t \equiv P_m$
- σ_b = Global bending stress
- F_m = Free surface correction factor for uniform stress
- F_b = Free surface correction factor for global bending stress

The critical bending stress for fracture, σ_b^c, is calculated from Eqs. 6-1 and 6-2 as:

$$\sigma_b^c = \frac{K_{Ic} - \sigma_m F_m (\pi a)^{1/2}}{F_b (\pi a)^{1/2}}$$

or

$$\sigma_b^c = \frac{K_{Ic}}{F_b (\pi a)^{1/2}} - \sigma_m (F_m/F_b) \qquad (6\text{-}3)$$

where a conservative estimate of K_{Ic} is taken as 65 ksi in$^{1/2}$ from the discussion in Section 4.

6.2 Correction Factors F_m and F_b

The free surface correction factors are functions that depend on crack angle, θ/π, and casting geometry, R/t. For a range of R/t between 10 and 15, a simplified "curve-fit" expression was developed from the work of Folias (6) and Erdogan (7) for short length cracks and Sanders (8, 9) for long cracks as reported in NUREG/CR-4572 (10).

For uniaxial tension case (10):

$$F_m = 1 + A_m (\theta/\pi)^{1.5} + B_m (\theta/\pi)^{2.5} + C_m (\theta/\pi)^{3.5} \qquad (6\text{-}4)$$

where,

$$A_m = -2.02917 + 1.67763\,(R/t) - 0.07987\,(R/t)^2 + 0.00176\,(R/t)^3$$
$$B_m = 7.09987 - 4.42394\,(R/t) + 0.21036\,(R/t)^2 - 0.00463\,(R/t)^3$$
$$C_m = 7.79661 + 5.16676\,(R/t) - 0.24577\,(R/t)^2 + 0.00541\,(R/t)^3$$

For global bending, the corresponding equations are (10):

$$F_b = 1 + A_b(\theta/\pi)^{1.5} + B_b(\theta/\pi)^{2.5} + C_b(\theta/\pi)^{3.5} \qquad (6\text{-}5)$$

where,

$$A_b = -3.26543 + 1.52784\,(R/t) - 0.072698\,(R/t)^2 + 0.0016011\,(R/t)^3$$
$$B_b = 11.36322 - 3.91412\,(R/t) + 0.18619\,(R/t)^2 - 0.004099\,(R/t)^3$$
$$C_b = -3.18609 + 3.84763\,(R/t) - 0.18304\,(R/t)^2 + 0.00403\,(R/t)^3$$

For the case when $R/t > 15$, the Eqs. 6-4 and 6-5 become overly conservative. For this situation, the solutions reported by Zahoor (11) and Sanders (8, 9) are used to determine F_m and F_b. For $10 \leq R/t \leq 20$, the solution given by Zahoor (11) is:

$$F_m = 1 + A\left[5.3303\,(\theta/\pi)^{1.5} + 18.773\,(\theta/\pi)^{4.24}\right] \qquad (6\text{-}6)$$

$$F_b = 1 + A\left[4.5967\,(\theta/\pi)^{1.5} + 2.6422\,(\theta/\pi)^{4.24}\right] \qquad (6\text{-}7)$$

where,

$$A = \left[0.4\,(R/t) - 3.0\right]^{0.25} \qquad (6\text{-}8)$$

The expressions given by Eqs. 6-6 and 6-7 are used to estimate F_m and F_b for short length cracks when R/t > 15. For long cracks, the solutions by Sanders (8, 9) are substituted for Eqs. 6-6 and 6-7. These solutions are reported by Tada (12) after some algebraic manipulations to obtain a consistent definition with Eq. 6-2, as

$$F_m = C\left\{\theta + \frac{1 - \theta \cot\theta}{2\cot\theta + \sqrt{2}\cot[(\pi - \theta)/\sqrt{2}]}\right\} \tag{6-9}$$

$$F_b = C\sin\theta\left\{1 + \frac{\theta - \cot\theta\,(1 - \theta\cot\theta)}{4\cot\theta + 2\sqrt{2}\cot[(\pi - \theta)/\sqrt{2}]}\right\} \tag{6-10}$$

where,

$C = (R\sqrt{2}/\varepsilon\pi a)^{1/2}$
$\varepsilon^2 = (t/R)/[12(1 - \nu^2)]^{1/2}$
ν = Poisson's ratio

The reported accuracy for Eqs. 6-9 and 6-10 is better than 1% for $\theta/(t/R)^{1/2} > 5$ (12).

6.3 Fracture Results

The solution of Eq. 6-3 was obtained for a range of crack angles, θ/π. For NPS in the range of 3-inch to 10-inch, Eqs. 6-4 and 6-5 are used to compute F_m and F_b (R/t < 15). For the larger sizes (14- 24- and 30-inch), Eqs. 6-6 through 6-9 are used as appropriate. The calculated results are given in Tables 6-1 through 6-8.

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Table 6-1
SUMMARY OF FRACTURE RESULTS FOR 3-INCH NOMINAL PIPE SIZE

__Input Parameters:__

D_o = 3.5 in t = 0.216 in
R = 1.642 in R/t = 7.60
P_R = 10.317 in σ_m = 486 psi

__Calculated Parameters:__

A_m = 6.8815 A_b = 4.8513
B_m = -16.4079 B_b = -9.4324
C_m = 35.2476 C_b = 17.2558

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	F_m (Eq. 6-4)	F_b (Eq. 6-5)	σ_b^c (ksi)
0.001	0.0103	0.0031	1.0002	1.0002	510.03
0.005	0.0516	0.0157	1.0024	1.0017	227.47
0.010	0.1032	0.0314	1.0067	1.0048	160.21
0.015	0.1548	0.0471	1.0122	1.0087	130.22
0.020	0.2063	0.0628	1.0186	1.0132	112.20
0.025	0.2579	0.0785	1.0257	1.0183	99.80
0.030	0.3095	0.0942	1.0334	1.0238	90.56
0.040	0.4127	0.1257	1.0503	1.0360	77.43
0.050	0.5158	0.1571	1.0688	1.0494	68.31
0.060	0.6190	0.1885	1.0885	1.0639	61.46
0.070	0.7222	0.2199	1.1094	1.0792	56.05
0.080	0.8254	0.2513	1.1311	1.0952	51.62
0.090	0.9285	0.2827	1.1536	1.1118	47.90
0.100	1.0317	0.3142	1.1769	1.1290	44.72
0.110	1.1349	0.3456	1.2008	1.1468	41.94
0.120	1.2380	0.3770	1.2253	1.1649	39.50
0.130	1.3412	0.4084	1.2505	1.1836	37.32
0.140	1.4444	0.4398	1.2763	1.2027	35.37
0.150	1.5475	0.4712	1.3029	1.2222	33.59
0.200	2.0634	0.6283	1.4481	1.3269	26.68
0.250	2.5792	0.7854	1.6228	1.4465	21.78
0.300	3.0951	0.9425	1.8432	1.5874	18.01
0.350	3.6109	1.0996	2.1299	1.7586	14.93
0.400	4.1268	1.2566	2.5073	1.9713	12.33
0.450	4.6426	1.4137	3.0031	2.2380	10.10
0.500	5.1585	1.5708	3.6479	2.5730	8.19
0.550	5.6743	1.7279	4.4751	2.9919	6.55
0.600	6.1902	1.8850	5.5202	3.5115	5.17
0.700	7.2219	2.1991	8.4188	4.9262	3.09
0.800	8.2536	2.5133	12.6731	6.9741	1.71
0.900	9.2853	2.8274	18.6441	9.8278	0.81

Table 6-2
SUMMARY OF FRACTURE RESULTS FOR 4-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 4.5 in
R = 2.1315 in
P_R = 13.393 in
t = 0.237 in
R/t = 8.99
σ_m = 570 psi

Calculated Parameters:

A_m = 7.8788
B_m = -19.0405
C_m = 38.3209
A_b = 5.7599
B_b = -11.7608
C_b = 19.5445

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	F_m (Eq. 6-4)	F_b (Eq. 6-5)	σ_b^c (ksi)
0.001	0.0134	0.0031	1.0002	1.0002	447.50
0.005	0.0670	0.0157	1.0028	1.0020	199.44
0.010	0.1339	0.0314	1.0077	1.0056	140.35
0.015	0.2009	0.0471	1.0140	1.0103	113.96
0.020	0.2679	0.0628	1.0213	1.0156	98.09
0.025	0.3348	0.0785	1.0294	1.0217	87.16
0.030	0.4018	0.0942	1.0382	1.0282	79.00
0.040	0.5357	0.1257	1.0574	1.0426	67.39
0.050	0.6696	0.1571	1.0785	1.0584	59.30
0.060	0.8036	0.1885	1.1010	1.0753	53.22
0.070	0.9375	0.2199	1.1247	1.0932	48.41
0.080	1.0714	0.2513	1.1494	1.1119	44.47
0.090	1.2053	0.2827	1.1748	1.1312	41.17
0.100	1.3393	0.3142	1.2011	1.1511	38.34
0.110	1.4732	0.3456	1.2279	1.1716	35.88
0.120	1.6071	0.3770	1.2555	1.1925	33.71
0.130	1.7410	0.4084	1.2836	1.2138	31.78
0.140	1.8750	0.4398	1.3124	1.2355	30.05
0.150	2.0089	0.4712	1.3419	1.2577	28.49
0.200	2.6785	0.6283	1.5012	1.3747	22.43
0.250	3.3482	0.7854	1.6892	1.5052	18.19
0.300	4.0178	0.9425	1.9227	1.6557	14.97
0.350	4.6874	1.0996	2.2235	1.8361	12.36
0.400	5.3570	1.2566	2.6176	2.0582	10.16
0.450	6.0267	1.4137	3.1344	2.3359	8.28
0.500	6.6963	1.5708	3.8068	2.6849	6.66
0.550	7.3659	1.7279	4.6705	3.1226	5.27
0.600	8.0356	1.8850	5.7638	3.6675	4.09
0.700	9.3748	2.1991	8.8055	5.1607	2.31
0.800	10.7141	2.5133	13.2871	7.3396	1.13
0.900	12.0533	2.8274	19.5981	10.3973	0.36

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Table 6-3
SUMMARY OF FRACTURE RESULTS FOR 6-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 6.625 in
R = 3.1725 in
P_R = 19.933 in
t = 0.280 in
R/t = 11.33
σ_m = 710 psi

Calculated Parameters:

A_m = 9.2855
B_m = -22.7542
C_m = 42.6558
A_b = 7.0417
B_b = -15.0449
C_b = 22.7727

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	F_m (Eq. 6-4)	F_b (Eq. 6-5)	σ_b^c (ksi)
0.001	0.0199	0.0031	1.000	1.000	366.54
0.005	0.0997	0.0157	1.003	1.002	163.16
0.010	0.1993	0.0314	1.009	1.007	114.66
0.015	0.2990	0.0471	1.016	1.013	92.96
0.020	0.3987	0.0628	1.025	1.019	79.89
0.025	0.4983	0.0785	1.035	1.026	70.86
0.030	0.5980	0.0942	1.045	1.034	64.12
0.040	0.7973	0.1257	1.068	1.052	54.50
0.050	0.9967	0.1571	1.092	1.071	47.78
0.060	1.1960	0.1885	1.119	1.091	42.72
0.070	1.3953	0.2199	1.146	1.113	38.72
0.080	1.5947	0.2513	1.175	1.135	35.44
0.090	1.7940	0.2827	1.205	1.159	32.68
0.100	1.9933	0.3142	1.235	1.182	30.33
0.110	2.1927	0.3456	1.266	1.207	28.28
0.120	2.3920	0.3770	1.298	1.231	26.49
0.130	2.5913	0.4084	1.330	1.256	24.89
0.140	2.7907	0.4398	1.363	1.282	23.46
0.150	2.9900	0.4712	1.397	1.308	22.18
0.200	3.9867	0.6283	1.576	1.442	17.24
0.250	4.9834	0.7854	1.783	1.588	13.83
0.300	5.9800	0.9425	2.035	1.752	11.28
0.350	6.9767	1.0996	2.356	1.945	9.23
0.400	7.9734	1.2566	2.773	2.181	7.52
0.450	8.9700	1.4137	3.320	2.474	6.05
0.500	9.9667	1.5708	4.031	2.843	4.77
0.550	10.9634	1.7279	4.946	3.307	3.68
0.600	11.9600	1.8850	6.107	3.888	2.74
0.700	13.9534	2.1991	9.351	5.491	1.32
0.800	15.9467	2.5133	14.153	7.855	0.37

Table 6-4
SUMMARY OF FRACTURE RESULTS FOR
8-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 8.625 in
R = 4.1515 in
P_R = 26.085 in
t = 0.322 in
R/t = 12.89
σ_m = 804 psi

Calculated Parameters:

A_m = 10.0957
B_m = -24.8928
C_m = 45.1519
A_b = 7.7799
B_b = -16.9361
C_b = 24.6317

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	F_m (Eq. 6-4)	F_b (Eq. 6-5)	σ_b^c (ksi)
0.001	0.0261	0.0031	1.000	1.000	320.23
0.005	0.1304	0.0157	1.004	1.003	142.41
0.010	0.2608	0.0314	1.010	1.008	99.97
0.015	0.3913	0.0471	1.018	1.014	80.97
0.020	0.5217	0.0628	1.027	1.021	69.51
0.025	0.6521	0.0785	1.038	1.029	61.59
0.030	0.7825	0.0942	1.049	1.038	55.67
0.040	1.0434	0.1257	1.073	1.057	47.21
0.050	1.3042	0.1571	1.100	1.078	41.30
0.060	1.5651	0.1885	1.129	1.101	36.84
0.070	1.8259	0.2199	1.159	1.124	33.31
0.080	2.0868	0.2513	1.190	1.149	30.42
0.090	2.3476	0.2827	1.222	1.174	27.99
0.100	2.6085	0.3142	1.255	1.200	25.91
0.110	2.8693	0.3456	1.288	1.227	24.11
0.120	3.1302	0.3770	1.323	1.254	22.54
0.130	3.3910	0.4084	1.357	1.281	21.14
0.140	3.6519	0.4398	1.393	1.309	19.88
0.150	3.9127	0.4712	1.429	1.337	18.76
0.200	5.2169	0.6283	1.619	1.481	14.45
0.250	6.5212	0.7854	1.837	1.636	11.51
0.300	7.8254	0.9425	2.100	1.808	9.32
0.350	9.1296	1.0996	2.432	2.008	7.57
0.400	10.4339	1.2566	2.863	2.251	6.11
0.450	11.7381	1.4137	3.426	2.554	4.85
0.500	13.0423	1.5708	4.160	2.934	3.76
0.550	14.3466	1.7279	5.105	3.413	2.81
0.600	15.6508	1.8850	6.305	4.014	2.00
0.700	18.2593	2.1991	9.665	5.682	0.77

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Table 6-5
SUMMARY OF FRACTURE RESULTS FOR 10-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 10.75 in
R = 5.1925 in
P_R = 32.625 in

t = 0.365 in
R/t = 14.23
σ_m = 884 psi

Calculated Parameters:

A_m = 10.7399
B_m = -26.5926
C_m = 47.1359

A_b = 8.3667
B_b = -18.4393
C_b = 26.1094

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	F_m (Eq. 6-4)	F_b (Eq. 6-5)	σ_b^c (ksi)
0.001	0.0326	0.0031	1.000	1.000	286.17
0.005	0.1631	0.0157	1.004	1.003	127.15
0.010	0.3263	0.0314	1.010	1.008	89.18
0.015	0.4894	0.0471	1.019	1.015	72.16
0.020	0.6525	0.0628	1.029	1.023	61.89
0.025	0.8156	0.0785	1.040	1.031	54.79
0.030	0.9788	0.0942	1.052	1.041	49.48
0.040	1.3050	0.1257	1.078	1.061	41.88
0.050	1.6313	0.1571	1.107	1.084	36.56
0.060	1.9575	0.1885	1.137	1.108	32.55
0.070	2.2838	0.2199	1.169	1.133	29.37
0.080	2.6100	0.2513	1.202	1.160	26.77
0.090	2.9363	0.2827	1.236	1.187	24.58
0.100	3.2625	0.3142	1.270	1.215	22.72
0.110	3.5888	0.3456	1.306	1.243	21.10
0.120	3.9151	0.3770	1.342	1.271	19.68
0.130	4.2413	0.4084	1.379	1.300	18.43
0.140	4.5676	0.4398	1.416	1.330	17.31
0.150	4.8938	0.4712	1.454	1.360	16.30
0.200	6.5251	0.6283	1.654	1.512	12.46
0.250	8.1564	0.7854	1.880	1.674	9.86
0.300	9.7876	0.9425	2.151	1.852	7.93
0.350	11.4189	1.0996	2.492	2.058	6.39
0.400	13.0502	1.2566	2.934	2.308	5.10
0.450	14.6814	1.4137	3.511	2.617	3.99
0.500	16.3127	1.5708	4.262	3.006	3.02
0.550	17.9440	1.7279	5.231	3.498	2.18
0.600	19.5753	1.8850	6.462	4.115	1.46
0.700	22.8378	2.1991	9.915	5.833	0.36

Table 6-6
SUMMARY OF FRACTURE RESULTS FOR
14-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 14.00 in
R = 6.875 in
P_R = 43.197 in
σ_m = 1680 psi
t = 0.250 in
R/t = 27.5
ν = 0.3

Calculated Parameters:

A = 1.6818 (Eq. 6-8)
ϵ = 0.1049 (Eq. 6-9)

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	cot θ	F_m* (Eq. 6-6 or 6-9)	F_b* (Eq. 6-7 or 6-10)	σ_b^c (ksi)
0.001	0.0432	0.0031	318.3088	1.0003	1.0002	247.79
0.005	0.2160	0.0157	63.6567	1.0032	1.0027	109.61
0.010	0.4320	0.0314	31.8205	1.0090	1.0077	76.62
0.015	0.6480	0.0471	21.2049	1.0165	1.0142	61.84
0.020	0.8639	0.0628	15.8945	1.0254	1.0219	52.92
0.025	1.0799	0.0785	12.7062	1.0354	1.0306	46.74
0.030	1.2959	0.0942	10.5789	1.0466	1.0402	42.11
0.040	1.7279	0.1257	7.9158	1.0718	1.0619	35.46
0.050	2.1598	0.1571	6.3138	1.1003	1.0864	30.78
0.060	2.5918	0.1885	5.2422	1.1320	1.1136	27.22
0.070	3.0238	0.2199	4.4737	1.1664	1.1432	24.37
0.080	3.4558	0.2513	3.8947	1.2035	1.1750	22.02
0.090	3.8877	0.2827	3.4420	1.2432	1.2089	20.03
0.100	4.3197	0.3142	3.0777	1.2853	1.2447	18.31
0.110	4.7517	0.3456	2.7776	1.3298	1.2824	16.81
0.120	5.1836	0.3770	2.5257	1.3766	1.3219	15.48
0.130	5.6156	0.4084	2.3109	1.4257	1.3631	14.30
0.140	6.0476	0.4398	2.1251	1.4772	1.4060	13.23
0.150	6.4795	0.4712	1.9626	1.5309	1.4505	12.27
0.200	8.6394	0.6283	1.3764	1.7859	1.6744	8.75
0.250	10.7992	0.7854	1.0000	2.1048	1.9058	6.43
0.300	12.9591	0.9425	0.7265	2.4670	2.1437	4.79
0.350	15.1189	1.0996	0.5095	2.8965	2.4026	3.53
0.400	17.2788	1.2566	0.3249	3.4235	2.6996	2.49
0.450	19.4386	1.4137	0.1584	4.0894	3.0566	1.60
0.500	21.5984	1.5708	0.0000	4.9548	3.5052	0.81
0.550	23.7583	1.7279	-0.1584	6.1137	4.0933	0.09

*For F_m and F_b, Eqs. 6-6 and 6-7 are used up to θ/π = 0.15; Eqs. 6-9 and 6-10 are used when θ/π > 0.15.

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Table 6-7
SUMMARY OF FRACTURE RESULTS FOR
24-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 24.00 in
R = 11.875 in
P_R = 74.613 in
σ_m = 2880 psi

t = 0.250 in
R/t = 47.5
ν = 0.3

Calculated Parameters:

A = 2.0000 (Eq. 6-8)
ϵ = 0.07982 (Eq. 6-9)

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	cot θ	F_m* (Eq. 6-6 or 6-9)	F_b* (Eq. 6-7 or 6-10)	σ_b^c (ksi)
0.001	0.0746	0.0031	318.3088	1.0003	1.0003	186.93
0.005	0.3731	0.0157	63.6567	1.0038	1.0033	81.75
0.010	0.7461	0.0314	31.8205	1.0107	1.0092	56.61
0.015	1.1192	0.0471	21.2049	1.0196	1.0169	45.32
0.020	1.4923	0.0628	15.8945	1.0302	1.0260	38.49
0.025	1.8653	0.0785	12.7062	1.0421	1.0363	33.75
0.030	2.2384	0.0942	10.5789	1.0554	1.0478	30.18
0.040	2.9845	0.1257	7.9158	1.0853	1.0736	25.05
0.050	3.7306	0.1571	6.3138	1.1193	1.1028	21.42
0.060	4.4768	0.1885	5.2422	1.1569	1.1351	18.66
0.070	5.2229	0.2199	4.4737	1.1979	1.1703	16.44
0.080	5.9690	0.2513	3.8947	1.2421	1.2081	14.61
0.090	6.7152	0.2827	3.4420	1.2892	1.2484	13.06
0.100	7.4613	0.3142	3.0777	1.3393	1.2910	11.72
0.110	8.2074	0.3456	2.7776	1.3922	1.3359	10.55
0.120	8.9535	0.3770	2.5257	1.4478	1.3828	9.52
0.130	9.6997	0.4084	2.3109	1.5688	1.5261	7.95
0.140	10.4458	0.4398	2.1251	1.6373	1.5859	7.15
0.150	11.1919	0.4712	1.9626	1.7054	1.6440	6.44
0.200	14.9226	0.6283	1.3764	2.0473	1.9195	3.92
0.250	18.6532	0.7854	1.0000	2.4130	2.1848	2.32
0.300	22.3838	0.9425	0.7265	2.8282	2.4575	1.15
0.350	26.1145	1.0996	0.5095	3.3206	2.7544	0.21

*For F_m and F_b, Eqs. 6-6 and 6-7 are used up to θ/π = 0.12; Eqs. 6-9 and 6-10 are used when θ/π > 0.12.

Table 6-8
SUMMARY OF FRACTURE RESULTS FOR
30-INCH NOMINAL PIPE SIZE

Input Parameters:

D_o = 30.00 in
R = 14.875 in
P_R = 93.462 in
σ_m = 3600 psi

t = 0.250 in
R/t = 59.5
ν = 0.3

Calculated Parameters:

A = 2.1356 (Eq. 6-8)
ϵ = 0.07132 (Eq. 6-9)

Crack Angle (θ/π)	Crack Length (in) $L = (\theta/\pi)P_R$	θ	cot θ	F_m* (Eq. 6-6 or 6-9)	F_b* (Eq. 6-7 or 6-10)	σ_b^c (ksi)
0.001	0.0935	0.0031	318.3088	1.0004	1.0003	165.99
0.005	0.4673	0.0157	63.6567	1.0040	1.0035	72.00
0.010	0.9346	0.0314	31.8205	1.0114	1.0098	49.52
0.015	1.4019	0.0471	21.2049	1.0209	1.0180	39.42
0.020	1.8692	0.0628	15.8945	1.0322	1.0278	33.29
0.025	2.3366	0.0785	12.7062	1.0450	1.0388	29.04
0.030	2.8039	0.0942	10.5789	1.0592	1.0510	25.84
0.040	3.7385	0.1257	7.9158	1.0911	1.0785	21.23
0.050	4.6731	0.1571	6.3138	1.1274	1.1098	17.96
0.060	5.6077	0.1885	5.2422	1.1676	1.1443	15.47
0.070	6.5424	0.2199	4.4737	1.2113	1.1819	13.47
0.080	7.4770	0.2513	3.8947	1.2745	1.2612	11.40
0.090	8.4116	0.2827	3.4420	1.3564	1.3385	9.71
0.100	9.3462	0.3142	3.0777	1.4351	1.4118	8.36
0.110	10.2809	0.3456	2.7776	1.5116	1.4820	7.24
0.120	11.2155	0.3770	2.5257	1.5863	1.5494	6.31
0.130	12.1501	0.4084	2.3109	1.6597	1.6145	5.51
0.140	13.0847	0.4398	2.1251	1.7322	1.6777	4.83
0.150	14.0194	0.4712	1.9626	1.8042	1.7393	4.23
0.200	18.6925	0.6283	1.3764	2.1659	2.0307	2.07
0.250	23.3656	0.7854	1.0000	2.5528	2.3114	0.67

*For F_m and F_b, Eqs. 6-6 and 6-7 are used up to θ/π = 0.07; Eqs. 6-9 and 6-10 are used when θ/π > 0.07.

7.0 CALCULATED CRITICAL BENDING RESULTS

7.1 Castings With No Cracks

When castings are dealloyed but are not cracked, the calculated critical bending stress (σ_c) was determined from the limit load results in Section 5. These results are shown in Figure 7-1. A lower limit of σ_c = 38 ksi is shown, which corresponds to the limiting case of 100% dealloying. One curve is shown for all casting sizes. This curve is based on the 30-inch NPS results and bounds all sizes < 30-inch NPS.

7.2 Castings With Cracks

The calculated critical bending results for both limit load and fracture failure modes are plotted together on common graphs. For example, Figure 7-2 is a plot of the critical bending stress (σ_c) for the 3-inch NPS pipe weld where the failure curves for limit load and fracture were obtained from the results given in Tables 5-1 and 6-1, respectively. The minimum critical bending stress is calculated from the lesser of the limit load failure model or the fracture model, and is a function of crack angle. Similar plots are provided for the other pipe sizes in Figures 7-3 through 7-9. For all casting sizes, the minimum calculated critical stress depends on the failure mode and crack angle as illustrated.

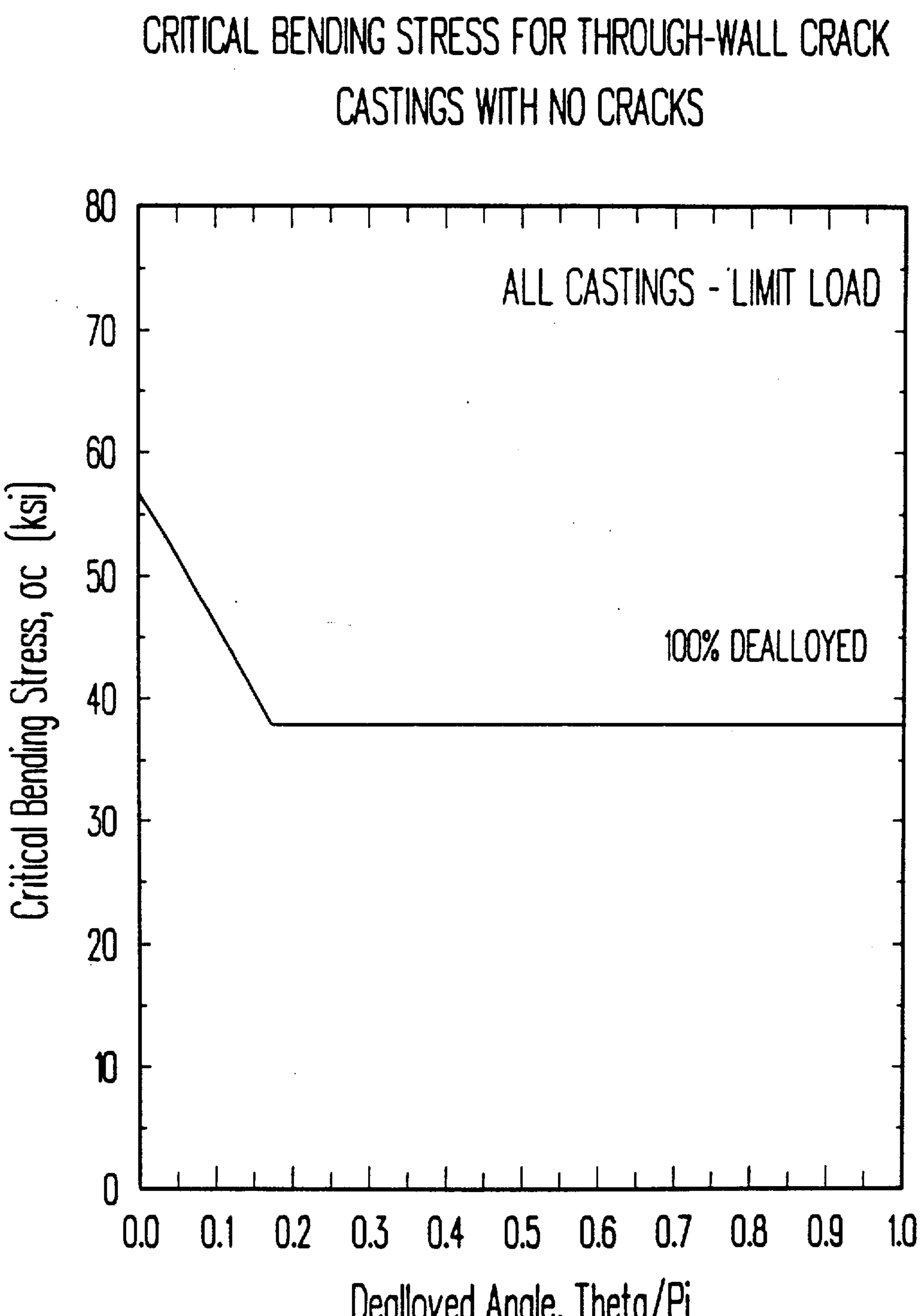

Figure 7-1 - Critical Bending Stress for Castings ≤ 30-Inch Nominal Pipe Size (No Cracks).

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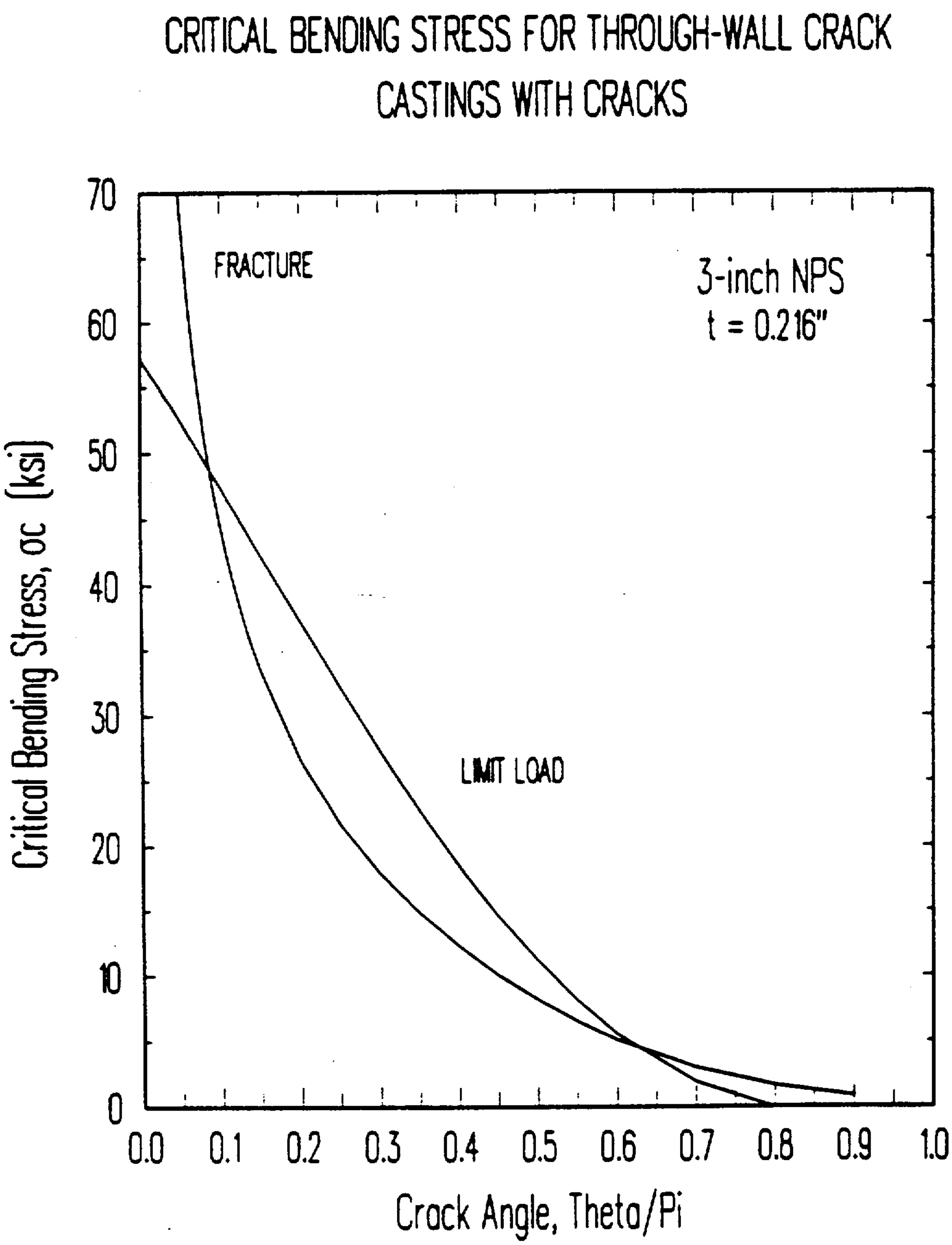

Figure 7-2 - Critical Bending Stress for 3-Inch Nominal Pipe Size Castings With Cracks.

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Title: Calculation of Critical Bending Stress for Dealloyed Aluminum-Bronze Castings in the ECW System	Checked by: JLG	Date: 13 DEC 93	Project No.: AES 93061964-1Q
	Revision No.: 0		Sheet No.: 37 of 44

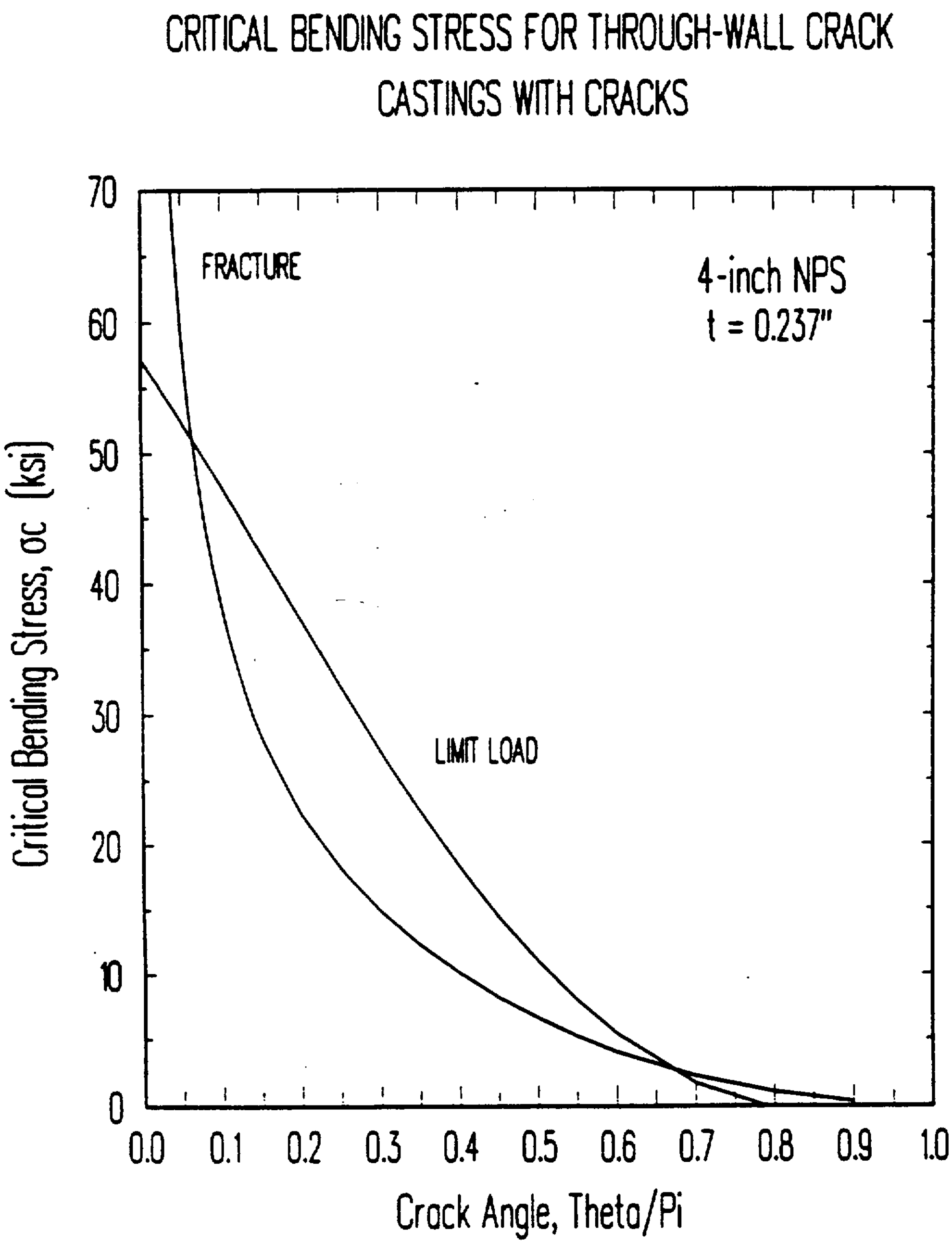

Figure 7-3 - Critical Bending Stress for 4-Inch Nominal Pipe Size Castings With Cracks.

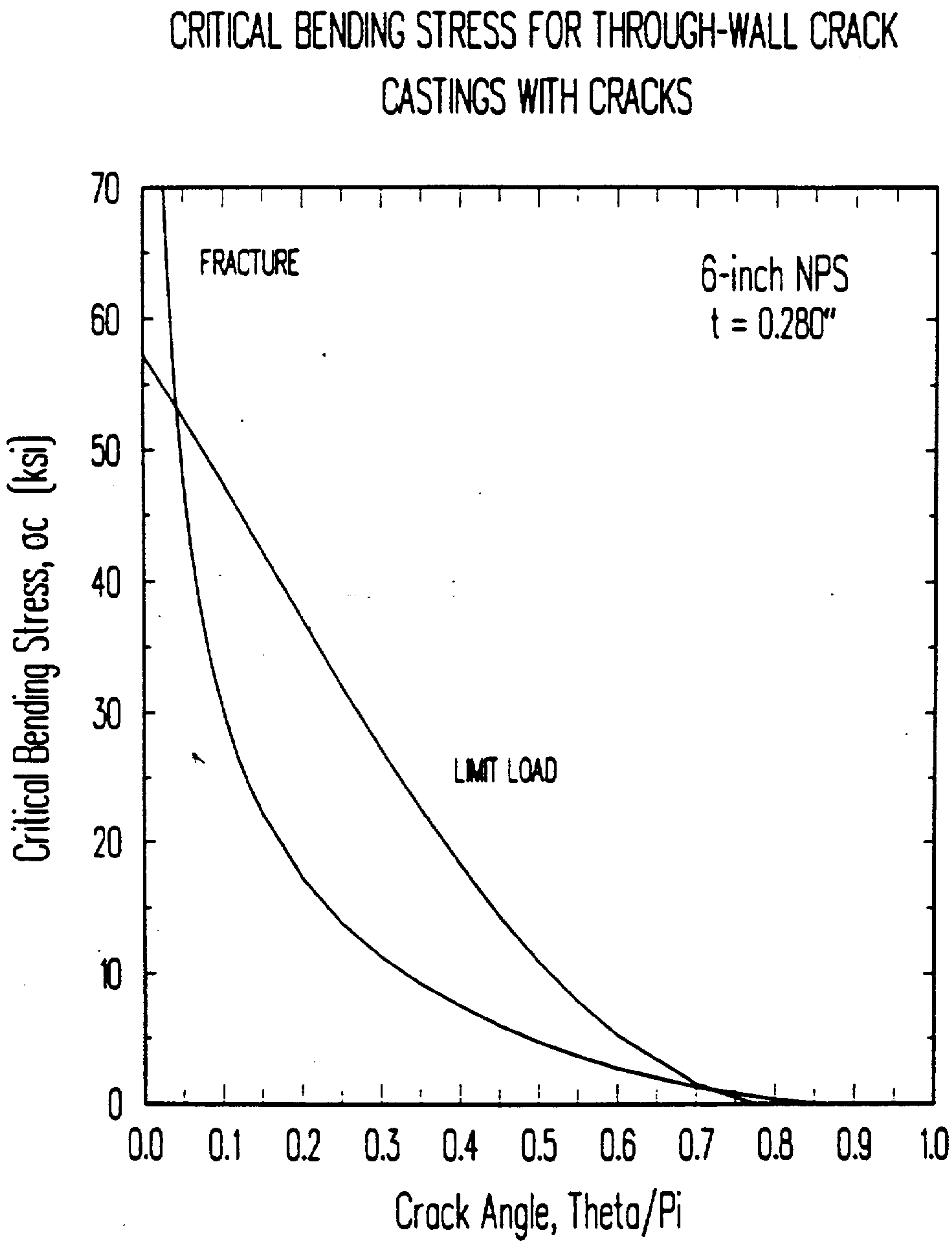

Figure 7-4 - Critical Bending Stress for 6-Inch Nominal Pipe Size Castings With Cracks.

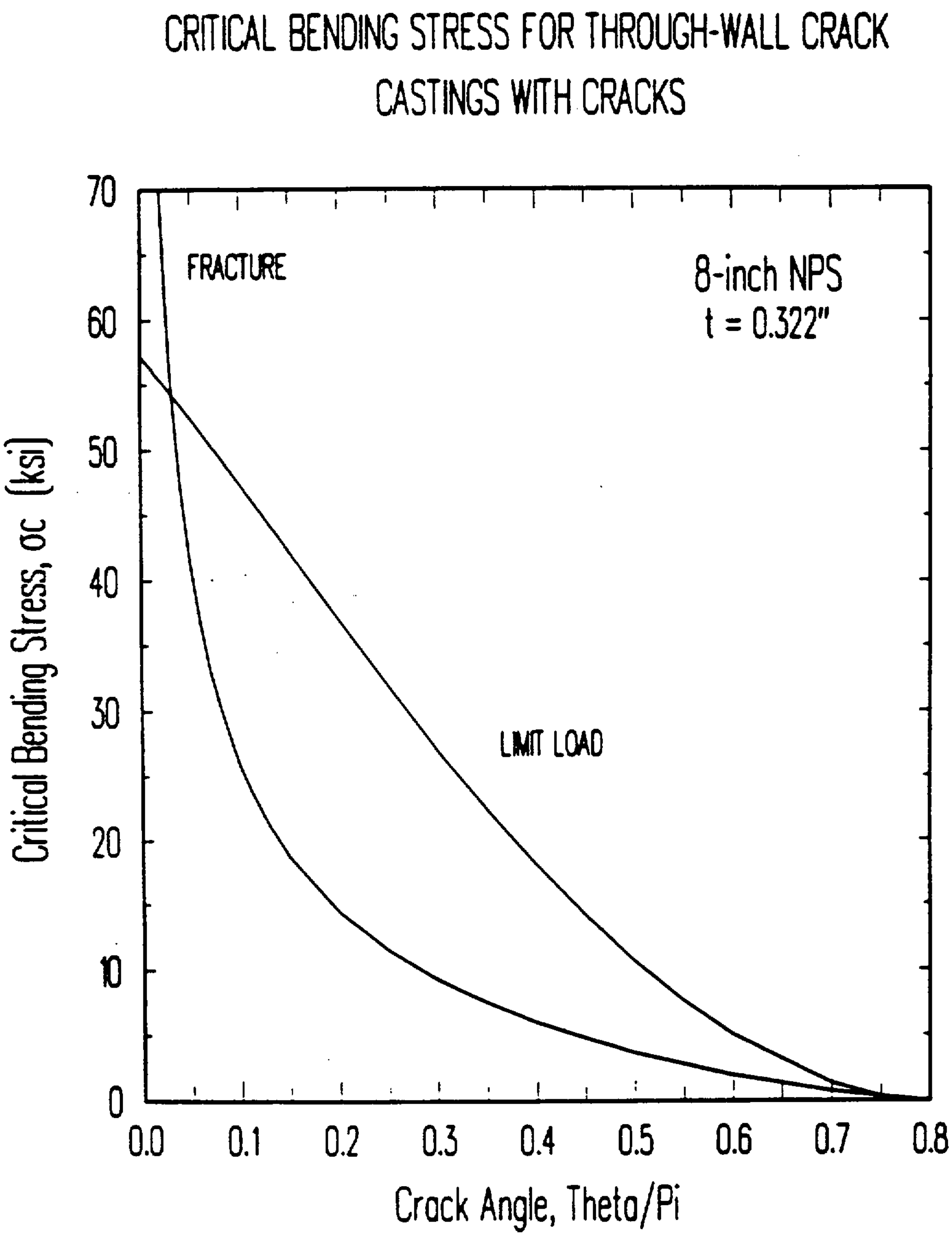

Figure 7-5 - Critical Bending Stress for 8-Inch Nominal Pipe Size Castings With Cracks.

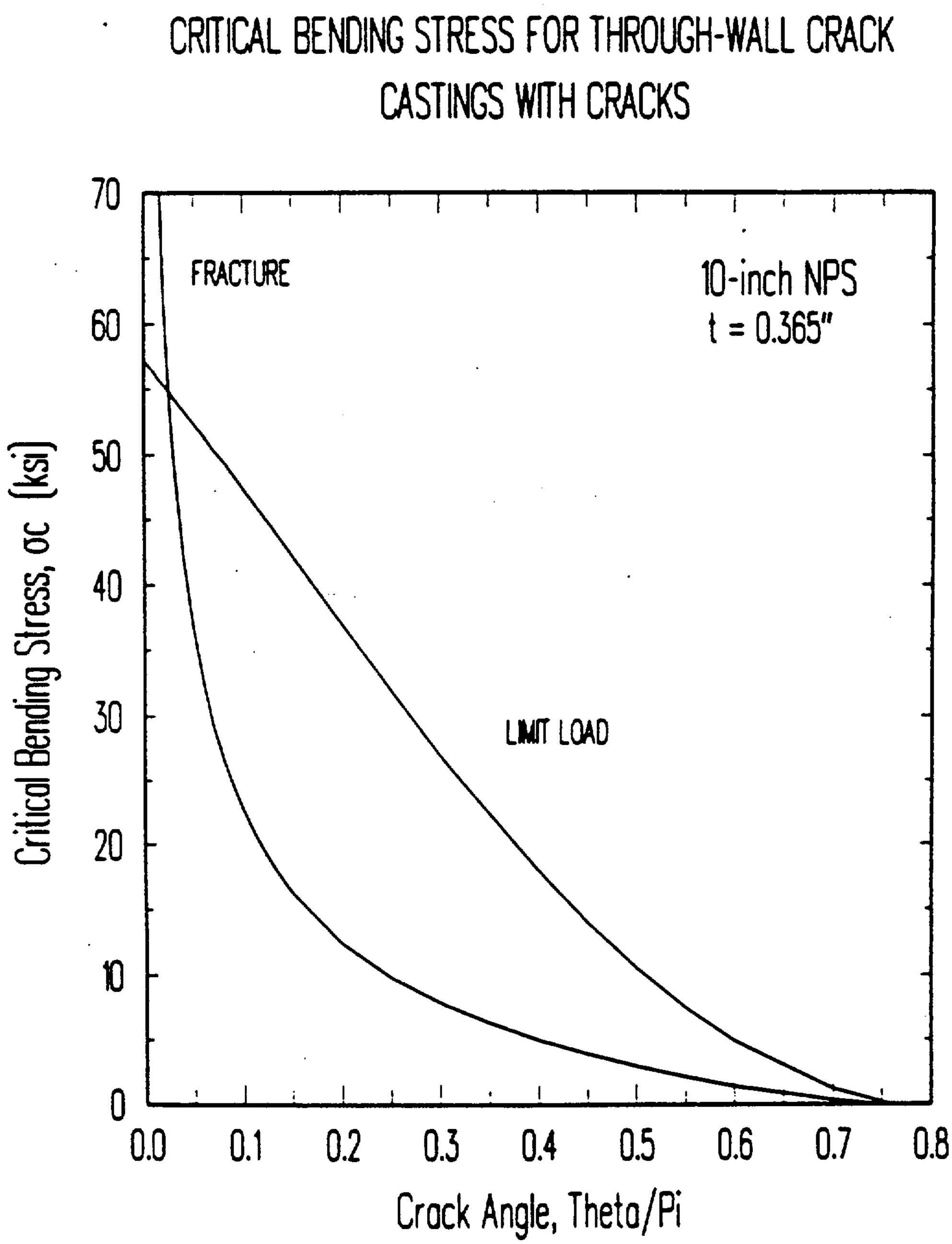

Figure 7-6 - Critical Bending Stress for 10-Inch Nominal Pipe Size Castings With Cracks.

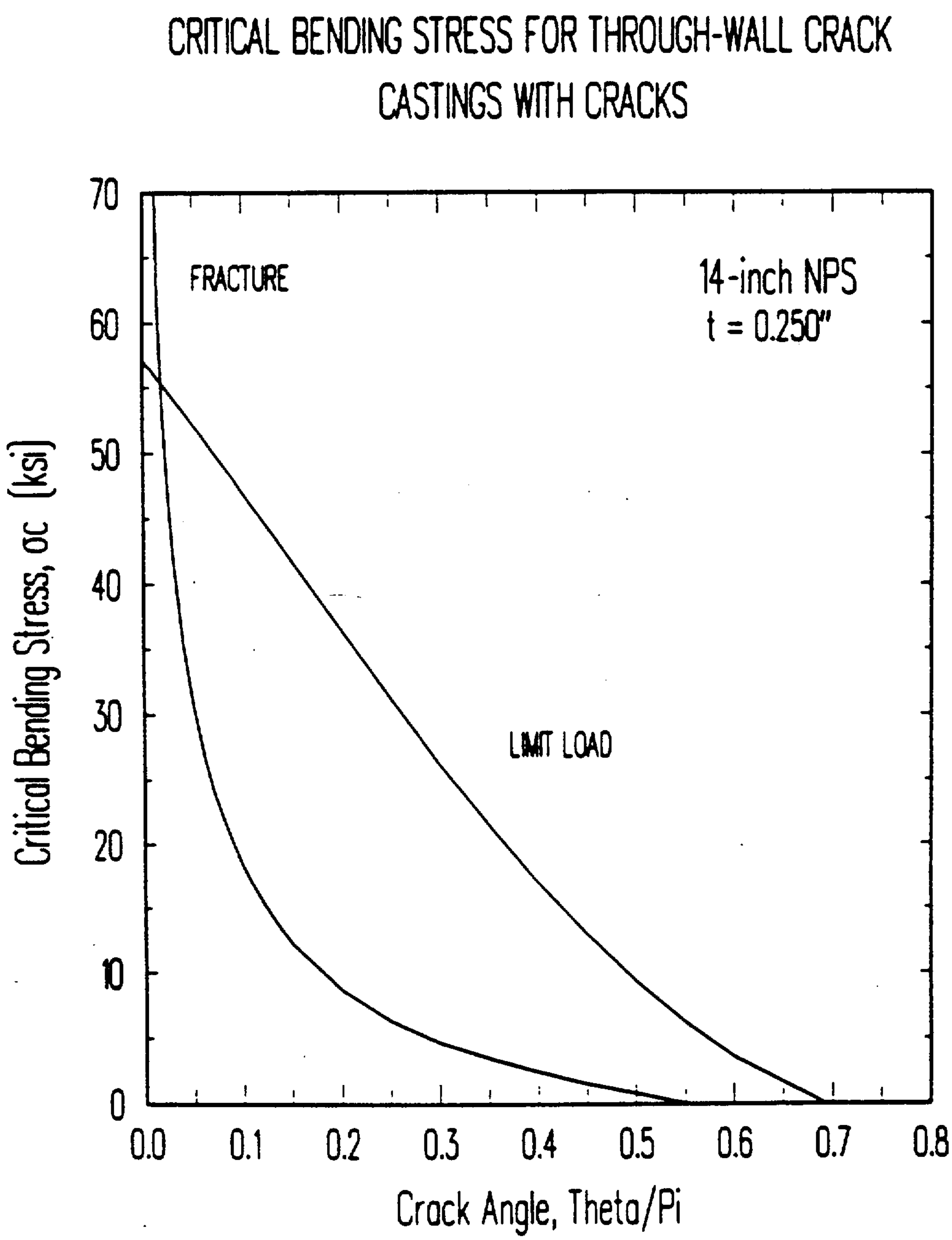

Figure 7-7 - Critical Bending Stress for 14-Inch Nominal Pipe Size Castings With Cracks.

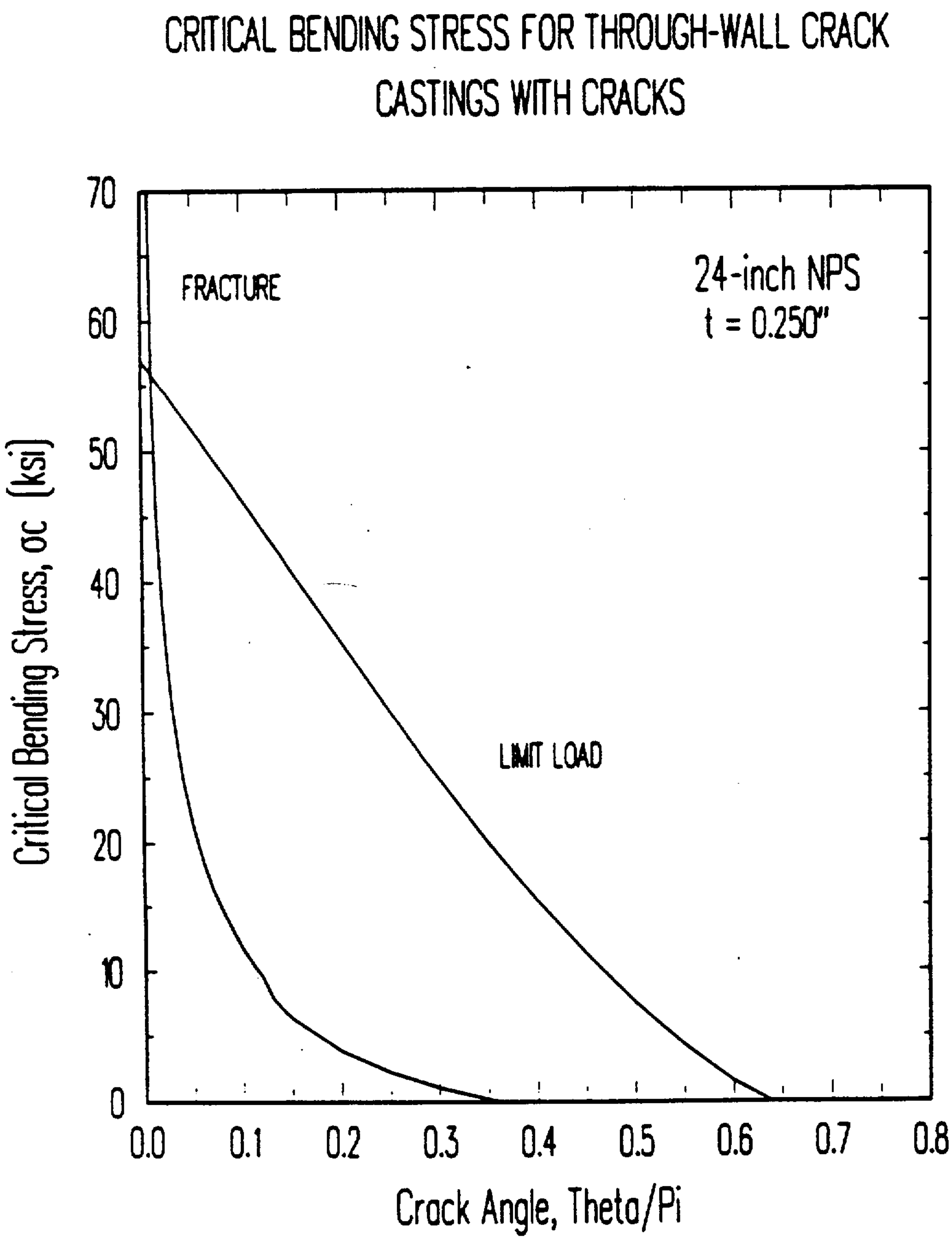

Figure 7-8 - Critical Bending Stress for 24-Inch Nominal Pipe Size Castings With Cracks.

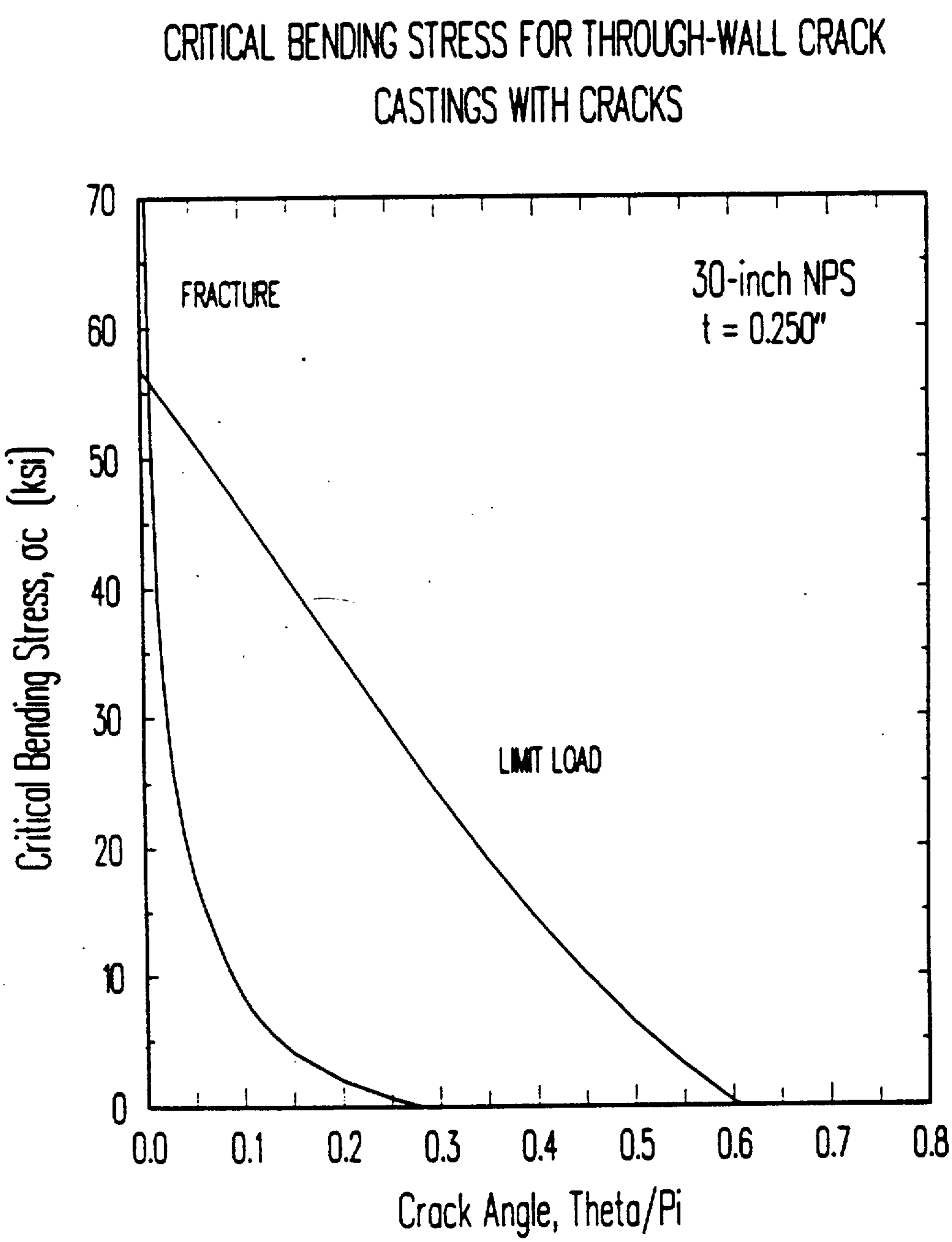

Figure 7-9 - Critical Bending Stress for 30-Inch Nominal Pipe Size Castings With Cracks.

8.0 REFERENCES

1. "Failure Analysis and Structural Integrity Evaluation of Leaking Small Bore Aluminum-Bronze Cast Valve Bodies and Fittings in the ECW System," Bechtel Report 8804-06FA, Revision 3 (August 1988).

2. ASME Boiler and Pressure Vessel Code, Section XI, "Inservice Inspection of Nuclear Power Plant Components," Appendix H (1989 Edition).

3. "Calculation of Critical Bending Stress for Flawed Pipe Welds in the ECW System", Document No. AES-C-1630-2, APTECH Project 92021630-1Q (June 19, 1992) (ICD I-3).

4. "Evaluation of Large Bore Aluminum-Bronze Cast Materials in the Essential Cooling Water System", South Texas Project, Bechtel Report (October 1988) (ECD E-1).

5. ASME Boiler and Pressure Vessel Code, Section II, "Material Specifications, Part B--Nonferrous Materials," (1983 Edition).

6. Folias, F. S., "An Axial Crack in a Pressurized Cylindrical Shell," International Journal of Fracture Mechanics, Vol. 1 (1965), Pp. 104-113.

7. Erdogan, F. and J. J. Kibler, "Cylindrical and Spherical Shells with Cracks," International Journal of Fracture Mechanics, Vol. 5 (1969), Pp. 229-237.

8. Sanders, J. L. Jr., "Circumferential Through-Cracks in Cylindrical Shells Under Tension," Journal of Applied Mechanics, Vol. 49 (March 1982), Pp. 103-107.

9. Sanders, J. L. Jr., "Circumferential Through-Crack in a Cylindrical Shell Under Combined Bending and Tension," Journal of Applied Mechanics, Vol. 50 (March 1983) P. 221.

10. Klecker, R., F. Brust, and G. Wilkowski, "NRC Leak-Before-Break Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads," Topical Report, NUREG/CR-4572 (May 1986).

11. Zahoor, A., "Ductile Fracture Handbook," Volume 1, EPRI NP-6301-D, Electric Power Research Institute (June 1989).

12. Tada, H., P. Paris, and G. Irwin, "The Stress Analysis of Cracks Handbook," Del Research Corporation (1985), Pp. 33.3 and 33.4.

NOTE: ICD and ECD references refer to internally and externally controlled documents in the project Quality Assurance files.