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Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Greater than Four Inches Thick

Martin W. Schwartz

Prepared for
U.S. Nuclear Regulatory Commission

Lawrence
Livermore
National
Laboratory

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PREFACE

This report summarizes the results of research conducted to provide recommendations for fracture toughness acceptance criteria for spent fuel shipping containers made from thick wall ferritic steels. The work was done by Lawrence Livermore National Laboratory and was funded by the Mechanical/Structural Engineering Branch within the Division of Engineering Technology of the U.S. Nuclear Regulatory Commission.

The author wishes to thank Richard Haelsig of the Nuclear Packaging Corporation in Tacoma, Washington for his valuable assistance in developing the cost analysis associated with the various criteria studied in this report.

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ABSTRACT

Various criteria for protecting against brittle fracture in spent-fuel shipping containers made from ferritic steel forgings greater than four inches thick are evaluated. A fracture initiation criterion based upon yield stress levels and allowable flaw sizes specified in Section XI of the ASME Code is recommended. This recommendation is based upon a value impact evaluation taking into account its effect upon industry and the risk of brittle fracture.

EXECUTIVE SUMMARY

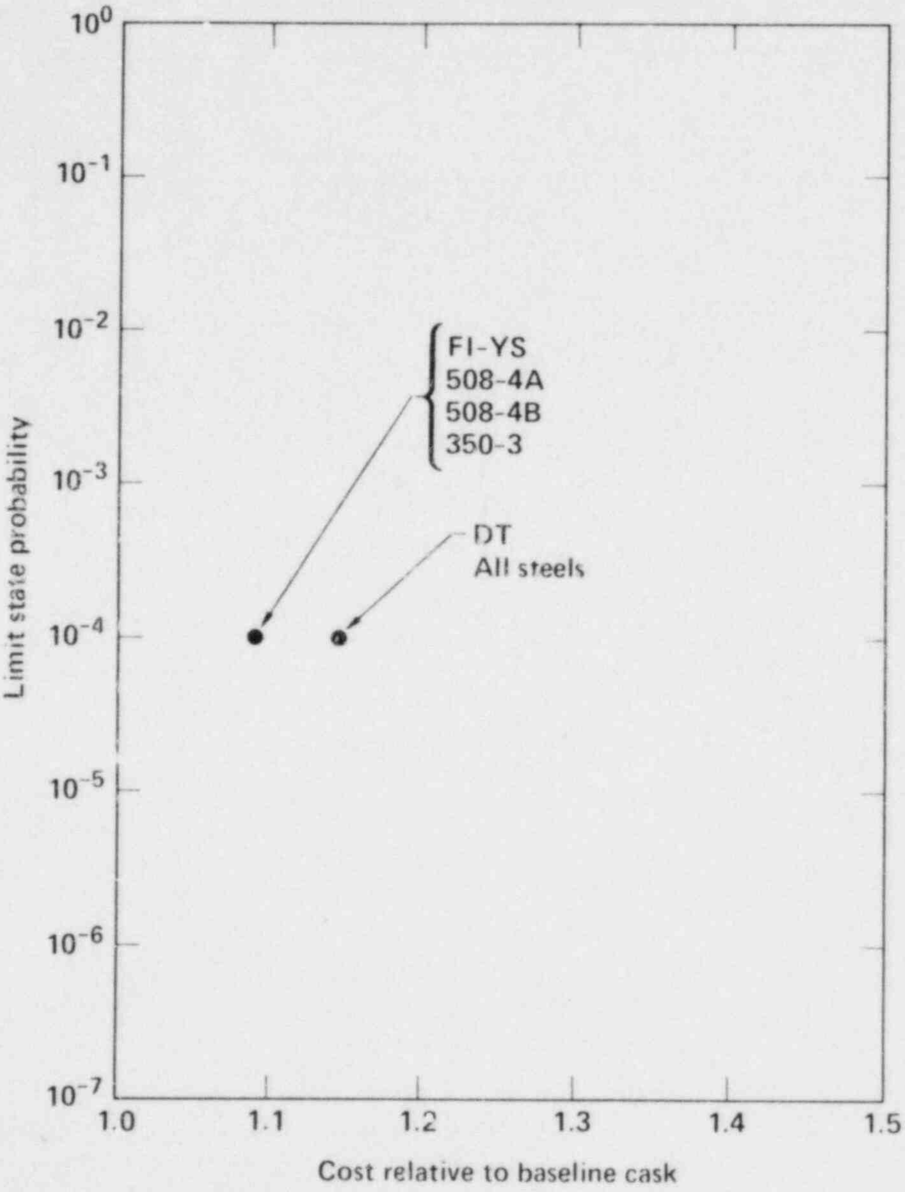
The Lawrence Livermore National Laboratory (LLNL) under contract to the U.S. Nuclear Regulatory Commission (NRC) conducted a study to develop recommendations for criteria that will prevent brittle fracture of shipping containers made of thick wall ferritic steel forgings under hypothetical accident conditions resulting in high levels of dynamic loading. These recommendations are based upon an assessment of their impact upon industry in the area of costs and safety considerations as manifested by the limit state probabilities associated with various criteria. The criteria examined were those developed during FY82 and are summarized as follows.

1. A fracture arrest criterion based upon an exponential extrapolation of the Pellini fracture toughness reference curve where it is applicable to a range of stress from 0.2 of the yield strength to the yield strength. The latter will, hereafter be referred to as the FA-EX-YS criterion; the former as the FA-EX-PS.
2. A fracture arrest criterion based upon an asymptotic extrapolation of the Pellini fracture toughness reference curve which is also applicable to a range of stress from 0.2 of the yield strength to the yield strength. The latter will, hereafter be referred to as the FA-AX-YS criterion; the former as the FA-AX-PS.
3. A fracture initiation criterion based upon the allowable flaw sizes specified in Table IWB-3510-1 of Section XI of the ASME Boiler and Pressure Vessel Code. At yield strength level this criterion will be referred to as FI-YS and at stress less than yield as FY-PS.
4. A drop test acceptance criterion based upon the introduction of flaws at critical locations in drop-test specimen. This criterion is referred to as DT.

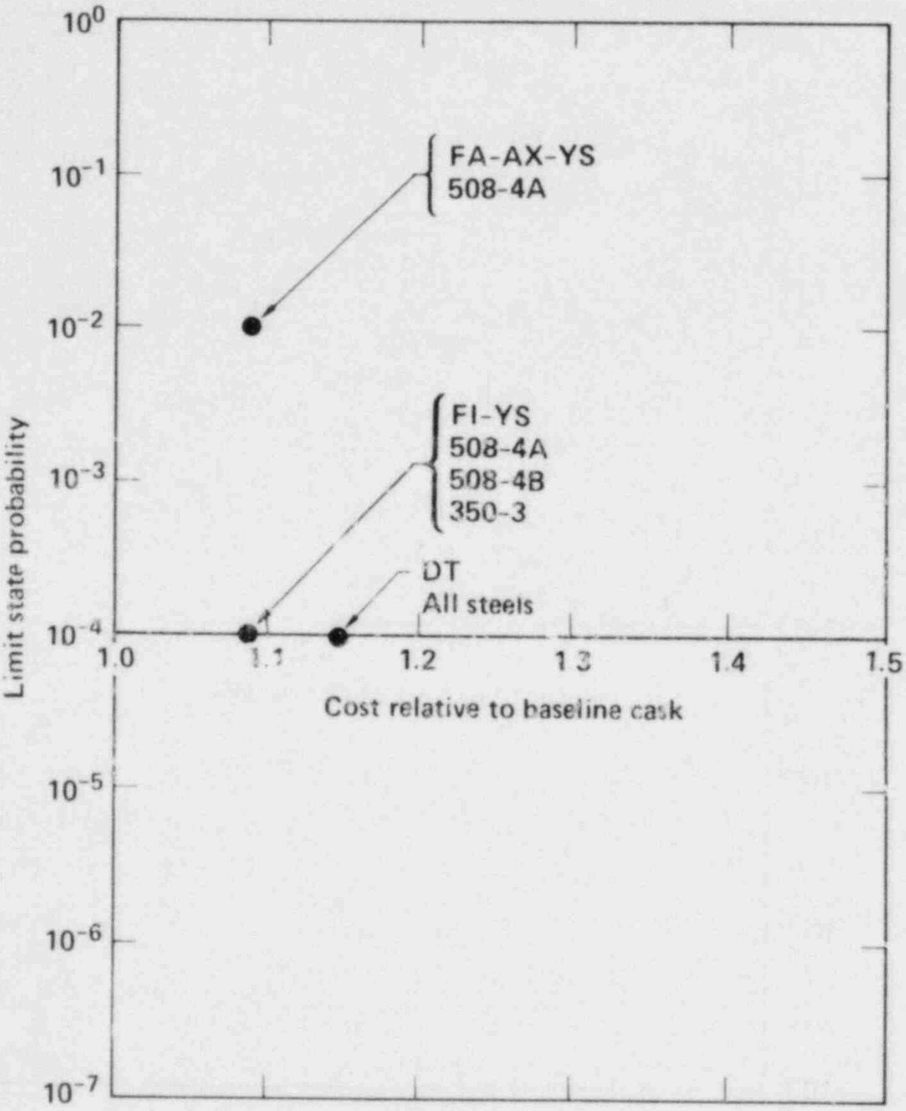
The approach adopted was to consider all the ferritic steels that might be candidates for the construction of shipping casks and to select from these the specific types that meet the various criteria for a particular thickness and lowest service temperature. The cost of fabricating a shipping container in accordance with each of the criteria was computed for the least expensive qualified steel, and the limit state probability associated with each steel type, thickness, and lowest service temperature, was assessed. The results are illustrated in the following pages for a twelve-inch wall section chosen to be most relevant for the purpose of selecting an acceptance criterion.

There is no significant difference in cost impact between the fracture arrest and fracture initiation criteria at yield stress levels. However, the limit state probabilities implied by the fracture initiation criterion at yield stress are lower than that of the fracture arrest criteria at a lowest service temperature of -20°F. The limit state probabilities connected with the fracture arrest criteria improve with an increase in lowest service temperature. However, only SA-508-4A can demonstrate a lower limit state probability for the fracture arrest criteria and then only at a lowest service temperature of 20°F. On the other hand, SA-508-4A, SA-508-4B, and A-350LF-3 can satisfy the fracture initiation criterion at -20°F.

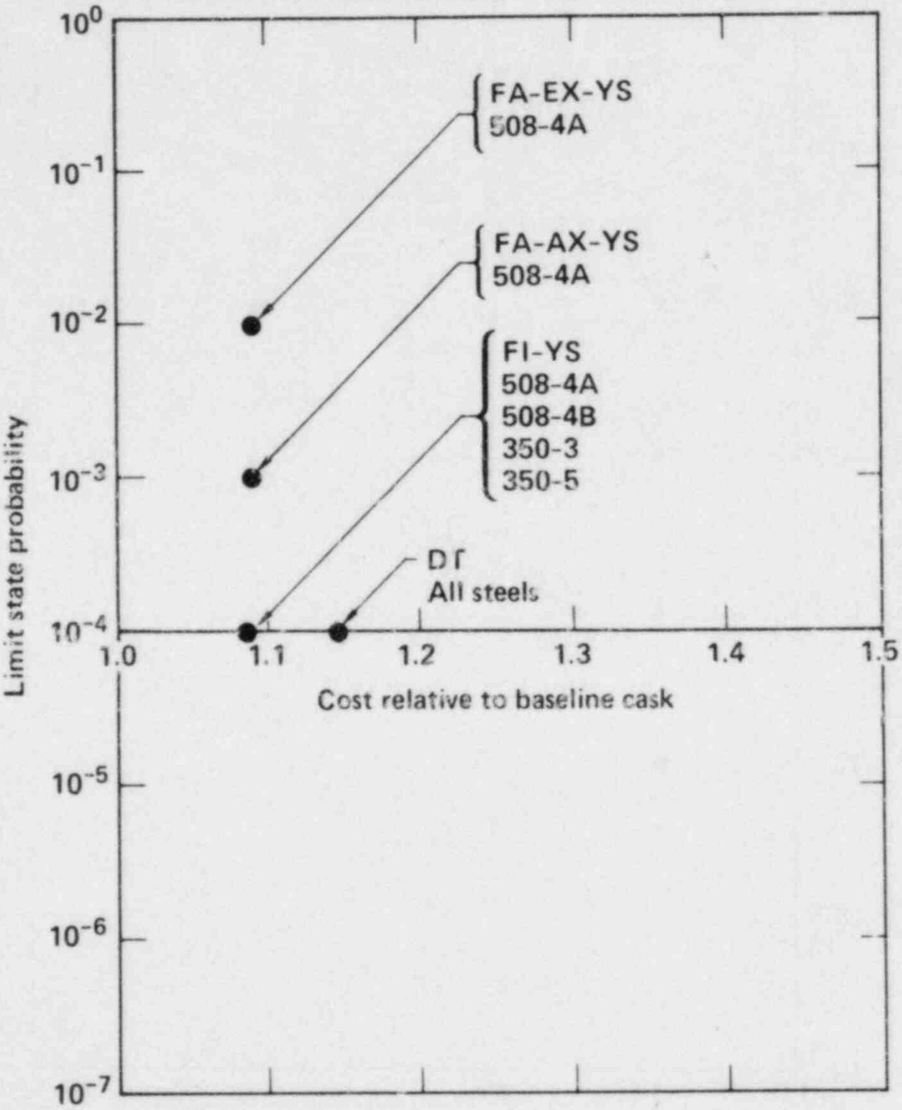
The drop test has a limit state probability equal to or better than the fracture initiation design criterion, however it is more costly. Criteria involving design stresses less than yield result in both higher costs and lower reliability. Consequently, the recommended criterion for qualifying ferritic steels for brittle fracture is fracture initiation at yield stress levels with initial flaw sizes not exceeding those indicated by Table IWB-3510-1 in Section XI of the ASME Code. However, if inspection procedures associated with steels qualified for prevention of fracture initiation are applied to steels selected in accordance with fracture arrest criteria, casks fabricated of such materials would have the lowest limit state probabilities with a relatively modest cost increase.



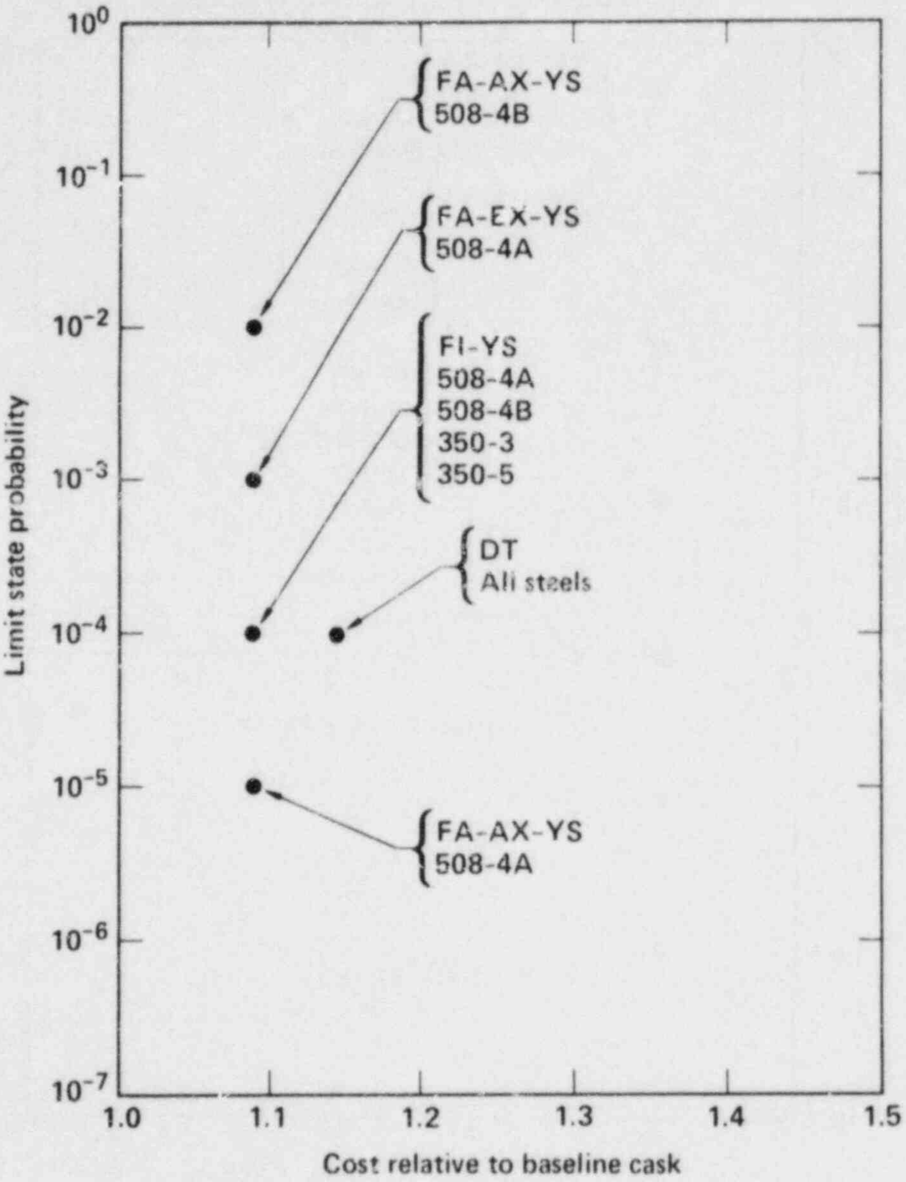
Applicable 12-inch-thick ferritic steels for lowest service temperature of -20°F.



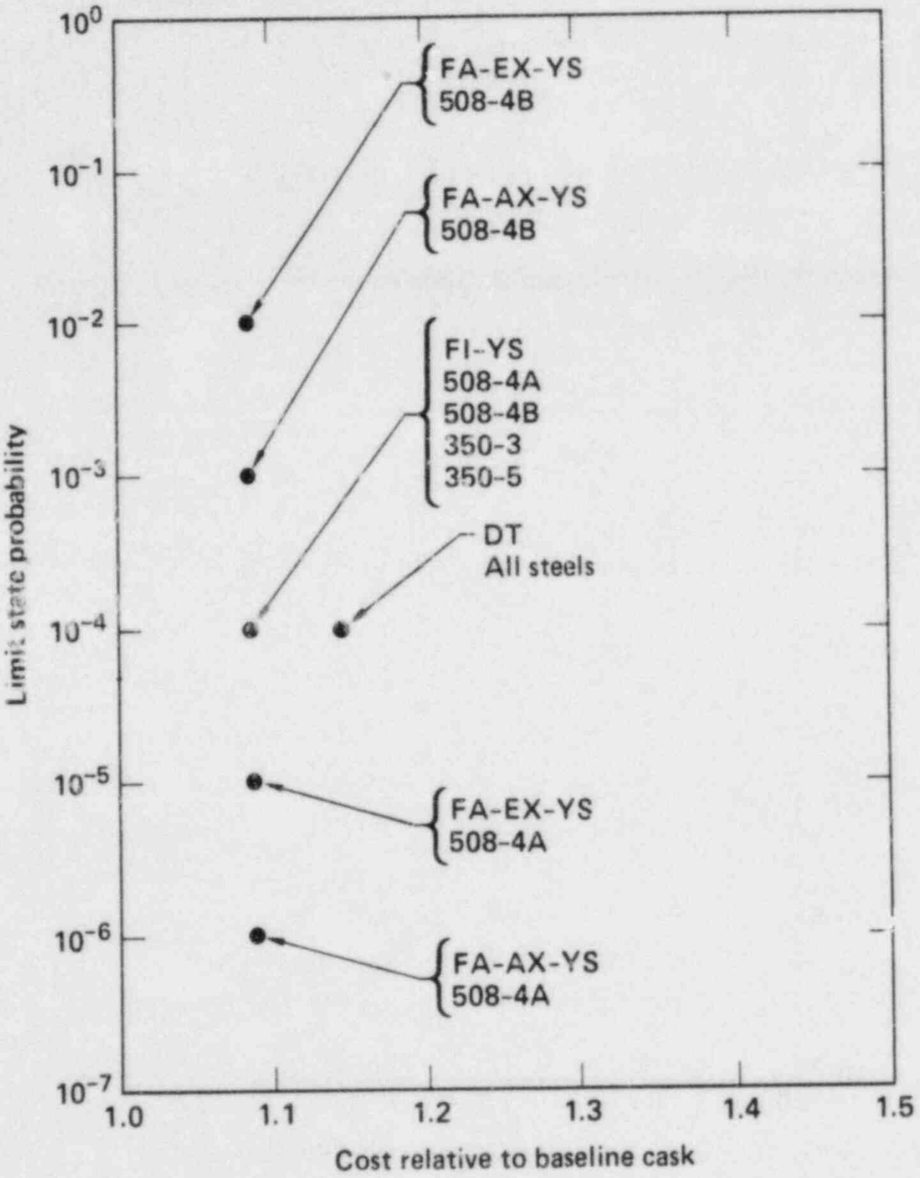
Applicable 12-inch-thick ferritic steels
for lowest service temperature of -10°F.



Applicable 12-inch-thick ferritic steels for lowest service temperature of 0°F.



Applicable 12-inch-thick ferritic steels for lowest service temperature of 10°F.



Applicable 12-inch-thick ferritic steels for lowest service temperature of 20°F.

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) is in the process of developing Regulatory Guides for the prevention of failure by brittle fracture in ferritic steel shipping containers greater than four inches thick. A research program was conducted in FY82 to investigate various criteria for preventing brittle fracture in such containers. The results of this research were deliberately published without specific recommendations (1), since such recommendations are to be accompanied by a value impact assessment. Consequently, this report provides recommendations for brittle fracture design criteria arrived at after consideration of their impact on the shipping container industry as well as on the safety margins implied by these recommendations. Assistance in evaluating the impact of the design criteria on industry was obtained from the Nuclear Packaging Corporation, a company experienced in the design and production of containers for the transport of radioactive material.

2.0 BRITTLE FRACTURE ACCEPTANCE CRITERIA

A study conducted in FY82 (1), examined a number of approaches for qualifying thick wall ferritic steel shipping containers for resistance to brittle fracture. These were:

A. A fracture arrest approach utilizing two different fracture toughness reference curves.

B. A fracture initiation approach based upon yield strength and below yield strength levels of dynamic stress.

C. Performance of a drop test to qualify the cask for brittle fracture resistance.

In the FY82 study, these criteria were investigated assuming a lowest service temperature (LST) of -20°F. This report also considers the effects of increasing this LST.

2.1 FRACTURE ARREST CRITERIA

Fracture arrest is a material selection criterion which guarantees that if a fracture initiated at flaws in embrittled areas of the cask, a through-wall crack may be generated without causing further catastrophic crack propagation. Choosing a suitable ferritic steel for the anticipated ambient temperature is facilitated using the Pellini fracture toughness reference curve, a description of which, together with the application of the methodology, is described in Refs. 1 and 2. For ferritic steels greater than four inches thick, it was necessary to extrapolate the Pellini curve to determine the required nil ductility transition temperature (NDTT) for candidate steels. Two extrapolation schemes were investigated. The first was based upon the assumption that the Pellini data could be described by an exponential function which could then be analytically extrapolated to NDTT's associated with ferritic steels as thick as twenty inches. The second extrapolation was based upon the assumption that beyond about NDTT plus 140°F the behavior of most ferritic steels applicable to casks would display upper shelf behavior and would be well outside the range of brittle fracture. This latter extrapolation is described by an inverse function asymptotic to NDTT plus 140°F. The T-NDTT requirements for ferritic steels to meet the fracture arrest criteria are summarized in Figs. 1 and 2. NDTT requirements for an LST of -20°F are summarized in Tables 1 and 2. Note that for brevity the fracture arrest criterion utilizing the exponential extrapolation is referred to as FA-EX, while the fracture arrest criterion utilizing the inverse function is referred to as FA-AX. A criterion based on yield strength levels of dynamic stress would then be FA-EX-YS and FA-AX-YS with respect to the two fracture arrest criteria. Where the material selection is based upon predicted stresses lower than yield, the designations are respectively FA-EX-PS and FA-AX-PS.

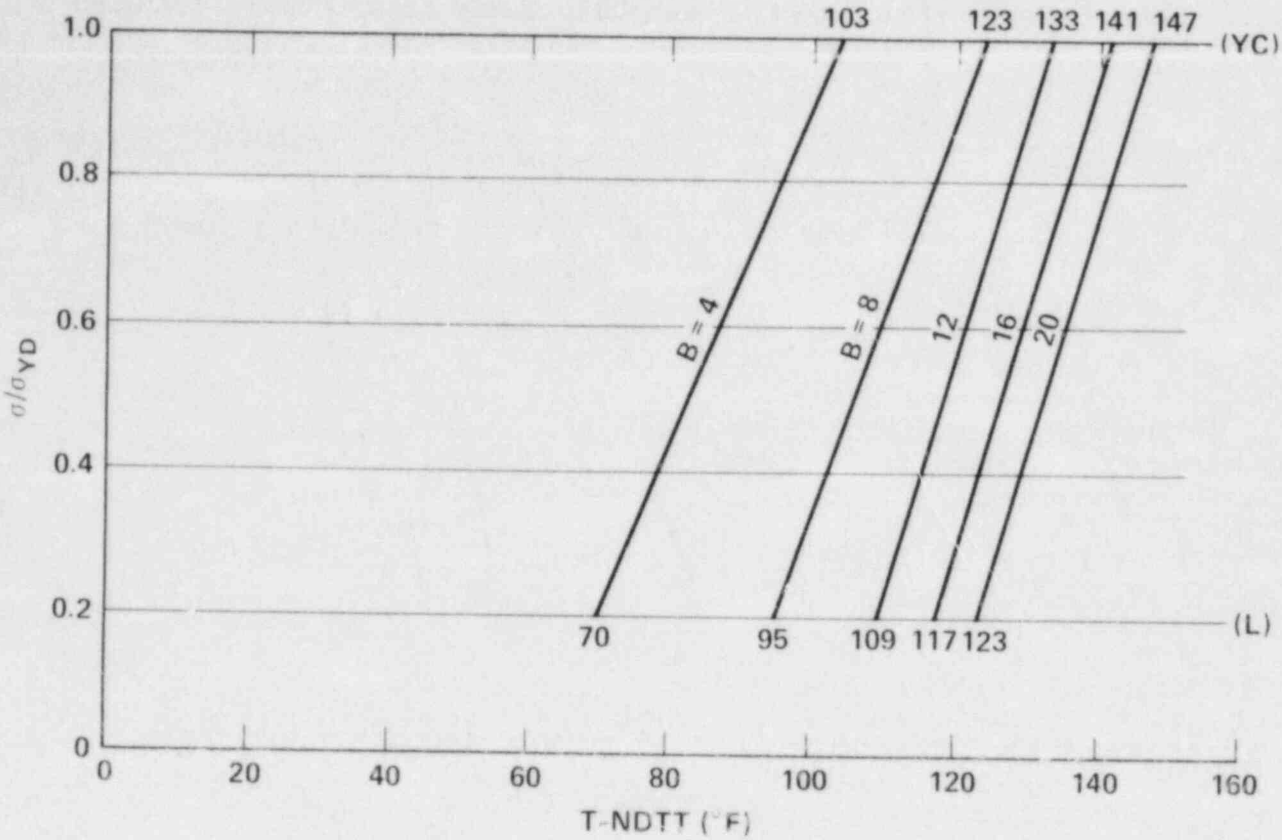


Figure 1. Fracture arrest boundary curves for a range of wall thickness based upon extrapolated exponential fracture-toughness reference curve (FA-EX).

Table 1. T_{NDT} requirements for LST = -20°F using exponential K_{ID}/σ_{YD} reference curve based on Pellini data (FA-EX).

Thickness (in.)	T_{NDT}(°F) $\frac{\sigma}{\sigma_{yD}} = 1.0$	$\frac{\sigma}{\sigma_{yD}} = 0.8$	$\frac{\sigma}{\sigma_{yD}} = 0.6$	$\frac{\sigma}{\sigma_{yD}} = 0.4$	$\frac{\sigma}{\sigma_{yD}} = 0.2$
4	-123	-115	-107	-98	-90
8	-143	-136	-129	-122	-115
12	-153	-147	-141	-135	-129
16	-161	-155	-149	-143	-137
20	-167	-161	-155	-149	-143

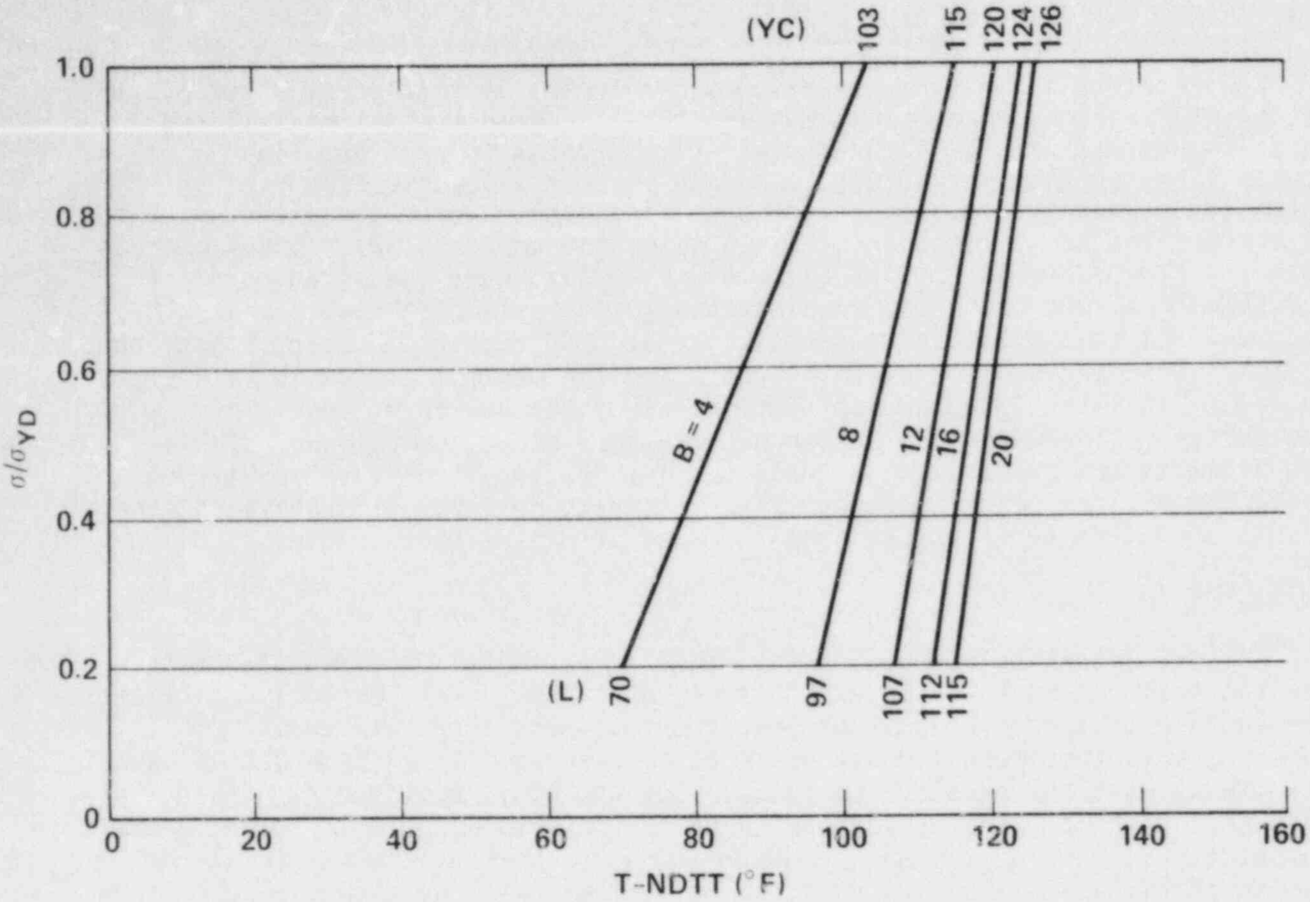


Figure 2. Fracture arrest boundary curves for a range of wall thicknesses based on asymptotic extrapolation of fracture toughness reference curve (FA-AX).

Table 2. T_{NDT} requirements for: LST = -20°F using asymptotic K_{ID}/σ_{YD} reference curve (FA-AX).

	T_{NDT}(°F)				
Thickness (in.)	$\frac{\sigma}{\sigma_{yD}} = 1.0$	$\frac{\sigma}{\sigma_{yD}} = 0.8$	$\frac{\sigma}{\sigma_{yD}} = 0.6$	$\frac{\sigma}{\sigma_{yD}} = 0.4$	$\frac{\sigma}{\sigma_{yD}} = 0.2$
4	-123	-115	-107	-98	-90
8	-135	-130	-126	-121	-117
12	-140	-137	-134	-131	-127
16	-144	-141	-138	-135	-132
20	-146	-143	-141	-137	-135

2.2 FRACTURE INITIATION CRITERIA

The fracture initiation criterion prevents the initiation of crack propagation at locations where flaws may exist. It requires that the selected material demonstrates sufficient fracture toughness to preclude flaw instability for whatever stress level and maximum allowable flaw size are permitted by design and fabrication specifications. To be consistent with the fracture arrest criterion, a materials selection approach was adopted wherein both the stress levels and the allowable flaw size were specified, and the resulting fracture toughness requirements met by selecting steels having NDTTs that reflect this fracture toughness. These NDTT requirements are based upon a yield strength level of dynamic stress and the maximum allowable flaw sizes indicated in Table IWB-3510-1 of Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code. These requirements are summarized in Table 3. The fracture initiation criterion hereafter will be referred to as FI-YS for fracture initiation at yield stress levels and FI-PS for fracture initiation at predicted stress levels.

2.3 DROP TEST

A third criterion for qualifying shipping containers for resistance to brittle fracture is the 9-meter (30-feet) drop test. This criterion mitigates the requirements for analysis of fracture toughness stress intensities. However, this test must demonstrate that catastrophic crack propagation cannot occur even with the presence of flaws. Consequently, a unique requirement of this test is that flaws be introduced at the most vulnerable location in the shipping cask. While the size and configuration of the flaw may be at the option of the applicant, it should be recognized that the flaw size used in a test that is ultimately successful is the flaw size that will establish the inspection limits for production shipping casks.

Table 3. T_{NDT} requirements based upon allowable ASME Section XI flaw sizes for brittle fracture using the fracture initiation approach (FI-YS).

Flaw aspect ratio, $a/\ell = 0.5$

Thickness B (in.)	a = 0.035B (in.)	a_i = 2a (in.)	K_{ID}/σ_{YD} $\sqrt{in.}$	T-NDTT (°F)	T_{NDT} (°F)
4	0.14	0.28	0.69	20	-40
8	0.28	0.56	0.97	53	-73
12	0.42	0.84	1.19	69	-89
16	0.56	1.12	1.38	80	-100
20	0.70	1.40	1.54	87	-107

Flaw aspect ratio, $a/\ell = 1/6$

Thickness B (in.)	a = 0.024B (in.)	a_i = 2a (in.)	K_{ID}/σ_{YD} $\sqrt{in.}$	T-NDTT (°F)	T_{NDT} (°F)
4	0.10	0.20	0.87	44	-64
8	0.19	0.38	1.20	70	-90
12	0.29	0.58	1.48	85	-105
16	0.38	0.76	1.69	94	-114
20	0.48	0.96	1.90	101	-121

Flaw aspect ratio, $a/\ell \rightarrow 0$

Thickness B (in.)	a = 0.018B (in.)	a_i = 2a (in.)	K_{ID}/σ_{YD} $\sqrt{in.}$	T-NDTT (°F)	T_{NDT} (°F)
4	0.072	0.144	0.84	41	-61
8	0.144	0.288	1.19	69	-89
12	0.216	0.432	1.46	84	-104
16	0.288	0.576	1.66	93	-113
20	0.360	0.720	1.88	100	-120

3.0 COST AND SAFETY ANALYSIS

3.1 APPROACH

Recommendations relating to which of the criteria is most applicable to the prevention of brittle fracture in shipping casks under dynamic loading conditions are based upon what they imply with regard to levels of safety and their impact upon the shipping cask industry. Thus, it is necessary to rank each of the criteria with respect to some quantitative measure of these implications. For industry the controlling factor is cost, while safety can be quantified in terms of relative risk. The approach used in the evaluation of these criteria was to identify all the ferritic steels that may be applicable for the construction of shipping casks, assemble a data base for cost and fracture toughness properties of these steels, develop a cask model that could serve as a basis for comparison of costs, and finally, determine the limit state probabilities associated with each of the candidate materials and for each fracture toughness qualification criterion. Assistance in identifying candidate ferritic steels, compiling the cost and properties data base, and analyzing the cask model for cost comparisons was provided by a representative of the shipping cask industry under a sub-contract.

3.2 CANDIDATE FERRITIC STEELS

A list of candidate materials together with their cost and fracture toughness properties as reflected by their NDTT's is shown in Table 4. Information about these materials appears in detail in Refs. 3 - 10 as indicated in the last column of the table. The plate materials would be applicable to shipping casks of up to about seven-inch wall thickness, while forgings would probably be required for shipping casks of greater thicknesses. To illustrate the relationship between cost and toughness, the data in Table 4 is plotted on Fig. 3. If the NDTT requirements associated with each brittle fracture prevention criterion are superposed on Fig. 3, the candidate ferritic steels that can meet the criterion for the entire range of thicknesses can be identified. This is shown, for example, in Fig. 4 for criterion FA-EX-YS at an LST of -20°F. This type of diagram applicable to all the relevant criteria and for a range of LSTs is placed in Appendix A.

Table 4. Candidate ferritic steels for shipping casks.

Material	Billet Cost $/lb.	NDTT (°F)		Ref
		Mean	Std. Dev.	
Plate				
A 36	0.36	25.1	10.78	3
A 516, GR. 70	0.55	-23.8	15.66	3
Forgings				
SA-508-1	0.65	-47.71	10.99	4
SA-508-2	0.72			
B&W		19.40		5
Swedish		-9.40		6
Japan Stl		-27.68	16.01	7
SA-508-2A	0.72	19.40		6
SA-508-3	0.72			
U.S.		-22.00		6
Japan Stl		-24.39	15.02	7
SA-508-4A	0.89	-158.33	10.52	*
SA-508-4B	0.89	-148.00		8
SA-350-LF5	0.65	-76.00		9
SA-350-LF3	0.77	-120.00		10

*Nuclear Packaging Corporation, personal communication from Dr. R. J. Andreini, Jorgenson Steel, Forge Division, Seattle, WA, April 1983.

3.3 COST ANALYSIS

The impact of the various criteria on cost was determined by comparing the cost of a forged ferritic steel baseline cask having no particular fracture toughness requirements with identical casks made of candidate steels selected in accordance with the various fracture toughness criteria.

Figure 5 shows the configuration of this baseline cask. The payload was assumed to be 7 PWR fuel assemblies each with a decay heat of about 1 Kw and a weight of 1262 lbs. The wall thickness was established on the basis of strength assuming impact loads of about 100 g's and shielding requirements equivalent to six inches of lead (CO^{60}). Both neutron shielding and impact limiters were ignored, since they are not influenced by fracture toughness considerations for a comparative cost study.

The elements making up the total cost of the shipping cask are identified in Fig. 6. Basic information relating to labor and material costs, overhead, and corporate GPA may be found in Appendices C through H.

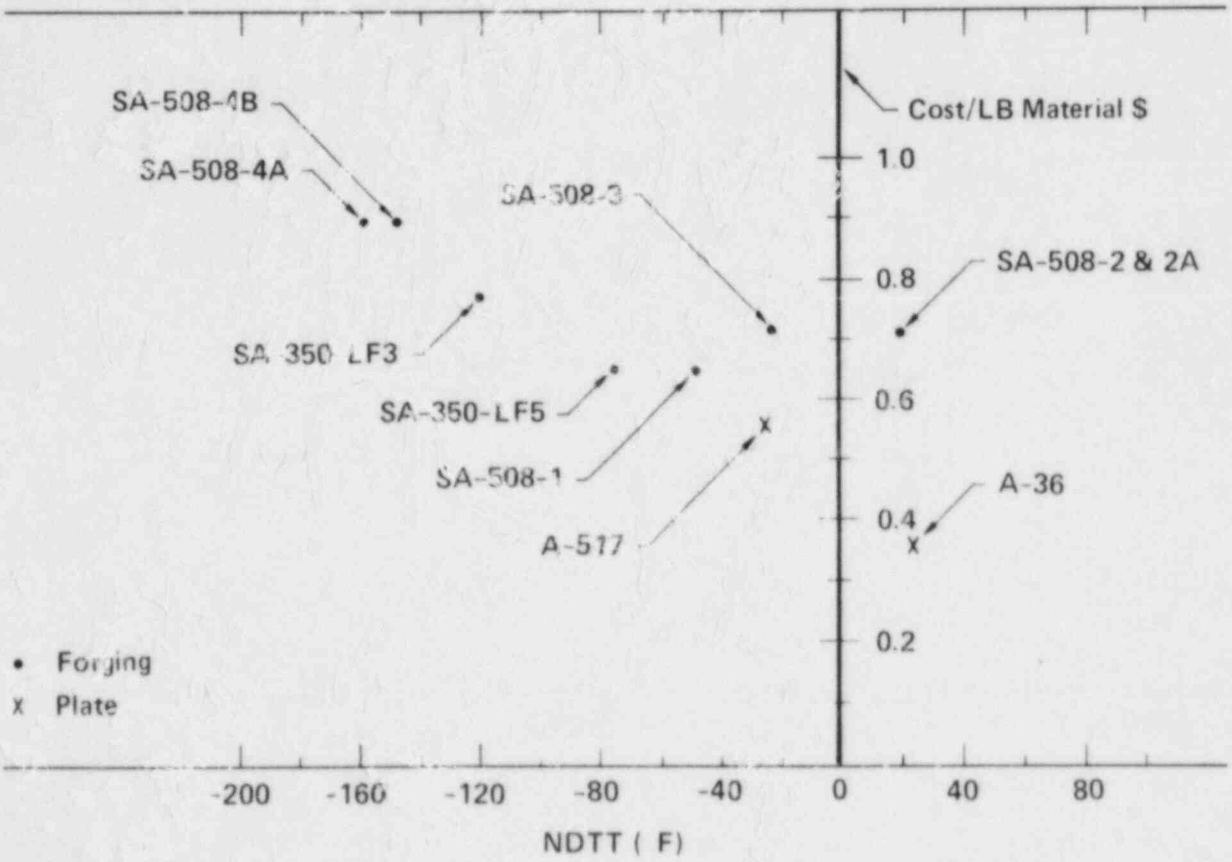


Figure 3. Relationship between cost and fracture toughness for ferritic steels.

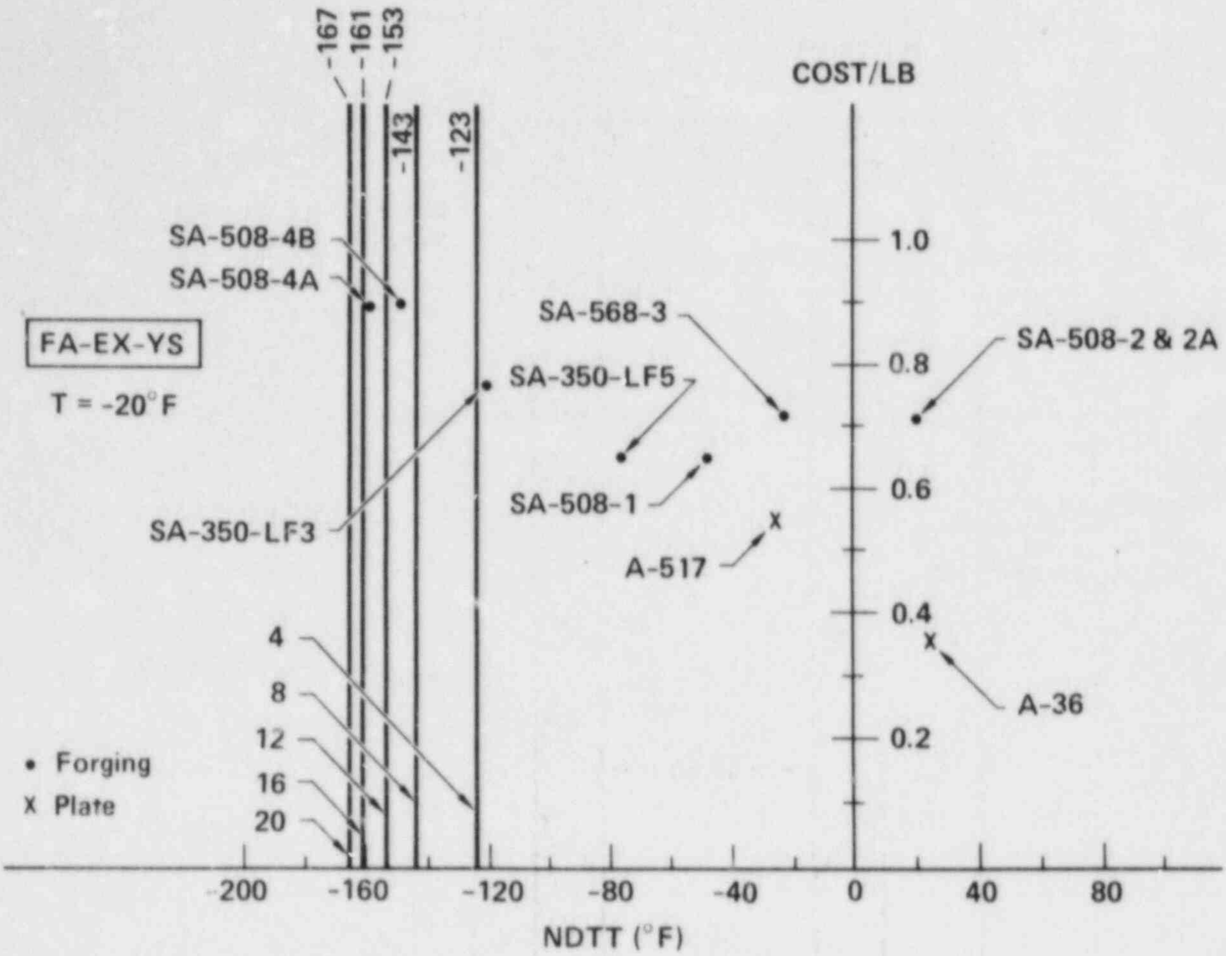


Figure 4. Ferritic steels applicable to FA-EX-YS at -20°F lowest service temperature. Thicknesses range from 4 to 20 inches.

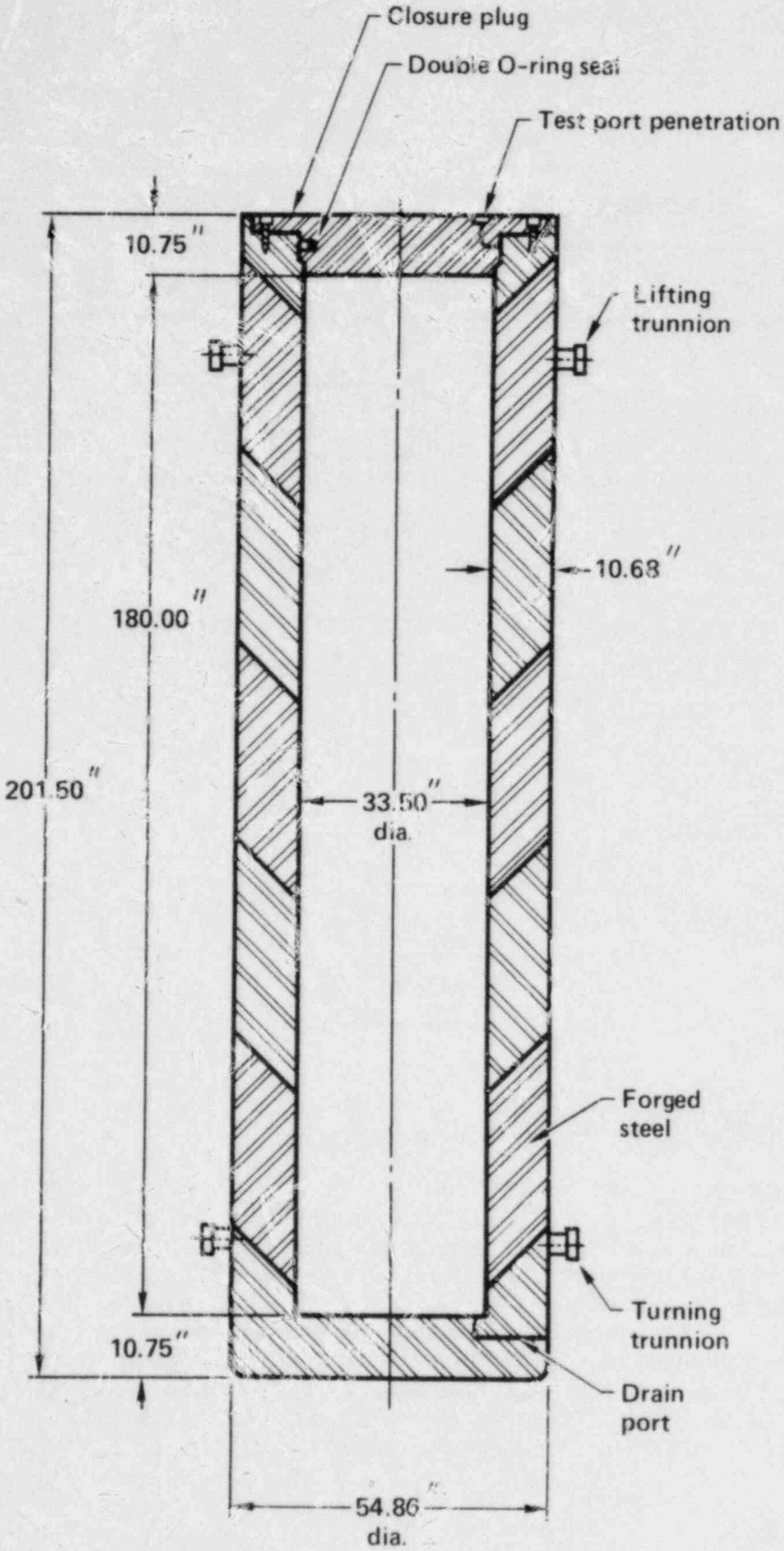


Figure 5. Baseline forged steel cask.

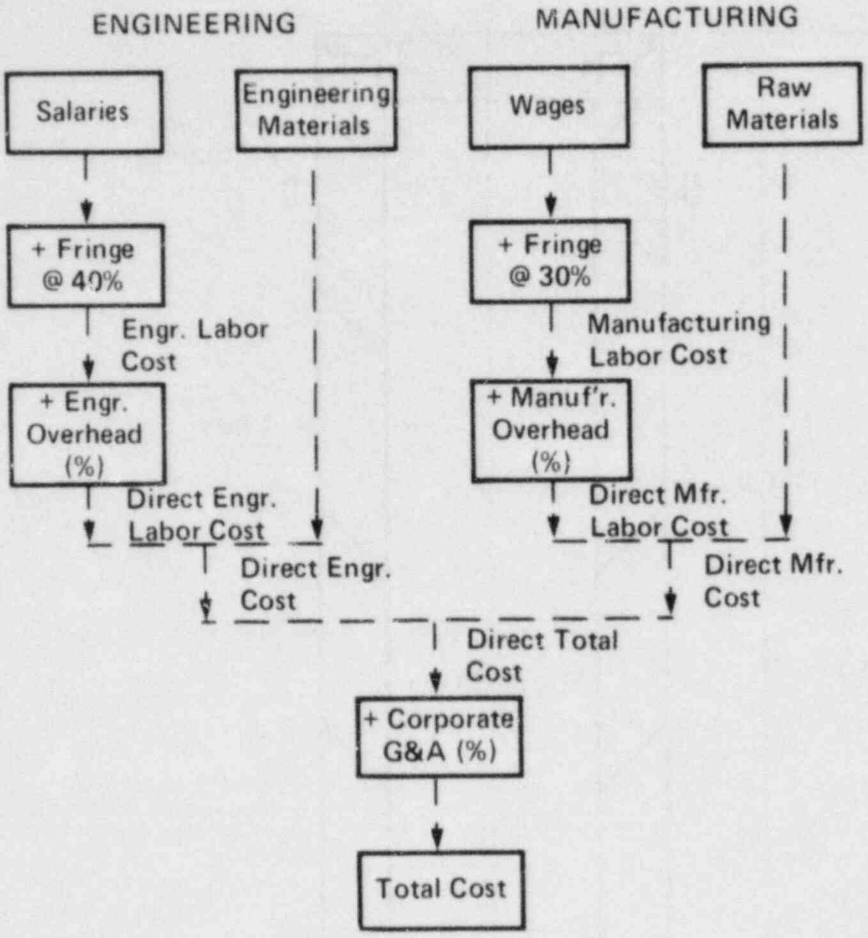


Figure 6. Corporate cost markup model.

The differences in cost manifested by the various criteria are due to the level of analytical effort required, the degree of quality assurance to be maintained, and the material cost applicable for each criterion. The fracture arrest and initiation criteria, assuming yield stress levels, require lesser analytical effort than those cases where specified stress levels may not be exceeded. On the other hand, the fracture initiation criteria, at any stress level, require a higher degree of quality control to assure that flaw sizes do not exceed the specified maxima. The material cost used was that corresponding to the lowest cost material that would qualify for a particular criterion based on the thickness of the baseline cask.

A summary of the cost of the forged ferritic steel shipping casks relative to the baseline cask is presented in Table 5 for each fracture toughness acceptance criterion. The cost breakdown, computed in accordance with the corporate cost markup model shown in Fig. 6, is given in Appendix B for the baseline cask and for each of the fracture toughness acceptance criteria.

Table 5. Summary of forging cost estimates for various brittle fracture criteria.

Criterion	Total Engr. Cost ($)	Fabr. Cost ($)	Total Unit Cost* ($)	Cost Relative to Baseline Cask
Baseline Cask	578337	289641	456986	1.0
FA/EX-YS	607688	317416	494921	1.083
FA/EX-PS	695733	322711	520745	1.140
FA/AX-YS	607688	317416	494921	1.083
FA/AX-PS	695733	322711	520745	1.140
FI-YS	641876	314994	499899	1.094
FI-PS	872526	314769	551995	1.208
DT	867978	289641	522300	1.143

*Based upon a production run of five casks.

3.4 SAFETY ANALYSIS

3.4.1 Fracture Arrest Criteria

The fracture arrest criterion provides a fracture toughness requirement based upon the thickness of the containment which is then translated into a required NDTT by means of the Pellini fracture toughness reference curve. This criterion assures that the behavior of the steel chosen for a particular ambient temperature is well beyond the transition from brittle to ductile fracture. Since the Pellini curve is based upon a lower bound of fracture toughness for all ferritic steels, it can be concluded that the T-NDTT indicated by the Pellini curve represents an upper bound on the T-NDTT requirement, and that the probability of a requirement exceeding this is essentially zero. While it may be argued that there is a finite probability of a lesser requirement, the rules of the fracture arrest criterion make this assumption inadmissable. Consequently, instead of representing the T-NDTT requirement as a probabilistically distributed parameter, we are forced to regard it as a deterministic quantity in computing the limit state probability. On the other hand, the material selected to meet the T-NDTT requirement will display a variation in fracture toughness and it is the statistical characterization of the material that will determine the limit state probability associated with this criterion. The limit state probability is then simply the probability of non-exceedance of the T-NDTT for the selected steel. This is illustrated in Fig. 7 for FA-EX-YS, and Fig. 8 for FA-AX-YS, using an eight-inch wall thickness of SA-508-4A as an example. In Fig. 7 the toughness requirement for an eight-inch wall thickness is a T-NDTT of 123°F, while for a LST of -20°F, the mean T-NDTT value for SA-508-4A is 138°F. Based on a standard deviation of 10.50 for this steel, the limit state probability is 7.6×10^{-2}. For the FA-AX-YS criterion the lower NDTT requirement results in a limit state probability of 1.4×10^{-2}. It is important to point out that the limit state probability is not necessarily the failure probability. It is, rather, the probability of exceeding the capability of the material as defined by the relevant criterion.

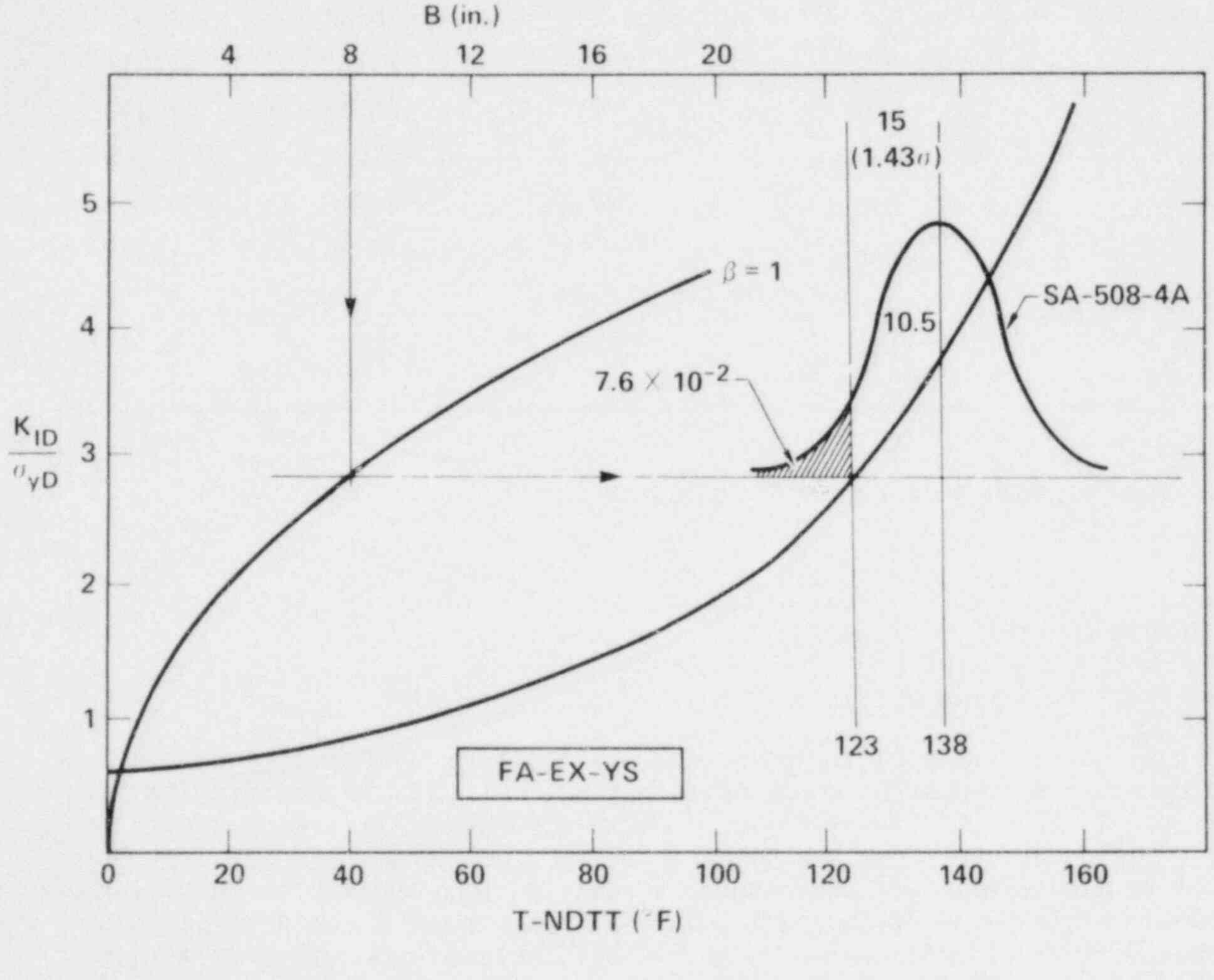


Figure 7. Limit state probability for FA-EX-YS.

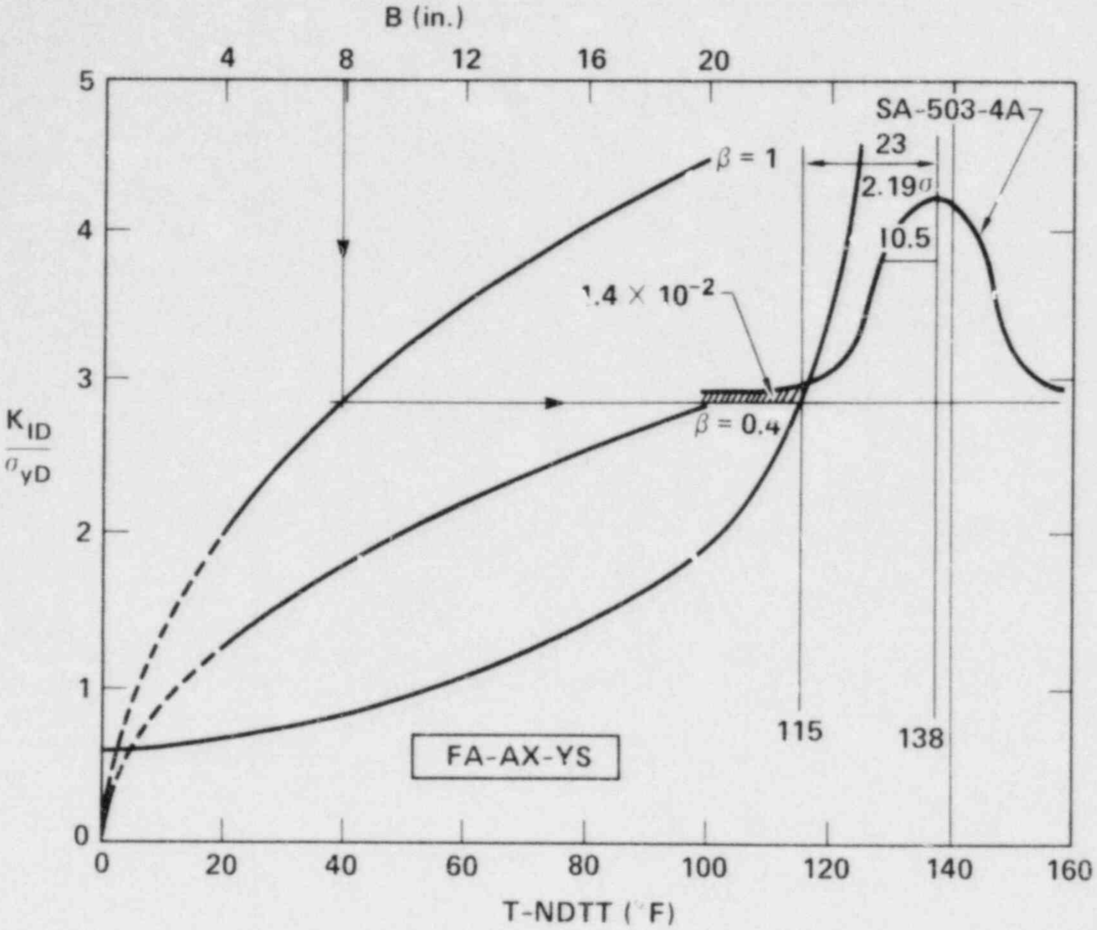


Figure 8. Limit state probability for FA-AX-YS.

The analysis described above was performed for each of the steels that met the fracture arrest criterion within the thickness range considered. A tabulation of the results of this analysis is provided in Appendix I and curves summarizing these results for FA-EX-YS and FA-AX-YS at -20°F are illustrated in Figs. 9 and 10, respectively.

3.4.2 Fracture Initiation Criteria

The fracture initiation criterion provides a fracture toughness requirement that is governed both by anticipated levels of stress and the size and configuration of an existing flaw. The magnitude and dispersion of these parameters determine the magnitude and dispersion of the applied normalized dynamic stress intensity, K_I/σ_{YD}. Combining this with the distribution function for the critical stress intensity of the ferritic steel yields the limit state probability associated with the fracture initiation criterion.

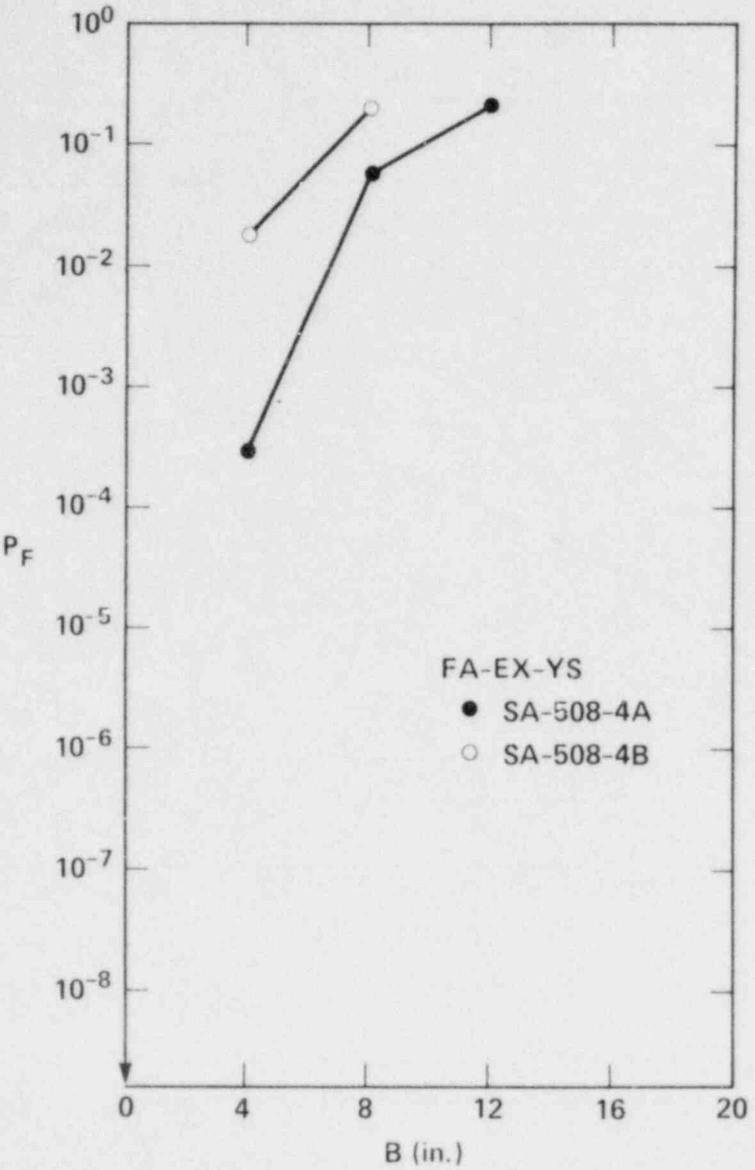


Figure 9. Limit state probability versus thickness FA-EX-YS.

For the case where yield stress levels are assumed (FI-YS), the expression for applied stress intensity due to a surface flaw is simply,

$$\frac{K_I}{\sigma_{yD}} = C\sqrt{a}\ , \tag{1}$$

where C is a constant reflecting the configurations of the flaw, and a is the flaw depth. In this case only the statistics associated with the flaw depth are required to determine the probability density function of the stress intensity. The uncertainty regarding the flaw depth is associated with the

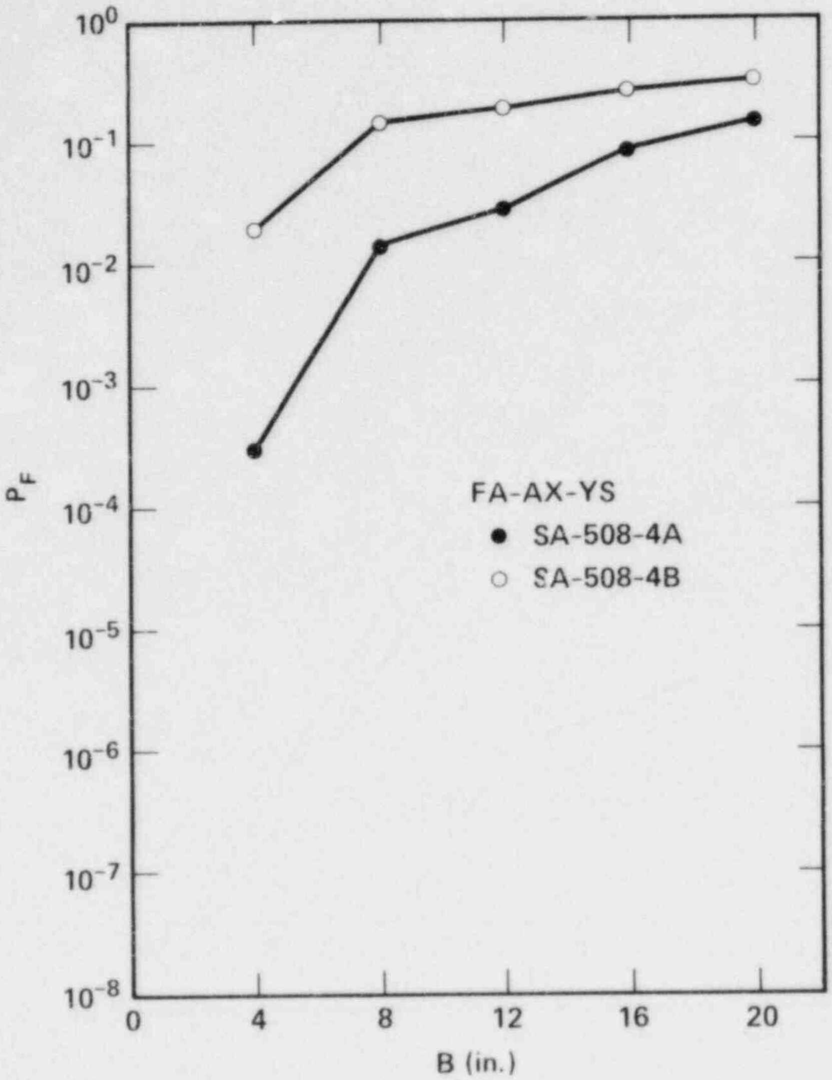


Figure 10. Limit state probability versus thickness for FA-AX-YS.

probability of non-detection of the flaw. The results of considerable research in this area are summarized in Fig. 11 which shows the probability of non-detection of a flaw as a function of its depth obtained by a number of investigators. The values chosen for this study are those recommended by Harris (11). For a log-normally distributed probability density function, these values are 0.25 for the median flaw depth, and 1.33 for the reciprocal of the standard deviation of the log of the flaw depth.

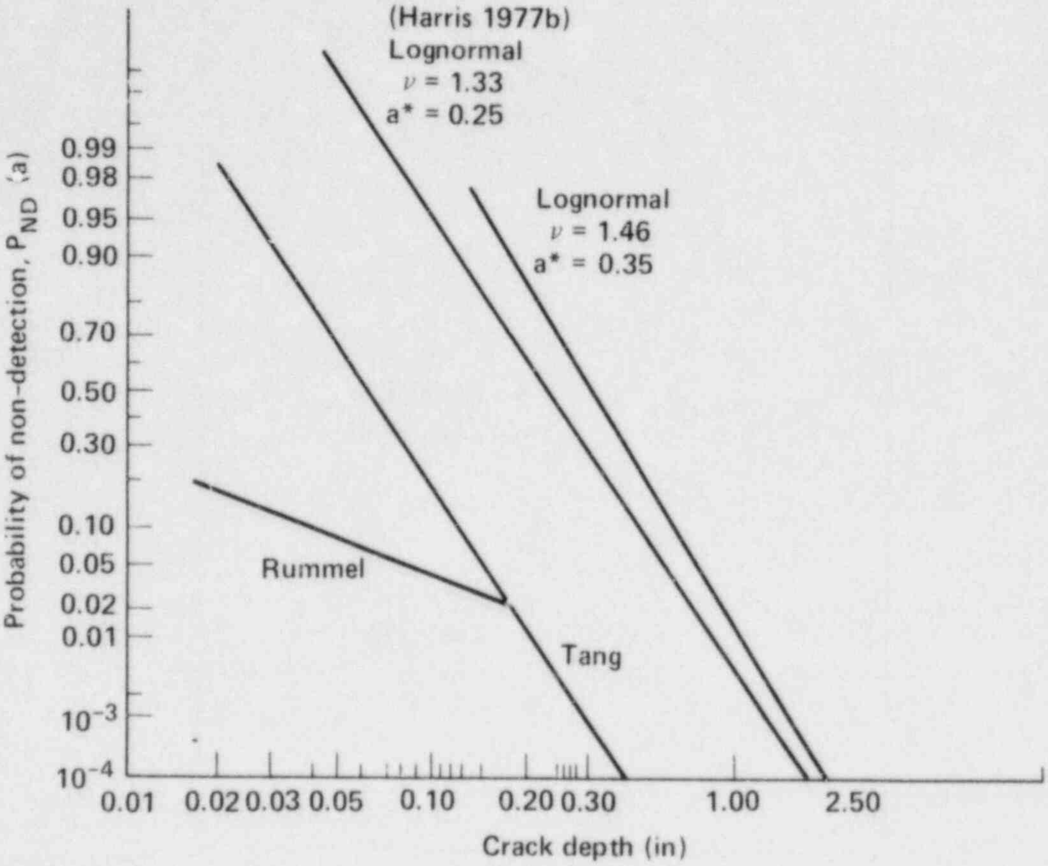


Figure 11. Probability of non-detection of a flaw as a function of its depth for an ultrasonic inspection.

The limit state probability associated with the fracture initiation criterion at yield stress levels is expressed by

$$P_F = \int_0^{\infty} \Phi\left[\frac{\ln \hat{k}_{ID} - \mu_{\ln \hat{K}_{ID}}}{\sigma_{\ln \hat{K}_{ID}}}\right] f_{\hat{K}_1}(\hat{k}_1)\, d\hat{k}_1 \qquad (2)$$

where

$$\phi = \int_{0}^{[---]} \frac{1}{\sqrt{2\pi}} \exp^{\frac{1}{2}[---]^{2}} d\hat{k}_{ID} \tag{3}$$

$$[---] = [\frac{\ln \hat{k}_{ID} - \mu_{\ln \hat{K}_{ID}}}{\sigma_{\ln \hat{K}_{ID}}}]$$

and

$$f_{\hat{K}_1}(\hat{k}_1) = \frac{2}{\hat{k}_1 \sigma_{\ln A} \sqrt{2\pi}} \exp - \frac{1}{2} \{ \frac{1}{\sigma_{\ln A}} \ln[\frac{k_1^2}{c^2 Y m_A}] \}^2 \tag{4}$$

The derivation of the above equation is given in Appendix J.

The statistical parameters for the fracture toughness of ferritic steel in linear elastic fracture mechanics units were obtained from the data collection shown in Fig. 12. The data, which are presented in terms of K_{IR} versus temperature relative to NDTT, represent the results of tests conducted by numerous investigators to determine the fracture toughness of ferritic steels used by the nuclear industry. A regression analysis of this data after normalization at a dynamic yield stress level of 70 ksi and using an exponential function resulted in the following expressions for the mean and standard deviation of the fracture toughness as a function of NDTT.

$$\mu(\frac{K_{ID}}{\sigma_{yD}}) = 0.3592 \exp 0.01284(T\text{-}NDTT) + 0.4 \tag{5}$$

$$\sigma(\frac{K_{ID}}{\sigma_{yD}}) = 0.264 \ \mu(\frac{K_{ID}}{\sigma_{yD}} - 0.4) \tag{6}$$

The probability density function for the fracture toughness properties was also assumed to be log-normal.

The method for determining the limit state probability associated with FI-YS is illustrated in Fig. 13. The limit state probability, P_F, is computed by convolving the pdf for the applied stress intensity with that of the critical stress intensity as shown for Fig. 13. The example shown considers the case of twenty-inch thickness with a flaw having an aspect ratio approaching zero, that is, a flaw that is very long compared with its depth. The maximum allowable flaw depth based on Table IWB-3510-1 of Section XI of the ASME BPV Code (13) is 0.360 inches and the critical flaw size is established at twice this depth, or 0.720 inches. The ferritic steel chosen for this application must be tough enough to resist fracture with a flaw depth of 0.720 inches so that it would require a T-NDTT value of 100°F corresponding to a K_{ID}/σ_{YD} of 1.88. (See Table 3.) For this case the limit state probability is 2.8×10^{-4}. The analysis was extended to include the full range of wall thicknesses and flaw aspect ratios. The results are summarized in Table 6 and plotted in Fig. 14.

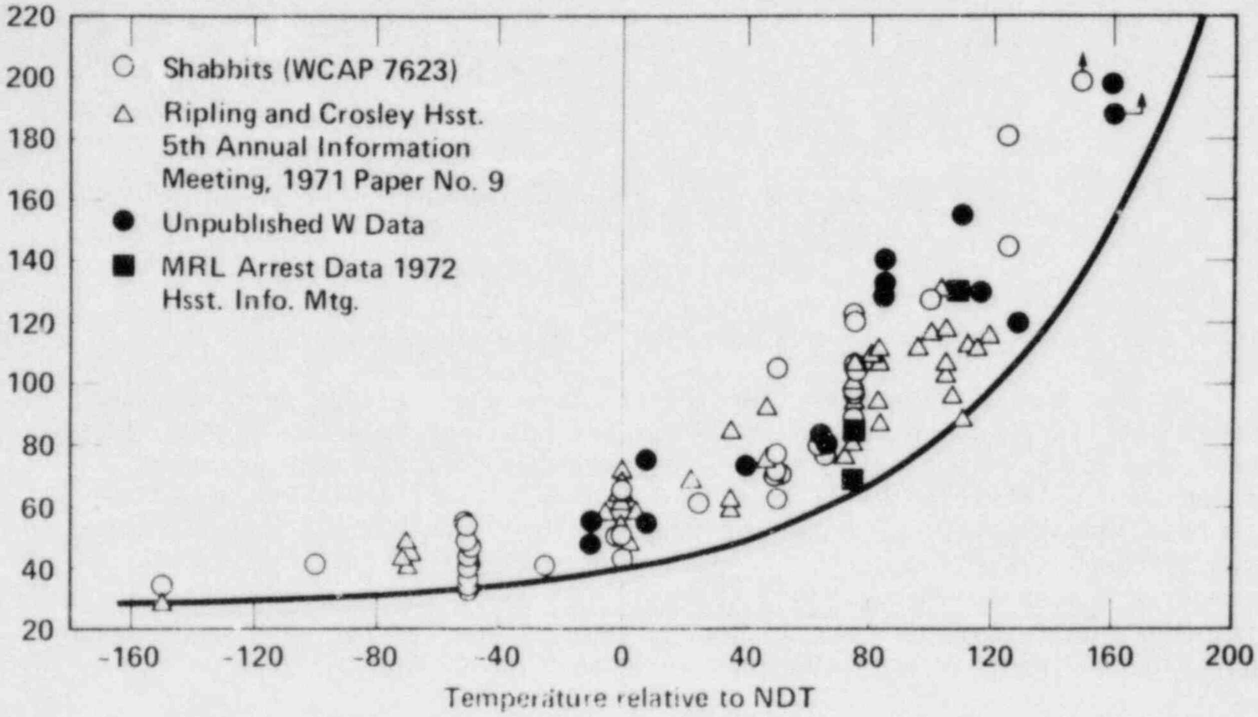


Figure 12. Derivation of curve of reference stress intensity factor (K_{IR}).

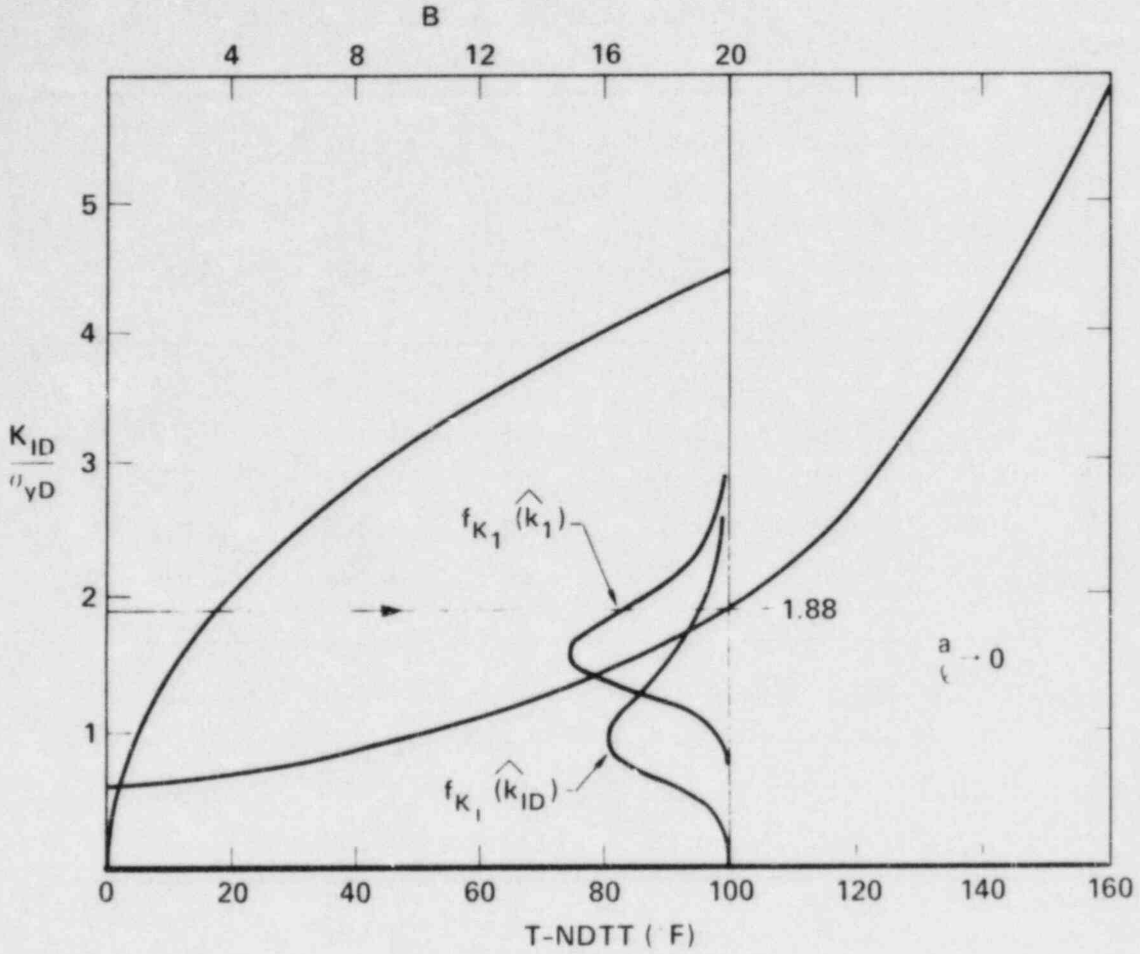


Figure 13. Limit state probability for FI-YS.

Table 6. Limit state probabilities implied by fracture initiation criterion (FI-YS).

Thickness B(in.)	a(in.)	a_i(in.)	Design K_{ID}/σ_{YD} ($\sqrt{in}$)	Design T-NDTT (°F)	μ ($\sqrt{in}$)	σ ($\sqrt{in}$)	P_F
Flaw Aspect Ratio $a/\ell = .5$; $\sigma/\sigma_{YD} = 1.0$; $C = 1.3$							
4	0.14	0.28	0.69	20	0.864	0.122	9.9×10^{-5}
8	0.28	0.56	0.97	53	1.109	0.187	2.4×10^{-5}
12	0.42	0.84	1.19	69	1.271	0.230	1.1×10^{-5}
16	0.56	1.12	1.38	80	1.403	0.265	6.4×10^{-6}
20	0.70	1.40	1.54	87	1.498	0.290	4.6×10^{-6}
Flaw Aspect Ratio $a/\ell = .167$; $\sigma/\sigma_{YD} = 1.0$; $C = 1.925$							
4	0.10	0.20	0.87	44	1.032	0.167	1.4×10^{-3}
8	0.19	0.38	1.20	70	1.282	0.233	4.3×10^{-4}
12	0.29	0.58	1.48	85	1.470	0.282	2.0×10^{-4}
16	0.38	0.76	1.69	94	1.601	0.317	1.3×10^{-4}
20	0.48	0.96	1.90	101	1.714	0.347	9.3×10^{-5}
Flaw Aspect Ratio $a/\ell = 0$; $\sigma/\sigma_{YD} = 1.0$; $C = 2.2$							
4	0.072	0.144	0.84	41	1.008	0.161	4.4×10^{-3}
8	0.144	0.228	1.19	69	1.271	0.230	1.3×10^{-3}
12	0.216	0.432	1.46	84	1.456	0.279	6.4×10^{-4}
16	0.288	0.576	1.66	93	1.586	0.313	4.0×10^{-4}
20	0.360	0.720	1.88	100	1.697	0.342	2.8×10^{-4}

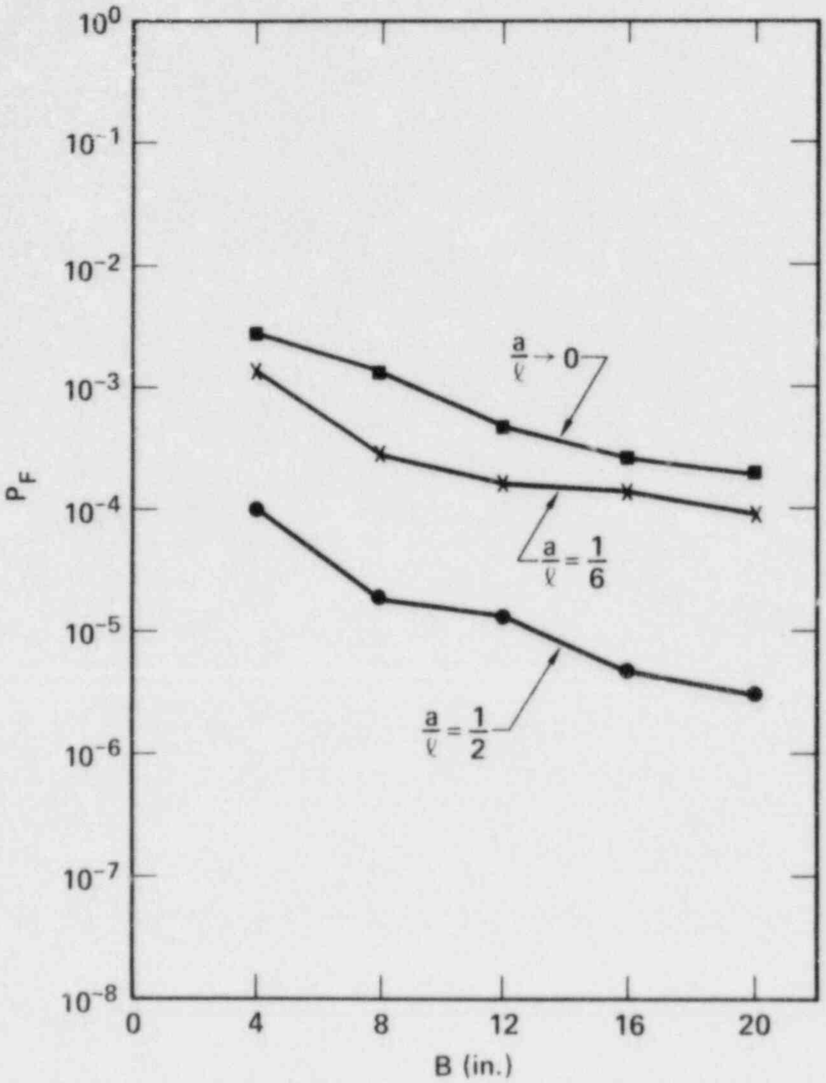


Figure 14. Limit state probabilities versus thickness implied by fracture initiation criterion (FI-YS).

4.0 DISCUSSION OF RESULTS

4.1 COST ANALYSIS

The results of the cost analysis shown in Tab . 5, indicate that a cost penalty is incurred by specifying a requirement for brittle fracture resistance under dynamic loading conditions. The least penalty is incurred when the fracture arrest criteria is based on yield stress levels, since little sophistication is required in the way of stress analyses or inspection procedures. The fracture initiation criteria at yield stress levels incurs a slightly higher cost primarily due to more stringent inspection requirements. All criteria which require a stress analysis to demonstrate acceptability are still higher in cost reflecting the additional expenditures required for stress analyses and computer time. The highest cost is incurred by the FI-PS criteria which require the most sophisticated analyses since a flaw initiated by a stress higher than the one computed could conceivably lead to catastrophic fracture. Finally, the cost of a drop test using full-scale specimens appears to be the same as that incurred by using the fracture arrest criteria at stress levels less than yield.

These observations reflect only the relative cost implied by each criterion. The absolute cost differences will be influenced by the number of shipping casks produced of a particular configuration. For one or two casks the difference in absolute costs could be significant. For a large number of casks, the additional analyses and quality assurance efforts comprise a corresponding smaller fraction of the unit cost. Even for a production run of five casks as assumed in the cost analyses, the difference in costs incurred between the fracture arrest and initiation criteria is negligible. In any event, the relative costs implied by all the criteria are close enough considering the uncertainties of the cost analyses, to conclude that cost is not the major consideration in selecting an appropriate acceptance criterion.

4.2 SAFETY ANALYSES

A summary of all the acceptable ferritic steels in accordance with the fracture arrest and initiation criteria of yield stress levels is presented for a range of limit state probabilities, thicknesses, and LSTs in Appendix K. This tabulated data shows that fewer ferritic steels qualify as the limit state probability decreases. No ferritic steel can be qualified in accordance with the fracture arrest criteria at an LST of -20° that has a limit state probability less than 10^{-2}, except for thicknesses less than four inches. However, the number of steels that can be qualified increases as the LST requirements are relaxed. The fracture initiation criterion, on the other hand, admits a number of ferritic steels at an LST of -20°F. However, this number decreases with decreasing limit state probability rather abruptly below 10^{-4} for flaw aspect values approaching zero and one-sixth, and below 10^{-5} for an aspect ratio of one-half.

The relative merits of each brittle fracture acceptance criterion can be brought into sharper focus if we devote our attention to the twelve-inch thickness. This thickness is selected because it is within the range of thicknesses required for monolithic thick walled shipping casks. For thicknesses less than twelve inches, the applicability of the fracture arrest criteria are enhanced since NDTT requirements decrease with thickness. For thicknesses greater than twelve inches, the fracture initiation criteria is enhanced since the probability of non-detection of a flaw decreases with thickness if the ASME Section XI rules for allowable flaw sizes are adopted. The matrix of acceptable ferritic steels approximately twelve inches thick with their associated LST and limit state probability is shown in Table 7.

Table 7. Applicable ferritic steels for twelve inch wall thickness.

Criterion	$P_F <$	-20°F	-10°F	0°F	10°F	20°F
FA-EX-YS	10^{-2}	X	X	508-4A	508-4A	508-4A 508-4B
	10^{-3}	X	X	X	508-4A	508-4A
	10^{-4}	X	X	X	X	508-4A
	10^{-5}	X	X	X	X	508-4A
	10^{-6}	X	X	X	X	508-4A
FA-AX-YS	10^{-2}	X	508-4A	508-4A	508-4A 508-4B	508-4A 508-4B
	10^{-3}	X	X	508-4A	508-4A	508-4A 508-4B
	10^{-4}	X	X	X	508-4A	508-4A
	10^{-5}	X	X	X	508-4A	508-4A
	10^{-6}	X	X	X	X	508-4A
FI-YS $a/\ell \rightarrow 0$	10^{-2}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5
	10^{-3}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5
FI-YS $a/\ell \rightarrow 1/6$	10^{-2}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5
	10^{-3}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5

Table 7. (continued)

Criterion	$P_F <$	-20°F	-10°F	0°F	10°F	20°F
F_I-YS $a/\ell \to 1/2$	10^{-2}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5
	10^{-3}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5
	10^{-4}	508-4A 508-4A 350-3	508-4A 508-4B 350-3	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5	508-4A 508-4B 350-3 350-5

5.0 CONCLUSIONS AND RECOMMENDATIONS

The cost difference between the fracture arrest material selection criteria and the fracture initiation criteria at yield stress levels is too narrow to influence a recommendation based upon cost impact alone; more significant, however, is the impact of these criteria on comparative limit state probabilities. On this basis, the lower limit state probabilities associated with FI-YS make it more desirable as a brittle fracture prevention criterion than either FA-EX-YS or FA-AX-YS. Furthermore, FI-YS allows the use of a variety of materials at the LST of -20°F. Note, however, that if inspection procedures associated with steels qualified for prevention of fracture initiation are applied to steels selected in accordance with fracture arrest criteria, casks fabricated of such steels would have the lowest limit state probabilities for a relatively modest increase in cost.

All criteria involving the specification of stresses less than yield suffer a cost penalty due to the necessity of performing a stress analysis. In addition to the cost penalty the uncertainties associated with these analyses can only result in a further reduction in limit state probability below those associated with criteria based on yield stress levels for FA-EX-PS and FA-AX-PS. In the case of FI-PS, the use of lower stresses in conjunction with ASME Section XI allowable flaw sizes would result in lower limit state probabilities. However, the uncertainties associated with the stress analysis would counter this advantage. To quantify this effect one would not only have to establish the statistics relating to the accuracy of the stress analysis, but would also have to evaluate the joint distribution of the stress analyses and the flaw size variations. This latter effort is beyond the scope of the program.

In the case of the drop test, the cost is somewhat greater than the design criteria based on yield stress levels. However, the uncertainties associated with the stress analyses need not be considered so that the limit state probabilities would be as low or lower than the criteria based on yield stress levels. Further quantification of limit state probabilities associated with the drop test cannot be done, since the allowable flaw size is established at some fraction of an arbitrary test flaw. If the test flaw is assumed critical or "quasi-critical," then the limit state probability would be about the same as that associated with FI-YS.

6.0 REFERENCES

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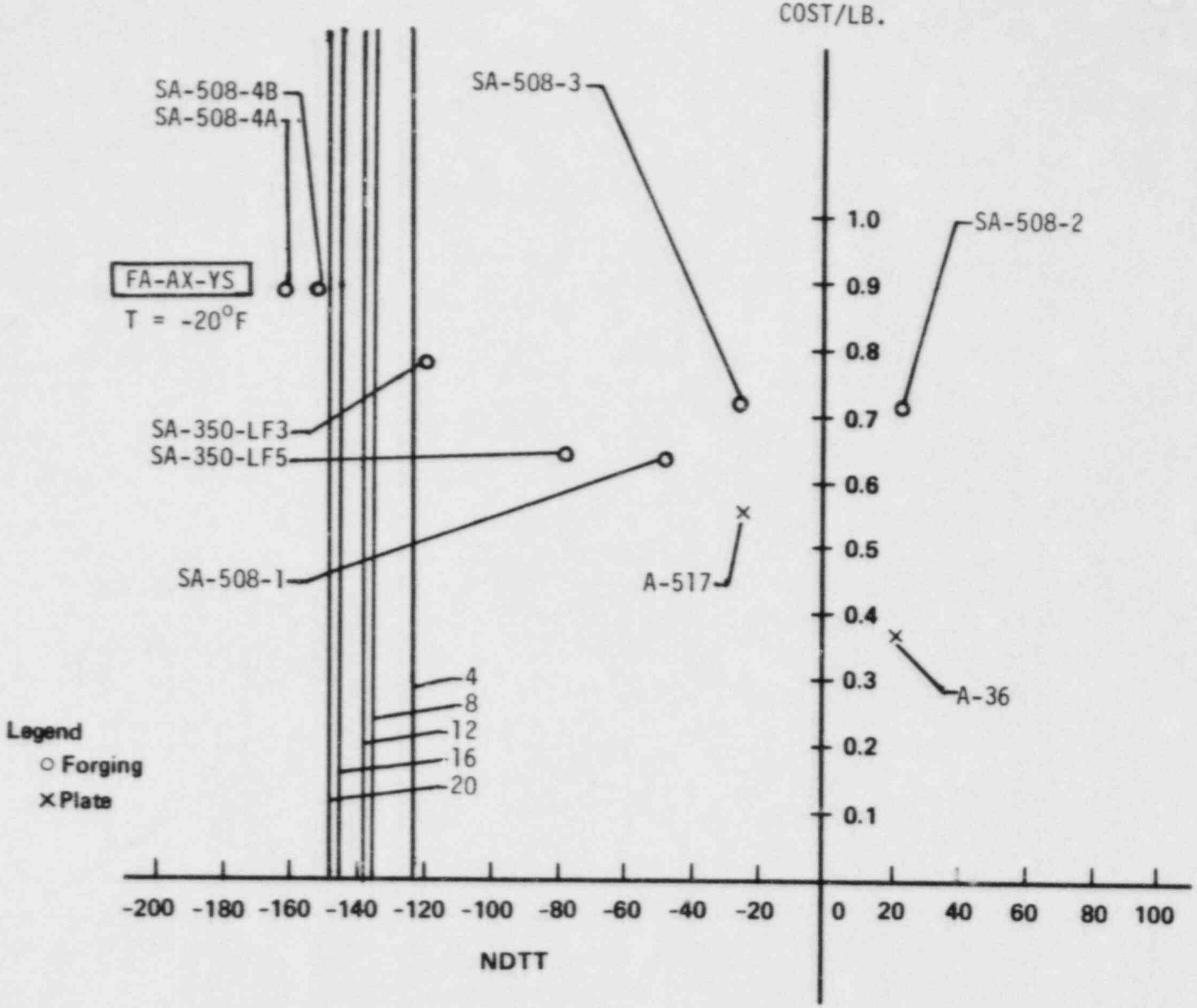
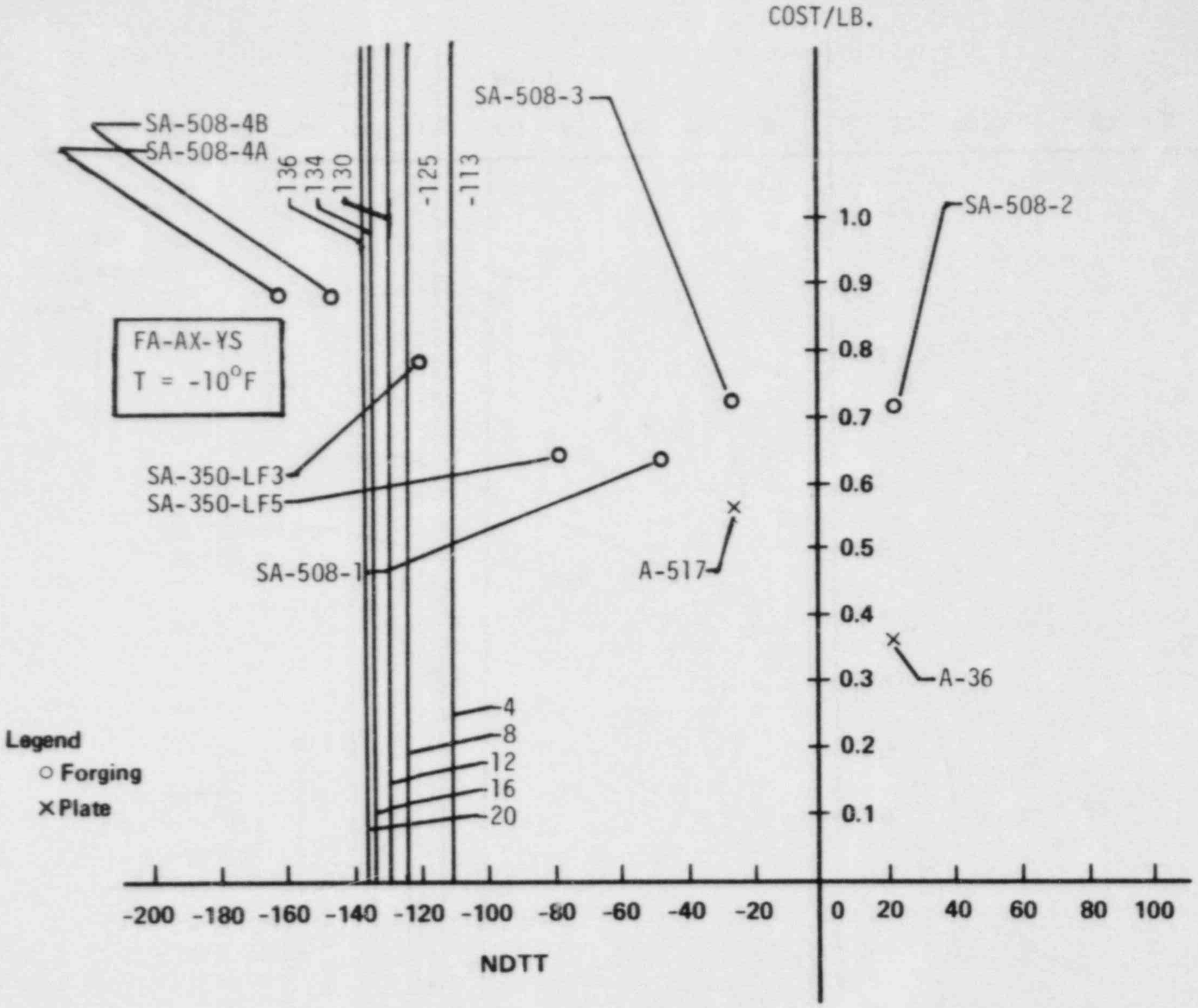
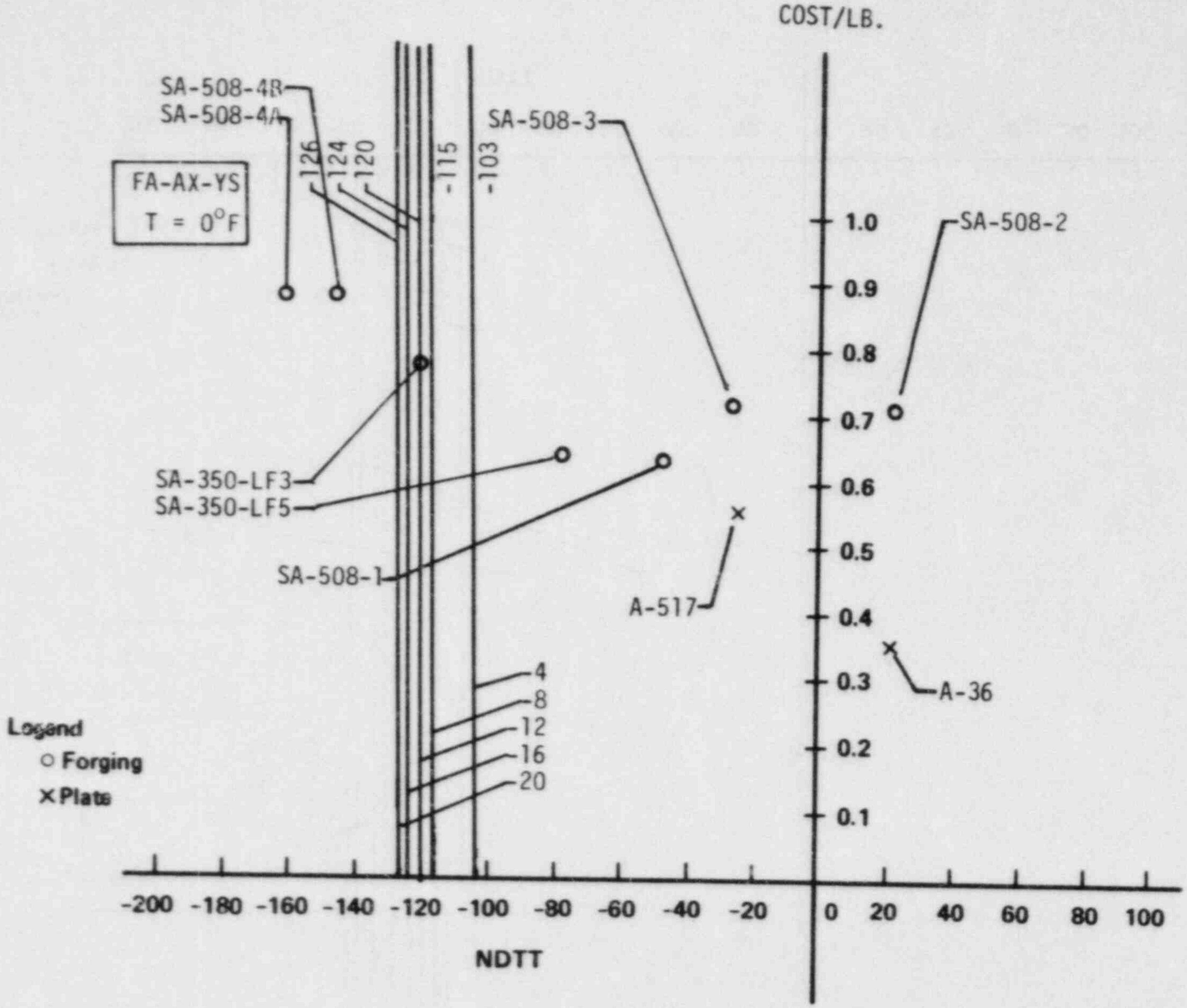
APPENDIX A

Charts Indicating Applicability of Ferritic Steels to Various Brittle Fracture Acceptance Criteria


COST/LB.
SA-508-4B
SA-508-4A
SA-508-3
FA-AX-YS
T = -20°F
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
4
8
12
16
20
Legend
○ Forging
× Plate
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
SA-508-4B
SA-508-4A
136
134
130
-125
-113
SA-508-3
SA-508-2
FA-AX-YS
T = -10°F
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
4
8
12
16
20
Legend
○ Forging
× Plate


COST/LB.
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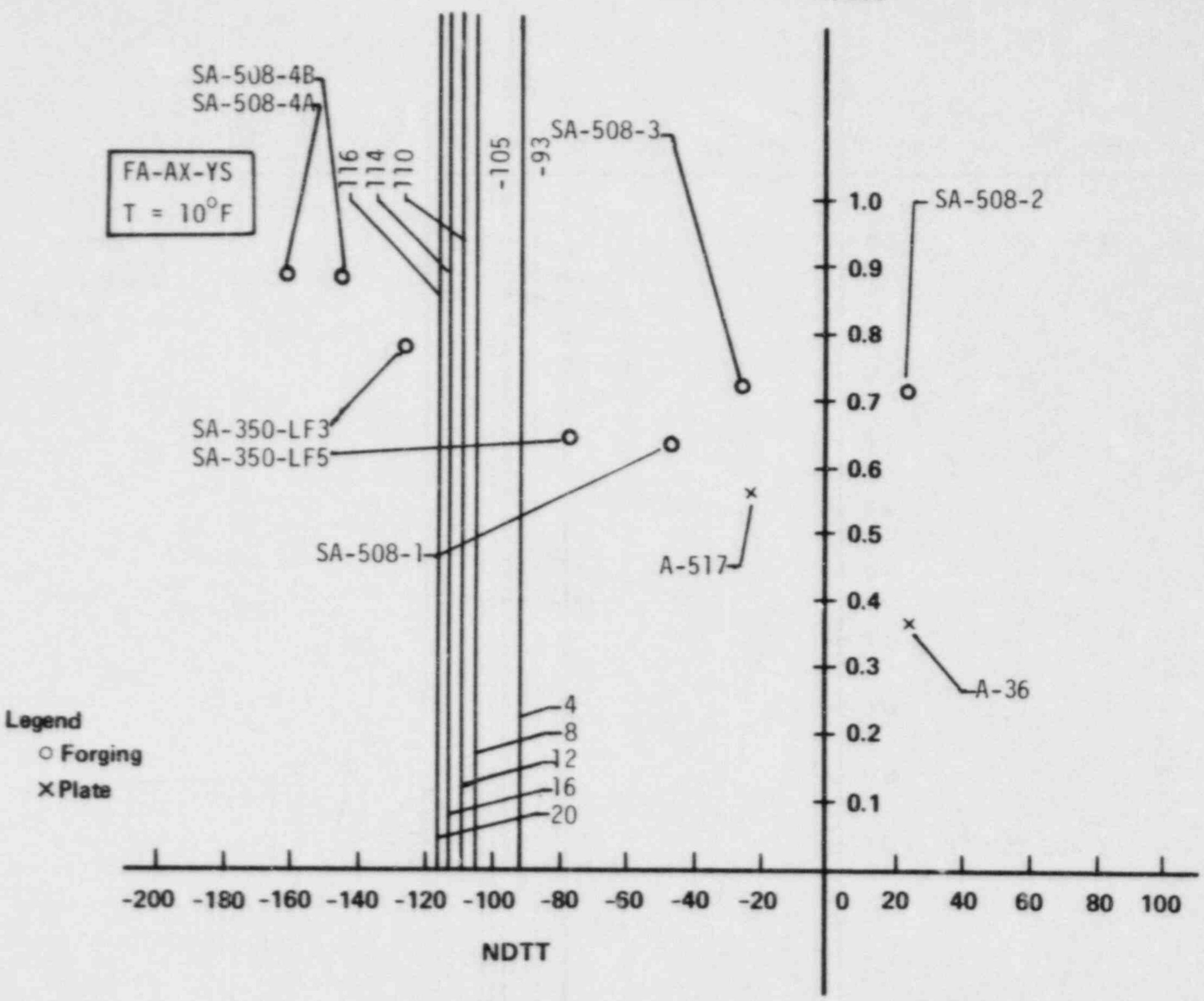
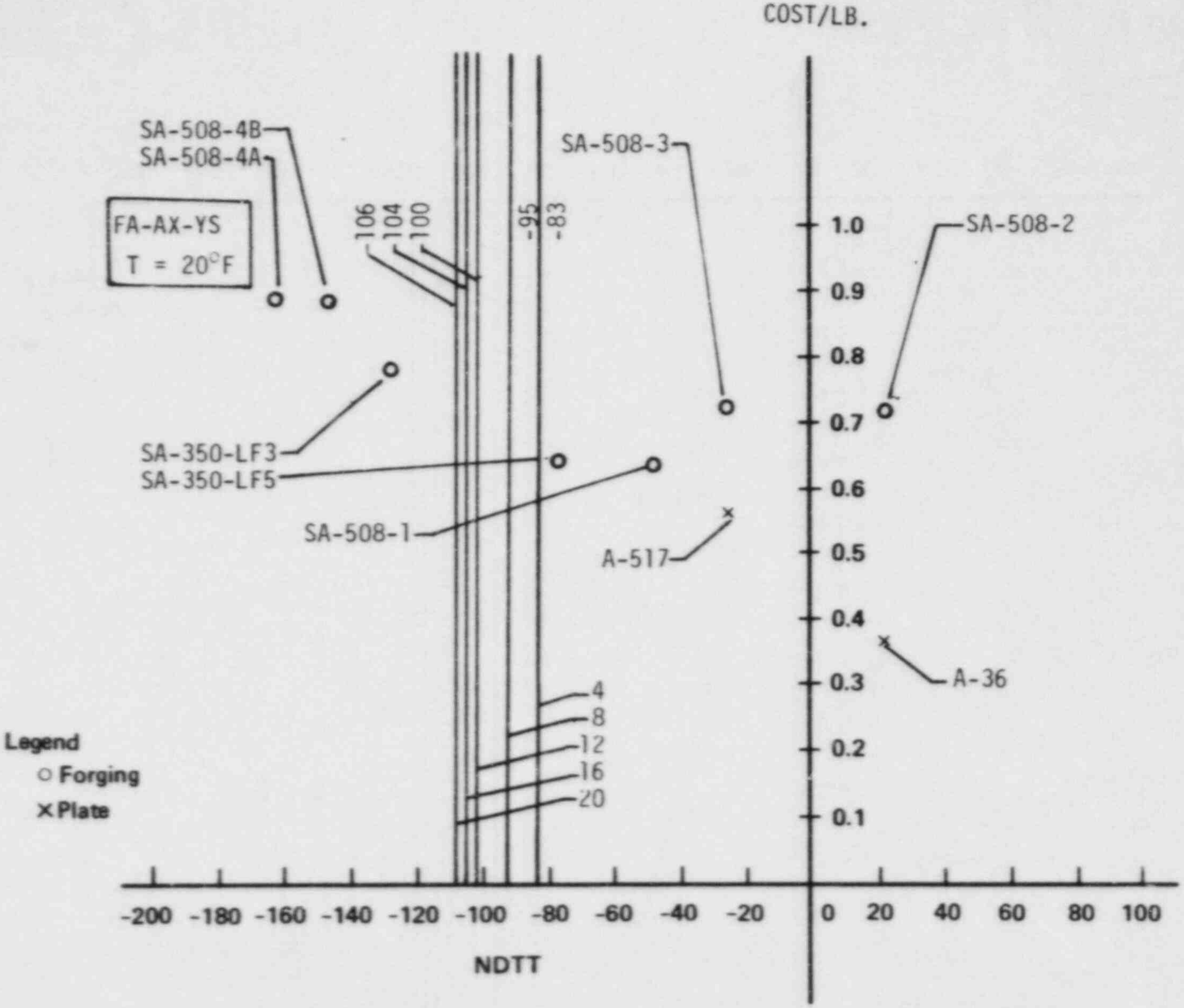
SA-508-4A
FA-AX-YS
T = 0°F
-126
-124
-120
-115
-103
SA-508-3
SA-508-2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
4
8
12
16
20
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
FA-AX-YS
T = 10°F
SA-508-4B
SA-508-4A
116
114
110
-105
-93
SA-508-3
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
4
8
12
16
20
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate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FA-AX-YS
T = 20°F
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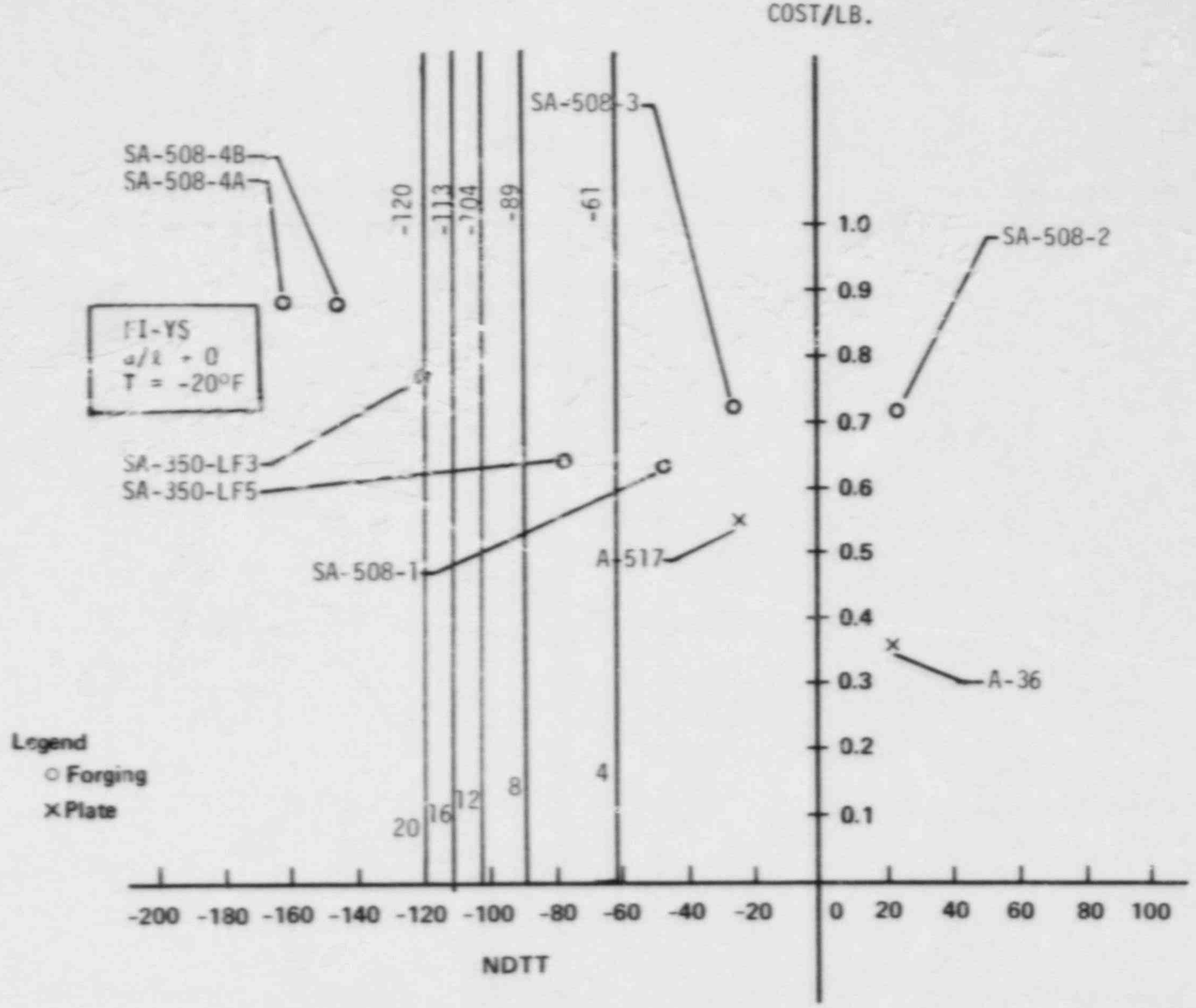
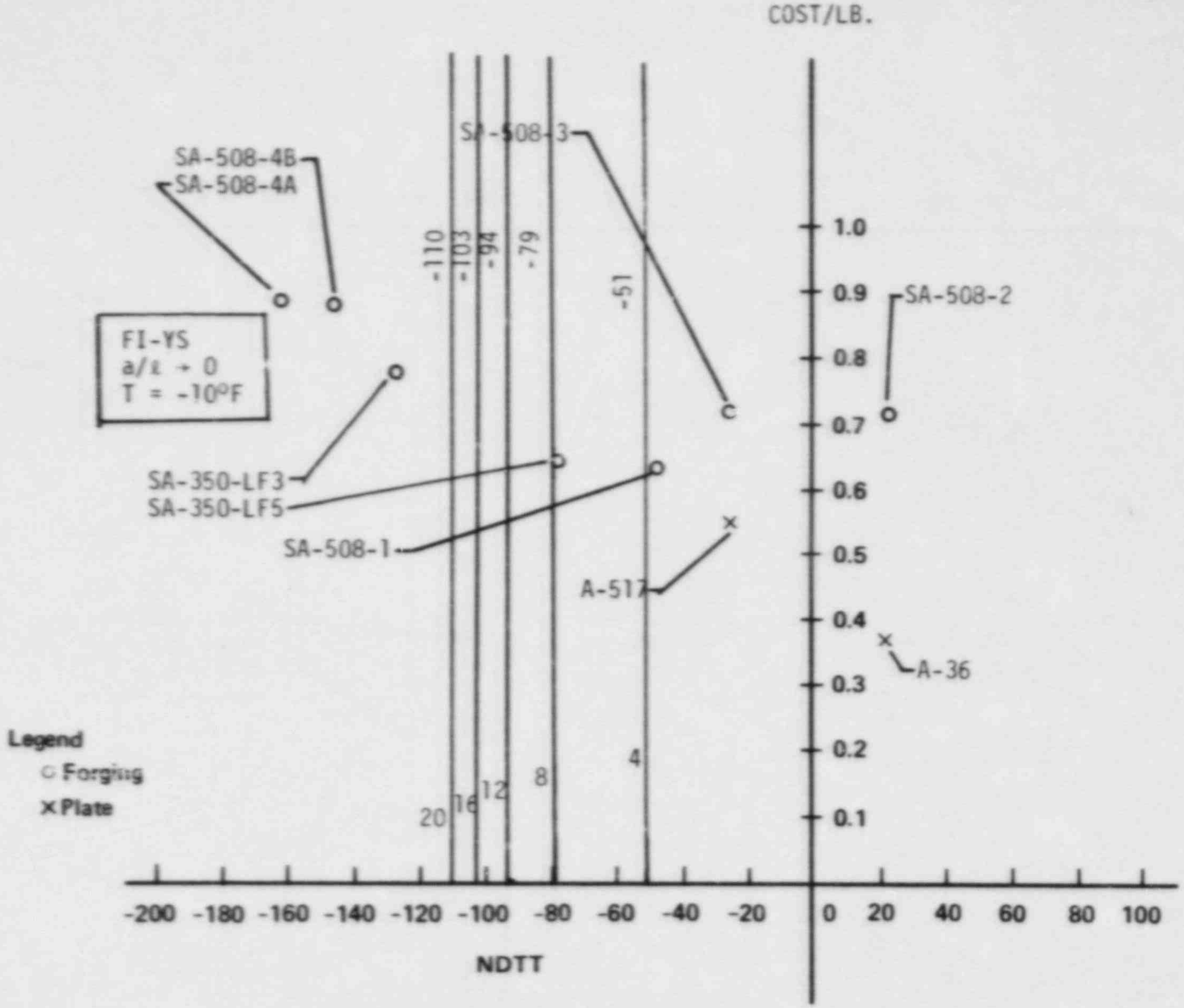
SA-508-4A
SA-508-3
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
-106
-104
-100
-95
-83
4
8
12
16
20
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate


COST/LB.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100
NDTT
-120
-113
-104
-89
-61
20
16
12
8
4
SA-508-4B
SA-508-4A
FI-YS
a/ℓ → 0
T = -20°F
SA-350-LF3
SA-350-LF5
SA-508-1
SA-508-3
A-517
SA-508-2
A-36
Legend
○ Forging
× Plate


COST/LB.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
SA-508-4B
SA-508-4A
FI-YS
a/ℓ → 0
T = -10°F
SA-350-LF3
SA-350-LF5
SA-508-1
SA-508-3
A-517
SA-508-2
A-36
-110
-103
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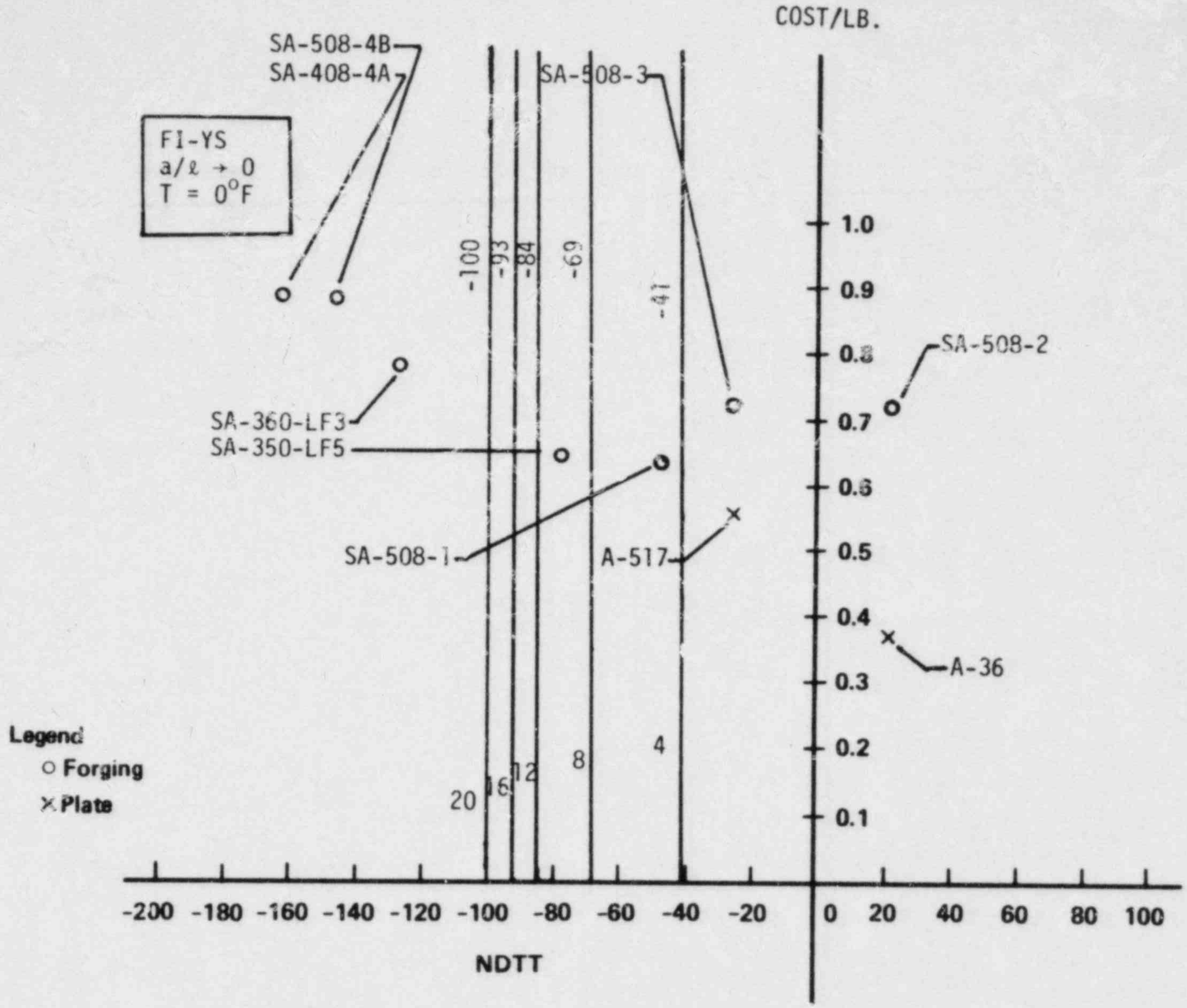
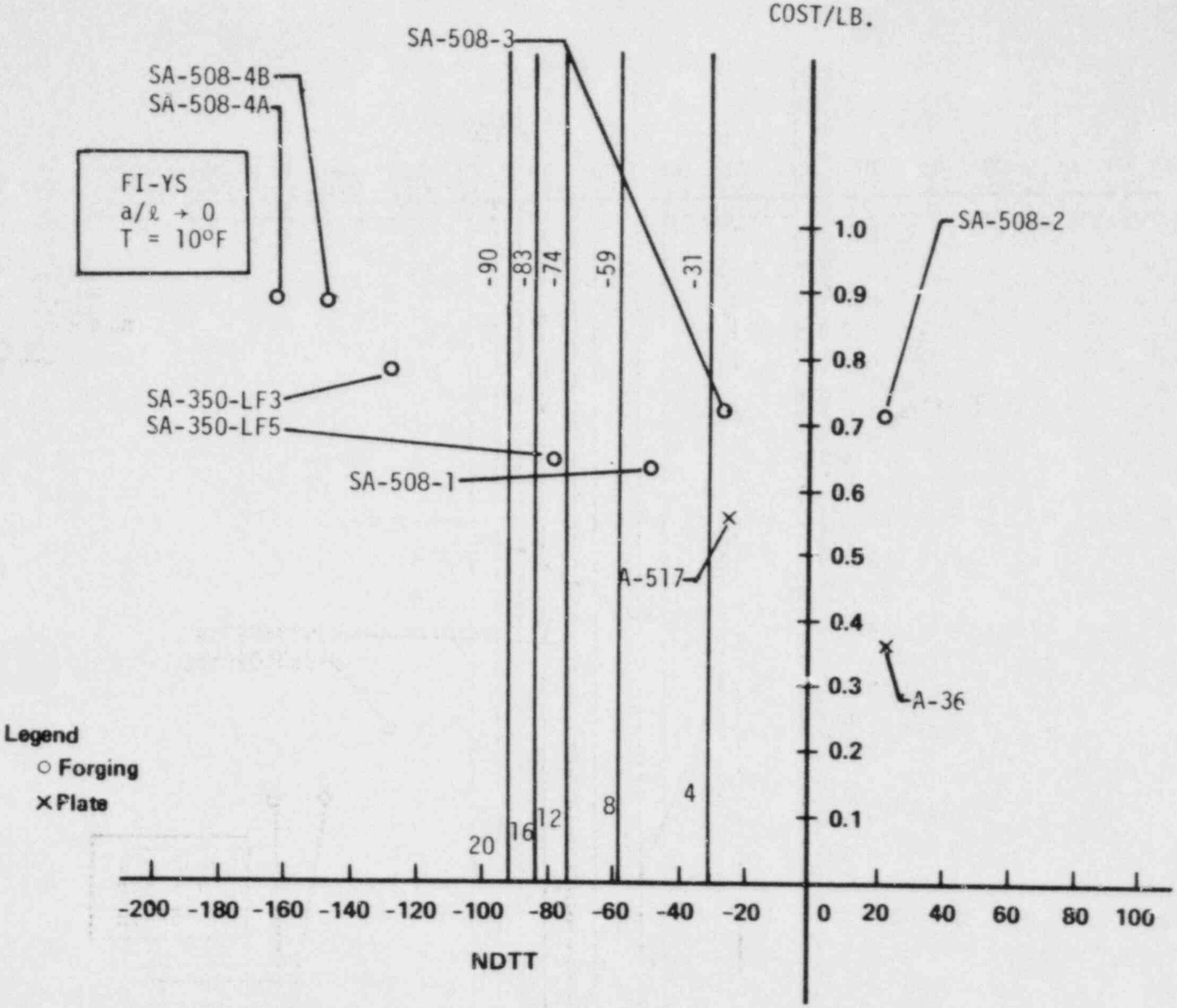
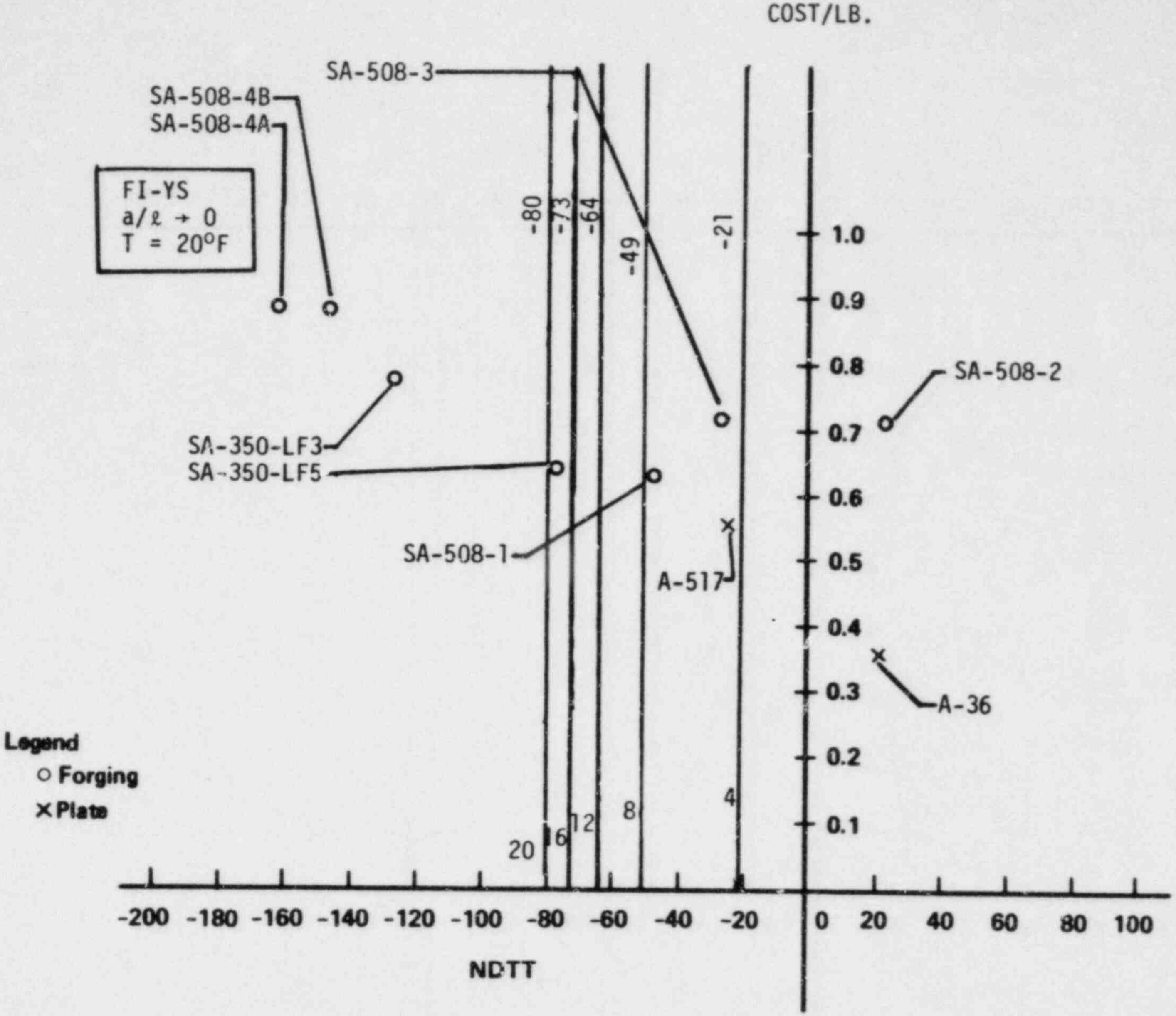
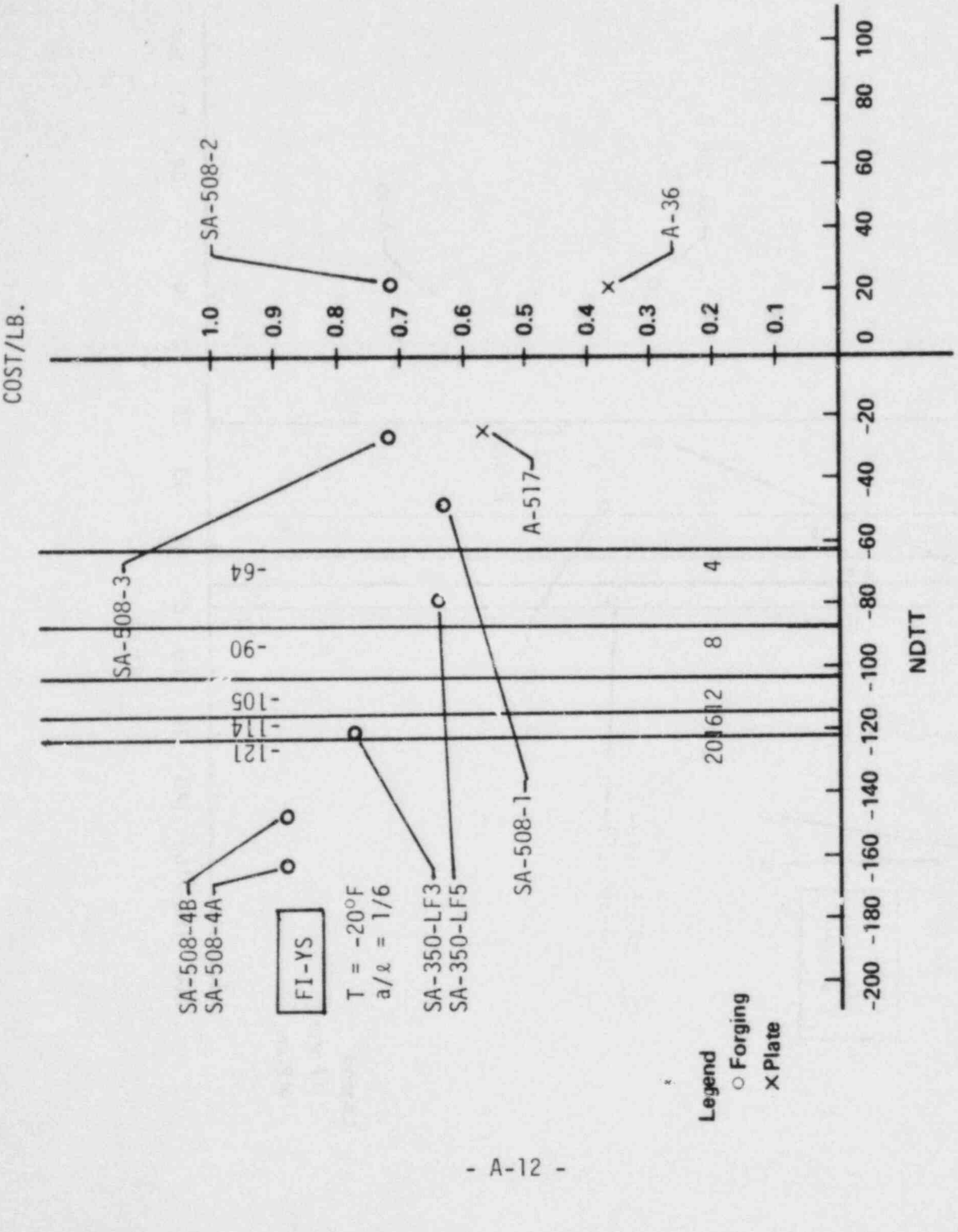
-79
-51
20
16
12
8
4
Legend
○ Forging
× Plate

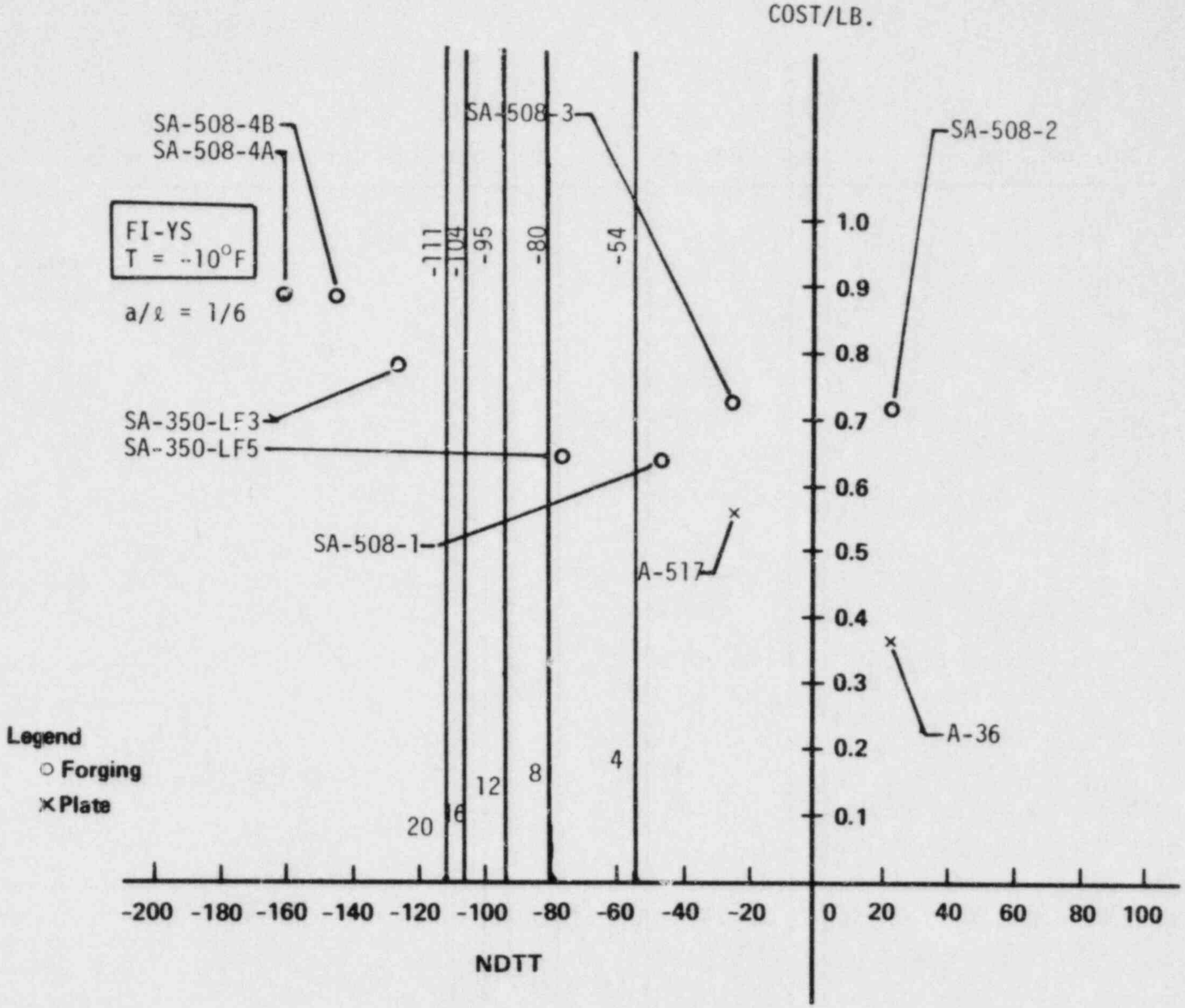

COST/LB.
FI-YS
a/ℓ → 0
T = 0°F
SA-508-4B
SA-408-4A
SA-508-3
SA-508-2
SA-360-LF3
SA-350-LF5
SA-508-1
A-517
A-36
-100
-93
-84
-69
-41
20
16
12
8
4
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate


COST/LB.
SA-508-3
SA-508-4B
SA-508-4A
FI-YS
a/ℓ → 0
T = 10°F
-90
-83
-74
-59
-31
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20
16
12
8
4
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate


COST/LB.
FI-YS
a/ℓ → 0
T = 20°F
SA-508-3
SA-508-4B
SA-508-4A
SA-350-LF3
SA-350-LF5
SA-508-1
SA-508-2
A-517
A-36
-80
-73
-64
-49
-21
20
16
12
8
4
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate



COST/LB.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
SA-508-2
A-36
SA-508-3
A-517
SA-508-1
SA-350-LF3
SA-350-LF5
SA-508-4B
SA-508-4A
-64
-90
-105
-114
-121
4
8
12
16
20
FI-YS
T = -20°F
a/ℓ = 1/6
Legend
○ Forging
× Plate


COST/LB.
SA-508-4B
SA-508-4A
FI-YS
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a/ℓ = 1/6
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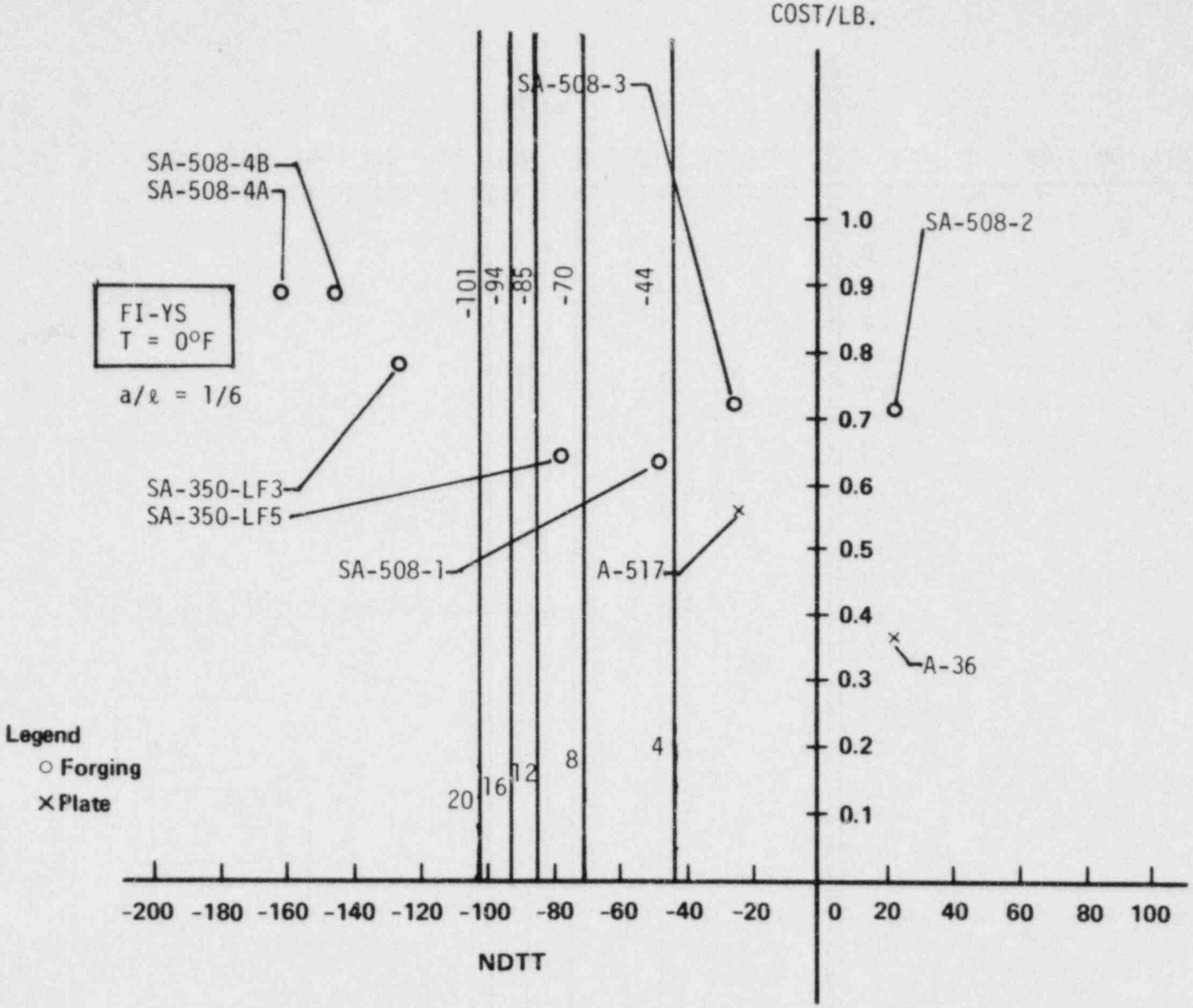
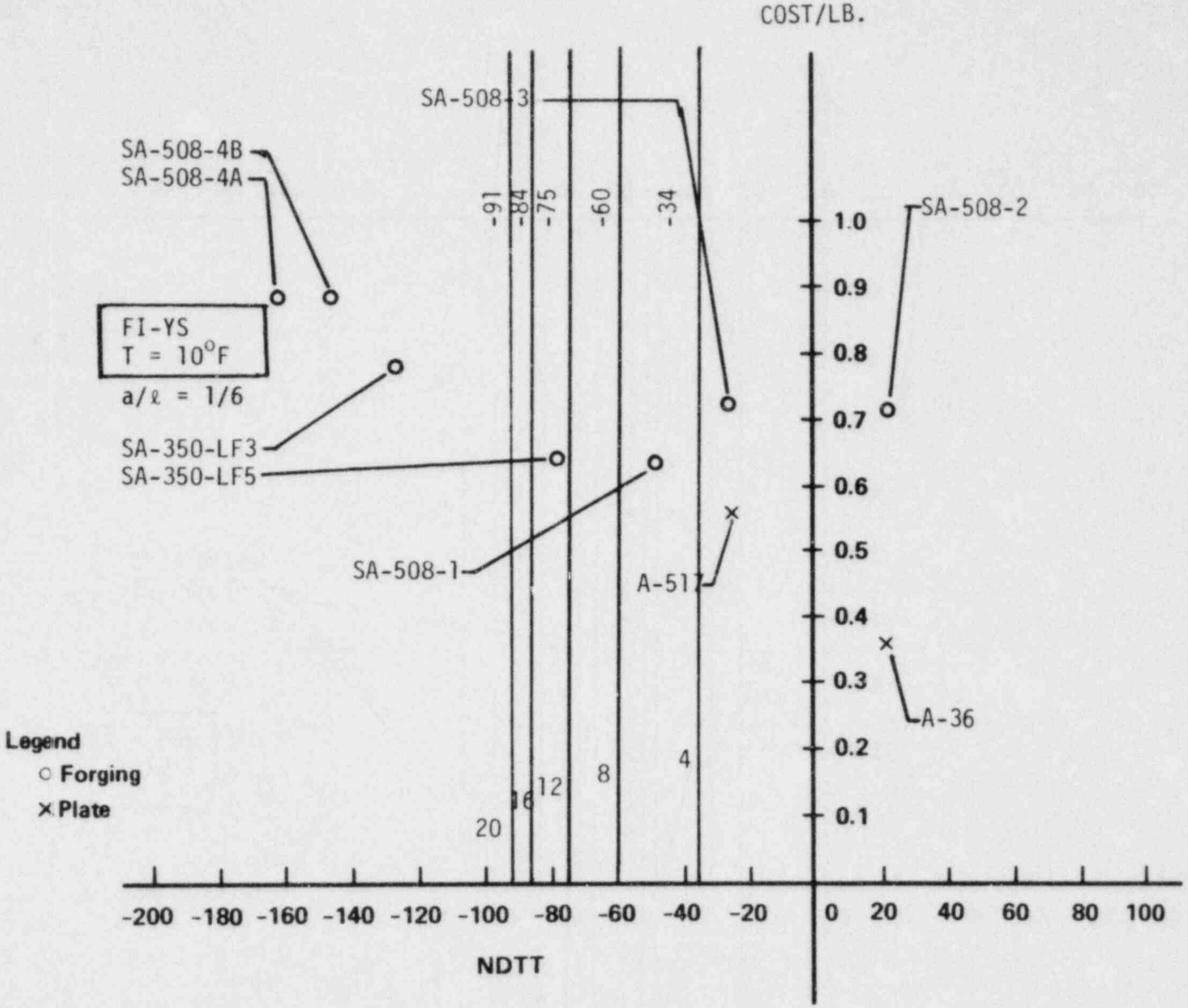
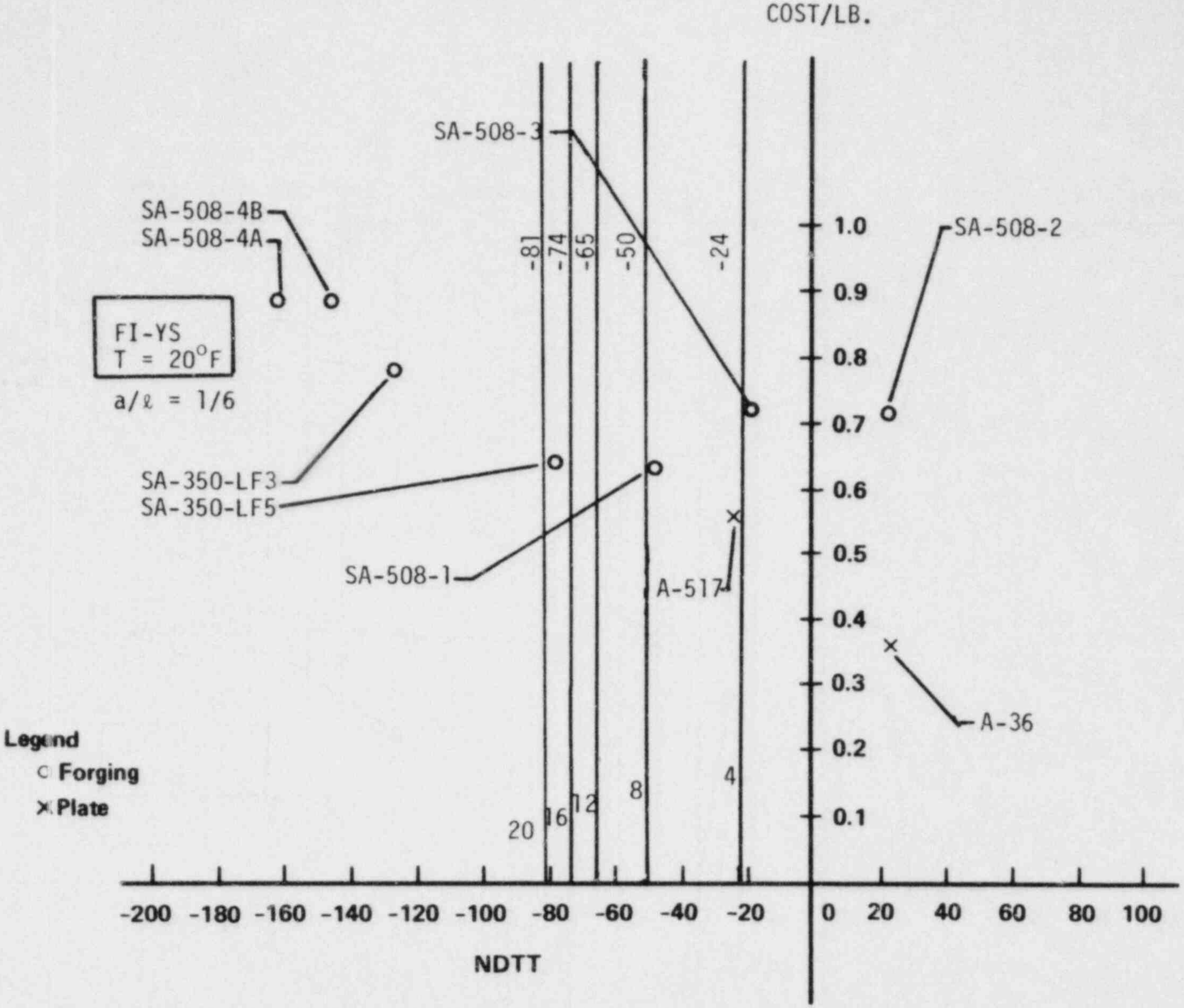
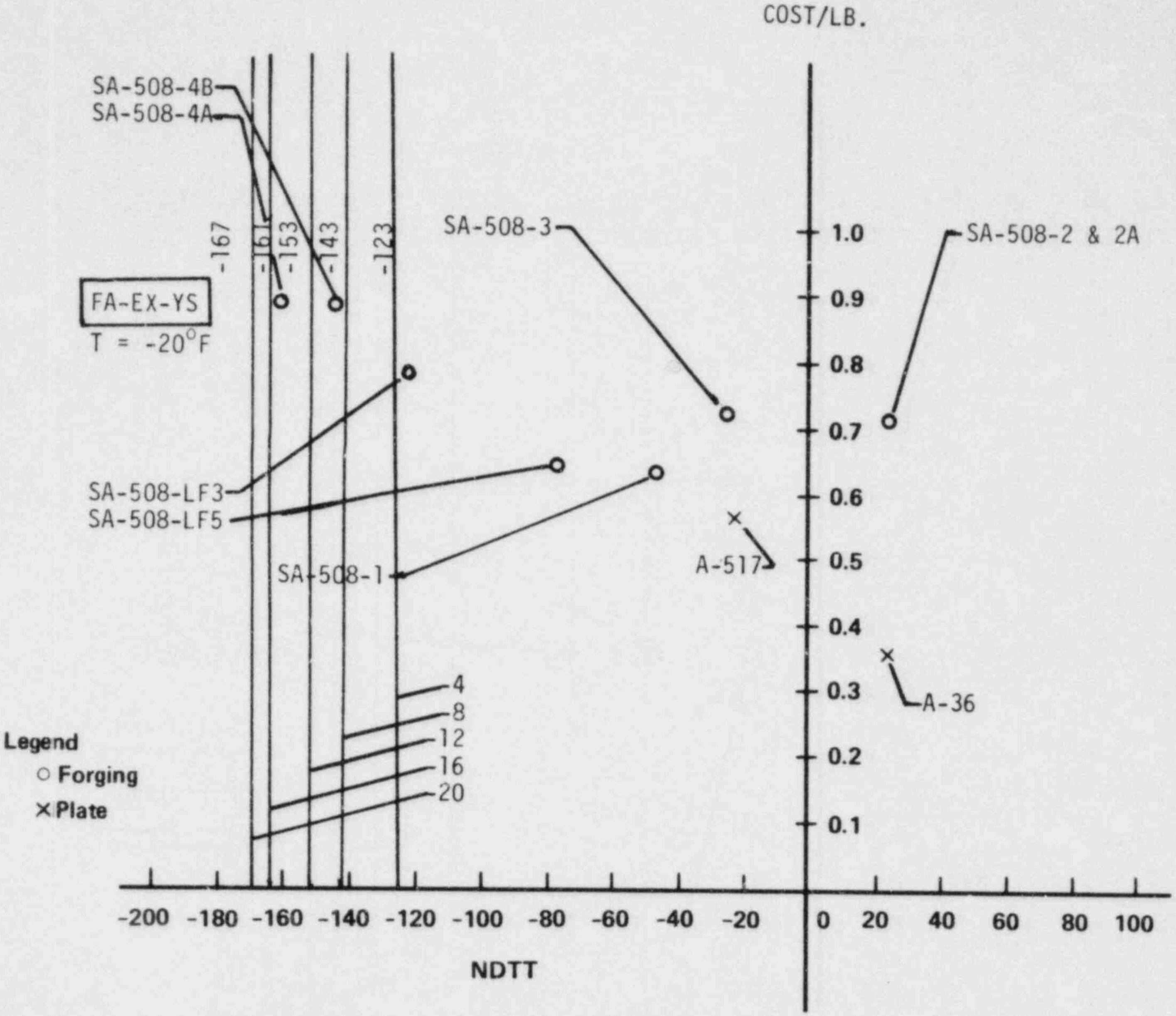
SA-508-2
-111
-104
-95
-80
-54
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20
16
12
8
4
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
SA-508-3
SA-508-4B
SA-508-4A
SA-508-2
FI-YS
T = 0°F
a/ℓ = 1/6
-101
-94
-85
-70
-44
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
20
16
12
8
4
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
SA-508-3
SA-508-4B
SA-508-4A
-91
-84
-75
-60
-34
SA-508-2
FI-YS
T = 10°F
a/ℓ = 1/6
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20
16
12
8
4
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT



COST/LB.
SA-508-3
SA-508-4B
SA-508-4A
FI-YS
T = 20°F
a/ℓ = 1/6
-81
-74
-65
-50
-24
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20
16
12
8
4
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT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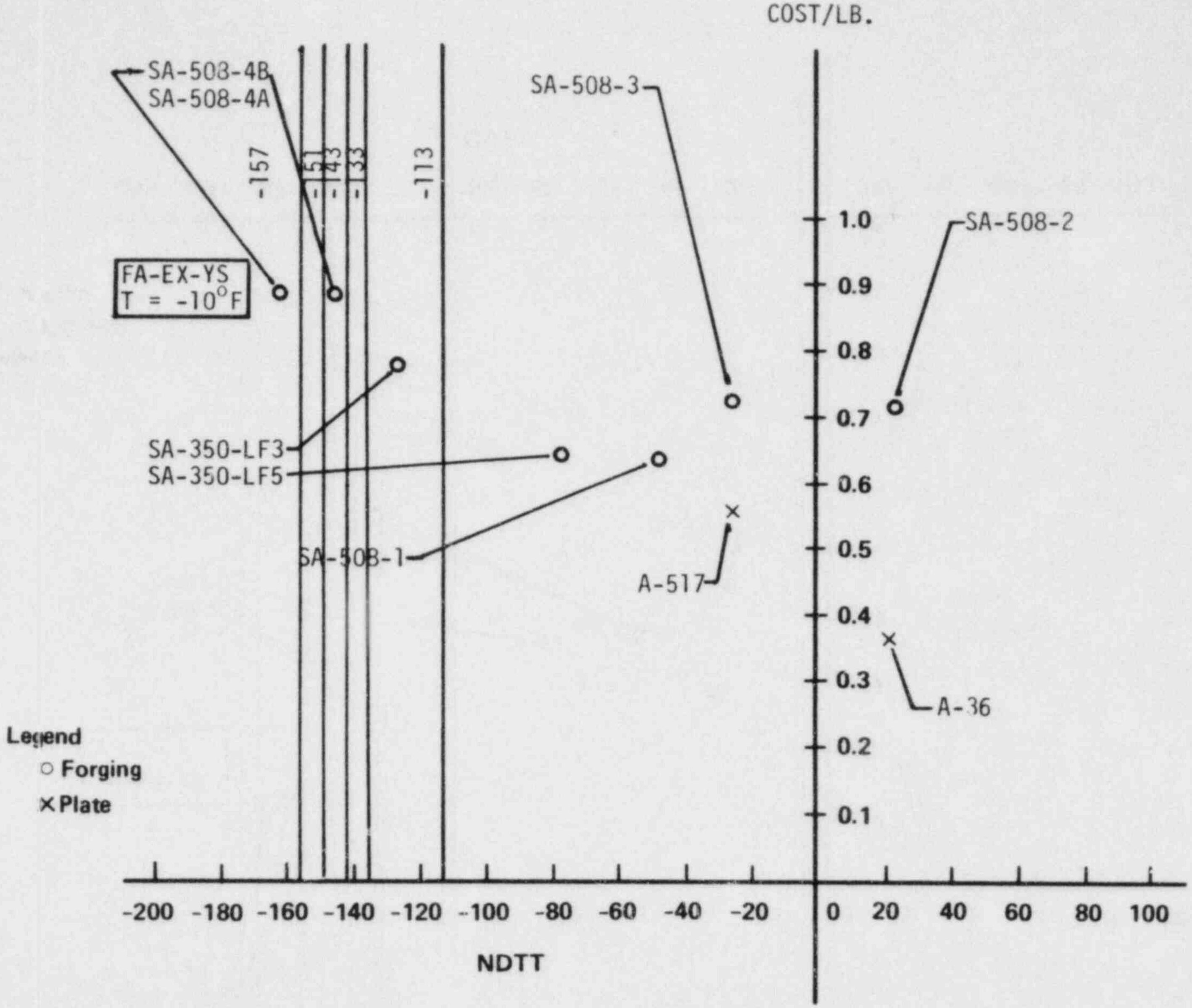
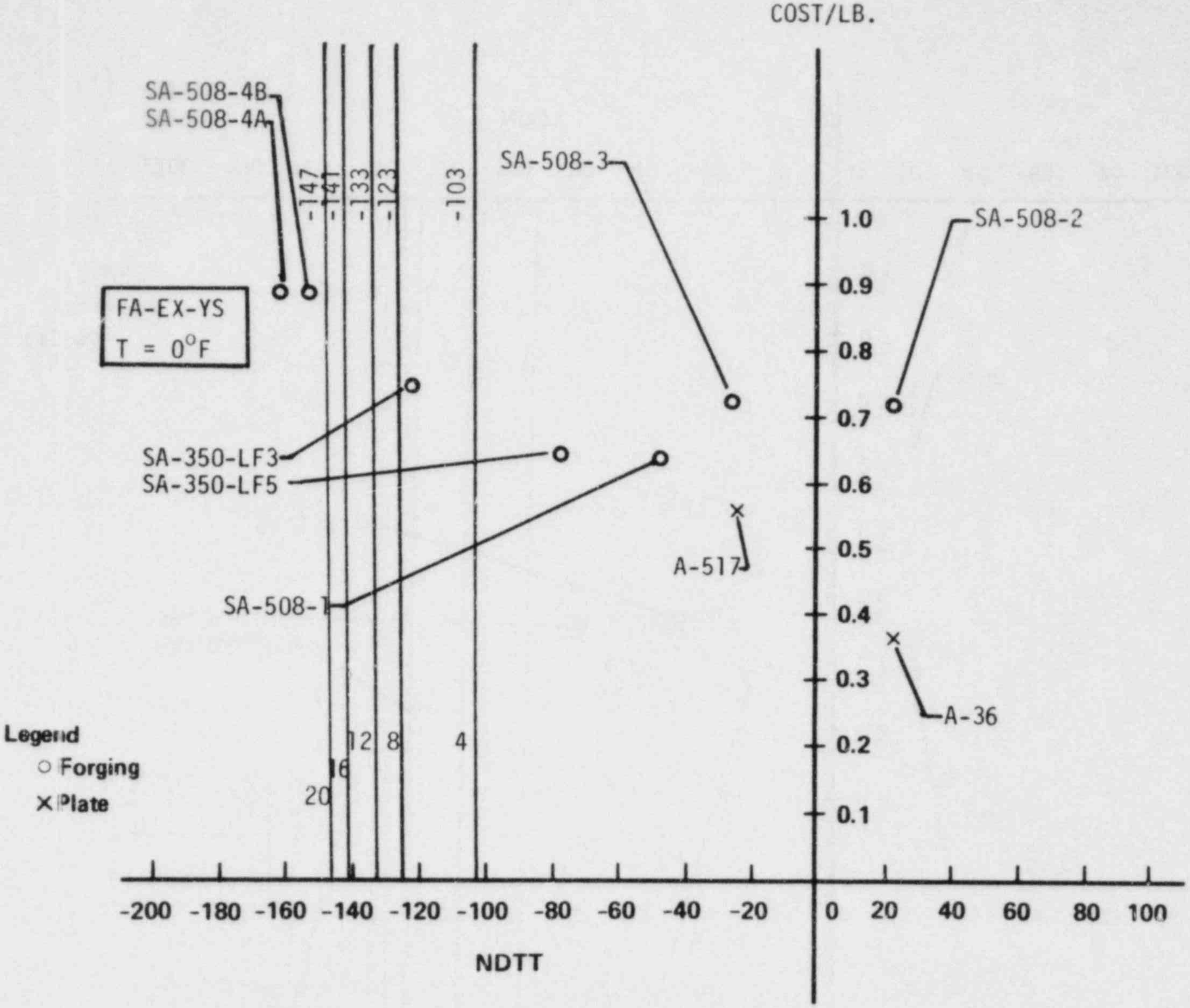
0.7
0.6
0.5
0.4
0.3
0.2
0.1
SA-508-4B
SA-508-4A
-167
-161
-153
-143
-123
FA-EX-YS
T = -20°F
SA-508-3
SA-508-2 & 2A
SA-508-LF3
SA-508-LF5
SA-508-1
A-517
A-36
4
8
12
16
20
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
SA-508-4B
SA-508-4A
-157
-151
-143
-133
-113
SA-508-3
SA-508-2
FA-EX-YS
T = -10°F
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate



COST/LB.
SA-508-4B
SA-508-4A
-147
-141
-133
-123
-103
SA-508-3
SA-508-2
FA-EX-YS
T = $0^{o}F$
SA-350-LF3
SA-350-LF5
A-517
SA-508-1
A-36
Legend
○ Forging
× Plate
12
8
4
16
20
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
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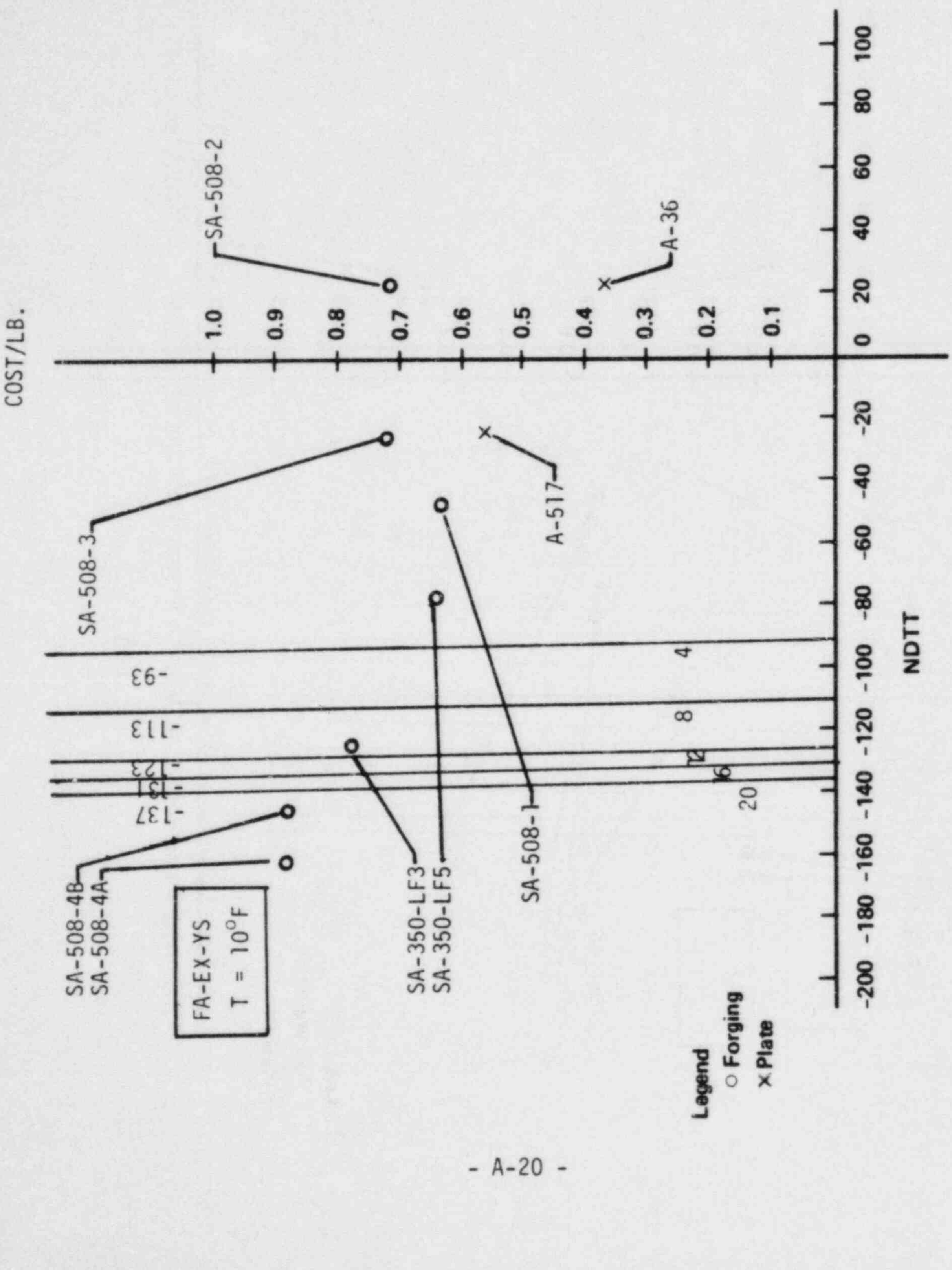
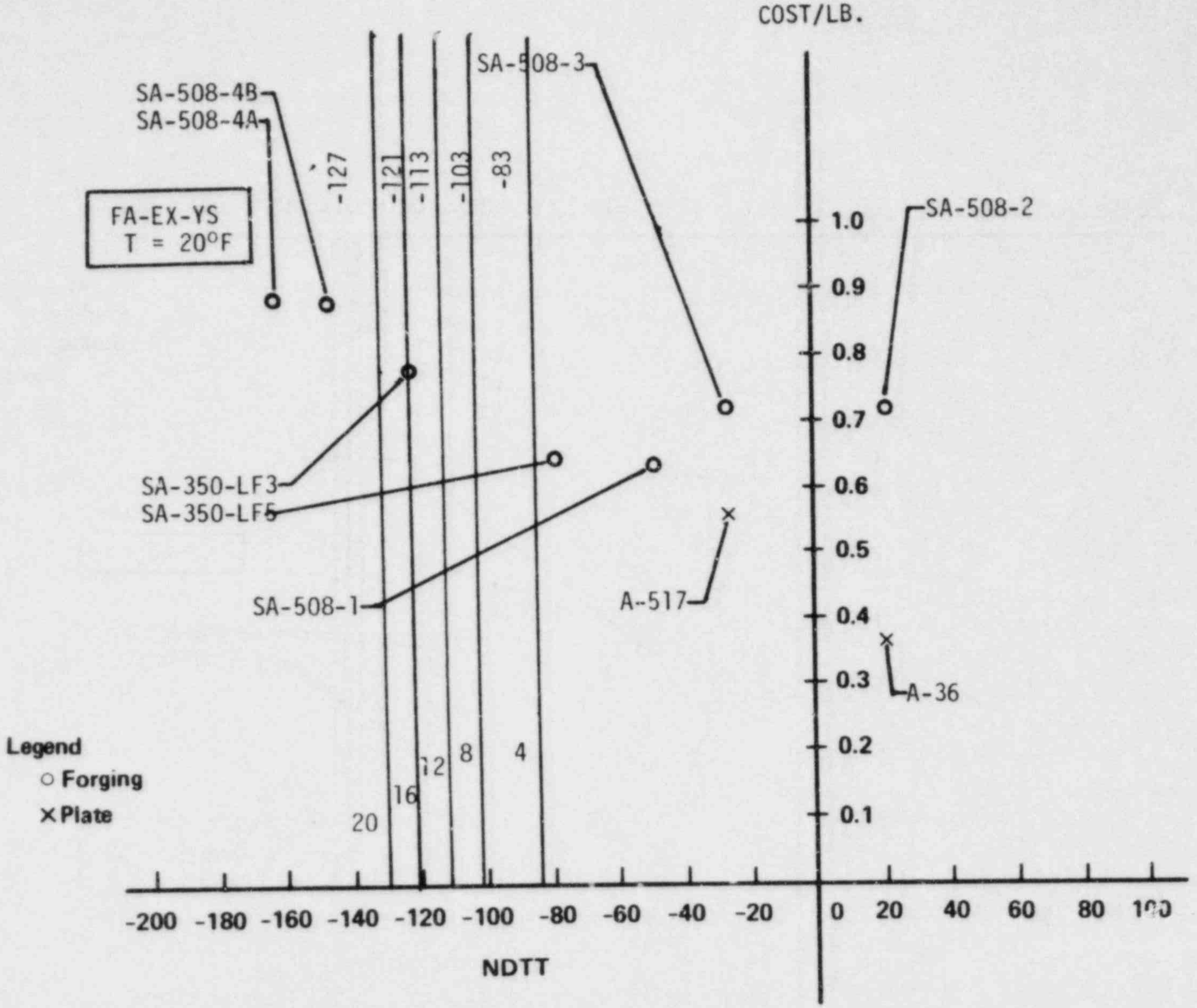
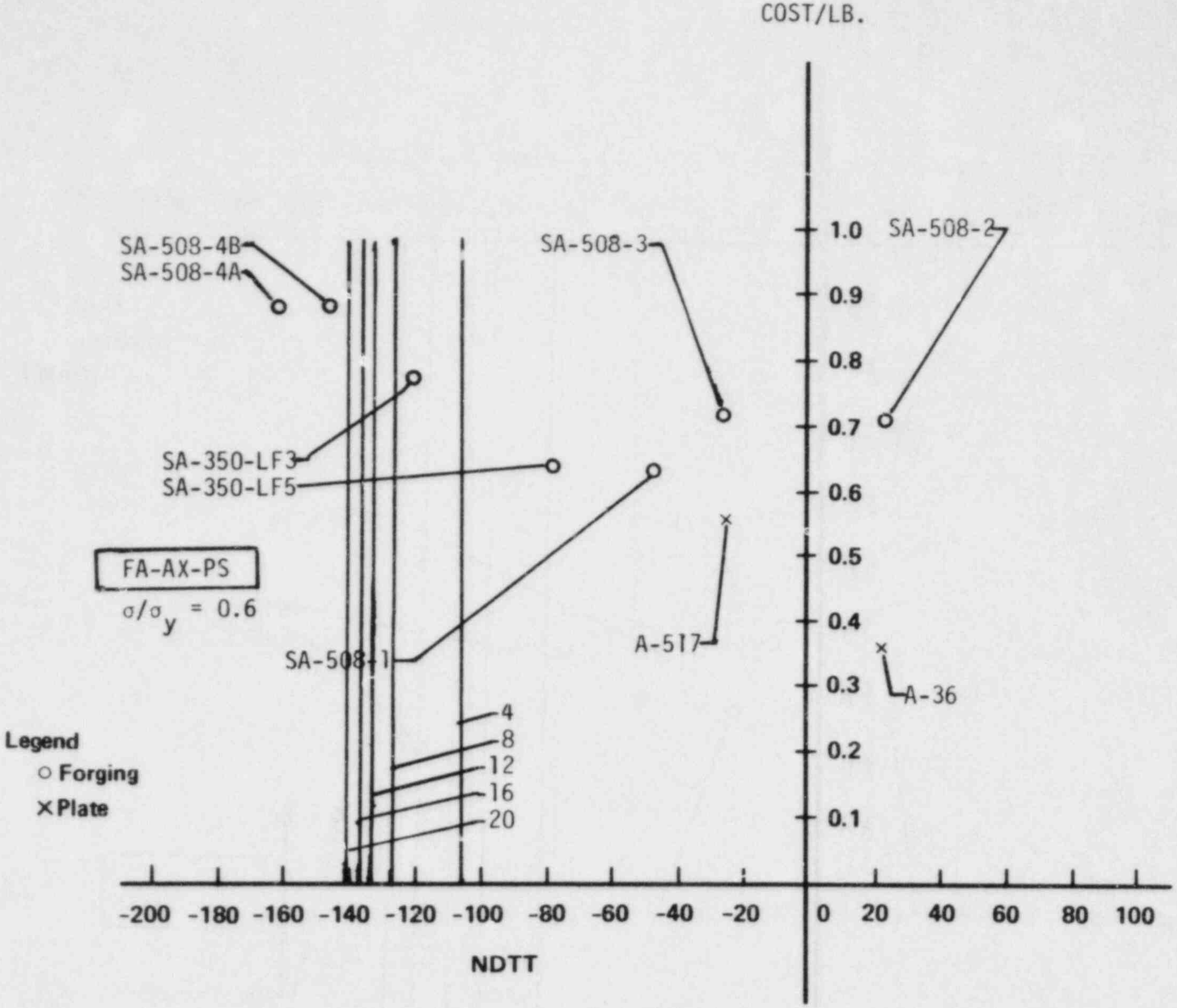
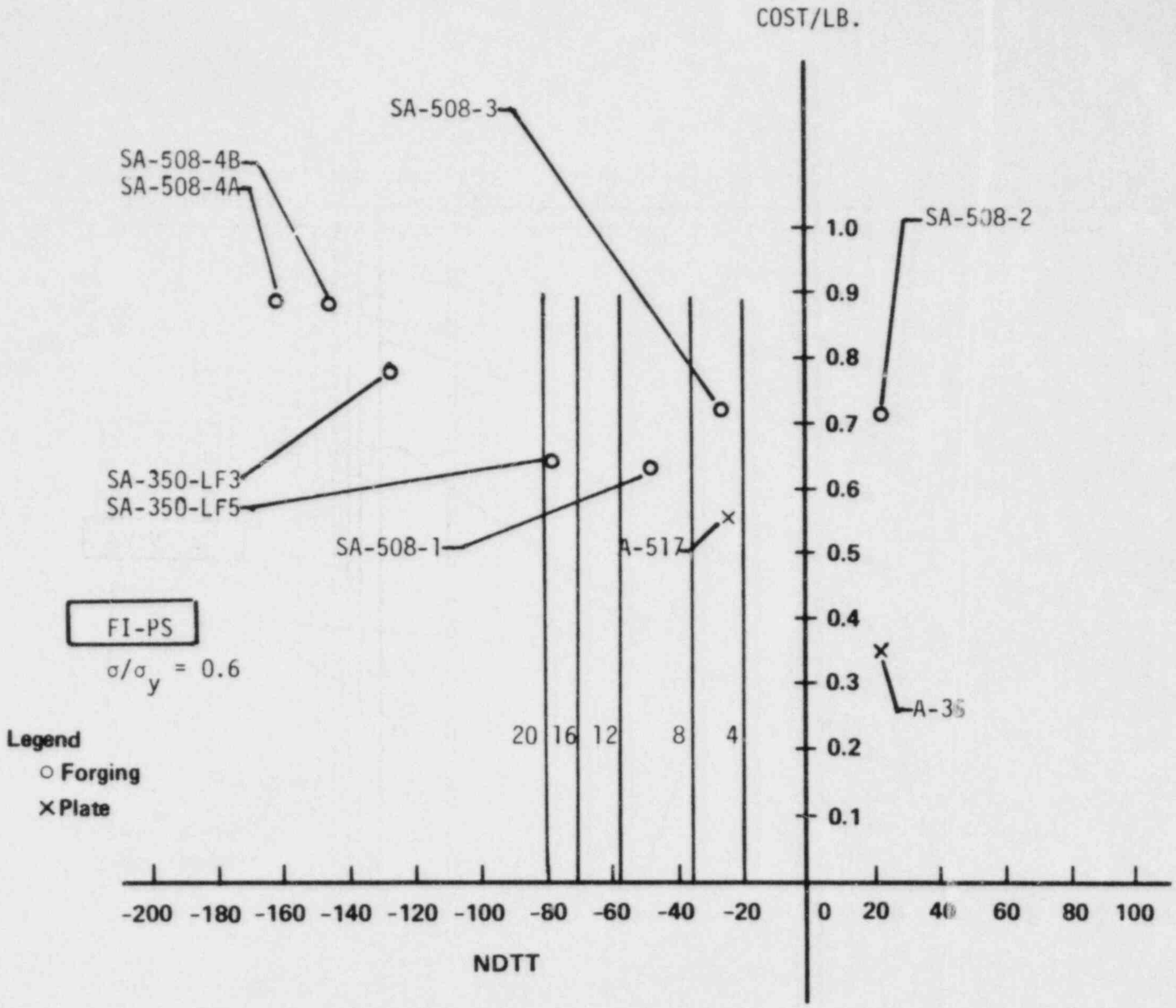
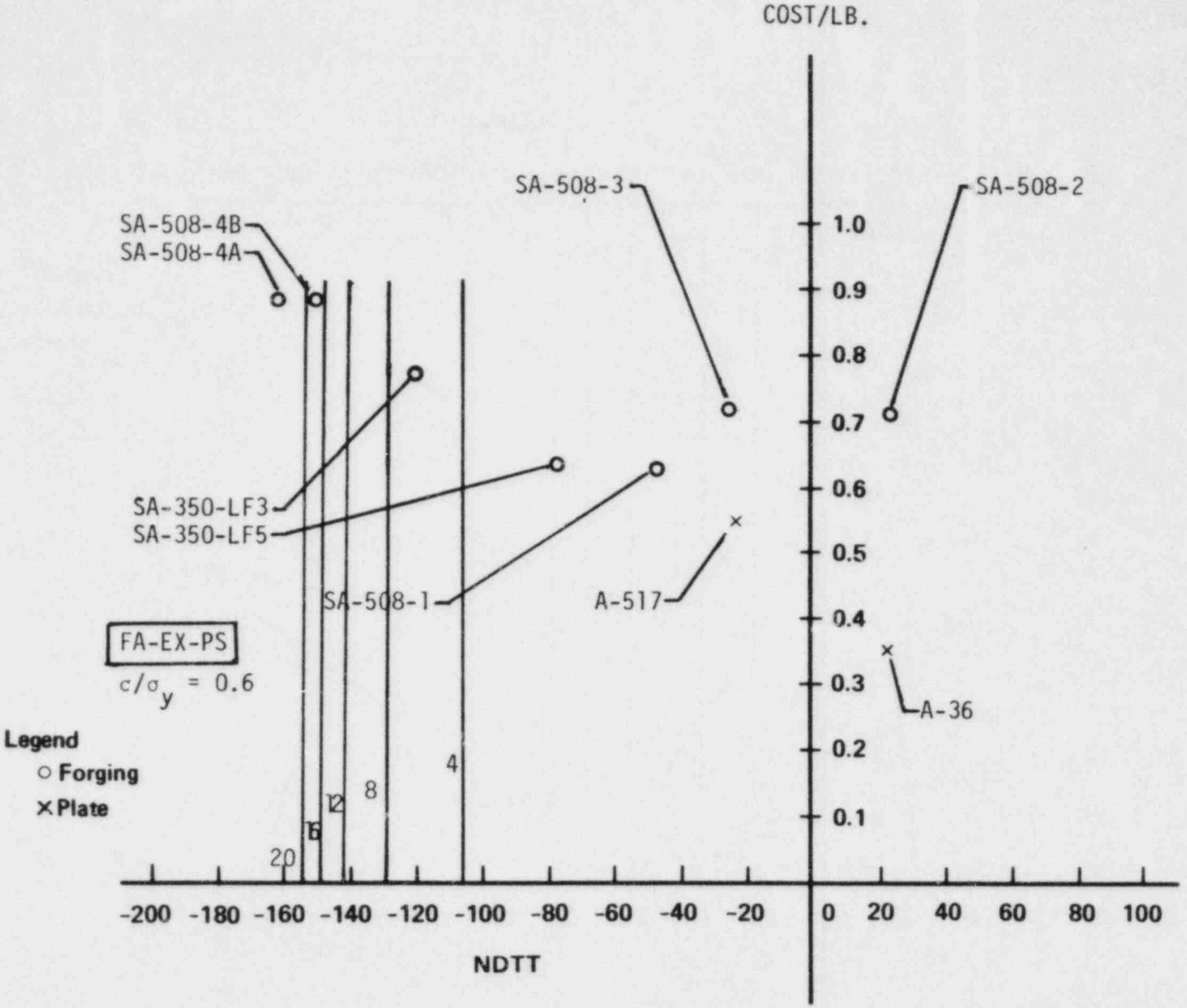
NDTT


COST/LB.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
NDTT
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
SA-508-2
A-36
SA-508-3
A-517
SA-508-4B
SA-508-4A
SA-350-LF3
SA-350-LF5
SA-508-1
-93
-113
-123
-131
-137
4
8
12
16
20
FA-EX-YS
T = 10°F
Legend
○ Forging
× Plate


COST/LB.
FA-EX-YS
T = 20°F
SA-508-4B
SA-508-4A
SA-508-3
SA-508-2
SA-508-1
SA-350-LF3
SA-350-LF5
A-517
A-36
-127
-121
-113
-103
-83
4
8
12
16
20
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT
Legend
○ Forging
× Plate


COST/LB.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
SA-508-4B
SA-508-4A
SA-508-3
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
FA-AX-PS
$\sigma/\sigma_y = 0.6$
4
8
12
16
20
Legend
○ Forging
× Plate
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
SA-508-3
SA-508-4B
SA-508-4A
SA-508-2
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
FI-PS
σ/σ_y = 0.6
Legend
○ Forging
× Plate
20
16
12
8
4
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT


COST/LB.
SA-508-3
SA-508-2
SA-508-4B
SA-508-4A
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
SA-350-LF3
SA-350-LF5
SA-508-1
A-517
A-36
FA-EX-PS
$c/\sigma_y = 0.6$
Legend
○ Forging
× Plate
4
8
12
16
20
-200
-180
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
NDTT

APPENDIX B

Ferritic Forging Cask Cost Estimate

APPENDIX B. FERRITIC FORGING CASK COST ESTIMATE

A detailed analysis of the cost associated with the baseline cask and each of the fracture toughness acceptance criteria is presented in Tables B1 through B7. An explanation of the bases for these costs is presented in the following subsequent appendices.

Appendix C	Design Cost Factors
Appendix D	Engineering Analysis Costs
Appendix E	Quarterly Assurance Engineering Costs
Appendix F	Manufacturing Cost Assumptions and Estimates
Appendix G	Wage and Salary Rates
Appendix H	Basic Cost Factors

Table B1. Baseline ferritic forging cost estimate.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	5210	18.84	98151				25158
Design Verification	1156	16.96	19617				981
Design QA	887	18.17	16110				806
Design Review	450	20.71	9320				466
Program Management	2653	26.34	69862				3493
Subtotals	12855	19.38	249128				32707
Labor Fringe @ 40%			99651				
Engr. O/H @ 56.44%			196851				
Direct Engr. Cost:							578337
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.65	58565
Mat'ls Engr.	540	18.74	10119				2300
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1066	18.17	19262				968
Program Management	489	26.34	12877				644
Subtotals	8516	13.78	117387				62675
Labor Fringe @ 30%			35216				
Mfr. O/H @ 47.73%			74364				
Direct Mfr. Cost:							289641
UNIT COST (5 Items)							
Direct Engr. Cost			115667				
Direct Mfr. Cost			2899641				
G&A @ 12.75%			51677				
TOTAL COST (5th Item):			456986				

Table B2. Forging cost estimate for criteria FA/EX-YS.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	5615	18.84	105721				25873
Design Verification	1217	16.96	20647				1032
Design QA	933	18.17	16956				848
Design Review	450	20.71	9320				466
Program Management	2786	26.34	73368				3668
Subtotals	13501	19.41	262080				33690
Labor Fringe @ 40%			104832				
Engr. O/H @ 56.44%			207085				
Direct Engr. Cost:							607688
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.89	80189
Mat'ls Engr.	600	18.74	11232				2600
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1124	18.17	20418				1021
Program Management	520	26.34	13686				684
Subtotals	8664	13.89	117387				84692
Labor Fringe @ 30%			35216				
Mfr. O/H @ 47.73%			74364				
Direct Mfr. Cost:							317416
UNIT COST (5 Items)							
Direct Engr. Cost			121538				
Direct Mfr. Cost			317416				
G&A @ 12.75%			57690				
TOTAL COST (5th Item):			494921				

Table B3. Forging cost estimate for criteria FA/EX-PS.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	6468	18.84	121855				53162
Design Verification	1345	16.96	22818				1141
Design QA	1031	18.17	18739				937
Design Review	450	20.71	9320				466
Program Management	3067	26.34	80760				4038
Subtotals	14861	19.48	289561				61547
Labor Fringe @ 40%			115824				
Engr. O/H @ 56.44%			228800				
Direct Engr. Cost:							695733
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.89	80189
Mat'ls Engr.	600	18.72	11232				2600
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1230	18.17	22356				1118
Program Management	547	26.34	14416				721
Subtotals	8799	13.98	123034				84826
Labor Fringe @ 30%			36910				
Mfr. O/H @ 47.73%			77941				
Direct Mfr. Cost:							322711
UNIT COST (5 Items)							
Direct Engr. Cost			139147				
Direct Mfr. Cost			322711				
G&A @ 12.75%			59576				
TOTAL COST (5th Item):			520745				

Table B4. Forging cost estimate for criteria FA/AX-YS.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	5615	18.84	121855				25873
Design Verification	1217	16.96	22818				1032
Design QA	933	18.17	18739				848
Design Review	450	20.71	9320				466
Program Management	2786	26.34	80760				3668
Subtotals	13501	19.41	262080				33690
Labor Fringe @ 40%			104832				
Engr. O/H @ 56.44%			207085				
Direct Engr. Cost:							607688
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.89	80189
Mat'ls Engr.	600	18.72	11232				2600
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1124	18.17	20418				1021
Program Management	520	26.34	13686				684
Subtotals	8664	13.89	120365				84692
Labor Fringe @ 30%			36109				
Mfr. O/H @ 47.73%			76250				
Direct Mfr. Cost:							317416
UNIT COST (5 Items)							
Direct Engr. Cost			121538				
Direct Mfr. Cost			317416				
G&A @ 12.75%			56656				
TOTAL COST (5th Item):			494921				

Table B5. Forging cost estimate for criteria FI-YS.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	6085	18.81	114449				26945
Design Verification	1288	16.96	21843				1092
Design QA	987	18.17	17938				897
Design Review	450	20.71	9320				466
Program Management	2940	26.34	77439				3872
Subtotals	14250	19.44	277058				35075
Labor Fringe @ 40%			110823				
Engr. O/H @ 56.44%			218920				
Direct Engr. Cost:							641876
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.77	69377
Mat'ls Engr.	690	18.71	12910				3050
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1194	18.17	21690				1084
Program Management	561	26.34	14781				739
Subtotals	8866	14.03	124410				74448
Labor Fringe @ 30%			37323				
Mfr. O/H @ 47.73%			78813				
Direct Mfr. Cost:							314994
UNIT COST (5 Items)							
Direct Engr. Cost			128375				
Direct Mfr. Cost			314994				
G&A @ 12.75%			58483				
TOTAL COST (5th Item):			499899				

Table B6. Forging cost estimate for criteria FI-PS.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	7791	18.83	146710				136101
Design Verification	1544	16.96	26186				1309
Design QA	1183	18.17	21505				1075
Design Review	450	20.71	9320				466
Program Management	3502	26.34	92224				4611
Subtotals	16970	19.56	332012				145366
Labor Fringe @ 40%			132805				
Engr. O/H @ 56.44%			262343				
Direct Engr. Cost:							872526
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.65	58565
Mat'ls Engr.	690	18.71	12910				3050
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1407	18.17	25567				1278
Program Management	617	26.34	16242				812
Subtotals	9135	14.20	129748				63903
Labor Fringe @ 30%			38924				
Mfr. O/H @ 47.73%			82194				
Direct Mfr. Cost:							314769
UNIT COST (5 Items)							
Direct Engr. Cost			174505				
Direct Mfr. Cost			314769				
G&A @ 12.75%			551995				
TOTAL COST (5th Item):			494921				

Table B7. Forging cost estimate for criteria DT.

COST COMPONENT	LABOR			MATERIALS			
	Hours	Rate $	Extension $	Qty	Unit	Rate $	Extension $
ENGINEERING DEVELOPMENT							
Design	2500	14.43	36067				1803
Analysis & Materials	5210	18.84	98151				25158
Design Verification	1156	16.96	19617				981
Design QA	887	18.17	16610				806
Design Review	450	20.71	9320				466
Program Management	2653	26.34	69862				3493
Subtotals	12855	19.38	249128				32707
Labor Fringe @ 40%			99651				
Engr. O/H @ 56.44%			196851				
Direct Engr. Cost:							867978
FABRICATION - 5th Article							
Forged Steel	6146	11.56	71076	90100	lbs	0.65	58565
Mat'ls Engr.	540	18.74	10119				2300
Mfr. Liaison	275	14.38	3953				198
QA @ 12.5%	1066	18.17	19362				968
Program Management	489	26.34	12877				644
Subtotals	8516	13.78	117387				62675
Labor Fringe @ 30%			35216				
Mfr. O/H @ 47.73%			74364				
Direct Mfr. Cost:							289641
UNIT COST (5 Items)							
Direct Engr. Cost			173596				
Direct Mfr. Cost			289641				
G&A @ 12.75%			59063				
TOTAL COST (5th Item):			522300				

APPENDIX C

Design Cost Factors

APPENDIX C. DESIGN COST FACTORS

Much of the engineering effort is proportional to the complexity of the design. Complexity takes many forms: numbers of subassemblies, differing types of subsystems, the required precision in the fabrication or machining of these subsystems, etc. The present focus of the U.S. nuclear industry is upon the transportation of well-aged nuclear fuel. This implies passive casks with "dry" cooling systems. The engineering level-of-effort factors presented in this section are applicable only to this form of transportation cask without active mechanical cooling systems and without "wet" cavities. This limitation avoids introduction of different major engineering disciplines into an already complex program.

Engineering design, along with analysis, is considered to be a "lead" discipline with other engineering functions derived from these activities. With the limitation noted above, the complexity of an irradiated fuel cask is proportional to the number of component subassemblies and the degree of fabrication or machining precision required. Engineering design is assumed to be directly proportional to these factors. Experience indicates that the average subassembly generates about 2.5 sheets of engineering fabrication drawings. Experience also indicates that each sheet of drawings requires, on the average, about 80 hours of engineering design/drafting effort, split equally between design and drafting. Since "false starts" are a fact of life with design, a "false start" correction factor of 1.25 is used. This results in a labor effort factor of 100 hours for each engineering drawing, or 250 hours for each subassembly. The total is increased by 15% to account for miscellaneous drawings of ancillary support equipment and presentation type materials (reports, reviews, etc.). This is subdivided among design phases as follows: 10% conceptual phase, 30% preliminary phase, 60% final design phase.

The remaining labor level-of-effort factors, for a conventional irradiated fuel cask design, are tabulated below along with a recapitulation of the engineering design effort described above. All values are based upon experience and judgment.

Labor Category	Factor	Base
• Engineering Design		
• Concept	30 hrs	Per subassembly
• Preliminary	85 hrs	Same
• Final Design	175 hrs	Same
• Design Verification	15%	All design and analysis disiplines
• Manufacturing Liaison	13%	Design hours, 1st article
	11%	Design hours, 5th article
	9%	Design hours, 20th article
• Quality Assurance (Conventional Only)		
• Design Phase	10%	Design, analysis, materials
• Fabrication	12%	Design, analysis, materials plus liaison, 1st article
	10%	Same, 5th article
	8%	Same, 20th article

	Labor Category	Factor	Base
•	Design Review	150 hrs	Per review (preparation and presentation)
•	Program Management	26%	All direct engineering

APPENDIX D

Engineering Analysis Costs

APPENDIX D. ENGINEERING ANALYSIS COSTS

D1. ANALYSIS REQUIREMENTS ASSUMPTIONS

The analysis requirements implied by the several brittle fracture recommendations differ. However, the required complexity is inversely proportional to the conservatism associated with each material selection criterion. In the following sections the bases for estimating the costs of engineering analyses are established.

D1.1 Fracture Arrest Analysis Requirements

Fracture arrest criteria based on yield stresses (FA-EX-YS, FA-AX-YS) require no additional stress analyses to assure prevention of brittle fracture. Fracture arrest criteria based on stresses less than yield (FA-EX-PS, FA-AX-PS) permit reductions in required T-NDTT provided it can be demonstrated that the stresses are less than yield. The analysis requirements for this demonstration are:

A. The required stress analysis methods need not exceed the levels of detail required by existing NRC Regulatory Guide 7.6, (14). Analysis conditions must be selected for physical realism and not merely for convenience.

B. Only linear elastic analysis methods need be used. This is consistent with the objective to demonstrate that stresses are at, or less than, yield.

C. Dynamic stresses may be determined by quasi-static simplified methods provided the deformable (crushable) elements and the containment vessel demonstrate that natural response frequencies differ by at least a factor of three. Fracture toughness levels associated with fracture arrest principles, based upon dynamic K_{ID} properties possess sufficient conservatism tc arrest a crack arising from transient dynamic phenomena.

D. 3-D stress analyses are not required provided the point of impact, in accident evaluation senarios, is not part of the homogeneous containment vessel. If impact limiters are provided or if the containment vessel and the outer shell structural elements are separated by intermediate shielding material, concentrated impact forces are distributed.

D1.2 Fracture Initiation Analysis Requirements

The two fracture initiation criteria impose stringent requirements upon the ability of inspection personnel to consistently detect flaws of a specified minimum size. The first of these fracture initiation recommendations (FI-YS) presumes stresses at yield. The only analysis requirement here is to consider normal service conditions to demonstrate that "end-of-life" flaw size remains consistent with criteria assumptions. Stress analysis methods used for normal conditions are sufficient for this purpose.

The second fracture initiation option (FI-PS) requires accurate determination of stresses for use in classical LEFM analyses. This is a severe challenge since, unlike the fracture arrest approach, the material is no longer presumed to possess sufficient toughness to arrest a running crack arising from a transient dynamic stress condition. Thus, the analysis method used must either be accurate or sufficiently conservative to provide an upper-bound estimate of stresses. For fracture initiation, "stress" refers to primary and secondary membrane and bending stresses as defined in NRC Regulatory Guide 7.6. Local stress concentrations are excluded. Exclusion is based upon the premise that crack growth will cease after modest extension due to the relaxation of localized constraints inducing this stress. The analysis requirements for this case are:

A. Linear elastic dynamic analysis.

B. Model in sufficient detail to determine transient dynamic states of stress. Where impact limiters are not provided, 3-D analyses will be required. If finite element methods are employed, the model will reveal both extensional and flexural modes of behavior. The degree of approximation implicit in the extensional model, due to finite geometry, should be demonstrated by comparison with a wave propagation idealization. If modal analysis methods are employed for dynamic analysis, sufficient modes should be utilized to limit the errors of modal truncation to no more than 5%, as determined on the basis of stress (not displacement). Evaluation of truncation errors should be required. If direct integration methods are employed, the truncation error implicit in the integration algorithm should be demonstrated and compared with the requirements of the dynamic analysis.

C. Dynamic properties of the package should be used. This would include modulus of elasticity and a conservatively chosen value for the damping coefficient.

D1.3 Drop Test Analysis Requirements

The drop test brittle fracture acceptance criteria (DT) requires that the cask be "flawed" at the location of maximum stress prior to test. The analysis requirements are that the location of maximum stress be determined. Note that this is a "qualitative" requirement not a "quantitative" requirement. Existing methods and procedures for analysis of accident conditions are considered sufficient for this determination.

D2. LEVEL OF EFFORT ESTIMATES

Analysis and materials technology labor estimates are defined in this section. For purposes of this study these estimates are assumed to vary little with the shipping cask construction details. The estimates are prepared for a "baseline" requiring no special brittle fracture prevention considerations to which is added one of the incremental labor estimate budgets corresponding to the different brittle fracture prevention criteria designated below:

Criterion	Description
FA-EX-YS	Fracture Arrest, Exponential Extrapolation (of Pellini curve), Yield Stress Assumed.
FA-EX-PS	Fracture Arrest, Exponential Extrapolation (of Pellini curve), Yield Stress Assumed.

FA-AX-YS	Fracture Arrest, Asymptotic Extrapolation (of Pellini curve), Predicted Stress Utilized.
FI-YS	Fracture Initiatiion, Yield Stress Assumed.
FI-PS	Fracture, Initiation, Predicted Stress Utilized.
DT	Drop Test qualification.

D2.1 Baseline Design and Materials Analysis Labor Estimate

Labor costs are estimated for concept design, preliminary design, SAR preparation and licensing, detail (final) design and fabrication. The summary estimate of hours and material dollars for "baseline" efforts is shown in Table D1. Labor rates used to derive composite rates for each phase are based upon the industry figures developed in Appendix G.

It should be emphasized that this baseline engineering estimate includes only analysis and materials labor skills and assumes that brittle fracture is not a substantive technical issue. Unlike fabrication estimates, engineering labor estimates vary widely, depending not only upon the engineering organization but also upon the judgement, experience, and degree of optimism of the estimator. However, these differences will have little impact upon conclusions based on relative costs.

Concept Design explores the feasibility of various ideas, or "concepts" and selects the "best" according to cost, licensability or performance criterion. Just enough analyses are done to size and select materials or components for pricing and general configuration compatibility.

Preliminary Design establishes the configuration, materials and sizes of all significant components and assemblies. "Scrap and rework" is a fact of life throughout this phase of work and a 25% markup is employed to cover this aspect. Subsystem specifications are drafted where external procurements appear likely. Analyses are performed to the extent that all functional and safety issues are examined for conformance with applicable criteria and regulations. Unless requested by the customer, no formal design analysis report is issued. However, results are typically available for in-house review in organized engineering note or analysis form.

SAR Preparation and Licensing translates the preliminary design information into a USNRC formatted Safety Analysis Report (SAR) to demonstrate conformance with 10 CFR 71 requirements. If a design analysis report has been prepared during Preliminary Design, the SAR repeats and expands the safety related portions. This document is limited to regulatory issues only and frequently differs from the design analysis report in several significant ways. "Worst-case" assumptions frequently replace "best-estimate" assumptions. "Proprietary" data is excluded to the greatest extent possible and functional behavior is neglected unless it impacts safety. Upon submittal to the NRC and review by their technical staff, a set of questions typically result. The process continues for, typically, three question-response cycles. In this cost model, labor markups of 30%, 20%, and 10% are assumed for three review cycles based on the labor totals of all prior work within this phase.

Detailed Design producing fabrication drawings and specifications is performed upon the completion of the licensing process. While this is a labor intensive phase for design engineering, the analysis functions are typically limited to the sizing of "non-structurals" and ancillary (non-licensed) support equipment.

Fabrication actions by the materials and analysis functions are typically limited to the support of Material Review Board (MRB) decisions concerning scrap and/or rework.

D2.2 Incremental Tasks, Criterion FA-EX-YS

The detailed assignment of incremental hours and material dollars for brittle fracture criterion FA-EX-YS is shown in Table D2. There is no additional analysis effort imposed by brittle fracture requirements. However, the SAR/Licensing phase is increased by 80 hours of analysis effort to allow preparation of a brittle fracture design criterion description. The incremental materials labor effort is assumed to be 20% of baseline for all phases to accommodate preparation of additional test and inspection criteria for brittle fracture.

D2.3 Incremental Tasks, Criterion FA-EX-PS

The detail assignment of incremental hours and material dollars for brittle fracture criterion FA-EX-PS is shown in Table D3. Additional analyses are required to determine the magnitude of dynamic stresses. Except for these additional analysis costs, the effort remains the same as for FA-EX-YS, which assumes yield stresses. An impact limiter, or energy absorber, is presumed to protect the package thus allowing use of quasi-static analysis methods or relatively coarse finite element modeling. The additional analysis tasks are:

A. Preparation of a Cask Half-Symmetric Model. This model is assumed to possess 6 nodes through the sidewall located at 10° circumferential increments and 25 longitudinal increments. Thus the model size is approximated by

Nodes:	(6) (180/10)(25)	=	2700
Elements:			
Shells	(17)(24)(2)	=	816
Quads	(17)(24)(5)	=	2040
# Elements		=	2856

This model size is reasonably consistent with the models used by General Atomics (15), and Sandia (17), for high-level waste casks. Labor for model development and checkout is estimated, from experience, at approxi- mately 5 minutes per node or,

$$(2700)(5)/60 = 225 \text{ hours.}$$

B. Three Solution Runs (Side, End, Corner). Labor is assumed at 20% of development labor for solution and 35% of development labor for engineering interpretation or,

$$(3)(225)(55\%) = 371 \text{ hours.}$$

Commercial computing cost estimates for this model are based upon representative DYNA3D runs using the CRAY at Boeing Computer Service (BCS).[†]

$ = (Rate)(CCU)
CCU = (#Elements)(#Timesteps)/100
= (2856)(4000)/100 = 114,240

Where: CCU = BCS Billing Unit
Rate = $ 0.015/CCU, overnight
$ 0.034/CCU, 1 hour
$ 0.0245/CCU, average used
#Elements = 2856
#Timesteps = 4000

The (#Timesteps) value is one-half to one-third that reported in Ref. 16. This reduction approximates the simplification achieved by use of an energy absorber (decoupling cask dynamic response from absorber dynamic response). Assuming two and one-half runs for every valid solution, the total computing cost is:

(3 Solutions)(2-1/2 Runs)(114,240CCU)($.0245) = $20,992.

This is increased by 30% for postprocessing (printing, plotting, and data manipulation) of computer results.

C. Documentation of Results. Labor is assumed at 25% of solution and model development, or

(225 + 371)(25%) = 150 hours.

D2.4 Incremental Tasks, Criterion FA-AX-YS

This effort is identical to that for criteria FA-EX-YS. (See Table D2.)

D2.5 Incremental Tasks, Criterion FA-AX-PS

This effort is identical to that for criteria FA-EX-PS. (See Table D3.)

D2.6 Incremental Tasks, Criterion FI-YS

The effort for this criterion is very similar to that for criterion FA-EX-YS. Incremental SAR/Licensing analysis labor is increased by 50% to 120 hours in order to evaluate end-of-life flaw size. The incremental materials labor effort is assumed at 50% of baseline, in all phases, to reflect the added concern for flaw size. The detailed assignment of incremental hours and material dollars for brittle fracture criterion FI-YS is shown in Table D4.

[†] Information obtained from Nuclear Packaging Corporation, personal communication from Robert C. Lundquist, Boeing Computer Services, Co., June 1983.

D2.7 Incremental Tasks, Criterion FI-PS

The effort for this criterion is identical to that for criterion FI-YS except that analysis tasks increase significantly to accurately calculate dynamic stresses. The model is assumed to be twice the size of that described in Section D2.3. The number of time steps is also assumed to increase by a factor of two. Thus, the labor and computing costs are estimated as:

Labor:	(225 + 371 + 150)(2) =	746 hours
Computing:	($20,992)(1.3)(2)(2) =	$109,156.

The detailed assignment of incremental hours and material dollars for brittle fracture recommendation FI-PS is shown in Table D5.

D2.8 Incremental Tasks, Criterion DT

For comparative purposes, this incremental effort is assumed identical to criteria alternative FA-EX-YS (Table D2). Test program development and execution is costed in Appendix B.

Table D1. Baseline design and materials analysis engineering labor estimates.

PROJECT PHASE	Hours	Salary Rate	Extension	Description	Amount
CONCEPT DESIGN					
** Analysis **	430.0	$18.89	$ 8124.47	Compute & Repro	$ 1250.00
** Materials **	180.0	$18.61	$ 3350.15	D. Base & Repro	$ 500.00
SUBTOTAL-Concept	610.0	$18.81	$11475.00		$ 1750.00
PRELIM. DESIGN					
** Analysis **	1068.8	$18.89	$20143.36	FEM Computing	$ 7812.50
** Materials **	440.0	$18.61	$ 8189.93	D. Base & Lab	$ 3075.00
SUBTOTAL-Prelim	1508.8	$18.81	$28383.28		$10887.50
SAR/LICENSING					
** Analysis **	2350.9	$18.89	$44419.61	Computing	$12520.00
** Materials **	360.0	$18.61	$ 6701.28		$ 0.00
SUBTOTAL-SAR	2710.9	$18.86	$51120.89		$12520.00
DETAIL DESIGN					
** Analysis **	280.0	$18.89	$ 5290.38		$ 0.00
** Materials **	100.0	$18.61	$ 1681.41		$ 0.00
SUBTOTAL-Detail	380.0	$18.82	$ 7151.79		$12520.00
FABRICATION (Per Unit)					
** Analysis **	240.0	$18.89	$ 4534.40		$ 800.00
** Materials **	300.0	$18.61	$ 5583.99	Travel	$ 1500.00
SUBTOTAL-Fab.	540.0	$18.74	$10118.39		$ 2300.00

Table D2. Design and materials analysis labor estimates for Criteria FA/EX-YS and DT.

PROJECT PHASE	LABOR Hours	 Salary Rate	 Extension	OTHER Expense Amount
CONCEPT DESIGN				
Baseline	610.0	$18.89	$11475.00	$ 1750.00
Increment-Materials	36.0	$18.61	$ 669.96	$ 100.00
SUBTOTAL-Concept:	646.0	$18.80	$12144.96	$ 1850.00
PRELIM. DESIGN				
Baseline	1508.8	$18.81	$28383.28	$10887.50
Increment-Materials	88.0	$18.61	$ 1637.68	$ 615.00
SUBTOTAL-Prelim:	1596.8	$18.80	$30020.96	$11502.50
SAR/LICENSING				
Baseline	2710.9	$18.89	$44419.61	$12520.00
Increment-Analysis	80.0	$18.89	$ 1511.20	$ 0.00
Increment-Materials	72.0	$18.61	$ 1339.92	$ 0.00
Review Markup	108.8	$18.76	$ 2041.40	$ 0.00
SUBTOTAL-SAR:	2710.9	$18.86	$51120.89	$12520.00
DETAIL DESIGN				
Baseline	380.0	$18.8[illegible]	$ 7151.79	$ 0.00
Increment-Materials	20.0	$18.61	$ 372.20	$ 0.00
SUBTOTAL-Detail:	400.0	$18.81	$ 7523.99	$ 0.00
TOTAL-All A/M Engr:	5614.5	$18.83	$105703.32	$25872.50
FABRICATION -Per Unit				
Baseline	540.0	$18.74	$10118.39	$ 2300.00
Increment-Materials	60.0	$18.61	$ 1116.60	$ 300.00
SUBTOTAL-Fab:	600.0	$18.72	$11234.99	$ 2600.00

Table D3. Design and materials analysis labor estimates for criteria FA/EX/PS and FA/AX/PS.

	LABOR			OTHER
PROJECT PHASE	Hours	Salary Rate	Extension	Expense Amount
CONCEPT DESIGN				
Baseline	610.0	$18.89	$11475.00	$ 1750.00
Increment-Materials	36.0	$18.61	$ 669.96	$ 100.00
SUBTOTAL-Concept:	646.0	$18.80	$12144.96	$ 1850.00
PRELIM. DESIGN				
Baseline	1508.8	$18.81	$28383.28	$10887.50
Increment Analysis	596.0	$18.89	$11258.44	$27289.60
Increment-Materials	88.0	$18.61	$ 1637.68	$ 615.00
SUBTOTAL-Prelim:	2192.8	$18.82	$41279.40	$38792.10
SAR/LICENSING				
Baseline	2710.9	$18.86	$51120.89	$12520.00
Increment-Analysis	230.0	$18.89	$ 4344.70	$ 0.00
Increment-Materials	72.0	$18.61	$ 1339.92	$ 0.00
Review Markup	216.2	$18.82	$ 4070.19	$ 0.00
SUBTOTAL-SAR:	3229.1	$18.85	$60875.70	$12520.00
DETAIL DESIGN				
Baseline	380.0	$18.82	$ 7151.79	$ 0.00
Increment-Materials	20.0	$18.61	$ 372.20	$ 0.00
SUBTOTAL-Detail:	400.0	$18.81	$ 7523.99	$ 0.00
TOTAL-All A/M Engr:	6467.9	$18.84	$121824.05	$53162.10
FABRICATION -Per Unit				
Baseline	540.0	$18.74	$10118.39	$ 2300.00
Increment-Materials	60.0	$18.61	$ 1116.60	$ 300.00
SUBTOTAL-Fab:	600.0	$18.72	$11234.99	$ 2600.00

Table D4. Design and materials analysis labor estimates for criteria FI-YS.

	LABOR			OTHER
PROJECT PHASE	Hours	Salary Rate	Extension	Expense Amount
CONCEPT DESIGN				
Baseline	610.0	$18.89	$11475.00	$ 1750.00
Increment-Materials	90.0	$18.61	$ 1674.90	$ 250.00
SUBTOTAL-Concept:	700.0	$18.79	$13149.90	$ 2000.00
PRELIM. DESIGN				
Baseline	1508.8	$18.81	$28383.28	$10887.50
Increment-Materials	220.0	$18.61	$ 4094.20	$ 1537.50
SUBTOTAL-Prelim:	1728.8	$18.79	$32477.48	$12425.00
SAR/LICENSING				
Baseline	2710.9	$18.86	$51120.89	$12520.00
Increment-Analysis	120.0	$18.89	$ 2266.80	$ 0.00
Increment-Materials	180.0	$18.61	$ 3349.80	$ 0.00
Review Markup	214.8	$18.72	$ 4021.49	$ 0.00
SUBTOTAL-SAR:	3229.1	$18.84	$60758.98	$12520.00
DETAIL DESIGN				
Baseline	380.0	$18.82	$ 7151.79	$ 0.00
Increment-Materials	50.0	$18.61	$ 930.50	$ 0.00
SUBTOTAL-Detail:	430.0	$18.80	$ 8082.29	$ 0.00
TOTAL-All A/M Engr:	6084.5	$18.81	$114468.65	$26945.00
FABRICATION -Per Unit				
Baseline	540.0	$18.74	$10118.39	$ 2300.00
Increment-Materials	150.0	$18.61	$ 2791.50	$ 750.00
SUBTOTAL-Fab:	690.0	$18.71	$12909.89	$ 3050.00

Table D5. Design and materials analysis labor estimates for criteria FI-PS.

	LABOR			OTHER
PROJECT PHASE	Hours	Salary Rate	Extension	Expense Amount
CONCEPT DESIGN				
Baseline	610.0	$18.89	$11475.00	$ 1750.00
Increment-Materials	90.0	$18.61	$ 1674.90	$ 250.00
SUBTOTAL-Concept:	700.0	$18.79	$13149.90	$ 2000.00
PRELIM. DESIGN				
Baseline	1508.8	$18.81	$28383.28	$ 10887.50
Increment-Analysis	1192.0	$18.89	$22516.88	$109156.00
Increment-Materials	220.0	$18.61	$ 4094.20	$ 1537.50
SUBTOTAL-Prelim:	2920.8	$18.83	$54994.36	$121581.00
SAR/LICENSING				
Baseline	2710.9	$18.86	$51120.89	$12520.00
Increment-Analysis	420.0	$18.89	$ 7933.80	$ 0.00
Increment-Materials	180.0	$18.61	$ 3349.80	$ 0.00
Review Markup	429.6	$18.81	$ 8079.06	$ 0.00
SUBTOTAL-SAR:	3740.5	$18.84	$70483.55	$12520.00
DETAIL DESIGN				
Baseline	380.0	$18.82	$ 7151.79	$ 0.00
Increment-Materials	50.0	$18.61	$ 930.50	$ 0.00
SUBTOTAL-Detail:	430.0	$18.80	$ 8082.29	$ 0.00
TOTAL-All A/M Engr:	7791.3	$18.83	$146710.10	$136101.00
FABRICATION -Per Unit				
Baseline	540.0	$18.74	$10118.39	$ 2300.00
Increment-Materials	150.0	$18.61	$ 2791.50	$ 750.00
SUBTOTAL-Fab:	690.0	$18.71	$12909.89	$ 3050.00

APPENDIX E

Quality Assurance Engineering Costs

APPENDIX E. QUALITY ASSURANCE ENGINEERING COSTS

E1. INSPECTION REQUIREMENTS

Cask design and fabrication, regardless of material selection or manufacturing techniques, involves similar Quality Engineering and Inspection activities. These activities include:

Design Review

The Quality Engineering effort during design review entails checks of material selection, special processes (welding, heat treatment, plating, etc.), NDE requirements, general inspectability, and adherence to contractual design criteria.

Quality Inspection Planning

Quality Engineering must develop Inspection Planning for use during manufacturing that can be utilized to assure adherence to the design requirements. The Planning provides direction for performance of material verification, dimensional checks, special process control or verification, NDE functional checks, identification, control and disposition of discrepancies, and final acceptance.

Inspection

The quality inspection function is critical to the success of the fabrication effort. The regulatory atmosphere present in the nuclear industry requires that all products are produced with strict controls throughout all phases. The requirements are certification of material, dimensions, processes, and function. The Inspector, utilizing appropriate quality planning documents, inspects those areas of concern and provides the certification of adherence to design and regulatory requirements.

E2. PROCESS CONTROL REQUIREMENTS

Regardless of the construction method, all casks require the same basic dimen- sional, special process and NDE Quality Control activity. The variation in cost is associated with the difficulty of inspection of welded laminate versus forged and welded fabrication. The ASTM-A508 series forged and welded casks are more difficult to inspect than a typical ferritic steel plate and lead shielded cask. Also, the potential for fabrication related discrepancies is slightly greater which results in more rigorous inspection and Quality Engineering (QA) requirements. Therefore, the labor hours for inspection of forgings is assumed to be 25% greater than that for a typical ferritic steel plate and lead cask.

Additionally, the NDE of a forged cask is somewhat more involved than the NDE of the welded plate cask due to the requirements to locate flaws in the forging utilizing UT methods. The size of the flaw is not a factor in the cost for the NDE. The increased NDE cost is simply a result of the increased time required to perform UT to locate the flaws.

E3. LEVEL OF EFFORT ESTIMATES

The QA fabrication labor factors of Appendix C are adjusted for forged ferritic steels as follows:

	Ferritic Plate	Ferritic Forging
1st Article	12%	15%
5th Article	10%	12.5%
20th Article	8%	10%

APPENDIX F

Manufacturing Cost Assumptions and Estimates

APPENDIX F. MANUFACTURING COST ASSUMPTIONS AND ESTIMATES

For simplicity, manufacturing costs consider only three major shop categories: forging, machining, and fabrication, which includes welding, cutting, grinding, and rolling operations.

For forging operations, the manufacturing costs added to the raw billet materials cost consists of both shop labor and equipment charges reflecting cost recovery of capital investment. Analysis of both domestic and Japanese forging prices indicates that, for cask size forgings, manufacturing costs are approximated by using \$1.66/lb for forged and rough machined products (1982 prices). For consistency with other manufacturing prices, this charge is converted to an equivalent labor charge of 5.5 hours per hundred pounds of forged and machined product, using the rates given in Appendix H. Thus, the labor for forged subassemblies is assumed to be:

Forge Hours = $5.5 * CWT_F$

where: CWT_F = Forged subassembly weight in hundred pounds.

For fabrication shop activities, the labor level of effort is basically proportional to the length of the welds, or cuts, and the thickness of the part (due to multiple weld passes, etc.). In plate type materials, this is also roughly proportional to fabricated steel weight. Experience indicates that approximately 3.6 labor hours are expended per 100 lbs of fabricated product of ferritic steels, such as ASTM 516, Grade 70. Using the rates given in Appendix H, this is equivalent to a present labor cost of \$1.09/lb.

For machined subassemblies, the labor costs tend to be proportional to the amount of metal removed and inversely proportional to the cutting speed. This is complicated by the fact that the absolute size of the machined component influences set-up and tear-down time charges, handling charges and stand-by time awaiting access to equipment. A review of available data has failed to disclose a simple model reflecting all these factors. It has been found, however, that cost differences in various materials are closely approximated by the traditional Machinability Index.

Taking the above factors into account, the labor effort ranges from 4.8 hours/CWT to 12.1 hours/CWT. Using the rates given in Appendix H, this is equivalent to a present labor cost of \$1.45 to \$3.66/lb. The higher value tends to be applicable to small machined parts, the lower value to large assemblies. Accounting for this size factor leads to the following assumptions, for machined subassemblies:

Machinist Hours = $7.54 * (CWT_M)^{.839} / MI$

where: CWT_M = Machined sub-assembly weight in hundred pounds

MI = Machinability Index
(AISI B1112 Steel = 100%).

APPENDIX G

Wage and Salary Rates

APPENDIX G. WAGE AND SALARY RATES

Wage and salary rates for both engineering and shop personnel are summarized in Table G1. The rates for engineering are tabulated by major functions which relate to development, licensing, or production of an irradiated fuel transportation package. The wage rates for engineering functions were developed by assuming a staff profile for each function. These staff profile assumptions were based solely upon experience and judgement. Wage rates for each hypothetical staff member were based upon U.S. Bureau of Labor Statistics (BLS) data, National Survey of Professional, Administrative, Technical, and Clerical Pay, March 1980, summarized in (17). These data are categorized by "level of experience and achievement", as shown in columns 2 and 3 of Table G1.

Shop rates for manufacturing personnel are derived in a similar fashion using BLS data, Federal Wage Survey - Blue Collar Workers, 1980, as summarized in Ref. 17. The Federal wage data was compared with other BLS data, Area Wage Surveys, describing equivalent private industry wage ranges. The Federal wage data was at, or slightly above, the mean of private industry data and was therefore appropriate for this cost analysis. Since blue collar wages for pertinent skills vary little, there was no attempt to provide the functional resolution applied to engineering wage rates.

Table G1. Analysis of industry data for engineering and manufacturing hourly rate data.

ENGINEERING AND SHOP LABOR CATEGORY	BLS Engr. Grade	Salary Quartile	1980 Annual Salary	1982-3 Hourly Wage	Staff Ratio (%)	1982-3 Hourly Contrib.
ANALYSIS						
Jr. Engr.	II	2	$21000.00	$11.89	5%	$ 0.59
Assoc. Engr.	III	2	$23821.00	$13.48	10%	$ 1.35
Sr Engr.	IV	3	$31111.00	$37.61	35%	$ 6.16
Engr. Specialist	VI	3	$41295.00	$23.38	20%	$ 4.68
Analysis Composite					100%	$18.89
MATERIALS						
Sr. Engr.	IV	2	$28200.00	$15.96	40%	$ 6.39
Engr. Specialist	V	3	$36000.00	$20.38	60%	$12.23
Materials Composite					100%	$18.61
DESIGN						
Jr. Engr.	II	1	$19492.00	$11.03	20%	$ 2.21
Assoc. Engr.	III	2	$23821.00	$13.48	40%	$ 5.39
Sr. Engr.	IV	2	$28200.00	$15.96	30%	$ 4.79
Engr. Suprv.	V	3	$36000.00	$20.38	10%	$ 2.04
Design Composite					100%	$14.43
QUALITY ASSURANCE						
Sr. Engr.	IV	2	$28200.00	$15.96	50%	$ 7.98
Engr. Specialist	V	3	$36000.00	$20.38	50%	$10.19
QA Composite					100%	$18.17
DESIGN VERIFICATION						
Analysis				$18.89	40%	$ 7.56
Design				$14.43	40%	$ 5.77
QA				$18.18	20%	$ 3.63
Verification Comp.					100%	$16.96
DESIGN REVIEW						
Design Verif.				$16.96	60%	$10.18
Project Mgmt.				$26.34	40%	$10.53
Design Review Comp.					100%	$20.71
ENGR./MFR. LIAISON						
Assoc. Engr.	III	1	$21840.00	$12.36	50%	$ 6.18
Sr Engr.	IV	2	$28200.00	$15.96	30%	$ 4.79
Engr. Specialist	V	2	$30083.00	$17.03	20%	$ 3.41
Liaison Composite					100%	$14.38

Table G1. (continued)

ENGINEERING AND SHOP LABOR CATEGORY	BLS Engr. Grade	Salary Quartile	1980 Annual Salary	1982-3 Hourly Wage	Staff Ratio (%)	1982-3 Hourly Contrib.
PROJECT MANAGEMENT						
Principal Engr.	VI	3	$41295.00	$23.38	30%	$ 7.01
Sr. Mgmt. Engr.	VII	3	$46908.00	$26.55	50%	$13.28
Executive Engr.	VIII	3	$53414.00	$20.24	20%	$ 6.05
Project Mgmt. Comp.					100%	$26.34
SHOP LABOR						
Boiler Maker			$21144.00	$11.97	25%	$ 2.99
Machinist			$20533.00	$11.62	30%	$ 3.49
Pipefitter			$21051.00	$11.92	10%	$ 1.19
Welder			$19654.00	$11.13	35%	$ 3.89
Shop Labor Composite					100%	$11.56

NOTES:

1. Escalation from 1980 to 1982-3 based on average hourly manufacturing earnings, Ref. (18): 17.74%.
2. BLS Engineering salary data, columns 2 to 4 taken from pages 413 to 415, Ref. 6.5.
3. Shop wage data for "Blue Collar" workers taken from page 659, Ref. 6.5.

APPENDIX H

Basic Cost Factors

APPENDIX H. BASIC COST FACTORS

GENERAL RATES

This Appendix discusses the corporate and individual labor rates consistently used for all subsequent cost analyses. These include corporate markups comprising overhead, general and administrative (G&A) expenses, and labor rates applicable to all engineering and manufacturing tasks.

OVERHEAD AND G&A MARKUPS

Few firms accumulate and report their indirect expenses in precisely the same fashion or use identical definitions of expense categories. Thus, side-by-side comparisons of reported overhead and G&A rates is relatively meaningless. To circumvent these difficulties, published expense ratios for major industries were categorized according to the conventional markup formula shown in Fig. 6 in the body of the report. The resulting markups are completely consistent, reflect the averaged expenses of all applicable U.S. industries, and are totally unbiased. The data is based upon averages derived from over 50 billion dollars revenue volume.

The financial ratios data, applicable to 1981-1982, are taken from Troy (18), which considers data for the following applicable industrial sectors:

- Fabricated Structural Metal Products
- Metal Forgings and Stampings
- Special Industrial Machinery
- Engineering Services

Financial ratios data, for each industrial sector, was categorized into overhead and G&A pools. This was done using a rule which limited G&A to "corporate" expenses such as officer salaries and financial costs. This suggests a categorization of the Troy data, as follows.

Overhead	G&A
Repairs	Compensation of Officers
Rent	Bad Debts
Pension & Benefit Plans	Taxes (excl. Fed.)
Other Expenses	Interest
	Depreciation
	Advertising

The detailed analysis is carried out in Table H1 and is self-explanatory. The Troy data lumps both purchased material and labor under the category "Cost of Operations." An assumption was used to split this category into the two basic elements. A 40% labor fraction (of operating costs) was assumed for all manufacturing operations. Discussions with fabrication shops dealing with ferritic materials, in the thickness range of concern have indicated that this percentage may vary from 37% to 48%. The final values for overhead and G&A derived in Table H1 are as follows.

OVERHEAD AS A % LABOR	Percent
Fabricated Structurals	41.33%
Forgings & Stampings	44.34%
Industrial Machinery	67.95%
All Manufacturing	48.73%
Engineering	56.44%
G&A, GLOBAL AVERAGE	12.75%

Table H1. Analysis of industry data for overhead and G&A markup factors.

	Fabricated Structures	Forgings & Stamping	Industrial Machinery	Engineering
Total Revenue M$:	20829.60	9101.70	10955.10	9509.90
EXPENSE ITEMS: (% Net Sales)				
Ops. Cost	75.0	73.30	68.80	54.20
Officers Salary	2.50	2.60	2.40	11.10
Repairs	0.50	1.70	0.60	0.30
Bad Debts	0.20	0.10	0.30	0.20
Rental	0.70	0.70	0.80	2.70
Taxes	2.40	2.70	2.80	3.30
Interest	1.40	1.10	1.40	1.10
Depreciation	2.00	2.50	2.30	2.40
Advertising	0.40	0.20	0.70	0.20
Benefits	1.40	2.80	2.40	2.50
Other Benefits	9.80	7.80	14.90	20.50
Net Profit	3.70	4.50	2.60	1.50
	100.00	100.00	100.00	100.00
OPS. COST DISTR. ASSUMPTIONS:				
Labor % of Cost	40.00	40.00	40.00	85.00
Fringe % of Wage	30.00	30.00	30.00	40.00
POOL ALLOCATION:				
Salary	23.08	22.55	21.17	32.91
Fringe	6.92	6.77	6.35	13.16
Subtotal, Labor	30.00	29.32	27.52	46.07
Materials	45.00	43.98	41.28	8.13
Subtotal, Ops.	75.00	73.30	68.80	54.20
Overhead	12.40	13.00	18.70	26.00
Subtotal, Direct	87.40	86.30	87.50	80.20
G&A	8.90	9.20	9.90	18.30
Profit	3.70	4.50	2.60	1.50
	100.00	100.00	100.00	100.00
MODEL ALLOCATION:				
Overhead & Labor	41.33	44.34	67.95	56.44
Overhead & Wage	53.73	57.64	88.34	79.01
G&A % Direct	10.18	10.66	11.31	22.82

Table H1. (continued)

	Fabricated Structures	Forgings & Stamping	Industrial Machinery	Engineering
Total Revenue M$:	20829.60	9101.70	10955.10	9509.90
INDUSTRY TOTALS:				
Materials, M$	9373.32	4002.93	4522.27	773.15
Wages, M$	4806.83	2052.78	2319.11	3129.44
Total Labor, M$	6248.88	2668.62	3014.84	4381.21
Overhead, M$	2582.87	1183.22	2048.60	2472.57
G&A, M$	1853.83	837.36	1084.55	1740.31
Total Revenue, M$	20819.60	9101.70	10955.10	9509.90
MODEL AVERAGES:		Manufacturer	Global	
Overhead, % Labor		48.73	50.80	
Overhead, % Wage		63.35	67.33	
G&A, % Direct		10.59	12.75	

APPENDIX I

Limit State Probability Implied by Fracture Arrest Criteria

Table I1. Limit state probability implied by FA-EX-YS, T = -20°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(\text{NDTT})}$	P_F
4	103	-20	-123	508-4B	-148	13	128	25	1.923	2.7×10^{-2}
4	103	-20	-123	508-4A	-158	10.5	138	35	3.333	4.4×10^{-4}
8	123	-20	-143	508-4B	-148	13	128	5	0.385	3.5×10^{-1}
8	123	-20	-143	508-4A	-158	10.5	138	15	1.428	7.6×10^{-2}
12	133	-20	-153	508-4A	-158	10.5	138	5	0.476	3.16×10^{-1}

Table I2. Limit state probability implied by FA-EX-YS, T = -10°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(\text{NDTT})}$	P_F
4	103	-10	-113	350-3	-120	13	110	7	0.538	3×10^{-1}
4	103	-10	-113	508-4B	-148	13	138	35	2.692	3.6×10^{-3}
4	103	-10	-113	508-4A	-158	10.5	148	45	4.29	9.1×10^{-6}
8	123	-10	-133	508-4B	-148	13	138	15	1.15	1.2×10^{-6}
8	123	-10	-133	508-4A	-158	10.5	148	25	2.38	8.6×10^{-3}
12	133	-10	-143	508-4B	-148	13	138	5	0.385	3.5×10^{-1}
12	133	-10	-143	508-4A	-158	10.5	148	15	1.43	7.7×10^{-2}
16	141	-10	-151	508-4A	-158	10.5	148	7	0.67	2.5×10^{-1}
16	147	-10	-157	508-4A	-158	10.5	148	1	0.01	5×10^{-1}

Table I3. Limit state probability implied by FA-EX-YS, T = 0°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	ΔT / σ(NDTT)	P_F
4	103	0	-103	350-3	13	-120	120	17	0.31	9.5×10^{-2}
4	103	0	-103	508-4B	13	-148	148	45	3.46	2.7×10^{-4}
4	103	0	-103	508-4A	10.5	-158	158	55	5.24	8.1×10^{-8}
8	123	0	-123	508-4B	13	-148	148	25	1.92	2.7×10^{-2}
8	123	0	-123	508-4A	10.5	-158	158	35	3.33	4.3×10^{-4}
12	133	0	-133	508-4B	13	-148	148	15	1.15	1.2×10^{-1}
12	133	0	-133	508-4A	10.5	-158	158	25	2.38	8.6×10^{-3}
16	141	0	-141	508-4B	13	-148	148	7	0.538	3.0×10^{-1}
16	141	0	-141	508-4A	10.5	-158	158	17	1.62	5.3×10^{-2}
20	147	0	-147	508-4B	13	-148	148	1	0.08	4.7×10^{-1}
20	147	0	-147	508-4A	10.5	-158	158	11	1.05	1.5×10^{-1}

Table I4. Limit state probability implied by FA-EX-YS, T = 10°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	ΔT / σ(NDTT)	P_F
4	103	10	-93	350-3	-120	13	130	27	2.08	1.9×10^{-2}
4	103	10	-93	508-4B	-148	13	158	35	4.23	1.2×10^{-5}
4	103	10	-93	508-4A	-158	10.5	168	65	6.19	3.0×10^{-10}
8	123	10	-113	350-3	-120	13	130	7	1.538	3.0×10^{-1}
8	123	10	-113	508-4B	-148	13	158	35	2.69	3.5×10^{-3}
8	123	10	-113	508-4A	-158	10.5	168	45	4.29	9.1×10^{-6}
12	133	10	-123	508-4B	-148	13	158	25	1.92	2.7×10^{-2}
12	133	10	-123	508-4A	-158	10.5	168	35	3.33	4.3×10^{-4}
16	141	10	-131	508-4B	-148	13	158	17	1.31	9.5×10^{-2}
16	141	10	-131	508-4A	-158	10.5	168	27	2.57	5.1×10^{-3}
20	147	10	-137	508-4B	-148	13	158	11	0.846	2.0×10^{-1}
20	147	10	-137	508-4A	-158	10.5	168	21	2.00	2.3×10^{-2}

Table I5. Limit state probability implied by FA-EX-YS, T = 20°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(NDTT)}$	P_F
4	103	20	-83	350-3	-120	13	140	37	2.85	2.2×10^{-3}
4	103	20	-83	508-4B	-148	13	168	65	5.0	2.9×10^{-7}
4	103	20	-83	508-4A	-158	10.5	178	75	7.14	4.6×10^{-13}
8	123	20	-103	350-3	-120	13	160	17	1.31	9.5×10^{-2}
8	123	20	-103	508-4B	-148	13	168	45	3.46	2.7×10^{-4}
8	123	20	-103	508-4A	-158	10.5	178	55	5.24	8.1×10^{-8}
12	133	20	-113	350-3	-120	13	140	7	0.538	3.0×10^{-1}
12	133	20	-113	508-4B	-148	13	168	35	2.69	3.5×10^{-3}
12	133	20	-113	508-4A	-158	10.5	178	45	4.29	9.1×10^{-6}
16	141	20	-121	508-4B	-148	13	168	27	2.08	1.9×10^{-2}
16	141	20	-121	508-4A	-158	10.5	178	37	3.52	2.1×10^{-4}
20	147	20	-127	508-4B	-148	13	168	21	1.62	5.3×10^{-2}
20	147	20	-127	508-4A	-158	10.5	178	31	2.95	1.6×10^{-3}

Table I6. Limit state probability implied by FA-AX-YS, T = -20°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(NDTT)}$	P_F
4	103	-20	-123	508-4B	-148	13	128	25	0.993	2.7×10^{-2}
4	103	-20	-123	508-4A	-158	10.5	138	35	3.333	4.4×10^{-4}
8	115	-20	-135	508-4B	-148	13	128	13	1.000	1.6×10^{-1}
8	115	-20	-135	508-4A	-158	10.5	138	23	2.190	1.4×10^{-2}
12	120	-20	-140	508-4B	-148	13	138	8	0.615	2.7×10^{-1}
12	120	-20	-140	508-4A	-158	10.5	138	18	1.71	4.4×10^{-2}
16	124	-20	-144	508-4B	-148	13	128	4	0.308	3.8×10^{-1}
16	124	-20	-144	508-4A	-158	10.5	138	14	1.333	9.2×10^{-2}
20	126	-20	-146	508-4B	-148	13	128	2	0.154	4.4×10^{-1}
20	126	-20	-146	508-4A	-158	10.5	128	12	1.143	1.3×10^{-1}

Table I7. Limit state probability implied by FA-AX-YS, T = -10°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(NDTT)}$	P_F
4	103	-10	-113	350-3	-120	13	110	7	0.538	3×10^{-1}
4	103	-10	-113	508-4B	-148	13	138	35	2.69	3.5×10^{-3}
4	103	-10	-115	508-4A	-158	10.5	148	45	4.29	9.1×10^{-6}
8	115	-10	-125	508-4B	-148	13	138	23	1.77	3.8×10^{-2}
8	115	-10	-125	508-4A	-158	10.5	148	33	3.14	8.4×10^{-4}
12	120	-10	-130	508-4B	-148	13	138	18	1.38	8.3×10^{-2}
12	120	-10	-130	508-4A	-158	10.5	148	28	2.57	3.8×10^{-3}
16	124	-10	-134	508-4B	-148	13	138	14	1.08	1.4×10^{-1}
16	124	-10	-134	508-4A	-158	10.5	148	24	2.24	1.1×10^{-2}
20	126	-10	-136	508-4B	-148	13	138	12	0.923	1.8×10^{-1}
20	126	-10	-136	508-4A	-158	10.5	148	22	2.10	1.8×10^{-2}

Table I8. Limit state probability implied by FA-AX-YS, T = 0°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(NDTT)}$	P_F
4	103	0	-103	350-3	-120	13	120	17	1.31	9.5×10^{-2}
4	103	0	-103	508-4B	-148	13	148	45	3.46	2.7×10^{-4}
4	103	0	-105	508-4A	-158	10.5	158	55	5.24	8.1×10^{-8}
8	115	0	-115	350-3	-120	13	120	5	0.385	3.5×10^{-1}
8	115	0	-115	508-4B	-148	13	148	33	2.54	5.6×10^{-3}
8	115	0	-115	508-4A	-158	10.5	158	43	4.10	2.1×10^{-5}
12	120	0	-120	508-4B	-148	13	148	28	2.15	1.6×10^{-2}
12	120	0	-120	508-4A	-158	10.5	158	38	3.62	1.5×10^{-4}
16	124	0	-124	508-4B	-148	13	148	24	1.85	3.2×10^{-2}
16	124	0	-124	508-4A	-158	10.5	158	34	3.24	6.0×10^{-4}
20	126	0	-126	508-4B	-148	13	148	22	1.69	4.5×10^{-2}
20	126	0	-126	508-4A	-158	10.5	158	32	3.05	1.2×10^{-3}

Table I9. Limit state probability implied by FA-AX-YS, T = 10°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(NDTT)}$	P_F
4	103	10	-93	350-3	-120	13	130	27	1.31	1.9×10^{-2}
4	103	10	-93	508-4B	-148	13	158	55	3.46	1.2×10^{-5}
4	103	10	-93	508-4A	-158	10.5	168	65	5.24	3.0×10^{-10}
8	115	10	-105	350-3	-120	13	130	15	0.385	1.2×10^{-1}
8	115	10	-105	508-4B	-148	13	158	43	2.54	4.7×10^{-4}
8	115	10	-105	508-4A	-158	10.5	168	53	4.10	2.2×10^{-7}
12	120	10	-110	350-3	-120	13	130	10	2.15	2.2×10^{-1}
12	120	10	-110	508-4B	-148	13	158	38	3.62	1.7×10^{-3}
12	120	10	-110	508-4A	-158	10.5	168	48	3.62	2.4×10^{-6}
16	124	10	-114	350-3	-120	13	130	6	1.85	3.2×10^{-1}
16	124	10	-114	508-4B	-148	13	158	34	3.24	4.5×10^{-3}
16	124	10	-114	508-4A	-158	10.5	168	44	3.24	1.4×10^{-5}
20	126	10	-116	350-3	-120	13	130	4	1.69	3.8×10^{-1}
20	126	10	-116	508-4B	-148	13	158	32	3.05	6.9×10^{-3}
20	126	10	-116	508-4A	-158	10.5	168	42	3.05	3.2×10^{-5}

Table I10. Limit state probability implied by FA-AX-YS, T = 20°F.

B (in.)	T-NDTT Reqd. °F	T °F	NDTT Reqd. °F	Matl.	Matl. NDTT °F	Matl. σ(NDTT) °F	Matl. T-NDTT °F	ΔT	$\frac{\Delta T}{\sigma(NDTT)}$	P_F
4	103	20	-83	350-3	-120	13	130	37	2.85	2.2×10^{-2}
4	103	20	-83	508-4B	-148	13	158	65	5.00	2.9×10^{-5}
4	103	20	-83	508-4A	-158	10.5	168	75	7.14	4.6×10^{-10}
8	115	20	-95	350-3	-120	13	130	25	1.92	2.7×10^{-1}
8	115	20	-95	508-4B	-148	13	158	53	4.08	2.3×10^{-4}
8	115	20	-95	508-4A	-158	10.5	168	63	6.00	1.0×10^{-7}
12	120	20	-100	350-3	-120	13	130	20	1.54	6.2×10^{-1}
12	120	20	-100	508-4B	-148	13	158	48	3.69	1.1×10^{-3}
12	120	20	-100	508-4A	-158	10.5	168	58	5.52	1.7×10^{-6}
16	124	20	-104	350-3	-120	13	130	16	1.23	1.1×10^{-1}
16	124	20	-104	508-4B	-148	13	158	44	3.38	3.6×10^{-3}
16	124	20	-104	508-4A	-158	10.5	168	54	5.14	1.4×10^{-5}
20	126	20	-106	350-3	-120	13	130	14	1.08	1.4×10^{-1}
20	126	20	-106	508-4B	-148	13	158	42	3.23	6.2×10^{-3}
20	126	20	-106	508-4A	-158	10.5	168	52	4.95	3.7×10^{-5}

APPENDIX J

Derivation of Expression for Limit State Probability Implied by the Fracture Initiation Criterion at Yield Stress Levels

APPENDIX J. DERIVATION OF EXPRESSION FOR LIMIT STATE PROBABILITY IMPLIED BY FRACTURE INITIATION CRITERION AT YIELD STRESS LEVELS

The limit state probability, P_F, associated with the fracture initiation criterion is defined by the probability that the applied stress intensity is greater than the critical fracture toughness stress intensity of the ferritic steel. With reference to Fig. J1, this is expressed by

$$P_F = P\{ K_{ID}/\sigma_{yD} < K_I/\sigma_{yD} \} \ . \qquad (J1)$$

For convenience in notation, the normalized applied fracture toughness stress intensity random variable K_1/σ_{yD} will be expressed by $\hat{K}_1$, while the normalized critical stress intensity random variable will be expressed by $\hat{K}_{1D}$, and particular values of these variables will be expressed by $\hat{k}_1$ and $\hat{k}_{1D}$, respectively. As illustrated in Fig. J1,

$$P\{ (\hat{K}_1 - \frac{d\hat{K}_1}{2}) > \hat{K}_1 > (\hat{K}_1 + \frac{d\hat{K}_1}{2}) \} = f_{\hat{K}_1}(\hat{k}_1)d(\hat{k}_1) \qquad (J2)$$

and

$$P\{ \hat{K}_{1D} < \hat{K}_1 \} = \int_0^{\hat{k}_1} f_{\hat{K}_{1D}}(\hat{k}_{1D})d(\hat{k}_{1D}) \ . \qquad (J3)$$

The infinitesimal of the limit state probability is the probability of the compound event defined by the simultaneous occurrence of the events expressed by Eqs. (2) and (3). Consequently

$$dP_F = f_{\hat{k}_1}(\hat{k}_1)d(\hat{k}_1) \times \int_0^{\hat{k}_1} f_{\hat{K}_{1D}}(\hat{k}_{1D})d(\hat{k}_{1D}) \ . \qquad (J4)$$

Integrating Eq. (4) gives

$$P_F = \int_0^{\infty} dP_F = \int_0^{\infty} f_{\hat{K}_1}(\hat{k}_1)[\int_0^{\hat{k}_1} f_{\hat{K}_{1D}}(\hat{k}_{1D})d(\hat{k}_{1D})]d(\hat{k}_1) \ . \qquad (J5)$$

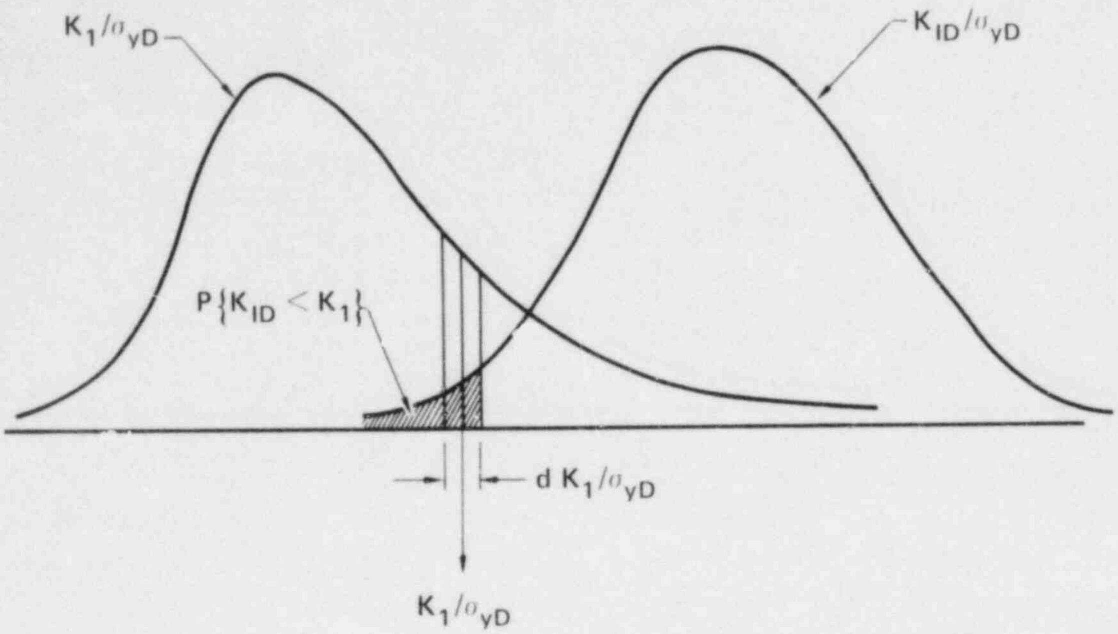


Figure J1. Overlap of response and resistance probability density function.

Probability density functions (pdf) $f_{\hat{K}_{1D}}(\hat{k}_{1D})$ and $f_{\hat{K}_1}(\hat{k}_1)$ are assumed to be log-normal since this avoids the occurrence of negative values for these parameters. Consequently,

$$f_{\ln\hat{k}_{1D}}(\ln\hat{k}_{1D}) = \frac{1}{\sigma_{\ln\hat{k}_{1D}}\sqrt{2\pi}} \exp - \frac{1}{2}\left[\frac{\ln\hat{k}_{1D} - \mu_{\ln\hat{k}_{1D}}}{\sigma_{\ln\hat{k}_{1D}}}\right]^2 \quad . \qquad (J6)$$

by a change of variable technique we note that

$$f_{\ln\hat{K}_{1D}}(\ln\hat{k}_{1D}) = \frac{f_{\hat{K}_{1D}}(\hat{k}_{1D})}{d\,\ln\hat{k}_{1D}} = \hat{k}_{1D}\, f_{\hat{k}_{1D}}(\hat{k}_{1D}) \quad , \qquad (J7)$$

and

$$f_{\hat{K}_{1D}}(\hat{k}_{1D}) = \frac{1}{\hat{k}_{1D}} f_{\ln\hat{K}_{1D}}(\ln\hat{k}_{1D}) \quad . \tag{J8}$$

substituting the expression for the pdf of $\ln\hat{k}_{1D}$ from Eq. (6) into Eq. (8) we have

$$f_{\hat{K}_{1D}}(\hat{k}_{1D}) = \frac{1}{\hat{k}_{1D}\sigma_{\ln\hat{K}_{1D}}\sqrt{2\pi}} \exp - \frac{1}{2}\left[\frac{\ln\hat{k}_{1D} - \mu_{\ln\hat{k}_{1D}}}{\sigma_{\ln\hat{k}_{1D}}}\right]^2 , \tag{J9}$$

and

$$\begin{aligned} \int_0^{\hat{k}_1} f_{\hat{K}_{1D}}(\hat{k}_{1D})\,d(\hat{k}_{1D}) &= \int_0^{\infty} \frac{1}{\hat{k}_{1D}\sigma_{\ln K_{1D}}\sqrt{2\pi}} \exp - \frac{1}{2}\left[\frac{\ln\hat{k}_{1D} - \mu_{\ln\hat{K}_{1D}}}{\sigma_{\ln\hat{K}_{1D}}}\right]^2 d(\hat{k}_{1D}) \\ &= \phi\left[\frac{\ln\hat{k}_{1D} - \mu_{\ln\hat{K}_{1D}}}{\sigma_{\ln\hat{K}_{1D}}}\right] \quad . \end{aligned} \tag{J10}$$

Since yield stress levels are assumed, the applicable stress intensity is only a function of the size and configuration of the flaw, or

$$\hat{k}_1 = C \sqrt{a} .$$

Consequently, the dispersion in values of $\hat{k}_1$ is determined by the uncertainty associated with the flaw size, "a." The pdf of $\hat{k}_1$ can be determined from the pdf of "a" by the relationship

$$f_{\hat{K}_1}(\hat{k}_1) = \frac{f_A(a)}{\frac{d}{da}\hat{k}_1(a)} \quad . \tag{J11}$$

Now

$$\frac{d}{da}\hat{k}_1(a) = \frac{c}{2\sqrt{a}} ,$$

so that

$$f_{\hat{K}_1}(\hat{k}_1) = \frac{2\sqrt{a}}{c} f_A(a) \quad , \tag{J12}$$

since

$$f_{\ln A}(\ln a) = \frac{1}{\sqrt{2\pi}\,\sigma_{\ln A}} \exp - \frac{1}{2}\left[\frac{\ln a - \check{m}_A}{\sigma_{\ln A}}\right]^2 \quad , \tag{J13}$$

and

$$f_{\ln A}(\ln a) = \frac{f_A(a)}{d \ln a} = a\, f_A(a). \tag{J14}$$

Then, combining Eqs. (12), (13), and (14) gives

$$f_{\hat{K}_1}(\hat{k}_1) = \frac{2}{\hat{k}_1 \sigma_{\ln A}\sqrt{2\pi}} \exp - \frac{1}{2}\left\{\frac{1}{\sigma_{\ln A}} \ln\left[\frac{(\hat{k}_1)^2}{c^2\, \check{m}_A}\right]\right\}^2. \tag{J15}$$

Finally, the expression for the limit state probability given by Eq. (5) may be cast in the form

$$P_F = \int_0^{\infty} \phi\left[\frac{\ln \hat{k}_{1D} - \mu_{\ln \hat{K}_{1D}}}{\sigma_{\ln \hat{K}_{1D}}}\right] f_{\hat{K}_1}(\hat{k}_1)\,d(\hat{k}_1) \qquad \text{(J16)}$$

which may be evaluated by numerical integration.

APPENDIX K

Applicable Ferritic Steels for Each Brittle Fracture Acceptance Criterion Assuming Yield Strength Levels of Stress

APPLICABLE FERRITIC STEELS FOR LIMIT STATE PROBABILITY < 10^{-2}

Material	Criterion B \ T	FA-EX-YS					FA-AX-YS					FI-YS a/ℓ → 0					FI-YS a/ℓ = 1/6					FI-YS a/ℓ = 1/2				
		-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20
SA-508-1	4													●	●	●			●	●	●	●	●	●	●	●
	8															●					●				●	●
	12																									
	16																									
	20																									
A-350-LF-5	4											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	8													●	●	●			●	●	●	●	●	●	●	●
	12														●	●				●	●			●	●	●
	16															●					●					●
	20																									●
A-350-LF-3	4					●					●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	8											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	12											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	16											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	20											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SA-508-4B	4		●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	8				●	●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	12					●				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	16									●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	20									●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SA-508-4A	4	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	8		●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	12			●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	16				●	●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	20					●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

APPLICABLE FERRITIC STEELS FOR LIMIT STATE PROBABILITY < 10^{-3}

Criterion		FA-EX-YS					FA-AX-YS					FI-YS a/ℓ → 0					FI-YS a/ℓ = 1/6					FI-YS a/ℓ = 1/2				
Material	B \ T	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20
SA-508-1	4																					●	●	●	●	●
	8																								●	●
	12																									
	16																									
	20																									
A-350-LF-5	4																					●	●	●	●	●
	8																		●	●	●	●	●	●	●	●
	12														●	●				●	●			●	●	●
	16															●					●					●
	20																									●
A-350-LF-3	4																					●	●	●	●	●
	8																●	●	●	●	●	●	●	●	●	●
	12											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	16											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	20											●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SA-508-4B	4			●	●	●			●	●	●											●	●	●	●	●
	8					●				●	●						●	●	●	●	●	●	●	●	●	●
	12										●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	16										●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	20										●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
SA-508-4A	4	●	●	●	●	●	●	●	●	●	●											●	●	●	●	●
	8			●	●	●		●	●	●	●						●	●	●	●	●	●	●	●	●	●
	12				●	●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	16					●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	20									●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

APPLICABLE FERRITIC STEELS FOR LIMIT STATE PROBABILITY $< 10^{-4}$

Criterion		FA-EX-YS					FA-AX-YS					FI-YS $a/\ell \to 0$					FI-YS $a/\ell = 1/6$					FI-YS $a/\ell = 1/2$				
Material	B T	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20
SA-508-1	4																					●	●	●	●	●
	8																								●	●
	12																									
	16																									
	20																									
A-350-LF-5	4																					●	●	●	●	●
	8																					●	●	●	●	●
	12																							●	●	●
	16																									●
	20																●	●	●	●	●					●
A-350-LF-3	4																					●	●	●	●	●
	8																					●	●	●	●	●
	12																					●	●	●	●	●
	16																					●	●	●	●	●
	20																					●	●	●	●	●
SA-508-4B	4				●	●				●	●											●	●	●	●	●
	8										●											●	●	●	●	●
	12																					●	●	●	●	●
	16																					●	●	●	●	●
	20																●	●	●	●	●	●	●	●	●	●
SA-508-4A	4		●	●	●	●		●	●	●	●											●	●	●	●	●
	8				●	●			●	●	●											●	●	●	●	●
	12					●				●	●											●	●	●	●	●
	16									●	●											●	●	●	●	●
	20									●	●						●	●	●	●	●	●	●	●	●	●

APPLICABLE FERRITIC STEELS FOR LIMIT STATE PROBABILITY $< 10^{-5}$

Material	Criterion	FA-EX-YS					FA-AX-YS					FI-YS $a/\ell \to 0$					FI-YS $a/\ell = 1/6$					FI-YS $a/\ell = 1/2$				
	B \ T	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20
SA-508-1	4																									
	8																									
	12																									
	16																									
	20																									
A-350-LF-5	4																									
	8																									
	12																									
	16																									
	20																									
A-350-LF-3	4																									
	8																									
	12																									
	16																					●	●	●	●	●
	20																					●	●	●	●	●
SA-508-4B	4					●					●															
	8																									
	12																									
	16																					●	●	●	●	●
	20																					●	●	●	●	●
SA-508-4A	4		●	●	●	●		●	●	●	●															
	8				●	●				●	●															
	12					●				●	●															
	16										●											●	●	●	●	●
	20										●											●	●	●	●	●

APPLICABLE FERRITIC STEELS FOR LIMIT STATE PROBABILITY < 10^{-6}

Criterion		FA-EX-YS					FA-AX-YS					FI-YS a/ℓ → 0					FI-YS a/ℓ = 1/6					FI-YS a/ℓ = 1/2				
Material	B \ T	-20	-10	0	10	20	-2C	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20	-20	-10	0	10	20
SA-508-1	4																									
	8																									
	12																									
	16																									
	20																									
A-350-LF-5	4																									
	8																									
	12																									
	16																									
	20																									
A-350-LF-3	4																									
	8																									
	12																									
	16																									
	20																									
SA-508-4B	4					●					●															
	8																									
	12																									
	16																									
	20																									
SA-508-4A	4			●	●	●			●	●	●															
	8					●				●	●															
	12										●															
	16										●															
	20										●															

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Various criteria for protecting against brittle fracture in spent-fuel shipping containers made from ferritic steel forgings greater than four inches thick are evaluated. A fracture initiation criterion based upon yield stress levels and allowable flaw sizes specified in Section XI of the ASME Code is recommended. This recommendation is based upon a value impact evaluation taking into account its effect upon industry and the risk of brittle fracture.

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