NEDO-32205-A
Class I
February 1994
Revision 1

10CFR50 APPENDIX G EQUIVALENT MARGIN ANALYSIS FOR LOW UPPER SHELF ENERGY IN BWR/2 THROUGH BWR/6 VESSELS

Licensing Topical Report for
the BWR Owners' Group

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IMPORTANT NOTICE REGARDING CONTENTS OF THIS REPORT

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

DEC 0 8 [illegible]

Mr. Lesley A. England, Chairman
Gulf States Utilities Company
P. O. Box 220
St. Francisville, LA 70775

Dear Mr. England:

SUBJECT: ACCEPTANCE FOR REFERENCING OF TOPICAL REPORT NEDO-32205, Revision 1, "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 Through BWR/6 Vessels"

We have completed our review of the subject topical report submitted by the BWR Owners' Group. We find the report to be acceptable for referencing in license applications to the extent specified and under the limitations delineated in the report and the associated NRC safety evaluation (SE), which is enclosed. The evaluation defines the basis for acceptance of the report.

We do not intend to repeat our review of the matters described in the report when the report appears as a reference in license applications, except to assure that the material presented is applicable to the specific plant involved as indicated in the conclusion section of the SE. Our acceptance applies only to the matters described in the report.

In accordance with procedures established in NUREG-0390, it is requested that the BWR Owners' Group publish this report within three months of receipt of this letter. The final version shall incorporate this letter and the enclosed evaluation between the title page and the abstract. The final version shall include an -A (designating accepted) following the report identification symbol.

Should our criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, licensees referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

James T. Wiggins, Acting Director
Division of Engineering
Office of Nuclear Reactor Regulation

Enclosure:
As stated

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ENCLOSURE

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

BWR OWNERS' GROUP TOPICAL REPORT

NEDO-32205, REVISION 1

ON UPPER SHELF ENERGY EQUIVALENT MARGIN ANALYSIS

MATERIALS INTEGRITY SECTION

MATERIALS AND CHEMICAL ENGINEERING BRANCH

DIVISION OF ENGINEERING

1.0 REVIEW SUMMARY

The staff has reviewed the equivalent margin analysis presented in the topical report submitted by the BWR Owners' Group (BWROG) and finds the report to be acceptable.

The staff has verified that the BWROG has complied with the analytical procedures and the acceptance criteria in The American Society of Mechanical Engineers (ASME) Code Case N-512 in calculating the minimum permissible upper-shelf energy (USE) for each type of material. Some minor deviations from the Code Case procedures and some unique approaches used by the BWROG due to lack of guidance in the Code Case have been identified, evaluated, and found to be acceptable. A unique approach by the BWROG is the statistical analysis of the BWROG's database, which is comprised of USE test data of some beltline materials from about 31 BWR reactor vessels. The BWROG has derived statistically the initial USE values for materials that originally did not have documented USE values. The BWROG predicted the end-of-life (EOL) USE values in accordance with Regulatory Guide 1.99, Revision 2 (RG 1.99, Rev. 2). The EOL USE value for each type of beltline materials is higher than the minimum permissible USE calculated by Code Case N-512; therefore, the topical report demonstrates that the materials evaluated have the margins of safety against fracture equivalent to Appendix G of the ASME Code, in accordance with Appendix G of 10 CFR 50.

2.0 INTRODUCTION

By letter dated April 30, 1993, the BWROG submitted a topical report entitled "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 Through BWR/6 Vessels," [1] for staff review and approval. Subsequent to the staff's preliminary review, the BWROG submitted its response to the staff's request for additional information (RAI) in a letter dated August 23, 1993 [2] to clarify some technical concerns. Recently, because Vermont Yankee was added to the topical report coverage and Oyster Creek's EOL USE drop for welds was changed from 33% to 34%, the BWROG faxed a revised version [3] (Revision 1) on December 2, 1993 to NRC. This topical report was intended to demonstrate through fracture mechanics analysis that there exists margins of safety against fracture equivalent to those required by Appendix G of ASME

Code Section III, for beltline materials having USE values below 50 ft-lbs.

3.0 EVALUATION

The BWROG followed the procedures and criteria developed by the ASME Section XI Working Group on Flaw Evaluation, which was recently approved by the ASME Boiler and Pressure Vessel Code, Section XI. A Section XI Code Case, N-512, on the subject of low USE equivalent margins has been published [4]. In accordance with the Code Case, the BWROG assumed a quarter-thickness deep flaw for Level A and B conditions and assumed a depth of 1/10 of the base metal wall thickness, plus cladding for Level C and D conditions. The flaw geometry for all service loadings is of the semi-elliptical surface flaw type with an aspect ratio of 6:1. In the equivalent margin analysis, both the axial and the circumferential flaw cases have been considered for plates, but only the more limiting axial flaw case has been considered for welds. The beltline plates covered by this topical report are SA302B low alloy steel plates (including SA302B-Modified plates) and 533B plates; the welds covered are submerged arc welds (SAW) with Linde 80 or non-Linde 80 flux, electroslag welds (ESW), and shielded metal arc welds (SMAW). For ease of referencing and evaluation, the staff has compiled copper contents, fluences, and predicted EOL USE drops for all eight types of materials covered in this report in Table 1. Also reported in Table 1 are the BWROG's final results from the equivalent margin analysis.

The equivalent margin analysis compared two EOL USE values for each type of beltline materials: the predicted EOL USE value obtained by using RG 1.99, Rev. 2 and the minimum permissible EOL USE value obtained by the equivalent margin analysis described in Code Case N-512. The adequacy of the equivalent margin analysis can be determined from the following considerations for each of the beltline materials mentioned above: (1) the determination of the predicted EOL USE value, (2) the selection of the model for generating the J-R curves, (3) the selection of transients, (4) the applied J calculation, and (5) the bounding nature of the analysis.

3.1 PREDICTED EOL USE VALUES

Based on the assumed copper contents and fluences shown in Table 1, the BWROG used RG 1.99, Rev. 2 to predict the EOL USE drops for all eight material types. They then used these predicted USE drops and the statistically determined initial USE values to obtain the predicted EOL USE values. The results from this procedure has been verified independently by the staff. The critical concerns here are the bounding nature of the assumed copper contents and fluence levels for all eight materials considered in this report and the bounding nature of the initial USE values derived for them. The first concern involves BWR licensees' responses to Generic Letter (GL) 92-01 and will be evaluated separately in Section 3.5; the second concern is self-contained and is evaluated here.

The concern about the initial USE values derived for all eight types of materials can be resolved by evaluating the BWROG's data gathering and statistical analysis. For the BWR/2 plants, all beltline plates are of SA302B material and all USE data are available for them; therefore, the BWROG used the lowest USE data point as the initial USE value for this type of material. For the rest of the majority BWR plants, the records on initial USE values for both plates and welds are incomplete; consequently, the BWROG relied on a statistical approach based on existing data from similar materials to derive initial USE values for their beltline materials. Initial Charpy USE values in BWROG's database are either from the surveillance programs or certified material test reports (CMTR), and are from materials fabricated by using the same vendor, fabrication time frame, fabrication process, and material specification representing all 31 BWR plants. Therefore, all beltline materials of the 31 plants belong to the same population.

The BWROG in their analysis of plate material in BWR/3-6 used the lowest observed USE as the lower limit of USE. The BWROG in their analysis of SMAW, electroslag, and non-Linde 80 welds used a 97.7 tolerance limit. However, the stated result is invalid because they did not consider the sample size. The staff has performed an independent statistical analysis that considers the sample size. This method is described in [5], where the lower tolerance limit is defined as the sample mean minus κ times s, where s is the sample standard deviation. The coefficient κ (Table T-11b in [5]) is determined from the sample size and provides 95% confidence that at least 95% of the population is greater than the tolerance limit. This approach is conservative because it provides 95% confidence that 95% of the population has been bounded by the statistically determined initial USE value, and the bounding approach in RG 1.99, Rev. 2 is used to predict the USE drop.

3.2 THE SELECTION OF THE J-R MODEL

The BWROG selected the J-R models for all eight types of material as shown in Table 3. In order to bound all plates by the equivalent margin analysis, the BWROG only used the more conservative SA302B plate model for plates. In the case of welds, the BWROG used two weld models for different types of welds. The derivation of J-R curves for the SA302B model involves two steps: first, establishing the relationship between material toughness values (J_{IC}) and Charpy energy values; second, establishing the relationship between the maximum J value and the J_{IC} value. Based on 21 experimental data points from SA302B plates in both longitudinal and transverse orientations as shown in Figure 4-1 of the topical report, the BWROG established a mean minus two sigma (Mean - 2σ) line relating J_{IC} values to EOL Charpy energy values for SA302B plates. They then used the only set of J-R curves (tested at 180 °F) [6] reported so far for the SA302B plate to conclude that the J-R curve will first reach a value of 1.3 times J_{IC}, and then the crack will keep on growing stably at the same J value. The tests, which were performed to study the size effect for SA302B plates, were conducted at 180 °F; therefore, some temperature adjustment has to be done in applying the results in [6] to predict J-R curves at the USE temperature (for example, 550 °F). In summary, for each assumed EOL USE value, the BWROG's SA302B model would give a J-R curve. The staff concludes that the approach described above is acceptable. The 21 data points, from which the Mean - 2σ line relating J_{IC} values to EOL Charpy energy values for SA302B plates was obtained, correspond to tests conducted at temperatures from 400 to 550°F; therefore, some temperature effect has already been reflected in the standard deviation of the database. Further, using the Mean - 2σ relationship for J_{IC} v.s. EOL USE in the statistical approach in the first step results in a 95% confidence for about 91% of the population, which is acceptable to the staff because a margin of 16 ft-lbs exists in the final result. Although the method of obtaining the maximum J value through multiplying J_{IC} by a factor of 1.3 is not rigorous, it is an acceptable engineering approach.

So far, no other methods have been attempted for predicting the J-R curves for SA302B plates except for the one described in a draft Regulatory Guide [7], which deals with materials with low USE values. The staff applied both the BWROG's method and the method in the draft Regulatory Guide to a typical SA302B plate at 525°F for different EOL USE values and presented the Mean - 2σ (for Level A, B, and C loadings only) $J_{0.1}$ results in Table 4. It can be seen that the $J_{0.1}$ values from the BWROG's method for all EOL USE values are smaller than the corresponding values predicted by the method in the draft Regulatory Guide. This indicates that the BWROG's method is conservative.

As to the Combined Database Charpy Model without thickness terms selected by the BWROG from NUREG/CR-5729 [8] for non-Linde welds, the staff has checked their bounding nature by comparing the J-R curves from the BWROG's selection to those from other models also available in the same source. In the response to the staff's RAI about the selection of the Combined Database Charpy Model for non-Linde 80 welds, the BWROG presented two J-R curves: one from the Combined Database Charpy Model and the other from the reactor pressure vessel (RPV) Weld Copper-Fluence Model (also available in [8]). These curves show clearly the conservative nature of BWROG's model selection. Regarding the BWROG's decision to use the Combined Database Charpy Model without thickness terms as opposed to the model with thickness terms, the staff agrees that the statistical quality of the J-R curve fit for these two cases is about the same (standard deviation of .229 versus .224), and using either J-R model is acceptable. Further, the staff calculated $J_{0.1}$ values for two more competing models from [8] that were not mentioned in [2] and made a comparison to that from the Combined Database Charpy Model used by BWROG. The results are 592 in-lb/in² for BWROG's Combined Database Charpy Model without thickness terms; 680 in-lb/in² for the RPV weld CVN_P model with thickness terms; and 668 in-lb/in² for the copper-fluence model with thickness terms. This sample calculation was based on the following assumptions: 0.35 Cu%, 4.9×10^{18} n/cm² fluence, 1 inch B_n, and 550 °F temperature. This confirms that the BWROG's J-R model for non-Linde welds is the most conservative one.

The BWROG chose the Linde 80 Copper-Fluence Model without thickness terms from NUREG/CR-5729 for their Linde 80 welds. Since the final results presented in Figure 5-5 of the topical report show large margins between the applied J curve and the J-R curve for both criteria, the staff has concluded that checking all possible J-R models for Linde 80 welds is not necessary and the results for Linde 80 welds are acceptable.

3.3 THE SELECTION OF TRANSIENTS

The topical report states that after a review of all BWR/2-6 thermal cycle diagrams for Level A and B transients, it was determined that the 100 °F/Hr heatup/cooldown case is bounding except for the Level B loss of feedwater pump transient. Consequently, both transient cases were analyzed by the BWROG.

Although the stress intensity factor K_{IT} due to the thermal loading associated with the loss of feedwater pumps (12 ksi.in$^{1/2}$) is higher than the K_{IT} associated with the 100 °F/Hr heatup/cooldown case (10 ksi.in$^{1/2}$), the former is less severe because the associated pressure loading is less than one-half the accumulation pressure of 1375 psi.

The BWROG reviewed all Level C transients associated with a BWR/6 standard plant and identified automatic blow down (Event 23) to be the limiting transient for BWR/2 vessels and the improper start of cold recirculation loop (Event 24) the limiting transient for BWR/3-6 vessels; for Level D loading, the loss of coolant accident (Event 27) was identified to be the most limiting case.

The staff believes that the transients selected for Level A, B, and C loadings are bounding. The BWROG made the transient selection for Levels A and B after they had reviewed all thermal cycle diagrams for all BWR/2 to BWR/6 plants. Further, the 100 °F/Hr heatup/cooldown case is the same as that used in NUREG/CR-6023 [9]. The Level C transient for BWR/3-6 vessels begins with a straight drop from 528°F to 268 °F in zero seconds followed by a constant temperature at 268 °F for 26 minutes and then straight back to 528°F in zero seconds. It is more severe than the two transients, referred to as Transients 1 and 2 in [9], where the cooldown rate is 43.75 °F/min from 550°F to 375°F and 5.55 °F/min from 375°F to 275°F for Transient 1, and is 4.75 °F/min from 550°F to 75°F for Transient 2. For Level D loading, the transient selected may not be bounding because many older BWR plants have no Level D loadings defined for the RPV. Considering that not much different results were reported in [9] for two rather different transients (Transients 1 and 2), and considering the lack of definition of Level D transient for older plants, the staff believes that using the limiting transients from a BWR/6 standard plant for Level C and D loadings is acceptable.

3.4 THE APPLIED J CALCULATION

Using the heatup/cooldown of 100°F/hour and a pressure of 1581 psi (1.15 times the accumulation pressure) for the $J_{0.1}$ criterion and a pressure of 1719 psi (1.25 times the accumulation pressure) for the stability criterion, the BWROG followed the procedure in Code Case N-512 and calculated the K_{Ip}, K_{It}, and applied J values for cracks with the orientations, shapes, and depths described in Section 3.0 for Level A and B loadings for all eight types of materials listed in Table 1. The applied J value for each type of material was then compared to the corresponding J-R curves (Mean - 2σ curves) with various assumed USE values to determine its minimum permissible EOL USE values. The results are acceptable based on the following considerations: (1) the procedure is straightforward and all equations for applied J calculation are clearly defined in Code Case N-512 for Level A and B loadings; (2) the BWROG's final results are comparable to those from similar analyses presented in NUREG/CR-6023; (3) there are additional margins of various magnitudes up to approximately 10 ft-lb (see Table 1) implicitly built into the BWROG's final results when the graphical results (Figures 5-2a,b, 5-3a,b, and 5-4 of the topical report) were transformed to numerical ones (the table on page 8-11 of the topical report) summarized in Table 1. These extra margins exist because for most cases the BWROG's equivalent margin analysis was stopped before the lowest permissible USE values had been reached. The NUREG results [9] are reproduced in the last column of Table 1 for comparison. Table 1 shows that based on staff's calculation the type of material with the least margin (3 ft-lbs) is ESW welds. The actual margin for ESW welds should be higher because the BWROG indicates in Revision 1 of the topical report that the actual EOL USE drop for ESW welds is 25%, not the bounding value of 34%.

Unlike the Level A and B loadings, Code Case N-512 does not provide procedures to calculate the stress intensity factor K for temperature transients with rates exceeding 100°F per hour. Therefore, the finite element method was employed in both the thermal and stress analyses for the Level C and D loadings by using the transients defined in Section 3.3. In the subsequent fracture mechanics evaluation, the BWROG employed the Raju-Newman method to calculate K values for the postulated axial flaws and a point force approach to calculate K due to clad. BWROG used the K values developed for the axial flaw for circumferential flaws and used the K equations derived for $0.2 < a/t < 0.5$ to the current situation of $a/t = 0.1$. In [2], the BWROG supplied K curves for both axial and circumferential surface cracks and showed that using the axial flaw curves for both flaw orientations is conservative. Also in [2] are results cited from another reference, which justifies the use of the formulas, Equations 3-1 to 3-3 of the topical report, to smaller flaws ($a/t = 0.1$). The staff accepts both explanations.

By comparing the final results for Level C (Figure 6-6 of the topical report) and Level D loading (Figure 6-10) for SA302B plate, the staff agrees that Level A and B results are controlling and the same conclusion can be applied to other types of material also. Therefore, the minimum permissible EOL USE values, listed under the heading "Code Case N-512 EOL USE" in Table 1, are actually results from Level A and B analyses.

3.5 THE BOUNDING NATURE OF THE ANALYSIS

To ensure that all 29 BWR plants of the participating utilities are covered by this topical report, the staff has compiled information on the copper contents and the fluence levels of the limiting beltline plates and welds reported by the BWROG licensees in their latest submittals including responses to GL 92-01. The staff has confirmed the bounding nature of the analysis by comparing the EOL USE drops of the limiting plate and weld of each plant to those predicted by the pertinent materials in the topical report. The results are summarized in Table 5, which show that the EOL USE drops reported by all BWROG plants for their limiting plates or welds are smaller than the corresponding values assumed in this topical report; therefore, all 29 BWROG plants are bounded by this topical report.

Since the eight types of material in the topical report assume the worst combination of copper content and fluence level, the limiting beltline materials of some plants may have either copper content or fluence level exceeding the values documented in the topical report. This is acceptable as long as the predicted EOL USE drops for those particular plants are smaller than those in the topical report because the USE drops are caused by the combined effect of copper content and fluence level, not by the effect of any single value.

4.0 CONCLUSION

As indicated by the results summarized in Table 1 under the heading "CODE CASE N-512 EOL USE", the BWROG's equivalent margin analysis passed the two criteria stated in Code Case N-512 with margins of at least 3.0 ft-lbs. Based on these results and the evaluation conducted in Section 3, the staff concludes that the reactor pressure vessels of the participating utilities should have adequate margins of safety against ductile failure in low USE plates and welds until the EOL (32 EFPY) for Level A, B, C, and D conditions, and meet the criteria of Code Case N-512.

Individual licensees that reference this topical report as the basis for addressing the USE requirements of 10 CFR Part 50, Appendix G, must confirm the plant specific applicability, as specified in Appendix B of the report, and request approval in accordance with 10 CFR Part 50, Appendix G.

5.0 REFERENCES

1. NEDO-32205, "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 Through BWR/6 Vessels," Licensing Topical Report for the BWR Owners' Group, GE Nuclear Energy, April 1993.

2. Response to RAI Questions on BWR Owners' Group Topical Report on Upper Shelf Energy Equivalent Margin Analysis, GE Nuclear Energy, August 23, 1993.

3. NEDO-32205, Revision 1, "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 Through BWR/6 Vessels," Licensing Topical Report for the BWR Owners' Group, GE Nuclear Energy (Faxed to NRC on December 2, 1993.)

4. Code Case N-512, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels, Section XI, Division 1," ASME Boiler and Pressure Vessel Code, February 12, 1993.

5. D. Lurie and R. H. Moore, "Applying Statistics," NUREG-1475, Version date: August 12, 1993 (not published yet).

6. A. L. Hiser and J. B. Terrell, "Size Effects on J-R Curves for a 302-B Plate," NUREG/CR-5265, January 1989.

7. "Evaluation of Reactor Pressure Vessels with Charpy Upper-Shelf Energy Less than 50 ft-lb.," Draft Regulatory Guide DG-1023, U. S. Nuclear Regulatory Commission, August, 1993.

8. E. D. Eason, J. E. Wright, and E. E. Nelson, "Multivariable Modeling of Pressure Vessel and Piping J-R Data," NUREG/CR-5729, May 1991.

9. T. L. Dickson, "Generic Analyses for Evaluation of Low Charpy Upper-Shelf Energy Effects on Safety Margins Against Fracture of Reactor Pressure Vessel Materials," NUREG/CR-6023, July 1993.

TABLE 1

Summary on results from equivalent margin analysis for eight types of beltline material

MATERIAL TYPE	CU %	FLUENCE $\times 10^{18}$ (n/cm^2)	INI. USE (ft-lb)	PREDICTED USE DROP %	PREDICTED EOL USE BWROG (ft-lb)	PREDICTED EOL USE NRC (FT-LB)	CODE CASE N-512 EOL USE (ft-lb)	CR-6023 EOL USE (FT-LB)
BWR/2 (L)*	.27	2.4	76	26	56	---	50[45]**	55
BWR/2 (T)	.27	2.4	49	26	36.5	---	35[25]	36
BWR/3-6(L)***	.17	3.8	91	21	72	78	59[59]	55
BWR/3-6(T)	.17	3.8	59	21	47	51	35[25]	36
SMAW	.35	2.4	87	34	57	56	35[33]	33
ELECTROSLAG	.35	2.4	69	34	46	36	35[33]	33
NON-LINDE 80	.35	2.4	71	34	47	46	35[33]	33
LINDE 80	.31	1.0	--	--	--	--		33

* Containing SA302B plates only.

** Values inside brackets are estimated by the staff directly from Figures 5-2a,b, 5-3a,b, and 5-4 of the topical report, which represent the lowest limits that the USE values of beltline materials may reach. These values are only used to assess margins; they do not represent the minimum permissible USE values acceptable to the staff.

*** Containing SA302B Modified and 533B plates.

TABLE 2

Summary on staff's statistical analyses
for predicting 95% of the entire population with a one-sided 95% confidence
for five types of beltline material

MATERIAL TYPE	NO. OF DATA	INITIAL USE BWROG* (ft-lb)	INITIAL USE NRC** (ft-lb)	PREDICTED USE DROP %	EOL USE BWROG (ft-lb)	EOL USE NRC (ft-lb)	N-512*** EOL USE (ft-lb)
BWR/3-6(L)	>200	91	99	21	72	78	59[59]
BWR/3-6(T)	>200	59	64	21	47	51	35[25]
SMAW	41	87	85	34	57	56	35[33]
ELECTROSLAG	11	69	55	34	46	36	35[33]
NON-LINDE 80	58	71	70	34	47	46	35[33]

* The first two in the column are lower bound values; the rest are Mean-2σ values.

** All are Mean-$\kappa\sigma$ values (κ values are, from top to bottom, 1.837, 1.837, 2.119, 2.823, and 2.030.)

*** these results are reproduced from Table 1 for comparison.

TABLE 3

BWROG's selection of J-R models for beltline materials

MATERIAL TYPE	J-R MODEL
BWR/2 (L)	SA302B
BWR/2 (T)	SA302B
BWR/3-6(L)	SA302B
BWR/3-6(T)	SA302B
SMAW	COMBINED DATABASE CHARPY
ELECTROSLAG	COMBINED DATABASE CHARPY
NON-LINDE 80	COMBINED DATABASE CHARPY
LINDE 80	LINDE 80 CU-FLUENCE

TABLE 4

Comparison of $J_{0.1}$ for low toughness SA302B plates

T= 525°F

EOL USE ft-lb	$J_{0.1}$ (BWROG) in-lb/in^2	$J_{0.1}$* (draft Regulatory Guide) in-lb/in^2
35	195	216
40	222	256
45	249	297
50	276	339

* A safety Factor (SF) of 0.749 for high tougnness plates has been applied

TABLE 5

Predicted EOL USE drops for the limiting plates and welds for the 29 participating plants

PLANT NAME	BWR TYPE	PLATE CU%	PLATE ΔUSE%	WELD CU%	WELD ΔUSE%	1/4T FLUENCE 10^{18} (n/cm^2)
Browns Ferry 1	4	0.15	13.5	0.31	23	0.86
Browns Ferry 2	4	0.17	14.5	0.25ES	22	0.73
Browns Ferry 3	4	0.15	13	0.25ES	22	0.72
Brunswick 1	4	0.15	15.2	0.05	12.0	1.42*
Brunswick 2	4	0.19	17.7	0.06	12.5	1.42*
Cooper	4	0.21	18	0.22	30.5**	1.10
Dresden 2	3	0.23	13.9	0.25	16.8	0.25
Dresden 3	3	0.24	15.4	0.30ES	21.0	0.37
Duane Arnold	4	0.15	18.3	0.03	14.9	3.60
FitzPatrick	4	0.18	17.8	0.26	26.6	1.70
Grand Gulf 1	6	0.04	11.9	0.06	12.5	1.42*
Hatch 1	4	0.17	17.3	0.28	29.0	1.8
Hatch 2	4	0.11	12.0	0.23	22.0	1.0
Hope Creek	4	0.15	14.0	0.10	14.0**	1.1
LaSalle 1	5	0.15	10.2	0.33	19.0	0.25*
LaSalle 2	5	0.12	9.0	0.04	8.1	0.28*
Limerick 1	4	0.12	12.6	0.09	13.9	1.20
Limerick 2	4	0.15	14.6	0.09	13.9	1.20
Millstone 1	3	0.23	18.3	0.21	29.0**	0.90
Monticello	3	0.17	20.6	0.10	19.0	3.80
Oyster Creek	2	0.27	25.7	0.35	34.0	2.36
Peach Bottom 2	4	0.13	11.1	0.21	17.9	0.55
Peach Bottom 3	4	0.15	11.9	0.21	17.6	0.50
Quad Cities 1	3	0.27	15.9	0.30ES	19.0	0.25
Quad Cities 2	3	0.18	12.3	0.30ES	20.5	0.35
Susquehanna 1	4	0.14	11.5	0.04	9.5	0.53
Susquehanna 2	4	0.13	11.0	0.06	9.9	0.53
Vermont Yankee	4	0.13	8.4	0.03	7.2	0.17
WNP 2	4	0.15	13.8	0.09	13.2	0.94
29						

* The fluence is from the most recent submittal since it was not reported in the response to GL 92-01

** Reported by the licensee from surveillance data

LIST OF PARTICIPATING BWR UTILITIES

Utility	Plant(s)
Carolina Power & Light	Brunswick 1 & 2
Commonwealth Edison	Dresden 2 & 3
	Quad Cities 1 & 2
	LaSalle 1 & 2
Entergy Operations	Grand Gulf
GPU Nuclear	Oyster Creek
Iowa Electric Light & Power	Duane Arnold
Nebraska Public Power District	Cooper
New York Power Authority	FitzPatrick
Northeast Utilities	Millstone 1
Northern States Power	Monticello
Pennsylvania Power & Light	Susquehanna 1 & 2
Philadelphia Electric	Peach Bottom 2 & 3
	Limerick 1 & 2
Public Service Electric & Gas	Hope Creek
Southern Nuclear Operating Company	Hatch 1 & 2
Tennessee Valley Authority	Browns Ferry 1, 2 & 3
Vermont Yankee Nuclear Power Corp.	Vermont Yankee
Washington Public Power Supply System	WNP-2

ABSTRACT

As a result of reviewing responses to Generic Letter 92-01, the NRC recommended that Owners' Groups perform equivalent margin analyses, following the methods provided in the then-draft Appendix X, which has since become Code Case N-512. Since many BWRs do not have the necessary initial upper shelf energy (USE) data to demonstrate 50 ft-lb USE per NRC methods, as required by 10CFR50 Appendix G, the BWR Owners' Group (BWROG) initiated an equivalent margin analysis for BWR/2-6 vessels.

The analysis addresses axial and circumferential flaws in plate material, with the corresponding longitudinal and transverse USE data used for comparison to analysis results. For welds, only the more limiting axial flaw case was evaluated. The analysis addressed BWR/2 plates separately from BWR/3-6 plates, due to differences in geometries, material properties and availability of USE data. The welds were addressed together for BWR/2-6 vessels, but were grouped by weld method type, specifically shielded metal arc, electroslag and submerged arc welding.

The Code Case analysis results, based on consistently conservative assumptions for Level A and B conditions, showed that equivalent margin is demonstrated for 35 ft-lb USE values, except in the longitudinal plate direction, where the results were 50 ft-lb for BWR/2 plates and 59 ft-lb for BWR/3-6 plates. The analysis results for Level C and D conditions were less limiting than Level A and B results.

Projections for each material type evaluated showed that, at 32 effective full power years (EFPY), the USE values will remain higher than, and therefore meet, the allowable limits from the equivalent margin analysis. The assumptions made in simplifying the analysis to cover all vessels considered were consistently conservative. In cases where statistical evaluation was done on the data available for a particular material type, the projections for as much as a 3σ, or 99.8% confidence, lower bound still met the allowables.

Specific BWR plants can compare their USE surveillance results to the predictions of Regulatory Guide 1.99 to verify that the comparisons of 32 EFPY USE with the equivalent margin analysis are bounding for their vessel beltline, using the approach provided in Appendix B. Once the bounding nature of the BWR Owners' Group analysis has been established, the plant can reference the analysis to demonstrate compliance with the USE requirements of 10CFR50 Appendix G for 32 EFPY of operation.

EXECUTIVE SUMMARY

10CFR50 Appendix G requires that 50 ft-lb upper shelf energy (USE) be maintained in the vessel beltline low alloy steel material throughout operation. It further requires, if 50 ft-lb USE cannot be demonstrated, that methods to show equivalent margin be provided. As a result of reviewing responses to Generic Letter 92-01, the NRC expressed concern in September 1992 that some plants could not demonstrate that their USE levels would remain above 50 ft-lb. The NRC recommended that Owners' Groups perform equivalent margin analyses, following the methods provided in the then-draft Appendix X, which has since become Code Case N-512. Since many BWRs do not have the necessary initial USE data to demonstrate 50 ft-lb USE per NRC methods, the BWR Owners' Group (BWROG) initiated an equivalent margin analysis for BWR/2 through BWR/6 vessels.

As a first step, analysis was done of an ASME Code Section XI example problem, to provide a check on some of the methods and assumptions which are not specifically defined in the Code Case. The GE results for the BWR example problem agreed closely with the NRC solutions for the same problem.

The scope of the equivalent margin analysis is intended to bound the materials and 32 effective full power year (EFPY) fluences of all U.S. BWR/2 through BWR/6 (BWR/2-6) vessels. The materials which the analysis addresses are as follows:

- SA302 Grade B and Grade B Modified low alloy steel plate
- SA533, Grade B Class 1 low alloy steel plate
- Shielded Metal Arc Welds (SMAW)
- Electroslag Welds (ESW)
- Submerged Arc Welds (SAW) made with non-Linde 80 flux
- SAW with Linde 80 flux

The approach used in performing the equivalent margin analysis was to evaluate axial and circumferential flaws for the geometric and loading conditions specified in the Code Case. The results provide an USE value above which adequate fracture toughness is assured. Throughout the analysis, bounding assumptions were made to assure that the results would be applicable to all U.S. BWR/2-6 vessels. The various aspects of the analysis, by report section, and the conservatisms of the analysis in that section are summarized next.

Section 2: Vessel Geometry Considerations

The radii and thicknesses of all U.S. BWR/2-6 vessels were evaluated against material types to determine the dimensions which would provide the bounding stress intensity factor (K_I), and thus the limiting $J_{applied}$, for each category of material evaluated.

Section 3: Evaluation Methodology

The methodology generally followed that of Code Case N-512. The pressure and thermal loadings for the most limiting BWR vessel were applied to the evaluations. While the Code Case requires, for Level A and B conditions, thermal stresses for heatup/cooldown conditions of 100°F/hr, all BWR thermal cycle diagrams were reviewed to determine whether any other Level A or B conditions caused more severe thermal loading. Similarly, Level C and D conditions from all BWR thermal cycle diagrams were reviewed to determine the event or events with the most severe thermal loading.

Section 4: J-R Curve Development

The material categories evaluated were ultimately reduced to four for the establishment of minimum allowable USE. The categories were SA302B plate, 533 plate, non-Linde 80 weld and Linde 80 weld.

J-R curves for the plates were developed from data for the V50 plate, tested as described in NUREG CR-5256, which was SA302B material. The V50 plate results are expected to be very conservative compared to typical vessel plates, due to the small amount of cross-rolling the V50 plate received during fabrication. The V50 J-R curve data from the NUREG were adjusted further in the conservative direction to account for effects of the nominal BWR operating temperature of 550°F. For analysis purposes, the resulting J-R curves were applied to BWR/2-4 vessel plates which are SA302B Modified material. In addition, 533 plate J-R curves were developed using methods in NUREG CR-5356. The 533 plate results show that the SA302B J-R curves based on the V50 plate are much lower, and are therefore very conservative.

NUREG CR-5356 provides methods for establishing J-R curves for SA533 Grade B plates, Non-Linde 80 welds and Linde 80 welds. The Linde 80 weld J-R curves were based on the highest copper content for a BWR Linde 80 weld and a 32 EFPY fluence higher than any expected for a BWR Linde 80 weld.

Section 5: Level A and B Evaluation

The Code Case methods were applied to the most limiting geometric and loading conditions for BWR/2 plate, BWR/3-6 plate, BWR/2-6 non-Linde 80 welds and BWR/2-6 Linde 80 welds (Linde 80 welds are actually only present in a few BWR/3,4 vessels). Results were compared to the appropriate J-R curves developed in Section 4. For the BWR/2 plate results, the SA302B J-R curve was used for comparison. For the BWR/3-6 plate results, both the SA302B and 533 J-R curves were used for comparison. While the SA302B J-R curve comparison requires USE of at least 59 ft-lb (longitudinal) for an axial flaw, the 533 J-R curve comparison shows that USE could be as low as 35 ft-lb. However, for purposes of establishing allowable USE in Section 8, the conservative results from the SA302B J-R curve are used for BWR/2 and BWR/3-6 plates.

The most severe upset event, involving loss of feedwater pumps, was analyzed and compared to the thermal loading for the 100°F/hr heatup/cooldown case. The upset event was not as severe.

Section 6: Level C and D Evaluation

The most severe Level C event involved the improper start of a cold recirculation loop in a jet pump plant. Next most severe was an automatic blowdown. Since the BWR/2 plants do not have jet pumps, the second event was applied to the BWR/2 case and the first to the BWR/3-6 case. For Level D evaluation, a recirculation line break was analyzed. The results of both Level C and D evaluations were less limiting than the results of the Level A and B evaluations.

Section 7: Summary of Equivalent Margin Requirements

Sections 2 through 6 establish the USE values above which equivalent fracture toughness margin is assured. The results are summarized in Section 7.

Section 8: Bounding Nature of Analyses

Evaluations of the BWR beltline material properties are done to show that the USE values established in Section 5 are lower than predicted for any U.S. BWR/2-6 at 32 EFPY, using the NRC-approved methods. In order to bound all BWRs, the limiting combination of copper content and fluence for each material type was applied to all appropriate vessels. The table below summarizes the bounding conditions for irradiation effect on USE:

Material	Cu Content	32 EFPY Fluence (n/cm^2)	USE Decrease
BWR/2 Plate	0.27%	2.4×10^{18}	26%
BWR/3-6 Plate	0.17%	3.8×10^{18}	21%
BWR/2-6 Welds (non-Linde 80)	0.35%	2.4×10^{18}	34%
BWR/3-4 Welds (Linde 80)	0.31%	1.0×10^{18}	N/A[a]

As long as a plant can show that their USE decrease will stay within the percentages above, the results of the equivalent margin analysis apply conservatively. Appendix B addresses evaluation of plant-specific surveillance program results needed to verify applicability.

[a] Linde 80 weld evaluation was based on Cu and fluence values, not on USE. The values shown bound those for the worst case BWR, 0.31% Cu and 5.3×10^{17} n/cm^2 fluence.

The results of the equivalent margin analysis are compared in Section 8 to predictions of the lowest expected 32 EFPY USE values. Factoring in all of the conservatisms discussed above, the comparisons show that all materials for all U.S. BWR/2-6 vessels will have USE values with acceptable equivalent margin for 32 EFPY of operation.

COMPARISON OF EXPECTED USE AT 32 EFPY
TO USE REQUIRED TO SHOW EQUIVALENT MARGIN

BWR Type	Material Type	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
BWR/2	Long Plate	56	≥50	Acceptable
BWR/2	Trans Plate	36.5	≥35	Acceptable
BWR/3-6	Long Plate	72	≥59	Acceptable
BWR/3-6	Trans Plate	47	≥35	Acceptable
BWR/2-6	SMAW	57	≥35	Acceptable
BWR/3-4	ESW	46	≥35	Acceptable
BWR/2-6	Non-L80 SAW	47	≥35	Acceptable
BWR/3-4	L80 SAW	Acceptable results for bounding Cu, fluence		

1.0 INTRODUCTION AND BACKGROUND

1.1 General

The nuclear reactor pressure vessels (RPVs) are typically made of low-alloy ferritic steels (e.g., SA302B; or SA533, Grade B, Class 1). They are exposed to high energy neutrons in the beltline region as a result of which the constituent parts (i.e., the plates, forgings, and welds) can experience degradation of material properties: yield and ultimate tensile strengths increase, brittle-to-ductile transition temperature increases, and the upper shelf toughness decreases. The last two effects are the most important from the point of view of structural margins during the operation of a RPV. The impact of low Charpy upper shelf energy (USE) on the vessel integrity analyses is the focus of this report.

10CFR50 Appendix G [1-1] states that the RPV must maintain USE throughout its life of no less than 50 ft-lb, unless it is demonstrated in a manner approved by the Director, Office of Nuclear Reactor Regulation, that lower values of upper shelf energy will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI the ASME Code [1-2]. Regulatory Guide 1.99 [1-3] provides a method to estimate the decrease in USE as a function of fluence and copper content. It is now recognized tnat some RPVs have materials where USE values may fall below 50 ft-lb due to irradiation embrittlement. In 1982, the Nuclear Regulatory Commission (NRC) published proposed procedures for the analyses required by 10CFR50 for operating RPVs as NUREG 0744 [1-4]. At the time of publication of the NUREG, the NRC officially requested the ASME to recommend criteria for evaluation of RPVs which do not meet USE requirements. In response to that request, the Working Group on Flaw Evaluation has developed a document which contains the criteria and the methodology, which is currently in the form of a Code Case [1-5] and a proposed Appendix to Section XI. A final draft copy of the text of the Code Case is included as Appendix A to this report. The evolution of the methodology and the technical background on the criteria are described in [1-6] through [1-9].

1.2 BWR Owners' Group Efforts

In September 1992, the NRC, in discussing the preliminary review of the responses to Generic Letter 92-01, strongly recommended that equivalent margin analyses be done by the Owners' Groups. The objective was to provide a "safety net" analysis for plants that could not quantitatively demonstrate, using NRC-approved methods, that USE would remain above 50 ft-lb and might, therefore, be subject to regulatory action. A second objective, which developed within the BWR Owners' Group in the process of performing the analysis, was to provide a topical report, which could be referenced by utilities as part of their licensing basis, to address compliance with the 50 ft-lb requirement on USE in 10CFR50 Appendix G.

The BWR Owners' Group authorized the equivalent margin analysis in October 1992. The preliminary results of the equivalent margin evaluation were presented to the NRC staff in a meeting in January 1993. Revision 0 of this report was submitted in April 1993. Revision 1 incorporates a change in the bounding weld metal percent decrease in USE from 33% to 34%, based on a BWR utility's input. The conclusions in the report have not changed. Locations where revisions have been made are shown by side bars.

1.3 Scope of Analysis

This BWROG equivalent margin analysis is applicable to all U.S. BWR/2 through BWR/6 RPVs. The evaluation included bounding assumptions on material chemistry, vessel fluence, vessel geometry, and Level A through D plant transients.

The analysis specifically addresses the following base metals and welds:

(1) SA302B and SA302B modified plate in the transverse and longitudinal orientations.

(2) SA533B plate in the transverse and longitudinal orientations.

(3) Submerged arc, shielded metal arc and electroslag welds. Linde 80 flux submerged arc welds (present in circumferential welds of four vessels) are treated separately.

The analysis consisted of the following broad steps:

(1) The RPV beltline material and geometry information on the US BWR/2-6 vessels were reviewed to determine the number of distinct materials involved and to select the limiting geometries. The reactor pressure and thermal loadings were also reviewed to select the appropriate values for the evaluation of Level A through D conditions.

(2) For the types of beltline materials selected in step 1, the fracture toughness characterization in the form of J-Resistance curves were developed.

(3) Using the procedures of the Code Case and considering material fracture toughness properties and operating condition loadings, the minimum required USE to meet the Code Case criteria in both the longitudinal and transverse directions were determined for plates. The output of this step was a set of minimum required USE values for each distinct beltline material type which would assure compliance with the Code Case criteria throughout the design life of the vessel.

(4) The available initial USE data on the BWR/2-6 beltline materials and the fluence information were compiled to estimate the projected 32 EFPY irradiated USE values. These USE values were compared with the minimum required values calculated in step 3 to assess the equivalent margins.

1.4 Report Outline

Section 2 summarizes the important material and geometry information on the US BWR/2-6 RPV beltline regions. Section 3 describes the methodology of the Code Case and how it was implemented in this evaluation. Fracture toughness characterizations and modeling of base metals and welds published in the technical literature were reviewed in Section 4 to determine the lower bound and best estimate J-Resistance (J-R) curves. Section 5 describes the evaluation of Level A and B conditions based on the lower bound toughness values. Evaluation of Level C and D conditions is covered in Section 6. Section 7 summarizes the results of analysis in terms of minimum required USE to meet the criteria of the Code Case.

Section 8 presents the 32 EFPY USE estimates for the U.S. BWR/2-6 vessels considering initial USE and fluence data. A comparison with the minimum USE requirements is presented to show the margins. Appendix B presents the steps required to show that the USE requirements developed in this report can be applied to individual BWR plants.

1.5 References

[1-1] "Fracture Toughness Requirements," Appendix G to Part 50 of Title 10, the Code of Federal Regulations, July 1983.

[1-2] "Fracture Toughness Criteria for Protection Against Failure," Appendix G to Section XI of the ASME Boiler & Pressure Vessel Code, 1989 Edition.

[1-3] "Radiation Embrittlement of Reactor Vessel Materials," USNRC Regulatory Guide 1.99, Revision 2, May 1988.

[1-4] Johnson, R., "Resolution of the Reactor Vessel Materials Toughness Safety Issue, Volumes 1 and 2," NRC Report NUREG 0744, 1982.

[1-5] "Assessment of Reactor Vessels With Low Upper Shelf Charpy Impact Energy Levels," Code Case No. N-512, February 1993.

[1-6] "Evaluation of Upper Shelf Toughness Requirements for Reactor Pressure Vessels," EPRI Report NP-6790-SL, April 1990.

[1-7] Merkle, J.G., "An Overview of the Low-Upper-Shelf Toughness Safety Margin Issue," NUREG/CR-5552, August 1990.

[1-8] Griesbach, T.J. and Smith, E., "A Review of the ASME Low Upper Shelf Toughness Evaluation Procedures for Nuclear Reactor Pressure Vessels," Nuclear Engineering and Design, 130 (1991), pp. 259-266.

[1-9] "Development of Criteria for Assessment of Reactor Vessels With Low Upper Shelf Fracture Toughness," Document prepared by ASME Section XI Working Group on Flaw Evaluation, December 1991.

2.0 BWR VESSEL MATERIALS AND GEOMETRIES

A review of RPV beltline materials and geometries for the U.S. BWR/2-6 vessels was conducted to determine the variations involved. Table 2-1 shows a summary of the beltline geometries and the material types.

2.1 Base Metals

The review of plate materials in the last column of Table 2-1 shows that, basically, three types of base metals are involved: SA302B (only two plates in one BWR/2), SA302B modified, and SA533B Class 1.

SA302B plates were used in the older RPVs. Nickel was added to SA302B to improve ductility, and this steel was designated as SA302B modified. After an interim period, the SA533B standard was issued. The chemical composition and the tensile requirements of the SA302B modified plates are similar to those of the SA533B Class 1 plates. Despite these similarities, there has been some concern, due primarily to the steel making practices of that time, that the fracture toughness of SA302B modified plates may not be comparable to that of SA533B plates [2-1]. Presently, not enough fracture toughness test data are available to address this issue. In response to this, a BWROG sponsored J-R curve test program using specimens made from archival SA302B modified material, is currently underway. In the meantime, for the purpose of this evaluation, it was conservatively assumed that the fracture toughness of SA302B modified plate material is similar to that of SA302 plate material.

Thus, two types of base metals were considered in the evaluation: SA302B and SA533B Class 1.

2.2 Weld Metals

A review of the second to last column in Table 2-1 shows that three types of welds were used in joining the plates in the beltline region: submerged arc welds (SAW), shielded metal arc welds (SMAW), and electroslag welds (ESW). The same column in Table 2-1 also identifies the flux type used in making the welds. The purpose was to identify the welds that were made with Linde 80 flux, which is known to produce somewhat lower toughness welds. Only one BWR/4 plant has a Linde 80 flux weld as its limiting beltline weld. A few other BWR plants (indicated by * in Table 2-1) also have Linde 80 flux in their circumferential welds in the beltline region.

For the purpose of material J-R curves, the combined data base model of [2-2] was used for all non-Linde 80 welds. The copper fluence model of [2-2] was used for the Linde 80 welds.

2.3 Beltline Geometries

Table 2-1 shows the radii, wall thicknesses and the calculated nominal circumferential stresses at the design pressure of 1250 psi, for the various U.S. BWR/2-6 plants. It is seen that the pressure stresses for the BWR/3-6 RPVs fall in a very narrow range, distinctly different from the BWR/2 stresses. Based on the review of stresses and wall thicknesses, the following two representative geometries were selected for evaluation: (1) R=106.7 inch and t=7.13 inch for BWR/2 RPVs, and (2) R=126.7 inch and t=6.19 inch for BWR/3-6 RPVs. These selected dimensions yield the highest combinations of pressure stress and flaw depth, thus producing the largest $J_{applied}$ values.

Based on the review of the reactor drawings, the clad thickness was assumed as 7/32 inch or 0.22 inch for the BWR/2s and 0.19 inch for the BWR/3-6s.

2.4 References

[2-1] Hiser, A.L. and Terrell, J.B., "Size Effects on J-R Curves for a 302B Plate," NUREG/CR-5265, January 1989.

[2-2] Eason, E.A., J.E. Wright and E.E. Nelson, "Multivariable Modeling of Pressure Vessel and Piping J-R Data," NUREG/CR-5729, May 1991.

TABLE 2-1
Data on BWR Geometries and Material Type

Type	R(in)	t(in)	PR/t	Weld Type (a)	Plate Type
BWR-2	106.7	7.13	18706	SAW,Arcos B5	302B-Mod
BWR-2	106.7	7.13	18706	SAW,Arcos B5	302B+B-Mod
BWR-3	125.7	6.13	25632	ESW,Linde 124(b)	302B-Mod
BWR-3	113.1	5.50	25705	SAW,Linde 1092	302B-Mod
BWR-3	103.2	5.06	25494	SMAW	533B
BWR-3	113.9	5.53	25746	SAW,Linde 1092	533B
BWR-3	125.7	6.13	25632	ESW,Linde 124(b)	302B-Mod
BWR-3	125.7	6.13	25632	ESW,Linde 124	302B-Mod
BWR-4	125.7	6.13	25632	SAW,Linde 80	302B-Mod
BWR-4	125.7	6.13	25632	ESW,Linde 124	302B-Mod
BWR-4	110.2	5.38	25604	SAW,Linde 124	533B
BWR-4	110.4	5.38	25651	SAW,Linde 1092	533B
BWR-4	92.7	4.47	25923	SMAW	533B
BWR-4	127.0	6.13	25897	SAW,Linde 1092	533B
BWR-4	110.4	5.38	25651	SAW,Linde 1092	533B
BWR-4	110.4	5.38	25651	SAW,Linde 1092	533B
BWR-4	110.4	5.38	25651	SAW,Linde 0091	533B
BWR-4	126.5	6.10	25922	SAW(c)	533B
BWR-4	126.7	6.19	25586	SAW,Linde 124	533B
BWR-4	125.7	6.13	25632	ESW,Linde 124	302B-Mod
BWR-4	126.7	6.19	25586	SMAW	533B
BWR-4	103.2	5.06	25494	SMAW	533B
BWR-5	127.0	6.13	25897	SAW,Linde 1092	533B
BWR-5	126.5	6.20	25504	SAW,Linde 124	533B
BWR-5	126.7	6.19	25586	SAW,Linde 124	533B
BWR-5	126.7	6.19	25586	SAW,Linde 124	533B
BWR-6	110.4	5.38	25651	SAW,Linde 124	533B
BWR-6	126.7	6.19	25586	SAW,Linde 124	533B
BWR-6	120.2	6.00	25042	SAW,Linde 124	533B
BWR-6	110.2	5.41	25462	SAW,Linde 124	533B

(a) SAW=Submerged Arc Weld
SMAW=Shielded Metal Arc Weld
ESW=Electroslag Weld

(b) These plants also have Linde 80 circumferential welds

(c) SAW performed by Ishikawajima-Harima Industries (IHI)

3.0 EVALUATION METHODOLOGY

The evaluation methods and acceptance criteria used in this report are those prescribed in the recently approved ASME Code Case N-512 [1-5]. There are essentially four steps involved: (1) postulate flaws in the reactor vessel, (2) determine the loading conditions at the location of the postulated flaws for Level A, B, C and D Service loadings, (3) obtain the material properties, including E, σ_y, and the J-Integral resistance curve (J-R curve), at the locations of the flaws, and (4) evaluate the postulated flaws according to the acceptance criteria.

Article A-3000 of the Code Case contains a general description of procedures used to evaluate the applied fracture mechanics parameters, as well as requirements for selecting the J-R curve for the material. Detailed calculation procedures for Level A and B Service loadings are given in A-4000. The Code Case does not include a detailed calculation procedure for Level C and D Service loadings since it was concluded by the ASME during its development that the possible combinations of loadings and material properties which may be encountered during these Service conditions are too diverse. This aspect is discussed later in this section.

The acceptance criteria and the calculation procedures from the Code Case, as applicable to the subject evaluation, are described in this section.

3.1 Acceptance Criteria

3.1.1 Level A and B Service Loadings

An interior semi-elliptical surface flaw with a depth one-quarter of the wall thickness (1/4t) and a length six times the depth is postulated. When evaluating adequacy of the upper shelf toughness for the base material, both interior axial and circumferential flaws shall be postulated, and toughness properties for the corresponding orientation shall be used. Two criteria which shall be satisfied are:

(1) The applied J-Integral evaluated at a pressure which is 1.15 times the accumulation pressure as defined in the plant-specific Overpressure Protection Report, with a factor of safety of 1.0 on thermal loading for the plant specified heatup and cooldown conditions, shall be shown to be less than the J-Integral characteristic of the material resistance to ductile tearing at a flaw growth of 0.10 inch.

(2) The flaw shall be shown to be stable, with the possibility of ductile flaw growth, at a pressure which is 1.25 times the accumulation pressure defined in (1), with a factor of safety of 1.0 on thermal loading for the plant specified heatup and cooldown conditions.

The J-Integral resistance versus crack growth curve (J-R curve) shall be a conservative representation for the vessel material under evaluation. The determination of the J-R curves for this evaluation are discussed in Section 4. The mathematical expressions for the calculation of applied J-Integral and for the evaluation of stability are discussed in Subsection 3.2.

3.1.2 Level C Service Loadings

While the aspect ratio and orientation of the postulate flaw are the same as those for the Level A and B Service loadings, the flaw depth for this service condition is up to 1/10 of the base metal wall thickness (1/10t), plus the cladding thickness, with total depth not to exceed 1.0 inch. For this analysis, the most conservative depth of 1/10t plus cladding thickness is used. Two criteria which shall be satisfied are:

(1) The applied J-Integral shall be shown to be less than the J-Integral characteristic of the material resistance to ductile tearing at a flaw growth of 0.10 inch, using a factor of safety of 1.0 on loading.

(2) The flaw shall be shown to be stable, with the possibility of ductile flaw growth, using a factor of safety of 1.0 in loading.

The material J-R curve shall be the same as used in the evaluation of Level A and B conditions. Thus, the key differences between the Level A/B evaluation and the Level C evaluation are the postulated flaw size and the factor of safety on pressure loading.

3.1.3 Level D Service Loadings

The postulated flaw geometry and orientation for this service condition is the same as that for the evaluation of Level C loadings. The flaw shall be shown to be stable, with the possibility of ductile flaw growth, using a factor of safety of 1.0 on loading. The J-R curve shall be a best estimate representation for the vessel material under evaluation. The stable flaw depth shall not exceed 75% of the vessel wall thickness, and the remaining ligament shall be safe from tensile instability.

3.2 Calculation of the Applied J-Integral

The calculation of applied J-Integral consists of three steps: Step 1 is to calculate the K values from pressure and heatup/cooldown loadings; Step 2 is to calculate the effective flaw depth which includes a plastic-zone correction; and Step 3 is to calculate the J-Integral for small-scale yielding based on this effective flaw depth.

For an axial flaw of depth, a, the stress intensity factor due to internal pressure is calculated with a safety factor (SF) on pressure using:

$$K_{Ip} = (SF)\ p\ [1 + (R_i/(t))]\ (\pi a)^{0.5}\ F_1 \qquad (3\text{-}1)$$

where,

$$F_1 = 0.982 + 1.006\ (a/t)^2 \qquad (3\text{-}2)$$

For the postulated circumferential flaw of depth 'a', the stress intensity factor due to internal pressure with a safety factor (SF) on pressure, is calculated using the following:

$$K_{Ip} = (SF)\ p\ [1 + (R_i/(2t))]\ (\pi a)^{0.5}\ F_2 \qquad (3\text{-}3)$$

where,

$$F_2 = 0.885 + 0.233(a/t) + 0.345(a/t)^2 \qquad (3\text{-}4)$$

where, R_i, t and a are vessel inside radius, vessel thickness and crack depth, respectively. This equation for K_{Ip} is valid for $0.20 \leq a/t \leq 0.50$, and includes the effect of pressure acting on the flaw faces. The units for K are shown in the report as ksi$\sqrt{in}$.

For an axial or circumferential flaw with a depth, a, the stress intensity factor due to radial thermal gradient was calculated by using the following:

$$K_{It} = ((CR)/1000)\, t^{2.5}\, F_3 \qquad (3\text{-}5)$$

$$F_3 = 0.584 + 2.647(a/t) - 6.294(a/t)^2 + 2.990(a/t)^3 \qquad (3\text{-}6a)$$

where CR is the cooling rate in °F/hour and the units of K are ksi$\sqrt{in}$. This equation for K_{It} is valid for $0.20 \leq a/t \leq 0.50$, and $0 \leq (CR) \leq 100$°F/hour.

A recent comparison [3-1] with the finite element calculated K values indicated that the K values predicted by using Equation (3-6a) may be underpredicted by as much as 18%. To correct this, [3-1] proposed the following modification of Equation (3-6a):

$$F_3 = 1.18132[0.584 + 2.647(a/t) - 6.294(a/t)^2 + 2.990(a/t)^3] \qquad (3\text{-}6b)$$

This modification essentially increases the old K_{It} values by ≈ 18%. The preceding equation has been incorporated in the Code Case as follows:

$$F_3 = 0.690 + 3.127(a/t) - 7.435(a/t)^2 + 3.532(a/t)^3 \qquad (3\text{-}6c)$$

The effective flaw depth, a_e, is then calculated by using:

$$a_e = a + (1/(6\pi))[(K_{Ip} + K_{It})/\sigma_y]^2 \qquad (3\text{-}7)$$

where, σ_y is the material yield stress.

The K'_{Ip} and K'_{It} are calculated by substituting a_e in place of a in equations 3-1 or 3-3 and 3-5.

The J-Integral due to the applied loads for small scale yielding is then given by:

$$J = 1000\,(K'_{Ip} + K'_{It})^2/E' \quad (3\text{-}8)$$

$$E' = E/(1-\nu^2) \quad (3\text{-}9)$$

where, E is Young's Modulus and ν is Poisson's ratio (0.3 for low alloy steel). The units of J are in-lb/in^2.

3.3 Evaluation Using Criterion for Flaw Growth of 0.1 Inch

The J-Integral due to the applied loads, J_1, for this case is calculated using a factor of safety of 1.15 on the accumulation pressure. The acceptance criterion for Level A and B Service loadings, based on 1/4t flaw ductile growth of 0.1 inch (Criterion 1 in 3.1.1), is satisfied when $J_1 < J_{0.1}$, where $J_{0.1}$ is the value of J-Integral in the material J-R curve at a Δa of 0.1 inch. The thermal gradient contribution (K_{It}) to the J-Integral due to the applied loads for the Level C and D conditions, was calculated using the finite element stress analysis and available K solutions in the literature.

3.4 Evaluation Procedures for Flaw Stability

The Code Case provides three approaches that are equally acceptable for applying the flaw stability acceptance criteria. The first is the J-R curve - crack driving force diagram approach. In this approach, flaw stability is evaluated by a direct application of the flaw stability rules given in A-3400. The other approaches are the failure assessment diagram approach and the J-Integral/tearing modulus approach. The first approach was used in this report.

The J-R curve - crack driving force diagram approach is illustrated graphically in Figure 3-1. The applied J-Integral curve is evaluated at a constant load. The J-R curve intersects the horizontal axis at the postulated initial flaw depth, a_0. Flaw stability at a given load is demonstrated when the slope of the J-R curve at the point on the J-R curve where the two curves intersect is greater than the slope of the applied J-Integral line. The onset of flaw instability occurs at an applied load corresponding to the point of tangency of the applied J-Integral curve and the J-R curve.

3.5 Level C and D Loading Evaluation Methods

The Code Case [1-5] outlines the detailed calculation procedures and the criteria for the evaluation of Level A and B service loadings. Similar procedures for Level C and D service loadings are not included since it was concluded by ASME that the possible combinations of loadings and material properties which may be encountered during these service conditions are too diverse. To assure that the Level C and D loadings evaluation results from different users of the Code Case are in reasonable agreement assuming the same input information, the ASME Section XI Working Group on Operating Plant Criteria and Flaw Evaluation proposed a set of five sample problems for a round robin of calculations [3-2]. The RPV geometry in the Sample Problem No. 4 was closely related to BWR vessel geometry and, therefore, was analyzed by GE. The results of the analysis were presented at the Section XI meeting in December 1992. The GE calculated values of allowable pressures were consistent with the values reported by other participants of the round robin. This confirmed the reasonableness of the methods used in this report to analyze Level C and D loadings. The results of GE's calculation results are also documented in [3-3].

The evaluation of BWR-specific Level C and D service loadings is covered in detail in Section 6 of the report.

3.6 Summary of Evaluation Methods

The acceptance criteria and the evaluation methods of the Code Case relevant to the USE requirement evaluation of U.S. BWR/2-6 RPVs are summarized in this section. The key inputs in this evaluation are the appropriate material J-R curves and the applied J-Integral values. The selection of appropriate material J-R curves is described in Section 4. Sections 5 and 6 describe the rationale for the selection of appropriate pressure and thermal loadings and the evaluation results for the Levels A/B and C and D conditions.

3.7 References

[3-1] Yoon, K, "Verification of K_{It} Equation in Appendix X," Presentation at Working Group on Flaw Evaluation at Albuquerque, NM, January 1993.

[3-2] Letter to Working Group Members from T.J. Griesbach, "Benchmark Problems for Low Upper Shelf Energy Material Calculations - Levels C&D," October 29, 1992.

[3-3] Mehta, H.S., "A Low Upper Shelf Energy Fracture Mechanics Evaluation for a Reactor Pressure Vessel," Paper to be presented at PVP Conference, July 1993.

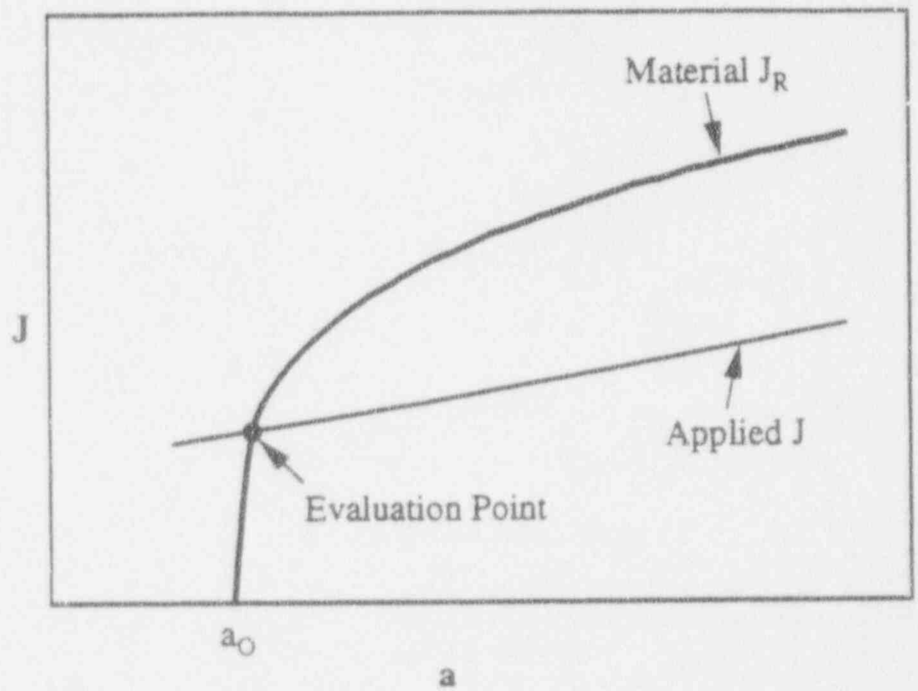

Figure 3-1 Comparison of the Slopes of the Applied J-Integral Curve and the J-R Curve

4.0 IRRADIATED FRACTURE TOUGHNESS CHARACTERIZATION

A key input in the evaluations based on the procedures of the Code Case is the material J-R curve. The beltline region materials of the RPV wall undergo irradiation-induced toughness changes during the operation of the plant. The irradiation-induced reduction in the initial USE is a function of material chemistry and fluence [1-3]. The objective of the analysis is to determine the lowest USE at which equivalent margin is demonstrated, so the material J-R curves were developed for several Charpy energy values.

Four distinct base metal and weld types were identified in Section 2: (1) SA302B, (2) SA533B, Class 1, (3) non-Linde 80 welds, and (4) Linde 80 welds. For material types (2) and (3), a combined data base model developed in [2-2] was used. Thus, there were essentially three distinct groups for the purpose of material J-R curve determination.

4.1 Definition of Conservative and Best Estimate J-R Curves

The Code Case states that the material J-R curve used for the evaluation of Levels A through C loadings should be a conservative estimate. However, the Code Case does not specify what constitutes a conservative estimate. For the purpose of this evaluation it was assumed that a "mean minus two standard deviation" (Mean-2σ) J-R curve constitutes a conservative estimate. In statistical terms, it means that if the variability in the material J-R curve were to be modeled by a normal distribution, then 98% of the actual J-R curves will lie above the Mean-2σ J-R curve. This is considered reasonable, since a similar approach was also used for the round robin problems on the use of this Code Case by the ASME Section XI working groups [3-2].

The evaluation of Level D loadings requires a best estimate J-R curve. It was assumed that a "mean" (as defined for a normal distribution) J-R curve constitutes a reasonable best estimate.

For the SA302B plate material, the J-R curve is based on estimated J_{Ic} value. For that case, the best estimate and conservative J-R curves were obtained from the Mean and Mean-2σ J_{Ic} values, respectively.

4.2 Charpy Energy Versus J-R Curve Correlations

The available information to assess the state of vessel wall embrittlement generally consists of initial Charpy V-notch (CVN) energy values, the material chemistry and the fluence level at the vessel wall. Regulatory Guide 1.99, Revision 2 [1-3] provides method to calculate the Charpy USE at any irradiation level given the preceding information. This information can be supplemented when the Charpy energy values from the testing of periodically removed surveillance specimens become available. Most of the material fracture test data available in the technical literature generally include the CVN energy values along with the J-R curve information. Similarly, most of the available models try to correlate J_{Ic} and the J-R curve parameters to CVN energy and material chemistry. The specific correlations/models used and the calculated J-R curves are described next.

4.3 J-R Curves for SA302 Grade B

The approach used to calculate the J-R curve for this material was that used in [4-1], in that the J-Integral values on the J-R curve were tied to the estimated J_{Ic} value. J-R curve data from [4-2] through [4-5] were reviewed and a CVN energy versus J_{Ic} correlation was developed to obtain the J_{Ic} values for the selected value of CVN energy.

To establish a J_{Ic} versus Charpy USE correlation that can be used to determine the mean and mean minus two standard deviation J-R curves, test data on SA302B base metal from [4-3] and [4-5] were compiled and plotted in [4-1]. Figure 4-1 shows the plot. The data in Figure 4-1 are for temperatures in the range of 400° F to 550° F for both the longitudinal and transverse orientations and irradiated as well as unirradiated material. Fluences ranged from 0.6 to 3.5 x 10^{19} n/cm^2.

The data in Figure 4-1 show a trend for decreasing J_{Ic} with decreasing Charpy USE. The mean and the mean minus two standard deviation lines shown in Figure 4-1 were obtained using linear regression analysis. The mean line was used to determine the best estimate J-R curve for the evaluation of Level D loadings. The mean minus two standard deviation line was used to establish a conservative representation of the J-R curve, as required in the evaluation of Levels A, B and C loading conditions.

The J-R curves for most materials can be represented by an equation of the following form:

$$J = C (\Delta a)^n \qquad (4\text{-}1)$$

This equation gives a convex upwards form of the J-R curve in which the J values keep increasing with increase in Δa. It is suggested in [4-4] that SA302 Grade B apparently exhibits a size effect where the J-R curve flattens significantly with increasing specimen thickness as illustrated in Figure 4-2. This result was also unusual in that the J-R curve of a thicker (larger) specimen was lower than that of a thinner (smaller) specimen. A subsequent evaluation [4-6] examined several possibilities for this unusual size effect but could not cite any clear cause.

Data in [4-4] show that the effect of thickness on J_{Ic} is relatively small. Therefore, only the size effect on the J-R curve at larger Δa values was considered. Results plotted in Figure 4-2 show that the J-R curve for the 6TCT specimen rises above J_{Ic} by a factor of about 1.3 and reaches a plateau. While it is not clear that this size effect seen at 180° F would be also present at 400°F to 550°F, it was conservatively assumed that this was the case.

Therefore, it was assumed in [4-1] that the J-R curves for both longitudinal and transverse direction will flatten out at 30% above J_{Ic}. The same conservative assumption was also used in this report to develop the J-R curves for SA302B material. Table 4-1 summarizes the conservative and the best estimate J_{Ic} and $1.3*J_{Ic}$ (i.e., the maximum value of J in the J-R curves) values. Figures 4-3a and b show the conservative J-R curves for several values of CVN energies. A comparison with the J-R curves calculated in the next subsection clearly illustrates the conservative nature of the J-R curves in Figures 4-3a and b.

4.4 SA533B and Non-Linde 80 Weld J-R Curves

A comprehensive multivariable modeling of RPV and piping J-R data is reported in [4-7] and [4-8]. Separate models were fitted for different materials groups, including

RPV welds, Linde 80 welds, RPV base metals, piping welds, piping base metals, and a combined materials group. The material data base did not include SA302B steel, but included SA533 Grade B steel.

To fit the available data base, the material J-R curve in [4-8] was represented in the following form:

$$J_d = C1\ (\Delta a)^{C2}\ \{\exp[C3(\Delta a)^{C4}]\} \qquad (4\text{-}2)$$

J_d is the deformation J-Integral. The use of deformation J-Integral, rather than the modified J-Integral, is currently favored in the fracture mechanics evaluations. The notation J without the subscript d is also used in this report to indicate deformation J-Integral. The expressions for C2 and C3 terms are:

$$C2 = d_1 + d_2\ (\ln C1) \qquad (4\text{-}3)$$

$$C3 = d_4 + d_5\ (\ln C1) \qquad (4\text{-}4)$$

The parameter C1 can be calculated from the following expression when the pre-irradiation Charpy USE (CVN_p) and the fluence (ϕt) values are available:

$$\ln (C1) = a_1 + a_2 \ln (CVN_p) + a_3 T + a_5 \phi t \qquad (4\text{-}5)$$

The variable T is the temperature at the crack tip at the particular time being analyzed, and ϕt is the fluence in the units of 1×10^{18} n/cm^2. When only the irradiated Charpy USE (CVN) is used as is the case in the combined database model, C1 is determined as follows:

$$\ln (C1) = a_1 + a_2 \ln (CVN) + a_3 T \qquad (4\text{-}6)$$

The parameters a_1, a_2, a_3, a_5, d_1, d_2, d_4, d_5, and exponent C4 are constants, the values for which are given in Table 4-2.

Using the CVN_p, ϕt values, and the base metals model, one can calculate a J-R curve. Alternately, using the CVN_p and ϕt values, one can calculate a value of CVN using the procedure outlined in [1-3] and then, using the combined data base model, obtain a J-R curve. The second approach generally gives a lower J-R curve [3-3]. Therefore, the J-R curves in this evaluation are calculated using the second approach.

The values of various parameters shown in Table 4-2 would give a best estimate or mean J-R curve which can be used for the evaluation of Level D loadings. A conservative material J-R curve for the evaluation of Level A through C condition loadings, is obtained by multiplying the J_d values obtained from equation (4-2) by the value of the ratio corresponding to $2S_e$ (shown at the bottom of Table 4-2). For example, the J_d values obtained using the combined data base model were multiplied by 0.632 to obtain the mean minus two standard deviation value of J_d.

Figure 4-4 shows the Mean-2σ J-R curves for CVN energies ranging from 35 to 60 ft-lb. A comparison of the J-R curves in Figure 4-4 and those in Figures 4-3a and b shows that the J values at the same crack extension in the latter case are considerably lower.

4.5 Linde 80 Weld J-R Curves

A separate model for the Linde 80 flux welds is provided in [2-2]. Similar to the case of the base metal, two approaches are provided. The first approach is based on CVN_p, copper content and fluence. The second approach does not use the CVN_p information. The second approach was used in this evaluation since it does not require a knowledge of CVN_p value, which is not generally available. The constant C1 in this approach is defined as the following:

$$\ln C1 = a1 + a2 * Cu * (\phi t)^{a5} + a3 * T \qquad (4\text{-}7)$$

The parameters a1, a2, a3 and a5, along with the other constants, are given in the third column from the right in Table 4-2. Table 8-1 in Section 8 shows the copper contents of the beltline region welds. From this table, the highest copper content for the plants that have Linde 80 flux welds was determined as 0.31%. The highest fluence for 32 EFPY of operation was determined to be $5.3x10^{17}$ n/cm^2. Since the minimum value of fluence for the model in [2-2] is $1x10^{18}$ n/cm^2, the fluence value was conservatively assumed as $1x10^{18}$ n/cm^2. Figure 4-5 shows the mean minus two sigma J-R curve for the Linde 80 welds based on a copper content of 0.31% and a fluence of $1x10^{18}$ n/cm^2.

4.6 Summary of J-R Curve Determination

From a review of the base metals and weld types involved in the BWR beltline region, three distinct material groups (SA302B, SA533B and other non-Linde 80 flux welds, and Linde 80 flux welds) were identified for the determination of J-R curves. The mean minus two standards deviation J-R curves are developed for use in the evaluation of Level A, B and C loadings while the mean J-R curves are developed for the evaluation of Level D loadings.

4.7 References

[4-1] "Reactor Pressure Vessel Evaluation Report for Yankee Nuclear Power Station," Report # YAEC-1735, July 1990, Chapter # 3, Yankee Atomic Electric Co., Bolton, Mass.

[4-2] J.R. Hawthorne, B.H. Menke, F.J. Loss, H.E. Watson, A.L. Hiser, and R.A. Gray, "Evaluation and Prediction of Neutron Embrittlement in Reactor Pressure Vessel Materials," EPRI NP-2782, December 1982.

[4-3] A.L. Hiser and D.B. Fishman, "J-R Curve Data Base Analysis of Irradiated Reactor Pressure Vessel Steels," EPRI Research Project 1757-24, MEA-2024, December 1983.

[4-4] A.L. Hiser and J.B. Terrell, "Size Effects on J-R Curves for A 302-B Plate," NUREG/CR-5256, MEA-2320, January 1989.

[4-5] J.R. Hawthorne and A.L. Hiser, "Influence of Fluence Rate on Radiation-Induced Mechanical Property Changes in Reactor Pressure Vessel Steels," NUREG/CR-5493, MEA-2376, March 1990.

[4-6] Landes, J.D., "Extrapolation of the J-R Curve for Predicting Reactor Vessel Integrity," NUREG/CR-5650, January 1992.

[4-7] E.A. Eason and E.E. Nelson, "Improved Model for Predicting J-R Curves from Charpy Data," NUREG/CR-5356, April 1989.

TABLE 4-1

J_{Ic} and J_{max} Values for SA302B Material

CVN Energy (ft-lb)	Mean - 2*Sigma J_{Ic} (in-lb/in^2)	Mean - 2*Sigma $1.3*J_{Ic}$ (in-lb/in^2)	Mean J_{Ic} (in-lb/in^2)	Mean $1.3*J_{Ic}$ (in-lb/in^2)
35	150	195	315	409.5
40	170	221	335	435.5
45	190	247	355	461.5
50	210	273	375	487.5
55	230	299	395	513.5
60	250	325	415	539.5
65	270	351	435	565.5
70	290	377	455	591.5
75	310	403	475	617.5

TABLE 4-2

Constants in the J-R Curve [2-2] Models

Parameter	Variable	RPV Welds CVN_p Model	Linde 80 CVN_p Model	Linde 80 $Cu\phi t$ Model
<u>ln*C1*</u>				
a_1	(constant)	-3.99	-4.27	2.413
a_2	$Cu(\phi t)^{a5}$	-0.584	-0.588	-0.506
a_3	T	-0.00266	-0.00307	-0.00250
a_5	(exponent)	0.469	0.498	0.634
a_6	$\ln CVN_p$	1.47	1.59	
<u>*C2*</u>				
d_1	(constant)	0.0770	0.0770	0.0770
d_2	$\ln C1$	0.116	0.116	0.116
<u>*C3*</u>				
d_4	(constant)	-0.0812	-0.0812	-0.0812
d_5	$\ln C1$	-0.00920	-0.00920	-0.00920
<u>*C4*</u>	(exponent)	-0.474	-0.489	-0.491
# Points		4152	3667	3667
S_e	ln units	0.194	0.202	0.234
<u>Ratios</u>				
-1.645 S_e		0.727	0.717	0.681
-1 S_e		0.824	0.817	0.791
-2 S_e		0.679	0.667	0.626
-3 S_e		0.559	0.545	0.496

TABLE 4-2 (Cont'd)

Constants in the J-R Curve [2-2] Models

Parameter	Variable	RPV Base Metals CVN_p Model	Combined Database Charpy Model
<u>ln*C1*</u>			
a_1	(constant)	-2.89	-4.13
a_2	ln*CVN* or lnCVN_p	1.22	1.48
a_3	T	-0.00270	-.00239
a_5	ϕt	-0.0104	
<u>*C2*</u>			
d_1	(constant)	0.0770	0.0770
d_2	ln*C1*	0.116	0.116
<u>*C3*</u>			
d_4	(constant)	-0.0812	-0.0812
d_5	ln*C1*	-0.00920	-0.00920
<u>*C4*</u>	(exponent)	-0.417	-0.455
# Points		2295	8463
S_e	ln units	0.150	0.229
<u>Ratios</u>			
-1.645 S_e		0.781	0.686
-1 S_e		0.861	0.795
-2 S_e		0.741	0.632
-3 S_e		0.637	0.503

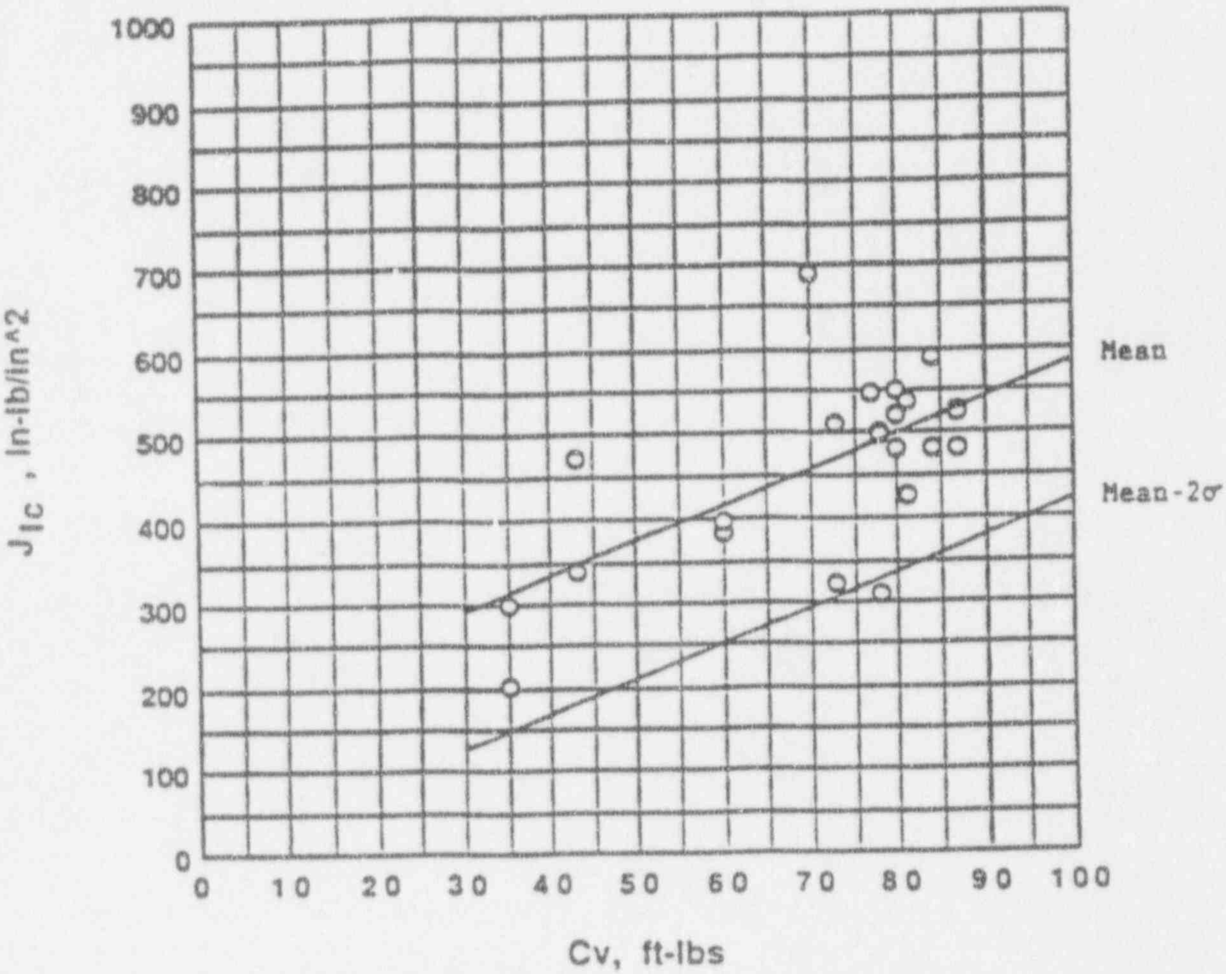

Figure 4-1 Least Squares Fit Mean and Mean Minus Two Sigma Lines, SA302B Plate, LT and TL Directions, 400-550°F (From [4-1])

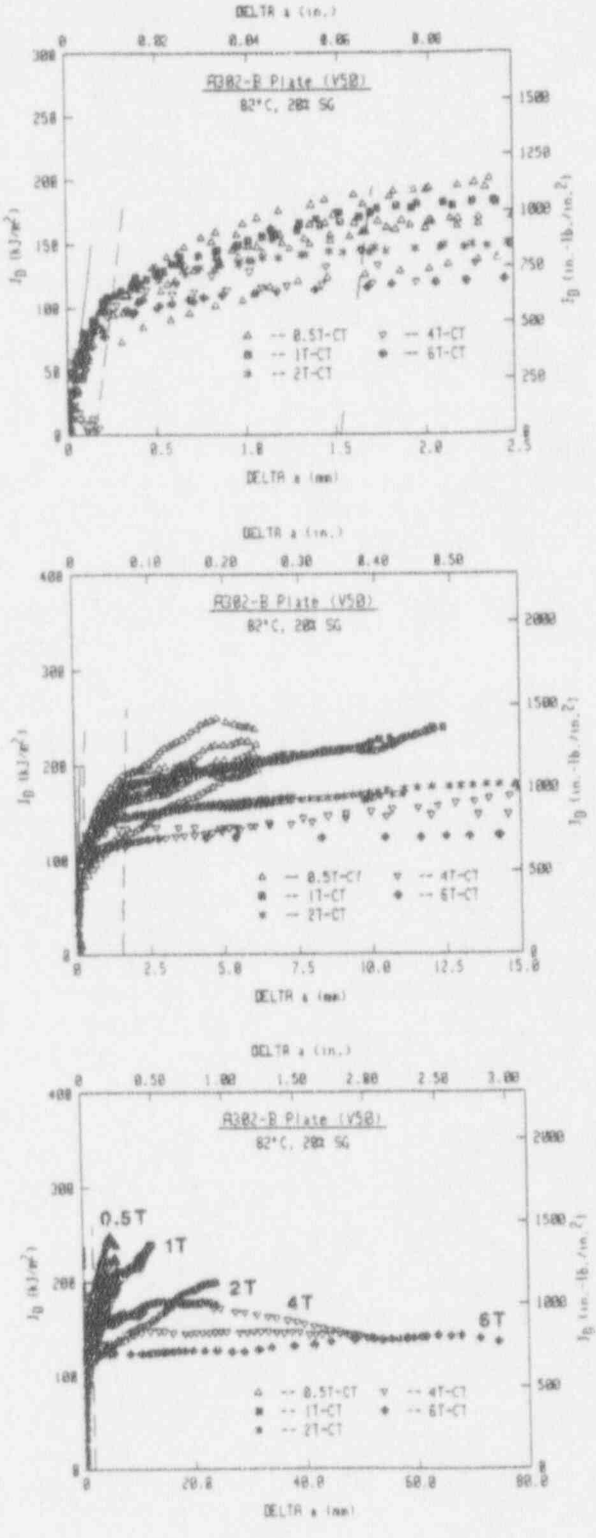

Figure 4-2 J-R Curves Illustrating Size Effect for SA302B Plate

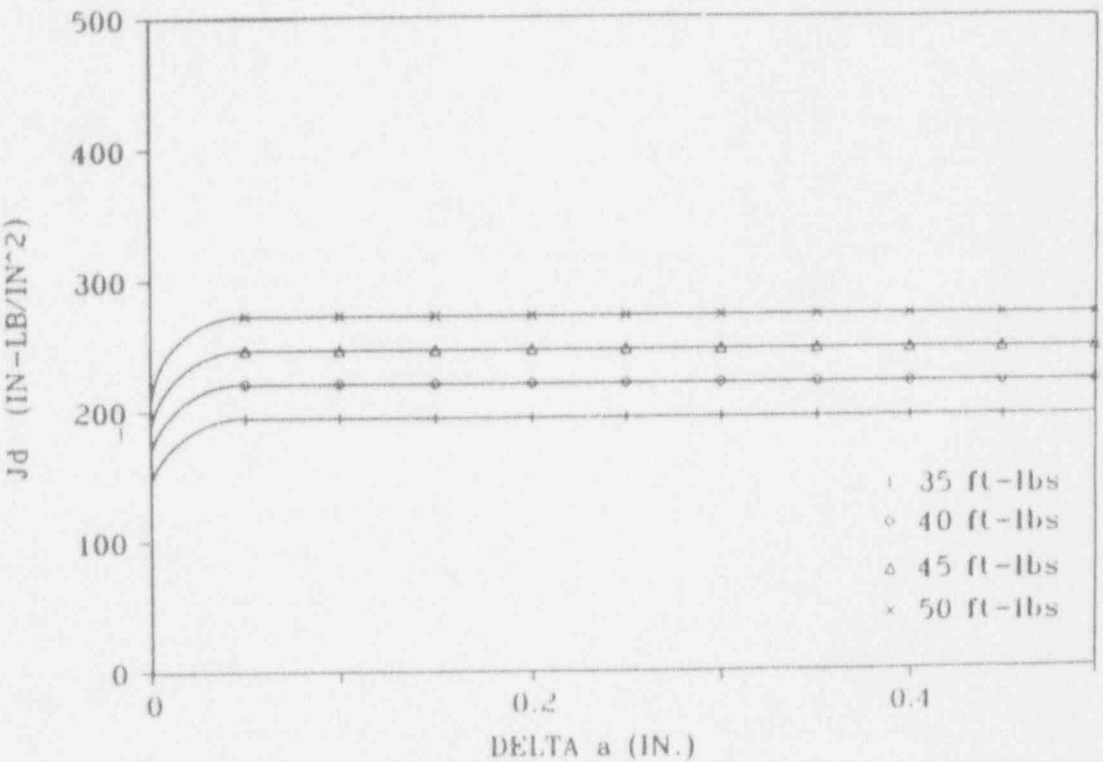

Figure 4-3a SA302B Material J-R Curves for 35 to 50 CVN Energies

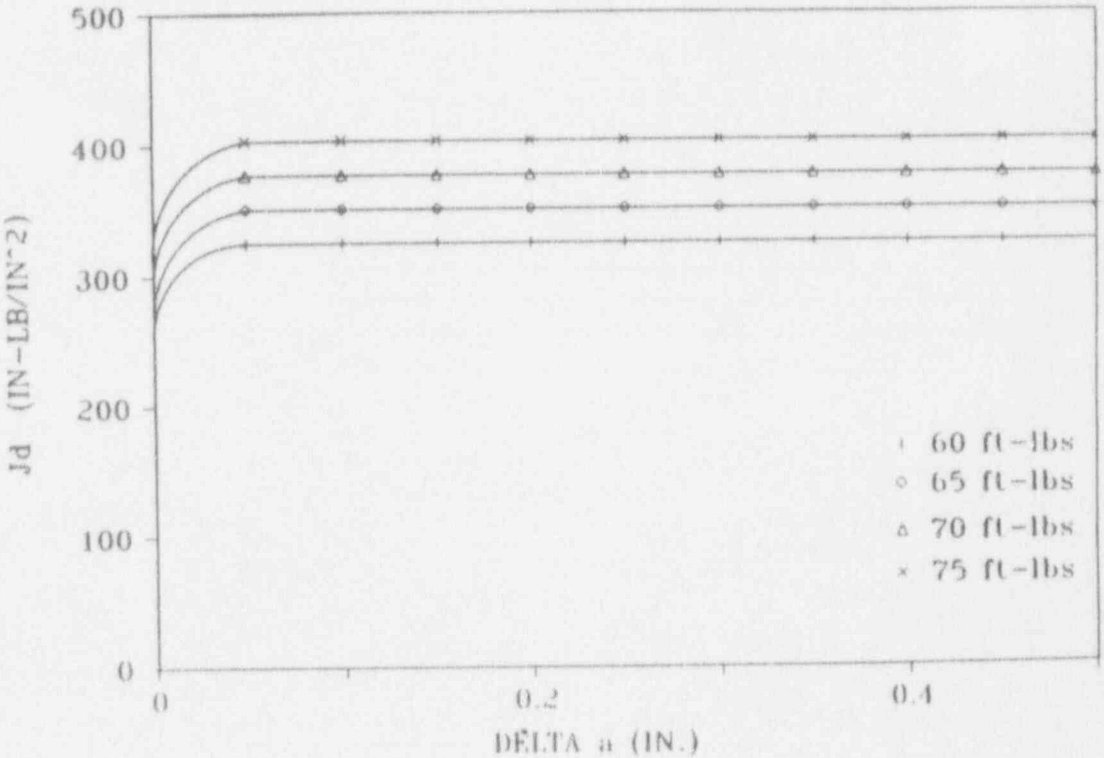

Figure 4-3b SA302B Material J-R Curves for 60 to 75 CVN Energies

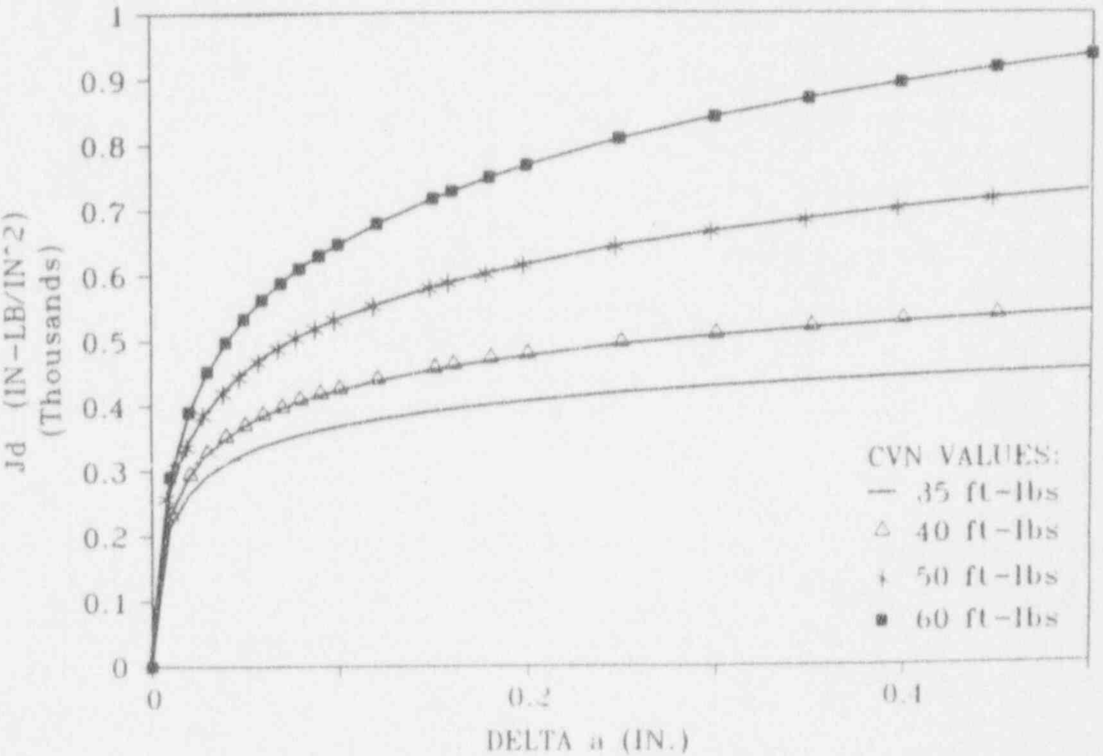

Figure 4-4 Combined Database (SA533B Plate/Non-Linde 80 Weld) Model J-R Curves for 35 to 60 CVN Energies

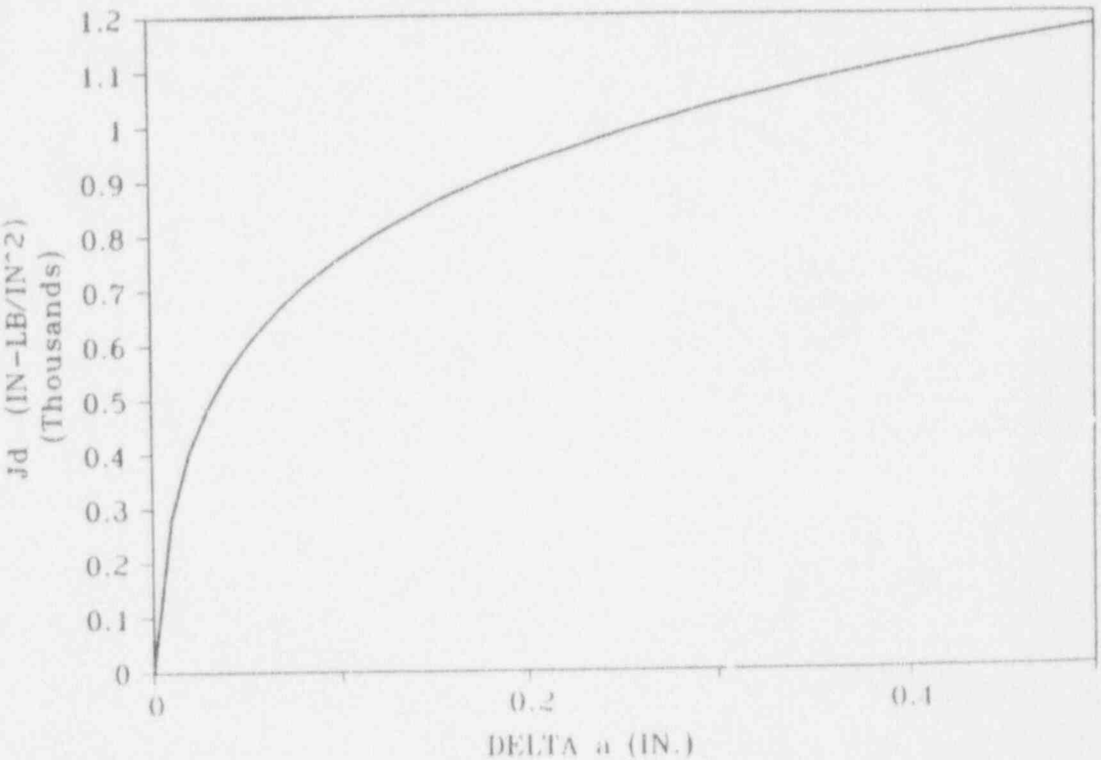

Figure 4-5 Linde 80 J-R Curves for Copper of 0.31% and Fluence = $1x10^{18}$ n/cm^2

5.0 EVALUATION OF LEVEL A AND B CONDITIONS

The methodology for the evaluation of Level A and B Service loadings was described in Section 3. Key steps in that evaluation are the calculation of applied J-Integral and the flaw stability evaluation. This Section describes the selection and the evaluation of appropriate loadings for Service Levels A and B, and their evaluation using the methods in the Code Case. Conservative J-R curves shown in Section 4 were used to determine the USE at which acceptance criteria of the Code Case are satisfied.

5.1 Level A and B Service Loadings

The two loadings to be considered are internal pressure and thermal heatup/cooldown rates. The heatup/cooldown rates for the BWR RPVs are specified in the reactor cycles drawing for the each plant. The definitions of reactor thermal cycles and the associated number of their occurrences have evolved over time. After reviewing all BWR/2-6 thermal cycle diagrams, it was determined that a more recent thermal cycle drawing [5-1], for the BWR/6 standard plant, was bounding for determination of the limiting heatup/cooldown rates. A review of this drawing indicated that the highest heatup/cooldown rate for all Level A and B events was 100° F/hour except for the Level B loss of feedwater pump transient. The pressure and temperature conditions during this transient are shown in Figure 5-1. As shown later, the limiting case was still found to be the 100° F/hour case.

The specified design pressure for BWR/2-6s is 1250 psi. The accumulation pressure is 1.1 times the design pressure and is, thus, equal to 1375 psi. The internal pressure value used in the $J_{0.1}$ criterion is 1.15 times the accumulation pressure (i.e., 1375x1.15 or 1581 psi). Similarly, the internal pressure value used in the flaw stability criterion is 1.25 times the accumulation pressure or 1719 psi.

The postulated flaw for this case has the depth equal to 1/4t (i.e., 7.125x.25 or 1.78 inch for the BWR/2s, and 6.19x.25 or 1.55 inch for BWR/3-6s). The internal pressure, cooldown rate, and the flaw depth information were input in equations (3-1) through (3-7) of Section 3 to determine the applied J-Integral values.

5.2 Evaluation per $J_{0.1}$ Criterion

Tables 5-1a (for BWR/2s) and 5-1b (for BWR/3-6s) show the calculated values of applied J-Integral for several crack depths beginning with the 1/4t crack depth. Both the axial and circumferential flaws are considered. The applied J-Integral values from these tables for use in this criterion were obtained at 0.1 inch crack extension (i.e., 1.88 inch for BWR/2s and 1.65 inch for BWR/3-6s).

Figure 5-2a shows a comparison of the applied J values for the axial flaw case with the material J-R curves for the SA302B plate material. Figure 5-2b shows the similar comparison for the circumferential flaw case. Although not shown, the margins are higher with the SA533B combined database and Linde 80 weld J-R curves. The overall USE requirements are discussed in Section 5.5.

5.3 Stability Evaluation

The applied J-Integral values for the stability evaluation were calculated using an internal pressure of 1719 psi (1.25 x accumulation pressure). The calculated values of applied J-Integral are shown in Tables 5-2a and b. Figures 5-3a through b show the applied J curve and the SA302B J-R curves for the axial and circumferential flaws. Flaw stability at a given applied load is assured when the slope of the applied J-Integral curve is less than the slope of the material J-R curve at the point on the J-R curve where the two curves intersect (see Figure 3-1).

Figures 5-4 and 5-5 show the stability assessments for the axial flaw case with the SA533B/Non-Linde 80 weld and the Linde 80 weld J-R curves, respectively. It is seen that the USE values at which equivalent margins are met are considerably lower than those in the SA302B J-R curve cases. The determination of minimum USE requirements based on the stability criterion is discussed further in Section 5.5.

5.4 Assessment of Loss of Feedwater Pump Transient

As stated earlier in this section, the heatup/cooldown rates during the loss of feedwater pump transient, which is a Level B transient, exceed 100° F/hour, the rate used in the preceding evaluations for the two criteria. Therefore, an assessment was conducted to see if the applied J-Integral values produced during this transient would be enveloped by those calculated in the preceding evaluations.

A review of the pressure-temperature conditions during the transient, as shown in Figure 5-1, shows both heatup and cooldown ramps are involved. However, only the cooldown ramps are of interest since they produce tensile stresses at the inside surface and, thus, a positive stress intensity factor. A one-dimensional axisymmetric finite element model of the RPV wall (R=126.7 inch, t= 6.19 inch) was created using the ANSYS computer program. Based on thermodynamic conditions, the convective heat transfer coefficient, h, at the ID surface was specified as 500 BTU/hr-ft^2-°F. The tensile thermal stresses were determined to be the highest at the end of the cooldown ramp from 561° F to 485° F (see Figure 5-1). Figure 5-6 shows the calculated values of K corresponding to the maximum thermal stress. The assumed flaw orientation was axial with length six times the depth. The K values were calculated using the Raju-Newman method [5-2]. The maximum value of K in Figure 5-6 is approximately 12 ksi$\sqrt{\text{in}}$.

The K_{It} values for 100° F/hour in Table 5-1b are ≈10 ksi$\sqrt{\text{in}}$ at comparable crack depth. However, a major component of the applied J-Integral value at the crack depths of interest is the K from pressure loading. The pressure at the end of cooldown ramp in the loss of feedwater pump transient (579 psi) is less than one-half the accumulation pressure of 1375 psi. Therefore, the applied J-Integral values for the loss of feedwater pump transient are enveloped by those shown in Tables 5-1a and b.

5.5 Required USE Determination

The USE values required to assure equivalent margins per 10CFR50 Appendix G are determined from Figures 5-2 through 5-5. A summary of the results from these figures, for each material of interest, follows.

BWR/2 Plates:

The flaw stability criterion is limiting. Figures 5-3a and 5-3b show the lines of $J_{applied}$ versus crack growth for the axial and circumferential flaw, respectively. The stability criterion is met where the $J_{applied}$ line crosses below the J-R curve for a particular CVN energy. In this case, the stability criterion is met for J-R curves, based on the SA302B material, with USE values of 50 ft-lb (longitudinal) for the axial flaw and at least 35 ft-lb (transverse) for the circumferential flaw.

BWR/3-6 Plates:

The flaw stability criterion is limiting. Figures 5-3a and 5-3b, based on SA302B J-R curves, show the required USE to be 59 ft-lb (longitudinal) for an axial flaw and at least 35 ft-lb (transverse) for a circumferential flaw, respectively. Note that, in Figure 5-4, based on the combined data base J-R curve, the axial flaw requirement is only 35 ft-lb (longitudinal), again showing the sizable conservatism in basing J-R curves on the SA302B data. However, the BWR/3-6 plates are evaluated against the 59 ft-lb requirement in Section 8.

Non-Linde 80 Welds:

The flaw stability criterion is limiting. Figure 5-4 provides J-R curves for both SA533B plates and for non-Linde 80 welds, so the axial flaw requirement is 35 ft-lb. The circumferential flaw case is not analyzed, because it has a lower $J_{applied}$ and weld metal USE is independent of orientation of the flaw.

Linde 80 Welds:

The flaw stability criterion is limiting. Figure 5-5, with a J-R curve based on bounding Cu and fluence assumptions, shows that the stability criterion is met.

Table 5-3 provides a summary of the required USE values for the various BWR types and material types. The required USE values in Table 5-3 are based on the Level A and B loadings. In Section 6, the evaluation of Level C and D loadings is described. The USE requirements of Table 5-3 are then revisited to see if they also envelope the USE requirements per the criteria for the Level C and D loadings.

5.6 Reference

[5-1] "Reactor Cycles - BWR/6 Standard," GE Drawing No. 795E949, Revision 0, July 1981 (GE proprietary information).

[5-2] Raju, I.S. and Newman, J.C., "Stress-Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical Vessels," PVP Volume 58, 1982.

TABLE 5-1a

Calculated Values of Applied J-Integral for 1.15xAccumulation Pressure (BWR/2)

PRESSURE(PSI)=	1581
VESSEL Ri (IN)=	106.7
VESSEL TH (IN)=	7.125
COOLING RATE(F/HR)	100
a0 (IN)=	1.78125
E(KSI)=	27700
YS (KSI)=	69

AXIAL FLAW

a	F1	F3	Kp	Kt	ae	F1'	F3'	Ktotal	Japp
1.78	1.04	1.06	62.43	14.39	1.85	1.05	1.06	78.25	201.17
1.83	1.05	1.06	63.52	14.40	1.90	1.05	1.06	79.38	206.99
1.88	1.05	1.06	64.60	14.39	1.95	1.06	1.06	80.50	212.86
1.93	1.06	1.06	65.69	14.38	2.00	1.06	1.06	81.61	218.79
1.98	1.06	1.06	66.78	14.37	2.05	1.07	1.06	82.72	224.78
2.03	1.06	1.06	67.87	14.35	2.11	1.07	1.06	83.82	230.84
2.08	1.07	1.06	68.96	14.32	2.16	1.07	1.05	84.93	236.96
2.13	1.07	1.05	70.06	14.29	2.21	1.08	1.05	86.03	243.15
2.18	1.08	1.05	71.16	14.25	2.26	1.08	1.05	87.13	249.41
2.23	1.08	1.05	72.26	14.21	2.31	1.09	1.04	88.23	255.75
2.28	1.09	1.04	73.37	14.16	2.37	1.09	1.04	89.33	262.17
2.33	1.09	1.04	74.48	14.10	2.42	1.10	1.03	90.43	268.67
2.38	1.09	1.04	75.60	14.04	2.47	1.10	1.03	91.54	275.26
2.43	1.10	1.03	76.72	13.98	2.52	1.11	1.02	92.64	281.94
2.48	1.10	1.03	77.85	13.91	2.58	1.11	1.02	93.75	288.71
2.53	1.11	1.02	78.99	13.83	2.63	1.12	1.01	94.85	295.58
2.58	1.11	1.01	80.13	13.75	2.68	1.12	1.00	95.97	302.54
2.63	1.12	1.01	81.27	13.67	2.73	1.13	0.99	97.08	309.62
2.68	1.12	1.00	82.43	13.58	2.78	1.14	0.99	98.20	316.80
2.73	1.13	0.99	83.59	13.48	2.84	1.14	0.98	99.32	324.09
2.78	1.14	0.99	84.76	13.38	2.89	1.15	0.97	100.45	331.50

WORKSHEET: BWROGUS3.WK1

CIRCUMFERENTIAL FLAW

a	F1	F3	Kp	Kt	ae	F1'	F3'	Ktotal	Japp
1.78	0.96	1.06	30.63	14.39	1.80	0.97	1.06	45.26	67.28
1.83	0.97	1.06	31.15	14.40	1.85	0.97	1.06	45.78	68.85
1.88	0.97	1.06	31.66	14.39	1.90	0.97	1.06	46.30	70.41
1.93	0.97	1.06	32.18	14.38	1.96	0.97	1.06	46.80	71.96
1.98	0.98	1.06	32.69	14.37	2.01	0.98	1.06	47.30	73.51
2.03	0.98	1.06	33.20	14.35	2.06	0.98	1.06	47.79	75.04
2.08	0.98	1.06	33.71	14.32	2.11	0.98	1.06	48.28	76.57
2.13	0.99	1.05	34.22	14.29	2.16	0.99	1.05	48.76	78.10
2.18	0.99	1.05	34.73	14.25	2.21	0.99	1.05	49.23	79.61
2.23	0.99	1.05	35.24	14.21	2.26	0.99	1.05	49.69	81.12
2.28	0.99	1.04	35.74	14.16	2.31	1.00	1.04	50.15	82.63
2.33	1.00	1.04	36.25	14.10	2.36	1.00	1.04	50.60	84.12
2.38	1.00	1.04	36.75	14.04	2.41	1.00	1.03	51.05	85.62
2.43	1.00	1.03	37.26	13.98	2.46	1.01	1.03	51.49	87.10
2.48	1.01	1.03	37.76	13.91	2.51	1.01	1.02	51.93	88.58
2.53	1.01	1.02	38.27	13.83	2.56	1.01	1.02	52.36	90.06
2.58	1.01	1.01	38.77	13.75	2.61	1.02	1.01	52.78	91.53
2.63	1.02	1.01	39.28	13.67	2.66	1.02	1.00	53.21	93.00
2.68	1.02	1.00	39.79	13.58	2.71	1.02	1.00	53.62	94.46
2.73	1.03	0.99	40.29	13.48	2.76	1.03	0.99	54.04	95.92
2.78	1.03	0.99	40.80	13.38	2.81	1.03	0.98	54.44	97.38

TABLE 5-1b

Calculated Values of Applied J-Integral for 1.15xAccumulation Pressure (BWR/3-6)

PRESSURE(PSI)=	1581
VESSEL Ri (IN)=	126.7
VESSEL TH (IN)=	6.19
COOLING RATE(F/HR)	100
a0 (IN)=	1.5475
E(KSI)=	27700
YS (KSI)=	69

AXIAL FLAW

a	F1	F3	Kp	Kt	ae	F1'	F3'	Ktotal	Japp
1.55	1.04	1.06	78.20	10.12	1.63	1.05	1.06	91.05	272.33
1.60	1.05	1.06	79.76	10.13	1.69	1.06	1.06	92.70	282.34
1.65	1.05	1.06	81.33	10.12	1.74	1.06	1.06	94.36	292.51
1.70	1.06	1.06	82.90	10.11	1.79	1.07	1.06	96.02	302.86
1.75	1.06	1.06	84.47	10.10	1.85	1.07	1.05	97.67	313.40
1.80	1.07	1.06	86.05	10.08	1.90	1.08	1.05	99.33	324.12
1.85	1.07	1.05	87.63	10.05	1.95	1.08	1.05	100.99	335.04
1.90	1.08	1.05	89.21	10.02	2.01	1.09	1.04	102.65	346.18
1.95	1.08	1.05	90.80	9.99	2.06	1.09	1.04	104.32	357.53
2.00	1.09	1.04	92.40	9.95	2.11	1.10	1.03	106.00	369.10
2.05	1.09	1.04	94.01	9.90	2.17	1.11	1.02	107.68	380.92
2.10	1.10	1.03	95.62	9.85	2.22	1.11	1.02	109.37	392.98
2.15	1.10	1.03	97.25	9.79	2.28	1.12	1.01	111.07	405.29
2.20	1.11	1.02	98.88	9.73	2.33	1.12	1.00	112.78	417.88
2.25	1.11	1.01	100.53	9.67	2.38	1.13	0.99	114.51	430.74
2.30	1.12	1.01	102.18	9.60	2.44	1.14	0.98	116.24	443.89
2.35	1.13	1.00	103.85	9.52	2.49	1.14	0.97	117.99	457.35
2.40	1.13	0.99	105.53	9.45	2.54	1.15	0.96	119.75	471.11
2.45	1.14	0.98	107.23	9.36	2.60	1.16	0.95	121.53	485.20
2.50	1.15	0.97	108.93	9.28	2.65	1.17	0.94	123.32	499.63
2.55	1.15	0.96	110.65	9.19	2.71	1.17	0.93	125.13	514.41

WORKSHEET: BWROGUS3.WK1

CIRCUMFERENTIAL FLAW

a	F2	F3	Kp	Kt	ae	F2'	F3'	Ktotal	Japp
1.55	0.96	1.06	37.78	10.12	1.57	0.97	1.06	48.29	76.60
1.60	0.97	1.06	38.52	10.13	1.62	0.97	1.06	49.03	78.99
1.65	0.97	1.06	39.25	10.12	1.67	0.97	1.06	49.77	81.38
1.70	0.97	1.06	39.98	10.11	1.73	0.98	1.06	50.50	83.78
1.75	0.98	1.06	40.71	10.10	1.78	0.98	1.06	51.22	86.18
1.80	0.98	1.06	41.44	10.08	1.83	0.98	1.06	51.93	88.59
1.85	0.99	1.05	42.16	10.05	1.88	0.99	1.05	52.63	91.01
1.90	0.99	1.05	42.88	10.02	1.93	0.99	1.05	53.33	93.44
1.95	0.99	1.05	43.60	9.99	1.98	0.99	1.04	54.02	95.88
2.00	1.00	1.04	44.32	9.95	2.03	1.00	1.04	54.71	98.32
2.05	1.00	1.04	45.04	9.90	2.08	1.00	1.03	55.39	100.78
2.10	1.00	1.03	45.76	9.85	2.13	1.01	1.03	56.06	103.25
2.15	1.01	1.03	46.47	9.79	2.18	1.01	1.02	56.73	105.73
2.20	1.01	1.02	47.19	9.73	2.23	1.01	1.02	57.39	108.21
2.25	1.02	1.01	47.91	9.67	2.28	1.02	1.01	58.05	110.72
2.30	1.02	1.01	48.62	9.60	2.34	1.02	1.00	58.71	113.23
2.35	1.02	1.00	49.34	9.52	2.39	1.03	0.99	59.36	115.76
2.40	1.03	0.99	50.06	9.45	2.44	1.03	0.98	60.01	118.30
2.45	1.03	0.98	50.78	9.36	2.49	1.03	0.97	60.65	120.86
2.50	1.04	0.97	51.50	9.28	2.54	1.04	0.97	61.30	123.44
2.55	1.04	0.96	52.22	9.19	2.59	1.04	0.96	61.94	126.03

TABLE 5-2a

Calculated Values of Applied J-Integral for 1.25xAccumulation Pressure (BWR/2)

PRESSURE(PSI)=	1719
VESSEL Ri (IN)=	106.7
VESSEL TH (IN)=	7.125
COOLING RATE(F/HR)	100
a0 (IN)=	1.78125
E(KSI)=	27700
YS (KSI)=	69

AXIAL FLAW

a	F1	F3	Kp	Kt	ae	F1'	F3'	Ktotal	Japp
1.78	1.04	1.06	67.88	14.39	1.86	1.05	1.06	84.06	232.11
1.83	1.05	1.06	69.06	14.40	1.91	1.05	1.06	85.28	238.94
1.88	1.05	1.06	70.24	14.39	1.96	1.06	1.06	86.51	245.84
1.93	1.06	1.06	71.42	14.38	2.01	1.06	1.06	87.73	252.82
1.98	1.06	1.06	72.61	14.37	2.07	1.07	1.06	88.94	259.88
2.03	1.06	1.06	73.80	14.35	2.12	1.07	1.06	90.15	267.01
2.08	1.07	1.06	74.98	14.32	2.17	1.08	1.05	91.36	274.23
2.13	1.07	1.05	76.18	14.29	2.22	1.08	1.05	92.57	281.54
2.18	1.08	1.05	77.37	14.25	2.27	1.08	1.05	93.78	288.94
2.23	1.08	1.05	78.57	14.21	2.33	1.09	1.04	94.99	296.44
2.28	1.09	1.04	79.78	14.16	2.38	1.09	1.04	96.20	304.04
2.33	1.09	1.04	80.98	14.10	2.43	1.10	1.03	97.41	311.75
2.38	1.09	1.04	82.20	14.04	2.48	1.10	1.03	98.63	319.56
2.43	1.10	1.03	83.42	13.98	2.54	1.11	1.02	99.84	327.49
2.48	1.10	1.03	84.65	13.91	2.59	1.11	1.01	101.06	335.53
2.53	1.11	1.02	85.88	13.83	2.64	1.12	1.01	102.28	343.70
2.58	1.11	1.01	87.12	13.75	2.69	1.13	1.00	103.51	351.99
2.63	1.12	1.01	88.37	13.67	2.75	1.13	0.99	104.74	360.42
2.68	1.12	1.00	89.62	13.58	2.80	1.14	0.98	105.98	368.98
2.73	1.13	0.99	90.89	13.48	2.85	1.14	0.98	107.22	377.68
2.78	1.14	0.99	92.16	13.38	2.91	1.15	0.97	108.47	386.53

WORKSHEET: BWROGUS3.WK1

CIRCUMFERENTIAL FLAW

a	F2	F3	Kp	Kt	ae	F2'	F3'	Ktotal	Japp
1.78	0.96	1.06	33.30	14.39	1.81	0.97	1.06	47.98	75.63
1.83	0.97	1.06	33.86	14.40	1.86	0.97	1.06	48.55	77.44
1.88	0.97	1.06	34.43	14.39	1.91	0.97	1.06	49.11	79.24
1.93	0.97	1.06	34.99	14.38	1.96	0.98	1.06	49.67	81.04
1.98	0.98	1.06	35.54	14.37	2.01	0.98	1.06	50.21	82.83
2.03	0.98	1.06	36.10	14.35	2.06	0.98	1.06	50.75	84.61
2.08	0.98	1.06	36.66	14.32	2.11	0.98	1.06	51.28	86.38
2.13	0.99	1.05	37.21	14.29	2.16	0.99	1.05	51.80	88.16
2.18	0.99	1.05	37.76	14.25	2.21	0.99	1.05	52.32	89.92
2.23	0.99	1.05	38.31	14.21	2.26	0.99	1.05	52.83	91.68
2.28	0.99	1.04	38.86	14.16	2.31	1.00	1.04	53.33	93.44
2.33	1.00	1.04	39.41	14.10	2.36	1.00	1.04	53.83	95.19
2.38	1.00	1.04	39.96	14.04	2.41	1.00	1.03	54.32	96.93
2.43	1.00	1.03	40.51	13.98	2.46	1.01	1.03	54.81	98.68
2.48	1.01	1.03	41.06	13.91	2.51	1.01	1.02	55.29	100.42
2.53	1.01	1.02	41.61	13.83	2.57	1.01	1.02	55.76	102.15
2.58	1.01	1.01	42.16	13.75	2.62	1.02	1.01	56.23	103.89
2.63	1.02	1.01	42.71	13.67	2.67	1.02	1.00	56.70	105.62
2.68	1.02	1.00	43.26	13.58	2.72	1.02	1.00	57.16	107.34
2.73	1.03	0.99	43.81	13.48	2.77	1.03	0.99	57.62	109.07
2.78	1.03	0.99	44.36	13.38	2.82	1.03	0.98	58.07	110.80

TABLE 5-2b

Calculated Values of Applied J-Integral for 1.25xAccumulation Pressure (BWR/3-6)

PRESSURE(PSI)=	1719
VESSEL Ri (IN)=	126.7
VESSEL TH (IN)=	6.19
COOLING RATE(F/HR)	100
a0 (IN)=	1.5475
E(KSI)=	27700
YS (KSI)=	69

AXIAL FLAW

a	F1	F3	Kp	Kt	ae	F1'	F3'	Ktotal	Japp
1.55	1.04	1.06	85.02	10.12	1.65	1.05	1.06	98.58	319.28
1.60	1.05	1.06	86.73	10.13	1.70	1.06	1.06	100.40	331.19
1.65	1.05	1.06	88.43	10.12	1.76	1.06	1.06	102.22	343.30
1.70	1.06	1.06	90.14	10.11	1.81	1.07	1.06	104.04	355.63
1.75	1.06	1.06	91.85	10.10	1.86	1.07	1.05	105.87	368.19
1.80	1.07	1.06	93.56	10.08	1.92	1.08	1.05	107.69	380.99
1.85	1.07	1.05	95.28	10.05	1.97	1.08	1.05	109.52	394.04
1.90	1.08	1.05	97.00	10.02	2.03	1.09	1.04	111.35	407.35
1.95	1.08	1.05	98.73	9.99	2.08	1.10	1.04	113.20	420.94
2.00	1.09	1.04	100.47	9.95	2.13	1.10	1.03	115.05	434.81
2.05	1.09	1.04	102.21	9.90	2.19	1.11	1.02	116.90	448.98
2.10	1.10	1.03	103.97	9.85	2.24	1.11	1.01	118.77	463.46
2.15	1.10	1.03	105.74	9.79	2.30	1.12	1.01	120.66	478.26
2.20	1.11	1.02	107.51	9.73	2.35	1.13	1.00	122.55	493.40
2.25	1.11	1.01	109.30	9.67	2.41	1.13	0.99	124.46	508.88
2.30	1.12	1.01	111.10	9.60	2.46	1.14	0.98	126.38	524.74
2.35	1.13	1.00	112.92	9.52	2.51	1.15	0.97	128.32	540.97
2.40	1.13	0.99	114.74	9.45	2.57	1.16	0.96	130.28	557.60
2.45	1.14	0.98	116.59	9.36	2.62	1.16	0.95	132.26	574.63
2.50	1.15	0.97	118.44	9.28	2.68	1.17	0.94	134.25	592.09
2.55	1.15	0.96	120.31	9.19	2.73	1.18	0.92	136.26	610.00

WORKSHEET: BWROGUS3.WK1

CIRCUMFERENTIAL FLAW

a	F2	F3	Kp	Kt	ae	F2'	F3'	Ktotal	Japp
1.55	0.96	1.06	41.08	10.12	1.58	0.97	1.06	51.68	87.73
1.60	0.97	1.06	41.88	10.13	1.63	0.97	1.06	52.49	90.51
1.65	0.97	1.06	42.68	10.12	1.68	0.97	1.06	53.29	93.30
1.70	0.97	1.06	43.47	10.11	1.73	0.98	1.06	54.09	96.11
1.75	0.98	1.06	44.27	10.10	1.78	0.98	1.06	54.87	98.92
1.80	0.98	1.06	45.05	10.08	1.83	0.98	1.06	55.65	101.74
1.85	0.99	1.05	45.84	10.05	1.88	0.99	1.05	56.42	104.57
1.90	0.99	1.05	46.62	10.02	1.93	0.99	1.05	57.18	107.42
1.95	0.99	1.05	47.41	9.99	1.98	1.00	1.04	57.94	110.28
2.00	1.00	1.04	48.19	9.95	2.04	1.00	1.04	58.69	113.15
2.05	1.00	1.04	48.97	9.90	2.09	1.00	1.03	59.43	116.04
2.10	1.00	1.03	49.75	9.85	2.14	1.01	1.03	60.17	118.95
2.15	1.01	1.03	50.53	9.79	2.19	1.01	1.02	60.91	121.86
2.20	1.01	1.02	51.31	9.73	2.24	1.01	1.02	61.63	124.80
2.25	1.02	1.01	52.09	9.67	2.29	1.02	1.01	62.36	127.75
2.30	1.02	1.01	52.87	9.60	2.34	1.02	1.00	63.08	130.72
2.35	1.02	1.00	53.65	9.52	2.39	1.03	0.99	63.80	133.71
2.40	1.03	0.99	54.43	9.45	2.44	1.03	0.98	64.51	136.73
2.45	1.03	0.98	55.21	9.36	2.49	1.03	0.97	65.22	139.76
2.50	1.04	0.97	56.00	9.28	2.54	1.04	0.96	65.93	142.81
2.55	1.04	0.96	56.78	9.19	2.60	1.04	0.95	66.64	145.88

TABLE 5-3

Minimum Required CVN Energies to Meet Level A & B Loading Criteria

Category	Required Minimum CVN Energies (ft-lb) Longitudinal	Transverse
BWR/2 plate (SA302B J-R curve)	50	35[a]
BWR/3-6 plate (SA302B J-R curve)	59	35[a]
BWR/3-6 plate (SA533B J-R curve)	35[a]	35[a]
BWR/3-4 Welds (Linde 80)	*	*
BWR/2-6 Welds (Non-Linde 80)	35[a]	35[a]

Notes:

* Satisfies the Code Case criteria with maximum reported copper of 0.31% and 1×10^{18} n/cm^2 fluence.

a Analyzed value. Actual values which meet Code Case criteria are even lower.

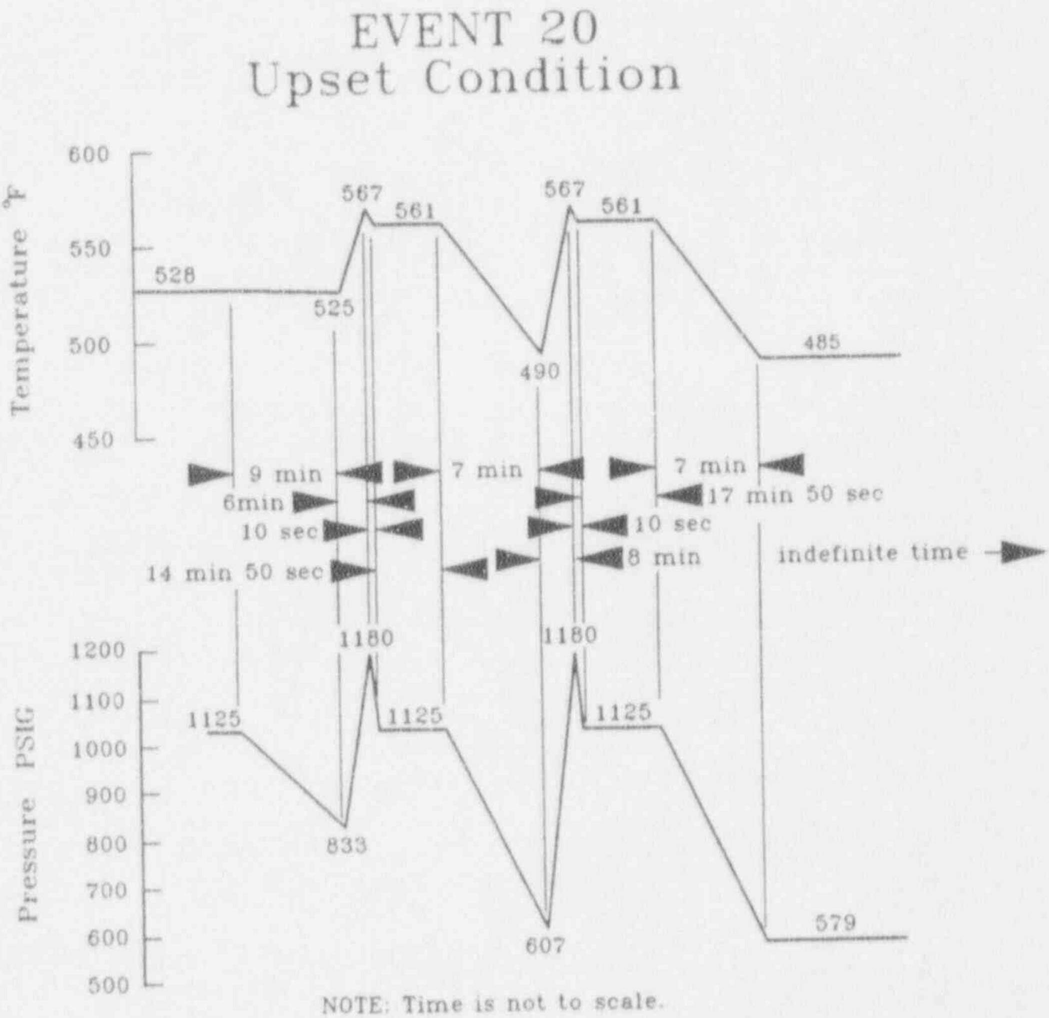

Figure 5-1 Loss of Feedwater Pump Transient (Level B Event)

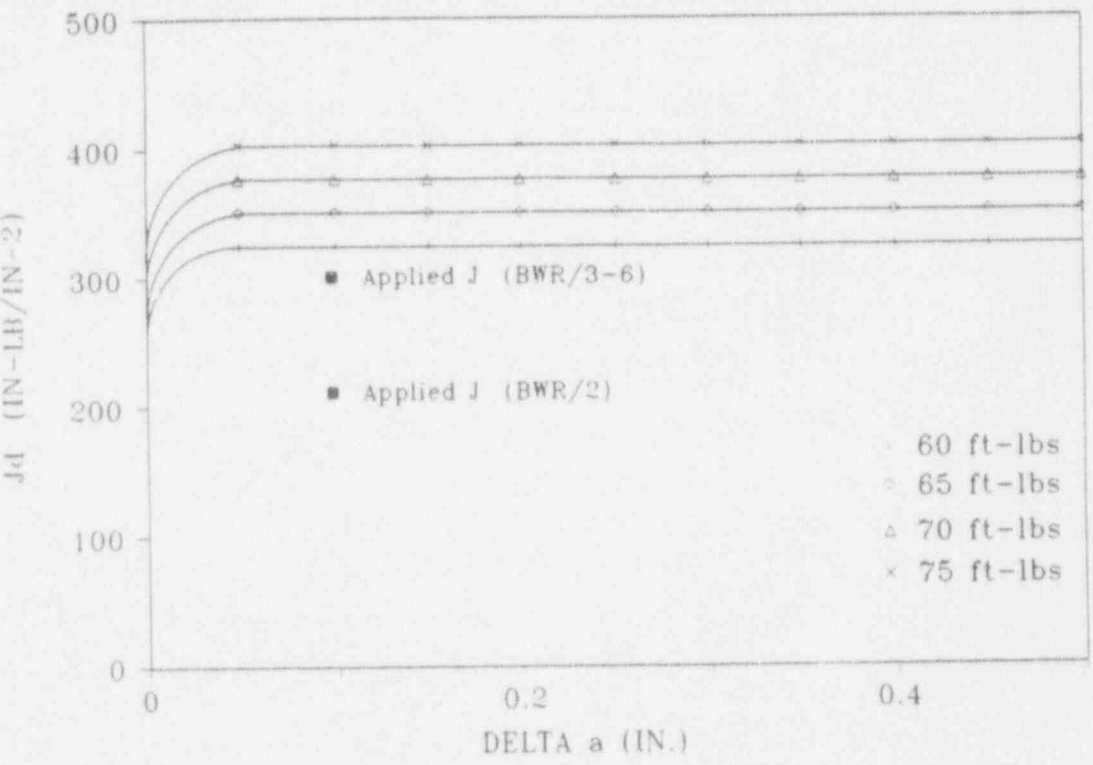

Figure 5-2a $J_{0.1}$ Criterion Evaluation for Axial Flaw with SA302B J-R Curves

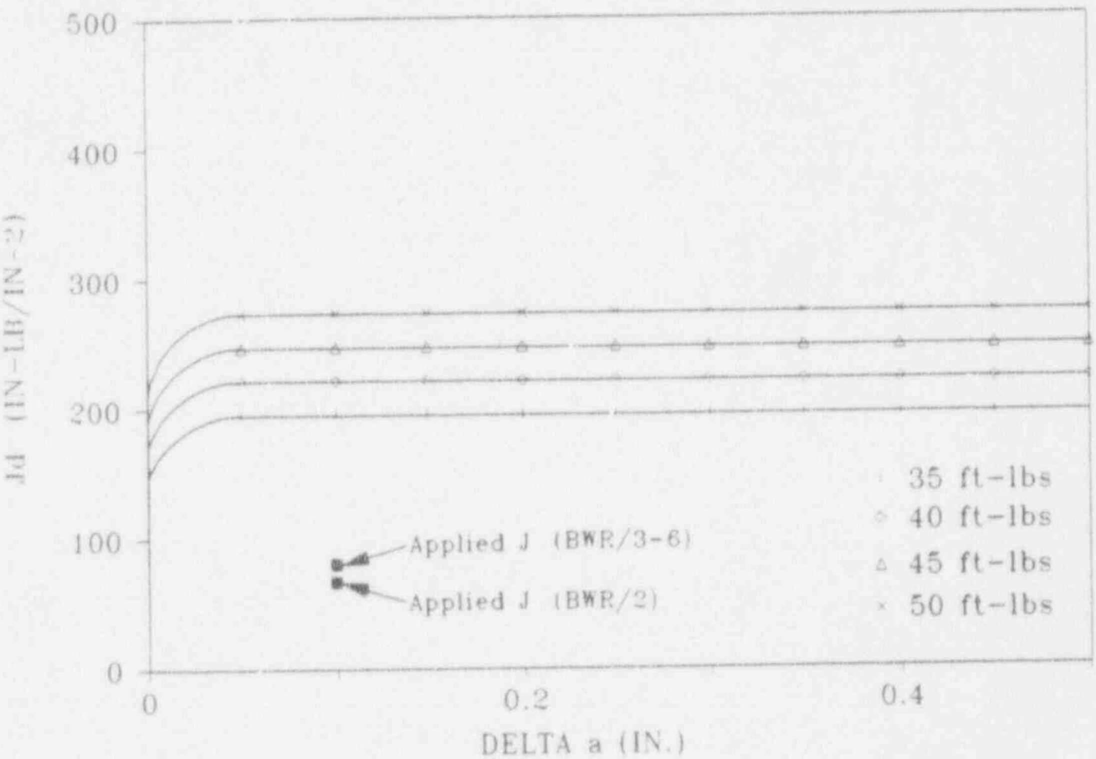

Figure 5-2b $J_{0.1}$ Criterion Evaluation for Circumferential Flaw with SA302B J-R Curves

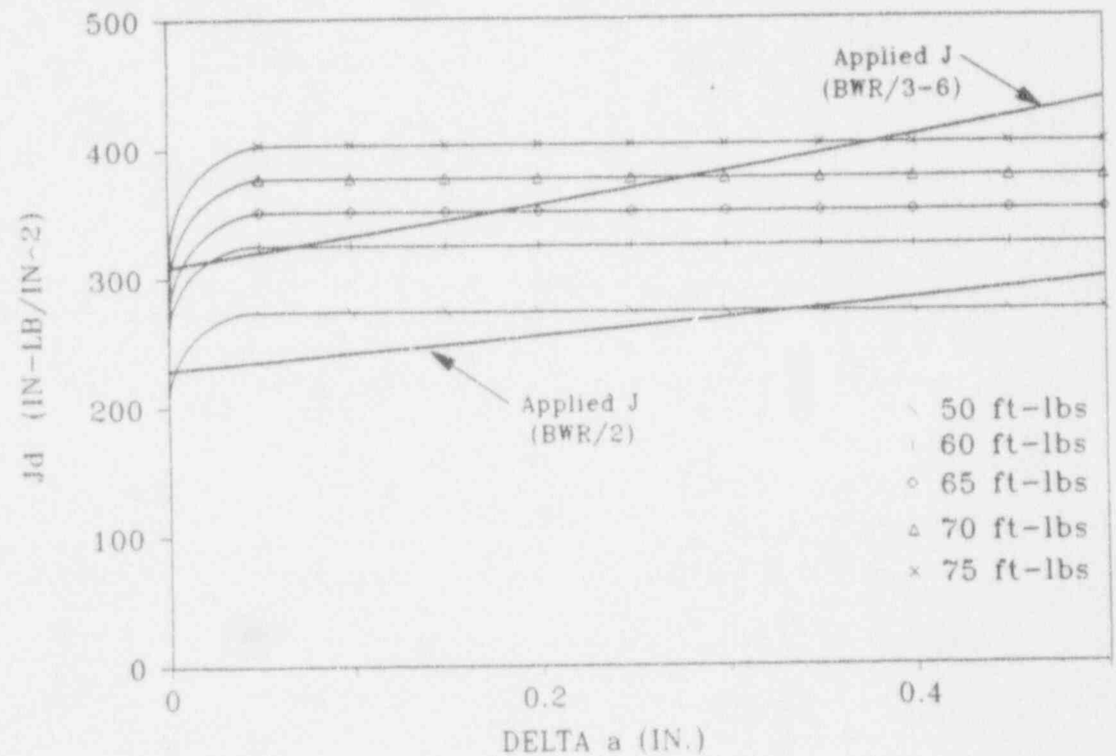

Figure 5-3a Flaw Stability Criterion Evaluation for Axial Flaw with SA302B J-R Curves

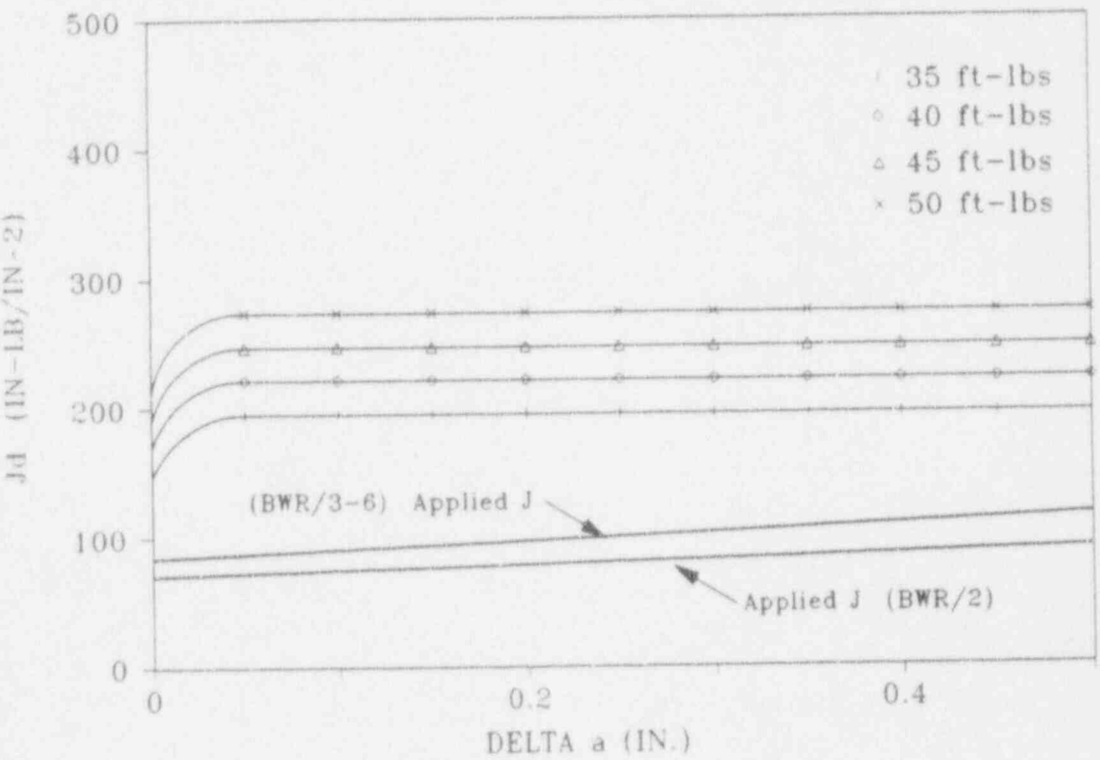

Figure 5-3b Flaw Stability Criterion Evaluation for Circumferential Flaw with SA302B J-R Curves

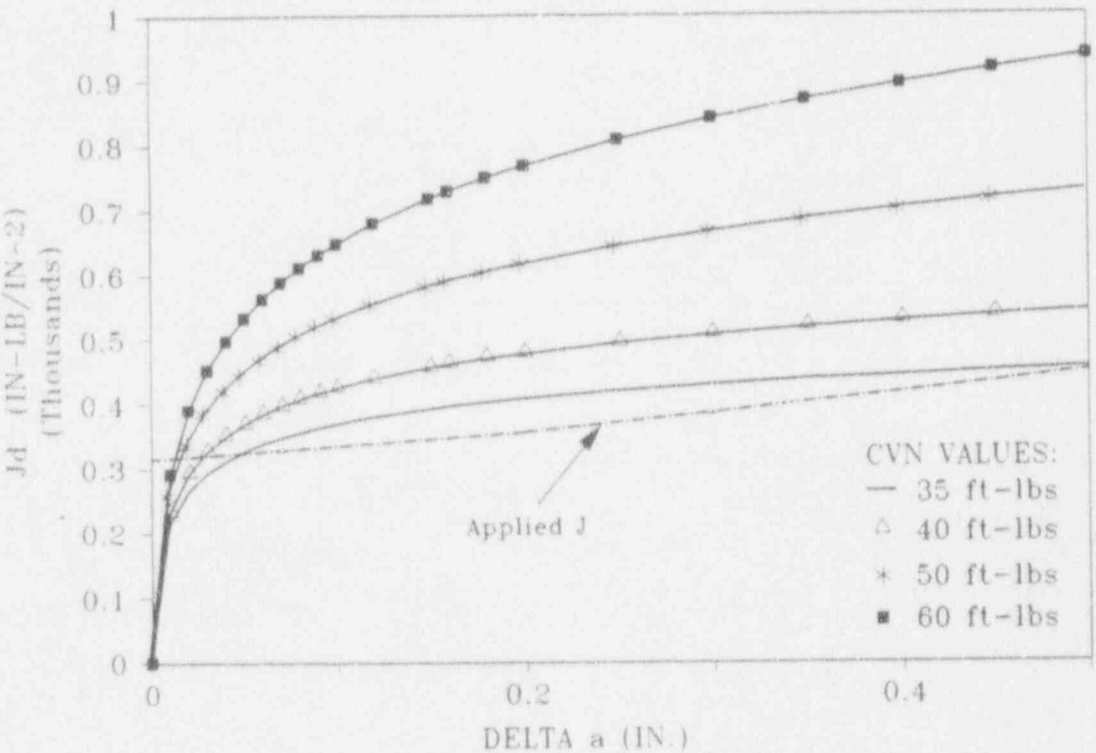

Figure 5-4 Flaw Stability Criterion Evaluation for Axial Flaw with the SA533 Plate/Non-Linde 80 Weld Combined Data Base J-R Curves

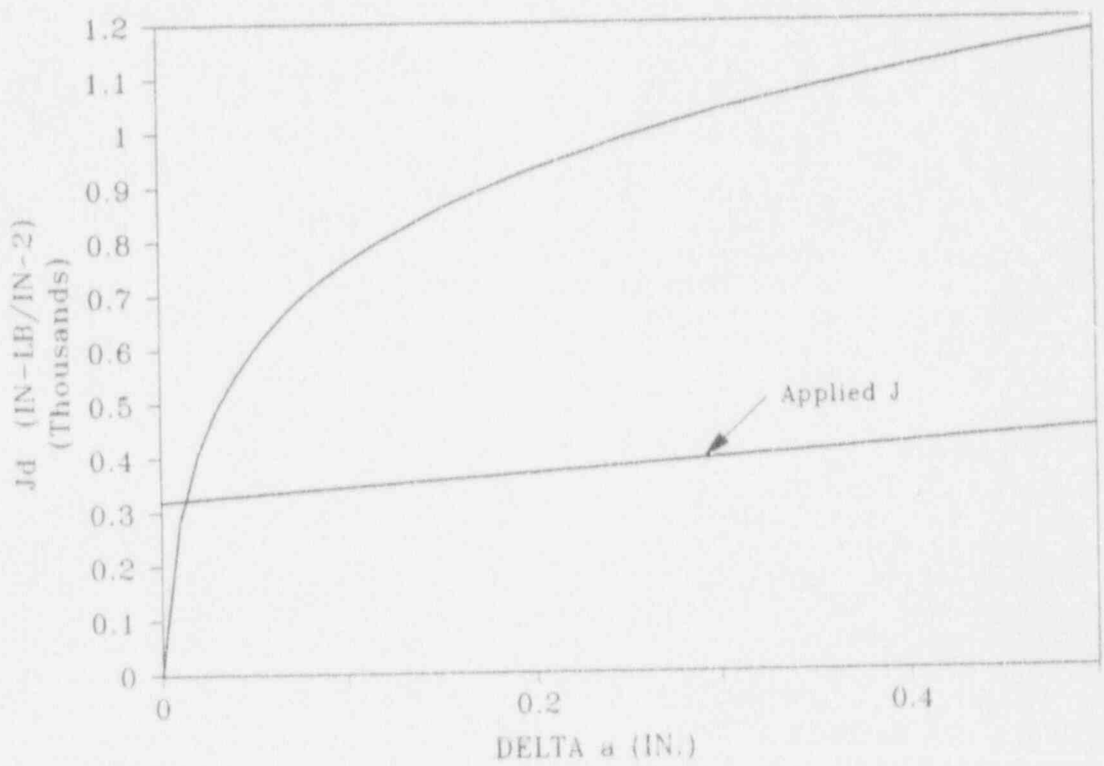

Figure 5-5 Flaw Stability Criterion Evaluation for Axial Flaw with Linde 80 Flux Weld J-R Curves

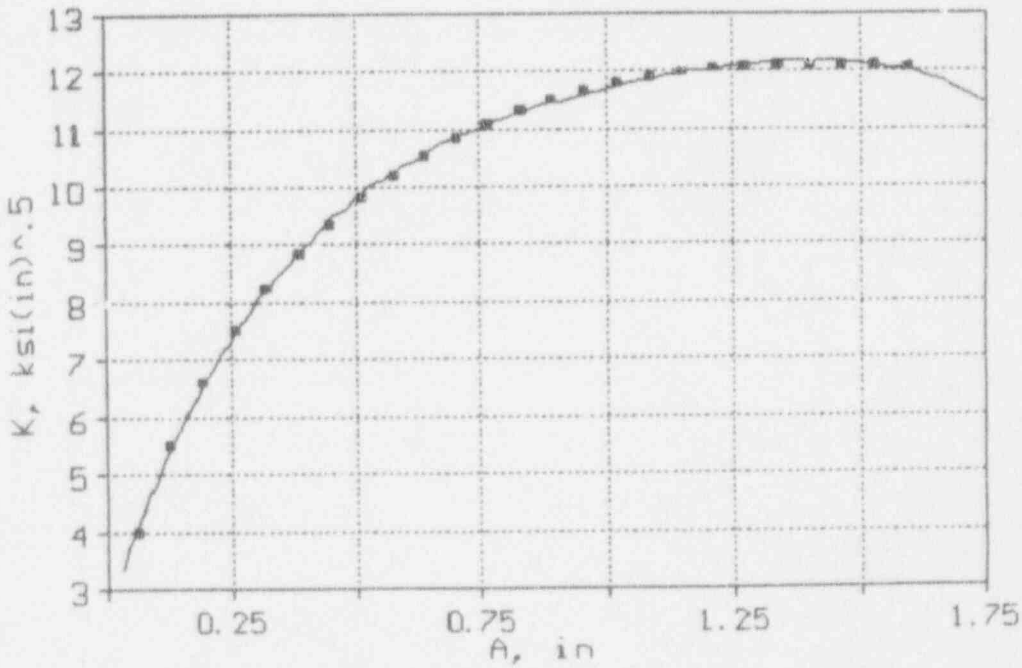

Figure 5-6 Calculated Values of K for Loss of Feedwater Pump Transient

6.0 EVALUATION OF LEVEL C AND D CONDITIONS

The Code Case procedures call for the evaluation of Service Level C and D loadings with a safety factor of 1.0 and a postulated flaw equal to 1/10 of the vessel wall thickness. Many of the early generation BWRs designed to ASME Section VIII or the 1965 edition of Section III did not have an explicit Service Level classification for various loadings. The later editions of the Code first introduced the Normal, Upset, Emergency and Faulted classification for the various plant transients and component loadings. To avoid confusion between the plant or system operating conditions and the component operating conditions, this classification was then changed for the components to Service Levels A through D.

As was the case for Level A and B loadings, a more recent thermal cycle drawing [5-1], for the BWR/6 standard plant, was shown to have the limiting transients. Once the transient was selected, the first step in the evaluation was to determine the throughwall stress distribution in the RPV wall when the stresses reach their peak. This was done by finite element analysis. The stress intensity factor, K, values and correspondingly the applied J-Integral values are then calculated using the methods available in the technical literature. The Code Case does not provide procedures to calculate K for temperature transients in which heatup/cooldown rates exceed 100° F per hour.

6.1 Evaluation of Level C Conditions

6.1.1 Selection of Transients

A review of [5-1] indicates that among the transients specified for the Emergency (Level C) condition, automatic blow down (Event 23, see Figure 6-1) and the improper start of cold recirculation loop (Event 24, see Figure 6-2), are the most limiting for the beltline region of the vessel. Of these, the second transient is not applicable to BWR/2 vessels, which do not have jet pumps. The internal pressure remains at the operating level throughout the second transient, whereas in the first transient it is much lower, corresponding to the saturation pressure when the thermal stresses reach their peak after depressurization. Thus, the second transient was determined to be more limiting for the BWR/3-6s.

Based on the preceding discussion, the BWR/2 RPV geometry was analyzed using transient 23 and the BWR/3-6 geometry was used with transient 24.

6.1.2 Finite Element Stress Analysis

Figure 6-3 shows the axisymmetric finite element model used for the evaluation of the BWR/2 case. The stainless steel clad on the ID surface, with a nominal thickness of 7/32 inch, is also included in the model. The ANSYS computer program [6-1] was used in both the transient temperature and the stress analyses. The value for the convective heat transfer coefficient, h, at the ID surface was assumed as 10,000 Btu/hr-ft^2-°F, based on a previous analysis [6-2] of a more severe transient. A model similar to that shown in Figure 6-3 was also developed for the BWR/3-6 geometry. The 'h' at the ID surface for transient 24 was assumed to be the same as that for transient 23.

In both the models, temperature distributions were calculated at several time points along the transient, and were then used in the subsequent stress analysis. A review of the stress distributions at different time points showed that the stresses reached a maximum at approximately 210 seconds in the BWR/2 model and at approximately 32 seconds in the BWR/3-6 model. Figures 6-4a and b show the circumferential stress distributions through the reactor wall in the two cases. The increased stress level in the clad (over and above the extrapolated trend from the base metal stress) is due to the difference between the thermal expansion coefficients of low alloy steel and stainless steel. This additional thermal stress in the clad was approximated as a point force for the calculation of stress intensity factor, K.

Since the axial and circumferential stress magnitudes through the reactor wall were essentially similar, the axial stress distribution plots are not shown.

6.1.3 Fracture Mechanics Evaluation

The geometry of the postulated flaw for the Level C service loadings is essentially the same as that for the Level A and B loadings except that the flaw depth is 1/10 of the base metal wall thickness plus the clad thickness. Thus, the postulated crack depth in the BWR/2 case was (0.1x7.13 + 0.22) or 0.93 inch, and (0.1x6.19 + 0.19) or 0.81 inch in the BWR/3-6 case. The K values for the postulated axial flaws were calculated using the Raju-Newman method [6-3]. The stress distribution in this approach is characterized in the form of a third order polynomial across the thickness:

$$\sigma = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \qquad (6\text{-}1)$$

Due to the dissimilarity in materials, a discontinuity stress is present at the clad-plate interface, as evident in Figures 6-4a and b. This discontinuity stress was excluded in the polynomial characterization but was considered separately by integrating it over the clad thickness. The resulting force per unit thickness, P, was assumed to be located at the middle of the clad. The following equation based on a solution given in [6-4] was used to calculate the K contributed by P:

$$K_{clad} = 2P \times 1.3/\sqrt{(\pi a)} \qquad (6\text{-}2)$$

where, a is crack depth. The calculated values of K from the Raju-Newman solution and from equation 6-2 were added together to obtain the overall K for the thermal transient being analyzed.

The same thermal K values were also used for the circumferential flaw evaluation. This was considered reasonable since the axial flaw K values are expected to envelope the circumferential flaw K values, given the same stress distribution.

Figures 6-5a and b show the values of K by the Raju-Newman method for the stress distributions in Figures 6-4a and b, respectively. For the convenience of J-Integral computation, the K values were curve-fitted as a fourth order polynomial versus crack depth, a.

Tables 6-1a and b show the summaries of the applied values of J-Integral at various crack depths for BWR/2 and BWR/3-6 cases, respectively. The initial flaw depth in each table is equal to 1/10t. The K values for pressure loading were calculated using equations 3-1 and 3-3. Although their stated applicability range is $0.2 < a/t < 0.5$, the equations were found to provide reasonable answers for a/t values of 0.1 and, therefore, were used in this evaluation. Both the pressure and thermal loadings are based on a safety factor of 1.0.

A review of Tables 6-1a and b shows that the applied J-Integral values in transient 24 are considerably larger than those in transient 23. This validated the decision to analyze the BWR/3-6 geometry for transient 24 only. The review also shows that the applied J-Integral values at 0.1 crack extension are smaller than those for Level A and B conditions at the same crack extension (Tables 5-1a and b). This is also a clear indication that the Level C conditions are not governing in terms of minimum CVN energy requirements.

6.1.4 Acceptance Criteria Evaluation

Figure 6-6 shows the applied J-Integral values at 0.1 inch crack extension for the axial flaw case, and the J-R curves for SA302B modified at several longitudinal USE values. It is seen that the first criterion for Level C loadings is satisfied even with USE as low as 35 ft-lb. The stability criterion is also satisfied since any reasonable ductile crack extension is expected to be stable. This is lower than the corresponding Level A,B allowable USE values of 50 ft-lb for BWR/2 or 59 ft-lb for BWR/3-6.

Based on the preceding, it is concluded that the acceptance criteria for Level C loadings are satisfied, and are less limiting than the Level A,B USE requirements.

6.2 Evaluation of Level D Loadings

For many of the older BWRs, there are no Level D condition loadings defined in the RPV loading drawing or the thermal cycles drawing. A review of all RPV thermal cycle diagrams showed that the Loss of Coolant Accident (LOCA) event, event 27 from the BWR/6 thermal cycle diagram, is the most limiting among the Level D events. Therefore, this event was considered in the evaluation for Level D acceptance criteria for all BWR/2-6 plants.

Figure 6-7 shows the temperature and pressure conditions during event 27. The event depicted assumes a sudden and complete break of a recirculation line. When this occurs, the reactor is depressurized by blowing the steam and water out the break into the primary containment. Temperature in the beltline region of the reactor vessel is assumed to drop to 259° F in 15 seconds while pressure drops to 20 psig.

6.2.1 Stress Analysis

The same BWR/3-6 finite element model that was used in the Level C transient evaluation was also used in this case. Based on the consideration of thermodynamic and heat transfer conditions, the convective heat transfer coefficient, h, was conservatively assumed as 10000 Btu/hr-ft^2-°F. Throughwall temperature distributions were determined at several time points along the transient, and were then used in the subsequent stress analysis. A review of the stress distributions at different time points showed that the stresses reached a maximum at approximately 125 seconds into the transient. Figure 6-8 shows the throughwall circumferential stress distribution at 125 seconds. The peak stress at the ID surface is 76550 psi.

Once the BWR/3-6 results for Level D were evaluated, it was clear that the acceptability of the BWR/2 vessels could be concluded without further analysis. The LOCA event causes surface thermal stresses, which are relatively insensitive to vessel thickness. Therefore, the BWR/2 stresses are not expected to be significantly higher than those of the BWR/3-6.

6.2.2 Fracture Mechanics Analysis Results

The same approach, as used in the Level C loadings evaluation, was also used to calculate the BWR/3-6 thermal and pressure K values, which were then used to determine applied J-Integral values. Figure 6-9 shows the plot of thermal K values as a function of crack depth. These K values do not include the contribution from clad discontinuity stresses which is added separately. Table 6-2 shows the applied J-Integral values for both the axial and circumferential flaws. It is seen that applied J-Integral values are considerably lower than those for event 24 in Level C loading. The main reason is that the pressure loading, which provides the largest contribution to the K and J values, is very low when the thermal K values reach a maximum.

The BWR/2 K and $J_{applied}$ values would be slightly higher than those shown in Figure 6-9 and Table 6-2, because the stresses and the 1/10t flaw depth are both slightly larger. This is discussed further in the next section.

6.2.3 Acceptance Criteria Evaluation

The material J-R curves to be used for the evaluation of Level D loadings are those based on the best estimate or the mean values. Figure 6-10 shows the comparison of applied J-Integral value at 0.1 inch crack extension for the axial flaw case, and the J-R curve for SA302B at a USE value of 35 ft-lb. It is seen that the criterion of stable and ductile flaw growth for Level D loadings is easily satisfied with USE of 35 ft-lb, so Level D acceptance criteria are satisfied, and are less limiting than the Level A,B USE requirements.

The BWR/3-6 conclusions are also applicable to the BWR/2 case because the applied J-Integral values in Table 6-2 would not change significantly for the BWR/2 1/10t flaw depth of 0.93 inches, compared to the BWR/3-6 flaw depth of 0.81 inches. The BWR/2 $J_{applied}$ values would have to be triple those of the BWR/3-6 analysis to approach the Level D J-R curve, and that is not the case.

6.3 Summary of Level C and D Loadings Evaluation

For the evaluation of Level C loadings, two limiting transients were analyzed, one each for the BWR/2 and BWR/3-6 cases. For the evaluation of Level D loadings, the recirculation line break transient was analyzed. The evaluation results showed that the USE requirements based on the Level C and D criteria of the Code Case are lower than those required by the criteria for Level A and B loadings. Thus, the Level C and D loadings are not governing in terms of USE requirements.

6.4 References

[6-1] ANSYS Computer Program, Version 4.1, Swanson Analysis Systems, Inc.

[6-2] Ranganath, S., "Fracture Mechanics Evaluation of a Boiling Water Reactor Vessel Following a Postulated Loss of Coolant Accident," Paper No. G 1/5, Transaction of the 5th SMiRT Conference, 1979.

[6-3] Raju, I.S. and Newman, J.C., "Stress-Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical Vessels," PVP-Volume 58, 1982.

[6-4] H. Tada and P.C. Paris, "The Stress Analysis of Cracks Handbook," Del Research Corporation, 1985.

TABLE 6-1a

Applied J-Integral Values for BWR/2 Case and Transient 23

EMERGENCY CONDITION EVENT 23, BWR/2

PRESSURE(PSI)=	170	Kt FIT COEFFICIENTS		CLAD STRESS	
VESSEL Ri (IN)=	106.7	a=	8.065965		
VESSEL TH (IN)=	7.125	b=	65.29311	S (KSI)=	6.1
CLAD THICKNESS=	0.2187	c=	-67.7254		
a0 (IN)=	[illegible]	d=	34.12458		
E(KSI)=	27700	e=	-6.80584		
YS (KSI)=	69				

AXIAL FLAW

a	F1	Kt	Kp	K,clad	ae	F1'	Kt'	Kp'	K',clad	Ktotal	Japp
0.93	1.00	32.58	4.64	2.16	0.95	1.00	32.68	4.69	2.14	39.50	51.26
0.98	1.00	32.86	4.77	2.10	1.00	1.00	32.95	4.82	2.08	39.84	52.14
1.03	1.00	33.10	4.90	2.04	1.05	1.00	33.18	4.95	2.02	40.15	52.96
1.08	1.01	33.32	5.03	1.99	1.10	1.01	33.39	5.08	1.97	40.44	53.72
1.13	1.01	33.51	5.16	1.94	1.15	1.01	33.58	5.20	1.92	40.70	54.43
1.18	1.01	33.69	5.28	1.89	1.20	1.01	33.75	5.33	1.87	40.95	55.09
1.23	1.01	33.84	5.41	1.85	1.25	1.01	33.90	5.45	1.83	41.18	55.71
1.28	1.01	33.98	5.53	1.81	1.30	1.02	34.02	5.57	1.79	41.39	56.29
1.33	1.02	34.10	5.65	1.77	1.35	1.02	34.14	5.70	1.76	41.59	56.82
1.38	1.02	34.20	5.77	1.74	1.40	1.02	34.23	5.82	1.72	41.77	57.31
1.43	1.02	34.27	5.89	1.70	1.45	1.02	34.30	5.94	1.69	41.92	57.74
1.48	1.03	34.33	6.01	1.67	1.50	1.03	34.34	6.05	1.66	42.05	58.10
1.53	1.03	34.35	6.13	1.64	1.55	1.03	34.35	6.17	1.63	42.15	58.38
1.58	1.03	34.34	6.24	1.61	1.60	1.03	34.33	6.29	1.60	42.22	58.56
1.63	1.03	34.29	6.36	1.59	1.65	1.04	34.26	6.41	1.58	42.25	58.63
1.68	1.04	34.20	6.48	1.56	1.70	1.04	34.15	6.53	1.55	42.22	58.56
1.73	1.04	34.05	6.60	1.54	1.75	1.04	33.97	6.64	1.53	42.14	58.34
1.78	1.04	33.83	6.71	1.51	1.80	1.05	33.73	6.76	1.50	41.99	57.93
1.83	1.05	33.54	6.83	1.49	1.85	1.05	33.41	6.88	1.48	41.76	57.30
1.88	1.05	33.17	6.95	1.47	1.90	1.05	33.00	6.99	1.46	41.45	56.44
1.93	1.06	32.69	7.06	1.45	1.95	1.06	32.48	7.11	1.44	41.03	55.32

WORKSHEET: BWROGUS2.WK1

CIRCUMFERENTIAL FLAW

a	F1	Kt	Kp	K,clad	ae	F1'	Kt'	Kp'	K',clad	Ktotal	Japp
0.93	0.92	32.58	2.27	2.16	0.95	0.92	32.67	2.29	2.14	37.10	45.22
0.98	0.92	32.86	2.34	2.10	1.00	0.92	32.94	2.36	2.08	37.37	45.89
1.03	0.93	33.10	2.40	2.04	1.05	0.93	33.17	2.42	2.02	37.62	46.49
1.08	0.93	33.32	2.47	1.99	1.10	0.93	33.38	2.49	1.97	37.84	47.05
1.13	0.93	33.51	2.53	1.94	1.15	0.93	33.57	2.55	1.92	38.04	47.55
1.18	0.93	33.69	2.59	1.89	1.20	0.93	33.74	2.61	1.88	38.23	48.01
1.23	0.94	33.84	2.65	1.85	1.25	0.94	33.89	2.67	1.83	38.40	48.44
1.28	0.94	33.98	2.72	1.81	1.30	0.94	34.02	2.74	1.80	38.55	48.82
1.33	0.94	34.10	2.78	1.77	1.35	0.94	34.13	2.80	1.76	38.68	49.16
1.38	0.94	34.20	2.83	1.74	1.40	0.94	34.22	2.85	1.72	38.80	49.46
1.43	0.95	34.27	2.89	1.70	1.45	0.95	34.29	2.91	1.69	38.90	49.71
1.48	0.95	34.33	2.95	1.67	1.50	0.95	34.34	2.97	1.66	38.97	49.89
1.53	0.95	34.35	3.01	1.64	1.55	0.95	34.35	3.03	1.63	39.01	50.00
1.58	0.95	34.34	3.07	1.61	1.60	0.95	34.33	3.09	1.60	39.02	50.02
1.63	0.96	34.29	3.12	1.59	1.65	0.96	34.27	3.14	1.58	38.99	49.94
1.68	0.96	34.20	3.18	1.56	1.70	0.96	34.15	3.20	1.55	38.91	49.73
1.73	0.96	34.05	3.24	1.54	1.75	0.96	33.98	3.26	1.53	38.77	49.37
1.78	0.96	15.87	3.29	1.51	1.79	0.97	33.81	3.30	1.51	38.62	48.99
1.83	0.97	14.40	3.35	1.49	1.84	0.97	33.51	3.35	1.49	38.36	48.34
1.88	0.97	12.70	3.40	1.47	1.88	0.97	33.14	3.41	1.47	38.01	47.47
1.93	0.97	10.73	3.46	1.45	1.93	0.97	32.66	3.46	1.45	37.57	46.38

TABLE 6-1b

Applied J-Integral Values for BWR/3-6 Case and Transient 24

EMFRGENCY CONDITION EVENT 24

PRESSURE(PSI)=	1050	Kt FIT COEFFICIENTS		CLAD STRESS	
VESSEL Ri (IN)=	126.7	a=	8.831288		
VESSEL TH (IN)=	6.19	b=	74.92595	S (KSI)=	6
CLAD THICKNESS=	0.19	c=	-107.681		
a0 (IN)=	0.809	[illegible]	63.6289		
E(KSI)=	27700		-14.3416		
YS (KSI)=	69				

AXIAL FLAW

a	F1	Kt	Kp	K,clad	ae	F1'	Kt'	Kp'	K',clad	Ktotal	Japp
0.81	1.00	26.52	35.91	1.98	0.86	1.00	26.28	36.99	1.92	65.19	139.62
0.86	1.00	26.26	37.08	1.91	0.91	1.00	25.98	38.18	1.86	66.01	143.15
0.91	1.00	25.96	38.23	1.85	0.96	1.01	25.65	39.34	1.80	66.79	146.54
0.96	1.01	25.64	39.37	1.80	1.01	1.01	25.30	40.48	1.75	67.53	149.82
1.01	1.01	25.30	40.48	1.75	1.06	1.01	24.94	41.60	1.70	68.25	153.02
1.06	1.01	24.95	41.59	1.70	1.11	1.01	24.57	42.72	1.66	68.94	156.16
1.11	1.01	24.58	42.68	1.66	1.16	1.02	24.19	43.82	1.62	69.62	159.25
1.16	1.02	24.21	43.76	1.62	1.21	1.02	23.79	44.91	1.58	70.29	162.29
1.21	1.02	23.82	44.83	1.58	1.26	1.02	23.39	46.00	1.55	70.93	165.27
1.26	1.02	23.43	45.89	1.55	1.31	1.03	22.96	47.07	1.51	71.54	168.15
1.31	1.03	23.01	46.95	1.52	1.37	1.03	22.50	48.14	1.48	72.13	170.91
1.36	1.03	22.57	48.00	1.49	1.42	1.03	22.01	49.21	1.45	72.67	173.49
1.41	1.03	22.09	49.04	1.46	1.47	1.04	21.46	50.27	1.43	73.16	175.83
1.46	1.04	21.56	50.09	1.43	1.52	1.04	20.85	51.33	1.40	73.58	177.86
1.51	1.04	20.97	51.13	1.41	1.57	1.05	20.15	52.39	1.38	73.92	179.50
1.56	1.05	20.30	52.17	1.38	1.62	1.05	19.36	53.44	1.35	74.15	180.64
1.61	1.05	19.54	53.21	1.36	1.67	1.06	18.44	54.49	1.33	74.26	181.18
1.66	1.05	18.66	54.25	1.34	1.72	1.06	17.38	55.54	1.31	74.23	181.02
1.71	1.06	17.64	55.30	1.32	1.77	1.06	16.16	56.58	1.29	74.03	180.05
1.76	1.06	16.45	56.34	1.30	1.82	1.07	14.74	57.62	1.27	73.64	178.15
1.81	1.07	15.08	57.39	1.28	1.87	1.07	13.12	58.66	1.26	73.03	175.22

WORKSHEET: BWROGUS2.WK1

CIRCUMFERENTIAL FLAW

a	F1	Kt	Kp	K,clad	ae	F1'	Kt'	Kp'	K',clad	Ktotal	Japp
0.81	0.92	26.52	17.33	1.98	0.83	0.92	26.40	17.60	1.95	45.95	69.36
0.86	0.92	26.26	17.90	1.91	0.88	0.93	26.12	18.17	1.88	46.18	70.06
0.91	0.93	25.96	18.47	1.85	0.93	0.93	25.81	18.74	1.83	46.38	70.66
0.96	0.93	25.64	19.03	1.80	0.98	0.93	25.48	19.29	1.77	46.55	71.18
1.01	0.93	25.30	19.58	1.75	1.03	0.93	25.13	19.84	1.73	46.70	71.64
1.06	0.93	24.95	20.12	1.70	1.08	0.94	24.77	20.38	1.68	46.83	72.04
1.11	0.94	24.58	20.65	1.66	1.13	0.94	24.40	20.91	1.64	46.95	72.41
1.16	0.94	24.21	21.17	1.62	1.18	0.94	24.02	21.43	1.60	47.05	72.74
1.21	0.94	23.82	21.69	1.58	1.23	0.95	23.63	21.95	1.57	47.14	73.02
1.26	0.95	23.43	22.21	1.55	1.28	0.95	23.22	22.46	1.53	47.22	73.24
1.31	0.95	23.01	22.72	1.52	1.33	0.95	22.79	22.97	1.50	47.26	73.39
1.36	0.95	22.57	23.22	1.49	1.38	0.95	22.33	23.47	1.47	47.28	73.43
1.41	0.96	22.09	23.72	1.46	1.43	0.96	21.83	23.97	1.45	47.25	73.34
1.46	0.96	21.56	24.22	1.43	1.48	0.96	21.27	24.47	1.42	47.16	73.07
1.51	0.96	20.97	24.72	1.41	1.53	0.96	20.65	24.96	1.39	47.00	72.58
1.56	0.97	20.30	25.21	1.38	1.58	0.97	19.94	25.45	1.37	46.76	71.83
1.61	0.97	19.54	25.70	1.36	1.63	0.97	19.13	25.93	1.35	46.41	70.75
1.66	0.97	18.66	26.18	1.34	1.68	0.97	18.19	26.41	1.33	45.93	69.31
1.71	0.98	17.64	26.67	1.32	1.73	0.98	17.11	26.89	1.31	45.31	67.44
1.76	0.98	16.45	27.15	1.30	1.78	0.98	15.86	27.37	1.29	44.52	65.10
1.81	0.98	15.08	27.63	1.28	1.83	0.98	14.42	27.84	1.27	43.53	62.24

TABLE 6-2

Applied J-Integral Values for BWR/3-6 LOCA Transient 27

FAULTED CONDITION EVENT 27							
PRESSURE(PSI)=	20		Kt FIT COEFFICIENTS			CLAD STRESS	
VESSEL Ri (IN)=	126.7		a=	14.00964			
VESSEL TH (IN)=	6.19		b=	130.9087		S (KSI)=	16.5
CLAD THICKNESS=	0.19		c=	-155.726			
a0 (IN)=	0.809		d=	89.8447			
E(KSI)=	27700		e=	-20.6397			
YS (KSI)=	69						

AXIAL FLAW

a	F1	Kt	Kp	K,clad	ae	F1'	Kt'	Kp'	K',clad	Ktotal	Japp
0.81	1.00	56.72	0.68	5.44	0.85	1.00	57.20	0.70	5.28	63.19	131.17
0.86	1.00	57.26	0.71	5.26	0.90	1.00	57.67	0.73	5.11	63.51	132.53
0.91	1.00	57.72	0.73	5.10	0.95	1.01	58.08	0.75	4.96	63.79	133.67
0.96	1.01	58.12	0.75	4.95	1.00	1.01	58.42	0.77	4.82	64.02	134.63
1.01	1.01	58.45	0.77	4.81	1.05	1.01	58.72	0.79	4.69	64.20	135.42
1.06	1.01	58.74	0.79	4.68	1.10	1.01	58.97	0.81	4.58	64.35	136.06
1.11	1.01	58.99	0.81	4.57	1.16	1.02	59.17	0.83	4.47	64.47	136.53
1.16	1.02	59.18	0.83	4.46	1.21	1.02	59.32	0.85	4.36	64.54	136.83
1.21	1.02	59.33	0.85	4.36	1.26	1.02	59.42	0.87	4.27	64.56	136.93
1.26	1.02	59.42	0.87	4.26	1.31	1.03	59.45	0.89	4.18	64.53	136.78
1.31	1.03	59.45	0.89	4.17	1.36	1.03	59.41	0.91	4.10	64.42	136.34
1.36	1.03	59.41	0.91	4.09	1.41	1.03	59.28	0.93	4.02	64.23	135.55
1.41	1.03	59.27	0.93	4.01	1.45	1.04	59.05	0.95	3.94	63.94	134.33
1.46	1.04	59.02	0.95	3.94	1.50	1.04	58.69	0.97	3.87	63.53	132.60
1.51	1.04	58.65	0.97	3.87	1.55	1.05	58.18	0.99	3.81	62.98	130.29
1.56	1.05	58.11	0.99	3.80	1.60	1.05	57.49	1.01	3.74	62.25	127.31
1.61	1.05	57.40	1.01	3.74	1.65	1.05	56.61	1.03	3.69	61.33	123.57
1.66	1.05	56.47	1.03	3.68	1.70	1.06	55.51	1.05	3.63	60.19	119.01
1.71	1.06	55.30	1.05	3.62	1.75	1.06	54.15	1.07	3.58	58.79	113.56
1.76	1.06	53.84	1.07	3.56	1.80	1.07	52.51	1.09	3.52	57.12	107.19
1.81	1.07	52.05	1.09	3.51	1.84	1.07	50.55	1.11	3.48	55.14	99.87

WORKSHEET: BWROGUS2.WK1

CIRCUMFERENTIAL FLAW

a	F1	Kt	Kp	K,clad	ae	F1'	Kt'	Kp'	K',clad	Ktotal	Japp
0.81	0.92	56.72	0.33	5.44	0.85	0.92	57.20	0.34	5.28	62.82	129.65
0.86	0.92	57.26	0.34	5.26	0.90	0.93	57.67	0.35	5.12	63.14	130.96
0.91	0.93	57.72	0.35	5.10	0.95	0.93	58.07	0.36	4.96	63.40	132.05
0.96	0.93	58.12	0.36	4.95	1.00	0.93	58.42	0.37	4.82	63.62	132.96
1.01	0.93	58.45	0.37	4.81	1.05	0.93	58.72	0.38	4.70	63.79	133.70
1.06	0.93	58.74	0.38	4.68	1.10	0.94	58.96	0.39	4.58	63.93	134.29
1.11	0.94	58.99	0.39	4.57	1.15	0.94	59.17	0.40	4.47	64.04	134.71
1.16	0.94	59.18	0.40	4.46	1.20	0.94	59.32	0.41	4.37	64.10	134.97
1.21	0.94	59.33	0.41	4.36	1.25	0.95	59.42	0.42	4.27	64.11	135.02
1.26	0.95	59.42	0.42	4.26	1.30	0.95	59.45	0.43	4.18	64.07	134.84
1.31	0.95	59.45	0.43	4.17	1.35	0.95	59.41	0.44	4.10	63.95	134.36
1.36	0.95	59.41	0.44	4.09	1.40	0.96	59.29	0.45	4.02	63.76	133.54
1.41	0.96	59.27	0.45	4.01	1.45	0.96	59.05	0.46	3.94	63.46	132.29
1.46	0.96	59.02	0.46	3.94	1.50	0.96	58.69	0.47	3.87	63.04	130.54
1.51	0.96	58.65	0.47	3.87	1.55	0.97	58.18	0.48	3.81	62.47	128.21
1.56	0.97	58.11	0.48	3.80	1.60	0.97	57.51	0.49	3.75	61.74	125.22
1.61	0.97	57.40	0.49	3.74	1.65	0.97	56.63	0.50	3.69	60.81	121.49
1.66	0.97	18.66	0.50	3.68	1.66	0.97	56.35	0.50	3.67	60.52	120.32
1.71	0.98	17.64	0.51	3.62	1.71	0.98	55.16	0.51	3.61	59.28	115.44
1.76	0.98	16.45	0.52	3.56	1.76	0.98	53.68	0.52	3.56	57.76	109.60
1.81	0.98	15.08	0.53	3.51	1.81	0.98	51.89	0.53	3.51	55.93	102.75

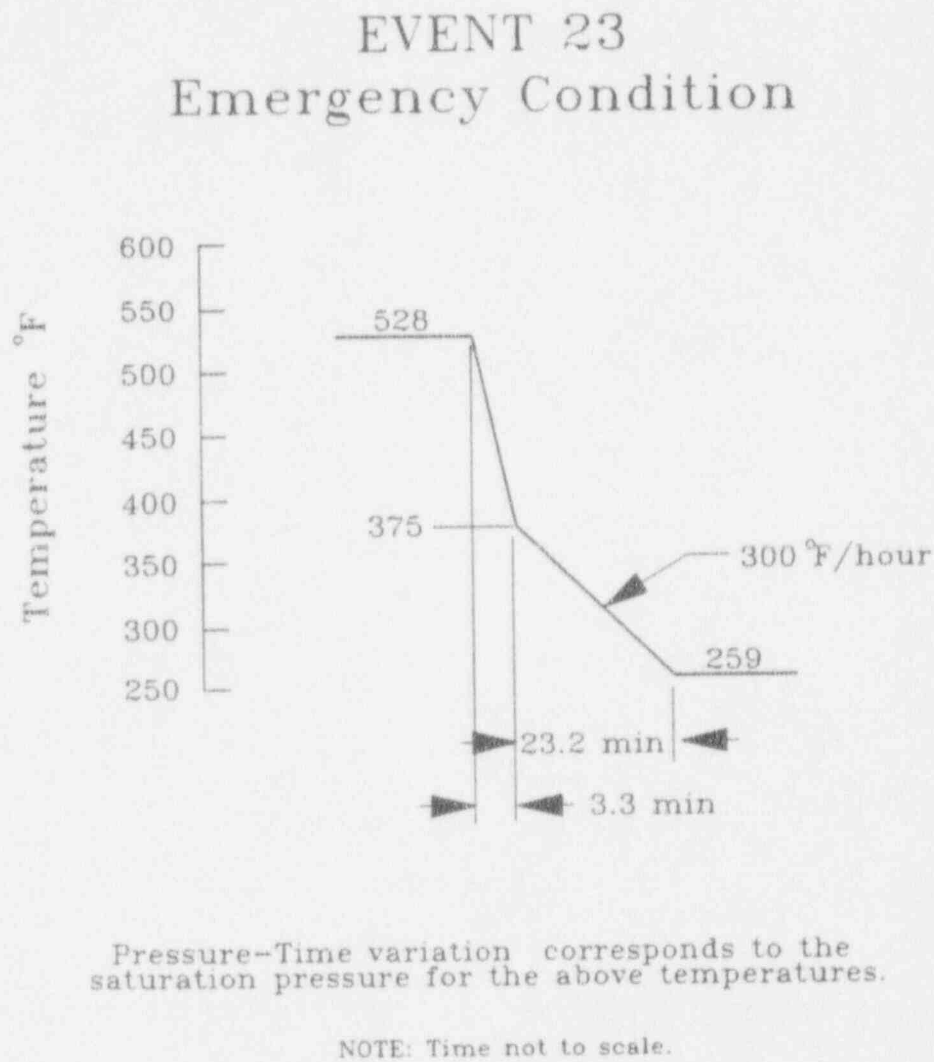

Figure 6-1 Pressure and Temperature Conditions During Automatic Blowdown Transient (Event 23)

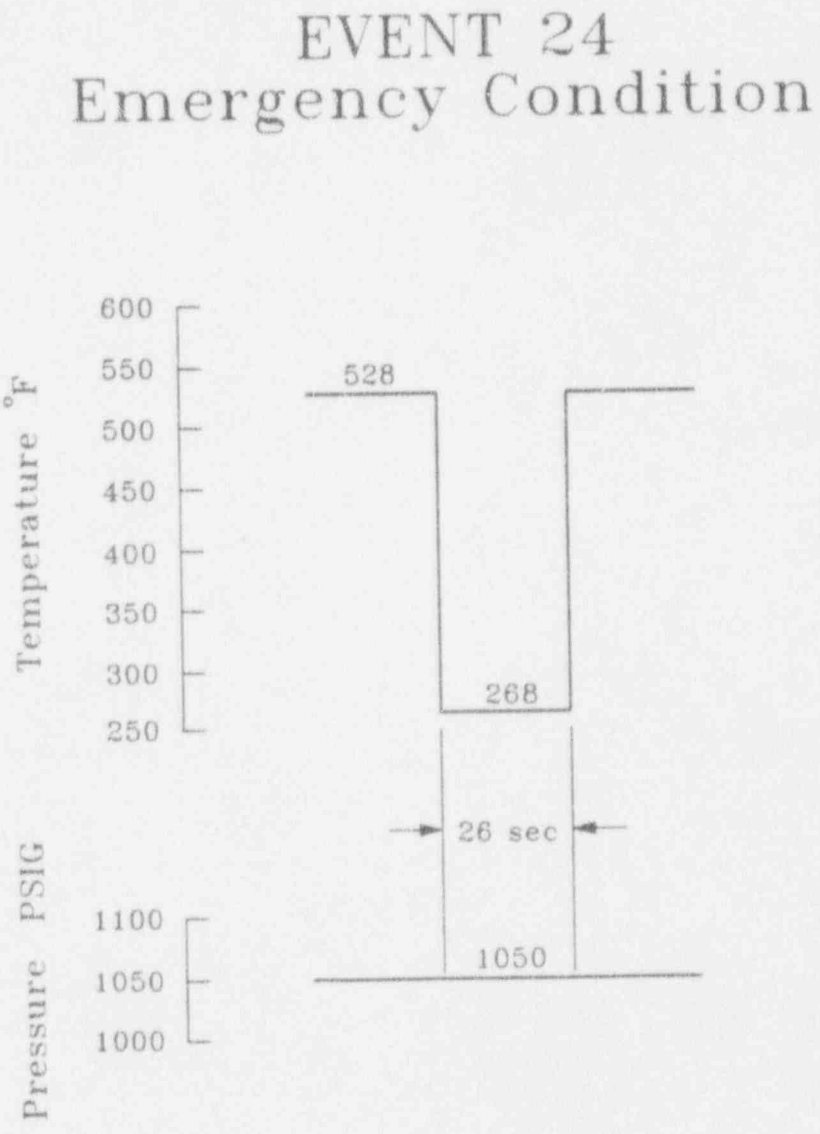

Figure 6-2 Pressure and Temperature Conditions During Improper Start of Cold Recirculation Loop Transient (Event 24)

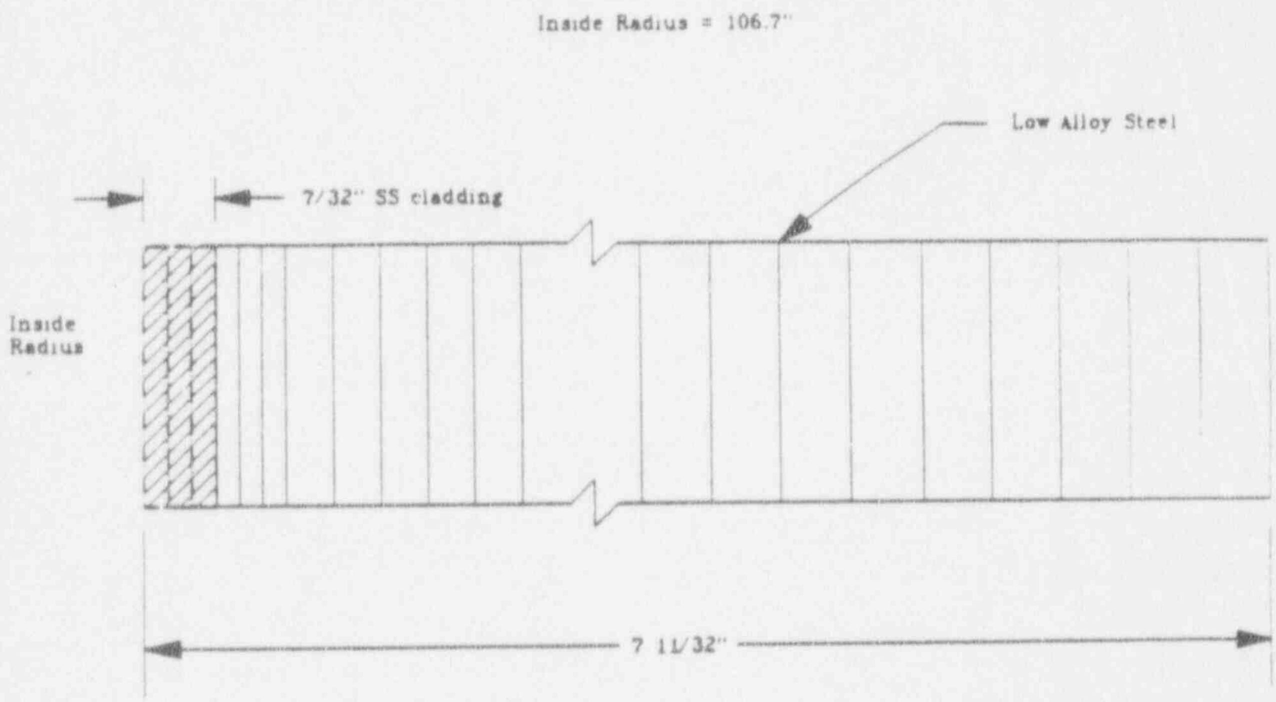

Figure 6-3 Axisymmetric Finite Element Model for BWR/2 Geometry

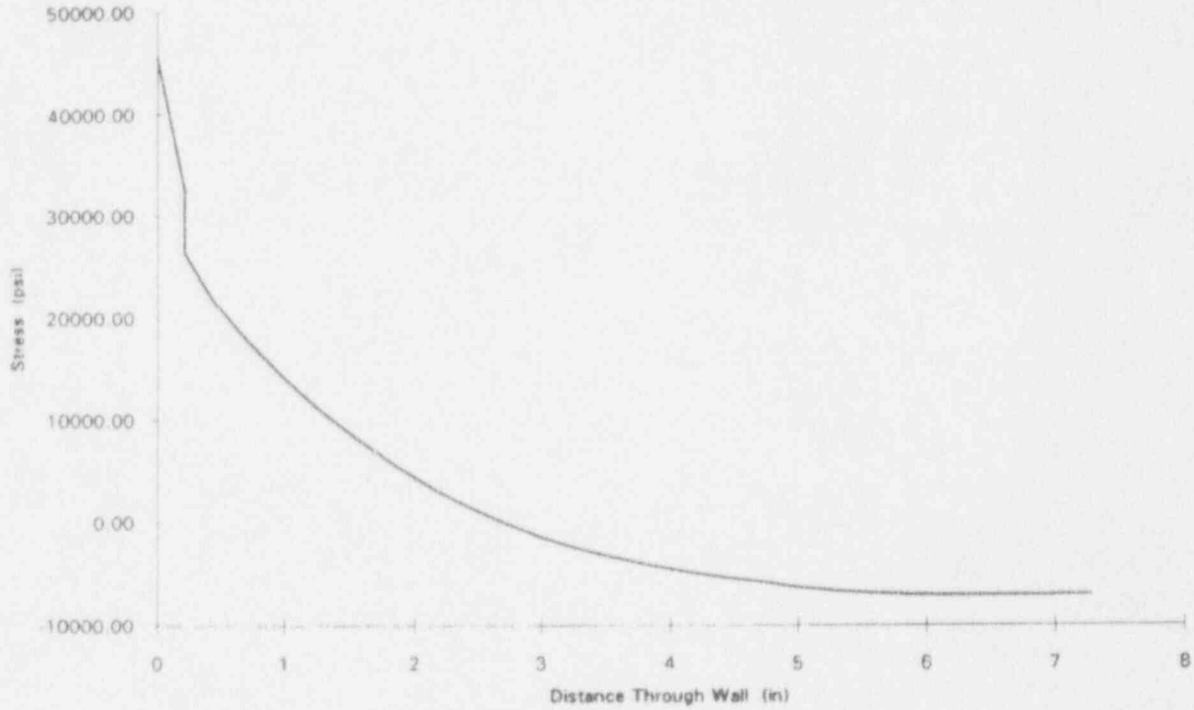

Figure 6-4a Throughwall Circumferential Stress for Event 23 (BWR/2)

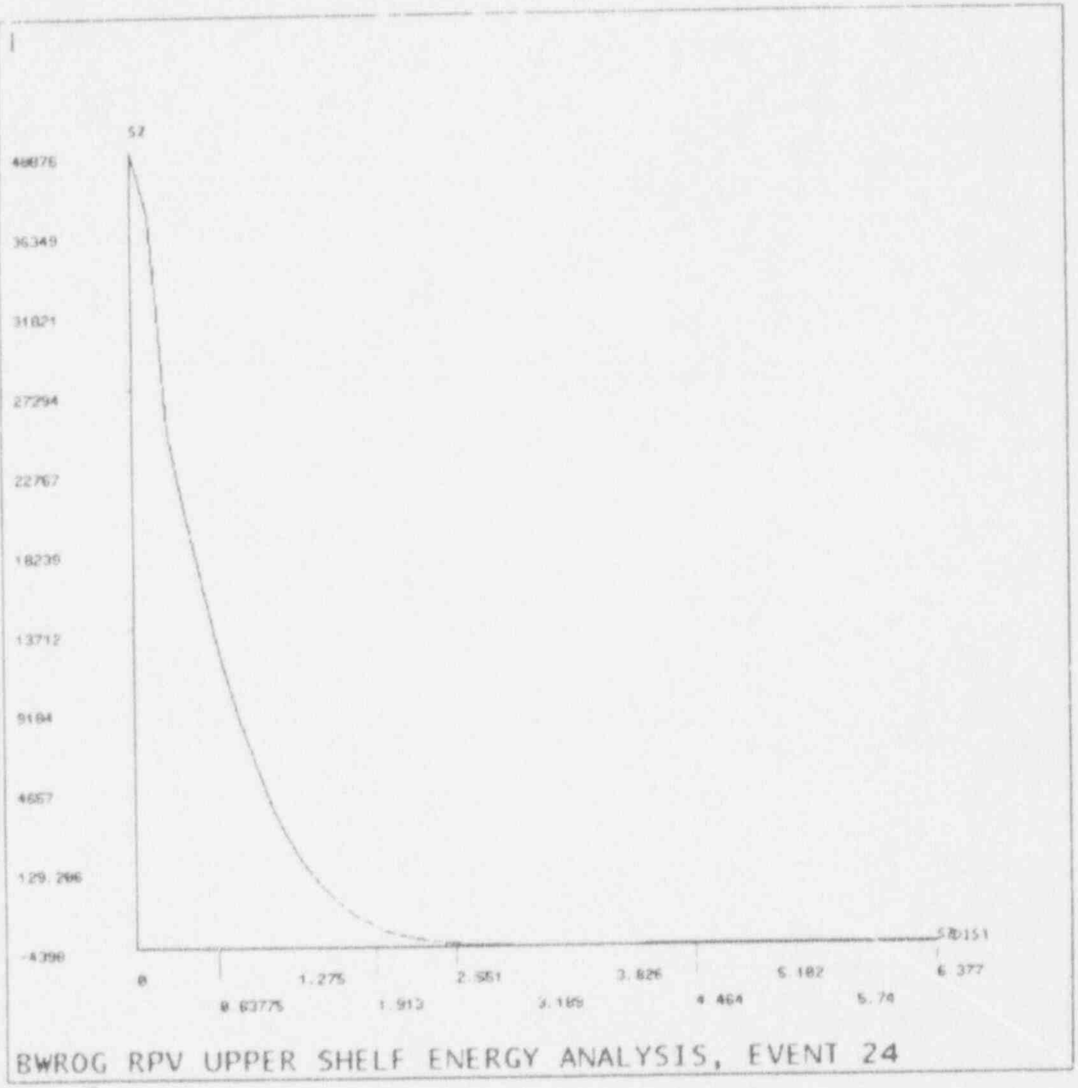

Figure 6-4b Throughwall Circumferential Stress for Event 24 (BWR/3-6)

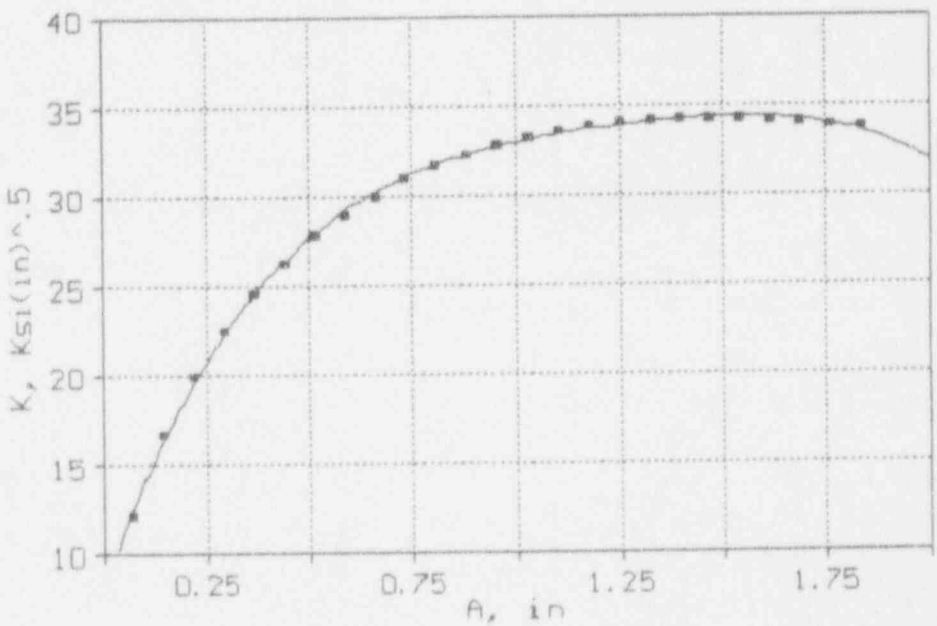

Figure 6-5a Raju-Newman K Values for Stress Distribution in Figure 6-4a

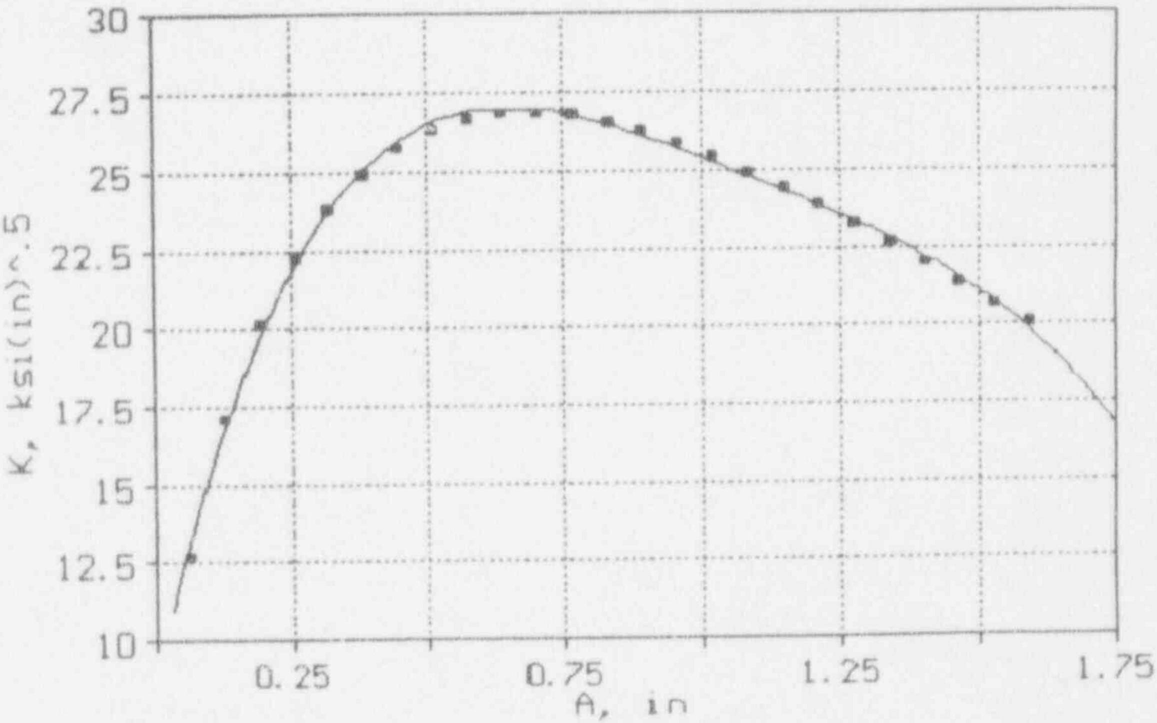

Figure 6-5b Raju-Newman K Values for Stress Distribution in Figure 6-4b

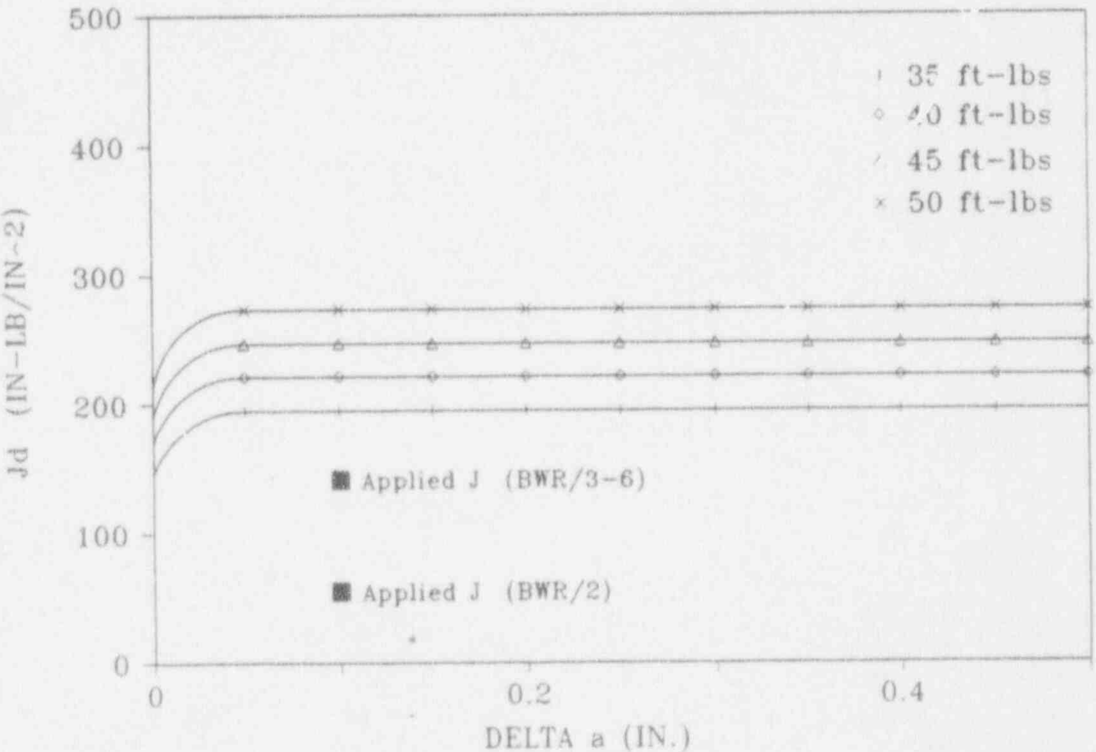

Figure 6-6 Applied Axial Flaw $J_{0.1}$ Values for Level C and SA302B J-R Curves

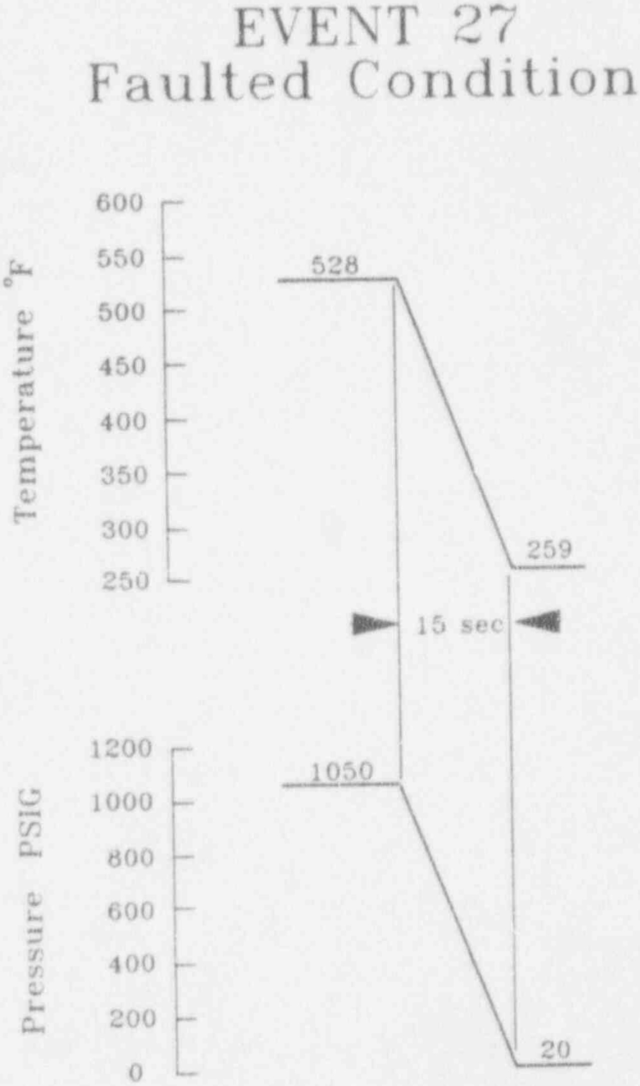

Figure 6-7 Limiting Level D Transient (Event 27)

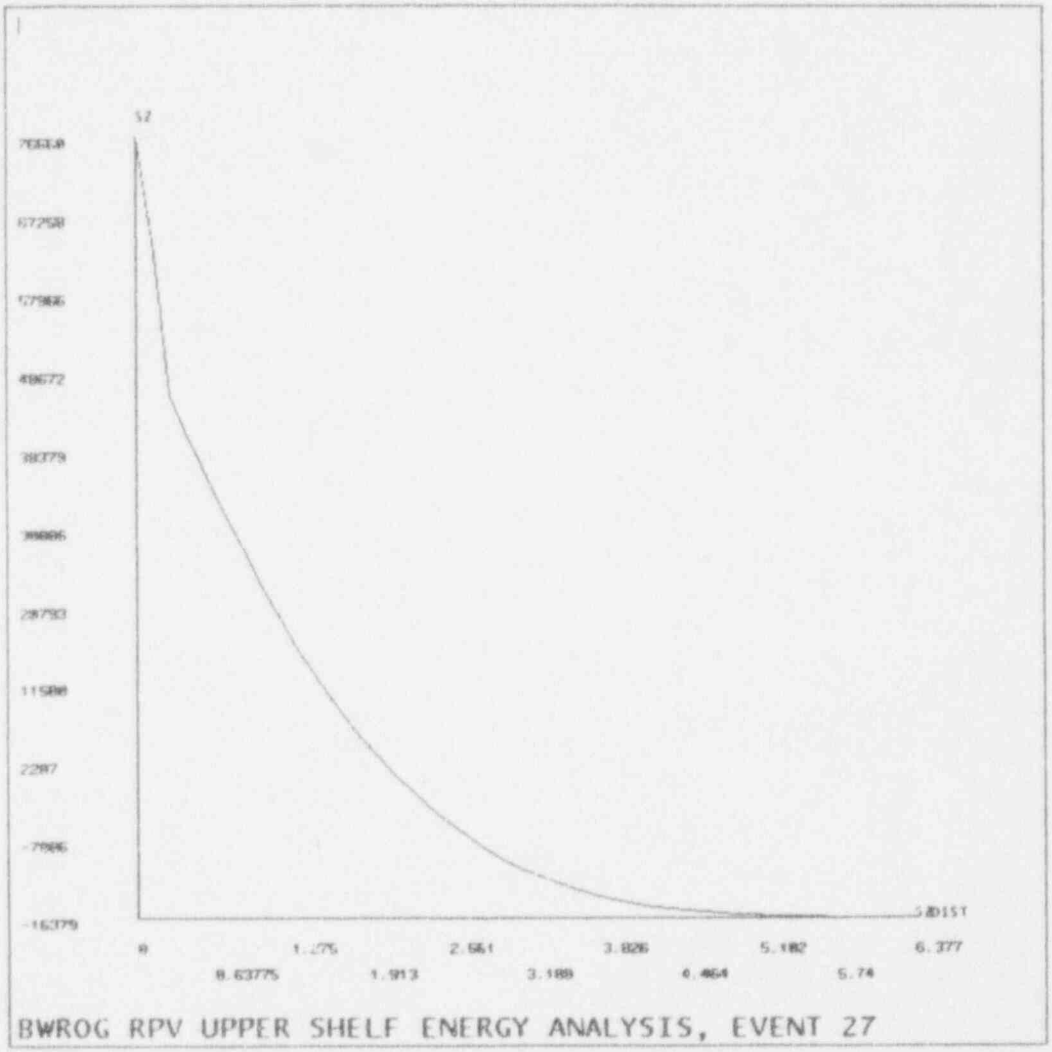

Figure 6-8 Circumferential Thermal Stress Distribution for BWR/3-6 at Limiting Transient Time

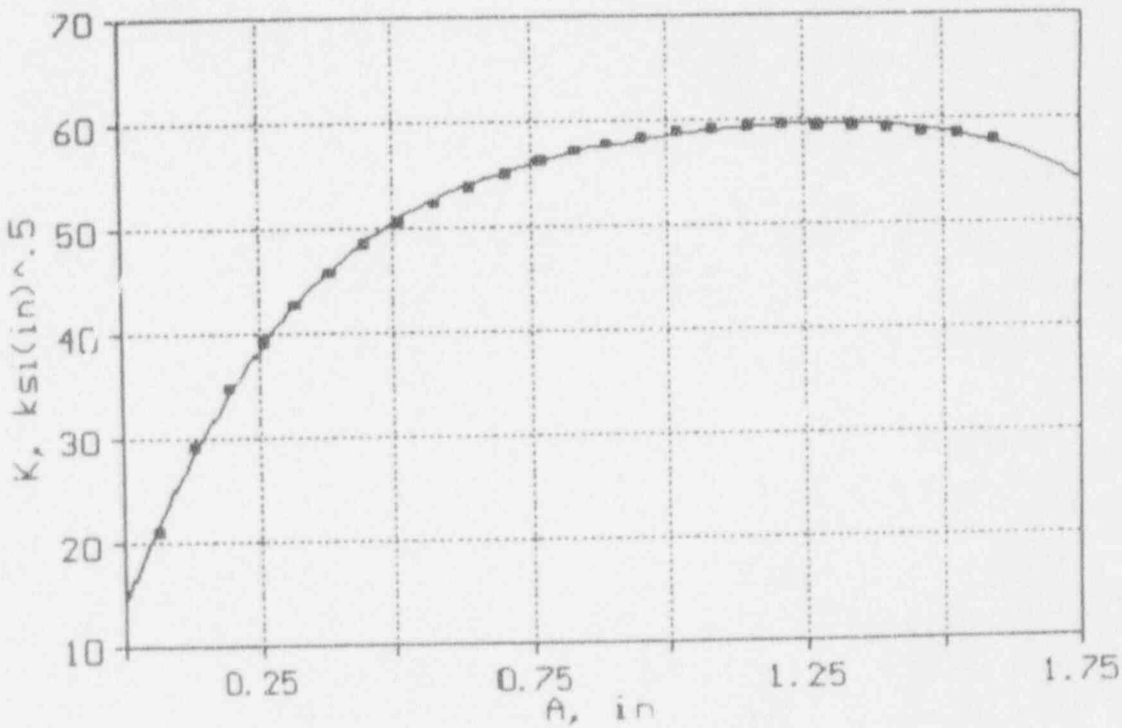

Figure 6-9 Raju-Newman K Values for Stress Distribution in Figure 6-8

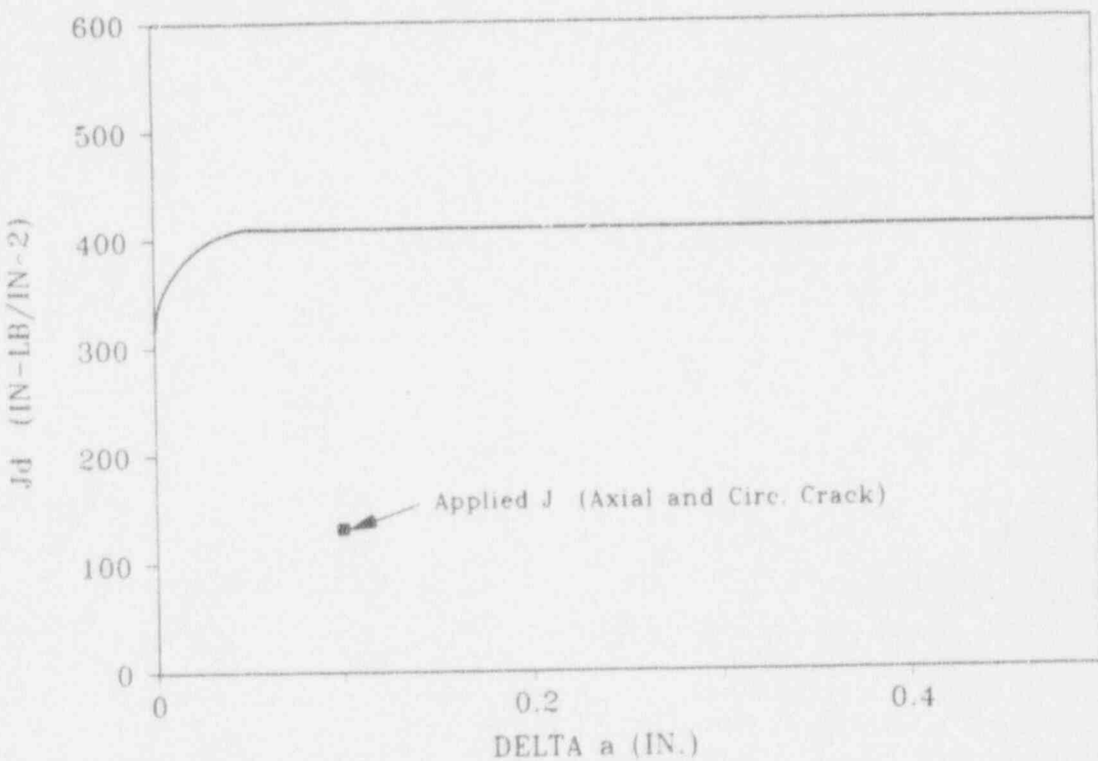

Figure 6-10 BWR/3-6 $J_{applied}$ for Level D and Mean SA302B J-R Curve for CVN of 35 ft-lb

7.0 SUMMARY OF MINIMUM USE REQUIREMENTS

Table 5-3 presented the minimum USE requirements for various plate and weld categories based on the Level A and B loadings criteria of the Code Case. The evaluation in Section 6 showed that the USE requirements for Level C and D loadings are lower than those for Levels A and B. Thus, the minimum USE requirements presented in Table 5-3 are governing for all service level loadings.

An inspection of Table 5-3 shows that the highest required USE, 59 ft-lb, is for a BWR/3-6 plate, based on the SA302B material J-R curves, which are believed to be very conservative. This USE value could be shown to be significantly lower once future fracture toughness testing of representative SA302B modified materials bear out the conservative nature of the SA302B J-R curve. However, for purposes of demonstrating equivalent margin in Section 8, the conservative USE of 59 ft-lb is taken as the allowable for BWR/3-6 plates.

Section 8 compares the USE requirements from Table 5-3 with the projected 32 EFPY USE values for the beltline plates and welds of the U.S. BWR/2-6 vessels.

8.0 BOUNDING NATURE OF ANALYSIS

The equivalent margin analysis presented in the previous sections establishes the minimum USE limits for BWR/2-6 vessel beltline materials. The purpose of this section of the report is to demonstrate, for all U.S. BWR/2-6 vessels, that the USE values predicted for the BWR vessel materials will, for 32 EFPY of operation, remain higher than the allowable USE limits, as required in 10CFR50 Appendix G.

In evaluating the BWR USE data, it is clear that the BWR/2 vessel plate materials should be evaluated separately, for two reasons:

All USE data for the BWR/2 beltline plates are available, so a comprehensive evaluation can be done. This is not the case for the BWR/3-6 plates, where a statistical approach is used.

The melting practice used in fabricating the BWR/2 plates was different from that used for the BWR/3-6 plates, resulting in significantly lower initial USE values.

The allowable BWR/2 longitudinal USE, 50 ft-lb from Table 5-3, is considerably lower than that for the BWR/3-6 plates, 59 ft-lb.

USE data and fabrication practices indicate no significant difference in weld properties for any of the BWR types, but there were several different types of welding done. Specifically, submerged arc welds (SAW), including some Linde 80 welds, shielded metal arc welds (SMAW) and electroslag welds (ESW) are evaluated in this section against the allowable USE limits for welds.

8.1 BWR/2 Plate Materials

The BWR/2 beltline shells consist of SA302B Modified plate, except for one plant which also has two plates (one heat) of SA302B plate. The plates were manufactured for

Combustion Engineering (CE) by Lukens Steel around 1964. The manufacturing date and vessel fabricator are significant for two reasons:

> Just after 1964, Lukens began to melt heats of steel in electric furnaces. Up to 1964, the melting practice used open hearth furnaces, which tended to cause inclusion of more impurities, such as manganese sulfide, in the heats. The furnace type can be determined from the heat number: heats beginning with P or T were open hearth heats. Heat numbers beginning with A, B or C were electric furnace heats (Lukens used three electric furnaces designated A, B and C). The heat numbers for the BWR/2 beltline plates start with P for the SA302B modified and with T for the SA302B, indicating the use of open hearth furnaces.
>
> All BWR/2 vessels were fabricated by CE, and it was CE's practice from the beginning to provide full Charpy curve data for the vessel materials. Therefore, initial USE data (longitudinal) for all BWR/2 beltline plates are known. The USE values, based on the average of two or three data, range from 76 ft-lb to 106 ft-lb.

Table 8-1 has a summary of the information needed to evaluate USE at 32 EFPY for all U.S. BWR/2-6 vessels. The information consists of the peak 1/4t fluence at 32 EFPY and the maximum plate and weld copper in each vessel's beltline. From these data the percent decrease is determined according to Figure 2 of R.G. 1.99. The results in the table show the maximum R.G. 1.99 decrease in USE for BWR/2 plates to be 26%.

Figure 8-1 shows the initial USE values for each BWR/2 beltline plate. A line is drawn through the lowest USE, 76 ft-lb. The 32 EFPY decrease in USE of 26%, or 20 ft-lb, is subtracted, leaving 56 ft-lb in the longitudinal direction. Taking 65% of the longitudinal data, per Branch Technical Position MTEB 5-2, and applying the same 26% decrease for irradiation gives a transverse USE at 32 EFPY of 36.5 ft-lb, as shown in Figure 8-2. These USE values compare to the equivalent margin analysis USE limits as shown:

Orientation	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
Longitudinal	56	$\geq$50	Acceptable
Transverse	36.5	$\geq$35	Acceptable

8.2 BWR/3-6 Plate Materials

The BWR/3-6 plates are SA533 Grade B, Class 1 low alloy steel and its predecessor, SA302B Modified. The plates were fabricated in the period between 1966 and 1974, by Lukens Steel in most cases, for several vessel fabricators. All heats of plate material in the BWR/3-6 vessels were from electric furnaces, as evidenced by the A, B or C designations for the heat numbers. The impurity levels for these plates are lower and, thus, the USE is generally higher. This can be seen in Table 8-2, where available plate USE data for each BWR are summarized.

In Table 8-2, the lowest USE values a BWR/3-6 vessel are at least 12 ft-lb higher than the BWR/2 plate values. In general, the BWR/3-6 plates have about 30 ft-lb higher USE. This appears to be due primarily to the melting practice, and the associated cleanliness of the heat. This is supported by the sulfur content data in Table 8-2, which show the BWR/3-6 plates to be generally lower in sulfur content than the BWR/2 plates.

Another factor may be that the BWR/3-6 plates are not as thick as the BWR/2 plates. The BWR/3-6 plates range in thickness from 4.5 inches to 6.2 inches. The BWR/2 plates are 7.1 inches. An evaluation by CE of plate Charpy data [8-1] showed that 6-8 inch SA533 plates had a 5% to 10% lower USE than 3-6 inch plates.

As mentioned previously, the BWR/3-6 vessels were fabricated by several companies, including CE, Babcock & Wilcox (B&W) and Chicago Bridge & Iron (CB&I). CE continued the practice of recording full Charpy curves for each plate. Unfortunately, for BWR/3, BWR/4 and some BWR/5 plants, B&W and CB&I only recorded the required qualification Charpy data, typically at 10°F or 40°F, so initial USE data are not available for these plants' plates. Figure 8-3 is a plot of all available BWR/3-5 longitudinal plate USE data. BWR/6 data are not included, because by then Charpy tests were done in the transverse orientation.

Figure 8-3 has about 200 USE data points, each point representing the average of 2 or 3 individual Charpy specimen tests on a given heat of material. The data include SA533 and SA302B Modified heats, and were collected from several sources:

> Beltline plate data from CE-fabricated plants,
> Non-beltline data from CE-fabricated plants,
> Surveillance capsule unirradiated baseline plate data from all plants.

Not counting the plants with transverse data, there are 27 BWR/3-5 vessels in the U.S. Eight of these have complete initial USE data, and that data is included in Figure 8-3. However, 22 of the 27 plants are represented in the data base by at least 1 data point, typically baseline data for their surveillance capsule plate. Therefore, the data in Figure 8-3 are expected to be very representative of the initial USE values for the BWR/3-6 beltline plates.

The USE values for each heat of plate in Figure 8-3 are plotted against the corresponding 10°F impact energy values for convenience in presenting the data. The data range from a low USE of 91 ft-lb to a high of 177 ft-lb. The mean and standard deviation of the data base were determined, as follows:

$$\begin{aligned} \text{Mean USE} &= 127 \text{ ft-lb} \\ \sigma &= 15 \text{ ft-lb} \\ \text{Mean-}2\sigma &= 97 \text{ ft-lb (97.7\% confidence)} \\ \text{Mean-}3\sigma &= 82 \text{ ft-lb (99.8\% confidence)} \end{aligned}$$

Since there are data (2 out of 200 points) below the Mean-2σ USE, the lowest value of USE in the data base, 91 ft-lb, is evaluated against the equivalent margin analysis results.

Table 8-1 has the maximum R.G. 1.99 percent decreases in plate USE for each BWR/3-6 vessel, along with the copper and 32 EFPY fluence values which form the basis for the percentage determined. The maximum value for all BWR/3-6 vessels is 21%. Considering the limiting case of 21% effect on USE, the minimum expected longitudinal USE is

(91 ft-lb)*(1-0.21) = <u>72 ft-lb</u> longitudinal

This process is shown graphically in Figure 8-3.

Taking 65% of the longitudinal data, per Branch Technical Position MTEB 5-2, and accounting for the 21% decrease in USE due to irradiation gives a transverse USE of 47 ft-lb, as shown in Figure 8-4. These USE values compare to the minimum USE limits from the equivalent margin analysis as shown:

Orientation	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
Longitudinal	72	≥59	Acceptable
Transverse	47	≥35	Acceptable

It should be noted that even using the Mean-3σ value for initial USE, the results (65 ft-lb longitudinal, 42 ft-lb transverse) are acceptable.

8.3 BWR/2-6 Weld Materials

There is not a significant difference between BWR/2 welds and BWR/3-6 welds, as there was with plates, so BWR/2-6 welds are evaluated together. The three types of welds, SAW, SMAW and ESW are evaluated separately. In addition, the subset of SAW welds with Linde 80 flux, applicable to a few BWRs, is evaluated separately from the other SAW welds.

In order to simplify the analysis, and assure conservative results, the maximum weld USE decrease predicted by R.G. 1.99, due to the combination of copper content and 32 EFPY fluence, is assumed for all weld types. In Table 8-1, that value is 34%, which corresponds to 0.35% Cu and a 32 EFPY fluence of 2.4×10^{18} n/cm^2 for a SAW material. The percent decrease calculated for SMAW or ESW materials would be significantly lower, as Cu and 32 EFPY fluence numbers are lower for the vessels in which these materials were used.

8.3.1 SMAW

SMAW materials were generally used along with SAW, except for a few BWRs which were partially or completely field fabricated, in which cases entire seam welds were done with SMAW. The Cu content values of SMAW welds are quite low, on the order of 0.05%, because the electrodes were flux-coated, not copper-coated.

As with the BWR/3-6 plates, weld USE conditions were not tested by all vessel fabricators, so the data available on SMAW USE are treated statistically as a representative sample. The SMAW USE data are shown in Figure 8-5, plotted against the corresponding 40°F impact energy values for convenience. The data range from a low USE of 95 ft-lb to a high of 184 ft-lb. The mean and standard deviation of the data base were determined, as follows:

Mean USE = 129 ft-lb
σ = 21 ft-lb
Mean-2σ = 87 ft-lb (97.7% confidence)
Mean-3σ = 66 ft-lb (99.8% confidence)

The Mean-2σ USE value is evaluated against the equivalent margin analysis results.

As discussed earlier, the maximum USE decrease of 34% for all BWR/2-6 vessel welds is assumed. Considering a 34% decrease in USE, the minimum expected SMAW USE is

(87 ft-lb)*(1-0.34) = 57 ft-lb

This process is shown graphically in Figure 8-5. The Mean-2σ USE value compares to the required USE limit from the equivalent margin analysis as shown:

Weld Type	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
SMAW	57	≥35[a]	Acceptable

[a] 35 ft-lb is bounding for evaluation of both axial and circumferential flaws

It should be noted that even using the Mean-3σ value for initial USE, the result (44 ft-lb) is acceptable.

8.3.2 ESW

ESW materials were used to weld vertical seams in several BWR/3 and BWR/4 vessels fabricated by B&W. The Cu content values of ESW welds typically cover a range of 0.1% to 0.2%, with one documented value as high as 0.30%. More importantly, the 32 EFPY fluence values in the vessels with ESW are less than $8x10^{17}$ n/cm^2.

Again, USE conditions were not tested by all vessel fabricators, so the data available on ESW USE are treated statistically as a representative sample. The ESW USE data available from BWR vessels are shown in Figure 8-6, plotted against the corresponding 40°F impact energy values for convenience. The data, which are rather scarce because of the Code requirements at the time the vessels were fabricated, consist mainly of surveillance data points from most of the plants with ESW materials. Therefore, while scarce, the data are representative of the ESW in the applicable vessels. The scarcity of data is compensated for in the magnitude of the standard deviation of the data base.

The data range from a low USE of 72 ft-lb to a high of 136 ft-lb. The mean and standard deviation of the data base were determined, as follows:

Mean USE = 104 ft-lb
σ = 17.4 ft-lb
Mean-2σ = 69 ft-lb (97.7% confidence)
Mean-3σ = 52 ft-lb (99.8% confidence)

The Mean-2σ USE value is evaluated against the equivalent margin analysis results.

As discussed earlier, the maximum USE decrease of 34% for all BWR/2-6 vessel welds is assumed. Considering a 34% decrease in USE, the minimum expected ESW USE is

(69 ft-lb)*(1-0.34) = 46 ft-lb

This process is shown graphically in Figure 8-6. The Mean-2σ USE value compares to the required USE limit from the equivalent margin analysis as shown:

Weld Type	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
ESW	46	$\geq$35[a]	Acceptable

[a] 35 ft-lb is bounding for evaluation of both axial and circumferential flaws

It should be noted that even using the Mean-3σ value for initial USE, the result (34 ft-lb) is nearly acceptable. The ESW-specific evaluation is bounded by considering 0.30% Cu and a fluence of $8x10^{17}$ n/cm», which results in a USE decrease of 25%. Thus, for the ESW-specific USE at 32 EFPY, based on the Mean-3σ initial USE, gives 39 ft-lb, which is acceptable.

8.3.3 Non-Linde 80 SAW

SAW was the most widely used welding process for vessel seam weld fabrication. Aside from Linde 80, the flux types used included Arcos B5, Linde 0091, Linde 0124 and Linde 1092. The Cu content values of SAW materials vary considerably, depending on the vessel fabrication date. In cases where the Cu content of a weld was not tested, a default assumption of 0.35% Cu is used. The limiting weld case in Table 8-1 is based on a plant where the fluence is relatively high, $2.4x10^{18}$ n/cm^2, and the Cu content is assumed to be 0.35%. The resulting decrease in USE predicted by R.G. 1.99 is 34%.

Again, USE conditions were not tested by all vessel fabricators, so the data available on SAW USE are treated statistically as a representative sample. The SAW USE data available from BWR vessels, are shown in Figure 8-7, plotted against the corresponding 40°F impact energy values for convenience. The data range from a low USE of 77 ft-lb to a high of 150 ft-lb. The mean and standard deviation of the data base were determined, as follows:

Mean USE $= 108$ ft-lb
$\sigma = 18.5$ ft-lb
Mean-$2\sigma = 71$ ft-lb (97.7% confidence)
Mean-$3\sigma = 52.5$ ft-lb (99.8% confidence)

The Mean-2σ USE value is evaluated against the equivalent margin analysis results.

There is one BWR/4, fabricated by Ishikawajima-Harima Industries (IHI), with Japanese SAW materials. In that plant's FSAR, an extensive discussion and data evaluation was provided to show the equivalency of the Japanese SAW materials to U.S. SAW materials. While the USE data for the circumferential SAW materials is not known, the average impact energy at 10°F, with percent shear of about 60%, is 81 ft-lb. For the longitudinal welds, of most significance, the USE is known, and is 142 ft-lb. Therefore, the evaluation of SAW materials here clearly bounds this BWR/4's Japanese SAW materials.

As discussed earlier, the maximum USE decrease of 34% for all BWR/2-6 vessel welds is assumed. Considering a 34% decrease in USE, the minimum expected SAW USE is

(71 ft-lb)*(1-0.34) = <u>47 ft-lb</u>

This process is shown graphically in Figure 8-7. The Mean-2σ USE value compares to the required USE limit from the equivalent margin analysis as shown:

Weld Type	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
SAW	47	≥35[a]	Acceptable

[a] 35 ft-lb is bounding for evaluation of both axial and circumferential flaws

It should be noted that even using the Mean-3σ value for initial USE, the result (35 ft-lb) is acceptable.

8.3.4 Linde 80 SAW

There are four BWRs, all fabricated by B&W, which have Linde 80 SAW. In these vessels, ESW was used to fabricate the longitudinal welds and Linde 80 SAW was used for the circumferential welds. As it happens, the vessels are low fluence plants, even for BWRs. The 32 EFPY fluence predictions and maximum Cu values for the four plants follow.

Type	% Cu	32 EFPY Fluence (n/cm^2)
BWR/3	0.21	$2.5x10^{17}$
BWR/3	0.29	$3.5x10^{17}$
BWR/3	0.22	$2.4x10^{17}$
BWR/4	0.31	$5.3x10^{17}$

NUREG CR-5729 [2-2] provides a method of establishing the J-R curve for Linde 80 SAW based only on the fluence and Cu content information. This method was used in Section 4 to evaluate the acceptability of the $J_{applied}$ values calculated. In calculating the Linde 80 SAW J-R curve for Section 4, a Cu content of 0.31% and a fluence of $1x10^{18}$ n/cm^2 were used as the basis. In the resulting analysis, the $J_{applied}$ values were shown to be well within the J-R curve limits. Since the basis for the J-R curve used bounds all BWR Linde 80 conditions, the acceptable results are applicable to all BWRs with Linde 80 SAW for evaluation of both axial and circumferential flaws.

8.4 Summary of Evaluation

The lowest predicted values of 32 EFPY USE for all U.S. BWR/2-6 vessels have been compared to the USE values calculated to demonstrate equivalent margin on upper shelf fracture toughness.

> In cases where USE data for all plants were not available, a statistical lower bound USE of Mean-2σ, with a confidence of 97.7%, was taken from the BWR data base.

For plates, the NRC correlation of 65% has been applied to longitudinal USE data to estimate transverse properties.

The decrease in USE due to irradiation, based on Figure 2 of R.G. 1.99, for the most limiting combination of Cu content and 32 EFPY fluence has been applied.

The results, summarized below, are acceptable in all cases. In fact, results using initial USE values of Mean-3σ (99.8% confidence) are acceptable in all cases as well.

BWR Type	Material Type	32 EFPY Predicted USE (ft-lb)	Equiv. Margin Required USE (ft-lb)	Conclusion
BWR/2	Long Plate	56	≥50	Acceptable
BWR/2	Trans Plate	36.5	≥35	Acceptable
BWR/3-6	Long Plate	72	≥59	Acceptable
BWR/3-6	Trans Plate	47	≥35	Acceptable
BWR/2-6	SMAW	57	≥35	Acceptable
BWR/3-4	ESW	46	≥35	Acceptable
BWR/2-6	Non-L80 SAW	47	≥35	Acceptable
BWR/3-4	L80 SAW	Acceptable results for bounding Cu, fluence		

8.5 Reference

[8-1] Ayres, D.J. and Smith, R.E., "Statistical Analysis of Charpy-V Impact Properties SA533 Grade B Class 1 and SA516 Grade 70 Plate Material," Transactions of the ASME, February 1973.

Table 8-1

DATA ON BWR BELTLINE MATERIALS FOR R.G. 1.99 USE EVALUATION

BWR Type	Plate % Cu	Weld % Cu	32 EFPY Fluence	Plate %Decr	Weld %Decr
BWR/2	0.27	0.22	1.8×10^{18}	24.0	24.0
BWR/2	0.27	0.35*	2.4×10^{18}	**26.0**	**34.0**
BWR/3	0.23	0.30	2.5×10^{17}	13.5	19.0
BWR/3	0.24	0.30	3.5×10^{17}	15.0	20.5
BWR/3	0.23	0.26	1.2×10^{18}	20.0	24.5
BWR/3	0.17	0.10	3.8×10^{18}	**21.0**	19.0
BWR/3	0.14	0.35*	1.4×10^{18}	14.5	32.0
BWR/3	0.27	0.30	2.4×10^{17}	15.5	19.0
BWR/3	0.18	0.30	3.4×10^{17}	12.5	20.5
BWR/4	0.15	0.31	5.3×10^{17}	12.0	22.5
BWR/4	0.17	0.28	7.4×10^{17}	14.0	23.0
BWR/4	0.15	0.28	7.4×10^{17}	13.0	23.0
BWR/4	0.15	0.05	1.4×10^{18}	15.0	12.0
BWR/4	0.19	0.06	1.4×10^{18}	18.0	12.5
BWR/4	0.21	0.22	1.5×10^{18}	19.5	23.5
BWR/4	0.15	0.03	3.5×10^{18}	19.0	14.0
BWR/4	0.12	0.32	4.0×10^{17}	10.0	23.0
BWR/4	0.18	0.33	1.7×10^{18}	18.0	32.0
BWR/4	0.17	0.28	1.8×10^{18}	17.5	28.0
BWR/4	0.11	0.23	1.0×10^{18}	11.5	22.0
BWR/4	0.09	0.09	1.2×10^{18}	11.0	14.0
BWR/4	0.12	0.09	1.2×10^{18}	12.5	14.0
BWR/4	0.15	0.09	1.1×10^{18}	14.5	13.5
BWR/4	0.13	0.21	5.5×10^{17}	11.0	18.5
BWR/4	0.15	0.21	5.0×10^{17}	12.0	18.0
BWR/4	0.14	0.04	5.3×10^{17}	11.5	9.0
BWR/4	0.13	0.06	5.3×10^{17}	11.0	10.0
BWR/4	0.14	0.04	1.7×10^{17}	9.5	7.0
BWR/5	0.15	0.09	6.6×10^{17}	13.0	12.5
BWR/5	0.15	0.37	3.9×10^{17}	11.5	26.0
BWR/5	0.12	0.04	4.2×10^{17}	10.0	8.5
BWR/5	0.11	0.07	1.2×10^{18}	12.0	12.5
BWR/6	0.07	0.10	4.9×10^{18}	14.0	20.5
BWR/6	0.04	0.06	1.9×10^{18}	10.0	13.5
BWR/6	0.06	0.06	3.0×10^{18}	12.0	15.0
BWR/6	0.09	0.09	4.8×10^{18}	15.0	19.0

* 0.35% Cu used when data not available

Table 8-2

DATA ON BWR BELTLINE PLATES

Vessel	%Cu	Thick	%S	Plate Type	Avg. USE
BWR/2	0.27	7.13	.026-.034	302B-Mod	92
BWR/2	0.27	7.13	.021-.030	302B&B-Mod	88
BWR/3	0.23	6.13	.010-.040	302B-Mod	139 [a]
BWR/3	0.24	6.13	.017-.020	302B-Mod	132 [a]
BWR/3	0.23	5.50	.018-.027	302B-Mod	104
BWR/3	0.17	5.06	.010-.016	533B-1	109 [a, b]
BWR/3	0.14	5.53	.012-.018	533B-1	121
BWR/3	0.27	6.13	.015-.024	302B-Mod	106 [a]
BWR/3	0.18	6.13	.010-.022	302B-Mod	136 [a]
BWR/4	0.15	6.13	.010-.016	302B-Mod	131
BWR/4	0.17	6.13	.013-.015	302B-Mod	142 [a]
BWR/4	0.15	6.13	.013-.017	302B-Mod	158 [a]
BWR/4	0.15	5.38	.014-.016	533B-1	
BWR/4	0.19	5.38	.014-.016	533B-1	
BWR/4	0.21	5.38	.014-.018	533B-1	118
BWR/4	0.15	4.47	.010-.015	533B-1	163 [a]
BWR/4	0.12	6.13	.010-.018	533B-1	133
BWR/4	0.18	5.38	.015-.018	533B-1	123
BWR/4	0.17	5.38	.012-.015	533B-1	128
BWR/4	0.11	5.38	.016-.019	533B-1	129
BWR/4	0.09	6.10	.008-.014	533B-1	91(T) [a,c]
BWR/4	0.12	6.19	.014-.016	533B-1	
BWR/4	0.15	6.19	.015-.020	533B-1	
BWR/4	0.13	6.13	.015-.018	302B-Mod	126 [a]
BWR/4	0.15	6.13	.015-.018	302B-Mod	137 [a]
BWR/4	0.14	6.19	.010-.019	533B-1	135 [a]
BWR/4	0.13	6.19	.006-.015	533B-1	126 [a]
BWR/4	0.14	5.06	.013-.017	533B-1	137 [a]
BWR/5	0.15	6.19	.013-.020	533B-1	
BWR/5	0.15	6.13	.012-.015	533B-1	141
BWR/5	0.12	6.20	.015-.020	533B-1	96(T) [a]
BWR/5	0.11	6.19	0.015	533B-1	87(T)
BWR/6	0.07	5.38	.011-.015	533B-1	104(T)
BWR/6	0.04	6.19	.012-.015	533B-1	106(T)
BWR/6	0.06	6.00	.013-.025	533B-1	100(T)
BWR/6	0.09	5.41	.012-.020	533B-1	91(T)

[a] USE based on data for only 1 heat (e.g., surveillance plate).

[b] USE based on irradiated data, $f=3x10^{17}$.

[c] (T) = transverse Charpy data

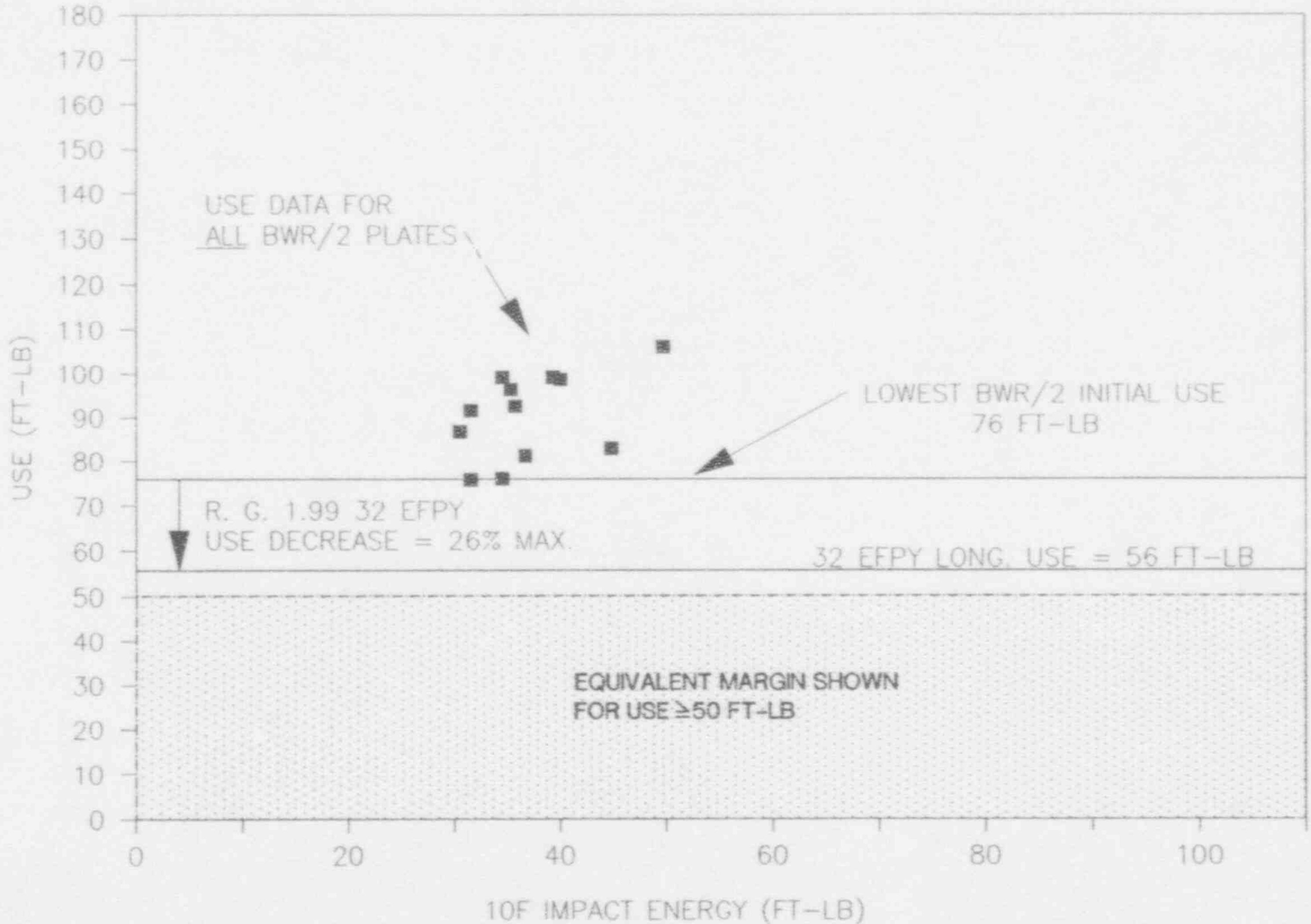

Figure 8-1. BWR/2 Plates (Longitudinal) Meet Equivalent Margin Requirements

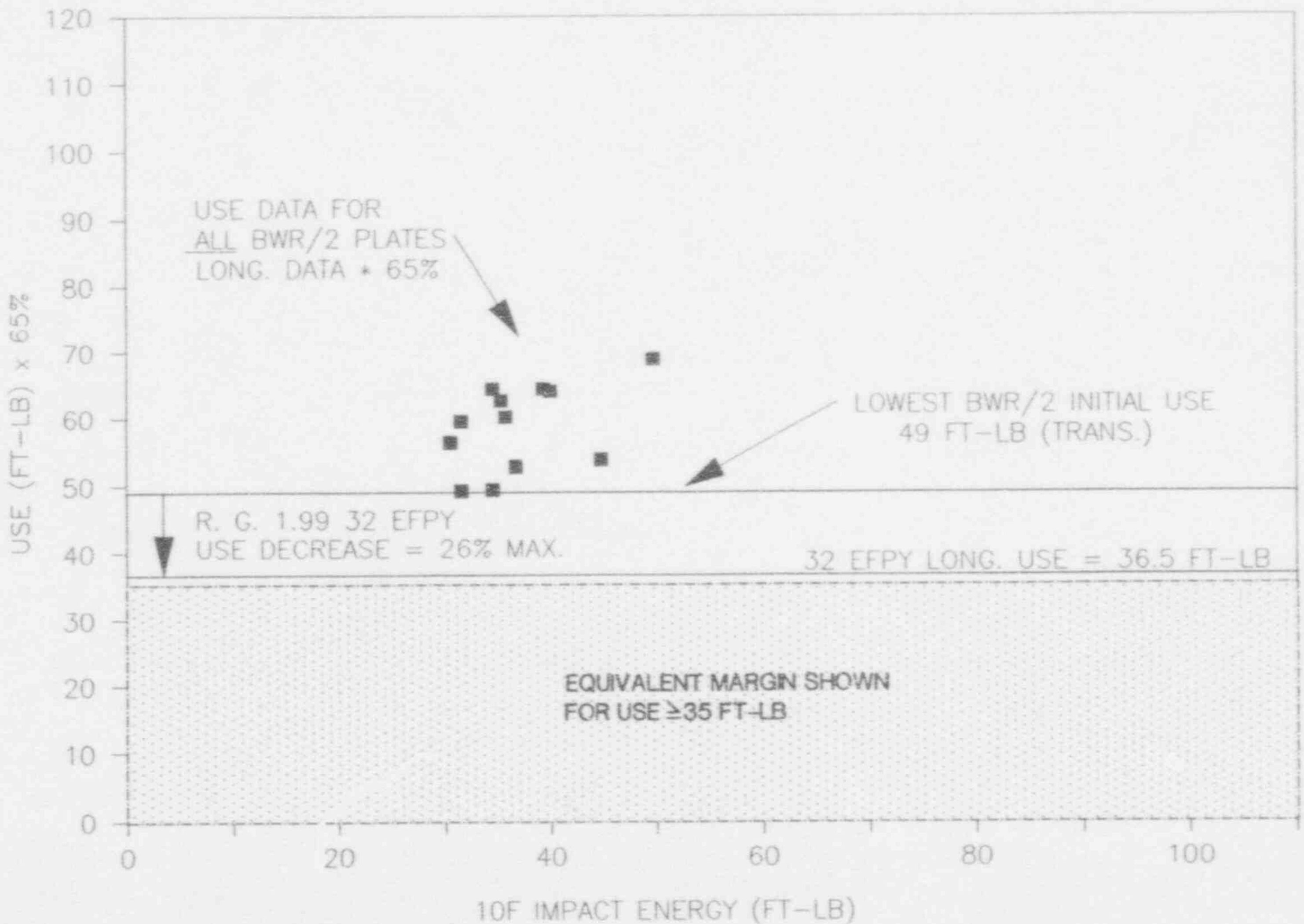

Figure 8-2. EWR/2 Plates (Transverse) Meet Equivalent Margin Requirements

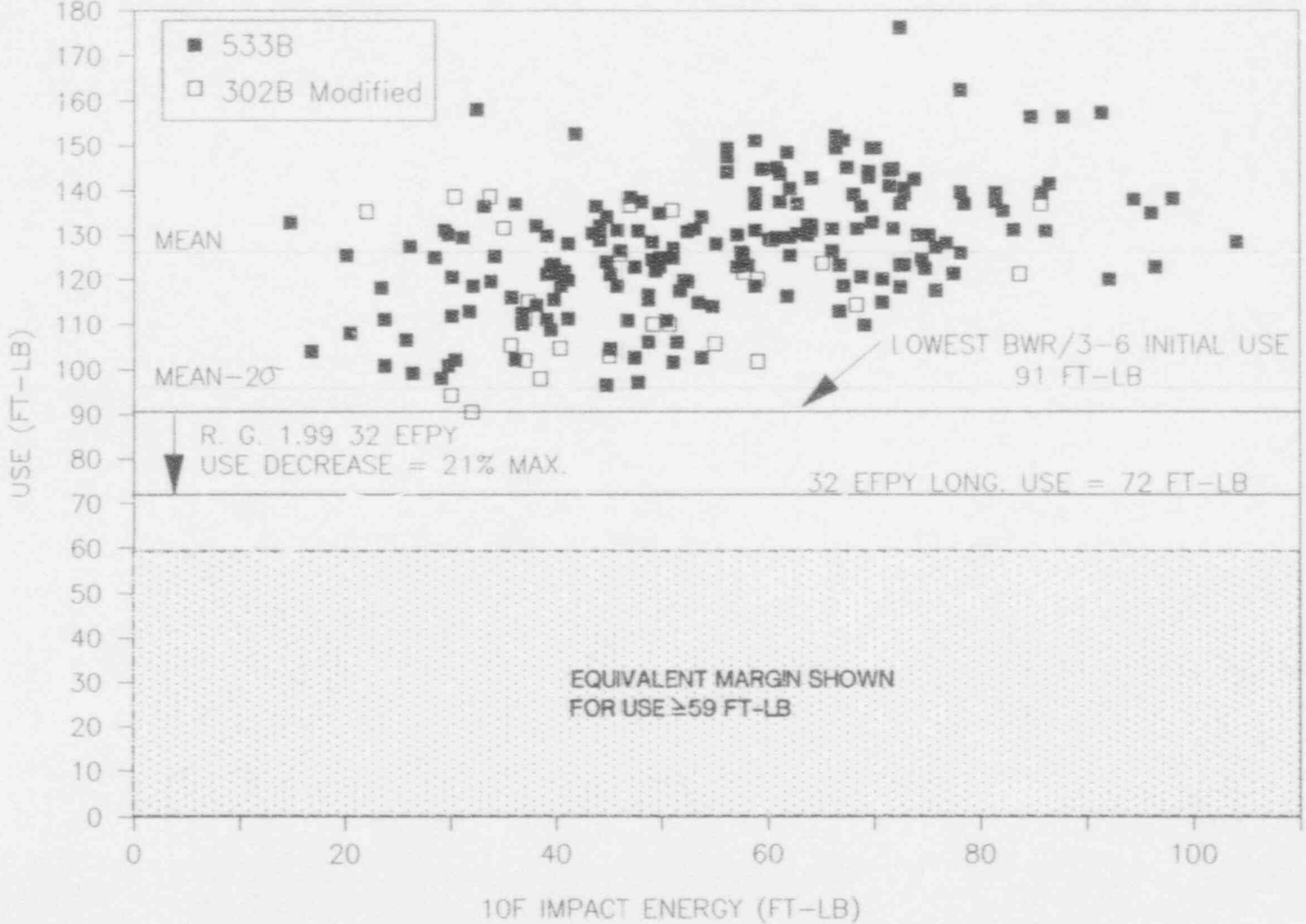

Figure 8-3. BWR/3-6 Plates (Longitudinal) Meet Equivalent Margin Requirements

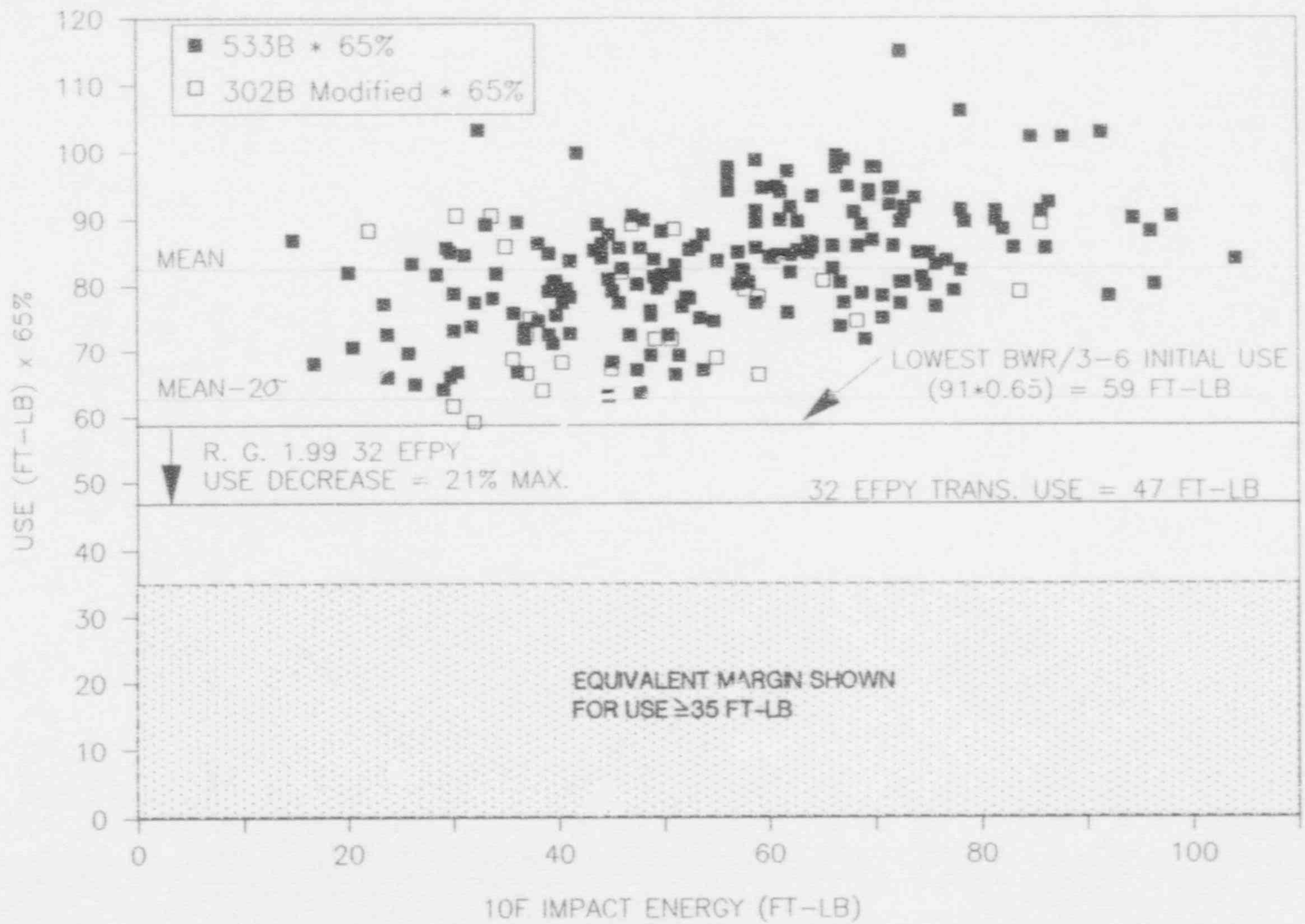

Figure 8-4. BWR/3-6 Plates (Transverse) Meet Equivalent Margin Requirements

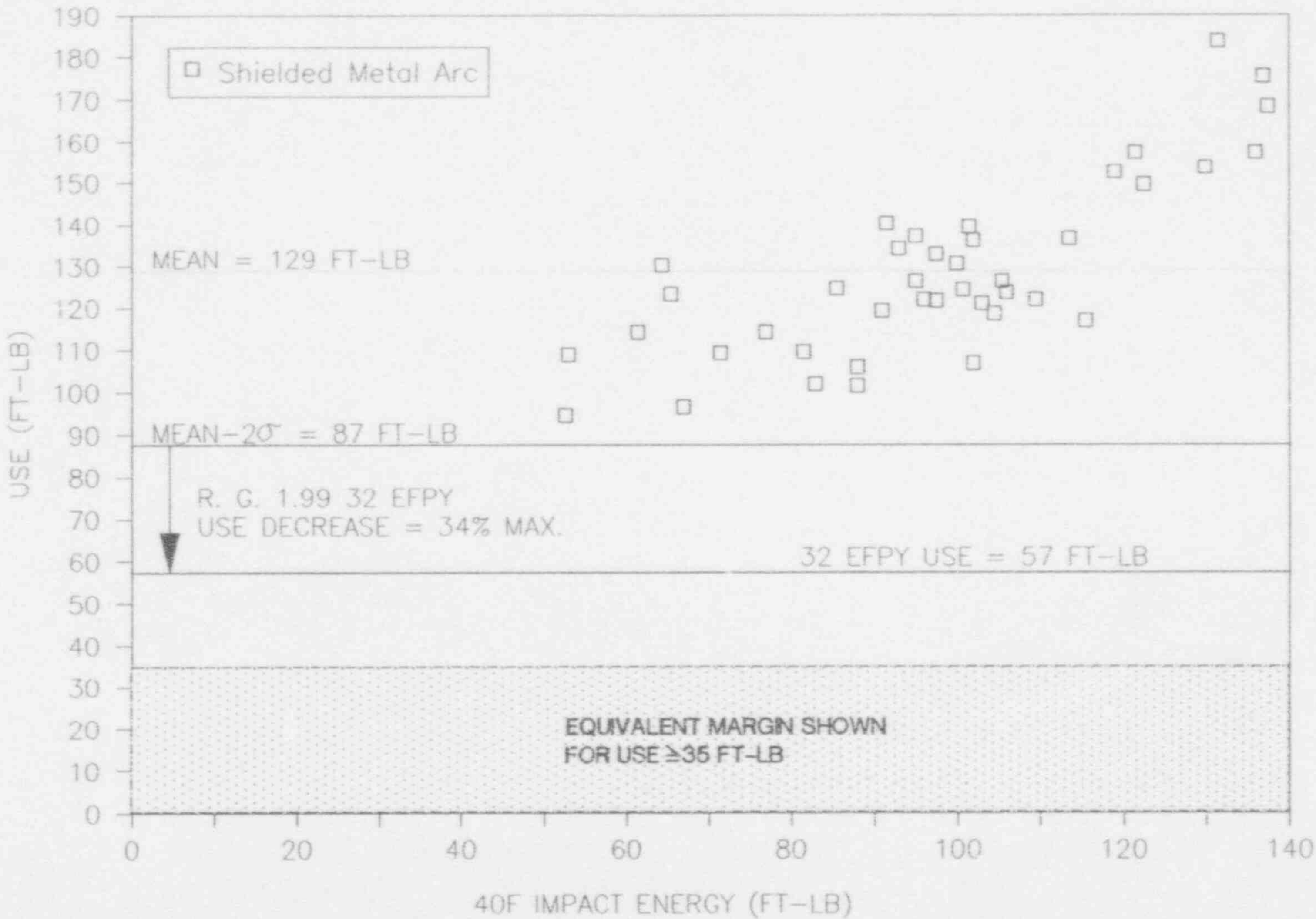

Figure 8-5. SMAW Materials Meet Equivalent Margin Requirements

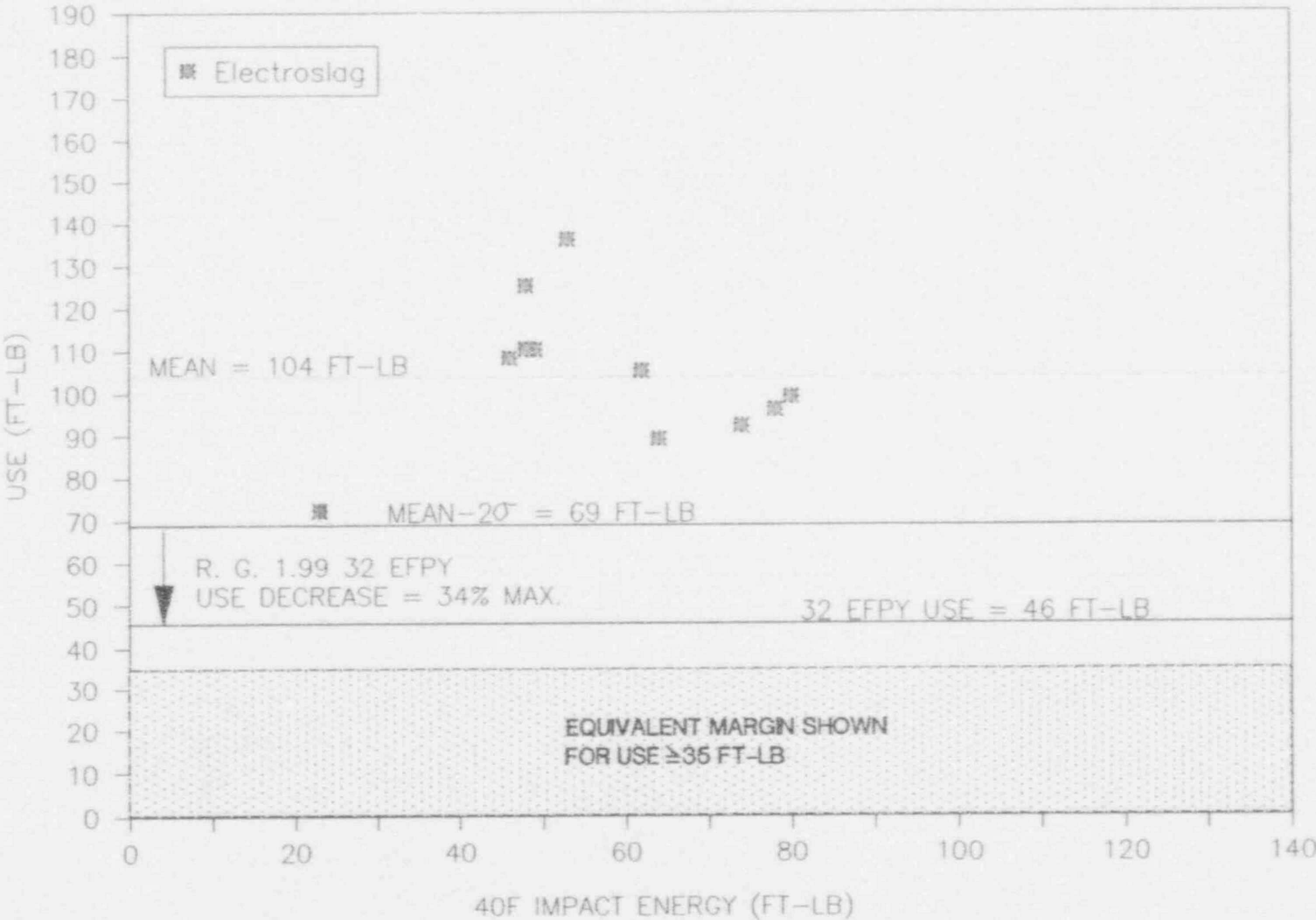

Figure 8-6. ESW Materials Meet Equivalent Margin Requirements

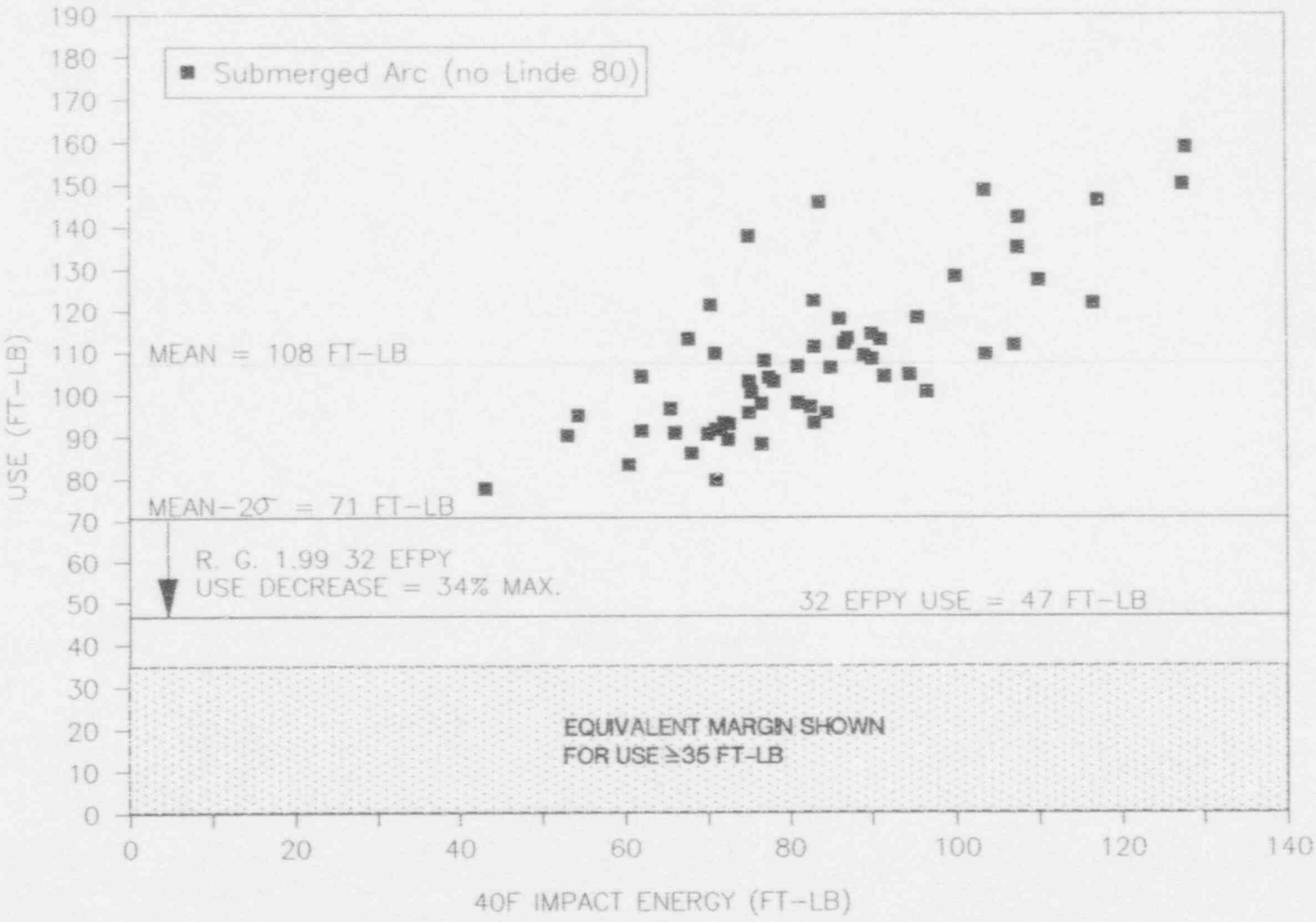

Figure 8-7. Non-Linde 80 SAW Materials Meet Equivalent Margin Requirements

APPENDIX A

ASME CODE CASE N-512

ASSESSMENT OF REACTOR VESSELS WITH LOW UPPER SHELF CHARPY IMPACT ENERGY LEVELS

Approval Date: February 12, 1993

See Numerical Index for expiration and any reaffirmation dates.

Case N-512
Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels
Section XI, Division 1

Inquiry: Section XI, Division 1, IWB-3730, requires that during reactor operation, load and temperature conditions shall be maintained to provide protection against failure due to presence of postulated flaws in ferritic portions of the reactor coolant pressure boundary. What procedure may be used to evaluate a reactor vessel for continued service when the predicted upper shelf Charpy impact energy level as defined in ASTM E 185-82 decreases below a specified value?

Reply: It is the opinion of the Committee that a reactor vessel with a low upper shelf Charpy impact energy level may be evaluated to demonstrate integrity for continued service for upper shelf conditions in accordance with the following.

-1000 INTRODUCTION

-1100 Scope

This Case provides acceptance criteria and evaluation procedures for determining acceptability for operation of a reactor vessel when the vessel metal temperature is in the upper shelf range. The methodology is based on the principles of elastic-plastic fracture mechanics. Flaws

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shall be postulated in the reactor vessel at locations of predicted low upper shelf Charpy impact energy, and the applied J-integral for these flaws shall be calculated and compared with the J-integral fracture resistance of the material to determine acceptability. All specified design transients for the reactor vessel shall be considered.

The evaluation shall be the responsibility of the Owner and shall be available for review by the regulatory and enforcement authorities having jurisdiction at the plant site.

-1200 Procedure

The following analytical procedure shall be used.

(a) Reactor vessel flaws shall be postulated in accordance with the criteria of -2000.

(b) Loading conditions at the locations of the postulated flaws shall be determined for Level A, B, C, and D Service Loadings.

(c) Material properties, including E, σ_y, and the J-integral resistance curve (J-R curve), shall be determined at the locations of the postulated flaws. Requirements for determining the J-R curve are provided in -3300.

(d) The postulated flaws shall be evaluated in accordance with the acceptance criteria of -2000. Requirements for evaluating the applied J-integral are provided in -3200, and for determining flaw stability in -3400. Three permissible evaluation methods are described in -3500. Detailed calculation procedures for Level A and B Service Loadings are provided in -4000.

-1300 General Nomenclature

a = flaw depth that includes ductile flaw extension (in.)

a_e = effective flaw depth that includes ductile flaw extension and a plastic-zone correction (in.)

a_e^* = effective flaw depth at onset of flaw instability, including ductile flaw extension and a plastic-zone correction (in.)

a_o = postulated initial flaw depth (in.)

Δa = amount of ductile flaw extension (in.)

Δa^* = amount of ductile flaw extension at onset of flaw instability (in.)

C_1, C_2 = material constants used to describe the power-law fit to the J-integral resistance curve for the material, $J = C_1 (\Delta a)^{C_2}$

(CR) = cooldown rate (°F/hour)

E = Young's modulus (ksi)

E' = $E/(1-\nu^2)$ (ksi)

F_1, F_2, F_3 = geometry factors used to calculate the stress intensity factor (dimensionless)

F_1^*, F_2^*, F_3^* = geometry factors used to calculate the stress intensity factor at onset of flaw instability (dimensionless)

J = J-integral due to the applied loads (in.-lb/in.^{2})

J_R = J-integral fracture resistance for the material (in.-lb/in.^{2})

$J_{0.1}$ = J-integral fracture resistance for the material at a ductile flaw extension of 0.10 in. (in.-lb/in.^{2})

J_1 = applied J-integral at a flaw depth of a_o + 0.10 in. (in.-lb/in.^{2})

J^* = J-integral at onset of flaw instability (in.-lb/in.^{2})

K_I = mode I stress intensity factor (ksi $\sqrt{\text{in.}}$)

K_{Ip} = mode I stress intensity factor due to internal pressure, calculated with no plastic-zone correction (ksi $\sqrt{\text{in.}}$)

K_{Ip}' = K_{Ip} calculated with a plastic-zone correction (ksi $\sqrt{\text{in.}}$)

K_{Ip}^* = K_{Ip} at onset of flaw instability, calculated with a plastic-zone correction (ksi $\sqrt{\text{in.}}$)

K_{It} = mode I stress intensity factor due to a radial thermal gradient through the vessel wall, calculated with no plastic-zone correction (ksi $\sqrt{\text{in.}}$)

K_{It}' = K_{It} calculated with a plastic-zone correction (ksi $\sqrt{\text{in.}}$)

K_{It}^* = K_{It} at onset of flaw instability, calculated with a plastic-zone correction (ksi $\sqrt{\text{in.}}$)

K_r = ordinate of the failure assessment diagram curve (dimensionless)

K_r' = ratio of the stress intensity factor to the fracture toughness for the material (dimensionless)

p = internal pressure (ksi)

P_a = accumulation pressure as defined in the plant specific Overpressure Protection Report, but not exceeding 1.1 times the design pressure (ksi)

P_s = pressure used to calculate the applied J-integral/tearing modulus line (ksi)

P^* = internal pressure at onset of flaw instability (ksi)
P_o = reference limit-load internal pressure (ksi)
R_i = inner radius of the vessel (in.)
S_r = abscissa of the failure assessment diagram curve (dimensionless)
S_r' = ratio of internal pressure to reference limit-load internal pressure (dimensionless)
(SF) = safety factor (dimensionless)
t = vessel wall thickness (in.)
T = tearing modulus due to the applied loads (dimensionless)
T_R = tearing modulus resistance for the material (dimensionless)
W = parameter used to relate the applied J-integral to the applied tearing modulus (dimensionless)
ν = Poisson's ratio (dimensionless)
σ_f = reference flow stress, specified as 85 ksi (ksi)
σ_y = yield strength for the material (ksi)

-2000 ACCEPTANCE CRITERIA

-2100 Scope

Adequacy of the upper shelf toughness of the reactor vessel shall be determined by analysis. The reactor vessel is acceptable for continued service when the criteria of -2200, and -2300, and -2400 are satisfied.

-2200 Level A and B Service Loadings

(a) When evaluating adequacy of the upper shelf toughness for the weld material for Level A and B Service Loadings, an interior semi-elliptical surface flaw with a depth one-quarter of the wall thickness and a length six times the depth shall be postulated, with the flaw's major axis oriented along the weld of concern, and the flaw plane oriented in the radial direction. When evaluating adequacy of the upper shelf toughness for the base material, both interior axial and circumferential flaws with depths one-quarter of the wall thickness and lengths six times the depth shall be postulated, and toughness properties for the corresponding orientation shall be used. Smaller flaw sizes may be used when justified. Two criteria shall be satisfied:

(1) The applied J-integral evaluated at a pressure 1.15 times the accumulation pressure as defined in the plant specific Overpressure Protection Report, with a factor of safety of 1.0 on thermal loading for the plant specific heatup and cooldown conditions, shall be less than the J-integral of the material at a ductile flaw extension of 0.10 in.

(2) Flaw extensions at pressures up to 1.25 times the accumulation pressure of -2200(1) shall be ductile and stable, using a factor of safety of 1.0 on thermal loading for the plant specific heatup and cooldown conditions.

(b) The J-integral resistance versus flaw extension curve shall be a conservative representation for the vessel material under evaluation.

-2300 Level C Service Loadings

(a) When evaluating adequacy of the upper shelf toughness for the weld material for Level C Service Loadings, interior semi-elliptical surface flaws with depths up to $^1/_{10}$ of the base metal wall thickness, plus the cladding thickness, with total depths not exceeding 1.0 in., and a surface length six times the depth, shall be postulated, with the flaw's major axis oriented along the weld of concern, and the flaw plane oriented in the radial direction. When evaluating adequacy of the upper shelf toughness for the base material, both interior axial and circumferential flaws shall be postulated, and toughness properties for the corresponding orientation shall be used. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Smaller maximum flaw sizes may be used when justified. Two criteria shall be satisfied:

(1) The applied J-integral shall be less than the J-integral of the material at a ductile flaw extension of 0.10 in., using a factor of safety of 1.0 on loading.

(2) Flaw extensions shall be ductile and stable, using a factor of safety of 1.0 on loading.

(b) The J-integral resistance versus flaw extension curve shall be a conservative representation for the vessel material under evaluation.

-2400 Level D Service Loadings

(a) When evaluating adequacy of the upper shelf toughness for Level D Service Loadings, flaws as specified for Level C Service Loadings in -2300 shall be postulated, and toughness properties for the corresponding

orientation shall be used. Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth. Smaller maximum flaw sizes may be used when justified. Flaw extensions shall be ductile and stable, using a factor of safety of 1.0 on loading.

(b) The J-integral resistance versus flaw extension curve shall be a best estimate representation for the vessel material under evaluation.

(c) The extent of stable flaw extension shall be less than or equal to 75% of the vessel wall thickness, and the remaining ligament shall not be subject to tensile instability.

-3000 ANALYSIS

-3100 Scope

This Article contains a description of procedures for evaluating applied fracture mechanics parameters, as well as requirements for determining the J-R curve for the material.

-3200 Applied J-Integral

Calculation of the J-integral due to applied loads shall account for elastic-plastic behavior of the stress-strain curve for the material. When elastic fracture mechanics with small scale yielding applies, the J-integral may be calculated using crack-tip stress intensity factor formulae with a plastic-zone correction. The method of calculation shall be documented.

-3300 Selection of the J-Integral Resistance Curve

When evaluating the vessel for Level A, B, and C Service Loadings, the J-integral resistance versus crack-extension curve (J-R curve) shall be a conservative representation of the toughness of the controlling beltline material at upper shelf temperatures in the operating range. When evaluating the vessel for Level D Service Loadings, the J-R curve shall be a best estimate representation of the toughness of the controlling beltline material at upper shelf temperatures in the operating range. One of the following options shall be used to determine the J-R curve.

(a) A J-R curve shall be generated for the material by following accepted test procedures. The J-R curve shall be based on the proper combination of crack orientation, temperature, and fluence level. Crack extension shall be ductile tearing with no cleavage.

(b) A J-R curve shall be generated from a J-integral database obtained from the same class of material with the same orientation using correlations for effects of temperature, chemical composition, and fluence level. Crack extension shall be ductile tearing with no cleavage.

(c) When (a) or (b) above cannot be used, an indirect method of estimating the J-R curve shall be used provided the method is justified for the material.

-3400 Flaw Stability

(a) The equilibrium equation for stable flaw extension is:

$$J = J_R$$

Where J is the J-integral due to applied loads for the postulated flaw in the vessel, and J_R is the J-integral resistance to ductile tearing for the material.

(b) The inequality for flaw stability due to ductile tearing is:

$$\frac{\partial J}{\partial a} < \frac{dJ_R}{da}$$

Where $\partial J/\partial a$ is the partial derivative of the applied J-integral with respect to flaw depth, a, with constant load, and dJ_R/da is the slope of the J-R curve. Under increasing load, stable flaw extension will continue as long as $\partial J/\partial a$ remains less than dJ_R/da.

-3500 Evaluation Method for Level A and B Service Loadings

(a) The procedure provided in -4200 shall be used to evaluate the applied J-integral for a specified amount of ductile flaw extension.

(b) There are three acceptable methods for applying flaw stability acceptance criteria in accordance with the governing flaw stability rules in -3400. The first is a J-R curve–crack driving force diagram method. In this method flaw stability is evaluated by a direct application of the flaw stability rules provided in -3400. Guidelines for using this method are provided in -4310. The second is a failure assessment diagram method. A procedure based on this method for the postulated initial one-quarter wall thickness flaw is provided in -4320. The third is a J-integral/tearing modulus method. A procedure based

on this method for the postulated initial one-quarter wall thickness flaw is provided in -4330.

-4000 EVALUATION PROCEDURES FOR LEVEL A AND B SERVICE LOADINGS

-4100 Scope

This Article contains calculation procedures to satisfy the acceptance criteria in -2000 for Level A and B Service Loadings. A procedure to satisfy the J-integral criteria for a specified amount of flaw extension of 0.10 in. is provided in -4200. Procedures to satisfy the flaw stability criteria are provided in -4300. These procedures include axial and circumferential flaw orientations.

-4200 Evaluation Procedure for the Applied J-Integral

-4210 Calculation of the Applied J-Integral

Calculation of the applied J-integral consists of two steps: Step 1 calculates effective flaw depth, including a plastic-zone correction; and Step 2 calculates the J-integral for small scale yielding based on this effective flaw depth.

Step 1.

(a) For an axial flaw of depth a, the stress intensity factor due to internal pressure shall be calculated with a safety factor (SF) on pressure using the following:

$$K_{Ip} = (SF)\, p\, [\, 1 + (R_i/t)]\, (\pi a)^{0.5} F_1 \qquad (1)$$

where:

$$F_1 = 0.982 + 1.006\, (a/t)^2$$

This equation for K_{Ip} is valid for $0.20 \leq a/t \leq 0.50$, and includes the effect of pressure acting on the flaw faces.

(b) For a circumferential flaw of depth a, the stress intensity factor due to internal pressure shall be calculated with a safety factor (SF) on pressure using the following:

$$K_{Ip} = (SF)\, p\, [\, 1 + (R_i/(2t))]\, (\pi a)^{0.5} F_2 \qquad (2)$$

where:

$$F_2 = 0.885 + 0.233\, (a/t) + 0.345\, (a/t)^2$$

This equation for K_{Ip} is valid for $0.20 \leq a/t \leq 0.50$, and includes the effect of pressure acting on the flaw faces.

(c) For an axial or circumferential flaw of depth a, the stress intensity factor due to radial thermal gradients shall be calculated using the following:

$$K_{It} = [(CR)/1000]\, t^{2.5} F_3 \qquad (3)$$

where:

$$F_3 = 0.690 + 3.127\, (a/t) - 7.435\, (a/t)^2 + 3.532 (a/t)^3$$

This equation for K_{It} is valid for $0.20 \leq a/t \leq 0.50$, and $0 \leq (CR) \leq 100$°F/hour.

(d) The effective flaw depth for small scale yielding, a_e, shall be calculated using the following:

$$a_e = a + (1/(6\pi))\, [(K_{Ip} + K_{It})\, /\sigma_y]^2$$

Step 2.

(a) For an axial flaw, the stress intensity factor due to internal pressure for small scale yielding, K_{Ip}', shall be calculated, substituting a_e for a in Eq. (1), including the equation for F_1. For a circumferential flaw, K_{Ip}' shall be calculated, substituting a_e for a in Eq. (2), including the equation for F_2. For an axial or circumferential flaw, the stress intensity factor due to radial thermal gradients for small scale yielding, K_{It}', shall be calculated, substituting a_e for a in Eq. (3), including the equation for F_3. Eqs. (1), (2) and (3) are valid for $0.20 \leq a_e/t \leq 0.50$.

(b) The J-integral due to applied loads for small scale yielding shall be calculated using the following:

$$J = 1000\, (K_{Ip}' + K_{It}')^2/E'$$

-4220 Evaluation Using Criterion for Flaw Extension of 0.1 in.

The J-integral due to applied loads, J_1, shall be calculated in accordance with -4210. A flaw depth a of $0.25t + 0.10$ in., a pressure p equal to the accumulation pressure for Level A and B Service Loadings, P_a, and a safety factor (SF) on pressure of 1.15 shall be used. Acceptance criteria for Level A and B Service Loadings based on a ductile flaw extension of 0.10 in. in -2000(a)(1) are satisfied when the following inequality is satisfied.

$$J_1 < J_{0.1}$$

where

J_1 = the applied J-integral for a safety factor on pressure of 1.15, and a safety factor of 1.0 on thermal loading

$J_{0.1}$ = the J-integral resistance at a ductile flaw extension of 0.10 in.

-4300 Evaluation Procedures for Flaw Stability

-4310 J-R Curve–Crack Driving Force Diagram Procedure

Flaw stability shall be evaluated by direct application of the flaw stability rules in -3400. The applied J-integral shall be calculated for a series of flaw depths corresponding to increasing amounts of ductile flaw extension. The applied J-integral for Level A and B Service Loadings shall be calculated using the procedures provided in -4210. The applied pressure p shall be equal to the accumulation pressure for Level A and B Service Loadings, P_a; and the safety factor (SF) on pressure shall be 1.25. The applied J-integral shall be plotted against crack depth on the crack driving force diagram to produce the applied J-integral curve, as illustrated in Fig. -4310-1. The J-R curve shall be plotted on the crack driving force diagram, and shall intersect the horizontal axis at the initial flaw depth, a_o. Flaw stability at a given applied load is verified when the slope of the applied J-integral curve is less than the slope of the J-R curve at the point on the J-R curve where the two curves intersect.

-4320 Failure Assessment Diagram Procedure

Use of this procedure shall be limited to a postulated initial flaw depth of one-quarter of the wall thickness.

-4321 Failure Assessment Diagram Curve

The failure assessment diagram curve of Fig. -4320-1 shall be used for axial and circumferential flaws. The coordinates S_r and K_r of the failure assessment diagram curve are provided in Table -4320-1. This curve is based on material properties which are characteristic of reactor pressure vessel steels.

-4322 Failure Assessment Point Coordinates

The flaw depth a for ductile flaw extension Δa is given by the following:

$$a = 0.25t + \Delta a$$

The failure assessment point coordinates, S_r' and K_r', for ductile flaw extension Δa shall be calculated as follows:

$$K_r' = K_I\,[1000/(E'J_R)]^{0.5}$$

where the stress intensity factor shall be calculated using flaw depth a without the plastic-zone correction, and is given by the following:

$$K_I = K_{Ip} + K_{It}$$

and

$$S_r' = (SF)\,p/P_o$$

where (SF) is the required safety factor on pressure. The procedure for calculating K_{Ip}, K_{It} and P_o for axial flaws is provided by -4322.1, and for circumferential flaws by -4322.2.

-4322.1 Axial Flaws

(a) The stress intensity factor due to internal pressure for axial flaws with a safety factor (SF) on pressure is given by Eq. (1). The stress intensity factor due to radial thermal gradients is given by Eq. (3).

(b) The reference limit-load pressure is given by the following:

$$P_o = \frac{(2/\sqrt{3})\sigma_y[0.905 - 0.379\,(\Delta a/t)]}{[0.379 + (R_i/t) + 0.379\,(\Delta a/t)]}$$

(c) For materials with yield strength σ_y greater than 85 ksi, σ_y in this equation shall be 85 ksi. This equation for P_o is valid for $0 \leq \Delta a/t \leq 0.10$.

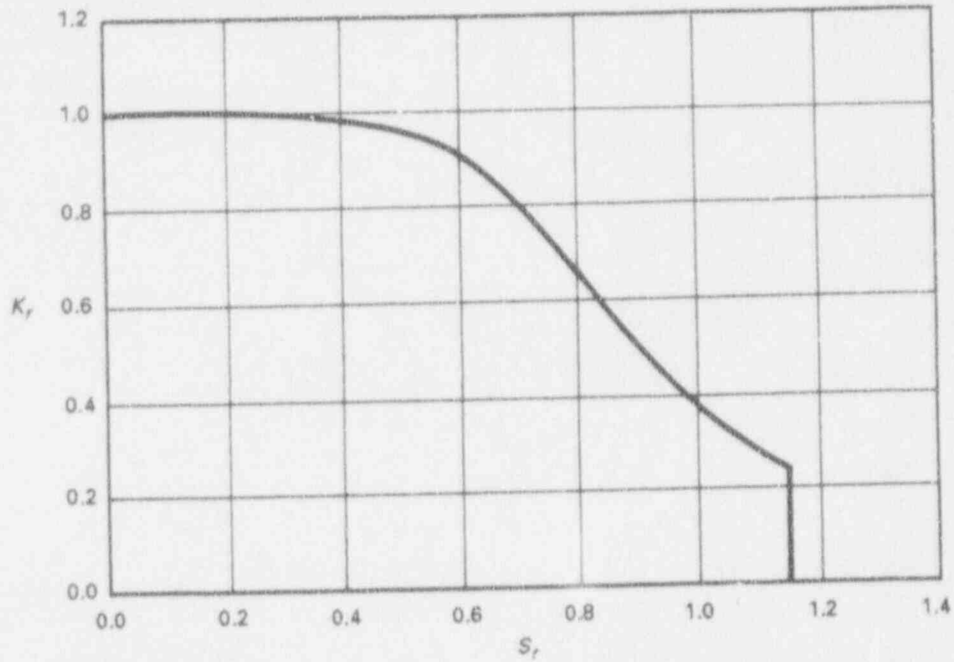

FIG. -4310-1 COMPARISON OF THE SLOPES OF THE APPLIED J-INTEGRAL CURVE AND THE J-R CURVE

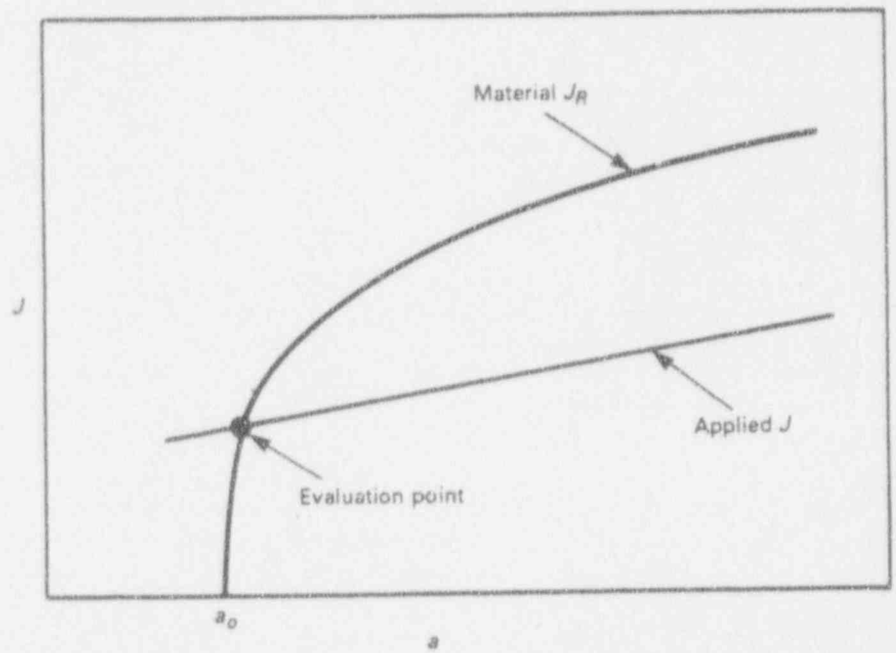

FIG. -4320-1 FAILURE ASSESSMENT DIAGRAM FOR THE ONE-QUARTER WALL THICKNESS FLAW

TABLE -4320-1
COORDINATES OF THE FAILURE ASSESSMENT DIAGRAM CURVE OF FIG. -4320-1

S_r	K_r
0.000	1.000
0.050	1.000
0.100	0.999
0.150	0.998
0.200	0.996
0.250	0.993
0.300	0.990
0.350	0.987
0.400	0.981
0.450	0.973
0.500	0.960
0.550	0.939
0.600	0.908
0.650	0.864
0.700	0.807
0.750	0.737
0.800	0.660
0.850	0.581
0.900	0.505
0.950	0.435
1.000	0.374
1.050	0.321
1.100	0.276
1.150	0.238

-4322.2 Circumferential Flaws

(a) The stress intensity factor due to internal pressure for circumferential flaws with a safety factor (SF) on pressure is given by Eq. (2). The stress intensity factor due to radial thermal gradients is given by Eq. (3).

(b) The reference limit-load pressure is given by the following:

$$P_o = \frac{\sigma_y\,[1 - 0.91\,(0.25 + (\Delta a/t))^2\,(t/R_i)]}{[1 + (R_i/(2t))]}$$

(c) For materials with yield strength σ_y greater than 85 ksi, σ_y in this equation shall be 85 ksi. This equation for P_o is valid for $0 \leq \Delta a/t \leq 0.25$.

-4323 Evaluation Using Criterion for Flaw Stability

Assessment points shall be calculated for each loading condition in accordance with -4322, and shall be plotted on Fig. -4320-1 as follows. A series of assessment points for various amounts of ductile flaw extension, Δa, up to the validity limit of the J-R curve shall be plotted. Pressure p equal to the accumulation pressure for Level A and B Service Loadings, P_a, and safety factor (SF) on pressure of 1.25 shall be used. When one or more assessment points lie inside the failure assessment curve, the acceptance criteria based on flaw stability in -2000(a)(2) are satisfied.

-4330 J-Integral/Tearing Modulus Procedure

Use of this procedure shall be limited to a postulated initial flaw depth of one-quarter of the wall thickness.

-4331 J-Integral at Flaw Instability

(a) In Fig. -4330-1, the onset of flaw instability is the point of intersection of the applied and material curves plotted on a graph of the J-integral versus tearing modulus (J versus T). The expression for the applied J versus T curve is given by the following:

$$J = (1000\,W\,t\,\sigma_f^2/E)T \qquad (4)$$

where σ_f is a reference flow stress of 85 ksi.

(b) For axial flaws Eq. (5) applies:

$$W = 0.235[1 + (0.083 \times 10^{-3})(CR)t^2/((SF)P_s)] \qquad (5)$$

where P_s is the pressure under evaluation. Eq. (5) is valid for $6 \leq t \leq 12$ in., $2.25 \leq ((SF)\,P_s) \leq 5.00$ ksi, and $0 \leq (CR) \leq 100$°F/hour. For circumferential flaws Eq. (6) applies:

$$W = 0.21[1 + (0.257 \times 10^{-3})(CR)t^2/((SF)P_s)] \qquad (6)$$

Eq. (6) is valid for $6 \leq t \leq 12$ in., $2.25 \leq ((SF)P_s) \leq 9.00$ ksi, and $0 \leq (CR) \leq 100$°F/hour. Eqs. (4), (5), and (6) are based on material properties which are characteristic of reactor pressure vessel steels.

(c) The tearing modulus for the material is determined by differentiation of the J-R curve with respect to flaw depth a.

$$T_R = (E/(1000\,\sigma_f^2))\,dJ_R/da \qquad (7)$$

The same values for E and σ_f shall be used in Eq's. (4) and (7). The J-integral versus tearing modulus J_R versus T_R curve for the material is obtained by plotting J_R against T_R for a series of increments in ductile flaw extension. Each coordinate for J_R shall be evaluated at the same ductile flaw extension as the coordinate for T_R.

(d) The value of the J-integral at the onset of flaw instability, J^*, corresponds to the intersection of the applied J versus T curve given by Eq. (4) with the material J_R versus T_R curve, as illustrated in Fig. -4330-1.

(e) The J-integral at the onset of flaw instability may be determined analytically when a power-law curve fit to the J-R curve of the form of the following:

$$J_R = C_1\,(\Delta a)^{C_2}$$

is available. The J-integral at the onset of flaw instability, J^*, is given by the following:

$$J^* = C_1\,(W\,t\,C_2)^{C_2}$$

-4332 Internal Pressure at Flaw Instability

(a) Calculation of the internal pressure at the onset of flaw instability is based on J^*. Ductile flaw extension at the onset of flaw instability, Δa^*, is taken from the

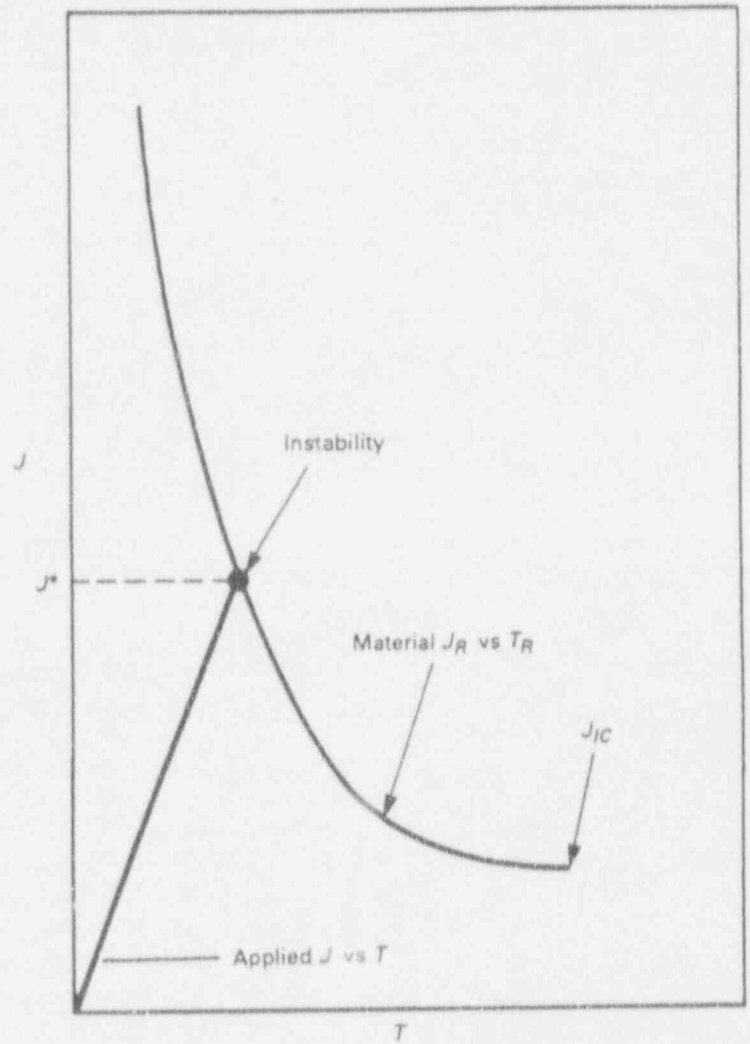

FIG. -4330-1 ILLUSTRATION OF THE J-INTEGRAL/TEARING MODULUS PROCEDURE

J-R curve. The effective flaw depth at the onset of flaw instability includes Δa^*, and is given by the following:

$$a_e^* = 0.25t + \Delta a^* + (1/(6\pi))[J^* E'/(1000\, q^2)]$$

(b) The stress intensity factor due to radial thermal gradients at the onset of flaw instability K_{It}^*, for axial or circumferential flaws is given by the following:

$$K_{It}^* = ((CR)/1000)\, t^{2.5} F_3^*$$

where

$$F_3^* = 0.690 + 3.127(a_e^*/t) - 7.435(a_e^*/t)^2 + 3.532(a_e^*/t)^3$$

E This equation for K_{It}^* is valid for $0.20 \leq a_e^*/t \leq 0.50$, and $0 \leq (CR) \leq 100$°F/hour. The stress intensity factor for small scale yielding due to internal pressure at the onset of flaw instability, K_{Ip}^*, is given by the following:

$$K_{Ip}^* = (J^* E'/1000)^{0.5} - K_{It}^*$$

(c) For a given value of K_{Ip}^*, the internal pressure at the onset of flaw instability for axial flaws is given by the following:

$$P^* = K_{Ip}^* / [(1 + (R_i/t))\, (\pi a_e^*)^{0.5}\, F_1^*]$$

where

$$F_1^* = 0.982 + 1.006(a_e^*/t)^2$$

and for circumferential flaws is given by the following:

$$P^* = K_{Ip}^* / [(1 + (R_i/(2t)))\, (\pi a_e^*)^{0.5}\, F_2^*]$$

where

$$F_2^* = 0.885 + 0.233(a_e^*/t) + 0.345(a_e^*/t)^2$$

These equations for P* are valid for $0.20 \leq a_e^*/t \leq 0.50$, and include the effect of pressure acting on the flaw faces.

-4333 Evaluation Using Criteria for Flaw Stability

The value of J^* shall be calculated in accordance with -4331 using pressure P_s in Eqs. (5) and (6) equal to the accumulation pressure for Level A and B Service Loadings, P_a, and safety factor (SF) on pressure of 1.25. The value of P^* shall be calculated in accordance with -4332. The acceptance criteria based on flaw stability in -2000(a)(2) are satisfied when the following inequality is satisfied:

$$P^* > 1.25\, P_a$$

-5000 LEVEL C AND D SERVICE LOADINGS

The possible combinations of loadings and material properties that may be encountered during Level C and D Service Loadings are too diverse to allow application of pre-specified procedures. It is recommended that each situation be evaluated on an individual case basis.

APPENDIX B

PLANT-SPECIFIC APPLICABILITY

The evaluations in Section 8, which demonstrate that the equivalent margin analyses are bounding for all U.S. BWR/2-6 vessels, are based on an important assumption, which must be verified on a plant-specific basis. It is assumed that the percent decreases in USE prescribed by R.G. 1.99 are appropriate for a given vessel's beltline materials. The validity of this assumption can be verified with vessel surveillance capsule USE data, when it becomes available.

Obviously, if the surveillance data show a decrease in USE less than predicted in R.G. 1.99, the equivalent margin analysis is bounding for the plant. Example 1 below for weld metal demonstrates this case.

Example 1: Surveillance data < R.G. 1.99 prediction

Decrease in USE for surveillance material, based on capsule data = 9%
Decrease in USE for surveillance material, predicted by R.G. 1.99 = 15%

32 EFPY USE decrease for limiting beltline weld, based on R.G. 1.99 prediction=20%

32 EFPY % decrease in USE assumed in equivalent margin analysis = 34%

20% ≤ 34%, so vessel beltline welds are
bounded by equivalent margin analysis

Since the R.G. 1.99 values for percent decrease in USE are the limiting values for the worst combinations of Cu and 32 EFPY fluence, it is possible that the results of a plant's surveillance USE data could exceed the predictions of R.G. 1.99 and yet still be used to show that the equivalent margin analysis is bounding. Example 2 demonstrates this case.

Example 2: Surveillance data > R.G. 1.99 prediction

Decrease in USE for surveillance material, based on capsule data = 18%
Decrease in USE for surveillance material, predicted by R.G. 1.99 = 15%

32 EFPY USE decrease for limiting beltline weld, based on R.G. 1.99 prediction = 20%
32 EFPY decrease in USE for limiting beltline weld, adjusted for capsule data = 24%
(adjustment made per Position 2.2 of R.G. 1.99)

32 EFPY decrease in USE assumed in equivalent margin analysis = 34%

24% ≤ 34%, so vessel beltline welds are
bounded by equivalent margin analysis

There are equivalent margin analyses for three vessel/material types, each with a percent decrease in USE assigned. The vessel/material types are BWR/2 plate (26%), BWR/3-6 plate (21%) and BWR/2-6 weld (34%). A fill-in-the-blank form, similar to the example above, is provided for each of these types. A utility can use the appropriate forms to verify that the equivalent margin analysis is bounding for their beltline conditions.

EQUIVALENT MARGIN ANALYSIS
PLANT APPLICABILITY VERIFICATION FORM
FOR ______________________

BWR/2 PLATE

Surveillance Plate USE:

%Cu = __________

Capsule Fluence = __________

Measured % Decrease = __________ (Charpy Curves)

R.G. 1.99 Predicted % Decrease = __________ (R.G. 1.99, Figure 2)

Limiting Beltline Plate USE:

%Cu = __________

32 EFPY Fluence = __________

R.G. 1.99 Predicted % Decrease = __________ (R.G. 1.99, Figure 2)

Adjusted % Decrease = __________ (R.G. 1.99, Position 2.2)

___% ≤ 26%, so vessel plates are bounded by equivalent margin analysis

EQUIVALENT MARGIN ANALYSIS
PLANT APPLICABILITY VERIFICATION FORM
FOR ______________________

BWR/3-6 PLATE

Surveillance Plate USE:

%Cu = __________

Capsule Fluence = __________

Measured % Decrease = __________ (Charpy Curves)

R.G. 1.99 Predicted % Decrease = __________ (R.G. 1.99, Figure 2)

Limiting Beltline Plate USE:

%Cu = __________

32 EFPY Fluence = __________

R.G. 1.99 Predicted % Decrease = __________ (R.G. 1.99, Figure 2)

Adjusted % Decrease = __________ (R.G. 1.99, Position 2.2)

___% ≤ 21%, so vessel plates are bounded by equivalent margin analysis

EQUIVALENT MARGIN ANALYSIS
PLANT APPLICABILITY VERIFICATION FORM
FOR ____________________________

BWR/2-6 WELD

Surveillance Weld USE:

%Cu = ____________

Capsule Fluence = ____________

Measured % Decrease = ____________ (Charpy Curves)

R.G. 1.99 Predicted % Decrease = ____________ (R.G. 1.99, Figure 2)

Limiting Beltline Weld USE:

%Cu = ____________

32 EFPY Fluence = ____________

R.G. 1.99 Predicted % Decrease = ____________ (R.G. 1.99, Figure 2)

Adjusted % Decrease = ____________ (R.G. 1.99, Position 2.2)

___% ≤ 34%, so vessel welds are bounded by equivalent margin analysis