Nine Mile Point Unit 1
Docket No. 50-220
DPR-63
TAC No. M83486

Generic Letter 92-01

# Elastic Plastic Fracture Mechanics

# Assessment for Nine Mile Point Unit 1:

# Response to NRC Request for Additional Information

August, 1993

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## 1.0 INTRODUCTION

Niagara Mohawk Power Corporation (NMPC) submitted the Reference [MA92] report to the NRC by letter dated October 16, 1992. Comments provided by the NRC were incorporated into the analysis and a revised report was submitted on December 17, 1992 [MA92b]. The NRC later concurred with NMPC that the A302B material model is appropriate for analysis of the Nine Mile Point Unit 1 (NMP-1) beltline plates, and a report [MA93] was prepared which contains only the A302B material model (the A533B model was deleted). The [MA93] report was not sent to the NRC because the A302B model and results are identical to those reported in Reference [MA92b]. These submittals contain a plant-specific elastic-plastic fracture mechanics assessment for NMP-1 under Service Level A and B loadings. A report which contains the results for Service Level C and D loadings [MA93b] was submitted to the NRC on February 26, 1993. The analyses described in these reports were performed in accordance with the draft ASME Appendix X [ASME92], and demonstrate that sufficient margins of safety against fracture exist through end-of-license (EOL).

In a letter dated July 22, 1993, the NRC indicated that a preliminary review of these reports has been completed and that additional information is required to complete the review. This report was prepared in response to the NRC's request for additional information and is fully responsive to all information requests provided in Enclosures 1 and 2 of the July 22, 1993 letter.

## 2.0 RESPONSES TO ENCLOSURE 1 REQUESTS FOR ADDITIONAL INFORMATION - SERVICE LEVELS A AND B

### 2.1 Information Request 1. - J-R Model

*"The report indicates that the J-R curve for a 6T specimen tested at 180°F is drawn to meet the J axis at $J_{IC}$ = 525 in-lb/in$^2$, then this curve is shifted down to make the J point coincide with the estimated $J_{IC}$ point, leaving the difference between the plateau level of J and $J_{IC}$ constant at 175 in-lb/in$^2$, independent of both temperature and USE. Provide justification for the asserted independence of the J difference (175 in-lb/in$^2$) with respect to temperature and USE values. Also justify that the proposed J-R model should breakdown when USE values reach zero. (Although this issue was addressed in a telephone conference held in January 1993, a written response is required.)"*

RESPONSE:

Background

In contrast with the J-R curve data trends for other pressure vessel materials, Reference [HI89] reported an unprecedented size effect for A302B steel. As shown in Figure 2.1-1, the thicker the specimen, the lower the J-R response level after initiation. While similar data trends have been observed for some pressure vessel materials, decreases in the J-R curves of the magnitude reported by Hiser have not been reported earlier. Based on chemical and microstructural considerations, it was determined that the modified A302B (A302M) NMP-1 plates would exhibit ductile fracture behavior similar to that presented in Reference [HI89]. Reference [HI89] reported J-R data for 0.5T, 1T, 2T, and 4T specimens, but only one 6T test was performed (180°F, T-L orientation).

The micromechanical explanation for the J-R curve behavior shown in Figure 2.1-1 has not been definitively established. Hiser [HI89] has reported brittle-like splits, or laminate tearing, for all of the specimens tested. These splits are oriented in the direction of crack growth with small amounts of microvoid coalescence in the region between the splits. The size, relative number, and distribution of the splits are approximately constant for various specimen sizes. Hiser concluded that the splits resulted from separation of the interface between the material matrix and the inclusions (sulfides, aluminides) and/or the splitting of the more brittle alloy rich bonded structure (possibly bainite). The only apparent difference in the fracture of small and large specimens is the total number of splits and not the relative proportion. A complete micromechanical explanation is not yet available.

Reference [MA92] Analysis

Since there are not sufficient thick-specimen data (6T to 8T) available at present to definitively establish the relationship between $J_{IC}$ and the J plateau ($\Delta J$), as a function of toughness level (in particular, USE level), the Reference [MA92] analysis was performed assuming that the difference between the plateau level of J and $J_{IC}$ is a constant equal to 175 in-

lb/in$^2$ (over the range of USE levels from 10 ft-lbs to 100 ft-lbs). At the time the analysis was performed, it was recognized that the 175 in-lb/in$^2$ difference may change somewhat as the toughness of the steel varies. However the USE level for this steel is 52 ft-lbs (T-L), which is roughly in the middle of the range over which the J-R curve scaling was done. Therefore, it was judged that the difference between the actual material behavior, and the material model based on the assumption of a constant $\Delta J$=175 in-lb/in$^2$, would be small and adequately represented by other conservatism in the model. Since there is no physical basis upon which to vary $\Delta J$ as the USE level is changed, the choice of a constant $\Delta J$ obtained from 6T data is a reasonable modelling assumption.

$\Delta J$ Characterization

The NRC has requested that justification for the constant $\Delta J$ used in the [MA92] calculations be provided. Unfortunately, as discussed above, without extensive additional testing and analysis, complete justification cannot be provided. In particular, since the plateau for the 6T A302B test is so low at 52 ft-lbs, it is possible that the $\Delta J$ variation at lower USE levels may not scale in the same manner as other RPV materials. In the absence of additional data, calculations have been performed using 0.5T and 1T data to assess the $\Delta J$ variation at low toughness. Since it is likely that these data are conservative in comparison with 6T A302B data, the calculations provided below should be viewed as worst case impact assessments.

In and effort to characterize the $\Delta J$ variation with toughness, 0.5 T and 1T data from References [MEA90] and [MEA83] were analyzed. The physical crack extension ($\Delta a_p$) for the analyses reported in Reference [MA92] is on the order of 0.1 in. Therefore, $\Delta J$ for the 0.5T and 1T data was calculated by subtracting $J_{IC}$ from J at $\Delta a_p$=0.1 in. ($J_{0.1}$). It is important to note that the thin specimens at intermediate to high toughness levels do not exhibit a plateau at small $\Delta a$ as with the 6T A302B data. However, the small specimen data can be used to obtain an estimate of the $\Delta J$ variation with toughness. In fact, at the present time, this is the only method available for characterizing the $\Delta J$ variation. These data are presented in Figure 2.1-2.

The Reference [MEA83] J-R power law formulation was used to model the data shown in Figure 2.1-2. The model, determined from least squares regression, is given by:

$$J = C(\Delta a)^n$$

where,

J= J-Integral (in-lb/in$^2$)

$C=1000[-0.4876\ (USE/100)+ 7.5611\ (USE/100)^2]$ (in-lb/in$^2$)

$\Delta a$= crack extension (in)

$$n = 0.267\ (C/1000)^{0.2962}$$

Figures 2.1-3 and 2.1-4 illustrate the functional form of C and n. The results obtained using the power law model are shown in Table 2.1-1 and in Figure 2.1-2. The model represents the 0.5T and 1T data well, and approaches a physically meaningful limit at low toughness. As expected,

the model shows that a constant $\Delta J = 175$ in-lb/in$^2$ is conservative for USE levels above about 40 ft-lb, but is somewhat non-conservative for USE levels below 40 ft-lb.

In order to assess the impact of a decreasing $\Delta J$ with toughness, the following material model was analyzed:

| USE (ft-lb) | $\Delta J$ (in lb/in$^2$) |
|---|---|
| 10 | 0 |
| 20 | 20 |
| 30 | 82 |
| 40-100 | 175 |

The above described J-R material model is the same as that described in Reference [MA92], except that below 40 ft-lb the $\Delta J$ varied in accordance with the above listed data. The results of this analysis are shown in Table 2.1-2. Review of these data shows that even if $\Delta J$ were to decrease dramatically at USE levels below 40 ft-lb, the minimum allowable USE is below the projected material USE at EOL.

Material Model Temperature Dependence

With regard to the question of temperature dependence of the J-R curves, the 6T J-R test at 180°F [HI89] is expected to conservatively represent the material behavior up to reactor operating temperature. As shown in Figure 2.1-5, the 6T test was performed at a temperature slightly higher than the on-set of the upper shelf. The Charpy data indicate temperature independence from about 165°F up to reactor operating temperature.

NMPC Position

It is NMPC's position that the results of the Appendix X analysis reported in Reference [MA92] are accurate and conservative. At present, there are not sufficient data available to characterize the variation of $\Delta J$ with toughness for thick section components. Therefore, the use of a constant $\Delta J = 175$ in lb/in$^2$ is reasonable and is expected to yield a material model which accurately represents thick section behavior.

$J_{IC}$-USE Model Behavior at Low Toughness

The J-R model for the A302B material relies on the correlation of $J_{IC}$ with USE as shown in Figure 4-12 of the December 17, 1992 submittal. If it were possible to produce a material with USE = 0 (i.e., no energy required to drive a crack), then $J_{IC}$ must also be zero (i.e., no crack driving force required). Therefore, the theoretical limit for a $J_{IC}$ vs. USE correlation as toughness decreases is the origin. This data trend is clearly demonstrated in Figure 4-12. However, as a practical consideration, the USE for ferritic RPV steels would not be expected to drop below the lower shelf energy level. Reference [MEA90] shows that the lower shelf for A302B steel is in the range of 4-18 ft-lbs. Therefore, as the material toughness decreases, the $J_{IC}$ - USE correlation is expected to describe the material fracture behavior as the USE level approaches the Charpy lower shelf energy level.

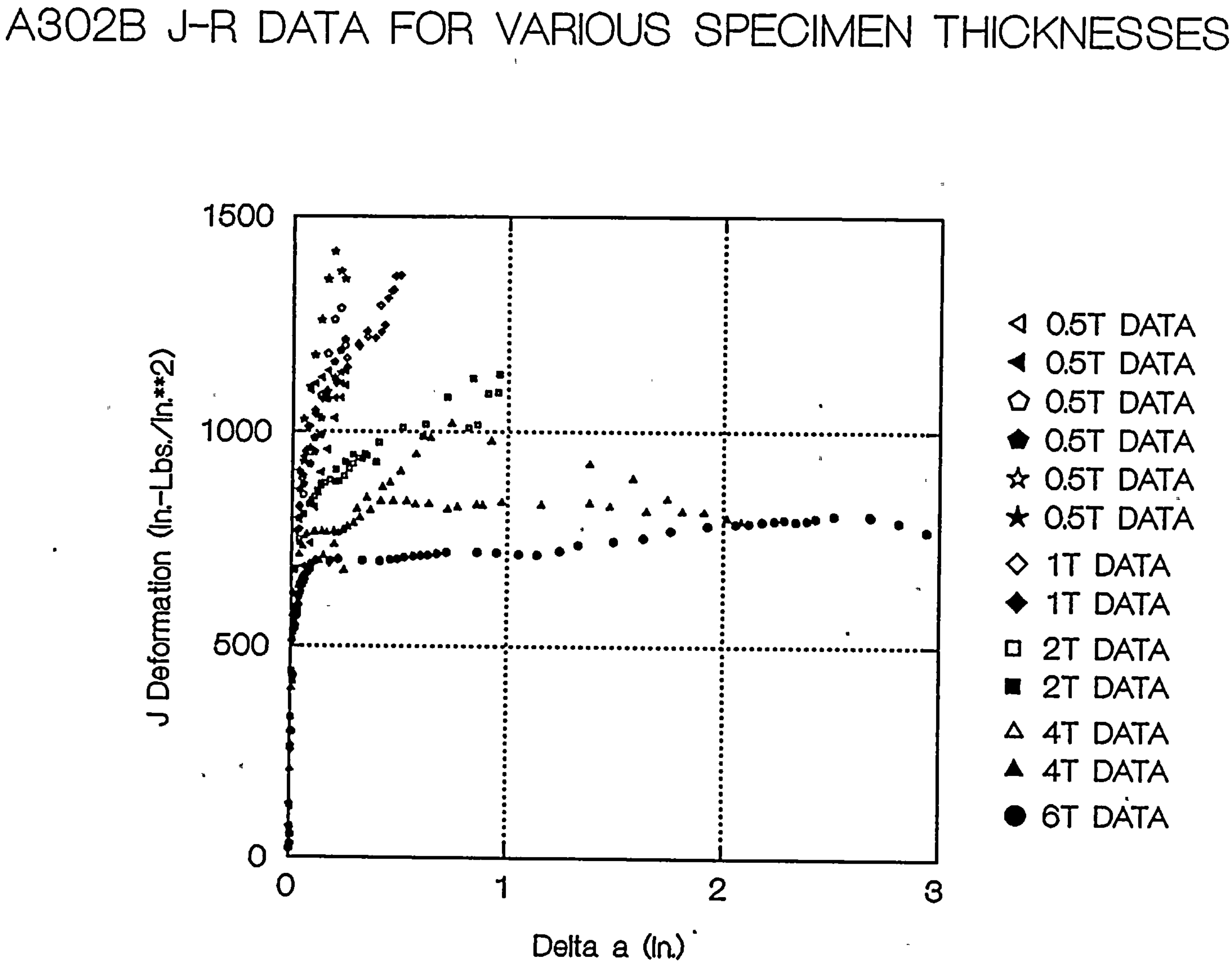



Figure 2.1-1
Comparison of $J_d$-R Curves for A302B Plate
(Data Taken from [HI89])

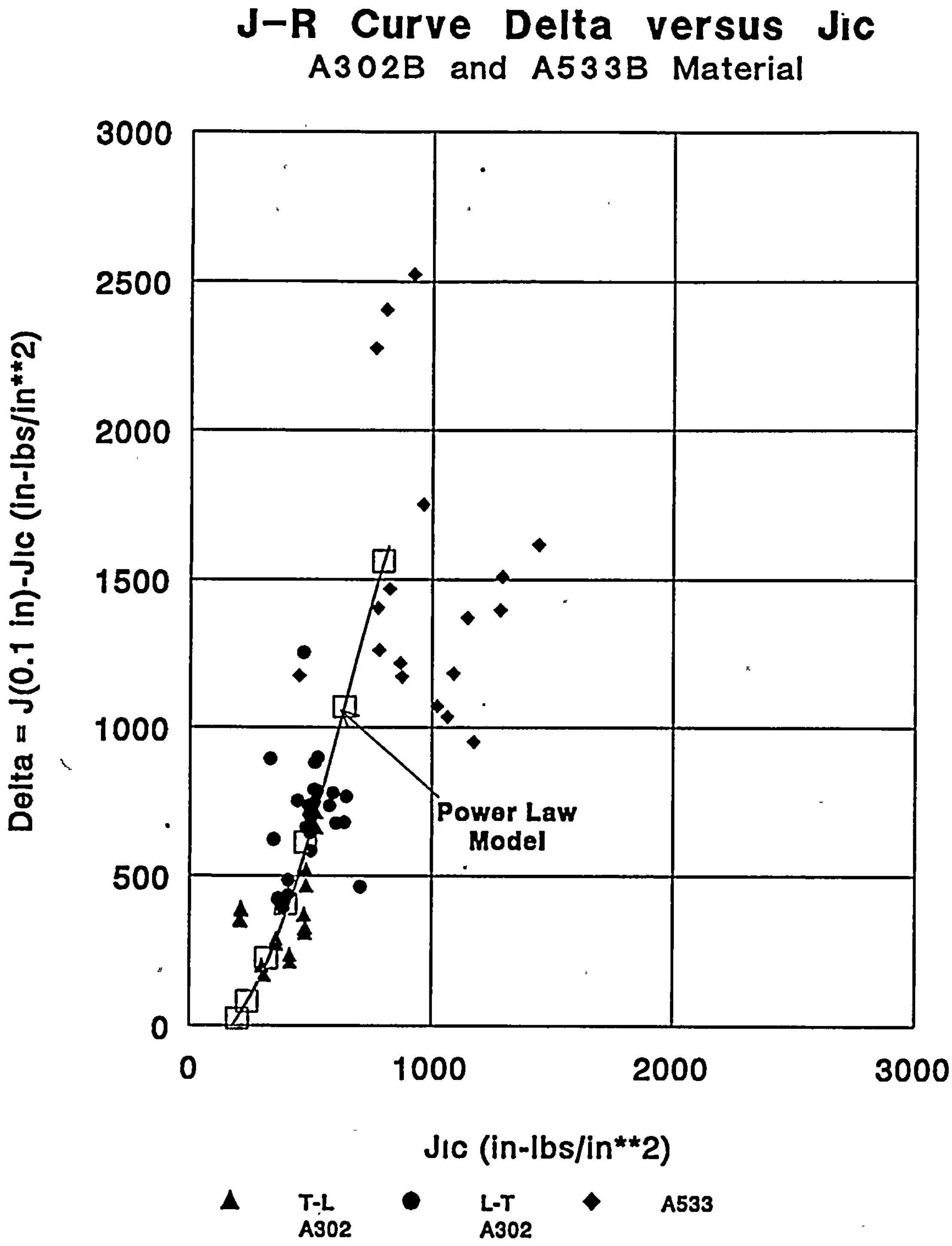



Figure 2.1-2
$\Delta J$ as a Function of $J_{IC}$ for 0.5 T and 1 T Specimens

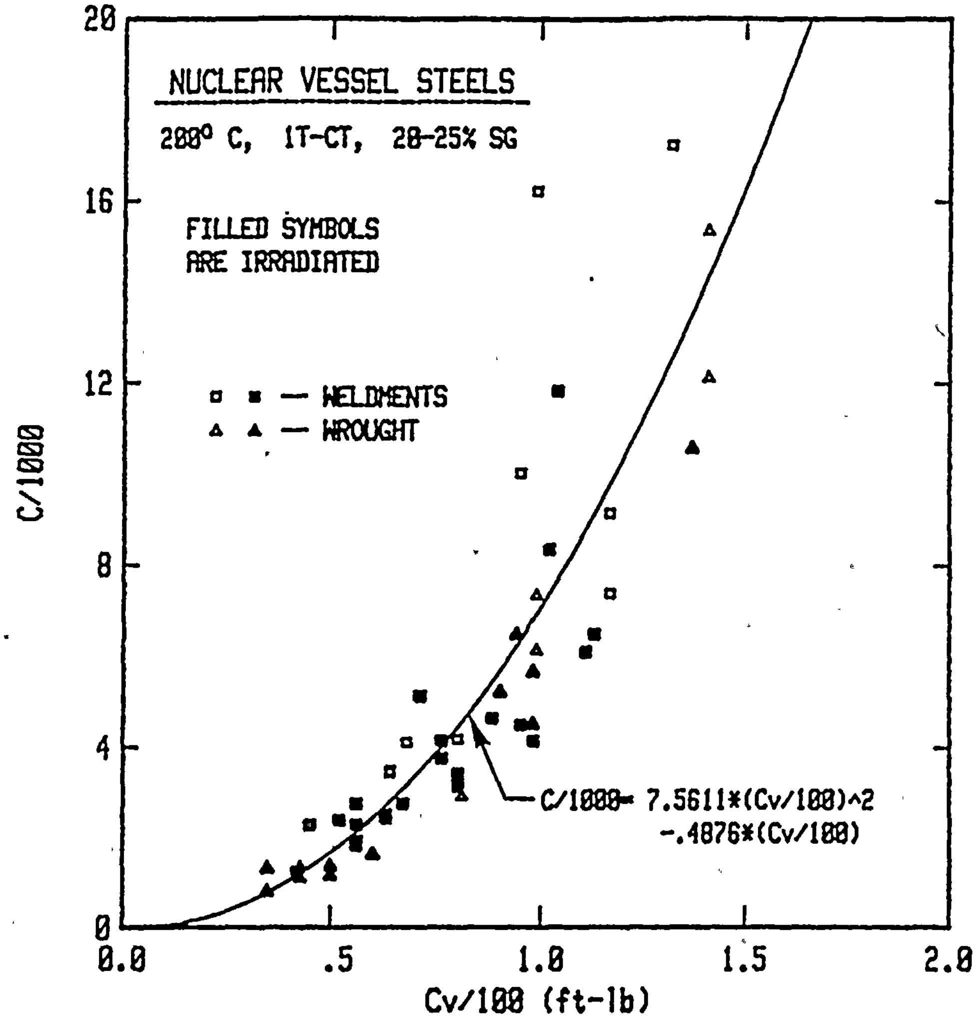



Figure 2.1-3
Correlation of Normalized Coefficients
with Normalized Charpy Upper Shelf Energy Values [MEA83]

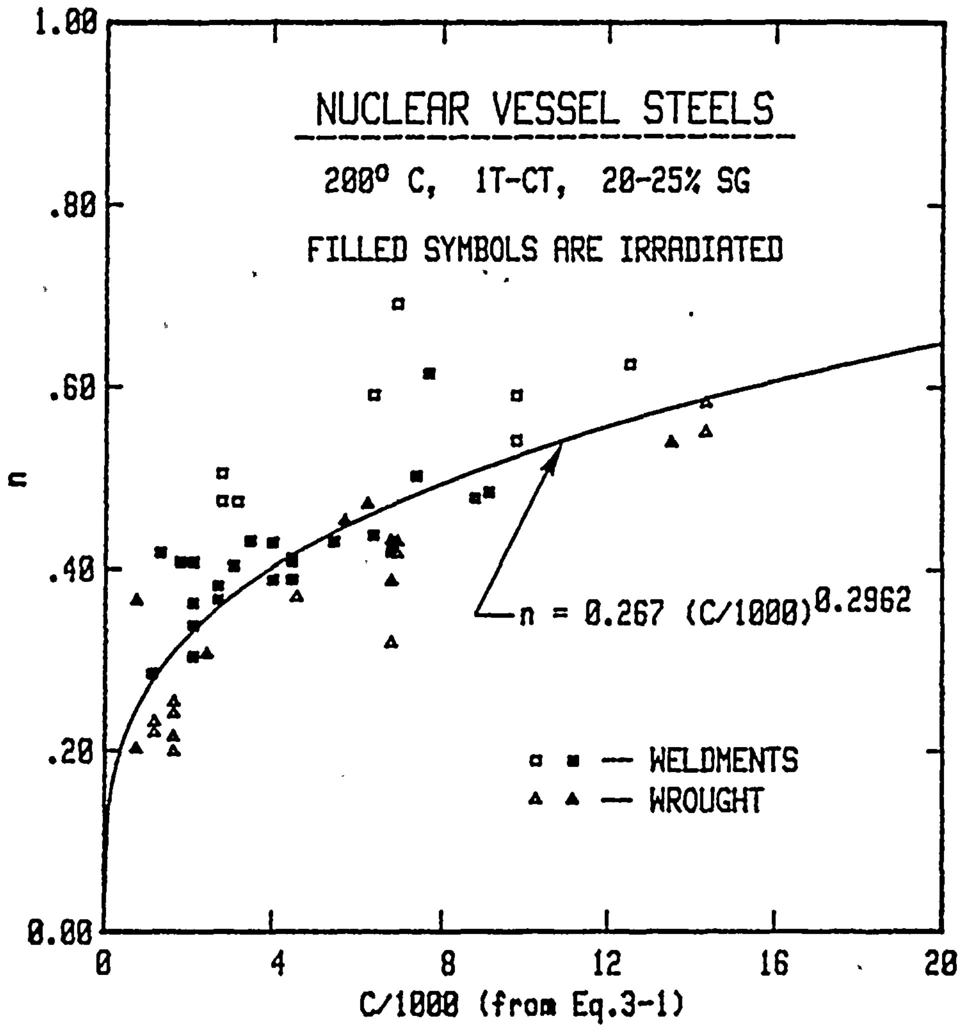



Figure 2.1-4 Correlation of Power Law Exponent "n" with Coefficient "C" [MEA83]

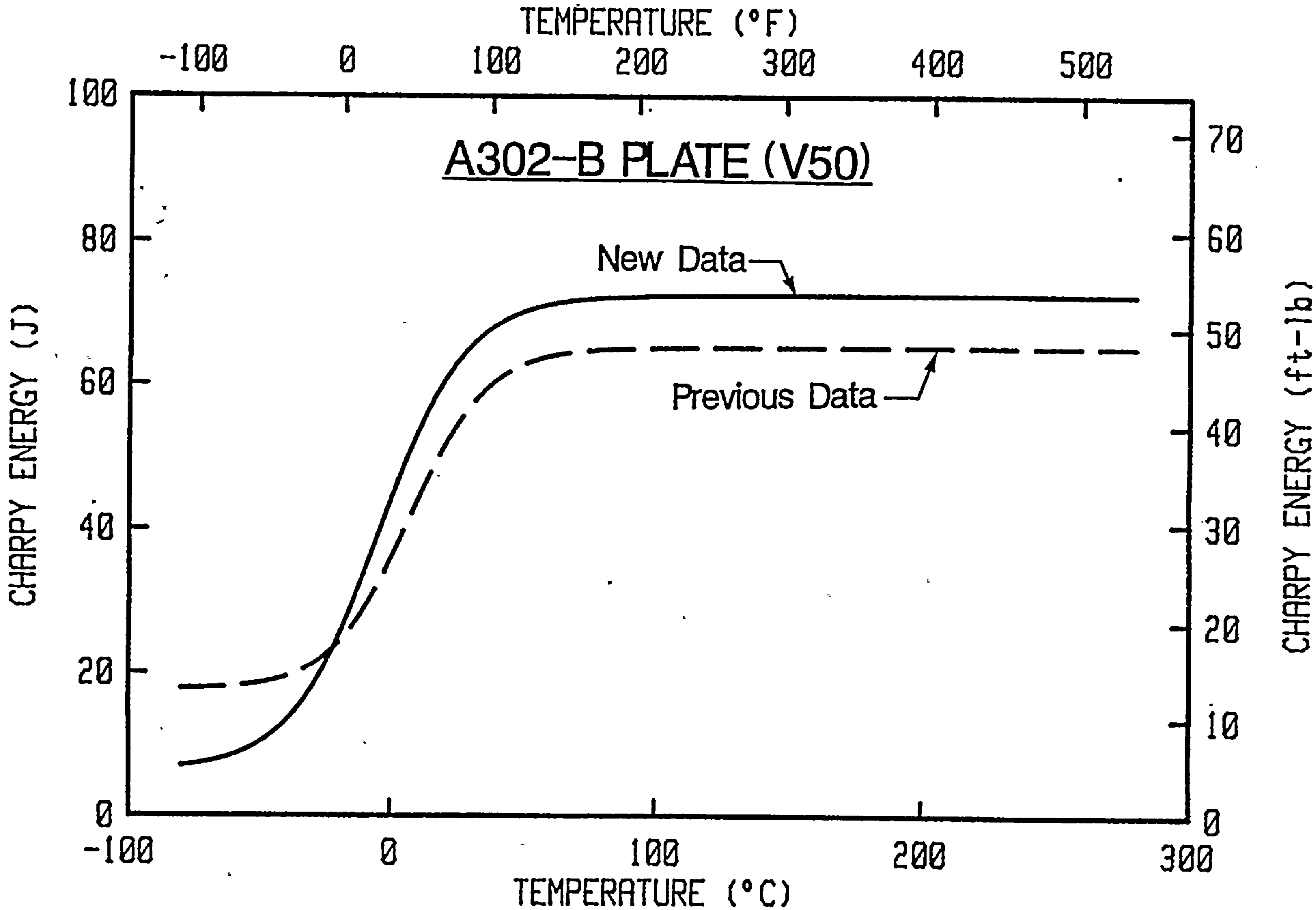



Figure 2.1-5 Comparison of the Average Curvefits to the New and the Previous $C_v$ Data for the A302-B Plate. The New Data Indicate Higher Overall Toughness, with a Higher Upper Shelf Energy Level and Lower Transition Temperatures. [HI89]

Table 2.1-1
Power Law Model for ΔJ as a Function of Toughness

| USE | Small Specimen Data | | | ΔJ Used in [MA92] (in-lb/in$^2$) |
|---|---|---|---|---|
| | J(0.1) (in-lb/in$^2$) | $J_{IC}$ (in-lb/in$^2$) | ΔJ (in-lb/in$^2$) | |
| 25 | 223 | 199 | 24 | 175 |
| 30 | 321 | 239 | 82 | 175 |
| 40 | 547 | 319 | 228 | 175 |
| 50 | 807 | 399 | 408 | 175 |
| 60 | 1091 | 479 | 612 | 175 |
| 80 | 1709 | 639 | 1070 | 175 |
| 100 | 2360 | 798 | 1562 | 175 |

Table 2.1-2
Effect of ΔJ Variation on the
Minimum Upper Shelf Energy Level for NMP-1 Plate G-8-1

| Plate | ASME Service Level | Material Model | Minimum USE (Ft-lbs) $\Delta J = 175$ in-lb/in$^2$ | | Minimum USE (Ft-lbs) Variable ΔJ | |
|---|---|---|---|---|---|---|
| | | | Flaw Growth of 0.1 in. Criterion $J_1 < J_{0.1}$ | Flaw Stability Criterion | Flaw Growth of 0.1 in. Criterion $J_1 < J_{0.1}$ | Flaw Stability Criterion |
| G-8-1 | A&B | A302B | 13 | 23 | 33 | 36 |
| G-8-1 | C | A302B | 10 | 10 | 31 | 31 |
| G-8-1 | D | A302B | n/a | 20 | n/a | 30 |

## 2.2 Information Request 2. - Mechanics Model

*"The report contains no description of the fracture mechanics analysis procedure, i.e. the equations used for calculating $J_{appl}$, $T_{appl}$, and $P_{Int}$. Only the name of a computer program is mentioned. Either confirm that the equations used are identical to those in Appendix X or list all the equations which differ."*

RESPONSE:

As mentioned in Section 3.0 of Reference [MA92], the procedure and equations specified in Appendix X [ASME92] for Service Levels A and B are identical to those used to calculate the applied J, the applied tearing modulus, and internal pressure at flaw instability, under the J-Integral/Tearing Modulus Procedure.

## 2.3 Information Request 3. - Effect of Cladding

*"Provide information regarding the effect of cladding to the calculated applied J value."*

RESPONSE:

Background

Reference [ASME92] does not explicitly recommend nor require that clad stress effects be included in the Service Level A and B analysis. Discussions with several members of the ASME Working Group on Flaw Evaluation (WGFE) indicated that the effects of cladding have been discussed, but the group does not plan to recommend incorporation of clad stress analysis procedures into Appendix X. ASME article A-3000, "Method for $K_I$ Determination", does require consideration of residual and applied stress of all forms, including clad-induced stress, to be included in stress intensity factor formulation. Therefore, NMPC included clad induced stress effects for Service Level C and D loadings, because the Service Level C and D analyses require calculations to be performed for shallow surface flaws where clad induced stress can be significant. However, clad stress effects were not included in the Service Level A and B analyses because 1/4 T flaws are postulated in these analyses and the clad induced stress were assumed to be negligible.

Estimated Clad Induced Stress Effect

In response to the NRC information request, the effect of cladding on the applied J for Service Level A and B loadings has been estimated. Surface tensile stresses result from differential thermal contraction from the stress relief heat treatment at 1150°F. A linear elastic model was formulated to calculate the stress resulting from cooldown from 1150°F, and the model predicts that the hoop stresses exceed yield before the vessel ID temperature reaches 100°F. An elastic-plastic finite element analysis of the cooldown from 1150°F to room temperature, followed by re-heating to 528°F, with a subsequent 100°F/hr cooldown, was performed. The results of the finite element analysis confirmed the analytical model prediction of a 36 ksi hoop stress in the clad due to differential thermal contraction when the cooldown of the vessel was terminated at a vessel ID temperature of 100°F. The stress intensity at the 1/4T flaw due to the clad stress ($K_{CLAD}$) was calculated and found to be 6.6 ksi$\sqrt{in}$. The stress intensity model includes the effects of the base metal compressive reaction force.

The minimum allowable USE was calculated by adding $K_{CLAD}$ to the stress intensity factors defined in Appendix X. The Appendix X calculative procedures were followed and the evaluation criteria applied. The results of these calculations are shown in Table 2.3-1. Review of these data shows that if clad stress effects were included in the Service Level A and B analysis, the minimum allowable USE is below the projected material USE at EOL.

Table 2.3-1
Effect of Clad Stress on the
Minimum Upper Shelf Energy Level for NMP-1 Plate G-8-1

| Plate | ASME Service Level | Material Model | Minimum USE (Ft-Lbs) Without Clad Stress Effect | | Minimum USE (Ft-Lbs) With Clad Stress Effect | |
|---|---|---|---|---|---|---|
| | | | Flaw Growth of 0.1 in. Criterion $J_1<J_{0.1}$ | Flaw Stability Criterion | Flaw Growth of 0.1 in. Criterion $J_1<J_{0.1}$ | Flaw Stability Criterion |
| G-8-1 | A&B | A302B | 13 | 23 | 26 | 37 |

## 3.0 RESPONSES TO ENCLOSURE 2 REQUESTS FOR ADDITIONAL INFORMATION - SERVICE LEVELS C AND D

### 3.1 Information Request 1. - Temperature Dependencies

*"The report indicates in Section 4.1 that temperature dependent properties were used in the thermal and stress analyses. Provide the details of these temperature dependencies."*

RESPONSE:

Table 3.1-1 shows the temperature dependent properties referred to in Section 4.1 of Reference [MA93b]. The finite element software [WELD3] uses linear interpolation within the material property tables. The volumetric heat capacity (c) is related to specific heat ($C_p$) and density ($\rho$) by:

$$c = \rho C_p$$

The instantaneous coefficient of thermal expansion is defined in terms of the slope of the thermal strain versus temperature curve:

$$\alpha = \frac{de_T}{dT}$$

The instantaneous coefficient is different from the average coefficient which is perhaps more commonly used. While the average coefficient must have an associated reference temperature (the temperature at which thermal strain is zero), the instantaneous value does not. Table 3.1-2 shows the average coefficient of thermal expansion that was automatically generated by the finite element software from the input instantaneous values. The values based on a reference temperature of 1150°F were used in computing the initial residual stress state due to slow cooling from a stress-free condition at 1150°F to 528°F. The values based on a reference temperature of 528°F were used for the transient thermal analyses associated with Level C and Level D loadings.

Table 3.1-1 Temperature Dependence of Material Properties

| | |
|---|---|
| Temperature (T): | °F |
| Conductivity (k): | Btu/in/sec/°F |
| Vol. Heat Capacity (c): | $Btu/in^3/°F$ |
| Elastic Modulus (E): | $lb/in^2$ |
| Poisson's Ratio (ν): | nondimensional |
| Inst. Coef. Th. Exp. (α): | 1/°F |

Stainless steel cladding (type 304)

| T | k | c | E | ν | α |
|---|---|---|---|---|---|
| 50. | 0.000182 | 0.0312 | 28700000. | 0.26 | 0.00000816 |
| 300. | 0.000212 | 0.0346 | 27100000. | 0.28 | 0.00000894 |
| 550. | 0.000242 | 0.0371 | 25800000. | 0.31 | 0.00000960 |
| 750. | | | 24200000. | 0.32 | 0.00001003 |
| 1000. | | | 22500000. | 0.30 | 0.00001056 |
| 1300. | | | 20200000. | 0.28 | 0.00001141 |

A302B base metal

| T | k | c | E | ν | α |
|---|---|---|---|---|---|
| 50. | 0.000534 | 0.0298 | 30000000. | 0.28 | 0.00000607 |
| 300. | 0.000572 | 0.0341 | 29000000. | 0.28 | 0.00000710 |
| 550. | 0.000553 | 0.0376 | 27700000. | 0.28 | 0.00000816 |
| 750. | | | 26200000. | 0.28 | 0.00000894 |
| 1000. | | | 24500000. | 0.28 | 0.00001000 |
| 1300. | | | 22200000. | 0.28 | 0.00001100 |

NOTE: Data for k and c at temperatures above 550°F are not provided since thermal transient analyses were performed at temperatures below 550°F.

Table 3.1-2
Average Coefficients of Thermal Expansion for
Reference Temperatures of 1150°F and 528°F

Stainless steel cladding (type 304)

| T | $\alpha_{ave}$ (1/°F) 1150°F | $\alpha_{ave}$ (1/°F) 528°F |
|---|---|---|
| 50. | 9.64330E-06 | 8.87958E-06 |
| 300. | 9.96485E-06 | 9.24096E-06 |
| 550. | 1.02544E-05 | 9.57096E-06 |
| 750. | 1.04741E-05 | 9.79082E-06 |
| 1000. | 1.07725E-05 | 1.00579E-05 |
| 1300. | 1.11975E-05 | 1.04181E-05 |

A302B base metal

| T | $\alpha_{ave}$ (1/°F) 1150°F | $\alpha_{ave}$ (1/°F) 528°F |
|---|---|---|
| 50. | 8.33523E-06 | 7.06121E-06 |
| 300. | 8.85000E-06 | 7.58336E-06 |
| 550. | 9.35833E-06 | 8.11336E-06 |
| 750. | 9.76250E-06 | 8.50673E-06 |
| 1000. | 1.02500E-05 | 9.01694E-06 |
| 1300. | 1.07500E-05 | 9.59326E-06 |

3.2 Information Request 2. - 95% Confidence Properties

*"Figure 4-12 in the report dated December 17, 1992, and in a previous report dated October 16, 1992, indicates that the Mean-2σ properties and the 95% confidence properties (Mean - 1.645σ) give the same lower bound line. Clarify this and confirm that Mean-2σ properties have been used for Levels A, B, and C analyses."*

RESPONSE:

The October 16, 1992, report is based on 95% lower bound confidence limits. In particular, the 95% lower bound $J_{IC}$ values shown in Figure 4-12 were calculated using:

$J_{IC} = 3.1$ (USE), USE $\leq 75$ ft-lbs

$J_{IC} = -363.4 + 7.93295$ (USE), USE > 75 ft-lbs

where,

$J_{IC}$ = in-lb/in$^2$

USE = ft-lb

The portion of the model between the origin and 75 ft-lbs was determined based on conservative engineering judgement. The portion of the model above 75 ft-lbs comes from the regression analysis and represents the 95% confidence lower bound.

In response to the NRC's request, the 95% confidence lower bound was replaced by a two sigma lower bound confidence interval and this model was described in the December 17, 1992, submittal. The two sigma lower bound model is given by:

$J_{IC} = 3.1$ (USE), USE $\leq 75$ ft-lbs

$J_{IC} = -363.4 + 7.915$ (USE), USE > 75 ft-lbs

The portion of the model above 75 ft-lbs comes from the regression analysis and represents the two sigma lower bound. The portion of the model below 75 ft-lbs is based on engineering judgement and is identical to the model used in the October 16, 1992 report. It is NMPC's position that the model used below 75 ft-lbs is more conservative than a two sigma lower bound level. Since the J-R curve model below 75 ft-lbs used in the October 16, 1992, report is the same as that used in the December 17, 1992, report, and the minimum allowable USE is below 75 ft-lb (calculations yielded 23 ft-lbs), the minimum allowable USE which was calculated did not change when the two sigma model was used.

In summary, mean-2σ properties have been used for Service Level A, B, and C analyses.

## 3.3 Information Request 3. - J-Material Values

*"The J-material values at 0.1 inch listed in Table 5-3 are lower than the corresponding values in Figures 5-1 to 5-4 and 5-7 to 5-10 in the Levels A & B report by approximately 6 lbs. Explain this difference."*

RESPONSE:

As described in Reference [MA93b], pointwise experimental data, scaled to account for the toughness level, were used in the analysis. The USE™ (3.0) code uses a multi-linear representation with interpolation when the pointwise input option is used. As an example, the material $J_{0.1}$ datum in Table 5-3 of Reference [MA93b] at 30 ft-lbs ($J_{0.1}$ = 261 in-lb/in$^2$) was determined by interpolating the pointwise J-R data. The material model input for this case is shown in Table 3.3-1. The data in Table 3.3-1 shows that the plateau begins at $\Delta a$ = 0.112 in. with J = 267.4 in-lb/in$^2$. Thus, the apparent discrepancy is an artifact of the pointwise model. Careful examination of Figures 5-1 to 5-4 and 5-7 to 5-10 of the Reference [MA92] report shows that the interpolated J-material values at 0.1 inch have been correctly calculated and the J-R curves are correctly plotted.

Table 3.3-1
USE 3.0 Output Listing Showing J-R Curve Pointwise Input

```
02/15/1993                           - 15 -                             10:28
NMP-1 PLATE G-8-1 A302B MATERIAL MODEL ANALYSIS


 CURVE # 3        JIC= 92.4
*************************************************************************
1. Corresponding upper shelf energy USE =          30 (ft-lbs)

2.         Delta a          J                    Delta a          J
 #  1:     0.002         21.600      # 21:      0.112         267.400
 #  2:     0.004         33.400      # 22:      3.000         268.000
 #  3:     0.005         55.300
 #  4:     0.006         75.000
 #  5:     0.010         95.000
 #  6:     0.017        109.400
 #  7:     0.017        116.400
 #  8:     0.022        136.400
 #  9:     0.023        144.400
 # 10:     0.025        154.400
 # 11:     0.030        165.400
 # 12:     0.032        183.400
 # 13:     0.036        191.400
 # 14:     0.043        201.400
 # 15:     0.048        210.400
 # 16:     0.056        218.400
 # 17:     0.068        225.400
 # 18:     0.073        240.400
 # 19:     0.083        247.400
 # 20:     0.098        260.400
*************************************************************************
```

3.4 Information Request 4. - Transient Duration

*"Levels C and D transients must be analyzed from the beginning of the transient to the time at which the metal at the tip of the flaw being analyzed reaches a temperature equivalent to the adjusted $RT_{NDT}$ plus 50°F. Confirm that this practice has been adopted or provide revised analyses."*

RESPONSE:

For service Levels C and D, the $ART_{NDT}$ for plate G-307-4 ranges between 144°F and 163°F from the 1/4T position to the ID surface at 18 EFPY. Therefore, the $ART_{NDT}$ plus 50°F would range from 199°F to 210°F. The blowdown transients are terminated when the pressure reaches 35 psig to account for the containment pressure level at that time in the transient. In the Reference [MA93b] thermal stress calculations, these transients were extended to longer times, conservatively assuming a 300°F per hour cooldown to a 212°F vessel ID temperature. Thus, the Level C and D transients were not analyzed to a temperature equivalent to the $ART_{NDT}$ plus 50°F at the flaw tip. However, as discussed in Reference [MA93b], the limiting transients experienced peak thermal and mechanical loads prior to the point when the transient analysis was terminated.

The cooldown from the final transient conditions to $ART_{NDT}$ plus 50°F is a controlled evolution which is not included in the transient definition and is properly considered as a recovery action. The cooldown from 212°F would be bounded by the emergency cooldown event and in most cases would be bounded by the normal operation cooldown analysis.

The standard GE thermal cycle transient definition used for the design basis emergency and faulted stress analysis does not include a cooldown to $ART_{NDT}$ plus 50°F. The standard GE thermal cycle diagram is the basis for the limiting Level C (emergency) and limiting Level D (faulted) thermal transient used for the Reference [MA93b] analyses. The standard Level C and D temperature and pressure transient are defined based on the design basis event and are terminated when the event is stabilized. The cooldown from the final stabilized transient condition to the $ART_{NDT}$ plus 50°F is controlled by operator actions and emergency operating procedure guidelines. In general, the operator guidelines include maintaining the cooldown within the 100°F per hour normal guideline. For all the Level C transient conditions, the operator can be assumed to have the ability to control the recovery cooldown rate within the normal operating guidelines after the event has stabilized.

For the limiting design basis Level D recirculation line break event, the emergency operating procedure guidelines include a containment floodup which occurs over a 6 to 12 hour period. Containment floodup is completed using lake water assumed to be at the maximum of 81°F and a minimum of approximately 35°F. The limiting assumption would be that the vessel wall temperature is rapidly cooled from 212 to 100°F (ambient containment temperature and pressure is approximated to remain greater than 100°F due to decay heat). This limiting condition is closely approximated by the normal cooldown rate assumptions.

Assuming the NMP-1 design basis LOCA scenario where the reactor is not reflooded, the ultimate cooldown from saturated conditions is controlled by the containment accident temperature. The primary containment wetwell and drywell temperature profile results in the drywell airspace temperature remaining greater that 175°F for approximately 4 hours with a subsequent slow cooldown rate (much less than 100°F per hour cooldown) linked to the containment heat removal systems.

In summary, the Level C and D transients were not analyzed to the time at which the metal at the tip of the flaw reaches a temperature equivalent to the adjusted $RT_{NDT}$ plus 50°F. However, the limiting transients reached peak thermal and mechanical loads prior to the point where the transient analysis was terminated. Therefore, the results reported in Reference [MA93b] are the most conservative results for any of the Service Level C and D transients.

3.5 Information Request 5. - Thermal Transient Parameters

*"Supply a complete list of input parameters and conditions for the transient thermal analysis, including specific heat, thermal conductivity, density, the resulting value of thermal diffusivity, coefficient of thermal expansion, elastic modulus and Poisson's ratio (for both cladding and base metal); also the relationships needed to determine the inside surface heat transfer coefficient."*

RESPONSE:

The information provided below defines the input parameters and conditions for the transient thermal analysis. The material properties are given in Tables 3.5-1 and 3.5-2. Specific heats ($C_p$) and densities ($\rho$) were not input to the thermal analysis. Volumetric heat capacity (c), the product of these two parameters, was input instead. Thermal diffusivity ($\kappa$) was also not a direct input to the analyses. However, it was computed from the conductivity (k) and heat capacity (c) properties as follows:

$$\kappa = k / c$$

Table 3.5-3 summarizes the thermal diffusivities resulting from the conductivities and heat capacities listed in Table 3.5-1.

The time dependent internal pressure and fluid temperature boundary conditions for the Level C and D loadings are given in Tables 3-7 (Level C) and 3-8 (Level D) of the report [MA93b]. The outer surface of the vessel is assumed to be insulated. The time dependent heat transfer coefficient at the inner vessel surface is also given in these tables.

The finite element software linearly interpolates (in time) between the input values of internal pressure and fluid temperature that are specified by Tables 3-7 and 3-8 of Reference [MA93b]. The heat transfer coefficients (h), however, are not linearly interpolated. The heat transfer coefficients are changed in the model in a stepwise manner. For example, in Table 3-7 [MA93b], h is held at 10,000 until a time of 380 seconds; then h is changed instantaneously to the new value of 164. Since h never increases during the critical times of these transients, this procedure results in larger h values being used further into the cooling transient. This results in larger thermal gradients being calculated and thus conservative thermal stress predictions. The heat transfer coefficients of Tables 3-7 and 3-8 are given in units of BTU/hr/ft$^2$/°F. The analysis used units of BTU/sec/in$^2$/°F. Table 3.5-4 provides the h values of Tables 3-7 and 3-8 [MA93b] in the units of the analysis.

Table 3.5-1
Temperature Dependence of Material Properties

| | |
|---|---|
| Temperature (T): | °F |
| Conductivity (k): | Btu/in/sec/°F |
| Vol. Heat Capacity (c): | Btu/in$^3$/°F |
| Elastic Modulus (E): | lb/in$^2$ |
| Poisson's Ratio (ν): | nondimensional |
| Inst. Coef. Th. Exp. (α): | 1/°F |

Stainless steel cladding (type 304)

| T | k | c | E | ν | α |
|---|---|---|---|---|---|
| 50. | 0.000182 | 0.0312 | 28700000. | 0.26 | 0.00000816 |
| 300. | 0.000212 | 0.0346 | 27100000. | 0.28 | 0.00000894 |
| 550. | 0.000242 | 0.0371 | 25800000. | 0.31 | 0.00000960 |
| 750. | | | 24200000. | 0.32 | 0.00001003 |
| 1000. | | | 22500000. | 0.30 | 0.00001056 |
| 1300. | | | 20200000. | 0.28 | 0.00001141 |

A302B base metal

| T | k | c | E | ν | α |
|---|---|---|---|---|---|
| 50. | 0.000534 | 0.0298 | 30000000. | 0.28 | 0.00000607 |
| 300. | 0.000572 | 0.0341 | 29000000. | 0.28 | 0.00000710 |
| 550. | 0.000553 | 0.0376 | 27700000. | 0.28 | 0.00000816 |
| 750. | | | 26200000. | 0.28 | 0.00000894 |
| 1000. | | | 24500000. | 0.28 | 0.00001000 |
| 1300. | | | 22200000. | 0.28 | 0.00001100 |

NOTE: Data for k and c at temperatures above 550°F are not provided since thermal transient analyses were performed at temperatures below 550°F.

Table 3.5-2
Average Coefficients of Thermal Expansion
for Reference Temperatures of 1150°F and 528°F

Stainless steel cladding (type 304)

| | $\alpha_{ave}$ (1/°F) | |
|---|---|---|
| T | 1150°F | 528°F |
| 50. | 9.64330E-06 | 8.87958E-06 |
| 300. | 9.96485E-06 | 9.24096E-06 |
| 550. | 1.02544E-05 | 9.57096E-06 |
| 750. | 1.04741E-05 | 9.79082E-06 |
| 1000. | 1.07725E-05 | 1.00579E-05 |
| 1300. | 1.11975E-05 | 1.04181E-05 |

A302B base metal

| | $\alpha_{ave}$ (1/°F) | |
|---|---|---|
| T | 1150°F | 528°F |
| 50. | 8.33523E-06 | 7.06121E-06 |
| 300. | 8.85000E-06 | 7.58336E-06 |
| 550. | 9.35833E-06 | 8.11336E-06 |
| 750. | 9.76250E-06 | 8.50673E-06 |
| 1000. | 1.02500E-05 | 9.01694E-06 |
| 1300. | 1.07500E-05 | 9.59326E-06 |

Table 3.5-3
Thermal Diffusivity

| Diffusivity ($\kappa$): $in^2/sec$ | | |
|---|---|---|
| Stainless steel cladding (type 304) | | |
| | T | $\kappa$ |
| | 50. | 5.83E-03 |
| | 300. | 6.13E-03 |
| | 550. | 6.52E-03 |
| A302B base metal | | |
| | T | $\kappa$ |
| | 50. | 1.79E-02 |
| | 300. | 1.68E-02 |
| | 550. | 1.47E-02 |

Table 3.5-4
Heat Transfer Coefficient Conversion

| $BTU/hr/ft^2/°F$ | $BTU/sec/in^2/°F$ |
|---|---|
| 69,188 | 1.33E-01 |
| 10,000 | 1.93E-02 |
| 500 | 9.65E-04 |
| 164 | 3.16E-04 |

## 3.6 Information Request 6. - Clad Equivalent Stress

*"Supply the detailed calculation procedure for determining the clad equivalent stress values listed in Table 5-1."*

The "Extrapolated Surface Stress" column in Table 5-1 of Reference [MA93b] is the stress at the pressure vessel ID surface obtained by fitting the base metal finite element calculated stress distribution to the following equation,

$$\sigma = A_O + A_1X + A_2X^2 + A_3X^3$$

where,

$A_i$ = regression constants

X = distance through the wall

and extrapolating to the ID surface. The "Clad Stress Minus Extrapolated Surface Stress" column is the difference between the discontinuous clad stress due to cooldown from reactor operating temperature during the transient and the extrapolated base metal stress at the surface. The "Residual Stress" column is the tensile stress in the clad due to cooldown from 1150°F to reactor operating temperature during final stress relief. The "Clad Total Stress" column is the sum of the "Clad Stress Minus Extrapolated Surface Stress" data and the clad "Residual Stress" data. The "Crack Surface Pressure" column is the stress on the crack faces due to coolant pressure.

The "Clad Equivalent Line Stress" column was obtained by multiplying the "Clad Total Stress" by the clad thickness (5/32 in.) to obtain the equivalent line stress for the stress intensity model, and adding the "Crack Surface Pressure" times the maximum anticipated flaw depth (1.0 in). It is recognized that the "Crack Surface Pressure" may be added to the base metal finite element calculated stress distribution and then fit as described earlier. However, the above described procedure is conservative and computationally simpler.

3.7 Information Request 7. - Stress Intensity Factor Equation

*"Provide the derivation or the reference (indicating the page number) of Equation (5-3)."*

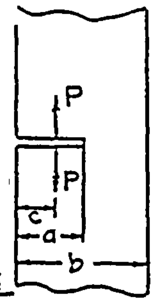
RESPONSE:

Equation 5-3 of Reference [MA93b] can be found in the following reference:

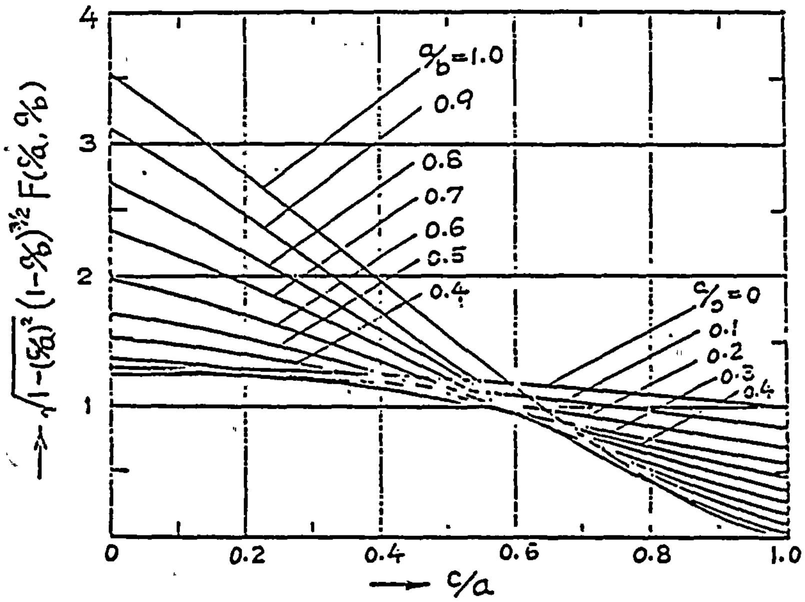
The Stress Analysis of Cracks Handbook, Tada, H., Paris, P., Irwin, G., Del Research Corporation, June, 1973, page 2.27

A copy of the Tada model is shown in Figure 3.7-1.

$$K_I = \frac{2P}{\sqrt{\pi a}} \cdot F(c/a, a/b)$$




$$F(c/a, a/b) = \frac{3.52(1-c/a)}{(1-a/b)^{3/2}} - \frac{4.35-5.28\,c/a}{(1-a/b)^{1/2}} + \left\{ \frac{1.30-0.30(c/a)^{3/2}}{\sqrt{1-(c/a)^2}} + 0.83 - 1.76\,c/a \right\} \left\{ 1-(1-c/a)\,a/b \right\}$$




Method: Estimated by Interpolation

Accuracy: F(c/a,a/b)-formula is expected to have 2 % accuracy for any values of c/a and a/b

Reference: Tada 1974

Figure 3.7-1
Equivalent Line Load Stress Intensity Factor Equation

## 3.8 Information Request 8. - Sample Calculation

*"Provide loads and values of $\Delta a$ for the results labelled under "Flaw Stability Criterion" in Tables 5-3 and 5-4. Supply details for one calculation."*

RESPONSE:

The applied stresses for the limiting Level C and D transients are provided in Reference [MA93b]. The applied J and $\Delta a$ values for the limiting postulated flaw depth under the ASME Appendix X flaw stability criterion for Level C loading conditions are given in Table 3.8-1. Similar data for Level D loading conditions are given in Table 3.8-2. The results shown are for the largest $\Delta a$ which corresponds to the deepest postulated initial flaw analyzed. Iterative calculations were performed which allow the crack to extend to its equilibrium length for cases where the initial $J_{app}$ is greater than $J_{IC}$. A spectrum of initial flaws, up to 1/10 of the base metal wall thickness, were assumed. The smallest postulated flaw is 0.05 in. and the initial flaw sizes were incremented by 0.05 in. up to a maximum initial flaw depth of 0.75 in.

As shown in Tables 3.8-1 and 3.8-2, for USE levels above 20 ft-lbs, the flaw growth is less than 0.08 in. Therefore the J-R curve plateau is not reached and stable tearing occurs until the equilibrium flaw depth is reached.

A sample flaw stability calculation for the Level C loading is provided in Attachment 1.

Table 3.8-1
Applied Loads and Crack Extension for Various USE Levels Analyzed
Under the ASME Appendix X Flaw Stability Criterion for
Level C Loading Conditions and an Axial Flaw Orientation[1]

| USE Level | Final Applied J[2] (in-lb/in$^2$) | Δa Physical (in.) | Applied T | Criterion Satisfied |
|---|---|---|---|---|
| 10 | 182.2 | 0.0793 | 0.096 | yes |
| 20 | 181.5 | 0.0508 | 0.107 | yes |
| 30 | 180.9 | 0.0324 | 0.114 | yes |
| 40 | 180.7 | 0.0246 | 0.117 | yes |
| 50 | 180.4 | 0.0180 | 0.120 | yes |
| 60 | 179.8 | 0.0 | 0.127 | yes, $J_{app}<J_{IC}$ |
| 70 | 179.8 | 0.0 | 0.127 | yes, $J_{app}<J_{IC}$ |
| 80 | 179.8 | 0.0 | 0.127 | yes, $J_{app}<J_{IC}$ |
| 90 | 179.8 | 0.0 | 0.127 | yes, $J_{app}<J_{IC}$ |
| 100 | 179.8 | 0.0 | 0.127 | yes, $J_{app}<J_{IC}$ |

[1] Results shown are for the largest Δa which occurs for the deepest postulated base metal flaw ($a_o$=0.75 in)
[2] The final applied J is iteratively calculated and represents the applied J after the crack reaches its equilibrium length

Table 3.8-2
Applied Loads and Crack Extension for Various USE Levels Analyzed
Under the ASME Appendix X Flaw Stability Criterion for
Level D Loading Conditions and an Axial Flaw Orientation[1]

| USE Level | Final Applied J[2] (in-lb/in$^2$) | $\Delta a$ Physical (in.) | Applied T | Criterion Satisfied |
|---|---|---|---|---|
| 10 | $J_{app}>J_{MAX}$ | - | - | no |
| 20 | 299.5 | 0.0730 | 0.129 | yes |
| 30 | 297.6 | 0.0255 | 0.158 | yes |
| 40 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |
| 50 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |
| 60 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |
| 70 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |
| 80 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |
| 90 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |
| 100 | 296.4 | 0.0 | 0.174 | yes, $J_{app}<J_{IC}$ |

1 Results shown are for the largest $\Delta a$ which occurs for the deepest postulated base metal flaw ($a_o$=0.75 in)
2 The final applied J is iteratively calculated and represents the applied J after the crack reaches its equilibrium length

## 4.0 REFERENCES


[ASME92] ASME Draft Code Case N-XXX, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Energy Levels", Revision 11, May 27, 1992.

[HI89] Hiser, A.L., Terrell, J.B., "Size Effects on J-R Curves for A302B Plate", NUREG/CR-5265, January, 1989.

[MA92] NMPC Letter from C.D. Terry to NRC, dated October 16, 1992, "Elastic-Plastic Fracture Mechanics Assessment of Nine Mile Point Unit 1 Beltline Plates for Service Level A and B Loadings".

[MA92b] NMPC Letter from C.D. Terry to NRC, dated December 17, 1992, "Elastic-Plastic Fracture Mechanics Assessment of Nine Mile Point Unit 1 Beltline Plates for Service Level A and B Loadings".

[MA93] Manahan, M.P. Sr., "Elastic-Plastic Fracture Mechanics Assessment of Nine Mile Point Unit 1 Beltline Plates for Service Level A and B Loadings", Final report prepared for NMPC, MPM-USE-293215, February, 1993.

[MA93b] NMPC Letter from C.D. Terry to NRC, dated February 26, 1993 "Elastic-Plastic Fracture Mechanics Assessment of Nine Mile Point Unit 1 Beltline Plates for Service Level C and D Loadings".

[MEA83] Materials Engineering Associates, Inc., Lanham, MD (Hiser, A.L., and Fishman, D.B.), "J-R Curve Data Base Analysis of Irradiated Reactor Pressure Vessel Steels", Final report prepared for EPRI, December, 1983.

[MEA90] Materials Engineering Associates, Inc., Lanham, MD, "Influence of Fluence Rate on Radiation-Induced Mechanical Property Changes in Reactor Pressure Vessel Steels Final Report on Exploratory Experiments", prepared for NRC, NUREG/CR-5493, March, 1990.

[WELD3] "WELD3 Computer Code Verification", MPM Research & Consulting, Calculation No. MPM-NMPC-99205, Rev. 0, January 21, 1993.

Appendix - Example Level C Flaw Stability Calculation

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