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EVALUATION OF REACTOR PRESSURE VESSELS WITH CHARPY UPPER-SHELF ENERGY LESS THAN 50 FT-LB.

CONTENTS

A. INTRODUCTION

Appendix G, "Fracture Toughness Requirements," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," requires, in part, that the reactor vessel beltline materials ". . .must have Charpy upper- shelf energy of no less than 75 ft-lb (102J) initially and must maintain upper-shelf energy throughout the life of the vessel of no less than 50 ft-lb (68J), 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 the ASME Code." Charpy upper-shelf energy is defined in ASTM E 185-79 (Ref. 1) and -82 (Ref. 2), which are incorporated by reference in Appendix H, "Reactor Vessel Material Surveillance Program Requirements," to 10 CFR Part 50. This guide describes general procedures acceptable to the NRC staff for demonstrating equivalence to the margins of safety in Appendix G of the ASME Code (Ref. 3). Several examples using these procedures are presented in Appendix A to this guide and in more detail in NUREG/CR-6023 (Ref. 4).

This regulatory guide contains information collections that are subject to the Paperwork Reduction Act of 1980 (44 U.S.C. 3501 et seq.). This regulatory guide has been submitted to the Office of Management and Budget for review and approval of the information collections. These information collections and record keeping are needed for demonstrating compliance with Appendix G to 10 CFR Part 50 for the remaining duration of the plant's license if Charpy upper-shelf energy of the materials in the beltline region may drop, or may have dropped, below the 50 ft-lb regulatory limit.

The public reporting burden for this collection of information is estimated to average 960 hours per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for further reducing the reporting burden, to the Information and Records Management Branch (T6F33), U.S. Nuclear Regulatory Commission, Washington DC 20555; and to the Desk Officer, Office of Information and Regulatory Affairs, NEOB-10202 (3150-0011), Office of Management and Budget, Washington, DC 20503.

B. DISCUSSION

The problem of evaluating materials that do not satisfy the 50 ft-lb upper-shelf energy requirement was recognized by the NRC staff several years ago and was designated Unresolved Safety Issue A-11, "Reactor Vessel Materials Toughness." In 1982, the staff completed resolution of USI A-11 by issuing NUREG-0744, "Resolution of the Task A-11 Reactor Vessel Materials Toughness Safety Issue" (Ref. 5), which provided methods for evaluating the fracture behavior of these materials. Further, Generic Letter 82-26 (Ref. 6) was issued to advise licensees of the USI resolution. No new requirements were implemented as part of the USI resolution. However, neither NUREG-0744 nor Generic Letter 82-26 contained criteria for demonstrating equivalence of margins with Appendix G of the ASME Code. Rather, the NRC staff asked Section XI of the ASME Boiler Pressure Vessel Code Committee to develop and suggest to the staff appropriate criteria.

In February 1991, the Chairman of the ASME Section XI Subgroup on Evaluation and Standards provided to the NRC staff criteria that had been developed by members of the Working Group on Flaw Evaluation (WGFE) and the Working Group on Operating Plant Criteria (WGOPC) (Ref. 7). Although these criteria did not represent ASME Code criteria, they did represent the best opinion of knowledgeable persons familiar with the problem and with the ASME Code.

Upon review, the NRC staff found these criteria to be acceptable for demonstrating margins of safety equivalent to those in Appendix G of the ASME Code (Ref. 3). However, specific methods for evaluating the criteria still were being developed by the cognizant ASME Code committees. Further, those efforts were not expected to provide specific guidance on determining event sequences and transients to be considered, nor were they expected to provide specific guidance on appropriate material properties.

This guide has been developed to provide comprehensive guidance acceptable to the NRC staff for evaluating reactor pressure vessels when the Charpy upper-shelf energy falls below the 50 ft-lb limit of Appendix G to 10 CFR Part 50. The analysis methods in the Regulatory Position are based on methods developed for the ASME Code, Section XI, Appendix K (Ref. 8). The staff has reviewed the analysis methods in Appendix K and finds that they are technically acceptable but are not complete, because Appendix K does not provide information on the selection of transients and gives very little detail on the selection of material properties. In this regulatory guide, specific guidance is provided on selecting transients for consideration and on appropriate material properties to be used in the analyses.

Ductile tearing is the dominant fracture process in the upper-shelf region of the Charpy impact energy versus temperature curve for RPV materials. The conditions governing cleavage mode-conversion of the ductile tearing process in materials with low Charpy upper-shelf energy are still not well understood and are not considered in this regulatory guide.

The material property needed to characterize ductile tearing in the analysis methods in this regulatory guide is the material's J-integral fracture resistance, the J-R curve. This curve is a function of the material, the irradiation condition, the loading rate, and the material temperature. The curve is determined by testing the specific material, under the conditions of interest, in accordance with the American Society for

Testing and Materials Standard Test Method E 1152-87, "Standard Test Method for Determining J-R Curves" (Ref. 9).

Unfortunately, the specific material of interest (i.e., the material from the beltline region of the reactor vessel under operation) is seldom available for testing. Thus, testing programs have used generic materials that are expected to represent the range of actual materials used in fabricating reactor pressure vessels in the United States. Statistical analyses of these generic data have been performed and reported in NUREG/CR-5729, "Multivariable Modeling of Pressure Vessel and Piping J-R Data" (Ref. 10). These analyses provide a method for determining the material's J-integral fracture resistance that the NRC staff finds acceptable for use in the methods described in this guide. Other methods for determining the material property may be used on an individual-case basis if justified.

NOMENCLATURE

The following terms are used in this regulatory guide and its equations.

a	The flaw depth, which includes ductile flaw growth (in inches).
a_e	The effective flaw depth, which includes ductile flaw growth and a plastic-zone correction (in inches).
a_e^*	The effective stable flaw depth, which includes ductile flaw growth and a plastic-zone correction (in inches).
a_e^{**}	The effective stable flaw depth at tensile instability of the remaining ligament, which includes ductile flaw growth and a plastic-zone correction (in inches).
a_o	The postulated initial flaw depth (in inches).
2c	The total flaw length, which includes ductile flaw growth (in inches).
B_n	Net-section thickness of the ASTM E 1152-87 (Ref. 9) test specimen used in determining material tearing resistance, J-R curve, behavior (in inches).
C1, C2 C3, C4	Coefficients used in the equation for the material tearing resistance, J-R curve.
CR	The cooldown rate (°F/hour).
CVN	Charpy v-notch upper-shelf energy (ft-lb.).
E	Young's modulus of elasticity (ksi).
E'	$E/(1-\nu^2)$ (ksi).
F_1, F_2, F_3	Geometry factors used to calculate the stress intensity factors (dimensionless).
$J_{applied}$	The J-integral from the applied loads (in.-lb/in.^{2}).
$J_{material}$	The material's J-integral fracture resistance (in.-lb/in.^{2}), J-R curve.
$J_{0.1}$	The material's J-integral fracture resistance at a ductile flaw growth of 0.10 in. (in.-lb/in.^{2}).
K_{IcL}	The mode I stress intensity factor caused by the radial thermal gradient through the cladding applied to the vessel inner surface, calculated with no plastic zone correction (ksi $\sqrt{\text{in.}}$).
K_{Ip}	The mode I stress intensity factor caused by the internal pressure, calculated with no plastic-zone correction (ksi $\sqrt{\text{in.}}$); K_{Ip}^{Axial} and $K_{Ip}^{Circum.}$ are the axial and circumferential values, respectively.
K_{Ip}'	K_{Ip} calculated with a plastic-zone correction (ksi $\sqrt{\text{in.}}$).
K_{It}	The mode I stress intensity factor caused by the 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 $\sqrt{\text{in.}}$).
p	Internal pressure (ksi).
p_a	The maximum accumulation pressure as defined in the plant-specific Overpressure Protection Report, but not exceeding 1.1 times the design pressure (ksi).
R_i	The inner radius of the vessel (in inches).
SF	The safety factor (dimensionless).
t	The wall thickness of the vessel's base metal (in inches).
t'	The sum of the vessel wall thickness, t, and the cladding thickness, t_{cL} (in inches).
t_{cL}	The thickness of the stainless steel cladding applied to the vessel inner surface (in inches).
T	Metal temperature, at crack-tip, used in the analysis (°F).

MF The margin factor = 2 standard deviations on test data (dimensionless).

σ_f A reference material's flow stress, specified as 85 ksi in ASME Section XI, Appendix K (Ref. 8), on Charpy upper-shelf energy.

σ_y The material's yield stress (ksi).

ν Poisson's ratio (dimensionless), specified as 0.3.

C. REGULATORY POSITION

1. ACCEPTANCE CRITERIA

The following criteria are acceptable to the NRC staff for demonstrating that the margins of safety against ductile fracture are equivalent to those in Appendix G to Section III of the ASME Code. Licensees may follow this regulatory guide to determine the equivalent safety margins, or they may use any other methods, procedures, or selection of materials data and transients to demonstrate compliance with Appendix G to 10 CFR Part 50. If licensees choose to follow this regulatory guide, they must use the acceptance criteria, analysis methods, material properties, and selection of transients as described in this regulatory guide. The acceptance criteria are to be satisfied for each category of transients, namely, Service Load Levels A and B (normal and upset), Level C (emergency), and Level D (faulted) conditions. These service load levels are described in Standard Review Plan 3.9.3 (Ref. 11). Because of differences in acceptable outcome during the various sevice load levels, different criteria have been developed for Levels A and B, C, and D.

1.1 Level A and B Conditions

When the upper-shelf Charpy energy of the base metal is less than 50 ft-lb, postulate both axial and circumferential interior flaws and use the toughness properties for the corresponding orientation. For a weld with Charpy upper-shelf energy less than 50 ft-lb, postulate an interior surface flaw oriented along the weld of concern and orient the flaw plane in the radial direction. Postulate a semi-elliptical surface flaw with an a/t = 0.25 and with an aspect ratio of 6-to-1 surface length to flaw depth. A smaller flaw size may be used on an individual-case basis if justified. Two criteria must be satisfied as described below. The maximum accumulation pressure, discussed below, is the maximum pressure defined in the Over Pressure Protection Report that satisfies the requirement of Section III, NB-7311(b), of the ASME Code (Ref. 12).

1.1.1 The crack driving force must be shown to be less than the material toughness as given by Equation 1:

$$J_{applied} < J_{0.1} \qquad (1)$$

where $J_{applied}$ is the J-integral value calculated for the postulated flaw under pressure and thermal loading where the assumed pressure is 1.15 times the maximum accumulation pressure, with thermal loading using the plant-specific heatup and cooldown conditions. The parameter $J_{0.1}$ is the J-integral characteristic of the material's resistance to ductile tearing ($J_{material}$), as denoted by a J-R curve test, at a crack extension of 0.1 inch.

1.1.2 The flaw must be stable under ductile crack growth as given by Equation 2:

$$\frac{\partial J_{applied}}{\partial a} < \frac{\partial J_{material}}{\partial a} \qquad (2)$$

(with load held constant)

at

$$J_{applied} = J_{material}$$

where $J_{applied}$ is calculated for the postulated flaw under pressure and thermal loading for all service level A and B conditions where the assumed pressure is 1.25 times the maximum accumulation pressure, with thermal loading, as defined above. The material's J-integral fracture resistance should represent a conservative estimate of the data for the vessel material under evaluation (i.e., mean - 2 standard deviations). Methods for determining the J-integral fracture resistance, J-R curve, are discussed in Regulatory Position 3 of this guide. Methods for determining the appropriate service level conditions are discussed in Regulatory Position 4 of this guide.

1.2 Level C Condition

When the Charpy upper-shelf energy of the base metal is less than 50 ft-lb, postulate both axial and circumferential interior flaws and use the toughness properties for the corresponding orientation. When the Charpy upper-shelf energy of any weld material is less than 50 ft-lb, postulate an interior surface flaw with its major axis oriented along the weld of concern and the flaw plane oriented in the radial direction. Consider postulated surface flaws with depths up to one-tenth the base metal wall thickness, plus the clad thickness, but with the total depth not to exceed 1.0 inch (2.54 cm) and with an aspect ratio of 6-to-1 surface length to flaw depth. A smaller maximum flaw depth may be used on an individual-case basis if justified. For these evaluations, two criteria must be satisfied.

1.2.1 The crack driving force must be shown to be less than the material toughness as given by Equation 3:

$$J_{applied} < J_{0.1} \qquad (3)$$

where $J_{applied}$ is the J-integral value calculated for the postulated flaw in the beltline region of the reactor vessel under the governing Service Level C condition, with a safety factor of 1.0 on the applied loading. $J_{0.1}$ is the J-integral characteristic of the material resistance to ductile tearing ($J_{material}$), as denoted by a J-R curve test, at a crack extension of 0.1 inch.

1.2.2 The flaw must also be stable under ductile crack growth as given by Equation 4:

$$\frac{\partial J_{applied}}{\partial a} < \frac{\partial J_{material}}{\partial a} \qquad (4)$$

(with load held constant)

at

$$J_{applied} = J_{material}$$

where $J_{applied}$ is calculated for the postulated flaw under the governing Service Level C condition, with a safety factor of 1.0 on the applied loading. The material's J-integral fracture resistance should represent a conservative estimate of the data for the vessel material under evaluation (i.e., mean - 2 standard deviations). The J-integral resistance versus crack growth, J-R curve, is defined in Regulatory Position 3 of this guide. Determination of the appropriate service level conditions is discussed in Regulatory Position 4 of this guide.

1.3 Level D Condition

When the Charpy upper-shelf energy of the base metal is less than 50 ft-lb, postulate both axial and circumferential interior flaws and use the toughness properties for the corresponding orientation. When the Charpy upper-shelf energy of any weld material is less than 50 ft-lb, postulate an interior semi-elliptic surface flaw with the major axis oriented along the weld of concern and the flaw plane oriented in the radial direction. Consider postulated surface flaws with depths up to one-tenth the base metal wall thickness, plus the clad thickness, but with total depth not to exceed 1.0 inch (2.54 cm) and with an aspect ratio of 6-to-1 surface length to flaw depth. A smaller maximum flaw depth may be used on an individual case basis if justified.

For these evaluations, the postulated flaw must be stable under ductile crack growth as given by Equation 5:

$$\frac{\partial J_{applied}}{\partial a} < \frac{\partial J_{material}}{\partial a} \qquad (5)$$

(with load held constant)

at

$$J_{applied} = J_{material}$$

where $J_{applied}$ is calculated for the postulated flaw under the governing Service Level D condition, with a safety factor of 1.0 on the applied loading. Additionally, the flaw depth, including stable tearing, should not be greater than 75% of the vessel wall thickness, and the remaining ligament should be safe from tensile instability. The material's J-integral fracture resistance should reflect a best estimate, i.e., the mean value, of the data representative of the vessel material under evaluation.

The J-integral resistance versus crack growth, J-R curve, is discussed in Regulatory Position 3 of this guide. Methods for determining the appropriate service level conditions are discussed in Regulatory Position 4 of this guide.

2. ANALYSIS METHODS

The analysis methods described in this guide are acceptable to the NRC staff for evaluating the criteria described above. Other methods may be used if justified on a case-by-case basis.

2.1 Level A and B Conditions

The acceptance criteria discussed in Regulatory Position 1.1 for Level A and B conditions involve a comparison of the applied J-integral to the material's J-integral fracture resistance at a ductile flaw extension of 0.1 inch and a determination that this flaw would be stable under the applied loading. Procedures are detailed below for (1) calculating the applied J-integral for Service Levels A and B flaws and loading conditions and (2) determining that the slope of the material's J-integral resistance curve is greater than the slope of the applied J-integral versus crack depth curve at the equilibrium point on the J-R curve where the two curves intersect, as illustrated in Figure 1.

2.1.1 Calculation of the Applied J-Integral

The calculation of the applied J-integral consists of two steps: Step 1 is to calculate the effective flaw depth, which includes a plastic-zone correction, and Step 2 is to calculate the J-integral for small-scale yielding based on this effective flaw depth.

Step 1

For an axial flaw with depth 'a' equal to (0.25t + 0.1 in.), calculate the stress intensity factor from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.15, using Equation 6:

$$K_{Ip}^{Axial} = (SF)\ p_a\ [1 + (R_i/t)]\ (\pi a)^{0.5}\ F_1 \qquad (6)$$

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

This equation for K_{Ip}^{Axial} is applicable to $0.05 \le a/t \le 0.50$, and it includes the effect of pressure acting on the flaw faces.

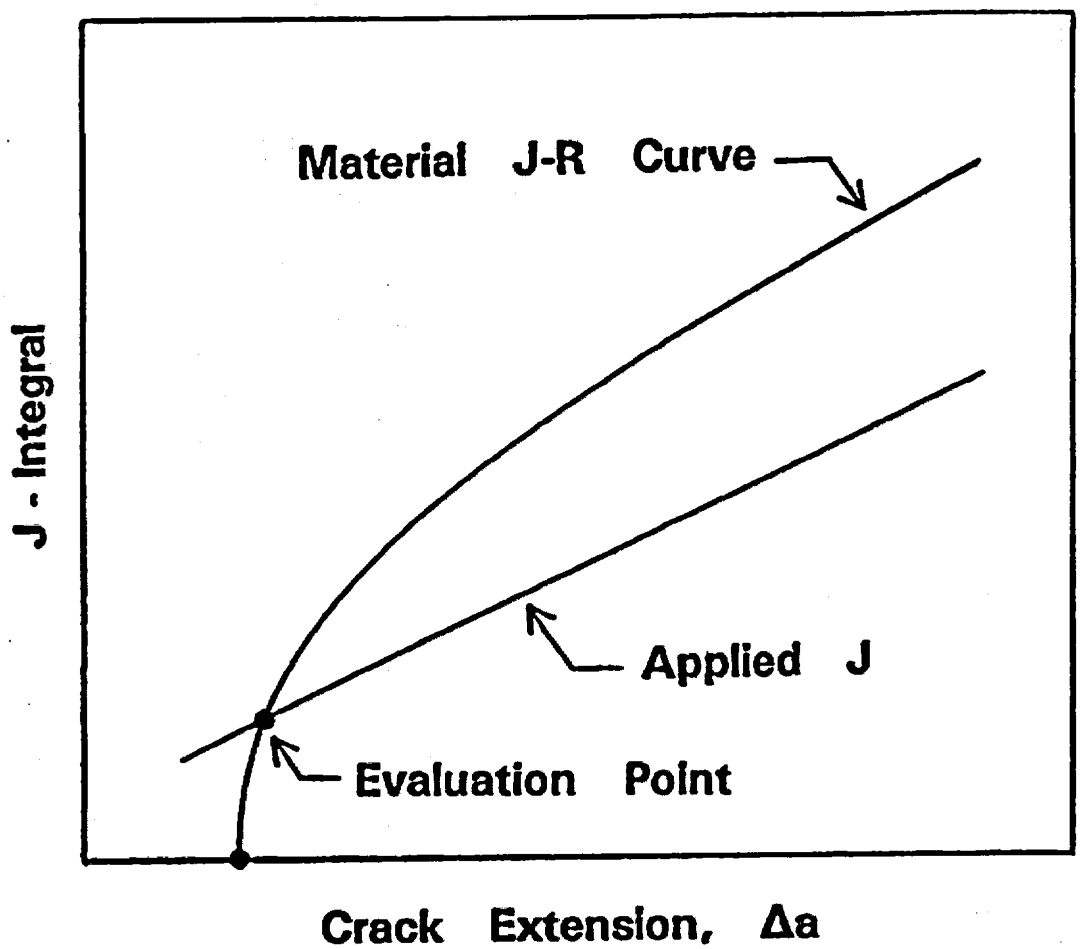

Figure 1. Comparison of the Slope of the Applied J-Integral and J-R Curve.

For a circumferential flaw with depth 'a' equal to (0.25t + 0.1 in.), calculate the stress intensity factor from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.15, using Equation 7:

$$K_{Ip}^{Circum.} = (SF) p_a [1 + (R_i/(2t))](\pi a)^{0.5} F_2 \quad (7)$$

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

This equation for $K_{Ip}^{Circum.}$ is applicable to $0.05 \le a/t \le 0.50$, and it includes the effect of pressure acting on the flaw faces.

For an axial or circumferential flaw with depth 'a' equal to (0.25t + 0.1 in.), the "steady-state" (time independent) stress intensity factor from radial thermal gradients is obtained by using Equation 8:

$$K_{It} = ((CR)/1000) t^{2.5} F_3 \quad (8)$$

$$F_3 = 0.69 + 3.127(a/t) - 7.435(a/t)^2 + 3.532(a/t)^3$$

This equation for K_{It} is valid for $0.2 \le a/t \le 0.50$, and $0 \le CR \le 100$°F/hr. This equation does not include the contribution to K_{It} from the cladding thickness, t_{cL}. If the steady-state values of thermally induced K_{It} are used, the material J-R curve should correspond to the temperature at the beginning of the transient, when a uniformly high temperature is present across the vessel wall thickness, leading to the lowest J-R curve. The above K_{It} expression can be replaced with an improved accuracy solution if an appropriate justification is provided.

Calculate the effective flaw depth for small-scale yielding, a_e, using Equation 9:

$$a_e = a + \left(\frac{1}{6\pi}\right) \left[\frac{(K_{Ip} + K_{It})}{\sigma_y}\right]^2 \quad (9)$$

Step 2

For an axial flaw, calculate the stress intensity factor from internal pressure for small-scale yielding, K'_{Ip}, by substituting a_e in place of 'a' in Equation 6, including the equation for F_1. For a circumferential flaw, calculate K'_{Ip} by substituting a_e in place of 'a' in Equation 7, including the equation for F_2. For an axial or circumferential flaw, calculate the stress intensity factor from the radial thermal gradients for small-scale yielding K'_{It}, by substituting a_e in place of 'a' in Equation 8, including the equation for F_3.

The J-integral from the applied loads for small-scale yielding is given by Equation 10:

$$J_{applied} = 1000 (K'_{Ip} + K'_{It})^2 / E' \quad (10)$$

Alternatively, in place of the steady-state Equation 8, a thermal transient stress analysis may be performed for the limiting cooldown rate, including the contributions of cladding to thermal stress and the thermal stress intensity factor. For this alternative analysis method (also described in Reference 4), the main features for computing K_{It} and K_{ItcL}, which are applied in examples in Appendix A, are given in Appendix B.[1,2] The limiting condition should be determined for the transient time at which the material's J-R curve will be greater than or equal to the $J_{applied}$ for evaluating Equations 1 and 2. The main steps are:

a. Determine the temperature gradient across the vessel wall thickness, in 10 to 20 time steps over the full duration of the transient; and compute the corresponding thermal stress history, taking into account the cladding thickness, t_{cL}.
b. For each time step, compute K_{It} and K_{ItcL} values as a function of the crack depth in the range $0.05 \le a/t' \le 0.5$.
c. For Equation 1, calculate the pressure-induced K_{Ip} and the $J_{applied}$, using Equations 9 and 10, at a crack-tip depth of (0.25t' + 0.1 in.) for each time step.
d. Use Step a to find crack-tip temperature history at each time step. See Figure A-1 in Appendix A for an example.
e. For a given material condition, determine the J-R values at the crack extension of 0.1 inch by using the crack-tip temperature history from Step d. See Figure A-2 in Appendix A for an example.
f. Compare the material's J-R values as a function of time in Step e with the $J_{applied}$ values in Step c. See Figure A-2 in Appendix A for an example. The time at which the J-R value is just equal to the $J_{applied}$ determines the critical condition for evaluating Equation 1.
g. At the time determined in Step f, evaluate Equation 2 to verify the stability of the predicted flaw growth.

2.1.2 Evaluation of Flaw Stability

Flaw stability is evaluated by a direct application of the flaw stability criterion given by Equation 2. The applied J-integral is calculated for a series of flaw depths corresponding to increasing amounts of ductile flaw growth. The applied pressure, p, is set equal to the maximum accumulated pressure for Service Level A and B conditions, p_a, with a safety factor, SF, equal to 1.25. The applied J-integral for Service Level A and B conditions may be calculated using Equations 6 through 10. Each pair of the applied J-integral and flaw depth is plotted on a crack driving force diagram to produce the

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[1] The equations provided in Appendix B may be used if the transient temperature history can be approximated adequately by either an exponential or a polynomial equation. If it cannot be approximated adequately, a more rigorous approach should be used.

[2] The computer code given in Appendix B is for general illustration. Licensees assume responsibility for the correctness of the computer codes they use.

applied J-integral curve as illustrated in Figure 1. The material's J-R curve also is plotted on the crack driving force diagram. Flaw stability at a given applied load is demonstrated if the slope of the applied J-integral curve is less than the slope of the material's J-R curve at the equilibrium point on the J-R curve where the two curves intersect.

2.2 Level C Condition

The acceptance criteria discussed in Regulatory Position 1 for Service Level C conditions are similar to those for Service Levels A and B, with the exceptions of the crack size to be considered and the safety factor applied to the pressure loading. For Service Level C conditions, flaw sizes up to one-tenth the base metal wall thickness, plus the clad thickness t_{cL}, but with a total depth not to exceed 1.0 inch (2.54 cm), are to be considered. A safety factor of 1.0 is used for both pressure and thermal loading. As with the Service Level A and B criteria, for Service Level C it must be demonstrated that the applied J is less than the material's fracture resistance at a crack extension of 0.1 inch, and that the flaw must be stable under the applied loading.

Procedures are described below for (1) determining the applied J-integral for Service Level C flaw and loading conditions and (2) determining that the slope of the material's J-integral fracture resistance, J-R curve, is greater than the slope of the applied J-integral versus crack depth curve.

2.2.1 Calculation of the Applied J-Integral

The calculation of the applied J-integral consists of two steps: Step 1 is to calculate the effective flaw depth, which includes a plastic-zone correction, and Step 2 is to calculate the J-integral for small-scale yielding based on this effective flaw depth.

Step 1

Postulate a series of flaws with depths ranging up to cladding thickness plus 0.1 times the base metal wall thickness, but not exceeding 1.0 inch (2.54 cm). The number of flaws and the specific flaw sizes to be postulated should be sufficient to determine the peak value of the applied J-integral over this size range. For each of these postulated flaws, the analysis flaw size 'a' should be the sum of the postulated flaw size plus 0.1-inch ductile crack extension. For axial flaws, at each analysis flaw size, calculate the stress intensity factor arising from internal pressure, p_a, with a safety factor, SF, on internal pressure equal to 1.0, using Equation 11:

$$K_{Ip}^{Axial} = (SF)p_a\,[1+(R_i/t')]\,(\pi a)^{0.5}F_1 \tag{11}$$
$$F_1 = 0.982 + 1.006(a/t')^2;\ with\ 0.05 \le a/t' \le 0.5$$

For circumferential flaws, at each analysis flaw size calculate the stress intensity factor arising from internal pressure, p_a, with a safety factor, SF, on pressure equal to 1.0, using Equation 12:

$$K_{Ip}^{Circum.} = (SF)p_a[1+R_i/(2t')](\pi a)^{0.5}F_2 \tag{12}$$

$$F_2 = 0.885 + 0.233(a/t') + 0.345(a/t')^2$$

These equations for $K_{Ip}^{Circum.}$ are valid for $0.05 \le a/t' \le 0.5$, and include the effect of pressure acting on the flaw faces.

If it can be demonstrated that the actual cooldown rate could be bounded by a "constant" cooldown rate, for each crack depth the stress intensity factor arising from radial thermal gradient, including cladding effects (see Example 4 in Appendix A) is given by Equation 13:

$$K_{It} = [-0.012771 + 0.849528(\frac{CR}{1000}) - 0.611382(\frac{CR}{1000})^2 + (0.565188 + 0.0467582(\frac{CR}{1000}))(\frac{a}{t'}) - 1.85371(\frac{a}{t'})^2 + 1.62878(\frac{a}{t'})^3](t')^{2.5} \tag{13}$$

This equation is applicable to $0.05 \le a/t' \le 0.5$, and $100 \le CR \le 600$°F/hour. The CR values less than 100°F/hour are covered under Service Levels A and B (see Equation 8). The cladding thickness is t_{cL} = 5/16 in., R_i = 86.875 in., base metal thickness t = 8.625 in., and R_i/t' ratio = 9.72. Details of the analysis results are given in Appendix A. Equation 13 is based on the current state of knowledge on K solutions for 6:1 aspect-ratio flaws subjected to non-uniform stress gradients in the crack-depth direction. The above K_{It} expression can be replaced with an improved accuracy solution if an appropriate justification is provided.

Calculate the effective flaw depth for small-scale yielding, a_e, using Equation 14:

$$a_e = a + (\frac{1}{6\pi})\,[\frac{(K_{Ip} + K_{It})}{\sigma_y}]^2 \tag{14}$$

Step 2

For each flaw size considered, calculate the stress intensity factor arising from internal pressure for small-scale yielding, K'_{Ip}, by substituting a_e in place of 'a' in Equation 11 for the axial flaws and in Equation 12 for the circumferential flaws. Similarly, calculate the stress intensity factor arising from radial thermal gradients for small-scale yielding, K'_{It}, by substituting a_e in place of 'a' in Equation 13. The J-integral arising from the applied loads for small-scale yielding is given by Equation 15:

$$J_{applied} = 1000(K'_{Ip} + K'_{It})^2\,/E' \tag{15}$$

In an actual transient the cooldown rate initially may vary significantly with time. Therefore, transient-specific peak thermal stress-induced K_{It} and K_{IcL} computations may be necessary. If so, in place of Equation 13, a thermal transient stress analysis may be performed for the specific transient, including the contributions of cladding to thermal stress and the stress intensity factor. For this alternative analysis method the main features for computing K_{It} and K_{IcL}, which are applied on examples in Appendix A, are given in Appendix B.[1,2] The limiting condition should be determined for the transient time at which the material's resistance (J-R curve) will be greater than or equal to the $J_{applied}$ for evaluating Equations 1 and 2. The main steps are:

a. Determine the temperature gradient across the vessel wall thickness, in 10 to 20 time steps over the full duration of the transient, and compute the corresponding thermal stress history, taking into account the cladding thickness, t_{cL}.
b. For each time step, compute K_{It} and K_{IcL} values as a function of the crack depth in the range $0.05 \leq a/t' \leq 0.5$.
c. For Equation 1, calculate the pressure-induced K_{Ip} and the $J_{applied}$, using Equations 14 and 15, at a crack-tip depth of $\{(0.1t + t_{cL} + 0.1 \text{ in.}) \leq 1 \text{ in.}\}$ for each time step.
d. Use Step a to find crack-tip temperature history at each time step. See Figure A-1 in Appendix A for an example.
e. For a given material condition, determine the J-R values at the crack extension of 0.1 inch by using the crack-tip temperature history from Step d. See Figure A-2 in Appendix A for an example.
f. Compare the material's J-R values as a function of time in Step e with the $J_{applied}$ values in Step c. See Figure A-2 in Appendix A for an example. The time at which the J-R value is just equal to the $J_{applied}$ determines the critical condition for evaluating Equation 1.
g. At the time determined in Step f, evaluate Equation 2 to verify the stability of predicted flaw growth.

2.2.2 Evaluation of Flaw Stability

Flaw stability is evaluated by a direct application of the flaw stability criterion given by Equation 4. The applied J-integral is calculated for a series of flaw depths corresponding to increasing amounts of ductile flaw growth. The applied pressure, p, is set equal to the peak pressure for the Service Level C transient under consideration with a safety factor, SF, equal to 1.0. The applied J-integral for Service Level C conditions may be calculated using Equations 11 through 15. Each pair of the applied J-integral and flaw depth is plotted on a crack driving force diagram to produce the applied J-integral curve as illustrated in Figure 1. The material's J-R curve also is plotted on the crack driving force diagram and intersects the abscissa at the initial flaw depth, a_o. Flaw stability at a given applied load is demonstrated if the slope of the applied J-integral curve is less than the slope of the material's J-R curve at the equilibrium point on the J-R curve where the two curves intersect.

2.3 Level D Condition

The acceptance criteria discussed in Regulatory Position 1 for Level D Service Conditions involve only the stability of the postulated flaws. Additionally, the stable flaw depth must not exceed 75% of the vessel wall thickness, and the remaining ligament must be safe from the tensile instability.

Stability of ductile crack extension is demonstrated for Service Level D in the same manner used for Service Level C. However, the material properties should represent only the best estimate (i.e., mean value) of the J-R curve for the vessel material under evaluation.

Tensile stability of the remaining ligament is conservatively demonstrated if Equation 16 is satisfied.

$$\sigma_f > 2p(R_i + a_e^{**}) / [\sqrt{3}(t - a_e^{**})] \qquad (16)$$

Where, from Reference 13, for a semi-elliptical flaw,

$$a_e^{**} = [a_e^*(1 - \{1 + 2c^2/t^2\}^{-0.5})] / [1 - (a_e^*/t)\{1 + 2c^2/t^2\}^{-0.5}]$$

3. MATERIAL PROPERTIES

The statistical analyses reported in Reference 10 addressed a broad range of materials and conditions. For the purposes of this guide, the NRC staff has concluded that only the ASTM E 1152-87 (Ref. 9) definition of the J-integral fracture resistance curve should be used. This determination requires that a test specimen's net thickness, B_n, be specified. Smaller specimens typically produce more conservative (lower) J-R curves than larger specimens. However, larger specimens are needed to provide large amounts of crack growth needed in evaluating certain stability criteria described in Regulatory Position 2 of this regulatory guide. The NRC staff recommends the test specimen's net-section thickness, B_n, to be 1.0 inches (2.54 cm) for determining the J-integral resistance curve using the methods specified in Regulatory Position 3. This is a reasonable compromise and slightly simplifies the equations for the material J-R curve. The neutron fluence attenuation at any depth in the vessel wall (such as near the crack tip) should be determined using Regulatory Guide 1.99 (Ref. 14).

This guide provides methods for determining the J-integral fracture resistance of three classes of materials: welds manufactured with Linde 80 welding flux, generic welds used in fabricating reactor pressure vessels, and plate materials (low and high toughness). The J-R curves for plant-specific materials may be used if justified on a case-by-case basis. Otherwise, the material's J-integral fracture resistance may be determined from Equation 17, developed in Reference 10:

$$J_R = (MF)\ \{C1(\Delta a)^{C2} \exp[C3\ (\Delta a)^{C4}]\} \qquad (17)$$

The coefficients in Equation 17 for each material type are discussed below. As noted earlier, the net-section thickness, B_N, of ASTM E 1152-87 (Ref. 9) compact-tension (CT) specimens to be considered is specified as 1 inch. In addition to the Charpy (CVN) models discussed in this guide, Reference 10 contains two other models, namely the Copper-Fluence (Cu-ϕt) models and the pre-irradiation Charpy (CVN_p) models, which may be used to determine the material's J-R curves.

3.1 Welds Made Using Linde 80 Flux

For analyses addressing Service Levels A, B, and C, a conservative representation of the J-R curve is obtained by setting the margin factor, MF = 0.648. For analyses addressing Service Level D, set MF = 1.0.

$$C1 = \exp[-3.67 + 1.45\ \ln(CVN) - 0.00308T] \qquad (18)$$

$$C2 = 0.077 + 0.116\ \ln C1 \qquad (19)$$

$$C3 = -0.0812 - 0.0092\ \ln C1 \qquad (20)$$

$$C4 = -0.5 \qquad (21)$$

3.2 Generic Reactor Pressure Vessel Welds

For analyses addressing Service Levels A, B, and C, a conservative representation of the J-R curve is obtained by setting the margin factor, MF = 0.629. For analyses addressing Service Level D, set MF = 1.0.

$$C1 = \exp[-4.12 + 1.49\ \ln(CVN) - 0.00249T \qquad (22)$$

$$C2 = 0.077 + 0.116\ \ln C1 \qquad (23)$$

$$C3 = -0.0812 - 0.0092\ \ln C1 \qquad (24)$$

$$C4 = -0.5 \qquad (25)$$

3.3 Reactor Pressure Vessel Base (Plate) Materials

The elastic-plastic fracture toughness of plate materials may be relatively high or quite low, depending on a variety of chemical, metallurgical, and thermo-mechanical processing variables. The statistical analyses reported in Reference 10 included only materials that exhibited a J-R curve with a significantly rising slope, i.e., the higher toughness materials. However, test results reported in NUREG/CR-5265, "Size Effects on J-R Curves for A-302B Plate" (Ref. 15), clearly show J-R curves with very little, if any, increase in slope. References 15, 16, and 17 provide some insight into the nature of the low toughness issue for the plate materials. While there are several variables that influence the fracture toughness, sulphur content seems to be a reasonable indicator of the plate toughness, with a "higher" sulphur content indicating "lower" fracture toughness (Ref. 17). A sulphur content of 0.018 wt-% is a good demarcation for high- and low-toughness values.

Because of the low-toughness plate issue, and because of the relatively sparse data base that could be used to estimate the fracture toughness for these materials, a fracture toughness model is only provided for high-toughness plate materials. If the sulphur content of the plate is less than 0.018 wt-%, the plate models described in Reference 10 may be used. However, if the sulphur content is greater than or equal to 0.018 wt-%, justification should be provided for use of the models in Reference 10. Factors that might justify use of these high-toughness models could include information about the year of manufacture of the plate and any special thermo-mechanical processing that would serve to improve the fracture toughness of the plate. If adequate justification cannot be provided, a low-toughness plate model should be developed and used.

The CVN value should be for the proper orientation of the plate material (see Figure 2). For example, for axial flaws the CVN value for the L-T (strong) orientation in the vessel wall should be used. Similarly, for circumferential flaws the CVN value for the T-L (weak) orientation should be used. In many cases, the CVN values for both orientations may not be known. If the CVN value for the T-L (weak) orientation is not available, the L-T (strong) orientation CVN value may be multiplied by a factor of 0.65 (Ref. 18) to obtain the CVN value for the T-L (weak) orientation. However, if the CVN value for the T-L (weak) orientation is known and the L-T (strong) orientation is to be estimated, the CVN value for the L-T (strong) orientation is assumed to be the same as that of the T-L (weak) orientation.

3.3.1 High-Toughness Model (S < 0.018 Wt-%)

For plate material with sulphur content greater than 0.018 wt-%, the use of this model should be justified as discussed above.

For analyses addressing Service Levels A, B, and C, a conservative representation of the J-R curve is obtained by setting the margin factor, MF = 0.749. For analyses addressing Service Level D, set MF = 1.0.

$$C1 = \exp[-2.44 + 1.13\ \ln(CVN) - 0.00277T] \qquad (26)$$

$$C2 = 0.077 + 0.116\ \ln C1 \qquad (27)$$

$$C3 = -0.0812 - 0.0092\ \ln C1 \qquad (28)$$

$$C4 = -0.409 \qquad (29)$$

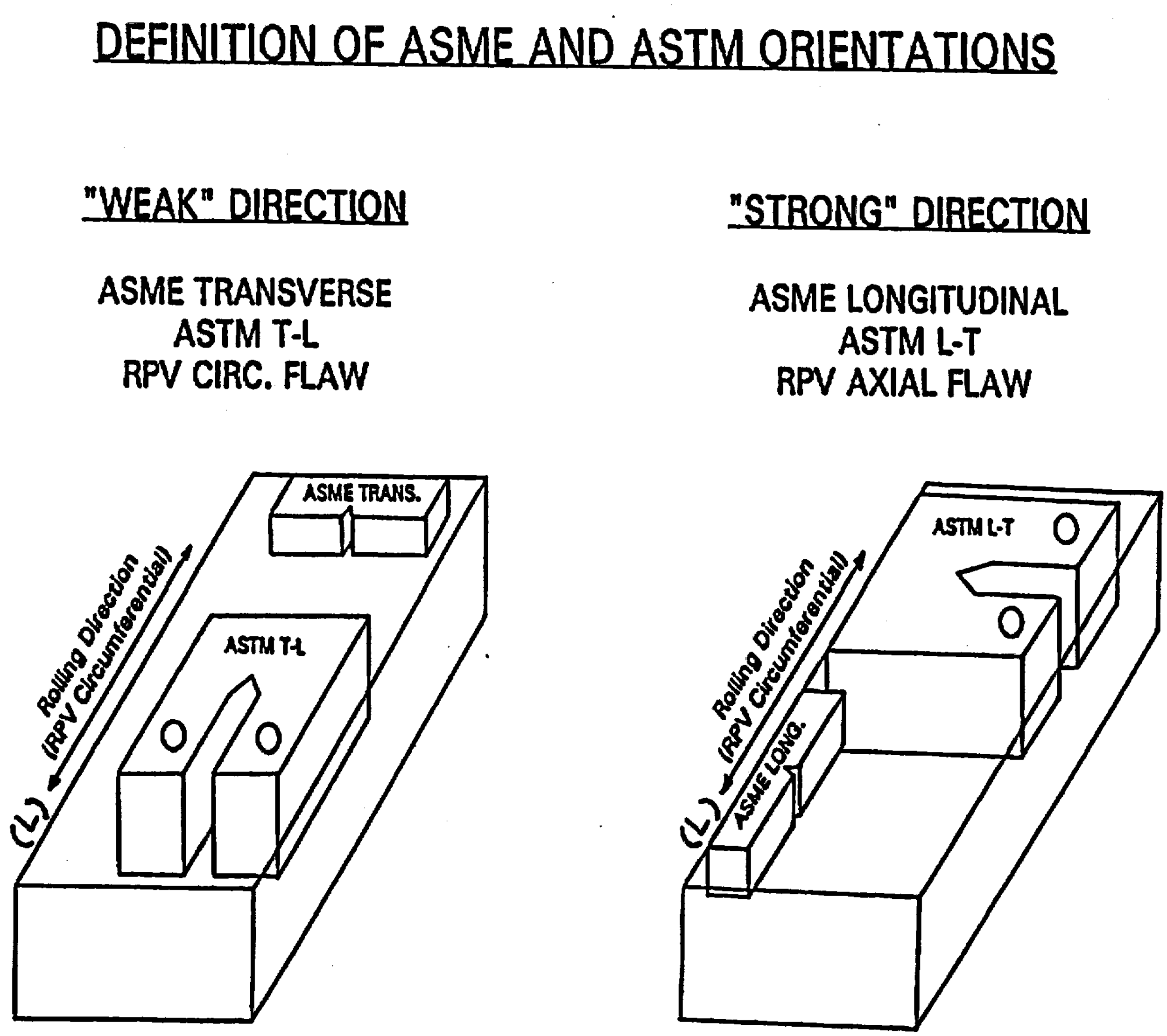

Figure 2. Definition of the ASME and ASTM Flaw Orientations in an RPV.

3.3.2 Low-Toughness Plate (S ≥ 0.018 Wt-%)

For analyses addressing materials with a sulphur content greater than 0.018 wt-%, the J-R curve data are scarce. Very limited J-R data for a 6-inch-thick specimen (ASTM 6T CT at 180°F temperature) from an A-302B plate in the T-L (weak) orientation, available in NUREG/CR-5265 (Ref. 15), may be used with adjustments for the specimen temperature and CVN value (Ref. 19), or a material-specific justification should be provided to support the use of other data. For analyses addressing Service Levels A, B, and C, a lower-bound representation (mean - 2 standard deviations) of the J-R curve should be used. For analyses addressing Service Level D, the mean value of the J-R curve should be used.

Additional J-R curve test data for the low-toughness A302B plate material are presently being generated. Regulatory guidance will be updated, if justified, based on the results obtained from the test data collected for J-R curve in low-toughness plate material.

4. TRANSIENT SELECTION

Selection of the limiting transients for Service Levels C and D is a key aspect of evaluating the integrity of reactor pressure vessels that contain materials with Charpy upper-shelf energy less than 50 ft-lb. Generally, Service Levels A and B are limiting. However, there may be plant-specific considerations that make Service Levels C or D controlling for ductile fracture.

To provide reasonable assurance that the limiting service loading conditions have been identified, either of two approaches may be used: a plant-specific transient evaluation or a generic bounding analysis. It should be noted that plants may be grouped and limiting transients for these groups may be determined. The plant-specific transient evaluation is the preferred approach. However, since some licensees may not have the specific transient information needed for this analysis, a conservative "bounding" analysis may be performed for each service level. Specific guidance for each of these approaches is provided below.

As described in the Discussion section of this guide, ductile tearing is the dominant fracture process in the upper-shelf region, and the possibility of mode-conversion to cleavage (brittle) fracture is not considered in this regulatory guide. The analyses using these bounding transients need only address the transient from its beginning 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. In this regulatory guide, an adjusted RT_{NDT} plus 50°F (which typically represents the low-temperature overpressure protection system's enabling temperature) is taken as the lower temperature limit for upper-shelf behavior.

This regulatory guide states that licensees should consider a spectrum of transients, including ATWS (anticipated transient without scram). Although ATWS is not a design basis transient, for compliance with Appendix G to 10 CFR Part 50 it was considered in Reference 4 for evaluation of low upper-shelf energy materials. Based on the generic analyses in Reference 4 and additional staff calculations, ATWS in currently operating light-water-reactor (LWR) vessels in the United States is not found to be a dominant transient with respect to the low Charpy upper-shelf energy issue, and no further action is necessary with respect to ATWS. However, for designs other than the currently operating LWR vessels in the United States, ATWS could become a dominating transient, and as such needs to be considered as a Service Level C transient for further evaluation. A plant-specific justification should be provided for consideration of such designs at another service load level. For such designs, licensees should consider the assumptions used in the generic analyses of Reference 4 to be sure that they are bounding for their plant-specific applications. If these generic analyses are not bounding, plant-specific analyses should be performed.

4.1 Plant-Specific Transients

To provide reasonable assurance that the limiting service loading conditions have been identified on a plant-specific basis, the Service Level C and D design transients and events that are necessary to demonstrate compliance with Standard Review Plan 3.9.3 (Ref. 11) should be used.

When this transient list is not available or is incomplete, the most complete list of transients for these service levels that is available for similar plant designs should be used. Typically, the most complete list of transients would be for the later-vintage plants from a particular vendor. This list should be reviewed, and the limiting transients for the reactor vessel being analyzed should be defined. Once the transients are defined, system-level thermal-hydraulic analyses should be performed to determine the limiting pressure-temperature-time history for each transient being considered. This history provides the input to the analyses described in this guide.

4.2 Bounding Transients

When the plant-specific transients are not available or when developing or updating the pressure-temperature-time history would be an undue burden, a conservative "bounding" pressure-temperature-time history may be used. This history should anticipate a pressure equal to the shut-off head for the high-pressure injection system and a cooldown rate of 400°F per hour for Service Level C and 600°F per hour for Service Level D. These values are based on the NRC staff's experience in performing the bounding analyses (for examples, see Appendix A of this regulatory guide and Reference 4). Alternatives to these cooldown rates may be used if justified by the plant-specific safety-injection flows and temperatures.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Except in those cases in which an applicant or licensee proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the methods described in this guide reflecting public comments will be used by the NRC staff in the evaluation of applications for new licenses and for evaluating compliance with Appendix G to 10 CFR Part 50.

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2. American Society for Testing and Materials, "Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactors," ASTM E 185-82, July 1982.[1]

3. American Society of Mechanical Engineers, Section XI, Division 1, "Rules for Inservice Inspection of Nuclear Power Plant Components," of the *ASME Boiler and Pressure Vessel Code*, New York, through 1988 Addenda and 1989 Edition.[2]

4. T.L. Dickson, "Generic Analyses for Evaluation of Low Charpy Upper-Shelf Energy Effects on Safety Margins Against Fracture of Reactor Pressure Vessel Materials," USNRC, NUREG/CR-6023, July 1993.[3]

5. R. Johnson, "Resolution of the Task A-11 Reactor Vessel Materials Toughness Safety Issue," USNRC, NUREG-0744, Volume 1 (Revision 1) and Volume 2 (Revision 1), October 1982.[3]

6. Generic Letter No. 82-26, "NUREG-0744 Rev. 1; Pressure Vessel Material Fracture Toughness," Issued by Darrel G. Eisenhut, Director, Division of Licensing, NRR, USNRC, November 12, 1982.[4]

7. Letter from Warren H. Bamford, Chairman of the ASME Subgroup on Evaluation Standards for ASME Section XI, to James E. Richardson, USNRC, Subject: Response to NRC Request, A-11 Issue, February 20, 1991.[4]

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9. American Society for Testing and Materials, "Standard Test Method for Determining J-R Curves," ASTM E 1152-87, May 1987.[1]

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11. A.W. Serkiz, "ASME Code Class 1, 2, and 3 Components, Components Supports, and Core Structures," Revision 1 to Appendix A to Section 3.9.3 of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," pages 3.9.3-12 to 3.9.3-20, April 1984.[3]

12. American Society of Mechanical Engineers, Section III, "Nuclear Power Plant Components," of the *ASME Boiler and Pressure Vessel Code*, New York, through 1988 Addenda and 1989 Edition.[2]

13. J.M. Bloom, "Validation of the Deformation Plasticity Failure Assessment Diagram (DPFAD) Approach - The Case of An Axial Flaw in a Pressurized Cylinder," Transactions of the ASME, *Journal of Pressure Vessel Technology*, Volume 112, pp. 213-217, 1990.

14. USNRC, "Radiation Embrittlement of Reactor Vessel Materials," Regulatory Guide 1.99, Revision 2, May 1988.[4]

15. A.L. Hiser and J.B. Terrell, "Size Effects on J-R Curves for A-302B Plate," USNRC, NUREG/CR-5265, January 1989.[3]

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[1] Copies may be obtained from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

[2] Copies may be obtained from the American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017.

[3] Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington DC 20555; telephone (202) 634-3273, fax (202) 634-3343. Copies may be purchased at current rates from the U.S. Government Printing Office, Post Office Box 37082, Washington, DC 20013-7082 (telephone (202) 512-1800); or from the National Technical Information Service by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161.

[4] Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington DC 20555; telephone (202)634-3273, fax (202)634-3343.

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APPENDIX A

EXAMPLES

Several cases are provided here to demonstrate examples of the methods of analysis described in this regulatory guide.

Example 1 (Levels A&B Loading, PWR Vessel)

Consider the following geometric and material properties:

Vessel Geometry and Loading Conditions:
Vessel internal radius, R_i = 86.5 in.; A-533B vessel with generic welds
Base metal thickness, $t = t_{BM}$ = 8.444 in.; Cladding thickness, t_{cl} = 5/32 in.
Total thickness, $t' = (t_{BM} + t_{cl})$ = 8.6 in.; Ratio (R_i/t') = 10.06
System accumulation pressure, p_a = 2.75 ksi; Cooldown transient = 100°F/hr

Base Metal Thermo-Elastic Properties:
Modulus of elasticity, E = 27E3 ksi; Poisson's ratio, ν = 0.3
Yield stress, σ_y = 80 ksi; Ultimate stress, σ_u = 90 ksi
Flow stress, σ_f = 85 ksi; Fluid heat transfer coeff. = 1000 BTU/hr-ft²-°F
Thermal diffusivity = 0.98 in²/minute; (E.α)/(1 - ν) = 0.305 ksi/°F

Cladding Thermo-Elastic Properties:
Thermal expansion coefficient, α = 9.1E-6/°F; Poisson's ratio, ν = 0.3
Modulus of elasticity, E = 27E3 ksi; Thermal conductivity = 10 BTU/hr-ft-°F
Stress-free temperature of cladding = 550°F; Initial operating temp. = 550°F

The VISA-II code,[1] with modifications for printing K_{Ip}, K_{It}, and K_{cl} for 6-to-1 aspect ratio flaws, was used to perform analyses for determining transient thermo-mechanical stresses and temperature gradients across vessel wall thickness. An axial flaw with an aspect ratio of 6 to 1 was postulated to exist in the vessel internal wall. To account for the effect of crack-face pressure on stress intensity factor solutions in VISA-II, the accumulation pressure was adjusted to be equal to $[p.t'.\{1 + R_i/t'\}/R_i]$, 3.02 ksi. At a fixed crack depth of (0.25t'+0.1) inch, the temperature history prediction is shown in Figure A-1 for a transient with a constant cooldown rate of 100°F/hr.

With a factor of safety, SF, of 1.15 on accumulation pressure for Equation 1 of this guide, the applied J-integral history at a crack depth of (0.25t'+ 0.1) inch for mechanical and thermal stresses, including the cladding effects, is shown in Figure A-2. The applied J-integral reaches the peak steady-state value of 486 in.-lb/in.² in about 150 minutes. Also shown in Figure A-2 are the J-R curves for generic welds (Equations 17, 24-25) at three Charpy V-notch upper-shelf energy (CVN) values. These J-R curves were drawn for a crack extension, Δa, of 0.1 inch and for the temperature history, in Figure A-1, at a crack depth of (0.25t'+0.1) inch. A study of Figure A-2 shows an interesting trend that the crack initiation is predicted to take place at about 45 minutes into the transient (with crack-tip temperature of 500°F) where the applied-J value (= 445 in.-lb/in.²) is less than the peak steady-state value and is just equal to the material's J-R curve at CVN value of 40 ft-lb. Thus, the more detailed analysis results in a lower CVN value that satisfies the acceptance criteria.

In order to satisfy Equation 2, with a safety factor of 1.25 on accumulation pressure, Figure A-3 shows that CVN value should be greater than or equal to 41 ft-lb. This is significantly lower than the 47 ft-lb value obtained by using the steady-state applied J-integral approach for analyzing transients with constant cooldown rates.

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[1] F.A. Simonen et al., "VISA-II - A Computer Code for Predicting the Probability of Reactor Pressure Vessel Failure," USNRC, NUREG/CR-4486, March 1986.

Example 2 (Levels C and D Loading, PWR Vessel)

The problem statement was presented in a meeting of the ASME Section XI Working Groups on Flaw Evaluation and Operating Plant Criteria (in Louisville, Kentucky, on December 1, 1992), where results of the analyses were compared by the participants. The vessel geometry and material properties are:

PWR vessel internal radius, $R_i = 90.0$ inch; A-533B plate material thickness, $t = t_{BM} = 9.0$ inch; Cladding thickness, $t_{cL} = 0$, $R_i/t = 10$ Copper, Cu = 0.35 wt%; Nickel, Ni = 0.3 wt%; Initial $RT_{NDT} = 0.0°F$
Pre-irradiated $CVN_p = 108$ ft-lb (L-T orientation)
Surface fluence, $\phi t = 3.0E19$ n/cm^2
Flaw orientation = Axial, in plate material; Flaw aspect ratio = 6 to 1
Fluid temperature at vessel surface, $T(tm) = [550 - 250\{1 - \exp(-0.1\ tm)\}]°F$ with time, tm, in minutes.
Heat transfer coeff. = 320 BTU/hr-ft^2-°F; Thermal diffusivity = 0.98 in.^{2}/min
Elastic modulus, E = 28E3 ksi; Poisson's ratio, $\nu = 0.3$; $\alpha = 8.1E\text{-}6$ in./in.-°F
Yield stress, $\sigma_y = 80$ ksi; Flow stress, $\sigma_f = 85$ ksi

J-R curve: $J = (SF).[C1.(\Delta a)^{C2}.\ \exp\{C3.(\Delta a)^{C4}\}]$ in.-kip/in.^{2}
where:

$\ln(C1) = [-2.89 + 1.22\ \ln(CVN_p) - 0.0027\ T + 0.014\ (\phi t)]$
C2 $= [0.077 + 0.116\ \ln(C1)]$
C3 $= [-0.0812 - 0.0092\ \ln(C1)]$
C4 $= -0.417$
SF $= 0.741$ for Level C events

The VISA-II code was used to determine thermal stress and temperature history for the Level C transient specified in the problem. It was found that at time tm = 20 minutes, the peak thermal stresses occur. The corresponding peak thermal stress intensity factor as a function of crack depth to vessel thickness ratio, a/t, of semi-elliptical flaws is given as:

$$K_{It} = [21.026+374.22(a/t)-1593.56(a/t)^2+2912.1(a/t)^3-2029.7(a/t)^4]\ \text{ksi}\sqrt{\text{in.}}\ \text{with}\ 0.05 \le a/t \le 0.5$$

Therefore, at a = 1 inch, $K_{It} = 46.6$ ksi$\sqrt{\text{in.}}$ At an internal pressure, p = 1 ksi, the pressure induced $K_{Ip} = 18.9$ ksi$\sqrt{\text{in.}}$ Now, if the pressure, p, is increased, then at a pressure of 6.75 ksi, the J-applied at a = $(0.1t + t_{cL} + 0.1)$ inch becomes equal to the material's J-R curve as shown in Figure A-4. This will mark an "initiation" of ductile flaw growth. The temperature at the crack-tip ($a = 0.1t + t_{cL}$) for time tm = 20 minutes is 400°F. If internal pressure p is further increased, in Figure A-4 it can be seen that at pressure p = 7.56 ksi the crack growth becomes unstable. That is, the slope of the J-applied curve becomes greater than the slope of the material's J-R curve.

Example 3 (Levels C and D Loading, BWR Vessel)

The problem statement is the same as in Example 2, except for a BWR vessel geometry. The vessel geometric details are:

BWR vessel internal radius, $R_i = 120.0$ inch; A-533B plate material
Thickness, $t = t_{BM} = 6.0$ in.; Cladding thickness, $t_{cL} = 0$; $R_i/t = 20$
Flaw orientation = Axial, in plate material; Flaw aspect ratio = 6 to 1

The VISA-II code was used to determine thermal stress and temperature history for the Level C transient specified in the problem. It was found that at time tm = 16 minutes, peak thermal stresses occur. The corresponding peak thermal stress intensity factor as a function of crack depth to vessel thickness ratio, a/t, of semi-elliptical flaws is given as:

$$K_{It} = [12.243+227.94(a/t)-972.71(a/t)^2+1785.2(a/t)^3-1249.3(a/t)^4]\ \text{ksi}\sqrt{\text{in.}},\ \text{with}\ 0.05 \le a/t \le 0.5$$

Therefore, at a = 1 inch, K_{It} = 27.9 ksi$\sqrt{in}$. At an internal pressure, p = 1 ksi, the pressure-induced K_{Ip} = 37.0 ksi$\sqrt{in}$. If the pressure, p, is increased, at a pressure of 4.55 ksi, the J-applied at a = (0.1t + t_{cL} + 0.1) inch becomes equal to the material's J-R curve as shown in Figure A-5, which will mark an "initiation" of ductile flaw growth. The temperature at the crack tip (a = 0.1t + t_{cL}) for time tm = 16 minutes is 405°F. If the pressure, p, is further increased (see Figure A-5), it can be seen that at a pressure p = 4.75 ksi the crack growth has become unstable. The slope of the J-applied curve is now greater than the slope of the material's J-R curve.

Example 4 (Thermal K_{It} for Prescribed Levels C and D Loading, PWR Vessel)

For a PWR vessel, thermal K_{It} values are determined for a few prescribed cooldown rate (CR) transients. The geometric and material properties are given as:

Vessel Geometry and Loading Conditions:
Vessel internal radius, R_i = 86.875 in.; A-533B plate material with cladding
Base metal thickness, t = t_{BM} = 8.625 in.; Cladding thickness, t_{cL} = 5/16 in.
Total thickness, t' = (t_{BM} + t_{cL}) = 8.9375 in.; Ratio, (R_i/t') = 9.72
Thermal cooldown rate, CR = 100°F/hr to 600°F/hr (constant, for each analysis)
Inner wall temperature, $T_{initial}$(R = R_i) = 550°F; T_{final}(R = R_i) = 150°F

Base Metal Thermo-Elastic Properties:
Modulus of elasticity, E = 27E3 ksi; Poisson's ratio, ν = 0.3
Fluid-film heat transfer coefficient = 1000 BTU/hr-ft²-°F
Thermal diffusivity = 0.98 in²/minute; (Eα)/(1 - ν) = 0.305

Cladding Thermo-Elastic Properties:
Thermal expansion coefficient, α = 9.1E-6/°F; Poisson's ratio, ν = 0.3
Modulus of elasticity, E = 27E3 ksi; Thermal conductivity = 10 BTU/hr-ft-°F
Stress-free temperature of cladding = 550°F; Initial operating temp. = 550°F

The VISA-II code was used to determine temperature and thermal stress history for constant CR transients of 100°F/hr, 150°F/hr, 200°F/hr, 300°F/hr, 400°F/hr, 500°F/hr, and 600°F/hr. The corresponding peak thermal stress intensity factors, K_{It}, as a function of crack depth to vessel thickness ratio, a/t', for 6-to-1 aspect ratio semi-elliptical flaws, were computed using the VISA-II code. These are shown in Figure A-6 and are presented here in polynomial expressions using least-square fits as:

<u>For CR = 100°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [27.284 - 5.838\,(a/t') - 0.3548\,(a/t')^2 - 8.3858\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

<u>For CR = 150°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [32.003 + 40.012\,(a/t') - 138.2\,(a/t')^2 - 113.98\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

<u>For CR = 200°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [36.362 + 82.011\,(a/t') - 265.01\,(a/t')^2 + 226.9\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

<u>For CR = 300°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [43.667 + 150.77\,(a/t') - 474.9\,(a/t')^2 + 415.01\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

<u>For CR = 400°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [49.254 + 201.12\,(a/t') - 632.1\,(a/t')^2 + 557.87\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

<u>For CR = 500°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [53.552 + 237.64\,(a/t') - 749.6\,(a/t')^2 + 666.62\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

<u>For CR = 600°F/hr,</u> with $0.05 \le (a/t') \le 0.5$:
$$K_{It} = [56.927 + 264.21\,(a/t') - 838.6\,(a/t')^2 + 750.88\,(a/t')^3]\ \text{ksi}\sqrt{\text{in}}.$$

These results were also used in developing the unified Equation 13 for K_{I} where the constant CR and the normalized crack depth, a/t', are used as dependent variables. A least-squares statistical fit was performed to obtain Equation 13. The cross-product term, (CR)(a/t'), was also used in developing this fit, in addition to the polynomial terms in a/t' and CR.

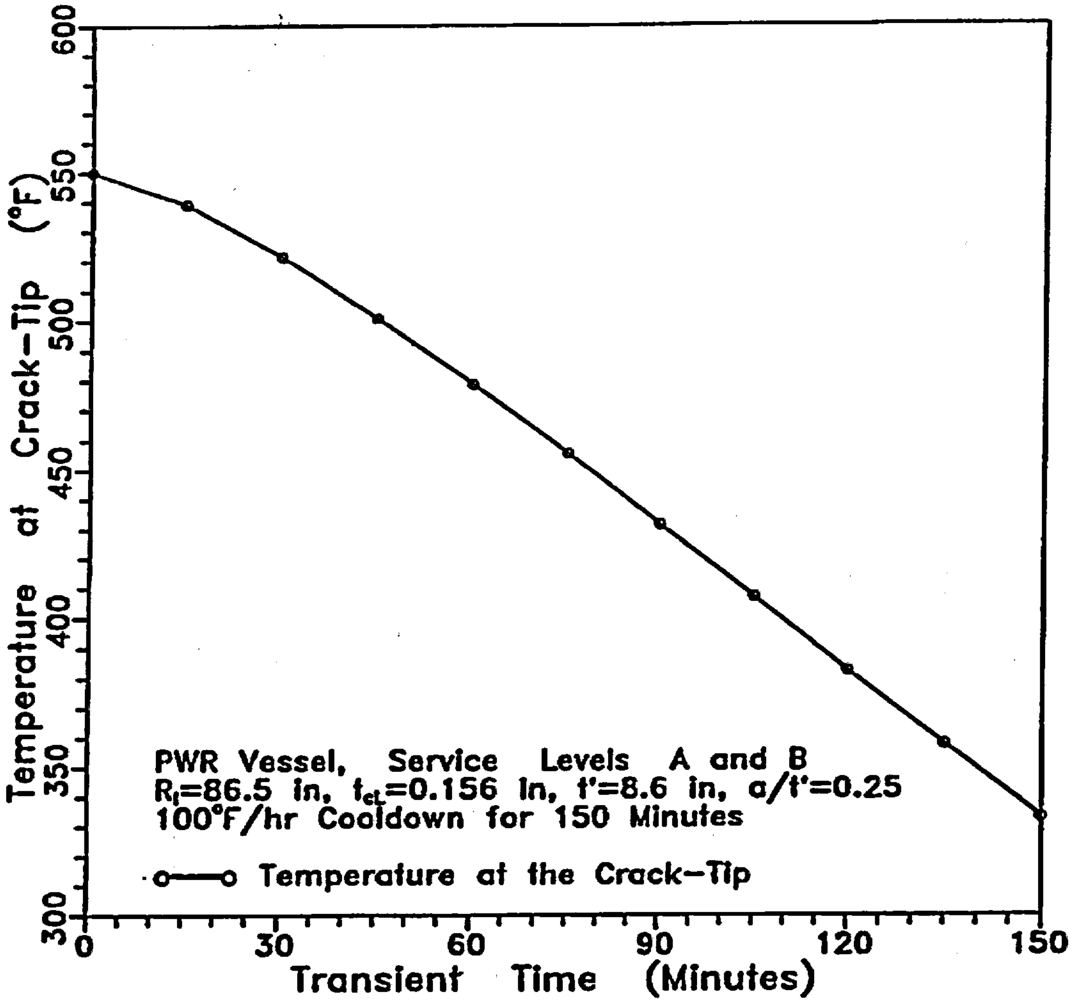

Figure A-1: Transient Temperature History at Crack Tip for Service Levels A and B.

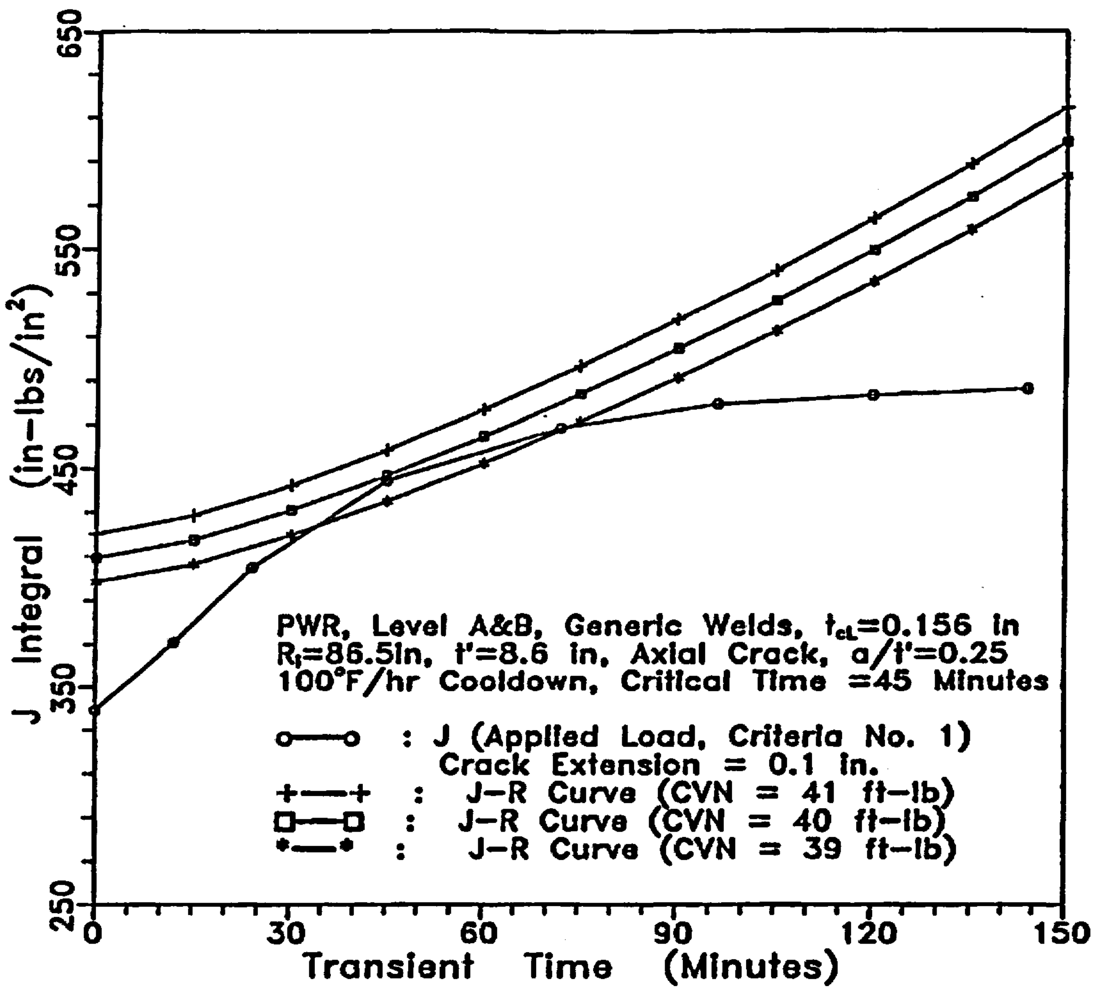

Figure A-2: J-Applied and J-R Curve History at Crack Tip for Service Levels A and B at a Crack Extension of 0.1 inch.

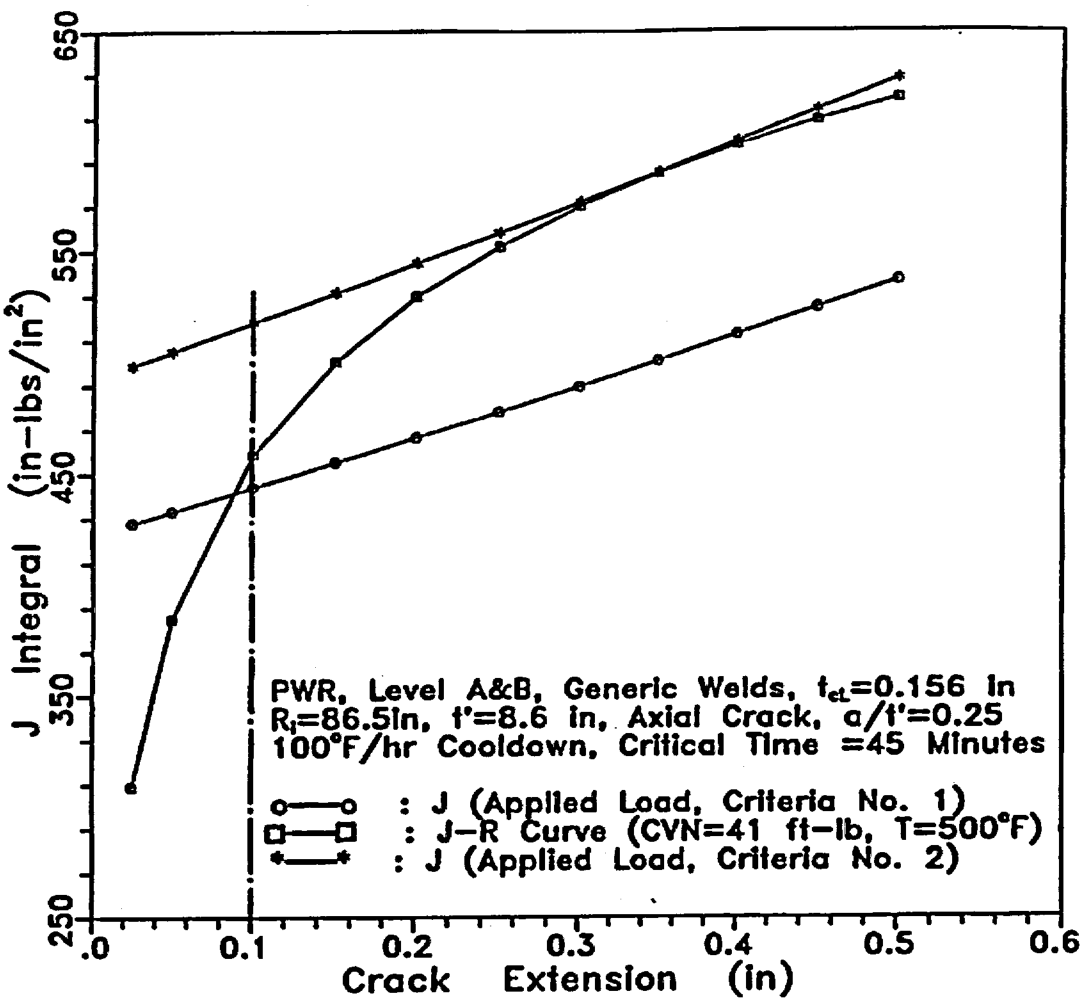

Figure A-3: Acceptable Upper-Shelf Energy in a PWR Vessel for Service Levels A and B.

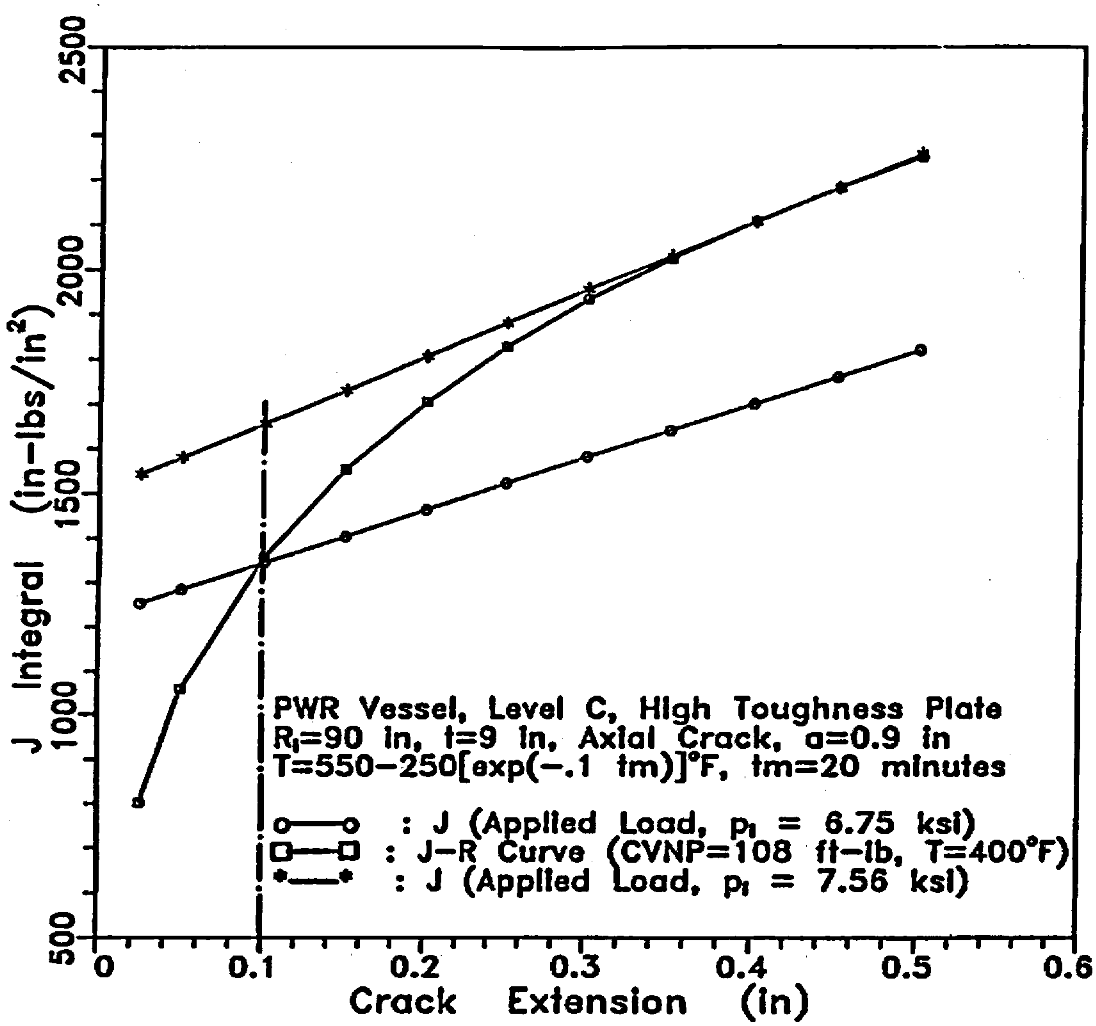

Figure A-4: Safety Margin Evaluation in a PWR Vessel for Service Level C.

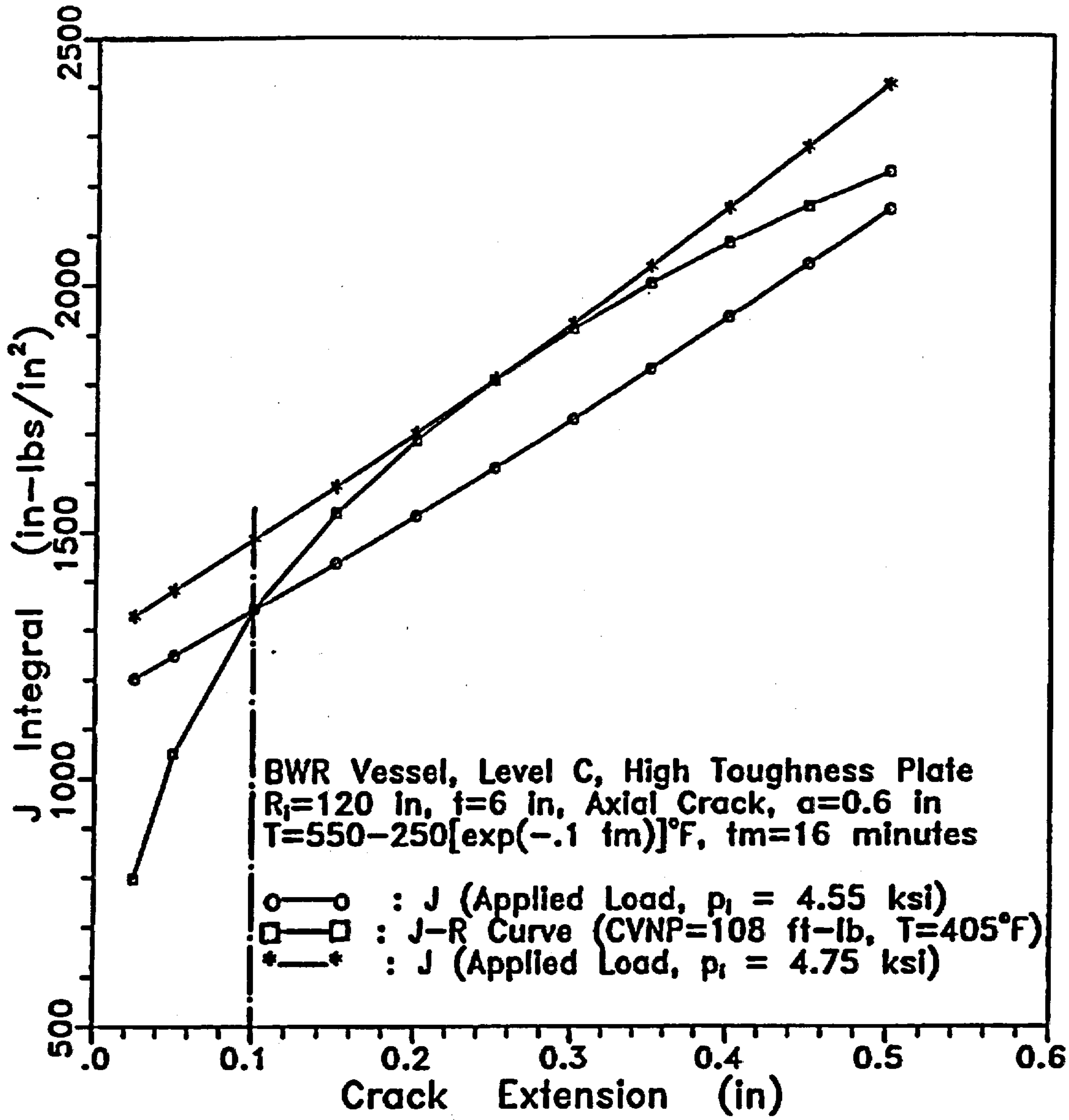

Figure A-5: Safety Margin Evaluation in a BWR Vessel for Service Level C.

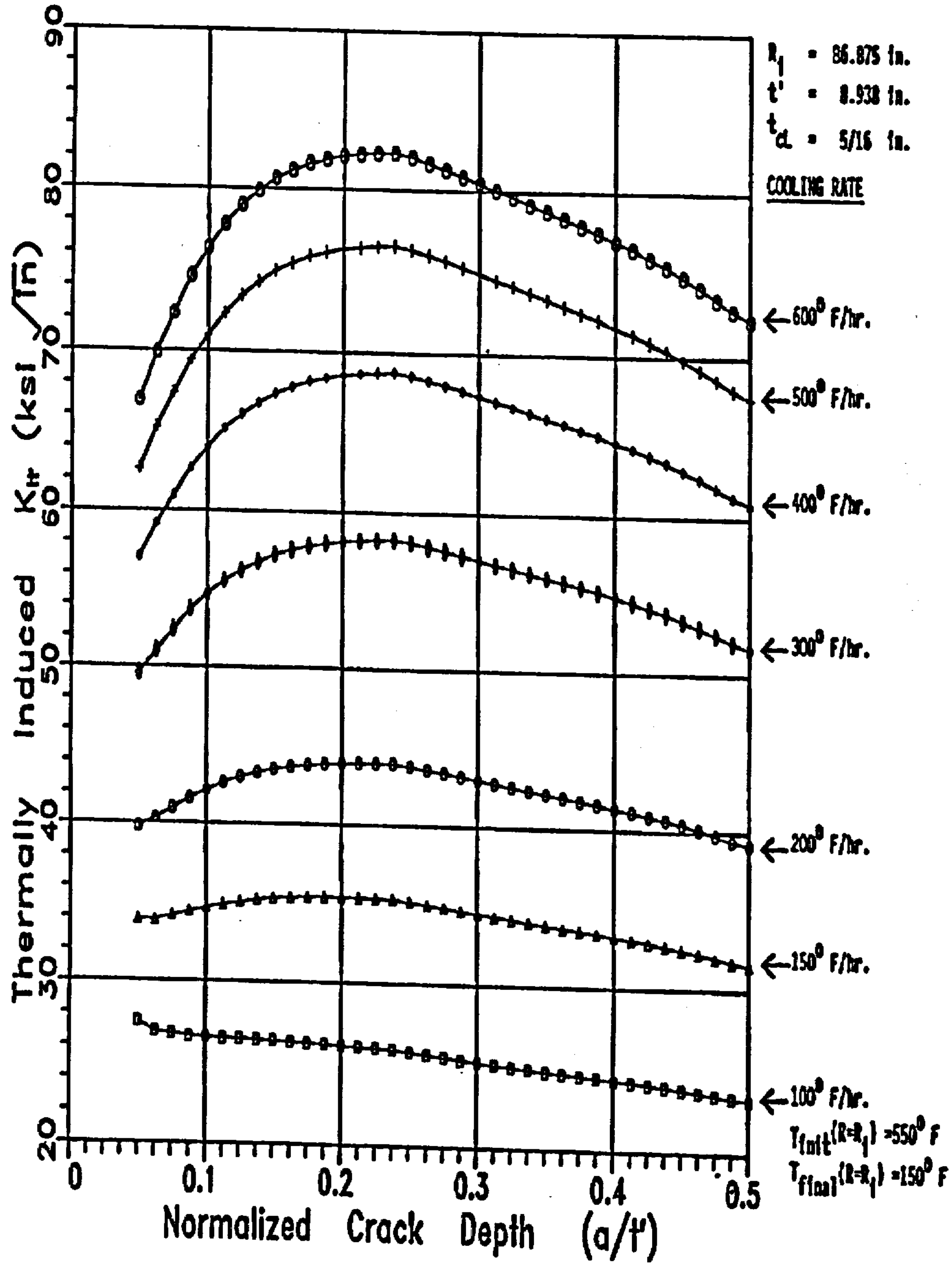

Figure A-6: Peak Thermal Stress Intensity Factors in a PWR Vessel for Transients with Several Different, but Constant, Cooldown Rates.

APPENDIX B

COMPUTATION OF STRESS INTENSITY FACTORS

Information about computing transient temperature gradient across the vessel wall thickness, thermal stresses, pressure, and thermal stress intensity factors (K_{Ip}, K_{It}) are provided in this Appendix as FORTRAN subroutines from the VISA-II code. Additional details on the computational method, theory used, limitations, and names of the major variables used are available in NUREG/CR-4486[1] and NUREG/CR-3384.[1] The computer code provided in this Appendix is for general illustration only, to show how the cladding effects could be incorporated for thermal stresses and thermal stress intensity factors caused by differential thermal expansion between the cladding and the base metal. Licensees should ensure that the computer codes they use include an indepth evaluation of these effects.

A description of cladding-induced thermal stress intensity factors is presented in Appendix A to NUREG/CR-4486. Limitations of the stress intensity factor correction factors for finite length semi-elliptical surface flaws are indicated in Appendix C to NUREG/CR-4486. In developing these correction factors, only uniform membrane and linear bending stresses were considered. In addition, the correction factors for circumferential flaws were assumed to be the same as the ones for axial flaws. Improved solutions may be used on a case-by-case basis if justified.

---

[1] F.A. Simonen et al., "VISA-II - A Computer Code for Predicting the Probability of Reactor Pressure Vessel Failure," USNRC, NUREG/CR-4486, March 1986. D.L. Stevens et al., "VISA - A Computer Code for Predicting the Probability of Reactor Pressure Vessel Failure," USNRC, NUREG/CR-3384, September 1983. Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555; telephone (202)634-3273; fax (202)634-3343. Copies of NUREG/CRs may be purchased at current rates from the U.S. Government Printing Office, Post Office Box 37082, Washington, DC 20013-7082 (telephone (202)512-1800); or from the National Technical Information Service by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161.

Taken From: VISA-II Code [NUREG/CR-4486 (1986), NUREG/CR-3384 (1983)]

```
C***************************************************************************
SUBROUTINE SPKI
C***************************************************************************C
Calculate Pressure Values, and, Stress Intensity Factor, PKI
   DIMENSION CONST(5)
   REAL I(5), IC(5)
   INTEGER CRACK, TIME
C  DETERMINE POLYNOMIAL REPRESENTATION OF PRESSURE
   CONST(1) = PDATA(1)
   CONST(2) = ((-25)*PDATA(1)+48*PDATA(2)-36*PDATA(3)+
  1         16*PDATA(4)-3*PDATA(5))/(3*TMAX)
   CONST(3) = (35*PDATA(1)-104*PDATA(2)+114*PDATA(3)-
  1         56*PDATA(4)+11*PDATA(5))*2/(3*TMAX**2)
   CONST(4) = ((-5)*PDATA(1)+18*PDATA(2)-24*PDATA(3)+
  1         14*PDATA(4)-3*PDATA(5))*16/(3*TMAX**3)
   CONST(5) = (PDATA(1)-4*PDATA(2)+6*PDATA(3)-4*PDATA(4)+
  1         PDATA(5))*32/(3*TMAX**4)
C Calculate PRESSURE Component of Applied K, PKI, For Each Time & Crack Depth
   OUTRAD = RAD + TH
   FACTOR = RAD**2.0 / (OUTRAD**2.0 - RAD**2.0)
C
   DO 120 TIME = 1, 10
   TT = TMAX*TIME/10.0
   DO 110 CRACK = 1, ICMAX
   X = Z(CRACK)/TH
C CALCULATE INFLUENCE COEFFICIENTS
   DO 100 M = 1, 5
    I(M) = ZZ(M,1) + X*ZZ(M,2) + (X**2)*ZZ(M,3) + (X**3)*ZZ(M,4)
    IC(M) = ZZC(M,1) + X*ZZC(M,2) + (X**2)*ZZC(M,3) + (X**3)*ZZC(M,4)
 100 CONTINUE
   PRES(TIME) = CONST(1)+CONST(2)*TT+CONST(3)*TT**2+CONST(4)*TT*
  1           *3+CONST(5)*TT**4
   PKI(CRACK,TIME) = PRES(TIME)*((3.1416*Z(CRACK))**.5)*(10.5238*I(1)
  1           -1.1524*I(2)*X+0.1729*I(3)*(X**2)-0.0230*I(4)
  2           *(X**3)+0.0029*I(5)*(X**4))
```

```
      PKIC(CRACK,TIME) = 5*PRES(TIME)*((3.1416*Z(CRACK))**.5)*IC(1)
      RATIO = RAD / (10.0*TH)
      PKI(CRACK,TIME) = RATIO * PKI(CRACK,TIME)
      PKIC(CRACK,TIME) = RATIO * PKIC(CRACK,TIME)
C     CALCULATE HOOP STRESS
      SHOOP(CRACK,TIME) = FACTOR * PRES(TIME) *
     1            (1.0 + (OUTRAD/(RAD + Z(CRACK)))**2.0 )
 110  CONTINUE
C     CALCULATE LONGITUDINAL STRESS
      SLONG(TIME) =  PRES(TIME) * FACTOR
 120  CONTINUE
      RETURN
      END
C*****************************************************************************
      SUBROUTINE  TPOLY
C*****************************************************************************
C  CALCULATE WATER TEMPERATURES USING A  "POLYNOMIAL"  MODEL
            REAL TEMP(5), CONST(5), S(5), AN(4), Y(4,5), KTEST
      REAL K, KO, CP(4), SUM(4)
      INTEGER TIME, CRACK, CONSTK, CONSTE
      INTEGER Q
C  "POLYNOMIAL" Modeling of The Water Temperature
C  Determine Metal Temperature For EACH CRACK DEPTH  AND TIME INTERVAL
      DO 100 N = 1, 5
      TEMP(N) = TDATA(N) - TINT
 100  CONTINUE
C  FIT A "POLYNOMIAL" TO THE WATER TEMERATURE
      CONST(1) = TEMP(1)
      CONST(2) = ((-25)*TEMP(1) + 48*TEMP(2) - 36*TEMP(3) +
     1            16*TEMP(4) - 3*TEMP(5))/(3*TMAX)
      CONST(3) = (35*TEMP(1) - 104*TEMP(2) + 114*TEMP(3) -
     1            56*TEMP(4) + 11*TEMP(5))*2/(3*TMAX**2)
      CONST(4) = ((-5)*TEMP(1) + 18*TEMP(2) - 24*TEMP(3) +
     1            14*TEMP(4) - 3*TEMP(5))*16/(3*TMAX**3)
      CONST(5) = (TEMP(1) - 4*TEMP(2) + 6*TEMP(3) - 4*TEMP(4) +
     1            TEMP(5))*32/(3*TMAX**4)
      DO 150 TIME = 1, 10
```

```
      TT = TMAX*TIME/10.
C     EQUATION FOR THE TEMPERATURE OF THE WATER
      TWATER(TIME) = TINT+CONST(1)+ CONST(2)*TT + CONST(3)*TT**2 +
     1         CONST(4)*TT**3 + CONST(5)*TT**4
      DO 150 CRACK = 1, 5
      K = KO
  110 X = ZQ(CRACK)/TH
      TAU = K*TT/TH**2
      DO 120 M = 1, 5
       S(M) = CONST(M) * ((TH**2/K)**(M-1))
  120 CONTINUE
      DO 130 N = 1, 4
      ALNQ  = AL(N,Q)
      AN(N) = 2 * SIN(ALNQ)/(ALNQ + SIN(ALNQ)* COS(ALNQ))
      CP(N) = COS(ALNQ * (1-X))
      Y(N,1) = 1 - EXP(-(ALNQ**2)*TAU)
      DO 130 M = 2, 5
       Y(N,M) = TAU**(M-1) - (Y (N,M-1)/ALNQ**2)*(M-1)
130   CONTINUE
      DO 140 N = 1, 4
       ALNQ = AL(N,Q)
       SUM(N) = AN(N) * CP(N) * (S(1) * EXP(-(ALNQ**2*TAU)) + S(2)
     1     * Y(N,1)/ALNQ**2 +2*S(3)* Y(N,2)/ALNQ**2 + 3 *S(4) * Y(N,3)
     2     /ALNQ**2 +4 *S(5)*Y(N,4)/ALNQ**2)
  140 CONTINUE
C     EQUATION FOR THE QUARTER POINT TEMPERATURES
      TQ(CRACK,TIME) = TWATER(TIME) - SUM(1) - SUM(2) - SUM(3) - SUM(4)
C     CONTROL FOR THE CONSTANT KAPPA OPTION
      IF (CONSTK .EQ. 1) GO TO  150
C     TEST FOR THE ACCURACY OF KAPPA FOR THE GIVEN METAL TEMPERATURE,
C      IF THE DESIRED ACCURACY IS NOT OBTAINED, ITERATE ON  KAPPA
C      FOR THIS CRACK DEPTH AND TIME.
      KTEST = 1.030 - (5.97E-7)*((T(CRACK,TIME))**2)
      IF ((ABS(KTEST-K)) .LE. 0.0001) GO TO  150
      K = KTEST
      GO TO  110
  150 CONTINUE
```

```
      RETURN
      END
C*********************************************************************************
      SUBROUTINE  TEXP
C*********************************************************************************
C  Calculate  WATER TEMPERATURES Using an  "Exponential Decay"  Model
      REAL B, KTEST, K, KO, SUM(4)
      INTEGER CRACK, TIME, CONSTK, CONSTE
      INTEGER Q
C  EXPONENTIAL DECAY MODEL OF THE WATER TEMPERATURE
      DO 130 TIME = 1, 10
      TT = TMAX*TIME/10.
C  EQUATION FOR THE TEMPERATURE OF WATER
      TWATER(TIME) = TO + DT * (1-EXP(-BE*TT))
      DO 130 CRACK = 1, 5
      K = KO
  100 WSQ = BE*TH*TH/K
      TAU = K*TT/(TH*TH)
      DO  120 N = 1, 4
       ALNQ = AL(N,Q)
       B  = -DT*((2*SIN(ALNQ)/(ALNQ+(SIN(ALNQ))*(COS(ALNQ))))
     1     *(EXP(-(ALNQ**2*TAU))-EXP(-WSQ*TAU))/((ALNQ**2/WSQ)-1))
       X  = ZQ(CRACK)/TH
       SUM(N) = B * COS(ALNQ*(1-X))
  120 CONTINUE
C  EQUATON FOR THE "QUARTER POINTS"  TEMPERATURE VALUES
      TQ(CRACK,TIME) = TWATER(TIME) - SUM(1) - SUM(2) - SUM(3) - SUM(4)
C  CONTROL FOR THE CONSTANT KAPPA OPTION
      IF (CONSTK .EQ. 1) GO TO  130
C  TEST FOR KAPPA ACCURACY AND CONTROL OF KAPPA OPTION
      KTEST = 1.030 - (5.97E-7)*((T(CRACK,TIME))**2)
      IF ((ABS(KTEST-K)) .LE. 0.0001) GO TO  130
      K = KTEST
      GO TO  100
  130 CONTINUE
      RETURN
      END
```

```
C*******************************************************************************
      SUBROUTINE SKIT
C*******************************************************************************
C  Calculate Stress and Temperature at Crack-Tip and  Thermal Stress
C  Intensity Factor,  SKIt
      REAL E(5,10), CC(5), I(5), IC(5)
      INTEGER CRACK, TIME
      INTEGER Q, CONSTE, CONSTK
C  DETERMINE POLYNOMIAL REPRESENTATION OF TEMPERATURE PROFILE
C  CONVERT CLAD THERMAL CONDUCTIVITY TO INCH AND MINUTE UNITS
      CCOND = CCOND / (12.0*60.0)
      COND  = COND / (12.0*60.0)
      DO 105 TIME = 1, 10
       TQ1 = TQ(1,TIME)
       TQ2 = TQ(2,TIME)
       TQ3 = TQ(3,TIME)
       TQ4 = TQ(4,TIME)
       TQ5 = TQ(5,TIME)
       C1 = TQ1
       C2 = (-25*TQ1+48*TQ2-36*TQ3+16*TQ4-3*TQ5)/(3*TH)
       C3 = (35*TQ1-104*TQ2+114*TQ3-56*TQ4+11*TQ5)*(2.0/3.0*TH**(-2))
       C4 = (-5*TQ1+18*TQ2-24*TQ3+14*TQ4-3*TQ5)*(16.0/3.0*TH**(-3))
       C5 = (TQ1-4*TQ2+6*TQ3-4*TQ4+TQ5)*(32.0/3.0*TH**(-4))
C  CALCUATE TEMPRATURE AT THE CRACK TIPS
       DO 100 CRACK = 1, ICMAX
        T(CRACK,TIME) = C1+C2*Z(CRACK)+C3*(Z(CRACK)**2)
     1            +C4*(Z(CRACK)**3)+C5*(Z(CRACK)**4)
  100 CONTINUE
      IF (CTH .LE. 0.0) GO TO  105
      T(1,TIME) = T(2,TIME) - (COND/CCOND)*(T(2,TIME)-T(1,TIME))
105   CONTINUE
      IF (CONSTE .EQ. 1) GO TO  120
      DO 110 TIME = 1, 10
      DO 110 CRACK = 1, 5
       E(CRACK,TIME) = 0.286+(5.400E-5 * (TQ(CRACK,TIME)))
     1           -(2.600E-8 * (TQ(CRACK,TIME))**2)
  110 CONTINUE
```

```
      GO TO  140
 120 DO 130  TIME  = 1, 10
     DO 130  CRACK = 1, 5
      E(CRACK,TIME) = EDATA
 130 CONTINUE
C  DETERMINE POLYNOMIAL REPRESENTATION OF STRESS DIST
 140 DO 170 TIME = 1, 10
      DO 150 CRACK = 1, 5
       CC(CRACK) = E(CRACK,TIME)*TQ(CRACK,TIME)
 150 CONTINUE
      A1 = CC(1)
      A2 = (-25*CC(1)+48*CC(2)-36*CC(3)+16*CC(4)-3*CC(5))/3.0
      A3 = (35*CC(1)-104*CC(2)+114*CC(3)-56*CC(4)+11*CC(5))*(2.0/3.0)
      A4 = (-5*CC(1)+18*CC(2)-24*CC(3)+14*CC(4)-3*CC(5))*(16.0/3.0)
      A5 = (CC(1)-4*CC(2)+6*CC(3)-4*CC(4)+CC(5))*(32.0/3.0)
      SIG1 =  A2/2.0 + A3/3.0 + A4/4.0 + A5/5.0
      SIG2 = -A2
      SIG3 = -A3
      SIG4 = -A4
      SIG5 = -A5
C  CALCULATE STRESS AT CRACK TIPS
      DO 170 CRACK = 1, ICMAX
       X = Z(CRACK)/TH
       STRESS(CRACK,TIME) = SIG1 + SIG2*X + SIG3*(X**2)
    1                 + SIG4*(X**3) + SIG5*(X**4)
C  CALCULATE INFLUENCE FUNCTIONS
       DO 160 M = 1, 5
        I(M)  = ZZ(M,1) + X*ZZ(M,2)+ (X**2)*ZZ(M,3)+ (X**3)*ZZ(M,4)
        IC(M) = ZZC(M,1)+X*ZZC(M,2)+(X**2)*ZZC(M,3)+(X**3)*ZZC(M,4)
 160 CONTINUE
       A = Z(CRACK)
C  EQUATION FOR THE THERMAL STRESS INTENSITY
       TK(CRACK,TIME)  = ((3.1416*A)**.5)*(SIG1*I(1)
    1              +SIG2*I(2)*X+SIG3*I(3)*X**2
    2              +SIG4*I(4)*X**3+SIG5*I(5)*X**4)
       TKC(CRACK,TIME) = ((3.1416*A)**.5)*(SIG1*IC(1)+SIG2*IC(2)
    1      *X+SIG3*IC(3)*X**2+SIG4*IC(4)*X**3+SIG5*IC(5)*X**4)
```

```
 170 CONTINUE
   RETURN
   END
C*************************************************************************
   SUBROUTINE  KICLAD
C*************************************************************************
C  THIS SUBROUTINE CALCULATES STRESSES AND STRESS INTENSITY FACTORS
C  DUE TO THE PRESENCE OF "CLADDING" ON THE I.D. SURFACE OF THE VESSEL
   INTEGER CRACK, TIME
   INTEGER CONSTE, CONSTK, Q
   REAL IO, I1
   DO 170  TIME = 1, 10
C  CALCULATE STRESS DISTRIBUTION THROUGH VESSEL WALL
C  TEMP AT CLAD/BASE METAL INTERFACE
   T1 = 0.5*(T(2,TIME) + T(3,TIME))
C  TEMPERATURE AT THE VESSEL I.D.
   TO = T(1,TIME)
C  STRESS-FREE TEMPERATURE
   TI = SFREET
C  CALCULATE STRESS DISTRIBUTION DUE TO CLAD
C  SIGC1 = STRESS IN CLAD AT VESSEL I.D.
C  SIGC2 = STRESS IN CLAD AT CLAD/BASE METAL INTERFACE
C  SIGB1 = STRESS IN BASE METAL AT CLAD/BASE METAL INTERFACE
C  SIGB2 = STRESS IN BASE METAL AT VESSEL O.D.
   DELEA = CLADE*CALPHA*(1-ARATIO)/(1-CLADNU)
C  CALCULATE STRESS IN CLAD (KSI)
   SIGC1 = DELEA * (TI - TO)
   SIGC2 = DELEA * (TI - T1)
C  CALCULATE FORCE DEVELOPED IN CLAD
   FCLAD = CTH*0.5*(SIGC1 + SIGC2)
C  CALCULATE STRESSES IN BASE METAL (KSI)
   RO = RAD
   R1 = RAD + CTH
   R2 = RAD + TH
   CONST = 1.0/((R2/R1)**2.0-1.0)*(RO-R1)/R1*DELEA
   1      *(TI-0.5*(TO+T1))
   SIGB1 = CONST * (1 + (R2/R1)**2.0)
```

```
      SIGB2 = CONST * 2.0
C     CALCULATE FORCE DEVELOPED IN BASE METAL
      FBASE = (CTH-TH)*0.5*(SIGB1+SIGB2)
C     ADJUST SIGB1 AND SIGB2 TO BALANCE FORCES FCLAD AND FBASE
      SIGINC = 0.5*(SIGB1-SIGB2)
      SIGAVE = 0.5*(SIGB1+SIGB2)*FCLAD/FBASE
      SIGB1 = SIGAVE + SIGINC
      SIGB2 = SIGAVE - SIGINC
C     CALCULATE CONSTANTS DESCRIBING STRESS DISTRIBUTION
C     QI = SLOPE OF CLAD STRESS DISTR.
      QI = (SIGC1-SIGC2)/SIGC1/(CTH/TH)
C     P = SLOPE OF BASE METAL STRESS DISTR.
      P = (SIGB2-SIGB1)/SIGC1 / ((TH-CTH)/TH)
C     -R = INTERCEPT OF BASE METAL STRESS GRAD. AT VESSEL I.D.
      R = -(SIGB1/SIGC1 - P*CTH/TH)
C     CALCULATE STRESS AND KI DUE TO CLAD FOR ALL Z(CRACK)'S
C     KI AT THE I.D. SURFACE EQUALS ZERO (I.E.,CRACKDEPTH = ZERO)
      SCLAD(1,TIME) = SIGC1
      CLADK(1,TIME) = 0.0
C     KI IN CLAD NEAR CLAD/BASE METAL INTERFACE
      SCLAD(2,TIME) = SIGC2
      ALP = Z(2)/TH
      IO = 1.122+0.9513*ALP-0.624*ALP**2.0+8.3306*ALP**3.0
      I1 = 0.6825+0.3704*ALP-0.0832*ALP**2.0+2.8251*ALP**3.0
      CLADK(2,TIME) = SQRT(3.14159*Z(2))*SIGC1*(IO-QI*ALP*I1)
C     CALCULATE KI IN BASE METAL
      XI = CTH/TH
      DO 170 CRACK = 3, 35
      ALP = Z(CRACK)/TH
      SCLAD(CRACK,TIME) = (-R+ALP*P)*SIGC1
      IO = 1.122+0.9513*ALP-0.624*ALP**2.0+8.3306*ALP**3.0
      CLADK(CRACK,TIME) = SQRT(3.14159*Z(CRACK))*SIGC1*1.751938
     1         *((IO-0.63662)*((1.0+R)*ASIN(XI/ALP)+ALP*((QI+R*P)
     2   *SQRT(1.-(XI/ALP)**2.)-QI)-1.570796*R)+(IO-1.0)*(((1.0+R)-XI/2.
     3   *(QI+R*P))*SQRT(1.-(XI/ALP)**2.)+ALP/2.0*(QI+R*P)*ASIN(XI/ALP)
     4   -1.0-0.7894*R*P*ALP))
  170 CONTINUE
```

```
      RETURN
      END
C*******************************************************************************
      SUBROUTINE  FACMB (AAA, BBB, THH, FMA, FMB, FBA, FBB)
C*******************************************************************************
C  THIS SUBROUTINE CORRECTS FOR "FINITE LENGTH" SEMI-ELLIPTICAL FLAWS
      DIMENSION ZM(2,4), ZB(2,4), Z(2)
      DIMENSION X1(12), YM(12,4), YB(12,4), Y(4)
      DATA X1/0., .0125, .025, .0375, .05, .075, .1,.15,.2,.3,.4,.5/
      DATA Y/ .05, .25, .5, .8 /
      DATA YM/ 1.0,.99,.98,.96,.95,.91,.87,.80,.75,.66,.60,.55,
     1        1.0,.94,.88,.83,.80,.76,.73,.68,.63,.55,.49,.44,
     2        1.0,.88,.77,.69,.64,.59,.55,.49,.44,.36,.31,.27,
     3        1.0,.72,.56,.48,.43,.38,.35,.29,.24,.18,.15,.13 /
      DATA YB/ 1.0,.98,.97,.95,.94,.92,.89,.85,.82,.74,.66,.58,
     2        1., .93,.88,.84,.80,.75,.72,.67,.63,.57,.50,.43,
     2        1., .84,.71,.63,.57,.49,.45,.39,.35,.29,.23,.18,
     3        1., .69,.50,.38,.29,.20,.14,.08,.05,.02,-.01,-.04/
      DATA Z/ 0.0, 0.5 /
      DATA ZM/ .44, .55, .40,.48,.31,.31,.23,.17 /
      DATA ZB/ .50, .62, .63, .67, .58, .50, .43,.32 /
      AOL = AAA/(2.0*BBB)
      AOT = AAA/THH
      DO 100 I = 1, 3
       J = I
       IF( Y(I+1) .GT. AOT ) GO TO 110
  100 CONTINUE
  110 N1 = J
      N2 = J+1
      DO 120 I = 1, 11
       J = I
       IF ( X1(I+1) .GT. AOL ) GO TO 130
  120 CONTINUE
  130 M1 = J
      M2 = J+1
      FAC1 = (AOL-X1(M1))/(X1(M2)-X1(M1))
      XX1  = YM(M1,N1)+FAC1*(YM(M2,N1)-YM(M1,N1))
```

```
XX2  = YM(M1,N2) + FAC1*(YM(M2,N2) - YM(M1,N2))
FAC  = (AOT - Y(N1))/(Y(N2)-Y(N1))
IF (AOT .LT. 0.05 )  FAC = 0.0
IF ( AOT .GT. 0.80 ) FAC = 1.0
FMA  = XX1 + FAC*( XX2 - XX1 )
XX1  = YB(M1,N1) + FAC1*(YB(M2,N1)-YB(M1,N1))
XX2  = YB(M1,N2) + FAC1*(YB(M2,N2)-YB(M1,N2))
FBA  = XX1 + FAC*( XX2 - XX1 )
FAC1 = AOL/0.5
XX1  = ZM(1,N1) + FAC1*(ZM(2,N1)-ZM(1,N1))
XX2  = ZM(1,N2) + FAC1*(ZM(2,N2)-ZM(1,N2))
FMB  = XX1 + FAC*( XX2-XX1)
XX1 = ZB(1,N1) + FAC1*(ZB(2,N1)- ZB(1,N1))
XX2 = ZB(1,N2) + FAC1*(ZB(2,N2)- ZB(1,N2))
FBB = XX1 + FAC*(XX2 - XX1)
RETURN
END
```

REGULATORY ANALYSIS

1. STATEMENT OF THE PROBLEM

Appendix G, "Fracture Toughness Requirements," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," requires, in part, that the reactor vessel beltline materials ". . . must have Charpy upper-shelf energy of no less than 75 ft-lb (102J) initially and must maintain upper-shelf energy throughout the life of the vessel of no less than 50 ft-lb (68J), 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 the ASME Code." This Regulatory Guide 1.161, "Evaluation of Reactor Pressure Vessels with Charpy Upper-Shelf Energy Less Than 50 ft-lb," has been developed to provide acceptance criteria and analysis methods acceptable to the NRC staff for demonstrating margins equivalent to those in Appendix G to Section III of the ASME Code.

Publication of regulatory guidance was undertaken because no comprehensive guidance currently exists, and there are reactors, both pressurized water reactors and boiling water reactors, with upper-shelf energy that is projected to fall below the 50 ft-lb regulatory limit before the end of the current license period. Without comprehensive regulatory guidance, each affected licensee will have to submit a plant-specific analysis, including acceptance criteria and evaluation methods, and the staff will have to evaluate each submittal without the benefit of stated acceptance criteria and approved evaluation methods.

2. OBJECTIVES

The objective of this guide is to provide acceptance criteria and evaluation methods acceptable to the NRC staff for demonstrating margins equivalent to those in Appendix G to Section III of the ASME Code for those beltline materials whose Charpy upper-shelf energy falls below the regulatory limit provided in Appendix G to 10 CFR Part 50.

3. ALTERNATIVES

Two alternatives to issuing evaluation procedures for pressure vessels with Charpy upper-shelf energy less than 50 ft-lb were considered: (1) endorse actions being implemented by Section XI of the ASME Code and (2) take no action.

3.1 Endorse ASME Code, Section XI, Appendix K

The ASME, in Section XI, has published Appendix K[1] that provides acceptance criteria and evaluation procedures for pressure vessels with Charpy upper-shelf energy less than 50 ft-lb. However, the Appendix K evaluation procedures currently address only Service Levels A and B, and no guidance on specific materials properties is provided. It is important that all four service levels be considered in the evaluations, and it is important that specific guidance on estimating material properties be provided. Given the ASME codification process, and the process whereby the NRC endorses ASME appendices and code cases, the time delay in obtaining suitable guidance would be excessive. At present, the ASME's Appendix K does not provide complete guidance. As discussed above, Appendix K does not provide information on the selection of transients, and it gives very little detail on the selection of material properties. As such, a request for revision of Appendix K to Section XI of the ASME Code will have to be made.

3.2 Take No Action

As discussed in SECY-93-048,[2] "Status of Reactor Pressure Vessel Issues Including Compliance With 10 CFR Part 50, Appendices G and H," using the NRC staff's generic criteria for estimating Charpy upper-shelf energy, there are currently 15 plants that would have calculated upper-shelf energy less than 50 ft-lb and 3 others that would have upper-shelf energy below 50 ft-lb before the end of their operating licenses. Appendix G to 10 CFR Part 50 requires that licensees submit

[1] Appendix K (previously, Code Case N-512), "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," American Society of Mechanical Engineers, Section XI, 1993.

[2] James M. Taylor, Executive Director for Operations, SECY-93-048, Policy Issue (Information) for the Commissioners, USNRC, February 25, 1993. Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555; telephone (202)634-3273; fax (202)634-3343.

analyses to demonstrate margins equivalent to those in Appendix G to Section III of the ASME Code 3 years before the upper-shelf energy of any beltline materials falls below 50 ft-lb. Therefore, taking no action is not a viable alternative.

4. COSTS AND BENEFITS OF ALTERNATIVES

The cost and benefits of the two alternatives discussed above are presented here.

4.1 Endorse Appendix K to ASME Code Section XI

The acceptance criteria proposed in Appendix K to ASME Section XI are identical to those proposed in this regulatory guide. The regulatory guide analysis procedures for Service Levels A and B were taken from Appendix K. However, the guide provides procedures applicable to Service Levels C and D. The regulatory guide provides specific guidance on appropriate material properties and on selection of transients for consideration, whereas Appendix K does not provide these procedures and guidance. Without this guidance, each affected licensee would have to develop appropriate procedures for Service Levels C and D, justify the choice of transients, and develop plant-specific material properties.

It is estimated that without the guidance of this regulatory guide, developing plant-specific procedures and material properties and applying them to check and report the analysis results would require an additional 6 staff-months (1040 hours) for each affected licensee. Assuming that half of the affected licensees either belong to owners' groups or could make use of common data, the total additional burden on the licensees that would be incurred by plant-specific analyses is estimated as 9 plants x 6 staff-months per plant, or 54 staff-months (9360 hours).

In addition to the increased burden on the licensees, it is estimated that an additional 1.5 NRC staff-month would be required to review each plant-specific submittal. Thus, the total increased burden on the NRC staff, assuming that half of the affected plants can be grouped, is estimated to be 9 plants x 1.5 staff-month per plant, or 13.5 staff-months (2340 hours). This estimate assumes that there would be only minor discussions with the licensees.

4.2 Take No Action

As discussed in Section 3.2 above, taking no action is judged to be a nonviable alternative.

5. DECISION RATIONALE

It is recommended that the regulatory guide be issued because it would offer a comprehensive set of acceptance criteria, evaluation procedures, and material properties that can be used to perform the analyses required under Appendix G to 10 CFR Part 50 for those pressure vessels that have Charpy upper-shelf energy of any beltline material that falls below 50 ft-lb. Issuing the regulatory guide is recommended over the alternative of endorsing Appendix K to ASME Section XI because Appendix K does not currently include (1) analysis procedures for Service Levels C and D, (2) guidance on selecting the transients for evaluation, or (3) details on temperature-dependent material properties. Further, it is estimated that preparing plant-specific analyses that include the procedures and data that are not addressed in Appendix K would require approximately 54 staff-months of effort for the industry and approximately 9 staff-months for the NRC to review the additional information.

The NRC staff considered the possibility of working with the ASME Code Section XI working group to modify Appendix K to include the missing procedures and data. However, given the number of plants that could need the guidance in the near term, and given the ASME codification process and the NRC's process for endorsing ASME documents, the time needed to modify and endorse Appendix K was judged to be excessive.

The efficacy of the procedures in the regulatory guide was demonstrated by generic bounding calculations[3] performed by the NRC staff in preparing SECY-93-048. These calculations demonstrated that the requirement in Appendix G to 10 CFR Part 50 to demonstrate margins equivalent to those in Appendix G to Section III to the ASME Code could be satisfied for materials with Charpy upper-shelf energy less than 50 ft-lb for all the generic vessel geometries and material combinations considered.

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[3] Charles Z. Serpan, Jr., NRC, Memorandum to Jack Strosnider, NRC, January 15, 1993, "Generic Bounding Analyses for Evaluation of Low Charpy Upper-Shelf Energy Effects on Safety Margins Against Fracture of RPV Beltline Plate and Weld Materials"; Charles Z. Serpan, Jr., NRC, Memorandum to Jack Strosnider, NRC, February 8, 1993, "Additional Information Regarding Results of Generic Bounding Analyses for Evaluation of Pressure Vessels Fabricated Using Low Charpy Upper-Shelf Energy Materials." Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555; telephone (202)634-3273; fax (202)634-3343.

The regulatory guide acceptance criteria were taken directly from the ASME efforts. The criteria were developed by the ASME Code Section XI working group over an 11-year period and represent the collective judgment of a body of experts representing the NRC staff, research contractors, nuclear utilities, nuclear power plant vendors, consultants, and academia. Similarly, the evaluation procedures for Service Levels A and B were developed by this group. The procedures in the regulatory guide for Service Levels A and B are essentially identical to those in Appendix K to ASME Section XI. Thus, the acceptance criteria and the evaluation procedures for the service levels that generally control the analyses are based on the consensus technical opinion of a large group of technical experts and were developed over an extended period.

The evaluation procedures for Service Levels C and D were developed by the staff and build on the procedures for Service Levels A and B. As part of a continuing effort by the ASME Section XI working group, the NRC staff has compared the regulatory guide procedures to other procedures that are being developed by various organizations. The comparison was very favorable, with the procedures proposed in the regulatory guide predicting lower acceptable Charpy upper-shelf energy values than would be predicted by the other procedures, which were less rigorous and, consequently, more conservative.

The procedures for transient selection are based on procedures that have already been endorsed by the staff. Alternatively, generic bounding transients can be used if justified.

The guidance on material properties is based on a state-of-the-art statistical evaluation of all available fracture toughness data. A broad range of alternatives is offered in the regulatory guide so that methods acceptable to the staff are offered for virtually every situation and combination of circumstances.

The regulatory guide provides timely, cost-effective guidance that is based on the consensus of a large group of technical experts representing diverse backgrounds and interests. The specific guidance is comprehensive and would provide an effective and definitive approach to performing equivalent margin analyses.

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