NUREG-0800
(Formerly NUREG-75/087)

U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

5.3.2 PRESSURE-TEMPERATURE LIMITS

REVIEW RESPONSIBILITIES

Primary - Materials Engineering Branch (MTEB)

Secondary - None

I. AREAS OF REVIEW

1. Pressure-Temperature Limits

The regulations requiring the imposition of pressure-temperature limits on the reactor coolant pressure boundary are the following:

Paragraph 50.55a of 10 CFR Part 50, "Codes and Standards," requires that structures, systems, and components be designed, fabricated, erected, constructed, tested, and inspected to quality standards commensurate with the importance of the safety function to be performed. In addition, General Design Criterion 1 of Appendix A of 10 CFR Part 50, "Quality Standards and Records," requires that the codes and standards used to assure quality products in keeping with the safety function be identified and evaluated to determine their adequacy.

General Design Criterion 14 of Appendix A of 10 CFR Part 50, "Reactor Coolant Pressure Boundary," requires that the reactor coolant pressure boundary be designed, fabricated, erected, and tested in order to have an extremely low probability of abnormal leakage, of rapid failure, and of gross rupture. Likewise, General Design Criterion 31, "Fracture Prevention of Reactor Coolant Pressure Boundary," requires, in part, that the reactor coolant pressure boundary be designed with sufficient margin to assure that when stressed under operating, maintenance and testing, the boundary behaves in a nonbrittle manner and the probability of rapidly propagating fracture is minimized. Further, in order to assess the structural integrity of the reactor vessel, General Design Criterion 32, "Inspection of Reactor Coolant Pressure Boundary," requires, in part, an appropriate materials surveillance program for the reactor vessel beltline region.

The pressure-temperature limits imposed on the reactor coolant pressure boundary during operation and tests are reviewed in this section of the Standard Review Plan (SRP) to assure adequate safety margins of structural integrity for the ferritic components of the reactor coolant pressure boundary.

II. ACCEPTANCE CRITERIA

The requirements of paragraph 50.55a and General Design Criteria 1, 14, 31 and 32 of Appendix A of 10 CFR Part 50 are met by the assurance that material of the reactor coolant pressure boundary possess adequate fracture toughness properties to resist rapidly propagating failure and act in a nonbrittle manner when stressed under operating, maintenance, testing, and anticipated operational conditions. The requirement, in part, of General Design Criterion 32 is met by conducting a surveillance program to monitor the change in fracture toughness properties of the ferritic materials in the reactor vessel.

The fracture toughness requirements for ferritic materials in the pressure-retaining components of the RCPB are specified for testing and operational conditions, including anticipated operational occurrences, in Section IV of Appendix G of 10 CFR Part 50. This appendix requires the acceptance and performance criteria of Appendix G of Section III of the ASME Boiler and Pressure Vessel Code. Pressure-temperature calculation procedures are described in Appendix G of the ASME code; while the detailed technical basis for the ASME code requirement is provided by the Welding Research Council (WRC) Bulletin 175, "PVRC Recommendation on Toughness Requirements for Ferritic Materials." Changes in the fracture-toughness properties of materials in the beltline region, resulting from neutron irradiation and the thermal environment, are monitored by a surveillance program in compliance to the requirements of Appendix H of 10 CFR Part 50. The effect of neutron fluence on the shift in the nil-ductility temperature of pressure vessel steel is predicted by Regulatory Guide 1.99, "Effect of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials."

1. Applicable Regulations, Codes, and Basis Documents

Appendices G and H of 10 CFR Part 50 describe the conditions that require pressure-temperature limits and provide the general basis for these limits. These appendices specifically require that pressure-temperature limits must provide safety margins at least as great as those recommended in the ASME Boiler and Pressure Vessel Code (hereinafter "the Code"), Section III, Appendix G, "Protection Against Nonductile Failure," during heatup, cooldown, and test conditions. Appendix G to 10 CFR Part 50 also requires additional safety margins whenever the reactor core is critical (except for low-level physics tests).

2. Technical Bases

Since many of the fracture toughness requirements for the ferritic materials in the pressure-retaining components were not required at the time some of the reactor facilities were designed and constructed, the Materials Engineering Branch Technical Position MTEB 5-2, "Fracture Toughness Requirements," describe procedures for making estimates and assumptions on the fracture toughness properties of materials in the older plants. Calculations are required, and an evaluation is made by the reviewer to show compliance with the regulations and to show an adequate margin of quality and safety for the facility. When it has been determined that certain requirements of Appendices G or H have not been strictly complied with by these older plants, and when it has been determined that an equivalent level of quality and safety, as required by the regulations exist, then exemption to the specific requirements of these appendices will be granted by the Commission.

a. The principles of linear elastic fracture mechanics (LEFM) are used to determine safe operational conditions. The basic parameter of LEFM is the stress intensity factor, K_I, which is a function of the stress state and flaw configuration. An analytical method is used to determine the effects of real or postulated flaws. The minimum K_I that can cause failure is defined as the critical stress intensity factor, K_{Ic}, and is the material parameter used in this method. The K_{Ic} of the material is either directly measured as a function of temperature, or is conservatively estimated, using information from other fracture toughness tests.

b. The Code specifies the maximum K_{Ic}, as a function of temperature, that can be assumed for the specific material, based on results of tests on the material used. This value is called K_{IR}, reference stress intensity factor. The Code also provides rules for calculating K_I, including definitions of postulated flaws, and specifies the safety factors to be applied. The acceptance criterion is that the K_{IR} of the material must always be higher than the K_I calculated.

c. Direct measurement of the K_{Ic} as a function of temperature is expensive and time consuming and requires more sample material than is usually available. Correlations between the K_{Ic} determined directly and results of simpler fracture toughness tests are not exact, but may be used if appropriate allowances are made for variations in material behavior and data scatter. The Code gives values of K_{IR} as a function of temperature relative to a conservative determination of the reference temperature of the material. This reference temperature, RT_{NDT}, is determined for the ferritic materials of components for which operating and testing limit curves must be calculated. The effects of radiation on the fracture toughness of the material in the beltline region of the reactor vessel is accounted for by adjusting the RT_{NDT} of the affected material upward. The amount of upward shift depends on the composition of the steel (especially its copper and phosphorous content), and the neutron fluence. Conservative predictions of the effect of radiation on the RT_{NDT} based on data in Regulatory Guide 1.99, are factored into the original limit curves. The continued conservatism of these predictions throughout plant life is verified by a mandatory material surveillance program described in Appendix H of 10 CFR Part 50.

d. The Code specifies the stress components that must be used for the K_I calculations, and the factors that must be applied to each to provide adequate safety margins. The Code, by reference to WRC-175, specifies the expression to use for calculating the K_I, using the applied stresses and the postulated flaw geometry. Although calculations are usually made by a computer, curves are provided in the Code to facilitate the use of conservative hand calculations if desired.

3. Pressure-Temperature Requirements

The requirements for the pressure-temperature limits are as follows:

a. Pressure-Temperature Limits for Preservice Hydrostatic Tests

During preservice hydrostatic tests (if fuel is not in the vessel), the K_{IR} must be greater than the K_I caused by pressure. The expression used is:

$$K_I = K_I(\text{pressure}) < K_{IR}$$

b. Pressure-Temperature Limits for Inservice Leak and Hydrostatic Tests

During performance of inservice leak and hydrostatic tests, the K_{IR} must be greater than 1.5 times the K_I caused by pressure. The expression used is:

$$K_I = 1.5\ K_I(\text{pressure}) < K_{IR}$$

c. Pressure-Temperature Limits for Heatup and Cooldown Operations

At all times during heatup and cooldown operations, the K_{IR} must be greater than the sum of 2 times the K_I caused by pressure and the K_I caused by thermal gradients. The expression used is:

$$K_I = 2K_I(\text{pressure}) + K_I(\text{thermal}) < K_{IR}$$

d. Pressure-Temperature Limits for Core Operation

At all times that the reactor core is critical (except for low power physics tests) the temperature must be higher than that required for inservice hydrostatic testing, and in addition, the pressure-temperature relationship shall provide at least a 40°F margin over that required for heatup and cooldown operations.

III. REVIEW PROCEDURES

The reviewer will select and emphasize material from the procedures described below, as may be appropriate for a particular case.

1. Preliminary Safety Analysis Report (PSAR)

Information in the PSAR is reviewed for a commitment that the fracture toughness of the ferritic materials in the reactor coolant pressure boundary will comply with the requirements of Appendix G of 10 CFR Part 50, as detailed in Section III of the ASME Boiler and Pressure Vessel Code and that the materials in the beltline region of the reactor vessel will comply with the requirements of Appendices G and H of 10 CFR Part 50 and Regulatory Guide 1.99, "Effect of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials."

2. Final Safety Analysis Report (FSAR)

The limits in the plant Technical Specifications will be shown using real temperature. These curves and their bases are reviewed to determine acceptability in the following areas:

a. The limiting RT_{NDT} has been properly determined, and radiation effects are included in a conservative manner.

b. Limits are shown for all required conditions.

c. The limits proposed are consistent with the acceptance criteria described in II. above.

d. The procedures for updating the limit curves, in conjunction with scheduled tests on material surveillance specimens, are well defined and included in the Technical Specifications.

3. Acceptability Determination Methods

The reviewer evaluates each limit curve for acceptability by performing check calculations using the simplified methods referenced in the Code and WRC Bulletin 175 that have been verified by the Materials Engineering Branch to yield conservative values. These methods are described in detail by examples below, and the curves necessary to perform the calculations are included herein as Figures 1, 2 and 3.

a. Preservice Hydrostatic Tests

The preservice hydrotest at 1.25 design pressure corresponds to the standard Code component hydrotest usually performed in the shop, but in this case it is the hydrotest for field welds, so it may involve the entire reactor coolant system.

The Code recommends that component hydrostatic tests be run at a temperature no lower than RT_{NDT} + 60°F, but also recommends that system tests should have more stringent requirements. The MTEB position is that the minimum temperature for the preservice test, if fuel is not in the vessel, be determined using the methods of Code Section III, Appendix G, using less stringent factors.

First, the RT_{NDT} of the vessel material must be determined. This is defined by the Code for new plants, and is essentially a conservative value of the NDTT as determined by drop weight test. Guidelines for estimating the RT_{NDT} if the prescribed tests have not been run are given by Branch Technical Position - MTEB 5-2, "Fracture Toughness Requirements." Technical justification for all estimates of RT_{NDT} must be provided by the applicant.

The toughness of the material is a function of the difference between the RT_{NDT} of the material and the temperature of interest. The Code provides a curve (Figure G-2210.1) for the allowable calculated stress intensity factor (K_{IR}) as a function of the temperature relative to RT_{NDT}. Refer to Figure 2 herein.

The Code also provides a recommended basis for calculating K_I, including recommendations for assumed flaw size and shape, and appropriate front and back surface correction factors. Because the assumed flaw size is proportional to the wall thickness, t (flaw depth = 0.25 t and length = 1.5 t), the K_I expressions are simplified to multiples that are a function only of wall thickness and stress level. These factors, M_m for membrane stresses and M_B for bending stresses, are provided in graphical form in Figure G-2214.1 of the Code. Refer to Figure 1 herein.

The criterion recommended by MTEB can be expressed as

$K_I < K_{IR}$ for the shell region.

To get K_I, the stress level and wall thickness must be known. The pressure for the hydrostatic test is 1.25 times the design pressure, so that the higher of two simple methods described below to approximate the membrane stress should be accurate enough for this purpose:

stress = 1.25 times the Code allowable (S_m)

$$\text{stress} = \frac{Pr}{t}$$

where P is the test pressure and r is the vessel radius. As an example, assume a vessel with a design pressure of 2500 psig, made of steel with an S_m of 26,700 psi, and a minimum yield strength of 50,000 psi. The stress for the preservice hydrotest is then

$26{,}700 \times 1.25 = 33{,}400$ psi, or

$\frac{(1.25)\ (2500)\ (95)}{9} = 33{,}400$ psi, for a vessel with a radius of 95 inches and a wall thickness of 9 inches.

The next step is to determine the factor to apply to this stress to obtain K_I. Figure G-2214.1 (reproduced here as Fig. 1) provides several curves, depending on the ratio of the stress level to the yield strength of the material. In this case, the stress level is 33,400; the yield strength is conservatively assumed to be 50,000 so the curve for a ratio of .7 should be used. (A ratio equal to or higher than the actual ratio must be used for conservatism.) For a 9-in. thick vessel ($\sqrt{t} = 3$), the value of M_m from Figure G-2214.1 is 2.94. The K_I for this case is then:

$$K_I = (M_m) \text{ (Membrane Stress)}$$

$$K_I = (2.94)\ (33{,}400) = 98{,}300 \text{ psi } \sqrt{\text{in.}}$$

From Figure G-2210.1 (reproduced here as Fig. 2), a temperature of at least RT_{NDT} + 120°F is necessary for a K_I of this level.

If, for example, an original RT_{NDT} of 40°F is assumed, the required temperature is then 40 + 120, or 160°F.

b. Inservice Leak and Hydrotest.

The temperatures for the inservice leak and hydrotest, performed at operating pressure and about 1.1 operating pressure, respectively, are calculated in essentially the same way. The differences are that a factor of 1.5 must be applied to the calculated K_I to provide extra margin, and the stress levels are lower, so the value of M_m is taken from a lower ratio curve.

Using the same vessel as an example, with a normal operating pressure (P_o) of 2250 psi, the membrane stress for the leak test can be approximated as:

$$\frac{\text{operating pressure}}{\text{design pressure}} \times \text{allowable stress}$$

$$\text{or } \frac{2250}{2500} \times 26{,}700 = 24{,}000 \text{ psi}$$

This is about half of the minimum yield strength, so the M_m is taken from the 0.5 ratio curve, and is 2.87. The calculated K_I that must be assumed is then:

$$K_I = (1.5)\ (M_m) \text{ (Membrane Stress)}$$

$$\text{or } K_I = (1.5)\ (2.87)\ (24{,}000) = 103{,}500 \text{ psi } \sqrt{\text{in.}}$$

From the K_{IR} curve, a temperature of about RT_{NDT} + 125°F is required. As this is an inservice test, the RT_{NDT} would probably have been increased from its original value of + 40°F by some shift caused by radiation. Assume this shift is 100°F, thus the temperature for the leak test must be at least:

$$40 + 100 + 125 = 265°\text{F}$$

The inservice hydrotest temperature (at 1.1 P_o) is determined in exactly the same way, and requires a minimum temperature of about RT_{NDT} + 133°F, or 273°F.

c. Heatup, Cooldown, and Normal Operation.

For normal operation, which includes upset conditions and startup and shutdown procedures, operating limit curves must be provided that show the maximum permissible pressure at any temperature from cold shutdown conditions to full pressurization conditions.

Reactor vendors have developed computer codes to perform the necessary calculations, because thermal stresses must be included, and hand calculations of even moderate sophistication are very time consuming. WRC Bulletin 175 includes a set of curves derived from computer programs that can be used to approximate the K_I caused by thermal stresses, as a function of wall thickness and rate of temperature change. Pressure-temperature curves developed using these approximations agree fairly well with those determined using much more rigorous procedures, and can be used with confidence to evaluate the proposed operating limits given in Technical Specifications. These curves require the calculation of only 3 to 5 points. Either allowable pressure at a given temperature, or allowable temperature at a given pressure can be calculated. It is usually more convenient to calculate allowable minimum temperature, so this method will be used in the example.

Using the same reactor vessel as in the previous example, and a rate of temperature change of 50°F per hour, calculations of required temperatures for several pressures are illustrated. The curves for thermal effects given in WRC Bulletin 175 are very conservative, thus no additional margin need by applied to the K_I from thermal stress, but a factor of 2.0 is used on primary stresses. The basic expression is then:

$$K_{IR} \geq 2\ K_I(\text{membrane}) + K_I\ (\text{thermal})$$

K_I(membrane) is calculated exactly as in the previous examples.

K_I(thermal) for a 9-in. thick wall, at 50°/hr is about 12,000 psi $\sqrt{\text{in.}}$ from Figure 4-5, WRC Bulletin 175 (reproduced here as Fig. 3).

Thus, for a pressure of 2250 psig, a membrane stress of 24,000 psi, and M_m of 2.87, the basic expression is given by

$$K_{IR} > (2)(24{,}000)(2.87) + 12{,}000 = 150{,}000 \text{ psi } \sqrt{\text{in.}}$$

From the K_{IR} curve, a temperature of RT_{NDT} + 158°F is required. With an RT_{NDT} of 140°F (including irradiation effects), the temperature required for operating pressure at a heatup or cooldown rate of 50°/hr is then

$$140 + 158 = 298°\text{F}$$

For a pressure of 1/2 of operating (1125 psig), the membrane stress is 1/2 of that at operating pressure, or 12,000 psi.

The M_m can be taken from the 0.5 $\frac{\sigma}{\sigma y}$ ratio curve in Figure G-2214.1 (reproduced as Figure 1 herein), so is again 2.87.

$$K_{IR} \geq (2)(12{,}000)(2.87) + 12{,}000 = 81{,}000 \text{ psi } \sqrt{\text{in.}}$$

From the K_{IR} curve, the minimum temperature is RT_{NDT} + 100°F, or 140 + 100 = 240°F.

The same calculation for a pressure of 1/5 operating pressure (450 psig and 4800 psi stress) is similar, but in this case the stress is less than .1 of the yield strength, so the M_m (from the .1 ratio curve) is only 2.82.

$$K_{IR} \geq (2)(4800)(2.82) + 12,000 = 39,000 \text{ psi } \sqrt{\text{in.}}$$

The K_{IR} curve shows that the minimum temperature is RT_{NDT} + 0°F, or 140°F.

Three points on a 50°/hr operating limit curve for this vessel at this time in its service lifetime have thus been calculated:

Pressure (psig)	Min. Temperature (Fahrenheit)
450	140
1150	240
2250	298

•A smooth curve drawn through these points will very closely approximate the results using more rigorous methods.

d. Core Operation

Appendix G, 10 CFR Part 50, specifies pressure-temperature limits for core operation to provide additional margin during actual power production.

The pressure-temperature limits for core operation (except for low power physics tests) are that the reactor vessel must be at a temperature equal to or higher than the minimum temperature required for the inservice hydrostatic test, and at least 40°F higher than the minimum pressure-temperature curve for heatup and cooldown calculated as described in the preceding section. The minimum temperature for the inservice hydrostatic test for the vessel used in the preceding example was 273°F. A vertical line at 273°F on the pressure-temperature curve, intersecting a curve 40°F higher than the pressure-temperature limit curve as determined in the preceding section, constitutes the limit for core operation for this example.

IV. EVALUATION FINDINGS

The reviewer verifies that sufficient information has been provided to satisfy the requirements of this SRP section and that the completeness and technical adequacy of his evaluation will support the following statement in the staff's safety evaluation report:

The pressure-temperature limits imposed on the reactor coolant system for all operating and testing conditions to assure adequate safety margins against nonductile or rapidly propagating failure are in conformance with the fracture toughness criteria of Appendix G of 10 CFR Part 50 and Section III, including Appendix G, "Protection Against Nonductile Failure," of the ASME Boiling and Pressure Vessel Code. The change in fracture toughness requirements of the pressure vessel during operation will be determined by Appendix H of 10 CFR Part 50. The use of operating limits, based upon the criteria defined in Standard Review Plan Section 5.3.2, provides reasonable assurance that nonductile or rapidly propagating failure will not occur, and constitutes an acceptable basis for satisfying the requirements of paragraph 50.55a of 10 CFR Part 50 and General Design Criteria 1, 14, 31 and 32 of Appendix A of 10 CFR Part 50.

V. IMPLEMENTATION

The following is intended to provide guidance to applicants and licensees regarding the NRC staff's plan to using this SRP section.

Except in those cases in which the applicant proposed an acceptable alternative method for complying with specific portions of the Commission's regulations, the method described herein will be used by the staff in its evaluation of conformance with Commission regulations.

Implementation schedules for conformance to parts of the method discussed herein are contained in the referenced regulatory guide.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criteria 1, 14, 31, and 32.

2. 10 CFR Part 50, Appendix G, "Fracture Toughness Requirements."

3. 10 CFR Part 50, Appendix H, "Reactor Vessel Material Surveillance Program Requirements."

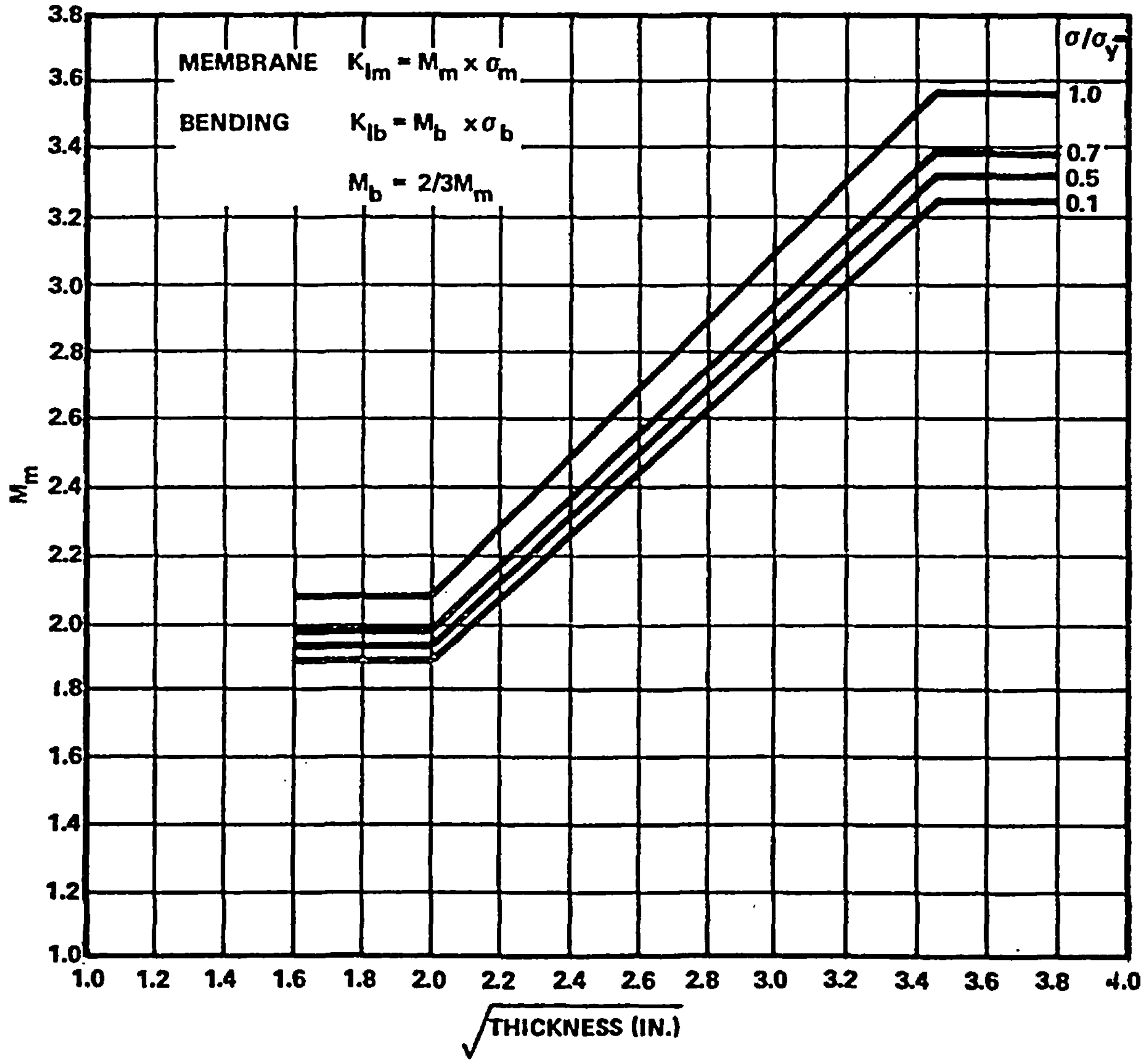
4. ASME Boiler and Pressure Vessel Code, Section III, including Appendix G, "Protection Against Nonductile Failure," American Society of Mechanical Engineers.

5. WRC Bulletin 175, "PVRC Recommendation on Fracture Toughness," Welding Research Council.

6. Branch Technical Position - MTEB 5-2, "Fracture Toughness Requirements for Older Plants," attached to this SRP section.

7. Regulatory Guide 1.99, "Effects of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials."

8. 10 CFR Part 50, paragraph 50.55a, "Codes and Standards."



M_m AND M_b VS. WALL THICKNESS FOR

SEMI-ELLIPTICAL SURFACE FLAW ¼T DEEP AND 1½T LONG

FIGURE 1

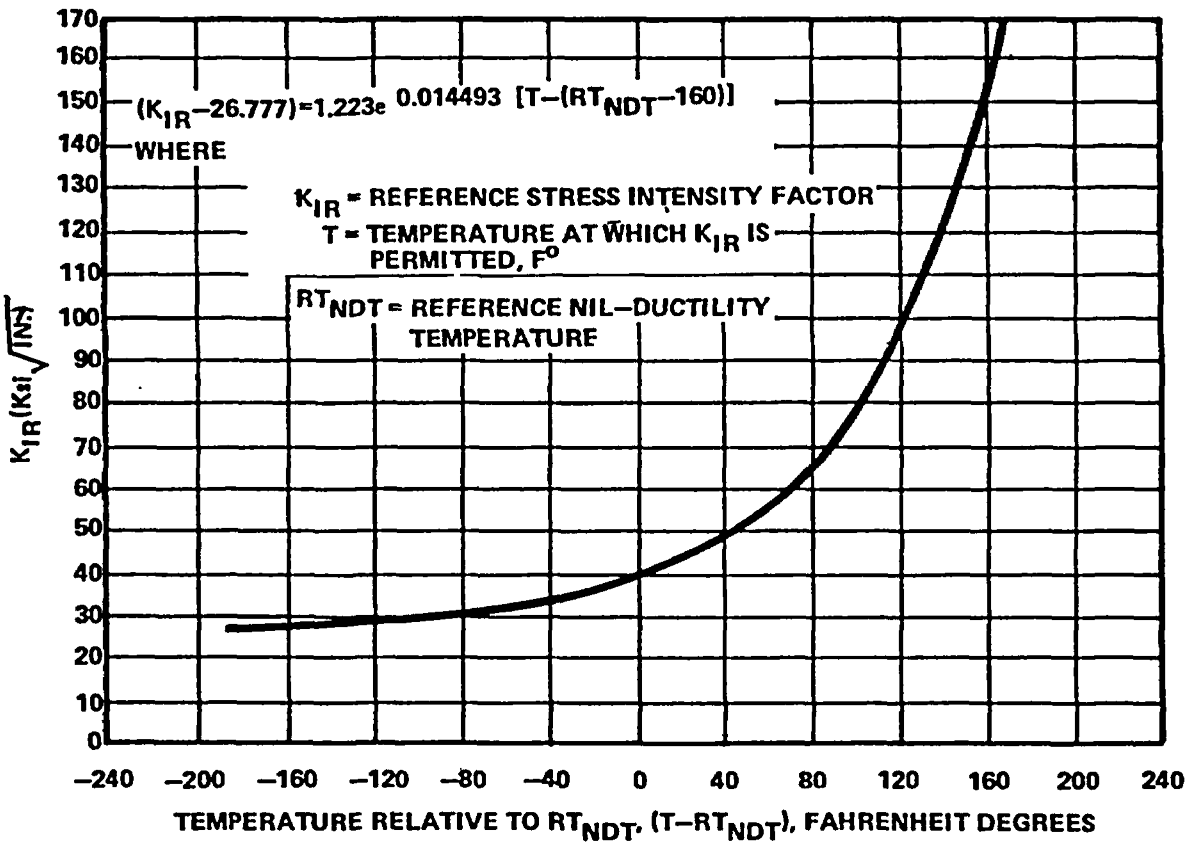
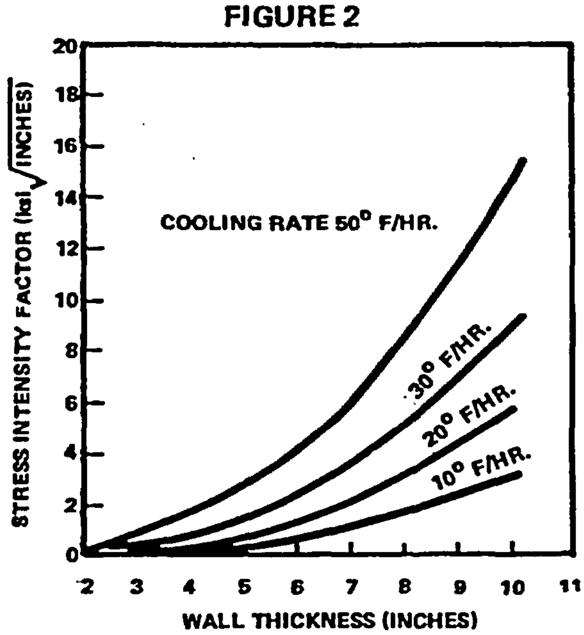


FIGURE 2



4-5 – STRESS INTENSITY FACTOR CAUSED BY THERMAL STRESS FOR CYLINDERS WITH RADIUS/THICKNESS = 10

FIGURE 3

BRANCH TECHNICAL POSITION - MTEB 5-2
FRACTURE TOUGHNESS REQUIREMENTS

A. Background

Current requirements regarding fracture toughness, pressure-temperature limits, and material surveillance are covered by the ASME Code and Appendices A, G, and H to 10 CFR Part 50. The purpose of this branch technical position is to summarize these requirements and provide clarification, as necessary.

Since many of these requirements were not in force when some plants were designed and built, this position also provides guidance for applying these requirements to older plants. Also included is a description of acceptable procedures for making the conservative estimates and assumptions for older plants that may be used to show compliance with the new requirements. It should be noted that the applicants must present adequate technical justifications for any estimates of material properties required by the regulations before exemption to the regulations may be granted.

B. Branch Technical Position

1. Preservice Fracture Toughness Test Requirements.

   The fracture toughness of all ferritic materials used for pressure-retaining components of the reactor coolant pressure boundary shall be evaluated in accordance with the requirements of Appendix G, 10 CFR Part 50, as augmented by Section III of the ASME Code. The fracture toughness test requirements for plants with construction permits prior to August 15, 1973 may not comply with the new Codes and Regulations in all respects. The fracture toughness of the materials for these plants must be assessed by using the available test data to estimate the fracture toughness in the same terms as the new requirements. This must be done because the operating limitations imposed on old plants must provide the same safety margins as are required for new plants.

1.1 Determination of RT_{NDT} for Vessel Materials

   Temperature limitations are determined in relation to a characteristic temperature of the material, RT_{NDT}, that is established from results of fracture toughness tests. Both drop weight NDTT tests and Charpy V-notch tests must be run to determine the RT_{NDT}. The NDTT temperature, as determined by drop weight tests (ASTM E-208) is the RT_{NDT} if, at 60°F above the NDTT, at least 50 ft-lbs of energy and 35 mils lateral expansion are obtained in Charpy V tests on specimens oriented in the weak direction (traverse to the direction of maximum working).

   In most cases, the fracture toughness testing performed on vessel material for older plants did not include all tests required to determine the RT_{NDT} in this manner. Acceptable estimation methods for the most common cases, based on correlations of data from a large number of heats of vessel material, are provided for guidance.

(1) If dropweight tests were not performed, but full Charpy V-notch curves were obtained, the NDTT for SA-533 Grade B, Class 1 plate and weld material may be assumed to be the temperature at which 30 ft-lbs was obtained in Charpy V-notch tests, or 0°F, whichever was higher.

(2) If dropweight tests were not performed on SA-508, Class II forgings, the NDTT may be estimated as the lowest of the following temperatures:

   (a) 60°F.

   (b) The temperatures of the Charpy V-notch upper shelf.

   (c) The temperature at which 100 ft-lbs was obtained on Charpy V-notch tests if the upper-shelf energy values were above 100 ft-lbs.

(3) If transversely-oriented Charpy V-notch specimens were not tested, the temperature at which 50 ft-lbs and 35 mils LE would have been obtained on traverse specimens may be estimated by one of the following criteria:

   (a) Test results from longitudinally-oriented specimens reduced to 65% of their value to provide conservative estimates of values expected from transversely oriented specimens.

   (b) Temperatures at which 50 ft-lbs and 35 mils LE were obtained on longitudinally-oriented specimens increased 20°F to provide a conservative estimate of the temperature that would have been required to obtain the same values on transversely-oriented specimens.

(4) If limited Charpy V-notch tests were performed at a single temperature to confirm that at least 30 ft-lbs was obtained, that temperature may be used as an estimate of the RT_{NDT} provided that at least 45 ft-lbs was obtained if the specimens were longitudinally oriented. If the minimum value obtained was less than 45 ft-lbs, the RT_{NDT} may be estimated as 20°F above the test temperature.

1.2 Estimation of Charpy V Upper-Shelf Energies

For the beltline region of reactor vessels, the upper shelf toughness must be adequate to accommodate degradation by neutron radiation. The original minimum shelf energy must be 75 ft-lbs for vessels with an estimated end of life neutron fluence (> 1 MeV) of 1×10^{19} and over. A value of 70 ft-lbs is considered adequate for material for vessels that will be subjected to lower fluences.

If upper-shelf Charpy energy values were not obtained, conservative estimates should be made using results of tests on specimens from the first surveillance capsule removed.

If tests were only made on longitudinal specimens, the values should be reduced to 65% of the longitudinal values to estimate the transverse properties.

1.3 Reporting Requirements

Fracture toughness information required by the Code and by Appendix G, 10 CFR Part 50, must be reported in the FSAR to provide a basis for evaluating the adequacy of the operating limitations given in the Technical Specifications. In the case of older plants, the data may be estimated, using the procedures listed above, or other methods that can be shown to be conservative.

2. Operating Limitations for Fracture Toughness

2.1 Required Pressure-Temperature Operating Limitations

As required by Appendix G, 10 CFR Part 50, the following operating limitations shall be determined and included in the Technical Specifications. The basis for determination shall be reported, and is the responsibility of the applicant, but in no case shall the limitations provide less safety margin than those determined in accordance with Appendix G, 10 CFR Part 50, and Appendix G to Section III of the Code.

(1) Minimum temperatures for performing any hydrostatic test involving pressurization of the reactor vessel after installation in the system.

(2) Minimum temperatures for all leak and hydrostatic tests performed after the plant is in service.

(3) Maximum pressure-minimum temperature curves for operation, including startup, upset, and cooldown conditions.

(4) Maximum pressure-minimum temperature curves for core operation.

2.2 Recommended Bases for Operating Limitations

2.2.1 Leak and Hydrostatic Tests

(1) It is recommended that no tests at pressures higher than design pressure be conducted with fuel in the vessel.

(2) Tests at pressures less than design pressure should be conducted at temperatures calculated according to Appendix G of Section III of the Code for the beltline region (including conservative estimates of radiation damage, see Section 3.0 below) if the maximum calculated primary stress in no other region of the vessel exceeds 1.25 S_m during the test, and the RT_{NDT} of the beltline is assumed to be at least 30°F above that of the higher stressed regions. If primary stresses are calculated to be over 1.25 S_m in any region during the test, the RT_{NDT} of the vessel must be assumed to be at least 50°F higher than that of

any region where the calculated primary stresses are over 1.25 S_m.

(3) Alternatively, a fracture mechanics analysis, with technical justification for all assumptions and bases, may be made to determine the minimum test temperature. In no event shall the minimum temperature be lower than that resulting from calculations for the beltline region in accordance with Appendix G of the Code.

2.2.2 Heatup and Cooldown Limit Curves

Heatup and cooldown pressure-temperature limit curves may be determined using single $\frac{pr}{t}$ stress calculations, using the method given in Appendix G of the Code. The effect of thermal gradients may be conservatively approximated by the procedures in Appendix G of the Code or from Figure 4-5 in WRC Bulletin 175.

Calculations need only be performed for the beltline region, if the RT_{NDT} of the beltline is demonstrated to be adequately higher than the RT_{NDT} for all higher stressed regions.

Alternatively, more rigorous analytical procedures may be used, provided that the intent of the Code is met, and adequate technical justification for all assumptions and bases is provided.

2.2.3 Core Operation Limits

To provide added margins during actual core operation, Appendix G, 10 CFR Part 50 requires a minimum temperature during core operation, and a 40°F margin in temperature over the pressure-temperature limits as determined for heatup and cooldown in 2.2.2 above. The minimum temperature, regardless of pressure, is the temperature calculated for the inservice hydrostatic test according to 2.2.1 above.

2.2.4 Upset Conditions

The pressure-temperature limits described in 2.2.2 and 2.2.3 above are applicable to upset conditions. Normal operating procedures must permit variations from intended operation, including all upset conditions, without exceeding the limit curves.

2.2.5 Emergency and Faulted Conditions

It is recognized that the severity of a transient resulting from an emergency or faulted condition is not directly related to operating conditions, and resulting temperature-stress relationships in the reactor coolant boundary components are primarily system dependent, and therefore not under direct control of the operator.

For these reasons, operating limits for emergency and faulted conditions are not a requirement of the Technical Specifications.

The SAR should present descriptions of the continued integrity of all vital components of the RCPB during postulated faulted conditions. It is recommended that such descriptions be made in as realistic a manner as possible, avoiding grossly overconservative assumptions and procedures.

2.3 Reporting Requirements

The Technical Specifications must include the operating and test limits discussed above, and the basis for their determination. The Technical Specifications must also include information on the intended operating procedures, and justify that adequate margins between the expected conditions and the limit conditions will be provided to protect against unexpected or upset conditions.

3. Inservice Surveillance of Fracture Toughness

The reactor vessel may be exposed to significant neutron radiation during the service life. This will affect both the tensile and toughness properties. A material surveillance program in conformance with Appendix H, 10 CFR Part 50, must be carried out.

3.1 Surveillance Program Requirements

The minimum requirements for the surveillance program are covered by Appendix H, 10 CFR Part 50. It is strongly recommended that consideration by given to the desirability of additional surveillance methods, such as the inclusion of CT, DWT, DT, or other specimens to provide the capability of redundant test methods and analytical procedures, particularly if the estimated neutron fluence is over 2×10^{19}, or the toughness of the vessel material is marginal.

The selection of material to be included in the surveillance program should be in accordance with ASTM E-185-73, unless the intent of the program is better realized by using more rigorous criteria. For example, the approach of estimating the actual RT_{NDT} and upper shelf toughness of each plate, forging, or weld in the beltline as a function of service life, and choosing as the surveillance materials those that are expected to be most limiting, may be preferable in some cases. This would include consideration of the initial RT_{NDT}, the upper shelf toughness, the expected radiation sensitivity of the material (based on copper and phosphorous content, for example) and the neutron fluence expected at its location in the vessel.

3.2 SAR Requirements

The adequacy of the surveillance program cannot be evaluated unless all pertinent information is included in the SAR. Information requested for beltline materials includes the following:

(1) Tensile properties.

(2) DWT and Charpy V test results used to determine RT_{NDT}.

(3) Charpy V test results to determine the upper shelf toughness.

(4) Composition, specifically the copper and phosphorous content.

(5) Estimated maximum fluence for each beltline material.

(6) List of materials included in the surveillance program, with basis used for their selection.

3.3 Surveillance Test Procedures

Surveillance capsules must be removed and tested at intervals in accordance with Appendix H, 10 CFR Part 50. The proposed removal and test schedule shall be included in the Technical Specifications.

3.4 Reporting Requirements

All information used to evaluate results of the tests on surveillance materials, evaluation methods, and results of the evaluation should be submitted with the evaluation report. This should include:

(1) Original properties and compositions of the materials.

(2) Fluence calculations, including original predictions, for both surveillance specimens and vessel wall.

(3) Test results on surveillance specimens.

(4) Basis for evaluation of changes in RT_{NDT} and upper shelf toughness.

(5) Updated prediction of vessel properties.

3.5 Technical Specification Changes

Changes in the operating and test limits recommended as a result of evaluating the properties of the surveillance material, together with the basis for these changes, shall be submitted to the Division of Licensing for approval.