Determination of ASME Code Requirements for BWR Hydrotest Temperature and PWR LTOP Set-points Using Probabilistic Fracture Mechanics Analysis

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ABSTRACT

Probability analyses were performed to determine pressure and temperature conditions that would satisfy safety goals for certain events associated with nuclear pressure vessel operation. The results show that the safety goal can be met at pressure and temperature conditions significantly less restrictive than those required by current ASME Code or regulatory practices.

KEYWORDS

Pressure vessel; failure probability; safety margin; radiation embrittlement; fracture mechanics.

INTRODUCTION

During the last several years, significant information describing radiation effects on reactor pressure vessel steels has been collected by industry and regulatory groups. Evaluation of this information has led to modifications in the previously used radiation effects model, as illustrated by recent work presented by the Nuclear Regulatory Commission (NRC) in Regulatory Guide 1.99 (1988).

In general, application of the revised radiation effects model indicates that measures, such as modified operation, flux reduction, or hardware changes, may be required for a number of nuclear plants prior to the end of design life to meet current NRC safety criteria. These criteria include Appendix G to 10CFR50 (1988) and Section XI of the ASME Code (1986) for normal and upset operation, and other criteria (Dircks, 1982; Regulatory guide 1.154, 1987) developed for less frequent events, such as pressurized thermal shock (PTS) events.

Two operating events that have been affected by recent changes in radiation embrittlement model are: (1) the time and temperature needed to perform a boiling water reactor (BWR) system hydrotest, and (2) start-up and shutdown operation of pressurized water reactors (PWRs) having protection against low temperature over pressurization (LTOP) events.

BWR Hydrotest Temperature

Revised radiation embrittlement models and current conservative procedures for defining hydrotest temperature may require BWR hydrotest temperatures near and above 200F during the operating life of boiling water reactors. BWR start-up at relatively high temperature, especially above 200F, extends plant start-up time and has significant adverse economic impact.

PWR Relief Valve Set-points

The relief valve pressure set-point for LTOP protection typically lies between the allowable pressure for normal plant start-up and the pressure associated with the reactor coolant pump (RCP) operating characteristics. As illustrated in Fig. 1, two parameters can be used to characterize the PWR LTOP relief valve set-points; namely, the minimum temperature, T_o, at which the vessel can be pressurized to normal operating pressure, and the maximum allowable pressure, p_o, in the temperature range from cold start-up to T_o.

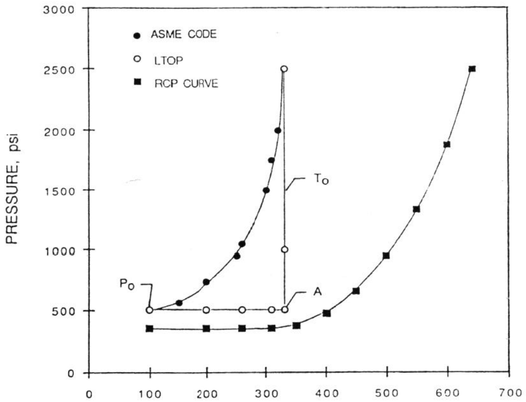

Fig. 1. Illustration of PWR LTOP Set-Points Relative to ASME and RCP Limits

The relative position of the LTOP set-point can create various operational difficulties. First, there is a relatively narrow allowable pressure range for the initial phase of reactor start-up, which lies between p_o and the RCP curve, as illustrated in Fig. 1. Because the allowable temperature during start-up increases with increasing neutron irradiation, the operating LTOP pressure temperature (P/T) limit moves closer to the P/T characteristics of the RCP and further narrows the operating range as the plant gets older.

Finally, depending on the radiation sensitivity of the vessel material, neutron irradiation may cause the operating range to close completely late in plant life, when Point A in Fig. 1 intersects the RCP curve.

These phenomena have significant economic impact because they extend plant start-up time and have the potential to significantly restrict plant operation. The narrow operating window also has safety impact because it increases the likelihood of inadvertent relief valve activation.

ASME Code Application

The work presented here was performed to determine if there is adequate technical justification to warrant using less stringent requirements for defining BWR hydrotest temperature and LTOP protection limits compared to that required by the ASME Code, while maintaining adequate margins against reactor vessel failure.

This work was completed by using probabilistic fracture mechanics methods to define hydrotest temperatures and LTOP limits that would satisfy a criterion defined to determine adequate margin against reactor vessel failure. The reactor vessel evaluation criterion was developed using recently published guidelines (Nuclear Regulatory Commission, 1986), and generally follows the procedures previously used to develop operating limits to protect against failure by PTS.

While this work was completed using probabilistic fracture mechanics methods, the overall goal was to develop simplified criteria that could be placed into the ASME Code for easy application by utility engineers. Generic criteria based on the well known parameter RT_{NDT} have been developed for both BWR hydrotest and PWR LTOP. The respective generic criteria can be used with plant specific material properties to establish operating parameters that provide adequate margin against vessel failure.

PROBABILISTIC EVALUATION CRITERION

The criterion employed to determine BWR hydrotest pressure and temperature conditions and the PWR LTOP protection set-points associated with acceptable margins against failure of the vessel beltline region is in the form previously used to evaluate reactor vessel pressurized thermal shock (PTS) events, or

$$CMF = P(E) \cdot P(F/E) \cdot P(CM/F) < \text{Allowable} \qquad (1)$$

where

CMF = number of core melts per reactor year resulting from a specific event that may lead to vessel failure,

P(E) = event frequency, number per reactor year,

P(F/E) = probability of vessel failure for the event, and

P(CM/F) = probability of core melt for the vessel failure.

The allowable for CMF originally was assigned the value 10^{-5} per reactor year for defining a generic PTS vessel screening criterion (Dircks, 1982); later, this value was reduced to 5×10^{-6} per reactor year for plant specific evaluation (Regulatory Guide 1.154, 1987).

Subsequently, the NRC (1986) published specific performance guidelines to assess compliance with intended safety goals. Based on the intended safety goals and other NRC recommendations (Taylor, 1987), the allowable in Eq. 1 was specified for this work as 10^{-6} per reactor year.

A probabilistic fracture mechanics assessment following the criterion in Eq. 1 is consistent with the general philosophy of the PTS evaluation and the ASME Code, where lower margins on load are required for low frequency or postulated (Service Level C and D) events compared to higher margins on load required for anticipated operating (Service Level A and B) events. As indicated by Eq. 1, a lower probability of vessel failure, P(F/E), is required to achieve the specified core melt frequency for normal operating events when $P(E) = 1$ compared to a higher failure probability for less frequent events, when $P(E) << 1$.

The probabilistic fracture mechanics analysis has an advantage over deterministic analysis methods generally because: (1) it couples event frequency, P(E), and margin against vessel failure, P(F/E), to the safety goal, (2) allows a more quantitative assessment of event frequency, (3) quantifies the contribution to failure of individual variables and events important to vessel integrity, and (4) clearly identifies the risk when vessel failure is the initiating event compared to other events that are risk contributors but are not initiated by vessel failure.

To apply Eq. 1 for this work two additional conservative assumptions also were made, including the events will occur approximately once per reactor year, or $P(E) = 1$, and that a core melt always occurs when the vessel fails, or $P(CM/F) = 1$.

Substituting the 10^{-6} per reactor year allowable, $P(E) = 1$, and $P(CM/F) = 1$ into Eq. 1 yields the relationship used to determine the vessel conditions for the BWR hydrotest and PWR LTOP events that meet the safety goal, or

$$P(F/E) < 10^{-6} \text{ per year.} \tag{2}$$

PROBABILISTIC ANALYSIS METHODS

General Computational Procedure

The probability of reactor vessel failure, P(F/E), was computed using Monte Carlo sampling methods. This method now is used generally for reactor vessel failure probability studies since its early U.S. application for LTOP assessment (Vesely, et al., 1978; Gamble and Strosnider, 1981) and normal operation (Gamble and Strosnider, 1981), and its later application for pressurized thermal shock events (Damesek and Gamble, 1983; Cheverton and Ball, 1984; Simonen et al., 1986).

Fracture Mechanics Methods

The probabilistic fracture mechanics analysis uses linear elastic fracture mechanics to predict conditions for which failure will occur in the vessel beltline region. For linear elastic stress fields, extension of an existing or postulated flaw, and subsequent vessel failure are predicted when

$$K_I \geq K_{IC}, \text{ and } K_I \geq K_{Ia}, \text{ respectively,} \tag{3}$$

where

K_I is the potential to extend a crack postulated to exist in the vessel, and is a function of load, flaw size and shape, and component geometry, and

K_{IC} and K_{Ia} are the material resistance to first crack extension and crack propagation, respectively, and are functions of metal temperature, neutron fluence, material residual element content, fabrication, and heat treatment.

For this work, there are four significant stress components that should be considered in the probabilistic evaluation. These are pressure stress, stress due to the difference in thermal expansion between the clad and base metal, residual stress associated with the vessel pressure boundary welds, and thermal stress, due to heat-up or cooldown of the vessel. The thermal component was applied for the LTOP evaluation only. All flaws were assumed to be inside surface flaws with length to depth ratio of six.

The mean K_{IC} and K_{Ia} relationships used in this study and the data used to obtain the mean curves are presented in Figs. 2 and 3, respectively. The data shown in Figs. 2 and 3 are the same data used to construct ASME K_{IC} and K_{Ia} curves for reactor vessel materials. Plots of the ASME K_{IC} and K_{Ia} curves also are presented for reference in Figs. 2 and 3, respectively.

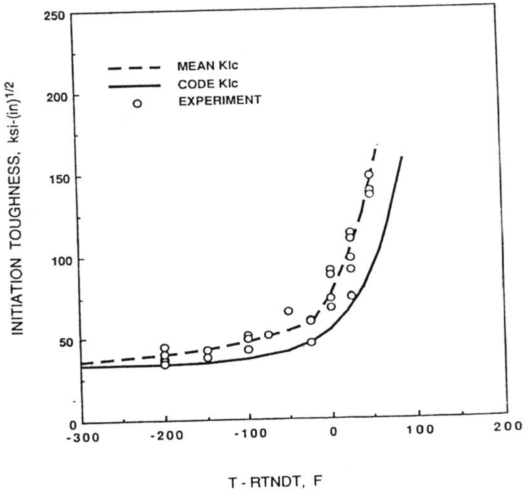

Fig. 2. Initiation Toughness vs. T - RT_{NDT}

The toughness values are plotted as a function of the difference between the metal temperature, T, and a reference temperature for the material, RT_{NDT}. The reference temperature is the sum of an unirradiated value, RT_{NDTo} (initial RT_{NDT}) and a shift in the initial value due to neutron irradiation, ΔRT_{NDT}, or

$$RT_{NDT} = RT_{NDTo} + \Delta RT_{NDT}. \tag{4}$$

ΔRT_{NDT} was determined using the formulation in Regulatory Guide 1.99 (1988), or

$$\Delta RT_{NDT} = (CF)\cdot f^{(0.28-0.10\log f)}, \qquad (5)$$

where

CF = the chemistry factor, which is a function of Cu and Ni contents, and is presented in tabular form for welds and base metal in Regulatory Guide 1.99 (1988),

$f = (f_s/10^{19})\cdot e^{-0.24x}$,

f_s = neutron fluence at the vessel inner surface, n/cm^2,

x = depth into the vessel wall from the vessel wetted inner surface.

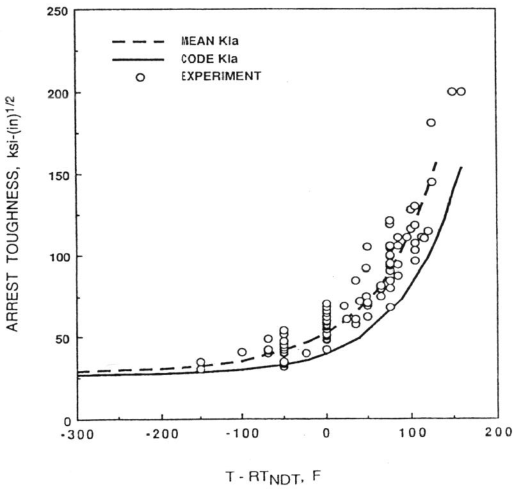

Fig. 3. Arrest Toughness vs. T - RT_{NDT}

Variable Definition

Some variables important to failure predictions are fixed quantities while others are distributed. The deterministic variables generally relate to vessel beltline geometry, and various mechanical and physical properties used to compute stress. The distributed variables are associated with parameters needed to compute K_I (except loads), and the initiation and arrest toughnesses.

Deterministic Variable Definition

Typical vessel beltline dimensions were used to represent the population of BWRs and PWRs. The BWR vessel dimensions were 112.6-inch outer radius and 5.25-inch wall thickness, while the PWR vessel had 91.3-inch outer radius and 8.6-inch wall thickness. Both vessels had cladding thickness of 0.20-inich.

Mechanical and physical properties used to compute stresses were: Poisson's Ratio = 0.3; elastic modulus = 28x10^6 psi; clad stress free temperature = 590F; clad thermal coefficient of expansion = 10^{-5} in/in-F; and base metal thermal coefficient of expansion = 0.8x10^{-5} in/in-F.

Distributed Variables

The distributed variables include flaw size, initial RT_{NDT}, copper and nickel content, ΔRT_{NDT}, RT_{NDT}, initiation toughness, K_{IC}, arrest toughness, K_{Ia}, and neutron fluence. The initial calculations to determine P(F/E) for the vessel beltline were based on variable values used to evaluate normal start-up shutdown conditions, LTOP events (Gamble and Strosnider, 1981), and the initial PTS screening criterion development by the NRC (Dircks, 1982). This set of distributed variables are designated as the reference condition. Table 1 lists the distribution types and limits for the distributed reference variables.

TABLE 1

Distribution Type and Limits for Reference Condition Variables

Variable	Distribution	Standard Deviation	Lower Limit	Upper Limit
Cu	Normal	5% of Mean[1] 15% of Mean[2]	0.0 0.0	0.4 0.4
Ni	Normal	5% of Mean	0.0	1.2
ΔRT_{NDT}	Normal	10 deg. F[1] 15 deg. F[2]	0.0 0.0	N/A N/A
RT_{NDTo}	Normal	17 deg. F	N/A	N/A
Fluence	Normal	45% of Mean 20% of Mean	60% of Mean[1] 75% of Mean[2]	130% of Mean[1] 125% of Mean[2]
Flaw	OCTAVIA[3]	-	0.25	3.5
K_{IC}	Normal	10% of Mean	70% of Mean	130% of Mean
K_{Ia}	Normal	10% of Mean	70% of Mean	130% of Mean

1. Plates
2. Welds
3. See Vesely et al., (1978). A total of two flaws is assumed in the vessel beltline, one in the total weld volume and one in the total base metal volume.

Additional analyses were performed subsequently to determine the effect of changes in selected variables listed in Table 1. These changes generally are consistent with guidance provided (Regulatory Guide 1.154, 1987) for performing plant specific PTS evaluations. The modified distributions and their values are presented in Table 2.

TABLE 2

Modified Distribution Values for Probabilistic Analysis

Variable	Distribution	Standard Deviation	Lower Limit	Upper Limit
Flaw	Marshall[1]	-	0.25	3.0
K_{IC}	Modified Normal	10% of Mean[2] 18% of Mean[3]	ASME K_{Ia} ASME K_{Ia}	110% of Mean 118% of Mean
K_{Ia}	Normal	10% of Mean	ASME K_{Ia}	130% of Mean

1. See UKAEA Study Group Report, 1976. A total of five flaws is assumed in the vessel beltline, four in the total weld volume and one in the total base metal volume.
2. $T\text{-}RT_{NDT} < 0F$, and $T\text{-}RT_{NDT} \geq$ Upper shelf temperature.
3. $0 < T\text{-}RT_{NDT} <$ Upper shelf temperature

Vessel Beltline Material Categories

During this work it was determined that the combination of beltline materials in reactor pressure vessels generally can be placed in one of three categories. These categories are: (1) base and weld metals all have relatively low and approximately equal values of ΔRT_{NDT}, (2) base and weld metals have moderate and approximately equal ΔRT_{NDT}, and (3) most beltline materials have moderate values of ΔRT_{NDT}, but one material has ΔRT_{NDT} approximately twice that of the other materials. Computations were performed for each of the three beltline material combinations.

RESULTS

BWR Hydrotest Temperature

Computations were performed to obtain P(F/E) for each material category as a function of temperature using neutron fluence at the vessel inner surface as a parameter. The failure probabilities were computed for a constant pressure of 1155 psi, which is slightly below the relief valve set-point and represents an upper limit on hydrotest pressure. The vessel was assumed to be at isothermal conditions. These computations were performed for the distributions listed in Table 1 and the modifications presented in Table 2.

Using these results the hydrotest temperature corresponding to the safety goal from Eq. 2, $P(F/E) = 10^{-6}$, was determined and a plot of allowable hydrotest temperature versus RT_{NDT} at the quarter thickness location for the limiting material in the vessel beltline was developed as shown in Fig. 4.

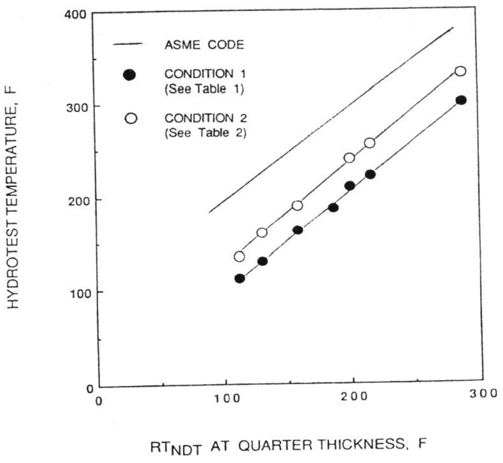

Fig. 4. Comparison of Hydrotest Temperature from ASME Code With Probabilistic Results

The RT_{NDT} shown in Fig. 4 contain the 2σ margin term described in Regulatory Guide 1.99 (1988). Also included in Fig. 4 is a comparison between the temperature versus RT_{NDT} relationship required to satisfy the safety goal and that determined using the hydrotest pressure temperature limits defined by the AMSE Code.

Fig. 4 shows that the results from the material categories are in a relatively narrow band for RT_{NDT} ranging from 100 to 350F. Because these results represent a wide range of material properties, material property combinations, and fluence levels, a generic relationship between hydrotest temperature and RT_{NDT} of the limiting beltline material is possible for ASME Code application.

The comparison of the results also indicates that the hydrotest temperature needed to satisfy the safety goal in Eq. 2 is approximately 45 to 85 F less than that required by the ASME Code, depending on the assumed flaw size and toughness distributions. Using the more conservative of these results implies a BWR hydrotest temperature of RT_{NDT} + 50F will meet the safety goal of Eqs. 1 and 2, compared to RT_{NDT} + 95F from the ASME Code.

PWR LTOP Set-points

As illustrated in Fig. 1, two parameters are used to establish the PWR LTOP relief valve set-points. These parameters include the minimum temperature, T_o, at which the vessel can be pressurized to normal operating pressure, and the maximum allowable pressure, P_o, in the temperature range from cold start to T_o.

The minimum temperature at which the vessel can be pressurized to full operating pressure was determined in the same manner as the BWR hydrotest temperature. P(F/E) was computed as a function of temperature for a constant pressure of 2,250 psi and a cooldown rate of 60F/Hr. These results were then used to determine T_o as a function of RT_{NDT} to satisfy the criterion in Eq. 2. The results indicate that T_o can be 70 to 120F less than required by the ASME Code, depending on the assumed flaw and toughness distributions. Using the more conservative results implies that a PWR LTOP set-point for T_o of RT_{NDT} + 80F will meet the safety goal of Eqs. 1 and 2, compared to RT_{NDT} + 150F from the ASME Code.

To determine the maximum allowable pressure in the low temperature range, P(F/E) was computed as a function of p_o using T-RT_{NDT} as a parameter and a constant cooldown rate of 10F/Hr. These results were used to determine the p_o as a function of T-RT_{NDT} to satisfy the criterion in Eq. 2. The results, summarized in Fig. 5 for the more conservative of the two distributions, indicate the probabilistic results are similar to those from the ASME Code at T-RT_{NDT} less than -275F, but become much less restrictive at T-RT_{NDT} greater than -250F.

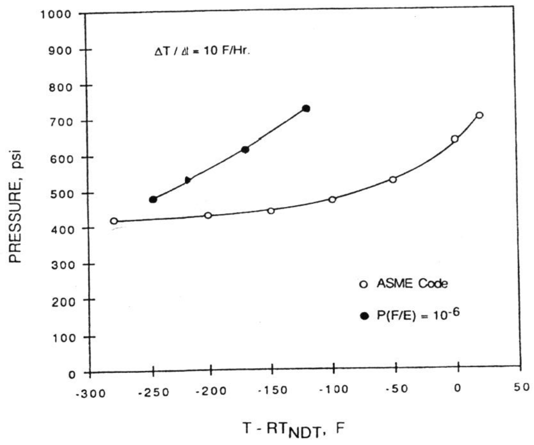

Fig. 5. Comparison of Allowable Pressure vs. T - RT_{NDT} from ASME Code With Probabilistic Results

CONCLUSION

The results from this work demonstrate that the safety goal for probability of reactor vessel failure can be met at BWR hydrotest and PWR LTOP temperature and pressure conditions significantly less restrictive than those required by Appendices G to 10CFR50 and Section XI of the ASME Code. This conclusion includes account of uncertainties in various distributed variables.

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