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Dear Mr. Elliot:

This letter is a revised version of our letter report of September 19, 1984, which makes some corrections and clarifications in response to your comments. The only substantial changes are for the sensitivity study for the effects of copper standard deviation. Our corrected results now show a much lower sensitivity to changes in copper standard deviation.

The calculations of this report were performed at Battelle Pacific Northwest Laboratory. The calculations are for the Indian Point Reactor Vessel and for crack dimensions based on the recent inservice inspection (ISI). These dimensions assume a maximum crack depth of 2.0 in. and a maximum crack length of 2.0 in. The calculations were performed with a special version of the probabilistic fracture mechanics code VISA. This code was developed by the NRC staff. However, we used recent enhancements that have been added as part of an on-going research project funded by NRC Research (monitored by J. Strosnider and more recently by M. Vagins). The enhancements have permitted us to consider the following factors that apply to the Indian Point flaw:

- The flaw is on the outside surface of the vessel and not on the inside surface as assumed in the initial version of VISA.
- The attenuation of fluence is governed by the displacements per atom model (DPA).
- The flaw is of finite length and not an infinite length surface flaw as assumed in the initial version of VISA.
- The default values for metallurgical variables have been reviewed to agree with the most recent NRC positions.
- Predictions of shift in RT_{NDT} have been based on the proposed Revision 2 of Regulation Guide 1.99. For these calculations we have used predicted shift values for plate material as given in the tables developed by Dr. P. N. Randall of the NRC staff.

The inputs and results of the probabilistic calculations are described in detail below.

INPUTS TO PROBABILISTIC CALCULATIONS

A set of inputs was specified by NRC for use in PNL's calculations of vessel failure probability. It was recognized at the onset that the failure probabilities would be very low for the normal operating loads, since the flaw sizes of interest were relatively small. Also, the location of the flaw was at the OD surface of the vessel and thereby at a location with little radiation damage. Preliminary calculations clearly showed that the calculated probabilities of failure would exceed 1.0E-06 only for severe combinations of high stress levels being imposed at relatively low temperatures. Furthermore, the fluence level used in the calculations corresponded to that projected at some 10 years into the future.

Flaw Specification

The flaw was a semi-elliptical surface flaw on the outside surface of the vessel. Its orientation was in the axial direction and its location was near an axial weld but in base metal and not in weld metal. The length of the flaw was 2.0 in. and its depth was to range from 0.3 to 2.0 in. Following preliminary calculations, PNL was directed by NRC to limit further analyses to a flaw depth of 1.2 in.

Transient Specification

All calculations were for a low temperature over pressurization (LTOP) transient of 2540 psi at a temperature of 110°F. Another transient of 500 psi at the same temperature of 110°F was also considered until it became clear that the failure probabilities for this transient were below the calculational capabilities of the VISA code.

Material Specification

The evaluation was for base metal toughness properties. Mean or best estimate parameters for the material characteristics were as follows.

Copper content = 0.20%

Nickel content = 0.66%

Initial RT_{NDT} = 20°F

In addition, PNL used the following estimates of the variability in material parameters.

Standard deviation on copper = 0.012%

Standard deviation on nickel = 0.00%

Standard deviation on RT_{NDT} = 12°F

Standard deviation on shift in RT_{NDT} = 0.00°F

Standard deviation on fluence = 0.30 times mean fluence.

These parameters were used throughout the calculations described in this report, except that the effects of variations from these fixed values were evaluated in a set of sensitivity calculations described later in this report.

The standard deviation in RT_{NDT} of 12°F is consistent with NRC recommendations. The standard deviation of zero for shift was assumed since the VISA code simulates the shift variability by treating the variability in copper, nickel and fluence. In the sensitivity calculations, the shift variability was simulated directly using a standard deviation of 15.6°F based on the recent work of Guthrie for NRC.

There is little information on the variability of copper for base metal. However, the NRC recommended value of 0.025% for standard deviation was judged to be excessive for plate materials. Thus, a value of 0.012% (half that for weld material) was assumed.

Effect of Fluence

All calculations were for an inside surface fluence of 3.55E18 at the flaw location. The attenuation of the fluence at the crack tip location was predicted using the DPA model [EXP(-0.24x)], where x = depth into the wall as measured in inches. The standard deviation or uncertainty in fluence was taken as 30% of the mean fluence in accordance with past analyses by and for NRC.

Scatter in Fracture Toughness

The standard deviation in fracture toughness from the mean curve was taken to be 10% of the predicted mean value. The mean curve (of fracture toughness versus temperature $T-RT_{NDT}$) was that used for welds by NRC in 1982 during development for the screening criteria for pressurized thermal shock. The data base for these curves incorporated both weld and base metal data.

The standard deviation of 10% was obtained by a statistical analysis performed by J. Strosnider at NRC. The data base was that used to develop the K_{Ic} and K_{Ia} reference curves for fracture toughness of ASME Section XI. The curves in VISA represent mean values of the data, rather than lower bound values as given in ASME Section XI. The 10% standard deviation was the result of the same statistical analysis which gave the mean curves used in VISA.

There was little to base differences between weld and base metal. It should be noted that ORNL has used a 15% value for standard deviation of fracture toughness in their Integrated Pressurized Thermal Shock (IPTS) calculations. In the sensitivity calculations we consider the effect of 15% versus 10%.

Residual Stress

Early in PNL's calculations it became clear that pressure induced stresses alone would not give predicted vessel failure probabilities that would give meaningful values to evaluate risks for the Indian Point reactor vessel. Therefore, NRC directed PNL to include the effect of residual stresses in the range of 0 to 15 ksi. PNL performed a parametric study which added a residual stress of 0 to 60 ksi to the stress at 110°F due to a LTOP event of 2540 psi. While the 60 ksi value exceeded any reasonable bound on unrelieved residual stress, it did serve to establish the trend of failure probability curves.

Arrest Versus Initiation

During the course of the calculations, NRC requested that failure probabilities be calculated on the basis of the applied stress intensity factor exceeding the simulated value of the arrest toughness (K_{Ia}). These results are presented along with results for initiation toughness (K_{Ic}). The arrest criterion assumes that an unspecified metallurgical factor initiates the crack (e.g., a brittle inclusion) and that the nominal material toughness must then arrest this running crack.

MODIFICATION OF THE VISA CODE

A number of very important but simple modifications were made to the VISA code to enable the calculations to be performed for the Indian Point vessel. The essential change was to directly specify as input data the values of the crack tip stress intensity factor and crack tip temperature. The deterministic parts of the VISA code were bypassed and no heat transfer or thermal stress calculations were performed. This simplification was consistent with the isothermal character of the LTOP event.

The only other change to VISA was to allow the user to specify whether failure was to be based on exceeding the simulated value of initiation toughness or the simulated value of arrest toughness.

STRESS INTENSITY FACTOR CALCULATION

The fact that the flaw was at the outside surface of the vessel and of a relatively short length required that the existing calculations of crack tip stress intensity factor be modified. The essential assumption was to transpose the given flaw to the inner surface of the vessel and then to apply available stress intensity factor solutions for inner surface flaws. In general, this approach would lead to unacceptable errors. However, in this evaluation the errors are believed to be insignificant because:

- The flaws of concern are relatively short (aspect ratio of length to depth is small). For such flaws the behavior of inside and outside surface flaws is similar.

- All stress intensity factors are based on the average stress in the uncracked vessel over the region of the semi-elliptical crack. Therefore, the inherent differences in stress levels between the outer and inner surfaces of the vessel are properly taken into account.

Figure 1 summarizes the calculations of crack tip stress intensity factors for the flaws of interest (2.0 in. long and of depths less than 2.0 in. in a vessel of inside diameter of 173.0 in. and outside diameter of 190.56 in.). The calculations used a set of finite length flaw correction factors. These factors have been described in PNL's draft report to NRC (February 1984) on the prediction of vessel failure modes for pressurized thermal shock accidents. These factors are essentially those to be included in a revision under development for ASME Section XI, and uses a review of all known stress intensity factor solutions for finite length flaws in vessels (this information was compiled by Dr. S. Yukawa of the General Electric Corporation). It should be noted in Figure 1 that flaws of relatively short length will have their propagation behavior governed by the stress intensity factor at the point where the flaw intersects the OD surface of the vessel rather than the point of maximum flaw depth.

We wish to note that the 2-in. deep by 2-in. long flaw is of interest to the Indian Point evaluation. This flaw geometry is outside the range of stress intensity factor solutions of which we have knowledge. We have extrapolated solutions for longer flaws and have also extrapolated solutions for flaws that are not as deep to estimate the value indicated on Figure 1 for the 2 x 2 in. flaw. Furthermore, we have applied "engineering insight" to rotate this flaw to treat it as an equivalent surface flaw that is as deep as it is long (illustrative figure not included). These various estimation procedures appear to converge to the value indicated on Figure 1.

RESULTS OF FAILURE PROBABILITY CALCULATIONS

Figure 2 summarizes the results of the failure probability calculations. These calculations are conditional on the postulated LTOP event occurring (2540 psi at 110°F) and that the indicated level of residual stress actually is present at the location of the flaw in the Indian Point vessel. Furthermore, it should be recognized that the "NDE indication" has been treated as a surface connected crack of a conservatively estimated size. I have discussed the Indian Point ultrasonic data with PNL specialists. Their interpretation of this data suggests that the "NDE indication" is a subsurface flaw rather than a surface flaw. Thus, our surface flaw analysis is probably conservative.

The two curves of Figure 2 are based on the probability that the applied crack tip stress intensity factor exceeds the initiation toughness in one case and the arrest toughness in the other case. The initiation toughness is a prediction of the probability that the crack will initiate given that its tip is entirely in a material with typical toughness characteristics. The arrest toughness case supposes that the crack propagation initiates at one location along the crack front within material of unrepresentative toughness; the curve of Figure 2 then corresponds to the probability that this running crack does not arrest.

The conclusion suggested by Figure 2 is that there is less than a probability of 1.0E-06 that the OD surface indication will lead to a vessel failure given that a severe LTOP accident occurs in a vessel with NRC's bounding level of residual stress (15 ksi).

SENSITIVITY STUDY

A number of assumptions are stated or implied in the fracture mechanics calculations of vessel failure probability. We will now describe a set of calculations that shows the effect of these assumptions on the predicted values of failure probability.

Effect of K_{Ic} Standard Deviation

All calculations shown by Figure 2 assumed that the variability of the fracture toughness of plate material can be described by a standard deviation of 10% of mean values as in the NRC calculations in 1982 for the PTS screening criteria. In 1984, ORNL performed failure probability calculations on the IPTS program and used a standard deviation on the "T-RT_{NDT} versus fracture toughness" curve of 15 rather than 10%. This change increases the failure probability from 1.18E-04 for the reference case described by Table 1 to 19.5E-04. This is a substantial increase by a factor of about 16.5.

Effect of Copper Standard Deviation

All the calculations of Figure 2 assume a standard deviation of 0.012% on copper, rather than the 0.025% value used by NRC and ORNL for weld material. When the copper standard deviation is increased to 0.025% in the present calculations, the calculation failure probability increases from 1.18E-04 to 1.67E-04. This factor of about 1.4 is relatively insignificant. Nevertheless, it indicates that the expected lower variability of copper in base metal relative to weld metal will tend to make the Indian Point vessel with a base metal flaw somewhat less likely to fracture than vessels of concern to PTS type events.

Effect of Alternate Simulation of Shift in RT_{NDT}

The results of Figure 2 assume that the variability in shift is adequately accounted for by simulating the uncertainty in copper, fluence and initial RT_{NDT}. The NRC position in the VISA code is that the introduction of further uncertainty in the predictive equation for shift would "introduce too much noise into the calculation". However, one can also describe the variability in shift by observing that the standard deviation in Guthrie's equation for shift prediction is 15.5°F for plate materials. A calculation has been performed that simulates this 15.5°F standard deviation in shift, but with the variability in copper and fluence set to zero so as to avoid the introduction of "too much noise". The simulation was performed by altering the input for the standard deviation of the initial value of RT_{NDT}. Following the recommendations of SECY-82-465 the standard deviation in the initial value and the shift in RT_{NDT} were added in a root mean square manner. The effective value of uncertainty in RT_{NDT} was thus calculated to be 19.6°F.