AN ALTERNATIVE METHOD FOR PERFORMING PRESSURIZED THERMAL SHOCK ANALYSIS

by

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ABSTRACT

In 1987, the NRC issued Regulatory Guide (RG) 1.154, which provides an analytical methodology to determine if adequate margins against reactor pressure vessel failure exist during Pressurized Thermal Shock (PTS) events when the vessel is predicted to exceed the PTS screening criteria. The RG 1.154 methodology is a complex analysis procedure involving probabilistic risk assessment (PRA), thermal-hydraulic and probabilistic fracture mechanics (PFM) evaluations. Following the shutdown of the Yankee Rowe Plant in 1992, the NRC committed to revising the PTS criteria and regulatory guidance in RG 1.154 with the goal of providing a definitive approach and analysis methodology. In 1995, EPRI initiated a program aimed at developing an alternative approach that would simplify the PFM analysis procedure and be economically efficient to implement without requiring the resolution of a substantial number of technical issues.

The fundamental concept of this alternative approach is that there is a relationship between the calculated probability of crack initiation (POI) and calculated critical crack depth (a_c). The critical crack depth is defined as the smallest flaw depth at which initiation would first occur during the specified PTS event. This is because a_c and POI are both influenced by the same parameters, such as RT_{NDT}, fracture toughness (K_{IC}), and the transient temperatures and pressures. POI was computed using PFM techniques and a_c was computed using deterministic fracture mechanics for a wide range of representative PTS transients.

Using this relationship, acceptable PTS transient frequency was then correlated with critical crack depth for a mean frequency of $5x10^{-6}$ per reactor year, which is specified as an acceptable frequency of significant flaw extension in RG 1.154. This correlation establishes the acceptability (or unacceptability) of the PTS event and can also be used to simply evaluate mitigative changes in transient frequency and/or severity that might result from a combination of plant operational, equipment, or system modifications.

This paper describes how POI and acceptable PTS frequency were correlated with a_c and summarizes several example applications, including evaluation of potential plant modifications. Plans for an industry supported pilot-plant application of the alternative PFM method for RG 1.154 are also discussed.

Keywords: Reactor Vessel, PTS, Probabilistic Fracture Mechanics, Risk Analysis

BACKGROUND

Reactor pressure vessels (RPVs) are generally considered to be the most critical component in the nuclear plant aside from the reactor core. The vessel is also the one major component that may limit the useful life of the nuclear plant because it is the heart of the nuclear steam supply system and, if it had to be replaced, an extraordinary amount of time and money would be required.

Reactor vessels undergo an aging phenomenon, called embrittlement , that is caused by the exposure of the RPV material to high energy neutron flux from the core. The area most likely to be affected by neutron embrittlement is the beltline region of the RPV due to its proximity to the core. Embrittlement is characterized by a gradual reduction in the RPV's fracture toughness and an increase in the material's strength. If this reduction in toughness were to continue to progress, and a crack existed, fracture of the vessel might be predicted to occur under postulated events such as pressurized thermal shock (PTS). For this reason, the U.S. Nuclear Regulatory Commission (NRC) established the PTS rule and defined screening criteria on reference nil-ductility transion temperature (RT_{NDT}) for PTS (RT_{PTS}) of 270°F for axial welds, plates and forgings and 300°F for circumferential welds. If the RT_{PTS} is predicted to exceed the screening criteria during the licensed operating period, an analysis must be performed to justify operation beyond the screening criteria.

In 1987, the NRC issued Regulatory Guide (RG) 1.154 [1], which provides a methodology to determine if adequate margins against failure exist during PTS events when the RT_{NDT} is predicted to exceed the PTS screening criteria. The methodology consists of a very complex analysis procedure involving probabilistic risk assessment (PRA), thermal hydraulic and fracture mechanics evaluations. In addition to determining the probability of vessel failure, this methodology also was intended to be used as a tool to evaluate mitigative actions that would reduce the risk of vessel failure. These actions include fluence reduction or changes in plant operations, equipment and/or systems.

Yankee Atomic Electric Company was the first organization to formally use RG 1.154 to justify operation of the Yankee Rowe vessel beyond the PTS screening criteria. In 1990, the NRC requested Yankee to perform a bounding PTS analysis because of concerns regarding the embrittlement of the RPV. The NRC reviewed the analysis and concluded that the calculated probability of vessel failure could vary considerably because of the inputs and assumptions used in the fracture mechanics analysis. After an extensive research and analysis program, the uncertainty associated with demonstrating the acceptability of vessel integrity following a PTS event ultimately contributed to the permanent shutdown of the plant. Subsequently, the NRC [2] committed to revise the criteria and guidance in RG 1.154 with the goal of providing a definitive approach and analysis methodology that would resolve the uncertainties associated with the technical issues. In 1995, the Electric Power Research Institute (EPRI) initiated a program aimed at developing a simplified method for evaluating PTS. Ultimately it is EPRI's intent to have this approach incorporated in the revised version of RG 1.154 either as a preferred method of evaluation or as an alternative to the NRC methodology.

RG 1.154 [1] requires the following steps in a vessel PTS risk analysis (see Figure 1): 1) A PRA is used to determine the probability of occurrence for the most severe PTS-type transients. This will result in a ranking of PTS event frequencies. 2) A thermal hydraulic analyses is performed to establish the pressure and temperature time histories for the various transient events. 3) A probabilistic fracture mechanics (PFM) analysis is performed to determine the conditional probability of vessel failure for each of the transients. 4) The summation of the product of event frequencies and conditional probability of vessel failure (risk) must be shown to be less than a through-wall crack penetration mean frequency of 5×10^{-6} per reactor year.

The selection of the input values and assumptions in the PFM analysis, which the industry benchmarking study report by EPRI [3] showed can have a significant effect on the calculated vessel failure probability, has been debated for several years. Issues concerning flaw size, the number of flaws and their distribution within the pressure vessel are just a few examples. EPRI decided to focus the effort on developing an alternative approach that would simplify the PFM analysis procedure and be economically efficient to implement without requiring the resolution of a substantial number of technical issues. It is important to point out that the selection of input values used in the probabilistic and deterministic analyses does require concurrence from the NRC. Therefore, irrespective of which analysis method is selected for RG 1.154, the inputs and assumptions must be well defined.

DEVELOPMENT OF METHOD

The fundamental concept of this alternative approach is that there is a relationship between the calculated probability of crack initiation (POI) and calculated critical crack depth (a_c). The critical crack depth is defined as the smallest flaw depth at which initiation would first occur on the flaw boundary during the specified PTS event. This is because a_c and POI are both influenced by such parameters as RT_{NDT}, fracture toughness (K_{IC}), and the transient temperatures and pressures, to name a few. For example, as the transient severity increases (higher pressures and lower temperatures), a_c becomes smaller and POI becomes larger because the stresses and resultant crack driving forces at the inner surface of the pressure vessel are larger, thus causing smaller crack sizes to initiate and propagate through the vessel wall. The opposite scenario is also true. Similarly, as RT_{NDT} increases, fracture toughness decreases resulting in lower values of a_c. Given this fact, it was determined that a_c is actually a very good measure of transient severity relative to the degree of embrittlement in the vessel. The development of the alternative PFM method using this concept is described in an EPRI interim technical report [4] and summarized below.

There were three major objectives defined for the development of the alternative PFM method including: (1) the procedure should be a well defined, easy to use deterministic computational method, (2) the uncertainties associated with probabilistic fracture mechanics method used to develop the correlation should be reduced, and (3) the procedure should be correlated to the results obtained by the NRC for the PTS screening criteria [5].

The calculated value of critical crack depth was selected as the deterministic parameter for the alterative PTS method. This is analogous to the use of RT_{NDT} in the PTS screening criteria. However, critical crack depth is a more robust parameter in that it accounts for all the major irradiation and material related parameters, in addition to the effects of transient specific temperatures and loads. The 1995 version of the FAVOR Code from ORNL [6] was selected as the computational tool to calculate critical crack depth. FAVOR was selected because it is relatively easy to use, can model any specified transient temperature and pressure time history, and automatically calculates critical crack depth as a function of aspect ratio at various locations along the crack boundary.

RT_{PTS} is used in the critical crack depth calculation because it is an already determined, well defined value. This reduces the uncertainty associated with variation in irradiated material toughness properties and alloy content. To ensure that the effect of variable changes or implementation of mitigative measures would not be masked by combinations of conservatively combined variables, the mean fracture initiation toughness (in combination with the more conservatively defined RT_{PTS}) was used to define the material resistance to crack initiation.

The 1995 version of the FAVOR Code [6], which was benchmarked with other industry PFM analysis codes [3], was also used to calculate the vessel failure probability. This reduced the uncertainty because the models (e.g. stress intensity factor correlations) were the same for both the deterministic and probabilistic analyses. Several analysis conditions that were also selected to reduce the uncertainty associated with PFM analysis included the following. First, the probability of crack initiation was used in the correlation rather than the probability of failure. This eliminates the uncertainty associated with crack arrest phenomena and through wall variations in material conditions that affect vessel failure predictions. Second, a randomly sampled aspect ratio was used in the probability of initiation computations. This reduces the error and uncertainty associated with selecting a single aspect ratio that an EPRI study [7] shows does not adequately model the fracture initiation conditions for a broad spectrum of transient conditions (EPRI, 1995a). Third, a flaw tolerance approach is used where only one flaw located at the vessel inner surface is used to determine initiation probability. This reduces the uncertainty associated with the number and location of the postulated flaws.

The alternative PTS method was also developed so that there is a connection with the NRC PTS risk study [5] using the results from the evaluation of the extended high pressure injection (HPI) transient. According to the FAVOR baselining of the NRC PTS risk study by ORNL [8], this limiting transient would be characterized as having a final temperature of 125°F, an exponential decay rate of 0.05 $min.^{-1}$ and a maximum pressure of 2,250 psi. The failure probability in the NRC PTS risk study for the HPI transient and a mean surface RT_{NDT} of 210°F (RT_{PTS} = 270°F) was approximately equal to $6x10^{-2}$ for six flaws (one in each longitudinal weld). Because cladding effects were included in the fracture mechanics model used for the alterative PTS evaluation procedure but were not included in the NRC analysis, an adjustment to the FAVOR input was needed to match the calculated failure probability. The variable selected for adjustment was the flaw distribution because it cannot be easily measured on a plant specific basis, has a relatively high degree of uncertainty, and is selected rather arbitrarily from the results of various studies that report widely differing results. The flaw distribution was adjusted until the probability calculated by FAVOR for one flaw was equal to the value obtained for one flaw in the NRC PTS risk study [5]. The cumulative flaw distribution that provided a benchmarking with the NRC PTS risk study results was then used in the PFM analysis performed to define the correlation between critical flaw critical flaw depth and probability of crack initiation.

Six representative PTS transients, ranging from mild to severe pressure-temperature conditions, were used to the establish the correlation between POI and a_c. Table 1 defines the PTS transients and frequency ranges that were used in the development of the alternative PFM method. The temperature history for a postulated PTS transient was stylized to fit an exponential decay form and the pressure was assumed to be constant with time:

$$T(t) = T_f + (T_0 - T_f)\, e^{-\beta t} \qquad (1)$$

$$P(t) = P_{max} \qquad (2)$$

where:
- $T(t)$ = Coolant temperature (°F) at any time t (minutes),
- T_0 = Initial temperature, normally 550 °F,
- T_f = Final temperature (°F),
- β = Exponential decay rate ($min.^{-1}$)
- $P(t)$ = Pressure (psi) at any time t (minutes) and
- P_{max} = Maximum pressure (psi) of concern.

To define a credible set of postulated PTS transients for the development of the alternative PFM method, the bounding plant-specific results of the Westinghouse Owners Group (WOG) PTS risk study [9] were used. This was done because the transient severity parameters and failure probabilities in this study were consistent with those already used in the NRC PTS risk study [5]. The limiting PTS transient with the highest failure probability that was selected in each frequency range in Table 1 could be characterized by low final temperatures and moderate (lower) pressures. However, there were also transients that induced comparable vessel failure probabilities but had lower event frequencies. To broaden the range of applicability, these transients were also included just in case their plant-specific frequencies were increased into the frequency range of concern. These transients in Table 1 are characterized by moderate (higher) final temperatures and high pressures.

Calculation of the critical depth required selection of the flaw aspect ratio. To determine the aspect ratio that was best suited to construct the correlation, a sensitivity study was performed to assess the effect on critical crack depth of aspect ratios of 2:1, 6:1, 10:1 and *infinite*. The results showed that crack initiation consistently occurred at the same location (surface) for the range of transient conditions in Table 1 when the 2:1 aspect ratio was used. Consequently, a 2:1 aspect ratio was selected to construct the correlation between critical crack depth and probability of crack initiation.

The critical crack depths at a 2:1 aspect ratio and initiation probabilities for one longitudinal and one circumferential flaw were calculated using the benchmarked cumulative flaw distribution for each transient in Table 1 and for three different values of RT_{PTS} (270, 280 and 290°F for longitudinal flaws and 300, 310 and 320°F for circumferential flaws). The resulting initiation probabilities as a function of critical crack depth are shown in Figure 2. These are called *probability index curves* because the critical crack depth is not a measured value but is calculated depending upon the severity of the transient and degree of embrittlement. Since the initiation probability also depends upon these same factors, calculated critical crack depth can be used as an index to calculate initiation probability directly. Equations were derived from a least-squares curve fit of the data shown in Figure 2. For one longitudinal flaw, the relationship between probability of initiation POI_l and calculated critical crack depth a_c is:

$$POI_l = EXP(\ 6.558707\ a_c^2 - 14.55218\ a_c - 2.711547\ ) \tag{3}$$

For one circumferential flaw, the relationship between probability of initiation POI_c and calculated critical crack depth a_c is:

$$POI_c = EXP(\ 7.087541\ a_c^2 - 16.1988\ a_c - 2.733123\ ) \tag{4}$$

What this means to the utility user is that equations (3) and (4) or Figure 2 can be used to estimate vessel probabilities of initiation based only on the deterministically calculated value of critical crack depth. Detailed probabilistic fracture mechanics (PFM) analyses are not required because the probability index curves of Figure 2 were derived from the results of one comprehensive PFM analysis that is generic to all reactor vessels and that has been benchmarked to the NRC's PTS risk study [5].

EXAMPLE APPLICATION

To apply the alternative PFM method, the risk contribution of a plant-specific PTS event can be compared with the PTS risk limit by using the following equation:

$$Risk_i = F_i * POI_i(a_c) \tag{5}$$

where: $Risk_i$ = the risk contribution for PTS transient i,
F_i = frequency per year for PTS event i and
$POI_i(a_c)$ = initiation probability as a function of critical crack depth.

Figure 3 graphically shows the transient frequencies that give different risk contributions as a function of the deterministically calculated critical crack depth for longitudinal flaws. A similar figure has also been developed for circumferential flaws. In Figure 3, four regions are shown: 1 (Below dotted curve for risk of $5x10^{-8}$ per year) - Since each PTS transient in this region would have a risk contribution less than 1% of the risk limit, many PTS transients in this region would be acceptable. 2 (Between dotted curve and dashed curve for risk of $5x10^{-7}$ per year) - Each PTS transient in this region would have a risk contribution between 1% and 10% of the risk limit. Therefore, less than 10 PTS transient in this region should be acceptable. 3 (Between dashed curve and solid curve for risk limit of $5x10^{-6}$ per year) - Each PTS transient in this region would have a risk contribution between 10% and 100% of the risk limit. If there are several PTS transients in this region, their acceptability relative to the total PTS risk limit should be calculated using equation (3) and evaluated. 4 (Above the solid curve for the PTS risk limit) - Since each PTS transient in this region would exceed the PTS risk limit, any PTS transients in this region would be unacceptable and remedial actions would be required.

The PTS risk limit for the evaluation is consistent with that given in RG 1.154 [1] and is equal to a through-wall crack penetration mean frequency of $5x10^{-6}$ per reactor year. The solid curve of Figure 3 thus reveals a graphical acceptance criterion whereby calculated values of transient frequency and a_c can determine the acceptability of the transient. This is termed the *transient index curve*. Having determined a_c based on the specific transient and embrittlement conditions and knowing the frequency of the transient from the PRA analysis, the data point establishes the acceptability (or unacceptability) of the PTS event. Values that lie above the curve are unacceptable and values that lie below the curve are acceptable. If the values are unacceptable, adjustments can be made in transient frequency and/or severity through a combination of plant operational, equipment, or system modifications. The severity adjustments will directly affect the calculated value of a_c. The analyst has only to modify the inputs of the deterministic analysis in order to define the conditions that would provide an acceptable result.

Figure 4 provides a simplified vessel risk evaluation for an example plant with three PTS transients having frequencies of $3.5x10^{-6}$, $2.1x10^{-5}$ and $1.0x10^{-3}$ per year and a postulated longitudinal flaw in the limiting axial weld that has an RT_{PTS} value of 273°F. As shown in Figure 4, the transient with the lowest frequency produces a risk contribution less than 1% of the limit. The PTS transient with the intermediate frequency contributes about 1% of the risk limit, while the transient with the highest frequency contributes about 10% of the limit. Quantitative evaluation of the total PTS risk for the example plant showed it would be acceptable (15.8% of the risk limit) even if the PTS screening criteria of 270°F were exceeded.

As can be demonstrated using Figure 3, if the PTS risk limit of $5x10^{-6}$/year is exceeded, there are two ways to reduce the risk. First, the frequency of the limiting PTS transient(s) can be reduced. For example, new procedures and training could be provided or new trip functions could be implemented (logic and/or hardware changes). Both of these types of changes would tend to reduce the chance (frequency) of the PTS transient occurring. The second way to reduce the risk is to increase the critical crack depth. The depth can be increased by reducing the degree of embrittlement, as measured by RT_{PTS}, by reducing the severity of the limiting PTS transient(s) or a combination of both of these. Examples of these types of reductions include shielding and/or fuel management to reduce fluence (embrittlement) or heating of the water in the refueling water storage tank to reduce the transient severity (specifically, to increase the final temperature).

An application of the alternative PFM method to evaluate changes in PTS transient frequency and severity is also provided in Figure 4 for an example plant. Even though it would not be required for this application, the benefits (risk reduction) of the following proposed changes were evaluated: 1) the final temperature for the two low-frequency PTS transients would be increased 15°F by heating of the water in the refueling water storage tank, 2) the frequency for the highest frequency transient would be reduced by a factor of 10 due to trip function logic and hardware upgrades and 3) flux reduction measures via fuel management would be implemented to reduce the RT_{PTS} value from 273 to 260°F. The combined effects of these changes, as shown in Figure 4, would be to reduce the total PTS risk for the example plant vessel by more than a factor of 8. Based upon this type of information and the implementation costs for the proposed changes, the utility would then be able to make better decisions regarding which PTS mitigation options are cost effective.

CONCLUSIONS

The following are some initial conclusions resulting from this work as reported by EPRI [4].

1) A simplified fracture mechanics approach has been developed for evaluating PTS for vessels that are projected to exceed the NRC's embrittlement (PTS) screening criteria.

2) It has been shown that there is a relationship between allowable transient frequency and calculated critical crack depth. This relationship affords the analyst a quick way to assess the acceptability of the transient and assess potential plant modifications if the result is unacceptable.

3) The method is based on one comprehensive PFM analysis that is generic to all vessels. This, however, does require concurrence from the NRC with regard to the input values that were used in the analysis. Examples of inputs that need to be agreed upon include cladding effects, flaw density and distribution, fracture toughness curves, mandating the use of surface flaws, etc.

4) The acceptance criterion is based on a non-exceedance of probability of initiation, rather than non-exceedance of probability of failure which includes the uncertainties associated with crack arrest. This eliminates further uncertainty associated with the determination of how and when propagating cracks will arrest.

5) The alternative PFM method has not introduced any new fracture mechanics analysis techniques that are unfamiliar to the NRC.

6) The alternative PFM method has been benchmarked to the NRC's PTS risk study [5] and compared to an actual plant evaluation recently performed by the NRC. The results show that the technique is consistent and compatible with the results of those studies.

FUTURE PLANS

It is EPRI's intent to quantify the benefit of this methodology through an application of a detailed pilot study for a PWR. The goals of this pilot study, which is being supported by the Westinghouse Owners Group, are: 1) show that the analysis can be economically implemented, 2) identify potential improvements to plant operations, equipment and /or systems to lessen the risk of RPV failure due to a PTS event and 3) demonstrate that the vessel can indeed be operated safely at levels of embrittlement in excess of the current PTS screening criteria. The results of this study will be documented in a future EPRI report.

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Table 1
Definition of Realistic Transients for the Alternative PFM Method

Type of Transient	Transient Parameter	Value for Transient Frequency Range of:		
		10^{-2} - 10^{-3} /yr	10^{-3} - 10^{-5} /yr	10^{-5} - 10^{-7} /yr
Currently Limiting Transients (Low Temp. and Pressure) in the WOG PTS Risk Study [9]	Final Temp.	206 °F	117 °F	97 °F
	Rate β	0.10/min.	0.08/min.	0.16/min.
	Max. Pressure	1500 psi	1100 psi	1100 psi
Potentially Limiting Transients if Frequency Increases Significantly (Higher Temp. and Pressure)	Final Temp.	218 °F	142 °F	117 °F
	Rate β	0.15/min.	0.08/min.	0.08/min.
	Max. Pressure	2250 psi	1500 psi	2000 psi

Note: Transients with frequency > 10^{-2} per year would have final temperatures > 270 °F and be covered by the NRC PTS risk study [5]. Transients with frequency < 10^{-7} per year would have minimal contribution to PTS risk.

Figure 1
Flow Chart for Vessel PTS Risk Analysis

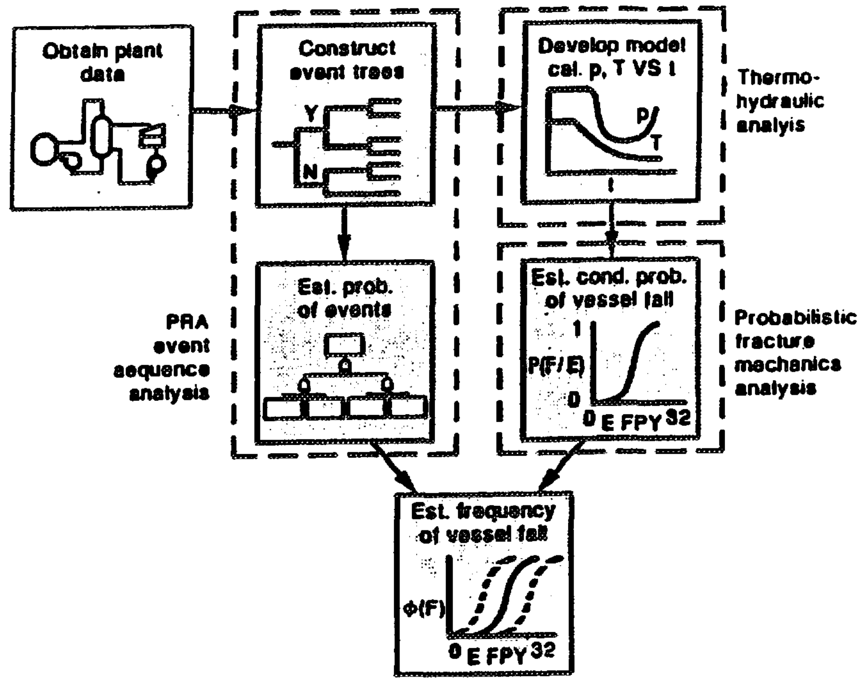

Figure 2
Alternative Method Probability Index Curves

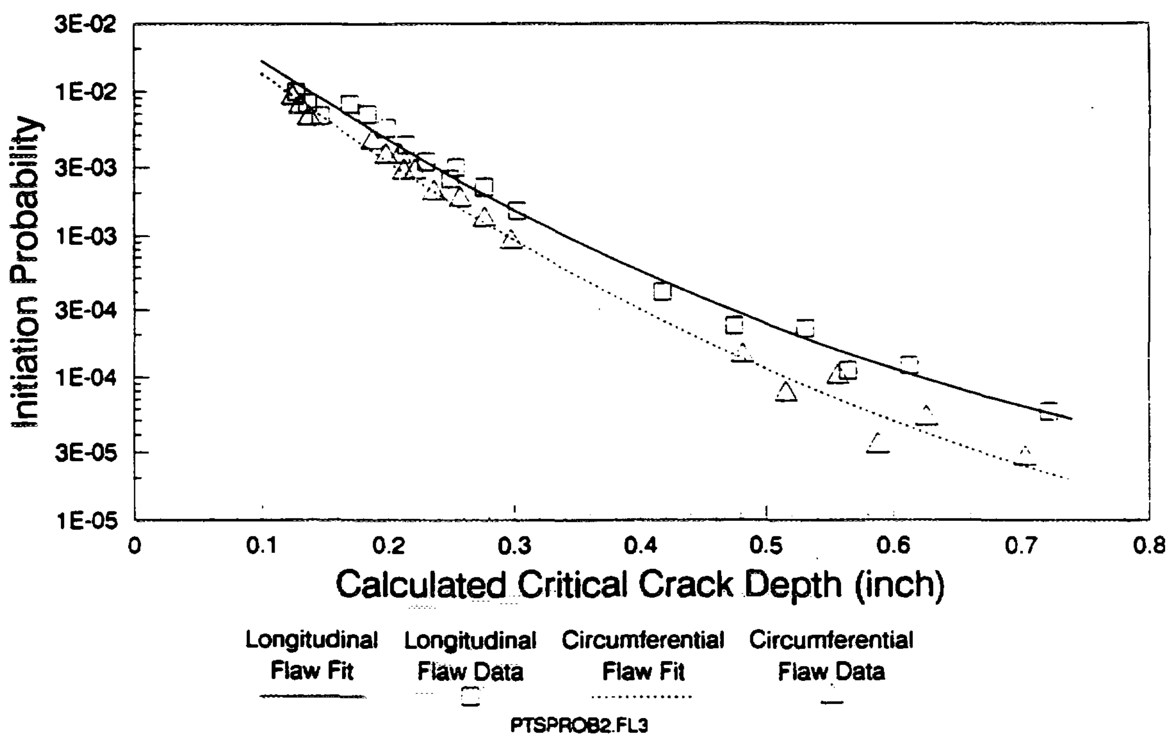

Figure 3
PTS Transient Index Curves for Long. Flaws

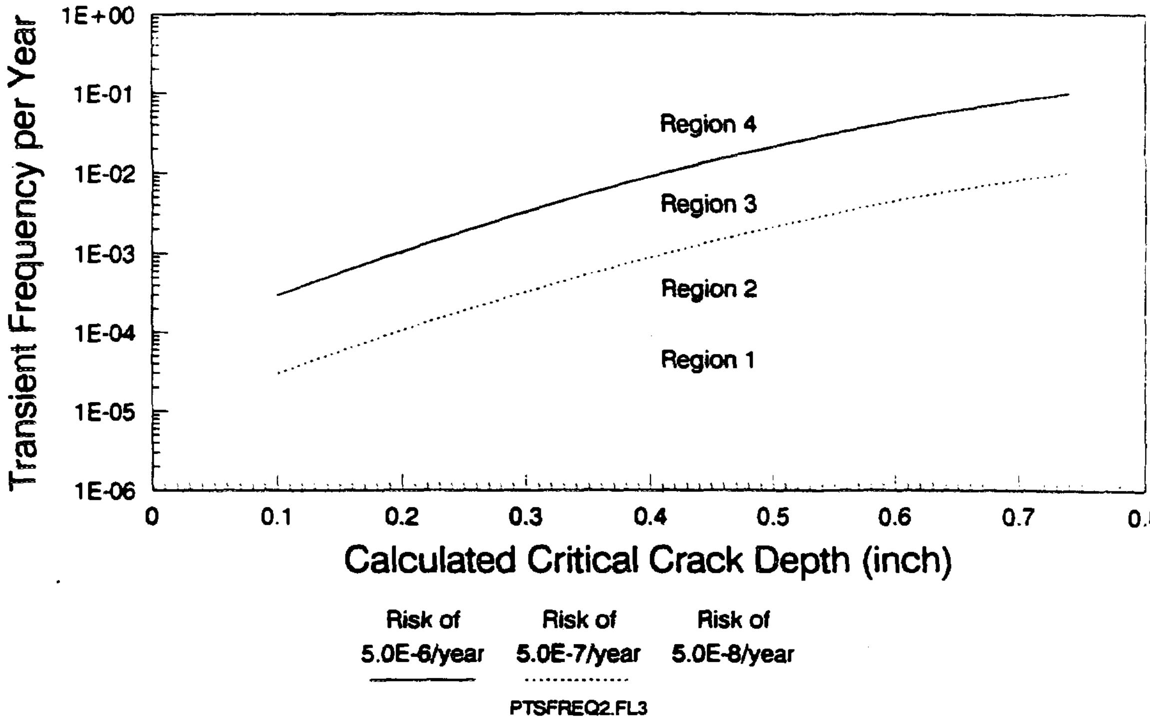

Figure 4
Example Plant PTS Risk Evaluation