FATIGUE 2000, an International Conference
at Robinson College Cambridge, England, 10th-12th April, 2000

PROBABILITY METHOD OF FRACTURE FOR REACTOR LIFE ESTIMATE[1]

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ABSTRACT

The state of the reactor vessel steel embrittlement as a result of neutron irradiation is reflected by its increase in ductile-brittle transition temperature (DBTT) in fracture toughness versus temperature curve. The increase in DBTT can be measured experimentally. Higher DBTT implies a decrease in fracture toughness and an increase in the chance of vessel fracture in brittle fracture mode. The extent of degradation that the High Flux Isotope Reactor (HFIR) vessel has experienced can be characterized by its probability of fracture. To ensure a continued operation safety of the HFIR under appropriate vessel pressure and temperature, a periodic hydrostatic tests (hydrotest) is performed. If the fracture probability on performing the hydrotest exceeds a certain imposed value, then the vessel can not be tested hydro-statically and, therefore, it determines the end of the life of the reactor vessel. The conventional method of fracture probability calculations such as that adopted by the NRC-sponsored PRAISE CODE and the FAVOR CODE developed in this Laboratory are based on Monte Carlo simulation. Heavy computations are required. A new method of fracture probability calculation is developed by direct probability integration shown in this paper. The present approach offers simple and expedient method to obtain numerical values of fracture probability and it retains all general features that a Monte Carlo simulation can possibly accomplish. This approach also provides a clear physical meaning on the probability of failure by fracture.

1. INTRODUCTION

The life of the High Flux Isotope Reactor (HFIR) vessel is degraded as a result of neutron irradiation that leads to a gradual reduction of the fracture toughness and an increasing chance of brittle fracture. The fracture probability of the HFIR vessel is calculated in order to measure the extent of the radiation induced embrittlement of the pressure vessel. To ensure the operating safety of the reactor, periodic hydrostatic pressure tests (hydrotest) is performed. The hydrotest is performed in order to determine a safe vessel operating pressure boundary. The fracture probability as a result of the hydrostatic pressure test is calculated and is used to determine the life of the vessel, because failure to perform hydrotest will end the operation of the reactor. The conventional method of fracture probability calculations such as that used by the NRC-sponsored PRAISE CODE and the FAVOR CODE developed in this Laboratory are based on the Monte Carlo simulation. Heavy computations are required.

[1]Based on work performed at Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp., for the U.S. Department of Energy under contract DE-AC05-96OR22464. Accordingly, the U.S. government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. government purposes.

An alternative method of fracture probability calculation by direct probability integration has been developed (Ref. 1) and the application to recent HFIR upgrade design is shown in this paper. The present approach offers a simple and expedient way to obtain numerical result and still retains all general features that a Monte Carlo simulation can accomplish. Moreover, this approach provides a clear physical meaning on the probabilistic nature of fracture and requires much less computation time. Numerical results on the probability of vessel fracture under several combinations of pressure and temperature as a result of the DBTT increase are obtained. Limiting the probability of the vessel fracture as a result of hydrotest (Ref. 1) implies that the reactor vessel life can be extended to 50 effective power year (EFPY) at 100 MW with the minimum vessel operating temperature of 85EF.

The state of the vessel steel embrittlement as a result of neutron irradiation can be measured and characterized by its increase in the ductile-brittle transition temperature (DBTT) (Ref. 2). The ductile-brittle transition temperature in the fracture toughness versus temperature curve is known to be shifted in the temperature coordinate to the higher temperature range with the amount that can be correlated to the amount of radiation received by the specimen. The DBTT is an engineering parameter which depends upon many factors; however, in general it defines a temperature below which one should expect brittle fracture with minimal plastic deformation and above which the probability for brittle fracture decreases with increasing temperature. Steel subjected to neutron irradiation will shift the DBTT to a higher temperature, thereby exposed to a wider range of brittle fracture region. In contrast to brittle fracture, the ductile fracture mode has higher toughness value and involves more active plastic deformation mechanism at the crack tip region during the fracture process. Ductile fracture, therefore, will provide greater reactor safety against vessel failure by fracture. A micro-mechanical theory on the characterization of the ductile-brittle transition temperature has also been advanced recently by applying the crack tip dislocation emission as a basic mechanism (Ref. 3). A distinct temperature of ductile-brittle transition has been observed beyond which the crack tip fracture is associated with more dislocation emission activities and, therefore, the fracture is substantially involved with plastic deformation. Several related articles can also be found in reference 2.

The present method of life estimate for the HFIR was initiated by Cheverton et al. (Ref. 2). Recently, Cheverton made a life extension calculation. The present paper is intended to confirm his analysis and, also, provides an alternative calculation approach that is required by this Laboratory on any reactor safety related calculations. The probability of fracture calculation developed by Cheverton (Ref. 2) for the reactor vessel was based on the Monte Carlo simulation through a large number of probabilistic simulation runs in several dimensions of possible sets of random variables. Typical random variables are crack depth, plain strain toughness, and ductile-brittle transition temperature shift. The new probability method of fracture presented in this paper is a method of simple probabilistic integration based on the same number of assumptions and same number of random variables. The method is straightforward, yet capable of reproducing essentially all Cheverton's probability of fracture results. This method of probability of fracture calculation has made use of the Marshall crack density distribution function (Ref. 4) that provides a possible estimate on the fraction of cracks that exceed the critical crack length. A simplified version of the present method, which only used the crack length as a random variable, was applied earlier for the HFIR vessel severe accident analysis (Ref. 5). It is also shown in the present paper that the probability method developed here can be reduced to the earlier (simplified) one (Ref. 5) as a special case where the crack length is the only random variable.

2. FRACTURE PROBABILITY INTEGRAL

The probability of fracture is shown in the following that it can be represented as a multiple integral. The multiplicity of the integral is equal to number of random variables needed in the model. For the present case three random variables are used, namely, crack depth, fracture toughness, and brittle-ductile transition temperature shifts a result of neutron irradiation. Here, the crack size is expressed by the Marshall distribution (Ref. 3) and the toughness is represented by the measured values that are distributed according to a Gaussian distribution. The ductile-brittle transition temperature is also assumed to vary following the property of a normal distribution. The Marshall distribution function of crack size is assumed to be independent of the degree of embrittlement experienced by the vessel. The crack density of 0.007 cracks/ft^2 is assumed in a critical area near the beam tube in accordance with Cheverton's estimate shown in reference 1. The probability of fracture as a result of hydrotest or other operating condition is shown in Equ. 2.14 at the end of this paragraph with the following form:

$$P = \frac{1}{\mu(RT)\sqrt{2\pi}} \int_{-4}^{4} P(w) \exp\left\{ - \frac{[w - M(RT)]^2}{2[\mu(RT)]^2} \right\} dw \tag{2.14}$$

where *P(w)* is a two-dimensional integral derived later in this paragraph and *RT* is the sum of the initial and radiation induced temperature shift.

The probability of fracture integral is derived in the following. The problem is to find the probability of fracture under the following conditions:

1. The distribution function for the crack depth *a* follows an exponential distribution (the Marshall distribution)

$$f(a) = 4.064 \exp(-4.064a) \quad a \text{ in inches} \tag{2.1}$$

and the probability of nondetection follows

$$B(a) = 0.005 + 0.995 \exp(-2.870a) \quad a \text{ in inches} \tag{2.2}$$

2. The toughness K_{Ic} is a function of the metal temperature *T*, initial (undamaged) value of the nil ductility temperature RT_O, and the radiation induced temperature shift *DRT*,

$$K_{Ic} = A + B \exp\left[C(T - RT_O - DRT)\right] \tag{2.3}$$

where *A*, *B*, and *C* are constantsshown in the following table:

	A, ksi $\sqrt{in.}$	B, ksi $\sqrt{in.}$	C, °F^{-1}
Lower bound K_{Ic}	33.2	20.73	0.02
Mean value K_{Ic}	33.2 × 1.43	20.73 × 1.43	0.02

3. K_{Ic} values are assumed to be scattered according to a Gaussian distribution with the standard deviation of 0.15 $M(K_{Ic})$. The notation $M(K_{Ic})$ is the median value of the scattered K_{Ic} at *T-RT*.

$$P(a < Y < a + \Delta a) = f(a)\, B(a)\, \Delta a$$

$$P(K_{Ic} < X < K_{Ic} + \Delta K_{Ic}) = \frac{\Delta K_{Ic}}{0.15\, M(K_{Ic})\sqrt{2\pi}} \exp\left\{-\frac{[x - M(K_{Ic})]^2}{2[0.15\, M(K_{Ic})]^2}\right\}$$

$$P(RT) = \int_0^{\infty} f(a) B(a) \int_{-\infty}^{K_I} \frac{1}{0.15\, M(K_{Ic})\sqrt{2\pi}} \exp\left\{-\frac{[x - M(K_{Ic})]^2}{2[0.15\, M(K_{Ic})]^2}\right\} dx\, da$$

$$K_I = \Phi$$

$$P = \int_0^4 f(y)B(y)H\left(\frac{\sqrt{By} - M(K_{Ic})}{0.001\ M(K_{Ic})}\right)dy = \int_a^4 f(y)\ B(y)\ dy \tag{2.11}$$

where a satisfies

$$\sqrt{Ba} = M(K_{Ic})\ . \tag{2.12}$$

The probability result in Ref.(5) is therefore recovered. In Ref. (5), lower bound K_{Ic} was used.

4. If the statistical variations of RT_O and DRT are taken into consideration, then the probability of fracture derived above needs to be multiplied by the following factor:

$$P(RT < W < RT \%)RT) = \frac{)RT}{\mu(RT)\sqrt{2B}} \exp\left\{-\frac{[w - M(RT)]^2}{2[\mu(RT)]^2}\right\} \tag{2.13}$$

where $M(RT)$ is the median value of $RT = RT_O + DRT$ and $\mu(RT)$ is the standard deviation of RT. The value of μ(RT) is determined to be 29EF.

5. The probability of fracture that includes the statistical variation of RT is the product of part (3) and part (4) above, that is,

$$P = \frac{1}{\mu(RT)\sqrt{2B}} \int_{-4}^{4} P(w) \exp\left\{-\frac{[w - M(RT)]^2}{2[\mu(RT)]^2}\right\} dw \tag{2.14}$$

Where $P(w)$ is the probability derived in part (3) defined by

$$P(w) = P(RT). \tag{2.15}$$

3. STRESS INTENSITY FACTOR AND TOUGHNESS

Stress intensity factor is in general a function of system pressure and geometry at various location of the pressure vessel. It is characterized by a geometrical factor and a possible residual stress. The stress intensity factor that appears in Equ. 2.6 is usually more complex than that shown in Equ. 2.7. In the numerical calculation, it has the following form

$$K_I = (p \% S) \cdot G\sqrt{Ba} \tag{3.1}$$

where

a = crack depth,
p = primary system pressure,
G = geometric factor for the corner crack due to primary system pressure, and
S = contribution to the stress intensity factor from the residual stress, expressed as the equivalent primary system pressure.

Toughnesses at different stages of material embrittlement are used in the calculation. For an irradiated steel, the toughness is modeled by

$$K_{IC} = A + B \exp\left[C\left(T - RT_0 - DRT\right)\right] \tag{3.2}$$

where

T	=	material temperature,
RT_0	=	initial (undamaged) value of the nil ductility temperature,
DRT	=	increase in RT_0 due to radiation, shown as RT_{NDT} in the figures, and
A,B,C	=	mean values shown in the table.

The shift in transition temperature DRT as a function of the sum of neutron and gamma radiation dpa is obtained from a recent paper by Remec (Ref. 6) with the following form,

$$RDT = 807.7 + 182.6 \log(dpa) + 10.62 \left[\log(dpa)\right]^2 - F \tag{3.3}$$

It is observed that it is not linear in dpa as was assumed earlier (Ref. 2). The amount of dpa as a function of the effective power year t that the reactor has been experienced at the region of interest is

$$2.74\times10^{-3} + 1.25\times10^{-3}\,(t - 22.6) \qquad t > 22.6\ efpy \tag{3.4}$$

4. RESULTS AND CONCLUSION

Recent HFIR upgrade design requires fracture probability calculations used as a renewed estimate of the total life of the reactor vessel. In certain part of the reactor vessel where the irradiation is rather intense in the upgrade design. The following figures show the probabilities of fracture and the related toughness changes at a number of areas along the reactor vessel. There are two figures shown below. It is noted that these results show a good agreement with the Monte Carlo results obtained by Cheverton recently.

Resulting probabilities of the recent HFIR upgrade design for region 1 and region 3 along the vessel, respectively, are shown in Figs. 1 and 2. The probability of fracture at each region is assumed to be subjected

5. REFERENCES

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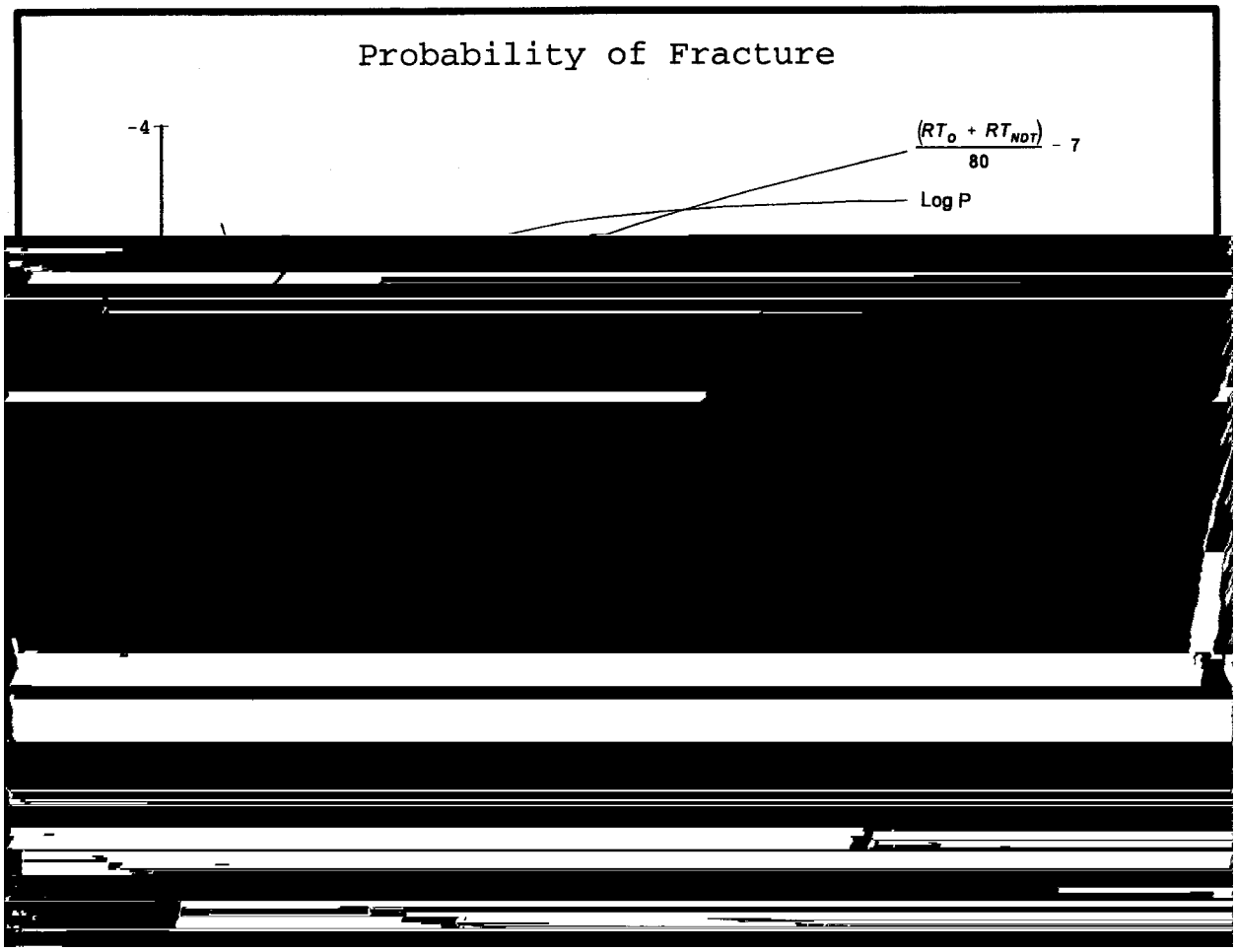

Fig. 1. Probability of fracture, plane strain toughness and transition temperature shift for region 1.

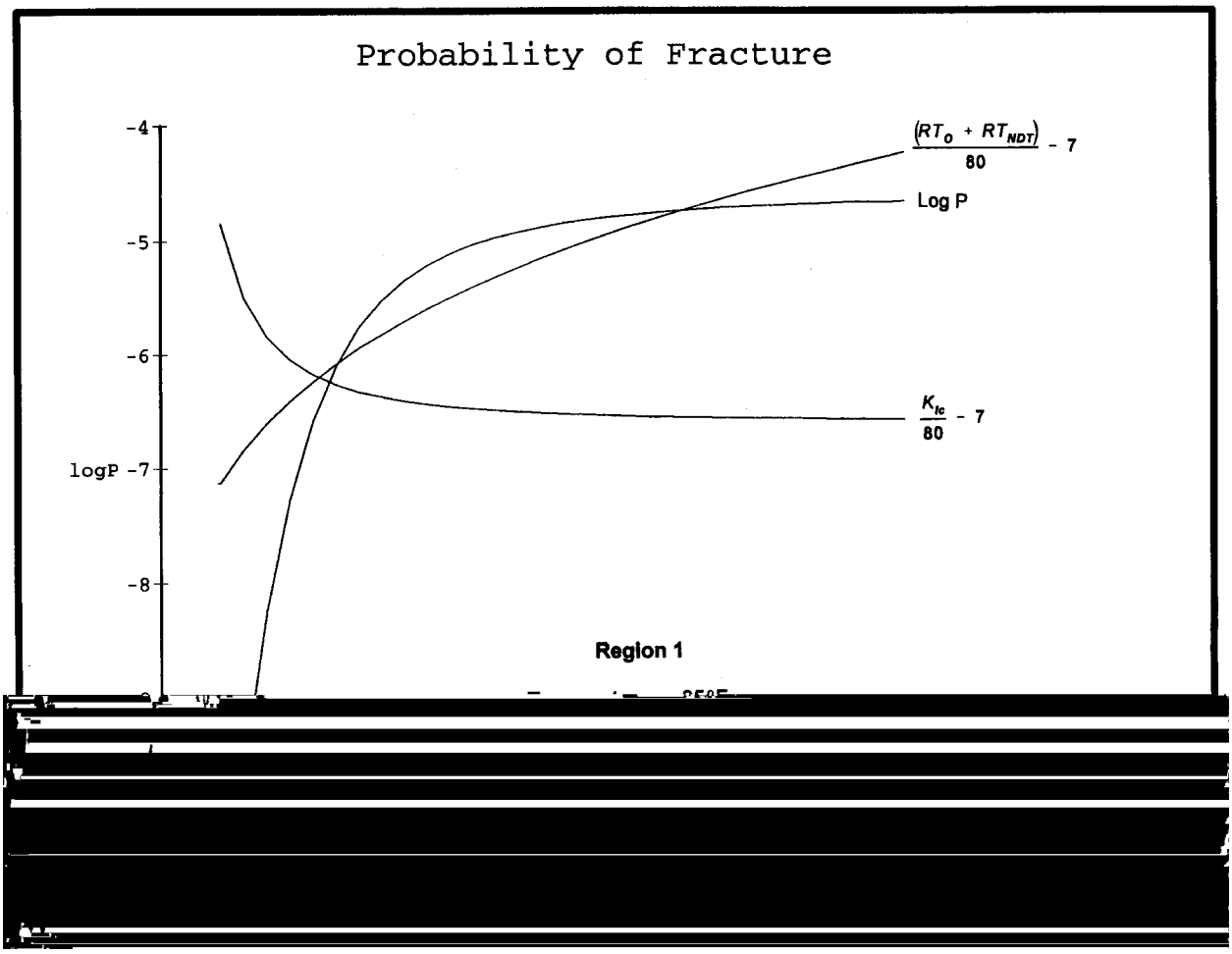

Fig. 2. Probability of fracture, plane strain toughness and transition temperature shift for region 3.