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**HFIR Vessel Maximum
Permissible Pressures for
Operating Period 26 to
50 EFPY (100 MW)**

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Information

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**HFIR VESSEL MAXIMUM PERMISSIBLE PRESSURES FOR
OPERATING PERIOD 26 TO 50 EFPY(100 MW)**

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	i
PREFACE	ii
ABSTRACT	iii
1. Introduction	1
2. Method of Analysis	2
3. Input to Calculations	3
4. Calculations	4
4.1 Parametric analysis	4
4.2 Maximum permissible pressure as a function of time for $\Delta t = 2.6$ EFPY(100 MW)	12
4.3 Sensitivity of $p(t)_{min}$ to the tolerance on Δt	17
4.4 Sensitivity of $p(t)_{min}$ to flaw growth	19
4.5 Sensitivity of $p(t)_{min}$ to characteristics of $K_{Ic} = f(T - RT_{NDT})$ curve	21
4.6 Minimum value of $p(t)_{min}$ for $\Delta t = 3.0$ and 3.12 EFPY(100 MW) and $\dot{a} = 8.8 \times 10^{-3}$ in./EFPY(100 MW)	21
5. Recommendations	22
6. Summary and Conclusions	23
References	24
Appendix A: Source of Standard Deviations (σ) for RT_{NDT_0} and ΔRT_{NDT}	26
Appendix B: Results of Calculations for the Parametric Study	28
Appendix C: Calculated values of $p(t)$ vs t for $T_v(t) = 110^\circ\text{F}$, $\Delta t =$ 2.6 EFPY(100 MW), $\dot{a} = 0$	34
Appendix D: Calculated Values of $p(t)$ vs t for $T_v(t) = 88^\circ\text{F}$, $\Delta t = 2.6$ EFPY(100 MW), $\dot{a} = 0$	35
Appendix E: Calculated Values of $p(t)$ vs t for $T_v(t) = 80^\circ\text{F}$, $\Delta t = 2.6$ EFPY(100 MW), $\dot{a} = 0$	36
Appendix F: Comparison of $p(t)$ vs e Obtained Using the ASME K_{Ic} and K_{IR} Curves	37

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PREFACE

This study was completed prior to concluding that (1) hydrostatic proof testing could be substituted for inservice volumetric inspection of some of the primary-system piping welds* and (2) enlargement of the HB-2 and HB-4 beam tubes was feasible.** If the hydrostatic proof-testing substitution and/or the design upgrade are in effect during the life-extension period 26 to 50 EFPY(100 MW), hydrostatic proof-test conditions and thus the maximum permissible pressures will be somewhat different than those mentioned in this report. The method of analysis, however, remains valid.

*R. D. Cheverton and J. R. Inger, *Determination of the Applicability of Hydrostatic Proof Testing for Demonstrating Integrity of HFIR Primary-System Piping, Vessel, and Related Components*, ORNL, RDC/JRI/RRD/LTR-97-2, February 9, 1998.

**R. D. Cheverton and T. L. Dickson, *HFIR Vessel Life Extension with Enlarged HB-2 and HB-4 Beam Tubes*, ORNL, ORNL/TM-13698, December 1998.

ABSTRACT

Extending the life of the HFIR pressure vessel from 26 to 50 EFY (100 MW) requires an updated calculation of the maximum permissible pressure for a range in vessel operating temperatures (40–120°F). The maximum permissible pressure is calculated using the equal-potential method, which takes advantage of knowledge gained from periodic hydrostatic proof tests and uses the test conditions (pressure, temperature, and frequency) as input.

The maximum permissible pressure decreases with increasing time between hydro tests but is increased each time a test is conducted. The minimum values that occur just prior to a test either increase or decrease with time, depending on the vessel temperature. The minimum value of these minimums is presently specified as the maximum permissible pressure. For three vessel temperatures of particular interest (80, 88, and 110°F) and a nominal time of 3.0 EFY (100 MW) between hydro tests, these pressures are 677, 753, and 850 psi. For the lowest temperature of interest (40°F), the maximum permissible pressure is 295 psi.

HFIR VESSEL MAXIMUM PERMISSIBLE PRESSURES FOR THE OPERATING PERIOD 26 TO 50 EFPY(100 MW)

1. Introduction

Extending the life of the HFIR pressure vessel from 26^a to 50 EFPY(100 MW) requires the recalculation of the maximum permissible pressures as a function of vessel temperature (T_v). For normal operation, the highest value of T_v is 110°F (primary-system coolant-inlet temperature equals 120°F, and pool temperature equals 90°F), and the lowest value is 80°F (minimum permissible temperature of coolant in the cooling-tower basin). An intermediate value of particular interest is that used to establish the vessel pressure safety limit. This temperature was specified as the primary-system inlet-coolant-temperature trip point for primary-system pressure reduction. This temperature is 88°F.¹ There also may be a need to pressurize the primary system when the coolant temperature is below 80°F, the lowest credible temperature being 40°F. Thus, maximum permissible pressures are needed for vessel temperatures in the range 40–120°F.

There are two basic methods for calculating the maximum permissible pressure: (1) ASME Code,² which uses rather large safety factors to account for uncertainties and (2) the equal-potential method, which takes advantage of knowledge gained from periodic hydrostatic proof tests. This latter method is the one used for calculating the hydro-test conditions³ and is also the method used in this report for calculating the recommended maximum permissible pressures. It results in higher pressures than obtained with the ASME Code because a successful hydro test reduces the uncertainties.

In previous calculations of pressures for the low end of the temperature range (40–80°F), the ASME Code approach was used,^{3,4,5} and the relatively low pressures did not constitute excessive restrictions. Even so, it is prudent to achieve as much operational flexibility as is reasonable, and this can be accomplished by using the method that results in the highest permissible pressure.

^aThe presently specified maximum permissible life for the HFIR pressure vessel is 26 EFPY(100 MW), which will be achieved in ~ 2005.

2.0 Method of Analysis

As discussed in Ref. 6, the condition that must be satisfied in the equal-potential method is

$$\frac{K_I(t)}{K_{Ic}(t)} \leq \frac{K_I(HT)}{K_{Ic}(HT)}, \quad (1)$$

- where $K_I(t)$ = stress intensity factor at time t during normal operation
 $K_I(HT)$ = stress intensity factor for hydro-test conditions
 $K_{Ic}(t)$ = fracture toughness of material at time t during "normal" operation
 $K_{Ic}(HT)$ = fracture toughness of material for hydro-test temperature and time.
 K_I/K_{Ic} = potential for propagation of flaw (vessel failure)

Substituting expressions for K_I ,

$$\begin{aligned} p(t) &= p(HT) \frac{K_{Ic}(t)}{K_{Ic}(HT)} \left(1 + \frac{\Delta a}{a} \right)^{-0.5} + S \left[\frac{K_{Ic}(t)}{K_{Ic}(HT)} \left(1 + \frac{\Delta a}{a} \right)^{-0.5} - 1 \right], \\ &= [p(HT) + S] \left(1 + \frac{\Delta a}{a} \right)^{-0.5} \cdot \frac{K_{Ic}(t)}{K_{Ic}(HT)} - S \end{aligned} \quad (2)$$

- where Δa = $\dot{a} \cdot \Delta t$ (3)
 = flaw growth during Δt
 a = flaw depth at time of "initial" hydro test^b
 $\dot{a}$ = rate of flaw growth
 Δt = time between hydro tests
 $p(t)$ = maximum permissible pressure at time t
 $p(HT)$ = hydro-test pressure

^bBecause Δa is quite small compared to a , and because $p(t)$ is insensitive to the value of a ,³ the same value of a is used for all pairs of t and $t(HT)$.

$$S = \frac{c_r \sigma_r}{c_m s_m + c_b s_b} \quad (4)$$

c = crack characterization factor

s = σ/p

σ = far-field stress

m, b, r = membrane, bending, residual

Use of the equality sign in Eq. (2) is justified by including appropriate uncertainty factors for specific parameters.

The expressions for K_{Ic} are

$$K_{Ic}(t) = A + B \exp [C \cdot E(t)] , \quad (5)$$

$$K_{Ic}(HT) = A + B \exp [C \cdot E(HT)] , \quad (6)$$

where

A, B, C = constants

$$E(t) = T_v(t) - RT_{NDT}(t) = T_v(t) - RT_{NDT_0} - e \cdot \Delta NDTT \cdot t \quad (7)$$

$$E(HT) = T_v(HT) - RT_{NDT}(HT) = T_v(HT) - RT_{NDT_0} - e \cdot \Delta NDTT \cdot t(HT) \quad (8)$$

$$t(HT) \leq t \leq t(HT) + \Delta t \quad (9)$$

$T_v(t)$ = temperature of vessel at time t

$T_v(HT)$ = temperature of vessel during hydro test

RT_{NDT} = nil-ductility reference temperature

RT_{NDT_0} = initial value of RT_{NDT}

$\Delta NDTT$ = rate of increase of nil-ductility transition temperature

e	=	uncertainty factor applied to $\Delta NDTT$
t	=	reactor operating time
$t(HT)$	=	time of hydro test
Δt	=	time between hydro tests

The flaw specified by the ASME Code² is a semi-elliptical surface crack normal to the surface and to the principle stresses. It has a surface-length to depth ratio of 6 and a depth of 1.0 in. The critical location (maximum value of K/K_{lc}) of the flaw is at the inner surface of the vessel in the nozzle weld directly above the HB-3 nozzle, and it is oriented axially.⁷

The above method of analysis is based on plain-strain linear elastic fracture mechanics (LEFM), the applicability of which is limited by $T-RT_{NDT}$ and dimensions of the "specimen" relative to the size of the plastic zone at the tip of the flaw. The dimensions of the vessel wall and of the hypothetical flaws are not limiting for the HFIR analysis, and as indicated by the results of the analyses, values of $T-RT_{NDT}$ are well below a marginally limiting value of 50°F.

3. Input to Calculations

With a few exceptions, input for the calculations was taken from Table 5.1 of Ref. 3 and is included here in Table 1. The exceptions pertain to values of $p(HT)$, $T_v(t)$, $t(HT)$, Δt , e , RT_{NDT_0} , and a . The value of the hydro-test pressure [$p(HT)$] included in Table 1 is the value proposed for operation beyond 26 EFPY(100 MW).⁸

As indicated in the "Introduction," several specific values of the vessel temperature [$T_v(t)$] are considered. For normal steady-state operation, the temperature of the primary-system coolant adjacent to the vessel wall is 120°F, the temperature of the pool water is 90°F, and the fluid-film heat transfer coefficients are nearly equal. Thus, the temperature at the tip of the assumed 1.0-in.-deep, inner-surface flaw is ~ 110°F.

Table 1. Input data for calculation of $p(t)$

Parameter	Value
K_{Ic} vs $T-RT_{NDT}$	ASME K_{Ic} (Ref. 9)
A , ksi $\sqrt{\text{in.}}$	33.2
B , ksi $\sqrt{\text{in.}}$	20.73
C , $^{\circ}\text{F}^{-1}$	0.0200
a , in.	1.0
$\dot{a}$, in./EFPY(100 MW)	0.0, 8.8×10^{-3} (Ref. 8)
c_b	0.741 (Ref. 4)
c_m	1.146 (Ref. 4)
c_r	0.860 (Ref. 4)
s_b	4.24 (Ref. 4)
s_m	16.8 (Ref. 4)
σ_r , ksi	8.5 (Ref. 4)
$p(HT)$, ksi	0.850 (Ref. 4)
RT_{NDT_0} , $^{\circ}\text{F}$	10 ± 34
$\Delta NDTT$, $^{\circ}\text{F}/\text{EFPY}(100 \text{ MW})$ ($a = 1.0 \text{ in.}$)	2.44 (Refs. 3, 8)
e	0.5–1.5
$T_v(HT)$, $^{\circ}\text{F}$	85
$T_v(t)$, $^{\circ}\text{F}$	40–120
$t(HT)$, EFPY(100 MW)	$26 + (n-1) \Delta t$, $n = 1, 2, \dots, 9$
Δt , EFPY(100 MW)	$2.6^{+0.12}_{-0.00}$, $3.0^{+0.12}_{-0.00}$

The next highest vessel temperature of particular concern is the minimum value corresponding to the primary-system coolant inlet-temperature trip point for system depressurization. This minimum value is 88°F , conservatively neglecting the difference in temperature between the primary-system coolant and that in the pool.

The lowest vessel temperature for "normal" operation is conservatively assumed to be equal to the minimum temperature of the coolant in the basin of the cooling tower. This limiting temperature has not yet been specified for reactor operation beyond 26 EFPY(100 MW) but is expected to be close to 80°F. Because of thermal inertia in the primary and secondary systems, it is very unlikely that the vessel temperature would be at the basin value. If the calculated maximum permissible pressure corresponding to the basin temperature is too low, a more rigorous evaluation of vessel temperature may be required.

For low-pressure/low-temperature operation, the range of temperatures of interest is 40 to 80°F.

The minimum value of the maximum permissible pressure is sensitive to the value of $t(HT)$, and depending on the vessel temperature, the proper value to use could be either early or late in the vessel life-extension period. Thus, values of $p(t)$ were calculated as a function of time to establish the trend, in which case several values of $t(HT)$ were used. The smallest value was 26 EFPY(100 MW); the largest value was $50 - \Delta t$; intermediate values were $26 + (n-1)\Delta t$, where n is the sequence number of the test.

Beginning in 1989, at the time of HFIR restart, the specified time between hydro tests was 1.0 EFPY(85MW), but recently a value of 3.0 EFPY(85 MW) [2.6 EFPY(100 MW)] was proposed¹⁰ and accepted for operation between 19.4 and 26 EFPY(100 MW). A value of 3.0 EFPY (100 MW) is tentatively proposed for the life-extension period 26 to 50 EFPY(100 MW).⁸

There are tolerances on $t(HT)$ and Δt to provide reasonable flexibility in scheduling. Presently specified tolerances on Δt are $^{+0.12}_{-0.00}$ EFPY(100 MW). A reasonable tolerance for the initial value of $t(HT)$ [~ 26 EFPY(100 MW)] cannot be specified at this time and thus has not been included in this study.

The value of e , the uncertainty factor applied to the damage rate ($\Delta NDTT$), that results in the lowest values of $p(t)$ is not the same for all cases (vessel temperatures), as illustrated below with reference to Eqs. (2)–(8):

Case 1: $T_v(t) > T_v(HT)$ For $e=0$, $K_{lc}(t) > K_{lc}(HT)$

$$\therefore p(t) > p(HT)$$

For $e=\infty$, $K_{lc}(t) = K_{lc}(HT)$

$$\therefore p(t) = p(HT)$$

Thus, e (max) tends to result in the lowest value of $p(t)$.**Case 2:** $T_v(t) < T_v(HT)$ For $e=0$, $K_{lc}(t) < K_{lc}(HT)$

$$\therefore p(t) < p(HT)$$

For $e=\infty$, $K_{lc}(t) = K_{lc}(HT)$

$$\therefore p(t) = p(HT)$$

Thus, e (min) tends to result in the lowest value of $p(t)$.**Case 3:** $T_v(t) = T_v(HT)$ For $e=0$, $K_{lc}(t) = K_{lc}(HT)$

$$\therefore p(t) = p(HT)$$

For $e=\infty$, $K_{lc}(t) = K_{lc}(HT)$

$$\therefore p(t) = p(HT)$$

For Case 3, there may be a value of e within specified extremes that results in $p(t) < p(HT)$. Thus, several values of e must be considered. A reasonable range is 0.5 to 1.5,³ although this range could shrink as more surveillance data become available.

The uncertainty of $\pm 34^\circ\text{F}$ included in Table 1 for RT_{NDT_0} is a two-standard deviation (2σ) value that was recommended by the Nuclear Regulatory Commission (NRC) for pressure vessel steels (see Appendix A) and was used in the evaluation of the HFIR vessel life extension.⁸ With reference to Eqs. (5)–(9), increasing RT_{NDT_0} tends to either increase or decrease $K_{lc}(t)/K_{lc}(HT)$ depending on the relative values of $T_v(t)$ and $T_v(HT)$, but in either case driving it to unity (K_{lc} approaches A). Thus, several values of RT_{NDT_0}

and e within the specified limits must be considered in a parametric evaluation to find the "optimum" values.

The value of $\Delta NDTT$ included in Table 1 was obtained from a transposition of surveillance data to the location of the flaw tip. This was done in Ref. 4 and was updated in Ref. 3, both times using the neutron flux above 1.0 MeV in the transposition process. More recently,⁸ the process was repeated, accounting for the effect of gammas on the distribution of damage. The value of $\Delta NDTT$ for the particular location was the same as obtained in Ref. 3 and is the value given in Table 1 of this report. It is expected that a more rigorous evaluation of the gamma effect will be made in the near future, but it is believed that the range of e values included in the present study is sufficient to cover the present uncertainty.⁷

The value of $\dot{a} = 8.8 \times 10^{-3}$ in./EFPY(100 MW) was taken from Ref. 8. It is ten times the value calculated using the method included in the ASME Code⁹ and is considered to be a $+2\sigma$ value. The effect of including flaw growth is quite small,⁸ and for that reason it was excluded from many of the earlier calculations and also from some of the calculations in this report, in which case $\dot{a} = 0$.

4.0 Calculations

4.1 Parametric analysis

The purpose of the parametric aspect of the analysis was to determine the values of t , e , and RT_{NDT_0} that result in the minimum value of the maximum permissible pressure. The parametric analysis was performed using at least three values of e (0.5, 1.0, and 1.5), three values of RT_{NDT_0} (-24, 10, and 44°F), $\dot{a} = 0$, $\Delta t = 2.6$ EFPY(100 MW), and two pairs of $t(HT)$ and t [26, 28.6, and 47.4, 50 EFPY(100 MW)].

The independent variable in the analysis is $T_v(t)$, and, as indicated earlier, the range of interest is 40–120°F. Parameters in Eqs. (2)–(8) that have values common to all calculations are $\dot{a}$, A , B , C , $\Delta NDTT$, the stress-related terms (c , s , σ_p), $p(HT)$, and $T_v(HT)$. By introducing the values of these parameters, Eqs. (2)–(8) become, in the order of the calculational process,

$$t = t(HT) + \Delta t$$

$$E(t) = T_v(t) - RT_{NDT_0} - 2.44e \cdot t$$

$$E(HT) = 85 - RT_{NDT_0} - 2.44e \cdot t(HT)$$

$$K_{Ic}(t) = 33.2 + 20.73 \exp [0.02E(t)]$$

$$K_{Ic}(HT) = 33.2 + 20.73 \exp [0.02E(HT)]$$

$$S = \frac{0.860 \times 8.5 \times 10^3}{1.146 \times 16.8 + 0.741 \times 4.24} = 326 \text{ psi}$$

$$\Delta a = 0.0$$

$$p(t) = 850 \frac{K_{Ic}(t)}{K_{Ic}(HT)} + 326 \left[\frac{K_{Ic}(t)}{K_{Ic}(HT)} - 1 \right]$$

All of the values of $p(t)$ calculated for $\Delta t = 2.6$ EFPY (100 MW) to determine the minimum value for each of the vessel temperatures considered in the range 40 to 120°F are included in Appendix B, and the minimum value for each temperature is included in Table 2, which also includes the corresponding "optimum" values of t , $t(HT)$, e , and RT_{NDT_0} . The time t in Table 2 is the time for which the minimum value of $p(t)$ was calculated, and $t(HT)$ is the time of the preceding hydro test.

The above minimum values of $p(t)$, which constitute the maximum permissible pressures, if only one value is specified for each temperature for the duration of the life-extension period, are plotted in Fig. 1 as a function of vessel temperature.

Table 2. Calculated minimum values of $p(t)$ vs vessel temperature, and the corresponding "optimum" values of t , $t(HT)$, e , and RT_{NDT_0} ; $\dot{a} = 0$, $\Delta t = 2.6$ EFPY(100 MW)

$T_v(t)$ °F	t	$t(HT)$	e	RT_{NDT_0}	$p(t)_{min}$, psi
	EFPY(100 MW)				
40	28.6	26	0.5	-24	308
50	28.6	26	0.5	-24	382
60	28.6	26	0.5	-24	472
70	28.6	26	0.5	-24	583
80	28.6	26	1.0	-24	705
85	28.6	26	1.4	-24	758
88	28.6	26	1.5	-24	785
90	28.6	26	1.5	-24	804
95	50	47.4	1.5	44	850
100	50	47.4	1.5	44	856
110	50	47.4	1.5	44	868
120	50	47.4	1.5	44	883

Fig. 1. Maximum permissible pressure [minimum value of $p(t)_{min}$] vs. temperature for life-extension period 26-50 EFY(100 MW), $p(HT) = 850$ psi, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.60$ EFY(100 MW), $\dot{a} = 0$.

The discontinuity in Fig. 1 indicates a step change in one or more of the parameters in the equations, and, as indicated in Table 2, there is a step change in t [28.6 to 50 EFPY(100MW)] and RT_{NDT_0} (-24 to 44°F) between $T_v(t) = 90$ and 95°F, consistent with the value of $T_v(t)$ at which the discontinuity occurs. Also, the results in Appendix B indicate that at $T_v(t) = 95^\circ\text{F}$ the minimum value of $p(t)$ is nearly independent of the values of t and RT_{NDT_0} and is approximately equal to 850 psi = $p(HT)$. For $p(t) = p(HT)$ and $\dot{a} = 0$, Eqs. (5) and (6) must be equal, and thus Eqs. (7) and (8) must also be equal. Setting Eqs. (7) and (8) equal to each other and solving for $T_v(t)$ results in

$$\begin{aligned} T_v(t) &= T_v(HT) - RT_{NDT_0} - e \cdot \Delta NDTT(t - \Delta t) + RT_{NDT_0} - e \cdot \Delta NDTT t \\ &= T_v(HT) + e \cdot \Delta NDTT \cdot \Delta t \end{aligned} \quad (10)$$

As indicated by Eq. (10) and also by the data in Appendix B, the value of $T_v(t)$ corresponding to $p(t) = p(HT)$ is independent of t and RT_{NDT_0} .

Consistent with Tables 1 and 2, Eq. (10) yields

$$T_v(t) (\dot{a} = 0, \Delta t = 2.6 \text{ EFPY}(100\text{MW})) = 85 + 1.5 \times 2.44 \times 2.6 = 94.5^\circ\text{F}$$

The reduction in $dp(t)/dT_v(t)$ at $T_v(t) = 94.5^\circ\text{F}$ is the result of the step increase in t and RT_{NDT_0} . Increasing these two parameters decreases $T_v(t) - RT_{NDT_0}$, in which case $K_{ic}(t)/K_{ic}(HT)$ approaches unity asymptotically. Thus, $dp(t)/d[T_v(t)]$ approaches zero.

4.2 Maximum permissible pressure as a function of time for $\Delta t = 2.6$ EFPY(100 MW)

Based on the above discussion, for $T_v(t) (\dot{a} = 0, \Delta t = 2.6) = 94.5^\circ\text{F}$, the maximum permissible pressure is independent of time and is equal to 850 psi, the hydro-test pressure. Thus, for $T_v(t) > 94.5^\circ\text{F}$, the maximum permissible pressure is greater than 850 psi but decreases with time, becoming asymptotic to 850 psi. For $T_v(t) < 94.5^\circ\text{F}$, the maximum permissible pressure is less than 850 psi but increases with time, also

becoming asymptotic to 850 psi. Thus, for $T_v(t) > 94.5^\circ\text{F}$, the minimum value of the maximum permissible pressure occurs at the end of the life-extension period, and it occurs at the "beginning" [28.6 EFPY(100 MW)] of the life-extension period for $T_v(t) < 94.5^\circ\text{F}$.

The above trends are indicated in Table 2 and are illustrated graphically in Figs. 2, 3, and 4, which are plots of $p(t)$ vs t for $T_v(t) = 110, 88$ and 80°F , $a' = 0$ and $\Delta t = 2.6$ EFPY(100 MW). (Tabulated data for these figures are included in Appendices C, D, and E.)

The solid line in Figs. 2, 3, and 4 represents the maximum permissible pressure, if only one hydro test were conducted for the life-extension period (no beneficial effect of hydro testing), and the minimum values occur at the end of the life extension period. When hydro tests are conducted periodically, $p(t)$ is characterized by a gradual decrease during the time between tests, but immediately following a hydro test, $p(t)$ is restored to nearly the maximum value corresponding to the previous test because of the step decrease in $K_{ic}(HT)$ in Eq. (2) each time a test is conducted. Thus, at the time of each hydro test there are both minimum (pretest) and maximum (post test) values of $p(t)$. As indicated above and in the figures, the minimum value of $p(t)$, $p(t)_{min}$, either increases or decreases with time, depending on the value of $T_v(t)$, becoming asymptotic to $p(HT)$. Thus, the minimum value of $p(t)_{min}$ occurs either at the beginning or end of the life-extension period, as indicated above. These are the values that are plotted in Fig. 1.

The calculations pertaining to Figs. 2, 3, and 4 were made using Eqs. (2)–(8) with values of e and RT_{NDT_0} that resulted in the minimum value of $p(t)_{min}$. For times substantially different than those corresponding to the minimum value of $p(t)_{min}$, the values of $p(t)_{min}$ may not be as low as those obtained with other values of e and RT_{NDT_0} . However, the lowest values achievable are not less than the minimum value of $p(t)_{min}$ in the figures. These trends are indicated by the data in Appendix B.

Fig. 2. Maximum permissible pressure vs time, with and without beneficial effect of hydro testing, for $T_v(t) = 110^\circ\text{F}$, $p(HT) = 850$ psi, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.6$ EFPY (100 MW), $t(HT)$ (initial) = 26 EFPY (100 MW), ($e = 1.5$, $RT_{NDT_0} = 44^\circ\text{F}$).

Fig. 3. Maximum permissible pressure vs time, with and without beneficial effect of hydro testing, for $T_v(t) = 88^\circ\text{F}$, $p(HT) = 850$ psi, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.6$ EFPY(100 MW), $t(HT)$ (initial) = 26 EFPY(100 MW), ($e = 1.5$, $RT_{NDT_0} = -24^\circ\text{F}$).

Fig. 4. Maximum permissible pressure vs time, with and without beneficial effect of hydrotesting, for $T_v(t) = 80^\circ\text{F}$, $p(HT) = 850 \text{ psi}$, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.6 \text{ EFPY (100 MW)}$, $t(HT) \text{ (initial)} = 26 \text{ EFPY (100 MW)}$, ($e = 1.0$, $RT_{NDT_0} = -24^\circ\text{F}$).

As indicated by Figs. 2, 3, and 4, and by the data in Appendices C, D, and E, the minimum values of $p(t)_{min}$ for $T_v(t) = 110, 88, \text{ and } 80^\circ\text{F}$ are 868, 785, and 705 psi. If only one value of the maximum permissible pressure is to be specified for each of these temperatures for a specified period of time, such as the entire life-extension period, these values must be specified. However, if values are specified for successive time periods, higher values can be specified for some of those periods. Also, as more surveillance data become available, it may be possible to reduce the extremes of e , and that also will increase $p(t)_{min}$.

4.3 Sensitivity of $p(t)_{min}$ to the tolerance on Δt

As indicated in Table 1, the presently specified tolerance on Δt is $^{+0.12}_{-0.00}$ EFPY(100 MW). To determine the effect of this tolerance, minimum values of $p(t)_{min}$ were calculated for $a = 0$ and $\Delta t = 2.60 + 0.12 = 2.72$ EFPY(100 MW) to compare with the values in Table 2. The comparison is made in Table 3, which indicates that the decrease in the minimum value of $p(t)_{min}$ that results from adding the tolerance to Δt increases from 1 psi for $T_v(t) = 40^\circ\text{F}$ to 4 psi for $T_v(t) = 90^\circ\text{F}$. For $T_v(t) > 95^\circ\text{F}$, the decrease is less than 1 psi. Thus, the effect is very small.

The temperature corresponding to $p(t) = p(HT)$ is obtained from Eq. (10) and for $\Delta t = 2.72$ EFPY(100 MW) is

$$T_v(t) [p(t) = p(HT)] = 85 + 1.5 \times 2.44 \times 2.72 = 95.0^\circ\text{F}.$$

Table 3. Calculated minimum values of $p(t)_{min}$ vs vessel temperature for $\Delta t = 2.60$, 2.72, 3.00, and 3.12 EFPY(100 MW) with $\dot{a} = 0$ or $\dot{a} = 8.8 \times 10^{-3}$ in./EFPY(100 MW)^a

$T_v(t)$ °F	$p(t)_{min}$, psi				
	$\Delta t = 2.60$ $\dot{a} = 0$	$\Delta t = 2.72$ $\dot{a} = 0$	$\Delta t = 2.72$ $\dot{a} \neq 0$	$\Delta t = 3.00$ $\dot{a} \neq 0$	$\Delta t = 3.12$ $\dot{a} \neq 0$
40	308	307	299	296	295
45			334		329
50	382	381	372	369	367
55			415		409
60	472	471	462	457	455
65			513		507
70	583	581	570	565	563
75			631		621
80	705	701	689	681	677
85			741		727
88	785	781	768	757	753
90	804	800	787	776	771
95			836		820
100	856	855	841	839	838
105			847		844
110	868	868	854	851	850
115			861		857
120	883	883	868	866	865

^a"Optimum" values of $t(HT)$, e , and RT_{NDT_0} used in the calculations are the same as those in Appendix B, with the exception of $T_v(t) = 95^\circ\text{F}$ and $\Delta t = 3.12$, for which the optimum values are the same as for $T_v(t) = 90^\circ\text{F}$.

4.4 Sensitivity of $p(t)_{min}$ to flaw growth

With reference to Eqs. (2) and (3), and considering the upper limit on Δt [2.72 EFPY(100 MW)] in Sect. 4.3,

$$\Delta a = 8.8 \times 10^{-3} \times 2.72 = 2.394 \times 10^{-2} \text{ in.}$$

$$(1 + \Delta a/a)^{-0.5} = (1 + 2.394 \times 10^{-2}/1.0)^{-0.5} = 0.98824$$

$$\therefore p(t) = (850 + 326) 0.98824 \frac{K_{Ic}(t)}{K_{Ic}(HT)} - 326$$

$$= 1.1622 \times 10^3 \frac{K_{Ic}(t)}{K_{Ic}(HT)} - 326$$

Corresponding minimum values of $p(t)_{min}$ are included in Table 3 and Fig. 5. As indicated, including flaw growth reduces $p(t)_{min}$ by 8 psi for $T_v(t) = 40^\circ\text{F}$ and by 14 psi for $T_v(t) = 110^\circ\text{F}$, a maximum decrease of only 2%.

Because of the inclusion of $\dot{a} \neq 0$ in Eq. (2), the discontinuity in the curve in Fig. 1 does not occur for $p(t) = p(HT)$, as it did for the two cases for which it was assumed that $\dot{a} = 0$ [$\Delta t = 2.60$ and 2.72 EFPY(100 MW)].

Fig. 5. Maximum permissible pressure [minimum value of $p(t)_{\min}$] vs temperature for life extension period 26 to 50 EFPY(100 MW), $p(\text{HT}) = 850$ psi, $T_v(\text{HT}) = 85^\circ\text{F}$, $\Delta t = 2.72$ EFPY(100 MW), $\dot{a} = 8.8 \times 10^{-3}$ in./EFPY(100 MW).

4.5 Sensitivity of $p(t)_{min}$ to characteristics of $K_{Ic} = f(T-RT_{NDT})$ curve

Previous studies have indicated a sensitivity of $p(t)_{min}$ to the characteristics of the $K_{Ic} = f(T-RT_{NDT})$ curve.^{3,9} It was concluded that for the calculation of $p(HT)$ and Δt , the ASME lower-bound K_{Ic} curve⁸ was appropriate.⁹ Thus, this curve was selected for the present study. As a further check, however, values of $p(t)_{min}$ were also calculated using the ASME K_{IR} curve,⁸ which is a lower bound to the dynamic and crack arrest data. Results of the comparison analysis (Appendix F) demonstrate that the ASME lower-bound K_{Ic} curve results in the smallest values of $p(t)_{min}$ and thus is appropriate for this study.

A point of interest with regard to using a lower-bound curve is that the lower-bound curve can be multiplied by a constant to obtain reasonable mean and upper-bound curves that do not alter the values of $p(t)_{min}$ because, as indicated by Eq. (2), the constant cancels.

4.6 Minimum value of $p(t)_{min}$ for $\Delta t = 3.0$ and 3.12 EFPY(100 MW) and $\dot{a} = 8.8 \times 10^{-3}$ in./EFPY(100 MW)

It may be that Δt will be increased from 2.6 to 3.0 EFPY(100 MW) for the life-extension period 26 to 50 EFPY. Thus, minimum values of $p(t)_{min}$ were calculated for this nominal value of Δt and also for its upper limit [3.12 EFPY(100 MW)], considering flaw growth.

For $\Delta t = 3.0$ EFPY(100 MW),

$$\Delta a = 8.8 \times 10^{-3} \times 3.0 = 0.02640 \text{ in.}$$

$$(1 + \Delta a/a)^{-0.5} = (1 + 0.02640/1.0)^{-0.5} = 0.98706$$

$$\therefore p(t) = 1.1608 \times 10^3 \frac{K_{Ic}(t)}{K_{Ic}(HT)} - 326$$

For $\Delta t = 3.12$ EFPY(100 MW),

$$\Delta a = 8.8 \times 10^{-3} \times 3.12 = 0.02746 \text{ in.}$$

$$(1 + \Delta a/a)^{-0.5} = (1 + 0.02746/1.0)^{-0.5} = 0.98655$$

$$\therefore p(t) = 1.1602 \times 10^3 \frac{K_{Ic}(t)}{K_{Ic}(HT)} - 326$$

For $\Delta t = 3.00$ EFPY(100 MW) and $T_v(t) = 40 - 90^\circ\text{F}$, $t = 29.00$ EFPY(100 MW) and $t(HT) = 26.00$; for $\Delta t = 3.00$ and $T_v(t) = 100 - 120^\circ\text{F}$, $t = 50.00$ and $t(HT) = 47.00$; for $\Delta t = 3.12$ and $T_v(t) = 40 - 90^\circ\text{F}$, $t = 29.12$ and $t(HT) = 26.00$; and for $\Delta t = 3.12$ and $T_v(t) = 100 - 120^\circ\text{F}$, $t = 50.00$ and $t(HT) = 46.88$, where t is the time of the minimum value of $p(t)_{min}$.

The calculated minimum values of $p(t)_{min}$ are included in Table 3. A comparison of these data with those for $\Delta t = 2.60$ and 2.72 EFPY(100 MW) indicates that the reduction in $p(t)_{min}$ due to increasing Δt from 2.6 to 3.0 EFPY(100 MW) is quite small. For $T_v(t) = 40^\circ\text{F}$, the difference in $p(t)_{min}$ is only 4 psi. At $T_v(t) = 95^\circ\text{F}$ it is 16 psi and at 100°F and above it is 4 psi.

In Ref. 8, a value of Δt was calculated for the life-extension period 26 to 50 EFPY(100 MW) assuming $p(HT) = 850$ psi, $T_v(HT) = 85^\circ\text{F}$, $p(E/F) = 679$ psi, $T_v(E/F) = 80^\circ\text{F}$, $RT_{NDT_0} = -24^\circ\text{F}$ (the -2σ value), $t(HT) = 26.0$ EFPY(100 MW), $a(HT) = 1.0$ in., and $\dot{a} = 8.8 \times 10^{-3}$ in./EFPY(100 MW). The result was 3.05 EFPY(100 MW). This value was rounded off to 3.00 EFPY(100 MW) for the calculation of $p(t)_{min}$ in this report, and this explains the difference between $p(E/F)$ (679 psi) and the value of $p(t)_{min}$ (681 psi) given in Table 3 for $\Delta t = 3.0$ EFPY(100 MW) and $T_v(t) = 80^\circ\text{F}$. It is also of interest to note that the value of $p(t)_{min}$ in Table 3 for $\Delta t = 3.12$ EFPY(100 MW) and $T_v(t) = 80^\circ\text{F}$ is slightly (2 psi) less than $p(E/F)$, as would be expected.

5.0 Recommendations

The pressures that should be used as operating limits for HFIR are those calculated using the upper limit on Δt and that include flaw growth. The corresponding curve for Δt (nominal) = 2.60 EFPY(100 MW) is presented in Fig. 5, and the digital data are included in Table 3 for Δt (nominal) = 2.60 and 3.00 EFPY(100 MW).

6.0 Summary and Conclusions

The equal-potential method, which takes advantage of knowledge gained from the hydrostatic proof tests, was used to calculate the maximum permissible pressure as a function of vessel temperature for the proposed vessel life-extension period 26 to 50 EFPY(100 MW). The hydro-test conditions considered were $p(HT) = 850$ psi, $T_v(HT) = 85^\circ\text{F}$, and $\Delta t = 2.60, 2.72, 3.00$ and 3.12 EFPY(100 MW), where Δt is the time between hydro tests. The four values of Δt are (1) the nominal value approved for the period 19.4 to 26.0 EFPY(100 MW), (2) the corresponding upper-tolerance value, (3) the tentatively proposed nominal value for the period 26 to 50 EFPY(100 MW), and (4) the corresponding upper-tolerance value.

The calculated pressures for $\Delta t = 3.12$ EFPY(100 MW) are 295, 677, 753, and 850 psi for vessel flaw-tip temperatures of 40, 80, 88, and 110°F . These temperatures are, respectively, the lowest expected, the lowest expected during normal operation, the vessel temperature corresponding to the vessel pressure safety limit, and the vessel temperature for normal operation. Pressures for $\Delta t = 2.72$ EFPY(100 MW) are at most only 16 psi higher.

The above pressures are based on the assumption that for each temperature a single value of the maximum permissible pressure is specified for the entire life-extension period. For shorter times, somewhat higher pressures could be specified for vessel temperatures greater than $\sim 95^\circ\text{F}$. For temperatures less than $\sim 95^\circ\text{F}$, the specified pressure could be increased somewhat with time, but it could never be greater than the hydro-test pressure (850 psi).

As more surveillance data are obtained, it may be possible to decrease the uncertainty factor used for the radiation-induced damage rate, and this would permit some increase in the maximum permissible pressure.

References

1. HFIR Technical Specifications, Oak Ridge National Laboratory, ORNL/TM-5711/R2, Sect. 3.17.4.
2. ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendix G, 1992 Edition.
3. R. D. Cheverton and R. K. Nanstad, *Evaluation of HFIR Vessel Surveillance Data and Hydro-Test Conditions*, Oak Ridge National Laboratory, ORNL/TM-12758, August 5, 1994.
4. R. D. Cheverton, J. G. Merkle, and R. K. Nanstad, *Evaluation of HFIR Pressure-Vessel Integrity Considering Radiation Embrittlement*, Oak Ridge National Laboratory, ORNL/TM-10444, April 1988.
5. R. D. Cheverton, *Calculation of HFIR Vessel Pressure/Temperature Limits for Temperatures Below 70 °F*, Oak Ridge National Laboratory, Calculation ID: C-HFIR-95-009, May 15, 1995.
6. R. D. Cheverton, *HFIR Vessel Maximum Permissible Pressure Based on a Vessel Normal Operating Temperature*, Oak Ridge National Laboratory, Calculation ID: C-HFIR-95-015, May 15, 1995.
7. R. D. Cheverton, *An Evaluation of Life Extension of the HFIR Pressure Vessel*, Oak Ridge National Laboratory, ORNL/TM-12877, December 1994.
8. R. D. Cheverton, *An Evaluation of Life Extension of the HFIR Pressure Vessel—Supplement 1*, Oak Ridge National Laboratory, ORNL/TM-12877/S1, August 1996.
9. ASME Boiler and Pressure Vessel Code, Section XI, Division 1, Appendix A, 1992 Edition.

10. R. D. Cheverton, *Synopsis of Technical Justification for Increasing the Time Between Hydro Tests from 1.0 to 3.0 EFPY(85MW)*, Letter to J. R. Inger, Oak Ridge National Laboratory, June 2, 1995.

APPENDIX A

SOURCE OF STANDARD DEVIATIONS (σ) FOR RT_{NDT_0} and ΔRT_{NDT}

The reference nil-ductility transition temperature (RT_{NDT}) is equal to an initial value (RT_{NDT_0}) plus the increase due to radiation exposure (ΔRT_{NDT}). That is

$$RT_{NDT} = RT_{NDT_0} + \Delta RT_{NDT} \quad (A.1)$$

For nuclear reactor pressure vessel steels, ΔRT_{NDT} can be obtained from NRC Regulatory Guide 1.99, which has undergone two revisions thus far.^{A.1,2,3} Between the first and second revisions, there was an "improved" version of the correlation that was specified by the NRC for use in the PWR PTS probabilistic fracture-mechanics analysis^{A.4} that was being developed at the time and applied to the PWR IPTS program.^{A.5} This correlation and its standard deviation (σ_Δ) were proposed by the NRC in an internal document^{A.6} and were eventually included in the Code of Federal Regulations.^{A.7} In Ref. A.6, $\sigma_\Delta = 24^\circ\text{F}$, and, in Ref. A.7, σ_Δ is given only in combination with σ_0 , the standard deviation for RT_{NDT_0} . The value of σ_0 is given in Ref. A.6 as 17°F .

In Refs. A.6 and A.7, it is specified that

$$2\sigma(RN_{NDT}) = 2 \sqrt{\sigma_0^2 + \sigma_\Delta^2} \quad (A.2)$$

and, consistent with the above values of σ_0 and σ_Δ , $2\sigma(RT_{NDT}) = 59^\circ\text{F}$, which is the combined value given in Ref. A.7 for a generic data base. (No distinction was made between weld, plate, and forging material.) These standard deviations were used in Ref. A.5 and were also used in the HFIR vessel probabilistic fracture-mechanics analyses.^{A.8}

For the calculation of the HFIR hydro-test conditions and maximum permissible pressures, $\sigma_0 = \pm 17^\circ\text{F}$ was used, but an uncertainty factor (e) with a range of 0.5 to 1.5 was applied to ΔRT_{NDT} , rather than using σ_Δ with ΔRT_{NDT} . Within these limits for e , there tends to be "optimum" values of e that result in the most restrictive test and operating conditions [maximum value of $p(HT)$, minimum value of Δt , minimum value of $p(t)_{min}$]. Thus, a search is made for the optimum values of the uncertainties in RT_{NDT_0} and ΔRT_{NDT} , using $2\sigma_0 = \pm 34^\circ\text{F}$ as a limit for RT_{NDT_0} .

References (for Appendix A):

- A.1 U. S. Nuclear Regulatory Commission, *Effects of Residual Elements on Predicted Radiation Damage to Reactor Pressure Vessel Materials*, Regulatory Guide 1.99, July 1975.
- A.2 U. S. Nuclear Regulatory Commission, *Effects of Residual Elements on Predicted Radiation Damage to Reactor Pressure Vessel Materials*, Regulatory Guide 1.99, Rev. 1, Sept. 16, 1976.
- A.3 U. S. Nuclear Regulatory Commission , *Radiation Embrittlement of Reactor Vessel Materials*, Regulatory Guide 1.99, Rev. 2, May 1988.
- A.4 R. D. Cheverton and D. G. Ball, OCA-P, *A Deterministic and Probabilistic Fracture-Mechanics Code for Application to Pressure Vessels*, Oak Ridge National Laboratory, NUREG/CR-3618 (ORNL-5991), May 1984.
- A.5 D. L. Selby, et. al., *Pressurized Thermal-Shock Evaluation of the HB Robinson Nuclear Power Plant*, Oak Ridge National Laboratory, NUREG/CR-4183, Vol. 1 (ORNL/TM-9567/V1), September 1985.
- A.6 U. S. Nuclear Regulatory Commission, *Pressurized Thermal Shock (PTS)*, SECY-82-465, Attachment A, Letter to USNRC Commissioners, November 23, 1982.
- A.7 Code of Federal Regulations, Part 10 CFR 50.61, *Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events*, Revised January 1, 1987.
- A.8 R. D. Cheverton and T. L. Dickson, *HFIR Vessel Probabilistic Fracture-Mechanics Analysis*, Oak Ridge National Laboratory, ORNL/TM-13303, January 1997.

APPENDIX B

RESULTS OF CALCULATIONS FOR THE PARAMETRIC STUDY

The purpose of the parametric study was to find which combinations of t , e , and RT_{NDT_0} resulted in the minimum values of $p(t)_{min}$. Equations (2)–(8) were used to calculate $p(t)_{min}$, which corresponds to the time just prior to each hydro test [$26 + (n-1) 2.6$] EFPY(100 MW) and the final time of the life-extension period [50 EFPY(100 MW)]. Minimum values of $p(t)_{min}$ occur at either $t = 28.6$ or 50 EFPY(100 MW) (see Appendices C, D, and E). Thus, with one exception, $p(t)_{min}$ was calculated for these two times only. Three values of e (0.5, 1.0, 1.5) and three values of RT_{NDT_0} (-24 , 10, 44°F) were also considered ($\pm 2\sigma$ and mean). The results of the calculations are tabulated below, and the minimum values of $p(t)_{min}$ are included in Tables 2 and 3 and Fig. 1 of the text and in a summary table at the end of this appendix.

$T_v(t)$ °F	t $t(HT)$ EFPY(100 MW)		e	RT_{NDT_0} °F	$p(t)_{min}$ psi
40	28.6	26	0.5	44	538
			0.5	10	416
			0.5	-24	308
			1.0	44	635
			1.0	10	518
			1.0	-24	391
			1.5	44	714
			1.5	10	620
			1.5	-24	497
			0.7	-24	337
			1.2	-24	432
40	50	47.4	0.5	44	626
			0.5	10	510
			0.5	-24	388
			1.0	44	757
			1.0	10	686
			1.0	-24	583
50	28.6	26	0.5	-24	382

$T_v(t)$ °F	t EFPY(100 MW)	$t(HT)$	e	RT_{NDT_0} °F	$p(t)_{min}$ psi
60	28.6	26	0.5	-24	472
			1.0	-24	517
			1.5	-24	585
			0.75	-24	491
70	28.6	26	0.5	-24	583
			1.0	-24	601
			1.5	-24	644
80	28.6	26	0.5	44	774
			0.5	10	744
			0.5	-24	718
			1.0	44	782
			1.0	10	745
			0.9	-24	705.3
			1.0	-24	704.8
			1.1	-24	705.3
			1.5	44	798
			1.5	10	763
			1.5	-24	716
80	50	47.4	0.5	44	795
			0.5	10	767
			0.5	-24	737
			1.0	44	821
			1.0	10	798
			1.0	-24	766
			1.5	44	837
			1.5	10	826
			1.5	-24	807
85	28.6	26	0.5	-24	796
			1.0	-24	765
			1.5	-24	758
			1.4	-24	758
			1.3	-24	758
88	28.6	26	1.5	-24	785

$T_v(t)$ °F	t EFPY(100 MW)	$t(HT)$	e	RT_{NDT_o} °F	$p(t)_{min}$ psi
90	28.6	26	0.5	44	869
			0.5	10	876
			0.5	-24	883
			1.0	44	841
			1.0	10	836
			1.0	-24	831
			1.5	44	832
			1.5	10	820
			1.5	-24	804
90	50	47.4	0.5	44	864
			0.5	10	871
			0.5	-24	878
			1.0	44	846
			1.0	10	843
			1.0	-24	839
			1.5	44	846
			1.5	10	842
			1.5	-24	835
95	28.6	26	1.5	44	852
			1.5	10	853
			1.5	-24	855
	39	36.4	1.5	44	851
			1.5	10	852
			1.5	-24	853
	50	47.4	1.5	44	850
			1.5	10	851
			1.5	-24	852

$T_v(t)$ °F	t EFPY(100 MW)	$t(HT)$	e	RT_{NDT_0} °F	$p(t)_{min}$ psi
100	28.6	26	0.5	44	985
			0.5	10	1037
			0.5	-24	1084
			1.0	44	913
			1.0	10	948
			1.0	-24	985
			1.5	44	874
			1.5	10	890
			1.5	-24	912
100	50	47.4	0.5	44	947
			0.5	10	997
			0.5	-24	1049
			1.0	44	877
			1.0	10	898
			1.0	-24	929
			1.5	44	856
			1.5	10	861
			1.5	-24	870
110	28.6	26	0.5	44	1126
			0.5	10	1235
			0.5	-24	1330
			1.0	44	1002
			1.0	10	1084
			1.0	-24	1174
			1.5	44	924
			1.5	10	976
			1.5	-24	1043

$T_v(t)$ °F	t EFPY(100 MW)	$t(HT)$	e	RT_{NDT_0} °F	$p(t)_{min}$ psi
110	50	47.4	0.5	44	1049
			0.5	10	1151
			0.5	-24	1259
			1.0	44	915
			1.0	10	965
			1.0	-24	1038
			1.5	44	868
			1.5	10	884
			1.5	-24	913
120	50	47.4	1.5	44	883

*Minimum values of $p(t)_{min}$.

Summary of minimum values of $p(t)_{min}$

$T_v(t)$	t	$t(HT)$	e	RT_{NDT_0}	$p(t)_{min}$
40	28.6	26	0.5	-24	308
50	28.6	26	0.5	-24	382
60	28.6	26	0.5	-24	472
70	28.6	26	0.5	-24	583
80	28.6	26	1.0	-24	705
85	28.6	26	1.4	-24	758
88	28.6	26	1.5	-24	785
90	28.6	26	1.5	-24	804
95	50	47.4	1.5	44	850
100	50	47.4	1.5	44	856
110	50	47.4	1.5	44	868
120	50	47.4	1.5	44	883

APPENDIX C

CALCULATED VALUES OF $p(t)$ vs t FOR $T_v(t) = 110^\circ\text{F}$,

$$\Delta t = 2.6 \text{ EFPY}(100 \text{ MW}), \dot{a} = 0$$

Equations (2)–(8) were used to calculate the time dependence of $p(t)$ for values of e and RT_{NDT_0} that result in the minimum value of $p(t)_{min}$ (see Appendix B). Calculations were made for $\Delta t = 2.6 \text{ EFPY}(100 \text{ MW})$ considering and also not considering the beneficial effect of hydro testing. The latter calculation was performed assuming a hydro test at 26 EFPY(100 MW) only. Results are presented below in Table C.1 and also in Fig. 2 of the text.

Table C.1. Calculated values of $p(t)$ vs t , with and without the beneficial effects of hydro testing, for $T_v(t) = 110^\circ\text{F}$, $p(HT) = 850 \text{ psi}$, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.6 \text{ EFPY}(100 \text{ MW})$, $t(HT) \text{ (initial)} = 26 \text{ EFPY}(100 \text{ MW})$, $e = 1.5$, $RT_{NDT_0} = 44^\circ\text{F}$, $\dot{a}=0$

t EFPY(100 MW)	$t(HT)$ EFPY(100 MW)	$T_v(t) - RT_{NDT}$ °F	$p(t)$ psi
26	26	-29	983
28.6	26	-39	924
28.6	28.6	-39	963
31.2	26	-48	876
31.2	28.6	-48	913
31.2	31.2	-48	946
33.8	26	-58	836
33.8	31.2	-58	904
33.8	33.8	-58	931
47.4	26	-107	715
47.4	44.8	-107	872
47.4	47.4	-107	882
50	26	-117	703
50	47.4	-117	868
50	50	-117	877

APPENDIX D

CALCULATED VALUES OF $p(t)$ vs t FOR $T_v(t) = 88^\circ\text{F}$,

$$\Delta t = 2.6 \text{ EFPY}(100 \text{ MW}), \dot{a} = 0$$

Equations (2)–(8) were used to calculate the time dependence of $p(t)$ for values of e and RT_{NDT_0} that result in the minimum value of $p(t)_{\min}$ (see Appendix B). Calculations were made for $\Delta t = 2.6 \text{ EFPY}(100 \text{ MW})$ considering and also not considering the beneficial effect of hydro testing. The latter calculation was performed assuming a hydro test at 26 EFPY(100 MW) only. Results are presented below in Table D.1 and also in Fig. 3 of the text.

Table D.1. Calculated values of $p(t)$ vs t , with and without the beneficial effects of hydro testing, for $T_v(t) = 88^\circ\text{F}$, $p(HT) = 850 \text{ psi}$, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.6 \text{ EFPY}(100 \text{ MW})$, $e = 1.5$, $RT_{NDT_0} = -24^\circ\text{F}$, $\dot{a} = 0$

t EFPY(100 MW)	$t(HT)$ EFPY(100 MW)	$T_v(t) - RT_{NDT}$ $^\circ\text{F}$	$p(t)$ psi
26	26	17	883
28.6	26	7	785
28.6	28.6	7	879
31.2	26	-2	704
31.2	28.6	-2	792
31.2	31.2	-2	876
33.8	26	-12	638
33.8	31.2	-12	798
33.8	33.8	-12	873
47.4	26	-61	437
47.4	44.8	-61	825
47.4	47.4	-61	861
50	26	-71	416
50	47.4	-71	829
50	50	-71	859

APPENDIX E

CALCULATED VALUES OF $p(t)$ vs t FOR $T_v(t) = 80^\circ\text{F}$,

$$\Delta t = 2.6 \text{ EFPY}(100 \text{ MW}), \dot{a} = 0$$

Equations (2)–(8) were used to calculate the time dependence of $p(t)$ for values of e and RT_{NDT_0} that result in the minimum value of $p(t)_{\min}$ (see Appendix B). Calculations were made for $\Delta t = 2.6 \text{ EFPY}(100 \text{ MW})$ considering and also not considering the beneficial effect of hydro testing. The latter calculation was performed assuming a hydro test at 26 EFPY(100 MW) only. Results are presented below in Table E.1 and also in Fig. 4 of the text.

Table E.1. Calculated values of $p(t)$ vs t , with and without the beneficial effects of hydro testing, for $T_v(t) = 80^\circ\text{F}$, $p(HT) = 850 \text{ psi}$, $T_v(HT) = 85^\circ\text{F}$, $\Delta t = 2.6 \text{ EFPY}(100 \text{ MW})$, $e = 0.5$ and 1.0 , $RT_{NDT_0} = -24^\circ\text{F}$, $\dot{a} = 0$

t EFPY(100 MW)	$t(HT)$ EFPY(100 MW)	$T_v(t) - RT_{NDT}$ $^\circ\text{F}$	$p(t)$, psi	
			$e = 1.0$	$e = 0.5$
26	26	41	782	
28.6	26		705	
28.6	28.6		785	
31.2	26	28	637	
31.2	28.6		712	720
31.2	31.2		789	
33.8	26	22	577	
33.8	31.2		720	722
33.8	33.8		792	
47.4	26	-12	362	
47.4	44.8		759	735
47.4	47.4		810	
50	26	-18	335	
50	47.4		766	737
50	50		814	

APPENDIX F
COMPARISON OF $p(t)$ vs e OBTAINED USING THE
ASME K_{Ic} AND K_{IR} CURVES

In Ref. 4, the ASME K_{IR} vs $T-RT_{NDT}$ curve² was used in the calculation of the hydro-test conditions. More recently,^{3,8} it was recognized that other "reasonable" curves might result in somewhat more stringent conditions, and eventually the ASME K_{Ic} curve was selected as the most reasonable. As indicated in Tables F1, 2, and 3, use of the K_{Ic} curve results in lower values of $p(t)_{min}$ than obtained using the K_{IR} curve. The two fracture-toughness curves used in the comparison calculations are as follows:

$$K_{Ic} = 33.2 + 20.73 \exp [0.02(T-RT_{NDT})],$$

$$K_{IR} = 26.8 + 12.44 \exp [0.0145(T-RT_{NDT})].$$

As discussed in the text, the values of $p(t)_{min}$ of concern are those that correspond to $0.5 \leq e \leq 1.5$, where e is the uncertainty factor applied to $\Delta NDTT$. These values of $p(t)_{min}$ are also given in Appendix B, and the corresponding times and temperatures listed in Appendix B are the ones that were used in this appendix for the comparison calculations.

Table F1. Values of $p(t)$ vs e obtained using the ASME K_{Ic} and K_{IR} curves, $T_v(t) = 40^\circ\text{F}$, $t = 28.6$ EFPY(100 MW), $t(\text{HT}) = 26.0$ EFPY(100 MW), $RT_{NDT_0} = -24^\circ\text{F}$, and $\dot{a} = 0$

e	$p(t)$, psi	
	K_{Ic} curve	K_{IR} curve
0.50	308	503
0.75	345	529
1.00	391	558
1.25	442	588
1.50	497	617
1.75	553	647
2.00	605	674

Table F2. Values of $p(t)$ vs e obtained using the ASME K_{Ic} and K_{IR} curves,
 $T_v(t) = 88^\circ\text{F}$, $t = 28.6$ EFPY(100 MW), $t(\text{HT}) = 26.0$ EFPY(100 MW),

$$RT_{NDT_0} = -24^\circ\text{F}, \text{ and } \dot{a} = 0$$

e	$p(t)$, psi	
	K_{Ic} curve	K_{IR} curve
0.50	847	848
0.75	822	834
1.00	804	824
1.25	791	816
1.50	785	812
1.75	784	809
2.00	787	809

Table F3. Values of $p(t)$ vs e obtained using the ASME K_{Ic} and K_{IR} curves, $T_v(t) = 110^\circ\text{F}$, $t = 50.0$ EFPY(100 MW), $t(\text{HT}) = 47.4$ EFPY(100 MW), $RT_{NDT_0} = 44^\circ\text{F}$, and $\dot{a} = 0$

e	$p(t)$, psi	
	K_{Ic} curve	K_{IR} curve
0.50	1049	967
0.75	967	927
1.00	915	900
1.25	885	881
1.50	868	869
1.75	859	861
2.00	854	857

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