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HFIR VESSEL
PRESSURE/TEMPERATURE
LIMITS CORRESPONDING TO THE
UPGRADE DESIGN

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Delta-21 Resources

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March 2000

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PREFACE

Pressure/temperature (P/T) limits were calculated for the HFIR pressure vessel for operation after a HFIR upgrade has been implemented. These P/T limits were published in ORNL/TM-1999/181.* After further consideration of the purpose and application of P/T limits and the way in which the integrity of the vessel is established, the authors concluded that an additional P/T curve should be included. The original report was published, and a revised report that includes the additional P/T curve was prepared. This report constitutes the revised edition and thus supersedes the original.

*R. D. Cheverton and J. W. Bryson, *HFIR Vessel Pressure/Temperature Limits Corresponding to the Upgrade Design*, ORNL/TM-1999/181, Oct. 6, 1999.

ABSTRACT

Pressure/temperature limits were calculated for the HFIR pressure vessel for a temperature range of 40 to 120°F. New values were necessary for the upgrade design of the reactor and were calculated using a probabilistic fracture mechanics approach that accounts for the success of periodic hydrostatic proof testing. The range of calculated pressures corresponding to the specific range of temperatures is 634 to 987 psi for the "pressure safety limit" and 564 to 895 psi for the "limiting conditions for operation."

HFIR VESSEL PRESSURE/TEMPERATURE LIMITS CORRESPONDING TO THE UPGRADE DESIGN

1. Introduction

An upgrade of HFIR that includes enlargement of the HB-2 and HB-4 beam tubes is to be implemented at ~ 22.6 EFPY(100 MW). Enlargement of the beam tubes results in higher dose rates and thus higher embrittlement rates in the two beam-tube nozzles and surrounding vessel areas[1]. By eliminating excessive conservatism in the vessel-integrity analytical models and modifying related criteria, it is still possible to achieve a vessel calculated lifetime of ~ 50 EFPY(100 MW)[1]. The same models and criteria must be used to calculate the vessel pressure/temperature (P/T) limits for "normal" operating conditions, and these calculations are the subject of this report.

Several methods of analysis are available for calculating the P/T limits. In Ref. 2, the ASME Code method[3] was used to calculate the P/T limits for temperatures less than 85°F, and for higher temperatures the deterministic equal-potential method[2], which accounts for the effect of successful hydrostatic proof testing, was used. When the expected life of the vessel was extended from 26 to 50 EFPY(100 MW)[4,5,6], the latter method was used to calculate the P/T limits for the full range of temperatures (40–120°F)[7].

The above methods tend to be very conservative because of the need to include large uncertainty factors. The large degree of conservatism was acceptable for the present design, as indicated in Refs. 2 and 4–7, but this is not the case for the upgrade design.

For the upgrade design, a probabilistic method that has the capability of accounting for the success of hydrostatic proof testing[1,8] was applied.

2. Definition of P/T Limits And Related Criteria

Two sets of P/T [pressure (p) vs temperature (T)] limits are to be derived. One set is to be used for the "pressure safety limits" (PSL)[9] and the other for the "limiting conditions for operation" (LCO)[9]. For both sets, the specified pressures are the pressure differentials for the vessel at the core horizontal midplane.

The PSL set must satisfy the following criteria:

- (1) For all specified vessel temperatures, the P/T-limit pressure must be such that the corresponding maximum best-estimate calculated conditional probability of vessel failure $[P(F|E)] \leq 1 \times 10^{-6}$.
- (2) For all temperatures, the pressure must be such that the best-estimate value of $P(F|E)$ for each hydro test is no less than that for all P/T sets Δt after a hydro test, where Δt is the specified maximum permissible time between hydro tests.

The use of best-estimate values of $P(F|E)$ in the calculation of the PSL P/T limits is justified because the probability of the LCO P/T limits being exceeded is very small ($< 2 \times 10^{-6} \text{y}^{-1}$)[10].

The LCO set of P/T limits must satisfy the first criterion for the PSL P/T limits and also one that is more restrictive because the LCO P/T limits represent permissible operating conditions. The LCO criteria are as follows:

- (1) For all specified vessel temperatures, the P/T-limit pressure must be such that the corresponding maximum best-estimate calculated conditional probability of vessel failure $[P(F|E)] \leq 1 \times 10^{-6}$.
- (2) For all temperatures, the pressure must be such that the best-estimate value of $P(F|E)$ for each hydro test is no less than that for all P/T sets 6 EFPY(100 MW) after a hydro test.

The use of a 6 EFPY(100 MW) interval for calculating the LCO P/T limits (criterion 2) accommodates substantial uncertainty in the $P(F|E)$ analysis because the maximum specified time between hydro tests is only 3 EFPY(100 MW)[1].

The reverse of the above process was used for establishing the maximum permissible time between hydro tests, in which case the emergency/faulted-condition loads ($p = 679$ psi, $T = 80^\circ\text{F}$) were used, and thus the degree of uncertainty accommodated in the calculation of the LCO P/T limits and the hydro-test frequency is essentially the same. The emergency/faulted-condition "P/T" set, however, falls slightly below the LCO P/T curve because the maximum permissible time between hydro tests was calculated to be 6.5 rather than 6.0 EFPY(100 MW)[1].

The hydro-test/P/T-limit equivalency criterion specified for the LCO analysis was included because in order for the hydro test to be a valid means of establishing vessel

integrity, the probability of failure of the vessel during a hydro test, regardless of the value, must be greater than that for all operating conditions during the time between that test and the next.

The P/T limits are a function of the time period over which the limits apply, and thus more than one function could be calculated and specified. Reactor Operations Division personnel specified that a single P/T curve be used for operation after the upgrade design is implemented[11], and the P/T limits are calculated accordingly.

3. Method of Analysis

The probabilistic method of analysis for evaluating vessel integrity for HFIR is discussed in Refs. 1, 6, and 8, and typical results are included in Fig. 1, which includes the conditional probability of vessel failure $[P(F|E)]$ for the specified hydro-test pressure ($p = 900$ psi) and temperature ($T = 85^\circ\text{F}$) with and without the effect of hydro testing included in the analysis. The curve reflecting the beneficial effect of hydro testing is obtained from[8]

$$P'(F|E)(HT)_t = P(F|E)(HT)_t - P(F|E)(HT)_{t(HT)}, \quad (1)$$

where $P(F|E)(HT)_t$ is the value of $P(F|E)$ for the hydro test loading conditions (pressure and temperature) at time t in the life of the vessel, $P'(F|E)(HT)_t$ is the value of $P(F|E)(HT)_t$ corrected for the beneficial effect of hydro testing, $t(HT)$ is the time of a hydro test, and $t(HT) \leq t$. Immediately following a hydro test, $P'(F|E)(HT) = 0$, if the vessel does not fail during the test. The probability increases thereafter because of continuing radiation-induced embrittlement and flaw growth but returns to zero at the

Fig. 1. $P(F|E)(HT)$ vs time with and without the beneficial effect of hydro testing considered.

conclusion of the next hydro test, resulting in the "sawtooth" shape of the partial lower curve in Fig. 1.

The values of $P'(F|E)$ of primary concern are the values just prior to the time of a hydro test. These values are obtained from

$$P'(F|E)(HT)_{t(HT)+\Delta t} = P(F|E)(HT)_{t(HT)+\Delta t} - P(F|E)(HT)_{t(HT)}, \quad (2)$$

where Δt is the time between hydro tests. These values of $P'(F|E)(HT)$, henceforth referred to as $P'(F|E)(HT)_{max}$, are the data points plotted in Fig. 1 (lower curve).

As indicated in Fig. 1, $P'(F|E)(HT)_{max}$ varies with time and is dependent on the values of Δt . The largest of these $P'(F|E)(HT)_{max}$ values, referred to as $P'(F|E)(HT)_{max,p}$, must satisfy criteria specified in Sect. 2 and Ref. 1 and if too large could be reduced by reducing Δt .

Values of $P'(F|E)_t$ for "normal" operating conditions are obtained from

$$P'(F|E)_t = P(F|E)_t - P(F|E)(HT)_{t(HT)}, \quad (3)$$

where $t \geq t(HT)$. It is apparent that for $t = t(HT)$, Eq. (3), depending on the values of p and T for "normal" operation, can yield

$$P'(F|E)_{t(HT)} < 0,$$

which means that for some period of time after the hydro test the probability of failure is zero but will eventually increase above zero if t is large enough. If not, $P'(F|E)_t$ will remain zero.

Values of $P'(F|E)_{\max}$ are obtained from

$$P'(F|E)_{\max} = P(F|E)_{t(HT)+\Delta t} - P(F|E)(HT)_{t(HT)} \quad (4)$$

For a given set of Δt values, such as those specified in Ref. 1, and a given value of T , there is a value of p that will result in $P'(F|E)_{\max,p}$ equal to the maximum permissible value specified in Sect. 2.

Values of $P(F|E)$ are calculated numerically for specified values of p , T , and t . To obtain the differences in Eqs. (2) and (4) with sufficient accuracy, the numerical results for each of the specified values of p and T , including those for the hydro test, are fitted to the equation

$$P(F|E) = \exp (M_0 + M_1 t + M_2 t^2 + M_3 t^3), \quad (5)$$

where $M_0 \dots M_3$ are coefficients obtained by a least-square fit. The curve so obtained for the hydro test is the upper curve in Fig. 1, and a family of curves so obtained for $T = 80^\circ\text{F}$ is included in Fig. 2, which also includes the numerically calculated data points. [Tabulated values of $P(F|E)$ are included in Table A1 (Appendix A) for the hydro test and in Tables A2 and A3 for $T = 80^\circ\text{F}$. The corresponding coefficients for Eq. (5) are included in Table A4.]

After developing Eq. (5) for all values of p and T , including the hydro test, Eqs. (4) and (5) are used to calculate sets of $P'(F|E)_{\max}$ for the hydro test and for the other values of p and T . [Values of $P'(F|E)_{\max}$ for the hydro test are included in Fig. 1 and Table A1, and a typical set for "normal" operation is included in Fig. 3 for $T = 80^\circ\text{F}$.] The corresponding values of $P'(F|E)_{\max,p}$ and p are fitted to a polynomial and the value of p corresponding to $P'(F|E) = 1 \times 10^{-6}$ calculated [a typical curve of $P'(F|E)_{\max,p}$ vs p for $T = 80^\circ\text{F}$ is included in Fig. 4].

Fig. 2. $\text{Ln } P(F|E)$ vs t for $T = 80^\circ\text{F}$ and $p = 500, 700, 900, 1000$ psi.

Fig. 3. $P'(F|E)_{\max}$ vs t for $T = 80^\circ\text{F}$ and $p = 500, 700, 900, 1000$ psi.

Fig. 4. $P'(F|E)_{\max,p}$ vs p for $T = 80^\circ\text{F}$.

The second PSL criterion states that

$$P(F|E)(P|T)[t = t(HT) + \Delta t] \leq P(F|E)(HT)[t = t(HT)], \quad (6)$$

For each temperature, the pressure that satisfies Eq. (6) is dependent on the value of $t(HT)$, and the smallest of these pressures must be used for the P/T limits. To obtain the pressures, the $P(F|E) = f(t)$ equations implied by Table A4 were used to calculate $P(F|E)$ for several values of $t(HT) + \Delta t$ and several values of p for a specified value of T . For each value of $t(HT) + \Delta t$, a polynomial equation was fitted to the calculated $P(F|E)$ vs p data, and then the value of p corresponding to $P(F|E)(HT) [t = t(HT)]$ was calculated. The minimum value of p so derived for each specified temperature was compared with the corresponding value based on the first criterion, and the minimum of these two and the corresponding temperature constituted a PSL P/T limit.

For the LCO P/T limits, the first criterion is the same as the first criterion for the PSL P/T limits, and thus the analytical procedures and results are the same.

The second LCO criterion states that

$$P(F|E)(P|T)[t = t(HT) + 6 \text{ EFY}(100\text{MW})] \leq P(F|E)(HT)[t = t(HT)] \quad (7)$$

The calculational procedure is the same as stated above for the PSL second criterion, except that the values of $P(F|E)$ were calculated for $t(HT) + 6 \text{ EFY}(100 \text{ MW})$ instead of $t(HT) + \Delta t$.

The LCO criterion is illustrated graphically in Fig. 5, which shows that the uncertainty factor applied to Δt accommodates an uncertainty in the calculated value of $P(F|E)$ for

Fig. 5. $P(F|E)(HT)$ and $P(F|E)(P/T)$ vs t , indicating method for calculating LCO P/T limits.

the actual time of the subsequent hydro test [1, 2, or 3 EFPY(100 MW)]. For the PSL second criterion, the uncertainty factor is not applied.

4. Input for $P(F|E)$ Analysis

With the exception of vessel pressure and temperature, input for the calculation of $P(F|E)$ is the same as that included in Ref. 1. As discussed in Ref. 7, the range of vessel temperatures of interest is 40–120°F. Vessel pressure is the dependent variable in the final analysis, but in the calculation of $P(F|E)$ a range of pressures must be considered to determine $P(F|E)_{\max,p} = f(p)$ for a given temperature, as illustrated in Fig. 4. The range of pressures that must be considered is determined by trial, and the range finally used was 500 to 1000 psi.

The values of Δt and thus $t(HT)$ used are those specified in Ref. 1. For the first and second periods, beginning at 22.6 EFPY(100 MW), $\Delta t = 1$ and 2 EFPY(100 MW), respectively, and thereafter, $\Delta t = 3$ EFPY(100 MW). Results of the P/T analysis indicated no reason to change these values.

5. P/T Limits

Values of p corresponding to $T = 40, 60, 80, 100,$ and 120°F for both criteria for the PSL and LCO limits are included in Table 1. It is apparent that the second criterion for both PSL and LCO result in the smaller values of p . Polynomials were fitted to these values to obtain equations for $p = f(T)$, and using these equations values of p were calculated for 5°F temperature increments from 40 to 120°F (Table 2). The PSL and LCO P/T curves and the corresponding polynomial coefficients are included in Fig. 6.

Table 1. Calculated pressures corresponding to the PSL and LCO criteria

Temp °F	Pressure psi			
	PSL		LCO	
	(1) ^a	(2) ^b	(1) ^a	(2) ^b
40	654	634	654	564
60	714	700	714	616
80	802	784	802	687
100	896	888	896	785
120	987	987	987	895

^aCompliance with first criterion.^bCompliance with second criterion.

**Table 2. HFIR vessel PSL and LCO P/T limits (p vs T)
for operation after implementation of the
upgrade design at ~ 22.6 EFPY(100 MW)**

Temp °F	p , psi	
	PSL ^a	LCO ^b
40	634	564
45	650	576
50	666	588
55	682	602
60	700	616
65	719	631
70	739	648
75	761	667
80	784	687
85	809	709
90	834	733
95	861	759
100	888	785
105	915	813
110	941	840
115	965	868
120	987	895

^aP/T curve based on PSL criteria.

^bP/T curve based on LCO criteria.

Fig. 6. HFIR vessel PSL and LCO P/T limits for operation after implementation of the upgrade design at ~ 22.6 EFPY(100 MW).

6. Summary

The pressure/temperature (P/T) limits were calculated for the HFIR vessel for operation following implementation of the upgrade design scheduled for ~ 22.6 EFPY(100 MW). To accommodate the large increase in dose rate associated with the upgrade, a probabilistic approach that includes the beneficial effect of the periodic hydrostatic proof test was used. The range of vessel temperatures considered was 40 to 120°F, and the corresponding values of the limiting pressures for the "pressure safety limits" are 634 and 987 psi, and for the "limiting conditions for operation" they are 564 and 895 psi.

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APPENDIX A

TABLES AND FIGURES PERTAINING TO $P(F|E)$ ANALYSIS

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Comments Regarding Tables and Figures

1. The values of $P(F|E)$ included in the first column of Table A1 and in Table A2 were calculated using numerical analysis techniques[1] and constitute the "raw" data for this report. The data in Table A3 are the natural log of the data in Table A2.
2. Curve fitting to the raw data was used to obtain the desired accuracy for the differences indicated by Eqs. (1), (2), (3), and (4). To improve the curve fitting, the raw data for $T = 80, 100$, and $120^\circ F$ were truncated as indicated in Figs. A1 and A2 and as reflected in later tables and figures. The truncation did not impact the calculated P/T limits.

Table A1. $P(F|E)(HT)$ and $P'(F|E)(HT)$ vs t ; $p = 900$ psi, $T = 85^\circ\text{F}$

t	$P(F E)(HT)^a$	$P(F E)(HT)^b$	$P'(F E)(HT)_{\max}^c$
22.6	2.47E-6	2.26E-6	
23.6		3.07E-6	8.16E-7
25.0	4.02E-6		
25.6		5.37E-6	2.30E-6
27.5	8.21E-6		
28.6		1.08E-5	5.45E-6
30.0	1.51E-5		
31.6		1.88E-5	7.99E-6
34.6		2.87E-5	9.93E-6
35.0	3.15E-5		
37.6		3.93E-5	1.06E-5 ^d
40.0	4.71E-5		
40.6		4.92E-5	9.84E-6
43.6		5.72E-5	8.02E-6
45.0	5.86E-5		
46.6		6.31E-5	5.88E-6
49.6		6.72E-5	4.14E-6
50.0	6.75E-5		
55.0	7.41E-5		

- a. Numerically calculated values (equal to those in Ref. 1).
b. Calculated using Eq. (5) with the coefficients in Table A.4.
c. Calculated using Eqs. (2) and (5).
d. $P'(F|E)(HT)_{\max,p}$.

Table A2. $P(F|E)$ vs t [EFPY(100 MW)] and p (psi) for $T = 40, 60, 80, 100, 120^\circ\text{F}$

$P(F|E)$, $T = 40^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=650
0	22.600	2.6000e-07	3.2500e-06	1.8005e-05	3.4231e-05	1.0955e-06	8.2875e-06	1.9225e-06
1	25.000	3.8400e-07	5.1295e-06	2.7239e-05	5.0322e-05	1.6200e-06	1.2737e-05	2.9540e-06
2	27.500	7.4200e-07	8.6250e-06	4.0528e-05	7.0977e-05	2.9460e-06	2.0212e-05	5.2390e-06
3	30.000	1.1955e-06	1.2915e-05	5.2818e-05	9.1615e-05	4.6275e-06	2.7938e-05	7.8075e-06
4	35.000	2.0880e-06	2.0157e-05	7.4417e-05	0.00012341	7.7160e-06	4.2186e-05	1.2776e-05
5	40.000	2.9625e-06	2.4640e-05	8.9026e-05	0.00014292	1.0397e-05	5.0311e-05	1.6543e-05
6	45.000	3.6155e-06	2.9530e-05	0.00010051	0.00016331	1.2042e-05	5.9023e-05	1.8832e-05
7	50.000	4.0605e-06	3.1325e-05	0.00010885	0.00017646	1.3142e-05	6.3773e-05	2.1132e-05
8	55.000	4.3890e-06	3.4603e-05	0.00011653	0.00018563	1.4326e-05	6.7358e-05	2.2738e-05

$P(F|E)$, $T = 60^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=725	P=715
0	22.600	1.0250e-07	1.4305e-06	8.2455e-06	1.6707e-05	4.1500e-07	3.6690e-06	1.8020e-06	1.6470e-06
1	25.000	1.5900e-07	2.2175e-06	1.2944e-05	2.5644e-05	6.7550e-07	5.9345e-06	2.8670e-06	2.5920e-06
2	27.500	2.9800e-07	4.3485e-06	2.2052e-05	4.0609e-05	1.4005e-06	1.0565e-05	5.5340e-06	5.0610e-06
3	30.000	6.0900e-07	7.1195e-06	3.2545e-05	5.7448e-05	2.4670e-06	1.6919e-05	9.2140e-06	8.3585e-06
4	35.000	1.3840e-06	1.3843e-05	5.3782e-05	8.7170e-05	5.3615e-06	2.9287e-05	1.6650e-05	1.5836e-05
5	40.000	2.2320e-06	1.9258e-05	6.9808e-05	0.00011000	7.7070e-06	3.8967e-05	2.3484e-05	2.1737e-05
6	45.000	2.7850e-06	2.3502e-05	8.1571e-05	0.00012648	9.7270e-06	4.5835e-05	2.8541e-05	2.5916e-05
7	50.000	3.2380e-06	2.6371e-05	9.0109e-05	0.00014254	1.0714e-05	5.0683e-05	3.1115e-05	2.9011e-05
8	55.000	3.5280e-06	2.8422e-05	9.8487e-05	0.00015672	1.2019e-05	5.5439e-05	3.4475e-05	3.2382e-05

Table A2 (cont'd)

P(F|E), T = 80°F

	EFPY	P=500	P=700	P=900	P=1000	P=800	P=800	P=850
0	22.600	3.3000e-08	4.7050e-07	3.2275e-06	6.7740e-06	1.3050e-07	1.3425e-06	2.1405e-06
1	25.000	4.8500e-08	7.7350e-07	5.2635e-06	1.0657e-05	2.3700e-07	2.2085e-06	3.4560e-06
2	27.500	1.0950e-07	1.8325e-06	1.0354e-05	1.9680e-05	5.3400e-07	4.7100e-06	7.0685e-06
3	30.000	2.6950e-07	3.6800e-06	1.7563e-05	3.2532e-05	1.1765e-06	8.7200e-06	1.3006e-05
4	35.000	8.1950e-07	9.0070e-06	3.4077e-05	5.9529e-05	3.1340e-06	1.8999e-05	2.6838e-05
5	40.000	1.5560e-06	1.3984e-05	5.1482e-05	8.0030e-05	5.4660e-06	2.8947e-05	3.7916e-05
6	45.000	2.0430e-06	1.7104e-05	6.2025e-05	9.9964e-05	7.3420e-06	3.5830e-05	4.7560e-05
7	50.000	2.6495e-06	2.0994e-05	7.0451e-05	0.00011352	8.8170e-06	4.2451e-05	5.4701e-05
8	55.000	3.0695e-06	2.4119e-05	8.0534e-05	0.00012507	1.0020e-05	4.5208e-05	6.1423e-05

P(F|E), T = 100°F

	EFPY	P=500	P=700	P=900	P=1000	P=800	P=950	P=880	P=890
0	22.600	9.5000e-09	1.1950e-07	9.7000e-07	2.2115e-06	3.6750e-07	1.4755e-06	8.3100e-07	9.0100e-07
1	25.000	1.2000e-08	2.3300e-07	1.6500e-06	3.6725e-06	6.6050e-07	2.4880e-06	1.3950e-06	1.5130e-06
2	27.500	2.7000e-08	6.0100e-07	3.9390e-06	7.8910e-06	1.7010e-06	5.7150e-06	3.3460e-06	3.6585e-06
3	30.000	9.8500e-08	1.5450e-06	8.2995e-06	1.5822e-05	3.9935e-06	1.1639e-05	7.2765e-06	7.7845e-06
4	35.000	4.1000e-07	5.1290e-06	2.2166e-05	3.6874e-05	1.1700e-05	2.8795e-05	1.9294e-05	2.0636e-05
5	40.000	9.8750e-07	9.8280e-06	3.4918e-05	5.6964e-05	1.9692e-05	4.4221e-05	3.2022e-05	3.3202e-05
6	45.000	1.4780e-06	1.3063e-05	4.6579e-05	7.4206e-05	2.6817e-05	6.0944e-05	4.2363e-05	4.4370e-05
7	50.000	2.0640e-06	1.6887e-05	5.5649e-05	8.7954e-05	3.2169e-05	7.1011e-05	5.1296e-05	5.2756e-05
8	55.000	2.4950e-06	1.9717e-05	6.3386e-05	9.8907e-05	3.6919e-05	7.9243e-05	5.7839e-05	6.0004e-05

Table A2 (cont'd)

$P(F|E)$, $T = 120^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=933
0	22.600	1.0000e-09	2.5000e-08	2.1800e-07	5.2550e-07	2.8650e-07
1	25.000	2.0000e-09	4.7000e-08	4.1950e-07	9.5600e-07	5.5850e-07
2	27.500	6.0000e-09	1.4750e-07	1.1895e-06	2.5620e-06	1.5780e-06
3	30.000	3.0500e-08	5.3550e-07	3.3790e-06	6.4980e-06	4.2050e-06
4	35.000	1.8350e-07	2.5980e-06	1.2474e-05	2.0797e-05	1.4594e-05
5	40.000	5.5800e-07	6.0670e-06	2.2346e-05	3.8461e-05	2.7889e-05
6	45.000	1.0195e-06	9.8465e-06	3.2823e-05	5.4989e-05	4.1005e-05
7	50.000	1.5350e-06	1.2821e-05	4.1832e-05	6.7244e-05	4.9001e-05
8	55.000	1.9440e-06	1.5792e-05	5.0043e-05	7.9871e-05	5.8447e-05

	EFPY	P=967	P=990	P=980	P=983	P=986
0	22.600	3.9600e-07	4.8250e-07	4.4600e-07	4.5200e-07	4.6650e-07
1	25.000	7.3650e-07	8.8200e-07	8.1900e-07	8.4000e-07	8.5800e-07
2	27.500	2.0230e-06	2.4025e-06	2.2410e-06	2.2830e-06	2.3310e-06
3	30.000	5.2780e-06	6.1410e-06	5.7715e-06	5.8920e-06	6.0365e-06
4	35.000	1.7958e-05	2.0168e-05	1.9130e-05	1.9316e-05	1.9515e-05
5	40.000	3.3382e-05	3.7224e-05	3.5390e-05	3.6606e-05	3.6891e-05
6	45.000	4.6161e-05	5.2675e-05	4.9919e-05	5.0156e-05	5.2684e-05
7	50.000	5.8186e-05	6.7195e-05	6.1178e-05	6.2578e-05	6.2839e-05
8	55.000	6.7341e-05	7.3809e-05	7.1838e-05	7.3082e-05	7.4094e-05

 Fig. A1. $P(F|E)$ vs t and p for $T = 40, 60, 80, 100, 120^\circ\text{F}$.

Fig. A1 (cont'd).

Fig. A1 (cont'd).

Table A3. $\ln P(F|E)$ vs t [EFPY(100 MW)] and p (psi) for $T = 40, 60, 80, 100, 120^\circ\text{F}$

$\ln P(F|E), T = 40^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=650
0	22.600	-15.163	-12.637	-10.925	-10.282	-13.724	-11.701	-13.162
1	25.000	-14.773	-12.181	-10.511	-9.8971	-13.333	-11.271	-12.732
2	27.500	-14.114	-11.661	-10.114	-9.5532	-12.735	-10.809	-12.159
3	30.000	-13.637	-11.257	-9.8486	-9.2979	-12.283	-10.486	-11.760
4	35.000	-13.079	-10.812	-9.5058	-9.0000	-11.772	-10.073	-11.268
5	40.000	-12.729	-10.611	-9.3266	-8.8532	-11.474	-9.8973	-11.010
6	45.000	-12.530	-10.430	-9.2052	-8.7199	-11.327	-9.7376	-10.880
7	50.000	-12.414	-10.371	-9.1255	-8.6424	-11.240	-9.6602	-10.765
8	55.000	-12.336	-10.272	-9.0573	-8.5917	-11.153	-9.6055	-10.691

$\ln P(F|E), T = 60^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=725	P=715
0	22.600	-16.093	-13.457	-11.706	-11.000	-14.695	-12.516	-13.227	-13.317
1	25.000	-15.654	-13.019	-11.255	-10.571	-14.208	-12.035	-12.762	-12.863
2	27.500	-15.026	-12.346	-10.722	-10.112	-13.479	-11.458	-12.105	-12.194
3	30.000	-14.311	-11.853	-10.333	-9.7646	-12.913	-10.987	-11.595	-11.692
4	35.000	-13.491	-11.188	-9.8306	-9.3477	-12.136	-10.438	-11.003	-11.053
5	40.000	-13.013	-10.858	-9.5698	-9.1150	-11.773	-10.153	-10.659	-10.737
6	45.000	-12.791	-10.658	-9.4140	-8.9754	-11.541	-9.9905	-10.464	-10.561
7	50.000	-12.641	-10.543	-9.3145	-8.8559	-11.444	-9.8899	-10.378	-10.448
8	55.000	-12.555	-10.468	-9.2256	-8.7610	-11.329	-9.8002	-10.275	-10.338

Table A3 (cont'd)

Ln P(F|E), T = 80°F

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=850
0	22.600	-17.227	-14.569	-12.644	-11.902	-15.852	-13.521	-13.054
1	25.000	-16.842	-14.072	-12.155	-11.449	-15.255	-13.023	-12.575
2	27.500	-16.027	-13.210	-11.478	-10.836	-14.443	-12.266	-11.860
3	30.000	-15.127	-12.513	-10.950	-10.333	-13.653	-11.650	-11.250
4	35.000	-14.015	-11.618	-10.287	-9.7290	-12.673	-10.871	-10.526
5	40.000	-13.373	-11.178	-9.8743	-9.4331	-12.117	-10.450	-10.180
6	45.000	-13.101	-10.976	-9.6880	-9.2107	-11.822	-10.237	-9.9535
7	50.000	-12.841	-10.771	-9.5606	-9.0835	-11.639	-10.067	-9.8136
8	55.000	-12.694	-10.633	-9.4268	-8.9866	-11.511	-10.004	-9.6977

Ln P(F|E), T = 100°F

	EFPY	P=500	P=700	P=900	P=1000	P=800	P=950	P=880	P=890
0	22.600	-18.472	-15.940	-13.846	-13.022	-14.817	-13.427	-14.001	-13.920
1	25.000	-18.238	-15.272	-13.315	-12.515	-14.230	-12.904	-13.483	-13.401
2	27.500	-17.427	-14.325	-12.445	-11.750	-13.284	-12.072	-12.608	-12.518
3	30.000	-16.133	-13.380	-11.699	-11.054	-12.431	-11.361	-11.831	-11.763
4	35.000	-14.707	-12.181	-10.717	-10.208	-11.356	-10.455	-10.856	-10.788
5	40.000	-13.828	-11.530	-10.263	-9.7731	-10.835	-10.026	-10.349	-10.313
6	45.000	-13.425	-11.246	-9.9744	-9.5087	-10.526	-9.7056	-10.069	-10.023
7	50.000	-13.091	-10.989	-9.7964	-9.3387	-10.345	-9.5527	-9.8779	-9.8498
8	55.000	-12.901	-10.834	-9.6663	-9.2213	-10.207	-9.4430	-9.7578	-9.7211

Table A3 (cont'd)

$\ln P(F|E)$, $T = 120^\circ\text{F}$

	EFY	P=500	P=700	P=900	P=1000	P=933
0	22.600	-20.723	-17.504	-15.339	-14.459	-15.066
1	25.000	-20.030	-16.873	-14.684	-13.861	-14.398
2	27.500	-18.932	-15.729	-13.642	-12.875	-13.359
3	30.000	-17.306	-14.440	-12.598	-11.944	-12.379
4	35.000	-15.511	-12.861	-11.292	-10.781	-11.135
5	40.000	-14.399	-12.013	-10.709	-10.166	-10.487
6	45.000	-13.796	-11.528	-10.324	-9.8084	-10.102
7	50.000	-13.387	-11.264	-10.082	-9.6072	-9.9237
8	55.000	-13.151	-11.056	-9.9026	-9.4351	-9.7474

	EFY	P=967	P=990	P=980	P=983	P=986
0	22.600	-14.742	-14.544	-14.623	-14.610	-14.578
1	25.000	-14.121	-13.941	-14.015	-13.990	-13.969
2	27.500	-13.111	-12.939	-13.009	-12.990	-12.969
3	30.000	-12.152	-12.001	-12.063	-12.042	-12.018
4	35.000	-10.927	-10.811	-10.864	-10.855	-10.844
5	40.000	-10.308	-10.199	-10.249	-10.215	-10.208
6	45.000	-9.9834	-9.8514	-9.9051	-9.9004	-9.8512
7	50.000	-9.7519	-9.6079	-9.7017	-9.6791	-9.6749
8	55.000	-9.6057	-9.5140	-9.5411	-9.5239	-9.5102

Fig. A2. $\ln P(F|E)$ vs t and p for $T = 40, 60, 80, 100, 120^\circ\text{F}$.

Fig. A2 (cont'd).

Fig. A2 (cont'd).

Table A4. Polynomial coefficients^a for $\ln P(F|E)(HT) = f(t)$ and for $\ln P(F|E) = f(t)$ for several values of p and T

Polynomial coefficients, $\ln P(F|E)(HT)$, $T = 85^\circ\text{F}$

	Pressure (psi)	M0	M1	M2	M3
0	900.00	-26.816	0.96321	-0.018209	0.00011662

Polynomial coefficients, $\ln P(F|E)$, $T = 40^\circ\text{F}$

	Pressure (psi)	M0	M1	M2	M3
0	500.00	-26.937	0.82182	-0.015769	0.00010279
1	700.00	-24.505	0.86683	-0.018035	0.00012695
2	900.00	-20.267	0.68825	-0.014478	0.00010318
3	1000.0	-18.659	0.61736	-0.012983	9.2578e-05
4	600.00	-25.495	0.83644	-0.016614	0.00011175
5	800.00	-22.040	0.75377	-0.015587	0.00010905
6	650.00	-25.042	0.85748	-0.017491	0.00012085

Polynomial coefficients, $\ln P(F|E)$, $T = 60^\circ\text{F}$

	Pressure (psi)	M0	M1	M2	M3
0	500.00	-28.275	0.79995	-0.013471	7.4796e-05
1	700.00	-26.096	0.88169	-0.016888	0.00010948
2	900.00	-23.119	0.82038	-0.016584	0.00011386
3	1000.0	-21.397	0.75612	-0.015607	0.00010982
4	600.00	-32.829	1.2903	-0.026341	0.00018166
5	800.00	-25.129	0.90374	-0.018178	0.00012390
6	725.00	-29.109	1.1404	-0.023511	0.00016375
7	715.00	-29.996	1.2026	-0.025065	0.00017643

Table A4 (cont'd)

Polynomial coefficients, $\ln P(F|E)$, $T = 80^\circ\text{F}$

	Pressure (psi)	M0	M1	M2	M3
0	500.00	-40.170	1.5720	-0.030740	0.00020440
1	700.00	-37.079	1.6101	-0.033447	0.00023495
2	900.00	-25.967	0.93362	-0.018044	0.00011880
3	1000.0	-24.324	0.87632	-0.017158	0.00011447
4	600.00	-36.819	1.4610	-0.028765	0.00019217
5	800.00	-31.892	1.2988	-0.026196	0.00017862
6	850.00	-31.597	1.3288	-0.027513	0.00019268

Polynomial coefficients, $\ln P(F|E)$, $T = 100^\circ\text{F}$

	Pressure (psi)	M0	M1	M2	M3
0	500.00	-54.301	2.4394	-0.049063	0.00033464
1	700.00	-44.102	1.9786	-0.040114	0.00027533
2	900.00	-36.299	1.5870	-0.032246	0.00022183
3	1000.0	-32.782	1.3955	-0.028227	0.00019360
4	800.00	-39.707	1.7563	-0.035593	0.00024396
5	950.00	-34.093	1.4562	-0.029326	0.00020008
6	880.00	-36.464	1.5796	-0.031847	0.00021746
7	890.00	-36.487	1.5924	-0.032288	0.00022163

Polynomial coefficients, $\ln P(F|E)$, $T = 120^\circ\text{F}$

	Pressure (psi)	M0	M1	M2	M3
0	500.00	-63.278	2.9061	-0.057580	0.00038771
1	700.00	-54.373	2.5518	-0.051198	0.00034777
2	900.00	-46.542	2.2018	-0.045107	0.00031264
3	1000.0	-41.209	1.8740	-0.037716	0.00025729
4	933.00	-42.259	1.8995	-0.037798	0.00025474
5	967.00	-41.728	1.8889	-0.037832	0.00025656
6	990.00	-40.180	1.7830	-0.035242	0.00023579
7	980.00	-41.250	1.8636	-0.037318	0.00025310
8	983.00	-41.131	1.8563	-0.037148	0.00025180
9	986.00	-40.799	1.8307	-0.036473	0.00024605
10	995.00	-39.859	1.7733	-0.035322	0.00023888

*The indicated polynomial equations should not be used for extrapolation. Limits of applicability are indicated by the data in the tables and figures.

Table A5. $P'(F|E)_{\max}$ vs t and p for $T = 40, 60, 80, 100, 120^\circ\text{F}$

$P'(F|E)_{\max}, T = 40^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=650
0	23.600	-1.9400e-06	1.7600e-06	1.9600e-05	3.8700e-05	-9.3900e-07	7.8800e-06	9.9000e-08
1	25.600	-2.5700e-06	3.0500e-06	2.7200e-05	5.1800e-05	-1.0200e-06	1.1600e-05	5.5900e-07
2	28.600	-4.4800e-06	4.8000e-06	3.9500e-05	7.2800e-05	-1.8200e-06	1.7600e-05	7.8700e-07
3	31.600	-9.4100e-06	4.0500e-06	4.9300e-05	9.0900e-05	-5.4100e-06	2.1400e-05	-1.6300e-06
4	34.600	-1.6800e-05	6.9900e-07	5.5100e-05	0.00010400	-1.1400e-05	2.2200e-05	-6.5200e-06
5	37.600	-2.6200e-05	-5.2900e-06	5.6300e-05	0.00011000	-1.9500e-05	1.9600e-05	-1.3700e-05
6	40.600	-3.6200e-05	-1.3000e-05	5.3600e-05	0.00011200	-2.8600e-05	1.4400e-05	-2.2200e-05
7	43.600	-4.5700e-05	-2.0900e-05	4.8900e-05	0.00010900	-3.7400e-05	8.1000e-06	-3.0500e-05
8	46.600	-5.3400e-05	-2.7600e-05	4.4500e-05	0.00010700	-4.4700e-05	2.4400e-06	-3.7500e-05
9	49.600	-5.9100e-05	-3.2300e-05	4.2300e-05	0.00010700	-5.0000e-05	-1.3600e-06	-4.2600e-05

$P'(F|E)_{\max}, T = 60^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=725	P=715
0	23.600	-2.1300e-06	-5.0500e-07	7.8900e-06	1.8100e-05	-1.8300e-06	2.3100e-06	-2.8700e-07	-5.0600e-07
1	25.600	-2.8600e-06	-1.8700e-07	1.2400e-05	2.6600e-05	-2.2500e-06	4.2300e-06	3.8300e-07	5.2700e-08
2	28.600	-4.9400e-06	1.3300e-08	2.0600e-05	4.1500e-05	-3.5600e-06	7.6100e-06	1.4600e-06	9.2100e-07
3	31.600	-1.0100e-05	-2.0400e-06	2.7800e-05	5.5400e-05	-7.5300e-06	9.3200e-06	5.7500e-07	-2.2800e-07
4	34.600	-1.7600e-05	-6.0800e-06	3.2800e-05	6.6400e-05	-1.3700e-05	9.0300e-06	-2.3500e-06	-3.4600e-06
5	37.600	-2.7000e-05	-1.2000e-05	3.4700e-05	7.2900e-05	-2.1900e-05	6.2200e-06	-7.5900e-06	-9.0500e-06
6	40.600	-3.7100e-05	-1.9100e-05	3.3400e-05	7.5200e-05	-3.1100e-05	1.3600e-06	-1.4500e-05	-1.6300e-05
7	43.600	-4.6400e-05	-2.6300e-05	3.0400e-05	7.4700e-05	-3.9900e-05	-4.3400e-06	-2.1900e-05	-2.3900e-05
8	46.600	-5.4100e-05	-3.2400e-05	2.7200e-05	7.3800e-05	-4.7300e-05	-9.5400e-06	-2.8300e-05	-3.0500e-05
9	49.600	-5.9800e-05	-3.6900e-05	2.5300e-05	7.4900e-05	-5.2600e-05	-1.3200e-05	-3.2800e-05	-3.5100e-05

Table A5 (cont'd)

 $P'(F|E)_{\max}, T = 80^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=600	P=800	P=850
0	23.600			1.7700e-06	6.0800e-06		-8.6100e-07	-5.9200e-08
1	25.600	-3.0100e-06	-2.1000e-06	3.7300e-06	1.0400e-05	-2.7800e-06	-3.4900e-07	1.1400e-06
2	28.600	-5.2000e-06	-2.8500e-06	7.7000e-06	1.9100e-05	-4.5900e-06	8.0500e-07	3.8900e-06
3	31.600	-1.0400e-05	-5.7100e-06	1.1000e-05	2.8100e-05	-9.1600e-06	6.9600e-07	5.8800e-06
4	34.600	-1.8100e-05	-1.0300e-05	1.3400e-05	3.6500e-05	-1.5900e-05	-6.3100e-07	6.7000e-06
5	37.600	-2.7600e-05	-1.6800e-05	1.4100e-05	4.2700e-05	-2.4300e-05	-3.7400e-06	5.2900e-06
6	40.600	-3.7700e-05	-2.4500e-05	1.3200e-05	4.6100e-05	-3.3500e-05	-8.5200e-06	1.5600e-06
7	43.600	-4.7200e-05	-3.2300e-05	1.1100e-05	4.7400e-05	-4.2200e-05	-1.4100e-05	-3.4500e-06
8	46.600	-5.4900e-05	-3.8800e-05	9.0500e-06	4.7600e-05	-4.9300e-05	-1.9200e-05	-8.1600e-06
9	49.600	-6.0500e-05	-4.3400e-05	7.8200e-06	4.8400e-05	-5.4500e-05	-2.2900e-05	-1.1000e-05

 $P'(F|E)_{\max}, T = 100^\circ\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=800	P=950	P=880	P=890
0	23.600								
1	25.600			-9.9200e-07	1.4400e-06	-2.2200e-06	5.1000e-08	-1.5100e-06	-1.1500e-06
2	28.600	-5.3200e-06	-4.4400e-06	2.0500e-07	5.4900e-06	-2.8300e-06	2.5000e-06	-5.8400e-07	-1.8600e-07
3	31.600	-1.0700e-05	-8.4300e-06	9.5500e-07	1.0400e-05	-4.9800e-06	5.1100e-06	-5.6500e-07	2.0800e-07
4	34.600	-1.8400e-05	-1.4100e-05	1.5200e-06	1.5800e-05	-8.0900e-06	7.9500e-06	-8.5900e-07	3.4000e-07
5	37.600	-2.8000e-05	-2.1100e-05	9.7600e-07	2.0100e-05	-1.2400e-05	9.8000e-06	-2.1600e-06	-6.1300e-07
6	40.600	-3.8300e-05	-2.8900e-05	-1.2000e-06	2.2200e-05	-1.7800e-05	9.7900e-06	-4.8400e-06	-3.1100e-06
7	43.600	-4.7800e-05	-3.6400e-05	-4.6100e-06	2.2000e-05	-2.3600e-05	8.1200e-06	-8.5000e-06	-6.7400e-06
8	46.600	-5.5500e-05	-4.2800e-05	-8.0600e-06	2.0900e-05	-2.8800e-05	5.9400e-06	-1.2100e-05	-1.0400e-05
9	49.600	-6.1200e-05	-4.7300e-05	-1.0100e-05	2.0900e-05	-3.2300e-05	4.8100e-06	-1.4400e-05	-1.2600e-05

Table A5 (cont'd)

 $P'(F|E)_{\max}, T = 120^{\circ}\text{F}$

	EFPY	P=500	P=700	P=900	P=1000	P=933
0	23.600					
1	25.600					
2	28.600	-5.3600e-06	-5.1000e-06	-3.4300e-06	-1.4300e-06	-2.8500e-06
3	31.600	-1.0800e-05	-9.8900e-06	-5.4900e-06	-1.0200e-06	-4.3000e-06
4	34.600	-1.8600e-05	-1.6500e-05	-7.7200e-06	3.4500e-07	-5.6000e-06
5	37.600	-2.8400e-05	-2.4300e-05	-1.0400e-05	1.9700e-06	-6.9400e-06
6	40.600	-3.8700e-05	-3.2500e-05	-1.3900e-05	2.7600e-06	-8.7800e-06
7	43.600	-4.8300e-05	-4.0200e-05	-1.8100e-05	2.2900e-06	-1.1300e-05
8	46.600	-5.6000e-05	-4.6500e-05	-2.2000e-05	1.2800e-06	-1.3800e-05
9	49.600	-6.1700e-05	-5.1000e-05	-2.4100e-05	1.3100e-06	-1.5300e-05

	EFPY	P=967	P=990	P=980	P=983	P=986
0	23.600					
1	25.600					
2	28.600	-2.1600e-06	-1.6300e-06	-1.8400e-06	-1.7700e-06	-1.7100e-06
3	31.600	-2.6900e-06	-1.5400e-06	-1.9900e-06	-1.8400e-06	-1.7000e-06
4	34.600	-2.6900e-06	-5.6000e-07	-1.4400e-06	-1.1600e-06	-8.7300e-07
5	37.600	-2.6100e-06	8.3000e-07	-7.3100e-07	-2.8700e-07	2.3200e-07
6	40.600	-3.2500e-06	1.6600e-06	-7.7000e-07	-1.5500e-07	6.5600e-07
7	43.600	-4.9000e-06	1.3900e-06	-1.9100e-06	-1.1400e-06	-5.1900e-08
8	46.600	-6.8900e-06	4.2100e-07	-3.5000e-06	-2.6100e-06	-1.3400e-06
9	49.600	-7.9000e-06	-7.0100e-08	-4.1700e-06	-3.1900e-06	-1.9100e-06

Fig. A3. $P'(F|E)_{\max}$ vs t and p for $T = 40, 60, 80, 100, 120^\circ\text{F}$.

Fig. A3 (cont'd).

Fig. A3 (cont'd).

 Fig. A4. $P'(F|E)_{\max,p}$ vs p for $T = 40, 60, 80, 100, 120^\circ\text{F}$.

Fig. A4 (cont'd).

Fig. A4 (cont'd).

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