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Beaver Valley Unit 1 Heatup and Cooldown Limit Curves for Master Curve Applications

Westinghouse Electric Company LLC

WCAP-15618

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FORWARD

WCAP-15624 summarizes application of the Master Curve fracture toughness data for assuring reactor pressure vessel (RPV) integrity for Beaver Valley Power Station, Unit 1 (BVPS-1). This application represents a lead-plant activity by the nuclear industry for an RPV that is life-limited by a beltline plate material. The fracture toughness data presented in this report were generated in part from the Westinghouse Owners Group (WOG) lead-plant applications program for the life-limiting plate material, and by First Energy Nuclear Operating Company (FENOC) as part of their long range strategic plan for management of the irradiation damage to the reactor vessel. Additionally, FENOC is implementing their program to base their irradiation damage management program on the fracture toughness approach by fracture toughness testing of the other beltline materials in the BVPS-1 RPV.

EPRI has recently published a support document further endorsing the use of the Master Curve approach, EPRI TR-1000707. This document not only further validates ASME Code Cases N-629 and N-631, but proposes a new Code Case in which the alternative reference temperature, RT_{To}, method of indexing the ASME Code K_{Ic} curve is replaced by using the measured 5% lower tolerance Master Curve itself. This alternative K_{Ic} curve is not used in this BVPS-1 analysis, but if approval through the Code process is reached, future analyses will utilize this approach by requesting use of the Code Case. The RT_{To} methodology has been applied for the BVPS-1 EOLE life-limiting plate material, similar to the approach taken for the Kewaunee EOLE life-limiting weld metal (see WCAP-15075).

WCAP-15624 provides a summary of the RT_{To} methodology used to determine the adjusted reference temperature for an irradiated RPV steel. The investigation in the report focuses on several key areas:

- The technical basis for application of the Master Curve to irradiated RPV steels;
- The basis and accuracy of T_o values measured using ASTM E1921-97 for different size specimens and loading configurations for the BVPS-1 limiting plate material in the unirradiated and irradiated conditions and for the remaining BVPS-1 beltline materials in the unirradiated condition;
- Determination of the T_o -based index reference temperature (RT_{To}) for the K_{Ic} curve, which incorporates the latest knowledge of a bias for irradiated materials between small precracked Charpy three-point bend tests versus larger compact tension tests; and
- A margin approach for RT_{To} that meets the intent of accepted regulatory methods (e.g., Reg. Guide 1.99 Rev. 2 procedures); issues related to copper/nickel variability and surrogate weld metal are eliminated in this application since the surveillance limiting material is an exact piece of the RPV plate material.

Due to the low lead factors for the surveillance locations in the BVPS-1 vessel, limited fluence levels are available for the surveillance materials irradiated in the BVPS-1 vessel. Current fluences do not extend out to end-of-life (EOL) or EOL extension (EOLE). A supplemental

capsule has been added to surveillance program for BVPS-1; this capsule has been installed in BVPS-2 where the lead factor is much higher. This higher lead factor, and the fact that previously irradiated specimen inserts are included, means that the time to reach an irradiated EOLE condition is less than a decade. All of the RPV beltline materials for BVPS-1 are included in this supplemental capsule, which is designed for Master Curve fracture toughness testing and evaluation. Thus, the integrity of the entire RPV will be validated with the testing of this capsule.

WCAP-15618 has been prepared which provides the new operating pressure-temperature curves for the BVPS-1 vessel based on use of the Master Curve results. These curves reflect the latest projected estimates for power up-rates and the removal of hafnium from the core. The second limiting plate material (B6607-2) now has become controlling plate for these curves, except for EOLE at ¼-thickness cool-down) due to their Charpy V-notch (CVN) basis using Regulatory Guide 1.99, Rev. 2. As a result, the improvement in the operating pressure-temperature curves is limited by the CVN correlative approach for the second limiting plate. Although the improvement is currently limited, gains are real for the plant operators. The current increase of 20+ psig in the over-pressure protection system (OPPS) set point allows operators to better control the reactor coolant pump (RCP) seal leak-off. Additionally, when trying to maintain pressure above the minimum for control of RCP seal leak-off and below the OPPS set point, operators must be very careful not to inadvertently actuate the OPPS. Thus, even the small increase in the OPPS set points provides additional margin during plant start-ups and reduces the potential for inadvertent actuation of the OPPS, which enhances plant safety due to fewer challenges to plant systems. The importance of having future measured irradiated fracture toughness results for this plate and the other beltline materials is paramount, since the move to a fracture toughness basis for all materials is expected to demonstrate that the current limiting plate (B6903-01) will remain the limiting material once all other materials are evaluated on the same testing basis (fracture toughness rather than CVN).

The projections for Pressurized Thermal Shock (PTS) are provided in WCAP-15624 based on applying the Master Curve methodology to the limiting plate, B6903-1. It should be noted that the change in the projected EOL PTS identified in WCAP-15624 is limited by the Charpy based values of the second most limiting plate, B6607-2. When the material from the supplemental surveillance capsule is removed and tested, it is expected that there will be a significant improvement not only in the EOL PTS values but also in the EOLE values. The BVPS-1 RPV stays below the PTS screening criterion of 270°F through and beyond EOLE.

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PREFACE

This report has been technically reviewed and verified by:

Reviewer: T. J. Laubham

1 INTRODUCTION

Heatup and cooldown limit curves are generated using the adjusted RT_{NDT} (reference nil-ductility temperature) of the limiting beltline region materials of the reactor vessel. The adjusted RT_{NDT} values of the limiting materials in the core region of the reactor vessel are traditionally determined by using the unirradiated reactor vessel material Charpy V-notch impact toughness properties, estimating the radiation-induced ΔRT_{NDT}, (which is usually the 30 ft-lb temperature shift) and adding a margin. The unirradiated RT_{NDT} is the higher of either the drop weight nil-ductility transition temperature (NDTT) or the temperature at which the material exhibits no less than 50 ft-lb of impact energy and 35-mil lateral expansion minus 60°F.

In this report, a different method for determining the adjusted RT_{NDT} of the limiting plate material is introduced, in addition to the Charpy V-notch impact toughness approach. The new method is based on the direct Master Curve irradiated fracture toughness derivation of T_o, which can then be converted into the newly defined alternative reference temperature, RT_{To}, using ASME Code Case N-629[1]: $RT_{To} = T_o + 35°F$. Note that in the unirradiated condition, RT_{To} can be defined in exactly the same manner following Code Case N629 or N631[2]. See the companion report (WCAP-15624 [3]) for a description of the approach taken for the Master Curve fracture toughness application and a review of the traditional Charpy approach.

In the Charpy based approach, RT_{NDT} increases as the material is exposed to fast-neutron radiation. Therefore, to find the most limiting RT_{NDT} at any time period in the reactor's life, ΔRT_{NDT} due to the radiation exposure associated with that time period must be added to the unirradiated RT_{NDT} (IRT). The extent of the shift in RT_{NDT} is enhanced by certain chemical elements (such as cooper and nickel) present in reactor vessel steels. The Nuclear Regulatory Commission (NRC) has published a method for predicting radiation embrittlement in Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials."[4] Regulatory Guide 1.99, Revision 2, is traditionally used for the calculation of Adjusted Reference Temperature (ART) values (IRT + ΔRT_{NDT} + margins for uncertainties) at the ¼T and ¾T locations, where T is the thickness of the vessel at the beltline region measured from the clad/base metal interface.

2 PURPOSE

First Energy Nuclear Operating Company contracted Westinghouse to analyze fracture toughness data generated for surveillance capsules W and Y, for the Beaver Valley Unit 1 limiting plate material, using the Master Curve approach. As a part of this analysis, Westinghouse generated new heatup and cooldown curves for 22 EFPY, end of life (EOL at 27.44 EFPY), and extended EOL (EOLE at 44.18 EFPY). These new Pressure-Temperature Curves are to be developed utilizing the following methodologies:

- ASME Code Case N-641[5], "Alternative Pressure – Temperature Relationship and Low Temperature Overpressure Protection System Requirements,"
- Elimination of the flange requirement of Appendix G to 10 CFR Part 50[6] (WCAP-15315[7]), "Reactor Vessel Head/Vessel Flange Requirements Evaluation for Operating PWR and BWR Plants,"
- Methodology of the 1996 version of ASME Section XI, Appendix G[8], "Fracture Toughness Criteria for Protection Against Failure,"
- The P-T Curves were developed without operating margins or instrumentation errors,
- ASME Code Case N-629[1], "Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials, Section XI, Division 1," and
- ASME Code Case N-631[2], "Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials Other Than Bolting for Class 1 Vessels, Section III, Division 1."

Axial flaw methodology, 1996 Appendix G to ASME Section XI and ASME Code Case N-641 (K_{Ic} methodology) along with the methodology to eliminate the 10 CFR Part 50 Appendix G flange requirements (WCAP-15315) were employed to develop P-T Curves for the limiting plate material. The final P-T Curves were developed by generating a P-T Curve based on the most limiting axial flaw material ART value.

The purpose of this report is to present the calculations and the development of the First Energy Nuclear Operating Company Beaver Valley Unit 1 heatup and cooldown curves for 22, 27.44 and 44.18 EFPY. This report documents the calculated adjusted reference temperature (ART) values, following the methods of Regulatory Guide 1.99, Revision 2[4], for the surveillance materials from Capsule W and Capsule Y and the development of the heatup and cooldown pressure-temperature limit curves for normal operation.

3 CRITERIA FOR ALLOWABLE PRESSURE-TEMPERATURE RELATIONSHIPS

3.1 OVERALL APPROACH

Appendix G to 10 CFR Part 50, "Fracture Toughness Requirements"[6] specifies fracture toughness requirements for ferritic materials of pressure-retaining components of the reactor coolant pressure boundary of light water nuclear power reactors to provide adequate margins of safety during any condition of normal operation, including anticipated operational occurrences and system hydrostatic tests, to which the pressure boundary may be subjected over its service lifetime. The ASME Boiler and Pressure Vessel Code forms the basis for these requirements. Section XI, Division 1, "Rules for Inservice Inspection of Nuclear Power Plant Components," Appendix G[8], contains the conservative methods of analysis.

The ASME approach for calculating the allowable limit curves for various heatup and cooldown rates specifies that the total stress intensity factor, K_I, for the combined thermal and pressure stresses at any time during heatup or cooldown cannot be greater than the reference stress intensity factor, K_{Ic}, for the metal temperature at that time. K_{Ic} is obtained from the reference fracture toughness curve, defined in Code Case N-641 of Appendix G of the ASME Code, Section XI. The K_{Ic} curve is given by the following equation:

$$K_{Ic} = 33.2 + 20.734 * e^{[0.02(T - RT_{NDT})]} \quad (1)$$

where,

K_{Ic} = reference stress intensity factor as a function of the metal temperature T and the metal reference nil-ductility temperature RT_{NDT}

This K_{Ic} curve is based on the lower bound of static K_I values measured as a function of temperature on specimens of SA-533 Grade B Class 1, SA-508-1, SA-508-2, and SA-508-3 steels.

3.2 METHODOLOGY FOR PRESSURE-TEMPERATURE LIMIT CURVE DEVELOPMENT

The governing equation for the heatup-cooldown analysis is defined in Code Case N-641 of Appendix G of the ASME Code as follows:

$$C * K_{Im} + K_{It} < K_{Ic} \quad (2)$$

where,

K_{Im} = stress intensity factor caused by membrane (pressure) stress

K_{It} = stress intensity factor caused by the thermal gradients

K_{Ic} = function of temperature relative to the RT_{NDT} of the material

C = 2.0 for Level A and Level B service limits

C = 1.5 for hydrostatic and leak test conditions during which the reactor core is not critical

For membrane tension, the K_I corresponding to membrane tension for the postulated defect is:

$$K_{Im} = M_m * (pR_i \div t) \quad (3)$$

where M_m for an inside surface is given by:

M_m = 1.85 for $\sqrt{t} < 2$,

M_m = $0.926\sqrt{t}$ for $2 \leq \sqrt{t} \leq 3.464$, and

M_m = 3.21 for $\sqrt{t} > 3.464$.

Similarly, M_m for an outside surface flaw is given by:

M_m = 1.77 for $\sqrt{t} < 2$,

M_m = $0.893\sqrt{t}$ for $2 \leq \sqrt{t} \leq 3.464$, and

M_m = 3.09 for $\sqrt{t} > 3.464$.

where:

Ri = vessel inner radius,

T = vessel wall thickness, and

P = internal pressure,

For Bending Stress, the K_I corresponding to bending stress for the postulated defect is:

$K_{Ib} = M_b$ * maximum bending stress, where M_b is two-thirds of M_m

For the Radial Thermal Gradient, the maximum K_I produced by radial thermal gradient for the postulated inside surface defect is:

$$K_{It} = 0.953\text{x}10^{-3} \text{ x CR x } t^{2.5} \quad (4)$$

where:

CR = the cooldown rate in °F/hr.

For the Radial Thermal Gradient, the maximum K_I produced by radial thermal gradient for the postulated outside surface defect is:

$$K_{It} = 0.753x10^{-3} \times HU \times t^{2.5} \quad (5)$$

where:

HU = the heatup rate in °F/hr.

The through-wall temperature difference associated with the maximum thermal K_I can be determined from ASME Section XI, Appendix G, Figure G-2214-1. The temperature at any radial distance from the vessel surface can be determined from ASME Section XI, Appendix G, Figure G-2214-2 for the maximum thermal K_I.

1. The maximum thermal K_I relationship and the temperature relationship in Fig. G-2214-1 are applicable only for the conditions given in G-2214.3 (a)(1) and (2) of Appendix G to ASME Section XI.

2. Alternatively, the K_I for radial thermal gradient can be calculated for any thermal stress distribution and at any specified time during cooldown for a ¼-thickness inside surface defect using the relationship:

$$K_{It} = (1.0359C_0 + 0.6322C_1 + 0.4753C_2 + 0.3855C_3) * \sqrt{\pi a} \quad (6)$$

or similarly, K_{IT} during heatup for a ¼-thickness outside surface defect using the relationship:

$$K_{It} = (1.043C_0 + 0.630C_1 + 0.481C_2 + 0.401C_3) * \sqrt{\pi a} \quad (7)$$

where the coefficients C_0, C_1, C_2 and C_3 are determined from the thermal stress distribution at any specified time during the heatup or cooldown using the form:

$$\sigma(x) = C_0 + C_1(x/a) + C_2(x/a)^2 + C_3(x/a)^3 \quad (8)$$

and x is a variable that represents the radial distance from the appropriate (i.e., inside or outside) surface to any point on the crack front and a is the maximum crack depth.

Note, that equations 3 through 8 were added to the OPERLIM computer program, which is the Westinghouse computer program used to generate pressure-temperature limit curves. No other changes were made to the OPERLIM computer program with regard to the pressure-temperature curve calculation methodology. Hence, the pressure-temperature curve methodology described in WCAP-14040[9] Section 2.6 (equations 2.6.2-4 and 2.6.3-1) remains valid for the generation of the pressure-temperature curves documented in this report with the exceptions described above.

At any time during the heatup or cooldown transient, K_{1C} is determined by the metal temperature at the tip of a postulated flaw at the ¼T and ¾T location, the appropriate value for RT_{NDT}, and the reference fracture toughness curve. The thermal stresses resulting from the temperature gradients through the vessel wall are calculated and then the corresponding (thermal) stress intensity factors, K_{It}, for the reference flaw are computed. From Equation 2, the pressure stress intensity factors are obtained and, from these, the allowable pressures are calculated.

For the calculation of the allowable pressure versus coolant temperature during cooldown, the reference flaw of Appendix G to the ASME Code is assumed to exist at the inside of the vessel wall. During cooldown, the controlling location of the flaw is always at the inside of the wall because the thermal gradients produce tensile stresses at the inside, which increase with increasing cooldown rates. Allowable pressure-temperature relations are generated for both steady-state and finite cooldown rate situations. From these relations, composite limit curves are constructed for each cooldown rate of interest.

The use of the composite curve in the cooldown analysis is necessary because control of the cooldown procedure is based on the measurement of reactor coolant temperature, whereas the limiting pressure is actually dependent on the material temperature at the tip of the assumed flaw. During cooldown, the ¼T vessel location is at a higher temperature than the fluid adjacent to the vessel inner diameter. This condition, of course, is not true for the steady-state situation. It follows that, at any given reactor coolant temperature, the ΔT (temperature) developed during cooldown results in a higher value of K_{1C} at the ¼T location for finite cooldown rates than for steady-state operation. Furthermore, if conditions exist so that the increase in K_{1C} exceeds K_{It}, the calculated allowable pressure during cooldown will be greater than the steady-state value.

The above procedures are needed because there is no direct control on temperature at the ¼T location and, therefore, allowable pressures may unknowingly be violated if the rate of cooling is decreased at various intervals along a cooldown ramp. The use of the composite curve eliminates this problem and ensures conservative operation of the system for the entire cooldown period.

Three separate calculations are required to determine the limit curves for finite heatup rates. As is done in the cooldown analysis, allowable pressure-temperature relationships are developed for steady-state conditions as well as finite heatup rate conditions assuming the presence of a ¼T defect at the inside of the wall. The heatup results in compressive stresses at the inside surface that alleviate the tensile stresses produced by internal pressure. The metal temperature at the crack tip lags the coolant temperature; therefore, the K_{1C} for the ¼T crack during heatup is lower than the K_{1C} for the ¼T crack during steady-state conditions at the same coolant temperature. During heatup, especially at the end of the transient, conditions may exist so that the effects of compressive thermal stresses and lower K_{1C} values do not offset each other, and the pressure-temperature curve based on steady-state conditions no longer represents a lower bound of all similar curves for finite heatup rates when the ¼T flaw is considered. Therefore, both cases have to be analyzed in order to ensure that at any coolant temperature the lower value of the allowable pressure calculated for steady-state and finite heatup rates is obtained.

The second portion of the heatup analysis concerns the calculation of the pressure-temperature limitations for the case in which a ¼T flaw located at the ¼T location from the outside surface is assumed. Unlike the situation at the vessel inside surface, the thermal gradients established at the outside surface during heatup produce stresses which are tensile in nature and therefore tend to reinforce any pressure stresses present. These thermal stresses are dependent on both the rate of heatup and the time (or coolant temperature) along the heatup ramp. Since the thermal stresses at the outside are tensile and increase with increasing heatup rates, each heatup rate must be analyzed on an individual basis.

Following the generation of pressure-temperature curves for both the steady state and finite heatup rate situations, the final limit curves are produced by constructing a composite curve based on a point-by-point comparison of the steady-state and finite heatup rate data. At any given temperature, the allowable pressure is taken to be the lesser of the three values taken from the curves under consideration. The use of the composite curve is necessary to set conservative heatup limitations because it is possible for conditions to exist wherein, over the course of the heatup ramp, the controlling condition switches from the inside to the outside, and the pressure limit must at all times be based on analysis of the most critical criterion.

3.3 CLOSURE HEAD/VESSEL FLANGE REQUIREMENTS

10 CFR Part 50, Appendix G contains the requirements for the metal temperature of the closure head flange and vessel flange regions. This rule states that the metal temperature of the closure flange regions must exceed the material unirradiated RT_{NDT} by at least 120°F for normal operation when the pressure exceeds 20 percent of the pre-service hydrostatic test pressure (3106 psig), which is 621 psig for the Beaver Valley Unit 1 reactor vessel.

This requirement was originally based on concerns about the fracture margin in the closure flange region. During the boltup process, stresses in this region typically reach over 70 percent of the steady-state stress, without being at steady-state temperature. The margin of 120°F and the pressure limitation of 20 percent of hydrotest pressure were developed using the K_{ia} fracture toughness, in the mid 1970s.

Improved knowledge of fracture toughness and other issues which affect the integrity of the reactor vessel have led to the recent change to allow the use of K_{ic} in the development of pressure-temperature curves, as contained in Code Case N-641, "Alternative Reference Fracture Toughness for Development of P-T Limit Curves for Section XI, Division 1."

The discussion given in WCAP-15315, "Reactor Vessel Closure Head/Vessel Flange Requirements Evaluation for Operating PWR and BWR Plants," concluded that the integrity of the closure head/vessel flange region is not a concern for any of the operating plants using the K_{ic} toughness. Furthermore, there are no known mechanisms of degradation for this region, other than fatigue. The calculated design fatigue usage for this region is less than 0.1, so it may be concluded that flaws are unlikely to initiate in this region. It is therefore clear that no additional boltup requirements are necessary, and therefore the requirement of 10 CFR Part 50, Appendix G, can be eliminated from the Pressure-Temperature Curves contained in this report.

4 CALCULATION OF ADJUSTED REFERENCE TEMPERATURE

Following Regulatory Guide 1.99, Revision 2, the adjusted reference temperature (ART) for each material in the beltline region is given by the following expression:

$$ART = IRT + Bias + \Delta RT + Margin \quad (9)$$

Initial RT is the reference temperature for the unirradiated material as defined in paragraph NB-2331 of Section III of the ASME Boiler and Pressure Vessel Code[10] for the Charpy approach and $T_{o(u)}$+35°F for the Master Curve methodology. If measured values of initial RT_{NDT} for the material in question are not available, generic mean values for that class of material may be used if there are sufficient test results to establish a mean and standard deviation for the class. The bias term is added for the application of Master Curve precracked Charpy three point bend test results only.

ΔRT is the mean value of the adjustment in reference temperature caused by irradiation and is calculated as follows:

$$\Delta RT = CF * f^{(0.28-0.10 \log f)} \quad (10)$$

For the Master Curve determinations, an effective CF(CF_{eff}) is used (see Reference 3). To calculate ΔRT at any depth (e.g., at ¼T or ¾T), the following formula must first be used to attenuate the fluence at the specific depth.

$$f_{(depth x)} = f_{surface} * e^{(-0.24x)} \quad (11)$$

where x inches (vessel beltline thickness is 7.875 inches) is the depth into the vessel wall measured from the vessel clad/base metal interface. The resultant fluence is then placed in Equation 10 to calculate the ΔRT at the specific depth.

The Westinghouse Radiation Engineering and Analysis group evaluated the vessel fluence projections and the results are presented in Section 6 of WCAP-15571[11]. The fluence projection values have been updated to reflect the latest schedule for hafnium removal and power up-rates. The new values are presented in WCAP-15624[3]. The evaluations used the ENDF/B-VI scattering cross-section data set. This is consistent with the methods presented in WCAP-14040-NP-A, "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves"[9]. Tables 4-1 through 4-6 contain the calculated vessel surface fluence values along with the Regulatory Guide 1.99, Revision 2, ¼T and ¾T calculated fluence values used to calculate the ART values for all beltline materials in the Beaver Valley Unit 1 reactor vessel for 22, 27.44 and 44.18 EFPY.

Ratio Procedure and Temperature Adjustment

The ratio procedure, as documented in Regulatory Guide 1.99, Revision 2 Position 2.1, was used, where applicable, to adjust the measured values of ΔRT of the weld materials for

differences in copper/nickel content. This adjustment is performed by multiplying the ΔRT by the ratio of the vessel chemistry factor to the surveillance material chemistry factor. The adjusted ΔRT values are then used to calculate the chemistry factor for the vessel materials.

From NRC Industry Meetings on November 12, 1997 and February 12 and 13 of 1998, procedural guidelines were presented to adjust the ΔRT for temperature differences when using surveillance data from one vessel applied to another vessel. The following guidance was presented at these industry meetings:

> Irradiation temperature and fluence (or fluence factors) are first order environmental variables in assessing irradiation damage. To account for differences in temperature between surveillance specimens and vessel, an adjustment to the data must be performed. Studies have shown that for temperatures near 550°F, a 1°F decrease in irradiation temperature will result in approximately a 1°F increase in ΔRT.
>
> For capsules with irradiation temperature of $T_{capsule}$ and a plant with an irradiation temperature of T_{plant}, an adjustment to normalize $\Delta RT_{,measured}$ measured to T_{plant} is made as follows:

$$\text{Temp. Adjusted } \Delta RT = \Delta RT_{,measured} + 1.0*(T_{capsule} - T_{plant}) \quad (12)$$

The irradiation temperature of the Beaver Valley Unit 1 reactor vessel is: 544.1°F

Chemistry Factor

The chemistry factors were calculated using Position 2.1 from the Regulatory Guide 1.99, Revision 2 using all available surveillance data. For only the lower shell plate, the effective chemistry factor determined from the Master Curve approach[3] is calculated in Table 4-1 and used to calculate ART values in Tables 4-2 through 4-7. All remaining chemistry factors were taken from Reference 12.

Explanation of Margin Term

The margin term for the lower shell plate only is explained in Reference 3. All remaining margin values were taken from Reference 12.

Explanation of Bias

The bias term is explained in Reference 3 and is only applicable to the Master Curve results for the lower shell plate.

Table 4-1 provides the calculation of the CF value based on fracture toughness surveillance capsule data following the guidance given in Regulatory Guide 1.99, Revision 2, Position 2.1.

Table 4-1 Calculation of Chemistry Factor and Determination of Credibility for the Lower Shell Plate Material using Beaver Valley Unit 1 Surveillance Capsule Fracture Toughness Data

Capsule	Measured Shift,[a] Deg. F	Adjusted Shift,[a] Deg. F	Fluence,[b] 10^{19} n/cm^2 (E>1 MeV)	Fluence Factor[c] (FF)	Adjusted Shift X FF	FF^2	Predicted Shift,[e] Deg. F	Scatter[f], Deg. F
W	156.2	156.2	0.986	0.996	155.6	0.992	162.5	-6.3
Y	202.2	202.2	2.15	1.208	244.3	1.459	197.1	5.1
				Σ =	399.9	2.451		
				CF[d] =163.2° F				

Notes:

(a) Adjusted shifts are equivalent to the measured shifts because no chemistry or temperature adjustments are required; these shift values are based on the Master Curve fracture toughness results[3]

(b) Calculated fluences taken from References 3 and 11

(c) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(d) CF = Σ(Adj. Shift * FF) ÷ Σ(FF^2)

(e) Predicted Shift = CF * FF

(f) Scatter = Adjusted Shift – Predicted Shift

Table 4-2 Calculation of ART Values for the ¼T Location @ 22 EFPY

Reactor Vessel Beltline Region Location Material Identification	CF_{eff} deg. F	f(surface)[a] x 10^{19} n/cm²	f(¼T)[b] x 10^{19} n/cm²	FF[h] @¼T	IRT[c] deg. F	Bias deg. F	Margin deg. F	ΔRT[f] deg. F	ART[g] deg. F
Lower Shell Plate B6903-1 (Master Curve data)	163.2	2.76	1.720	1.149	-5.2	8[d]	24[e]	187.6	214
Lower Shell Plate B7203-2	98.7	2.76	1.720	1.149	20	0	34	113.4	167
Intermediate Shell Plate B6607-1	100.5	2.76	1.720	1.149	43	0	34	115.5	192
Intermediate Shell Plate B6607-2	100.5	2.76	1.720	1.149	73	0	34	115.5	222
Lower Shell Longitudinal Weld 305414	210.5	0.552[i]	0.344	0.706	-56	0	65.5	148.6	158
using surveillance data	223.9	0.552	0.344	0.706	-56	0	65.5	158.1	168
Intermediate Shell Longitudinal Weld 305424	191.7	0.552	0.344	0.706	-56	0	65.5	135.3	145
using surveillance data	188.8	0.552	0.344	0.706	-56	0	65.5	133.3	143
Intermediate to Lower Shell Weld 90136	124.3	2.76	1.720	1.149	-56	0	65.5	142.9	152
using surveillance data	84.8	2.76	1.720	1.149	-56	0	44	97.5	85

Notes:

(a) Surface fluences for 9.4% uprating (References 3 & 11)

(b) f(¼T) or f(¾T) = $f_{surf} * e^{-0.24x}$, where x = ¼T or x = ¾T, 10^{19} n/cm² (E>1.0 MeV). T is the vessel thickness of 7.88 inches.

(c) IRT values are measured values. IRT values from Charpy approach are initial RT_{NDT} measurements, and IRT for the Master Curve results is $T_{o(u)}$+35°F.

(d) Bias = potential bias in testing CVN-size fracture toughness specimens in three-point bending (PCVN or RPCVN) (Reference 3)

(e) Margin = uncertainty in determining T_O is 12°F: $2\sigma T_O$=24°F; otherwise based on Charpy methodology[4]

(f) ΔRT = CF * FF

(g) ART = IRT + Bias + M + ΔRT

(h) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(i) Based on 20% of the peak fluence as calculated for 28 EFPY case in Reference 11

Table 4-3 Calculation of ART Values for the ¾T Location @ 22 EFPY

Reactor Vessel Beltline Region Location Material Identification	CF_{eff} deg. F	f(surface)[a] x 10^{19} n/cm²	f(¾T)[b] x 10^{19} n/cm²	FF[h] @¾T	IRT[c] deg. F	Bias deg. F	Margin deg. F	ΔRT[f] deg. F	ART[g] deg. F
Lower Shell Plate B6903-1	163.2	2.76	0.668	0.887	-5.2	8[d]	24[e]	144.8	172
Lower Shell Plate B7203-2	98.7	2.76	0.668	0.887	20	0	34	87.5	142
Intermediate Shell Plate B6607-1	100.5	2.76	0.668	0.887	43	0	34	89.1	166
Intermediate Shell Plate B6607-2	100.5	2.76	0.668	0.887	73	0	34	89.1	196
Lower Shell Longitudinal Weld 305414	210.5	0.552[i]	0.134	0.477	-56	0	65.5	100.5	110
using surveillance data	223.9	0.552	0.134	0.477	-56	0	65.5	106.9	116
Intermediate Shell Longitudinal Weld 305424	191.7	0.552	0.134	0.477	-56	0	65.5	91.5	101
using surveillance data	188.8	0.552	0.134	0.477	-56	0	65.5	90.1	100
Intermediate to Lower Shell Weld 90136	124.3	2.76	0.668	0.887	-56	0	65.5	110.3	120
using surveillance data	84.8	2.76	0.668	0.887	-56	0	44	75.2	63

Notes:

(a) Surface fluences for 9.4% uprating (References 3 & 11)

(b) f(¼T) or f(¾T) = $f_{surf} * e^{-0.24x}$, where x = ¼T or x = ¾T, 10^{19} n/cm² (E>1.0 MeV). T is the vessel thickness of 7.88 inches.

(c) IRT values are measured values. IRT values from Charpy approach are initial RT_{NDT} measurements, and IRT for the Master Curve results is $T_{o(u)}$+35°F.

(d) Bias = potential bias in testing CVN-size fracture toughness specimens in three-point bending (PCVN or RPCVN) (Reference 3)

(e) Margin = uncertainty in determining T_O is 12°F: $2\sigma T_O$=24°F; otherwise based on Charpy methodology[4]

(f) ΔRT = CF * FF

(g) ART = IRT + Bias + M + ΔRT

(h) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(i) Based on 20% of the peak fluence as calculated for 28 EFPY case in Reference 11

Table 4-4 Calculation of ART Values for the ¼T Location @ 27.44 EFPY

Reactor Vessel Beltline Region Location Material Identification	CF_{eff} deg. F	f(surface)[a] x 10^{19} n/cm²	f(¼T)[b] x 10^{19} n/cm²	FF[h] @¼T	IRT[c] deg. F	Bias deg. F	Margin deg. F	ΔRT[f] deg. F	ART[g] deg. F
Lower Shell Plate B6903-1	163.2	3.52	2.194	1.213	-5.2	8[d]	24[e]	198.0	225
Lower Shell Plate B7203-2	98.7	3.52	2.194	1.213	20	0	34	119.7	174
Intermediate Shell Plate B6607-1	100.5	3.52	2.194	1.213	43	0	34	121.9	199
Intermediate Shell Plate B6607-2	100.5	3.52	2.194	1.213	73	0	34	121.9	229
Lower Shell Longitudinal Weld 305414	210.5	0.704[i]	0.439	0.771	-56	0	65.5	162.3	172
using surveillance data	223.9	0.704	0.439	0.771	-56	0	65.5	172.6	182
Intermediate Shell Longitudinal Weld 305424	191.7	0.704	0.439	0.771	-56	0	65.5	147.8	157
using surveillance data	188.8	0.704	0.439	0.771	-56	0	65.5	145.6	155
Intermediate to Lower Shell Weld 90136	124.3	3.52	2.194	1.213	-56	0	65.5	150.8	160
using surveillance data	84.8	3.52	2.194	1.213	-56	0	44	102.9	91

Notes:

(a) Surface fluences for 9.4% uprating (References 3 & 11)

(b) f(¼T) or f(¾T) = $f_{surf} * e^{-0.24x}$, where x = ¼T or x = ¾T, 10^{19} n/cm² (E>1.0 MeV). T is the vessel thickness of 7.88 inches.

(c) IRT values are measured values. IRT values from Charpy approach are initial RT_{NDT} measurements, and IRT for the Master Curve results is $T_{o(u)}$+35°F.

(d) Bias = potential bias in testing CVN-size fracture toughness specimens in three-point bending (PCVN or RPCVN) (Reference 3)

(e) Margin = uncertainty in determining T_O is 12°F: $2\sigma T_O$=24°F; otherwise based on Charpy methodology[4]

(f) ΔRT = CF * FF

(g) ART = IRT + Bias + M + ΔRT

(h) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(i) Based on 20% of the peak fluence as calculated for 28 EFPY case in Reference 11

Table 4-5 Calculation of ART Values for the ¾T Location @ 27.44 EFPY

Reactor Vessel Beltline Region Location Material Identification	CF_{eff} deg. F	f(surface)[a] x 10^{19} n/cm²	f(¾T)[b] x 10^{19} n/cm²	FF[h] @¾T	IRT[c] deg. F	Bias deg. F	Margin deg. F	ΔRT[f] deg. F	ART[g] deg. F
Lower Shell Plate B6903-1	163.2	3.52	0.852	0.955	-5.2	8[d]	24[e]	155.9	183
Lower Shell Plate B7203-2	98.7	3.52	0.852	0.955	20	0	34	94.3	148
Intermediate Shell Plate B6607-1	100.5	3.52	0.852	0.955	43	0	34	96.0	173
Intermediate Shell Plate B6607-2	100.5	3.52	0.852	0.955	73	0	34	96.0	203
Lower Shell Longitudinal Weld 305414	210.5	0.704[i]	0.170	0.532	-56	0	65.5	112.0	121
using surveillance data	223.9	0.704	0.170	0.532	-56	0	65.5	119.1	129
Intermediate Shell Longitudinal Weld 305424	191.7	0.704	0.170	0.532	-56	0	65.5	102.0	111
using surveillance data	188.8	0.704	0.170	0.532	-56	0	65.5	100.4	110
Intermediate to Lower Shell Weld 90136	124.3	3.52	0.852	0.955	-56	0	65.5	118.7	128
using surveillance data	84.8	3.52	0.852	0.955	-56	0	44	81.0	69

Notes:

(a) Surface fluences for 9.4% uprating (References 3 & 11)

(b) f(¼T) or f(¾T) = $f_{surf} * e^{-0.24x}$, where x = ¼T or x = ¾T, 10^{19} n/cm² (E>1.0 MeV). T is the vessel thickness of 7.88 inches.

(c) IRT values are measured values. IRT values from Charpy approach are initial RT_{NDT} measurements, and IRT for the Master Curve results is $T_{o(u)}$+35°F.

(d) Bias = potential bias in testing CVN-size fracture toughness specimens in three-point bending (PCVN or RPCVN) (Reference 3)

(e) Margin = uncertainty in determining T_O is 12°F: $2\sigma T_O$=24°F; otherwise based on Charpy methodology[4]

(f) ΔRT = CF * FF

(g) ART = IRT + Bias + M + ΔRT

(h) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(i) Based on 20% of the peak fluence as calculated for 28 EFPY case in Reference 11

Table 4-6 Calculation of ART Values for the ¼T Location @ 44.18 EFPY

Reactor Vessel Beltline Region Location Material Identification	CF_{eff} deg. F	f(surface)[a] x 10^{19} n/cm²	f(¼T)[b] x 10^{19} n/cm²	FF[h] @¼T	IRT[c] deg. F	Bias deg. F	Margin deg. F	ΔRT[f] deg. F	ART[g] deg. F
Lower Shell Plate B6903-1	163.2	5.87	3.659	1.337	-5.2	8[d]	24[e]	218.1	245
Lower Shell Plate B7203-2	98.7	5.87	3.659	1.337	20	0	34	131.9	186
Intermediate Shell Plate B6607-1	100.5	5.87	3.659	1.337	43	0	34	134.3	211
Intermediate Shell Plate B6607-2	100.5	5.87	3.659	1.337	73	0	34	134.3	241
Lower Shell Longitudinal Weld 305414	210.5	1.174[i]	0.732	0.912	-56	0	65.5	192.1	202
using surveillance data	223.9	1.174	0.732	0.912	-56	0	65.5	204.3	214
Intermediate Shell Longitudinal Weld 305424	191.7	1.174	0.732	0.912	-56	0	65.5	174.9	184
using surveillance data	188.8	1.174	0.732	0.912	-56	0	65.5	172.3	182
Intermediate to Lower Shell Weld 90136	124.3	5.87	3.659	1.337	-56	0	65.5	166.1	176
using surveillance data	84.8	5.87	3.659	1.337	-56	0	44	113.3	101

Notes:

(a) Surface fluences for 9.4% uprating (References 3 & 11)

(b) f(¼T) or f(¾T) = $f_{surf} * e^{-0.24x}$, where x = ¼T or x = ¾T, 10^{19} n/cm² (E>1.0 MeV). T is the vessel thickness of 7.88 inches.

(c) IRT values are measured values. IRT values from Charpy approach are initial RT_{NDT} measurements, and IRT for the Master Curve results is $T_{o(u)}$+35°F.

(d) Bias = potential bias in testing CVN-size fracture toughness specimens in three-point bending (PCVN or RPCVN) (Reference 3)

(e) Margin = uncertainty in determining T_O is 12°F: $2\sigma T_O$=24°F; otherwise based on Charpy methodology[4]

(f) ΔRT = CF * FF

(g) ART = IRT + Bias + M + ΔRT

(h) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(i) Based on 20% of the peak fluence as calculated for 28 EFPY case in Reference 11

Table 4-7 Calculation of ART Values for the ¾T Location @ 44.18 EFPY

Reactor Vessel Beltline Region Location Material Identification	CF_{eff} deg. F	f(surface)[a] x 10^{19} n/cm²	f(¾T)[b] x 10^{19} n/cm²	FF[h] @¾T	IRT[c] deg. F	Bias deg. F	Margin deg. F	ΔRT[f] deg. F	ART[g] deg. F
Lower Shell Plate B6903-1	163.2	5.87	1.421	1.098	-5.2	8[d]	24[e]	179.1	206
Lower Shell Plate B7203-2	98.7	5.87	1.421	1.098	20	0	34	108.3	162
Intermediate Shell Plate B6607-1	100.5	5.87	1.421	1.098	43	0	34	110.3	187
Intermediate Shell Plate B6607-2	100.5	5.87	1.421	1.098	73	0	34	110.3	217
Lower Shell Longitudinal Weld 305414	210.5	1.174	0.284	0.656	-56	0	65.5	138.2	148
using surveillance data	223.9	1.174	0.284	0.656	-56	0	65.5	147.0	156
Intermediate Shell Longitudinal Weld 305424	191.7	1.174	0.284	0.656	-56	0	65.5	125.8	135
using surveillance data	188.8	1.174	0.284	0.656	-56	0	65.5	123.9	133
Intermediate to Lower Shell Weld 90136	124.3	5.87	1.421	1.098	-56	0	65.5	136.4	146
using surveillance data	84.8	5.87	1.421	1.098	-56	0	44	93.1	81

Notes:

(a) Surface fluences for 9.4% uprating (References 3 & 11)

(b) f(¼T) or f(¾T) = $f_{surf} * e^{-0.24x}$, where x = ¼T or x = ¾T, 10^{19} n/cm² (E>1.0 MeV). T is the vessel thickness of 7.88 inches.

(c) IRT values are measured values. IRT values from Charpy approach are initial RT_{NDT} measurements, and IRT for the Master Curve results is $T_{o(u)}$+35°F.

(d) Bias = potential bias in testing CVN-size fracture toughness specimens in three-point bending (PCVN or RPCVN) (Reference 3)

(e) Margin = uncertainty in determining T_O is 12°F: $2\sigma T_O$=24°F; otherwise based on Charpy methodology[4]

(f) ΔRT = CF * FF

(g) ART = IRT + Bias + M + ΔRT

(h) FF = fluence factor = $f^{(0.28-0.1*\log(f))}$

(i) Based on 20% of the peak fluence as calculated for 28 EFPY case in Reference 11

5 HEATUP AND COOLDOWN PRESSURE-TEMPERATURE LIMIT CURVES

Pressure-temperature limit curves for normal heatup and cooldown of the primary reactor coolant system have been calculated for the pressure and temperature in the reactor vessel beltline region using the methods discussed in Section 3 and 4 of this report. This approved methodology is also presented in WCAP-14040-NP-A[9], dated January 1996.

Figures 5-1 through 5-12 present the 22, 27.44, and 44.18 EFPY heatup and cooldown curves (without uncertainties for possible instrumentation errors) for heatup rates of 60 and 100°F/hr and cooldown rates of 0, 20, 40, 60, and 100°F/hr using the 1996 Appendix G methodology, Code Case N-641 and elimination of the flange requirement.

Allowable combinations of temperature and pressure for specific temperature change rates are below and to the right of the limit lines shown in Figures 5-1 through 5-12. This is in addition to other criteria, which must be met before the reactor is made critical, as discussed in the following paragraphs.

The reactor must not be made critical until pressure-temperature combinations are to the right of the criticality limit line shown on the heatup plots (for the specific heatup rate being utilized). The straight-line portion of the criticality limit is at the minimum permissible temperature for the 2485 psig inservice hydrostatic test as required by Appendix G to 10 CFR Part 50. The governing equation for the hydrostatic test is defined in Code Case N-641 and Appendix G to Section XI of the ASME Code[8] as follows:

$$1.5K_{Im} < K_{Ic} \tag{13}$$

where,

K_{Im} = the stress intensity factor covered by membrane (pressure) stress,

K_{Ic} = $33.2 + 20.734\, e^{[0.02\,(T - RTNDT)]}$,

T = the minimum permissible metal temperature, and

RT_{NDT} = the metal reference nil-ductility temperature

The criticality limit curve specifies pressure-temperature limits for core operation to provide additional margin during actual power production as specified in Reference 6. The pressure-temperature limits for core operation (except for low power physics tests) are that the reactor vessel must be at a temperature equal to or higher than the minimum temperature required for the inservice hydrostatic test, and at least 40°F higher than the minimum permissible temperature in the corresponding pressure-temperature curve for heatup and cooldown calculated as described in Section 3 of this report. The minimum temperature for the inservice hydrostatic leak test for the Beaver Valley Unit 1 reactor vessel at 22 EFPY is 278°F. The minimum temperature for the inservice hydrostatic leak test for the Beaver Valley Unit 1 reactor vessel at 27.44 EFPY is 285°F. The minimum temperature for the inservice hydrostatic

leak test for the Beaver Valley Unit 1 reactor vessel at 44.18 EFPY is 301°F. The approximately vertical line drawn from these points on the pressure-temperature curve, intersecting a curve 40°F higher than the pressure-temperature limit curve, constitutes the limit for core operation for the reactor vessel.

Figures 5-1 through 5-12 define all of the above limits for ensuring prevention of nonductile failure for the Beaver Valley Unit 1 reactor vessel. The data points for the heatup and cooldown pressure-temperature limit curves shown in Figures 5-1 through 5-12 are presented in Tables 5-1 through 5-6, respectively.

Additionally, Westinghouse Engineering has reviewed the minimum boltup temperature requirements for the Beaver Valley Unit 1 reactor pressure vessel. According to Paragraph G-2222 of the ASME Boiler and Pressure Vessel (B&PV) Code, Section XI, Appendix G, the reactor vessel may be bolted up and pressurized to 20 percent of the initial hydrostatic test pressure at the initial RT_{NDT} of the material stressed by the boltup. Therefore, since the most limiting initial RT_{NDT} value is -10°F (vessel flange), the reactor vessel can be bolted up at this temperature.

Table 5-1 Beaver Valley Unit 1 22 EFPY Cooldown Curve Data Points Without Uncertainties									
steady-state		-20°F/hr.		-40°F/hr.		-60°F/hr.		-100°F/hr.	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	60	0	60	0	60	0	60	0
60	655	60	613	60	569	60	525	60	434
65	657	65	614	65	571	65	527	65	436
70	659	70	616	70	573	70	529	70	438
75	661	75	618	75	575	75	531	75	440
80	663	80	620	80	577	80	533	80	442
85	665	85	623	85	579	85	535	85	445
90	668	90	626	90	582	90	538	90	448
95	671	95	629	95	585	95	542	95	451
100	674	100	632	100	589	100	545	100	455
105	678	105	636	105	593	105	549	105	460
110	682	110	640	110	597	110	554	110	465
115	686	115	645	115	602	115	559	115	471
120	691	120	650	120	608	120	565	120	478
125	697	125	656	125	614	125	571	125	485
130	703	130	662	130	620	130	579	130	493
135	710	135	669	135	628	135	587	135	503
140	717	140	677	140	636	140	596	140	513
145	725	145	686	145	646	145	605	145	525
150	734	150	695	150	656	150	617	150	538
155	744	155	706	155	667	155	629	155	552
160	755	160	718	160	680	160	643	160	568
165	767	165	731	165	694	165	658	165	586
170	781	170	745	170	710	170	675	170	606
175	795	175	761	175	727	175	693	175	629
180	812	180	779	180	746	180	714	180	653
185	830	185	798	185	767	185	737	185	681
190	850	190	820	190	791	190	763	190	711

Table 5-1 Beaver Valley Unit 1 22 EFPY Cooldown Curve Data Points Without Uncertainties (cont.)

steady-state		-20°F/hr.		-40°F/hr.		-60°F/hr.		-100°F/hr.	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
195	872	195	844	195	817	195	791	195	745
200	897	200	871	200	846	200	823	200	783
205	924	205	900	205	878	205	858	205	825
210	954	210	932	210	913	210	896	210	871
215	987	215	968	215	952	215	939	215	923
220	1023	220	1008	220	996	220	986	220	980
225	1064	225	1052	225	1044	225	1039	225	1043
230	1108	230	1101	230	1097	230	1097	230	1108
235	1157	235	1154	235	1156	235	1157	235	1157
240	1212	240	1212	240	1212	240	1212	240	1212
245	1272	245	1272	245	1272	245	1272	245	1272
250	1339	250	1339	250	1339	250	1339	250	1339
255	1412	255	1412	255	1412	255	1412	255	1412
260	1494	260	1494	260	1494	260	1494	260	1494
265	1583	265	1583	265	1583	265	1583	265	1583
270	1683	270	1683	270	1683	270	1683	270	1683
275	1792	275	1792	275	1792	275	1792	275	1792
280	1914	280	1914	280	1914	280	1914	280	1914
285	2048	285	2048	285	2048	285	2048	285	2048
290	2196	290	2196	290	2196	290	2196	290	2196
295	2359	295	2359	295	2359	295	2359	295	2359

Table 5-2 Beaver Valley Unit 1 22 EFPY Heatup Curve Data Points Without Uncertainties									
60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	278	0	60	0	278	0	260	2000
60	612	278	612	60	564	278	564	278	2485
65	612	278	612	65	564	278	565		
70	612	278	612	70	564	278	565		
75	612	278	614	75	564	278	566		
80	612	278	614	80	564	278	566		
85	612	278	616	85	564	278	568		
90	612	278	618	90	564	278	569		
95	612	278	619	95	564	278	571		
100	612	278	623	100	564	278	572		
105	612	278	624	105	564	278	575		
110	614	278	628	110	564	278	577		
115	616	278	631	115	564	278	580		
120	619	278	634	120	564	278	583		
125	624	278	641	125	564	278	586		
130	628	278	642	130	565	278	591		
135	634	278	648	135	566	278	593		
140	641	278	656	140	568	278	600		
145	648	278	657	145	571	278	601		
150	657	278	666	150	575	278	611		
155	666	278	677	155	580	278	612		
160	677	278	689	160	586	278	621		
165	689	278	702	165	593	278	625		
170	702	278	717	170	601	278	633		
175	717	278	733	175	611	278	641		
180	733	278	751	180	621	278	646		
185	751	278	771	185	633	278	659		
190	771	278	793	190	646	278	661		

Table 5-2 (cont.) Beaver Valley Unit 1 22 EFPY Heatup Curve Data Points Without Uncertainties

60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
195	793	278	818	195	661	278	677		
200	818	278	845	200	677	278	696		
205	845	270	875	205	696	278	716		
210	875	270	908	210	716	278	739		
215	908	270	944	215	739	278	764		
220	944	270	985	220	764	278	792		
225	985	270	1029	225	792	278	822		
230	1029	275	1079	230	822	278	856		
235	1079	280	1133	235	856	280	894		
240	1133	285	1193	240	894	285	936		
245	1193	290	1259	245	936	290	982		
250	1259	295	1332	250	982	295	1033		
255	1332	300	1413	255	1033	300	1089		
260	1413	305	1502	260	1089	305	1151		
265	1502	310	1590	265	1151	310	1219		
270	1590	315	1674	270	1219	315	1294		
275	1674	320	1767	275	1294	320	1378		
280	1767	325	1870	280	1378	325	1470		
285	1870	330	1983	285	1470	330	1571		
290	1983	335	2108	290	1571	335	1682		
295	2108	340	2246	295	1682	340	1806		
300	2246	345	2398	300	1806	345	1941		
305	2398			305	1941	350	2091		
				310	2091	355	2256		
				315	2256	360	2438		
				320	2438				

Table 5-3 Beaver Valley Unit 1 27.44 EFPY Cooldown Curve Data Points Without Uncertainties									
steady-state		-20°F/hr.		-40°F/hr.		-60°F/hr.		-100°F/hr.	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	60	0	60	0	60	0	60	0
60	653	60	610	60	567	60	523	60	431
65	654	65	612	65	568	65	524	65	432
70	656	70	613	70	570	70	525	70	434
75	658	75	615	75	572	75	527	75	435
80	660	80	617	80	573	80	529	80	437
85	662	85	619	85	576	85	531	85	440
90	664	90	621	90	578	90	534	90	442
95	667	95	624	95	581	95	536	95	445
100	670	100	627	100	584	100	539	100	449
105	673	105	630	105	587	105	543	105	452
110	676	110	634	110	591	110	547	110	457
115	680	115	638	115	595	115	551	115	462
120	685	120	642	120	600	120	556	120	467
125	689	125	647	125	605	125	562	125	474
130	695	130	653	130	611	130	568	130	481
135	700	135	659	135	617	135	575	135	489
140	707	140	666	140	624	140	582	140	498
145	714	145	673	145	632	145	591	145	508
150	722	150	682	150	641	150	601	150	519
155	730	155	691	155	651	155	611	155	531
160	740	160	701	160	662	160	623	160	545
165	751	165	712	165	674	165	636	165	560
170	762	170	725	170	688	170	651	170	578
175	775	175	739	175	703	175	667	175	597
180	789	180	754	180	719	180	685	180	618
185	805	185	771	185	738	185	705	185	642
190	823	190	790	190	758	190	727	190	669

Table 5-3 Beaver Valley Unit 1 27.44 EFPY Cooldown Curve Data Points Without Uncertainties (cont.)

steady-state		-20°F/hr.		-40°F/hr.		-60°F/hr.		-100°F/hr.	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
195	842	195	811	195	781	195	752	195	698
200	863	200	834	200	806	200	779	200	731
205	887	205	859	205	834	205	809	205	767
210	913	210	888	210	864	210	843	210	807
215	941	215	919	215	898	215	880	215	852
220	973	220	953	220	936	220	921	220	901
225	1008	225	992	225	978	225	967	225	956
230	1047	230	1034	230	1024	230	1017	230	1017
235	1090	235	1081	235	1075	235	1073	235	1084
240	1137	240	1132	240	1131	240	1135	240	1137
245	1190	245	1189	245	1190	245	1190	245	1190
250	1247	250	1247	250	1247	250	1247	250	1247
255	1311	255	1311	255	1311	255	1311	255	1311
260	1382	260	1382	260	1382	260	1382	260	1382
265	1460	265	1460	265	1460	265	1460	265	1460
270	1546	270	1546	270	1546	270	1546	270	1546
275	1642	275	1642	275	1642	275	1642	275	1642
280	1747	280	1747	280	1747	280	1747	280	1747
285	1864	285	1864	285	1864	285	1864	285	1864
290	1992	290	1992	290	1992	290	1992	290	1992
295	2135	295	2135	295	2135	295	2135	295	2135
300	2292	300	2292	300	2292	300	2292	300	2292
305	2466	305	2466	305	2466	305	2466	305	2466

Table 5-4 Beaver Valley Unit 1 27.44 EFPY Heatup Curve Data Points Without Uncertainties									
60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	285	0	60	0	285	0	267	2000
60	607	285	607	60	558	285	558	285	2485
65	607	285	607	65	558	285	558		
70	607	285	608	70	558	285	558		
75	607	285	608	75	558	285	559		
80	607	285	609	80	558	285	560		
85	607	285	610	85	558	285	561		
90	607	285	612	90	558	285	562		
95	607	285	614	95	558	285	564		
100	607	285	615	100	558	285	566		
105	607	285	620	105	558	285	568		
110	608	285	620	110	558	285	570		
115	609	285	624	115	558	285	573		
120	612	285	628	120	558	285	574		
125	615	285	630	125	558	285	579		
130	620	285	636	130	558	285	580		
135	624	285	639	135	558	285	587		
140	630	285	644	140	560	285	587		
145	636	285	652	145	562	285	595		
150	644	285	653	150	566	285	597		
155	652	285	661	155	570	285	604		
160	661	285	671	160	574	285	608		
165	671	285	683	165	580	285	614		
170	683	285	696	170	587	285	622		
175	696	285	710	175	595	285	625		
180	710	285	725	180	604	285	638		
185	725	285	743	185	614	285	638		
190	743	285	762	190	625	285	652		

Table 5-4 Beaver Valley Unit 1 27.44 EFPY Heatup Curve Data Points Without Uncertainties (cont.)

60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
195	762	285	783	195	638	285	656		
200	783	285	806	200	652	285	668		
205	806	285	832	205	668	285	685		
210	832	285	861	210	685	285	705		
215	861	285	893	215	705	285	726		
220	893	285	928	220	726	285	751		
225	928	285	967	225	751	285	777		
230	967	285	1009	230	777	285	807		
235	1009	285	1056	235	807	285	839		
240	1056	285	1109	240	839	285	875		
245	1109	290	1166	245	875	290	915		
250	1166	295	1230	250	915	295	959		
255	1230	300	1300	255	959	300	1008		
260	1300	305	1377	260	1008	305	1062		
265	1377	310	1463	265	1062	310	1121		
270	1463	315	1557	270	1121	315	1187		
275	1557	320	1640	275	1187	320	1259		
280	1640	325	1729	280	1259	325	1339		
285	1729	330	1827	285	1339	330	1427		
290	1827	335	1936	290	1427	335	1524		
295	1936	340	2056	295	1524	340	1631		
300	2056	345	2188	300	1631	345	1748		
305	2188	350	2334	305	1748	350	1879		
310	2334			310	1879	355	2022		
				315	2022	360	2180		
				320	2180	365	2354		
				325	2354				

Table 5-5 Beaver Valley Unit 1 44.18 EFPY Cooldown Curve Data Points Without Uncertainties									
steady-state		-20°F/hr.		-40°F/hr.		-60°F/hr.		-100°F/hr.	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	60	0	60	0	60	0	60	0
60	649	60	606	60	563	60	518	60	426
65	650	65	607	65	564	65	519	65	426
70	652	70	608	70	565	70	520	70	427
75	653	75	610	75	566	75	521	75	428
80	654	80	611	80	567	80	522	80	429
85	656	85	612	85	568	85	523	85	430
90	657	90	614	90	570	90	525	90	432
95	659	95	616	95	572	95	527	95	434
100	661	100	618	100	574	100	529	100	436
105	664	105	620	105	576	105	531	105	438
110	666	110	623	110	579	110	534	110	441
115	669	115	626	115	582	115	537	115	445
120	672	120	629	120	585	120	540	120	448
125	676	125	633	125	589	125	544	125	453
130	680	130	637	130	593	130	548	130	458
135	684	135	641	135	597	135	553	135	463
140	688	140	646	140	603	140	559	140	469
145	694	145	651	145	608	145	565	145	476
150	699	150	657	150	615	150	572	150	484
155	705	155	664	155	622	155	579	155	493
160	712	160	671	160	630	160	588	160	503
165	720	165	679	165	638	165	597	165	513
170	729	170	688	170	648	170	607	170	526
175	738	175	698	175	659	175	619	175	539
180	748	180	710	180	671	180	632	180	555
185	760	185	722	185	684	185	646	185	572
190	772	190	735	190	699	190	662	190	590

Table 5-5 Beaver Valley Unit 1 44.18 EFPY Cooldown Curve Data Points Without Uncertainties (cont.)

steady-state		-20°F/hr.		-40°F/hr.		-60°F/hr.		-100°F/hr.	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
195	786	195	751	195	715	195	680	195	612
200	802	200	767	200	733	200	699	200	635
205	819	205	786	205	753	205	721	205	661
210	838	210	806	210	775	210	745	210	690
215	859	215	829	215	800	215	772	215	722
220	882	220	854	220	827	220	802	220	758
225	907	225	881	225	857	225	835	225	797
230	935	230	912	230	891	230	871	230	841
235	966	235	946	235	928	235	912	235	890
240	1001	240	983	240	968	240	956	240	944
245	1039	245	1025	245	1014	245	1006	245	1004
250	1081	250	1071	250	1064	250	1061	250	1070
255	1127	255	1121	255	1119	255	1122	255	1127
260	1179	260	1177	260	1179	260	1179	260	1179
265	1235	265	1235	265	1235	265	1235	265	1235
270	1298	270	1298	270	1298	270	1298	270	1298
275	1367	275	1367	275	1367	275	1367	275	1367
280	1444	280	1444	280	1444	280	1444	280	1444
285	1528	285	1528	285	1528	285	1528	285	1528
290	1622	290	1622	290	1622	290	1622	290	1622
295	1725	295	1725	295	1725	295	1725	295	1725
300	1839	300	1839	300	1839	300	1839	300	1839
305	1966	305	1966	305	1966	305	1966	305	1966
310	2105	310	2105	310	2105	310	2105	310	2105
315	2259	315	2259	315	2259	315	2259	315	2259
320	2430	320	2430	320	2430	320	2430	320	2430

Table 5-6 Beaver Valley Unit 1 44.18 EFPY Heatup Curve Data Points Without Uncertainties									
60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
60	0	301	0	60	0	301	0	283	2000
60	598	301	598	60	546	301	546	301	2485
65	598	301	598	65	546	301	546		
70	598	301	598	70	546	301	546		
75	598	301	598	75	546	301	547		
80	598	301	600	80	546	301	548		
85	598	301	600	85	546	301	549		
90	598	301	602	90	546	301	549		
95	598	301	603	95	546	301	552		
100	598	301	605	100	546	301	552		
105	598	301	607	105	546	301	555		
110	598	301	608	110	546	301	555		
115	598	301	612	115	546	301	559		
120	600	301	613	120	546	301	560		
125	602	301	617	125	546	301	564		
130	605	301	622	130	546	301	566		
135	608	301	622	135	546	301	569		
140	612	301	628	140	546	301	573		
145	617	301	633	145	548	301	575		
150	622	301	635	150	549	301	581		
155	628	301	643	155	552	301	583		
160	635	301	648	160	555	301	591		
165	643	301	651	165	559	301	591		
170	651	301	661	170	564	301	600		
175	661	301	671	175	569	301	602		
180	671	301	683	180	575	301	611		
185	683	301	696	185	583	301	616		
190	696	301	710	190	591	301	622		

Table 5-6 (cont.) Beaver Valley Unit 1 44.18 EFPY Heatup Curve Data Points Without Uncertainties

60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
195	710	301	726	195	600	301	632		
200	726	301	744	200	611	301	635		
205	744	301	763	205	622	301	650		
210	763	301	785	210	635	301	650		
215	785	301	809	215	650	301	666		
220	809	301	835	220	666	301	684		
225	835	301	864	225	684	301	704		
230	864	301	896	230	704	301	726		
235	896	301	932	235	726	301	750		
240	932	301	971	240	750	301	777		
245	971	301	1015	245	777	301	807		
250	1015	301	1063	250	807	301	840		
255	1063	301	1116	255	840	301	877		
260	1116	305	1174	260	877	305	917		
265	1174	310	1238	265	917	310	962		
270	1238	315	1310	270	962	315	1011		
275	1310	320	1388	275	1011	320	1066		
280	1388	325	1472	280	1066	325	1126		
285	1472	330	1543	285	1126	330	1192		
290	1543	335	1622	290	1192	335	1265		
295	1622	340	1710	295	1265	340	1346		
300	1710	345	1806	300	1346	345	1435		
305	1806	350	1912	305	1435	350	1533		
310	1912	355	2029	310	1533	355	1641		
315	2029	360	2159	315	1641	360	1760		
320	2159	365	2302	320	1760	365	1892		
325	2302	370	2459	325	1892	370	2037		

Table 5-6 (cont.) Beaver Valley Unit 1 44.18 EFPY Heatup Curve Data Points Without Uncertainties									
60°F/hr. Heatup		60°F/hr. Criticality		100°F/hr. Heatup		100°F/hr. Criticality		Leak Test Limit	
T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)	T(°F)	P (psig)
330	2459			330	2037	375	2197		
				335	2197	380	2373		
				340	2373				

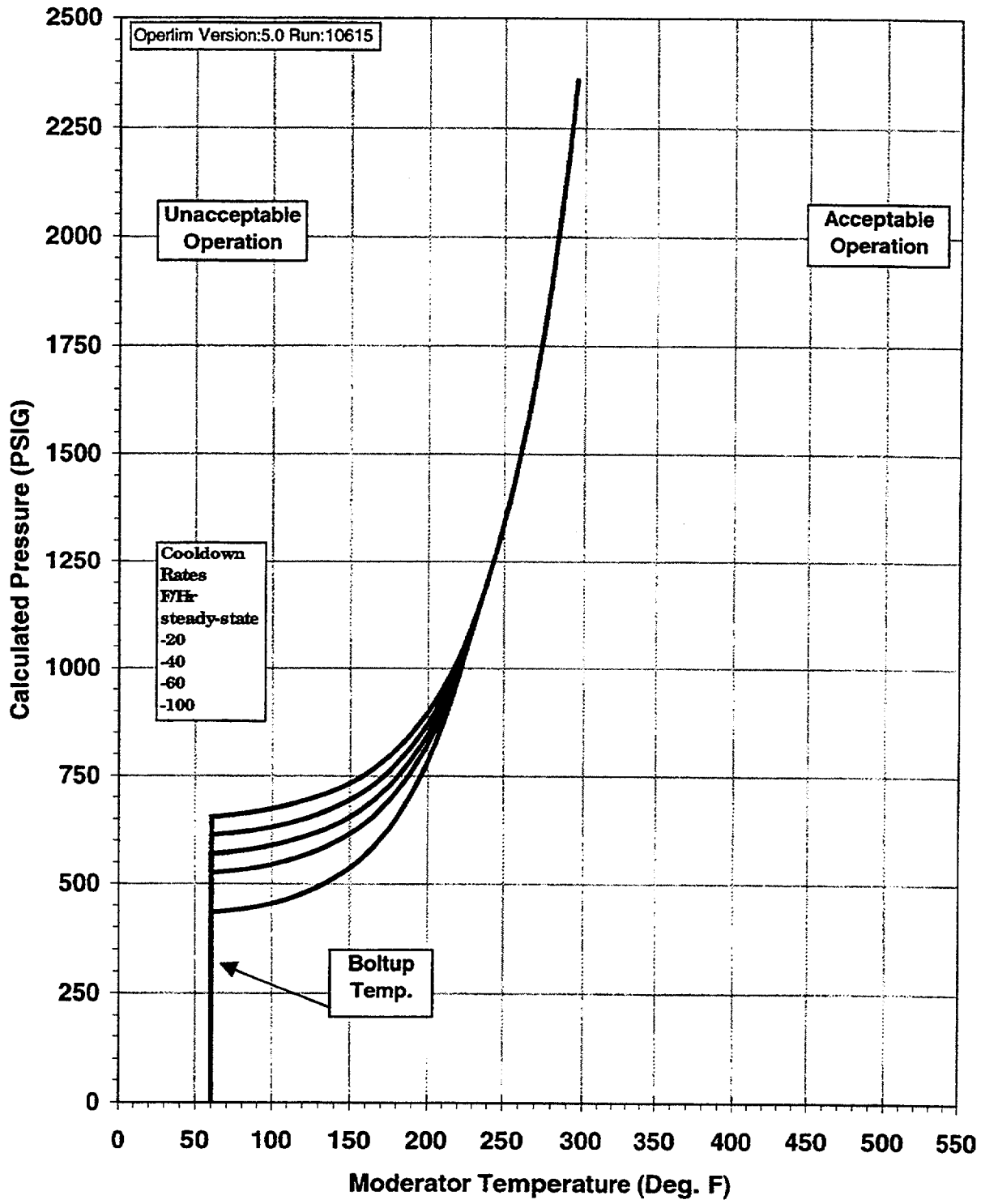

Figure 5-1 Cooldown Curves for 22 EFPY (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

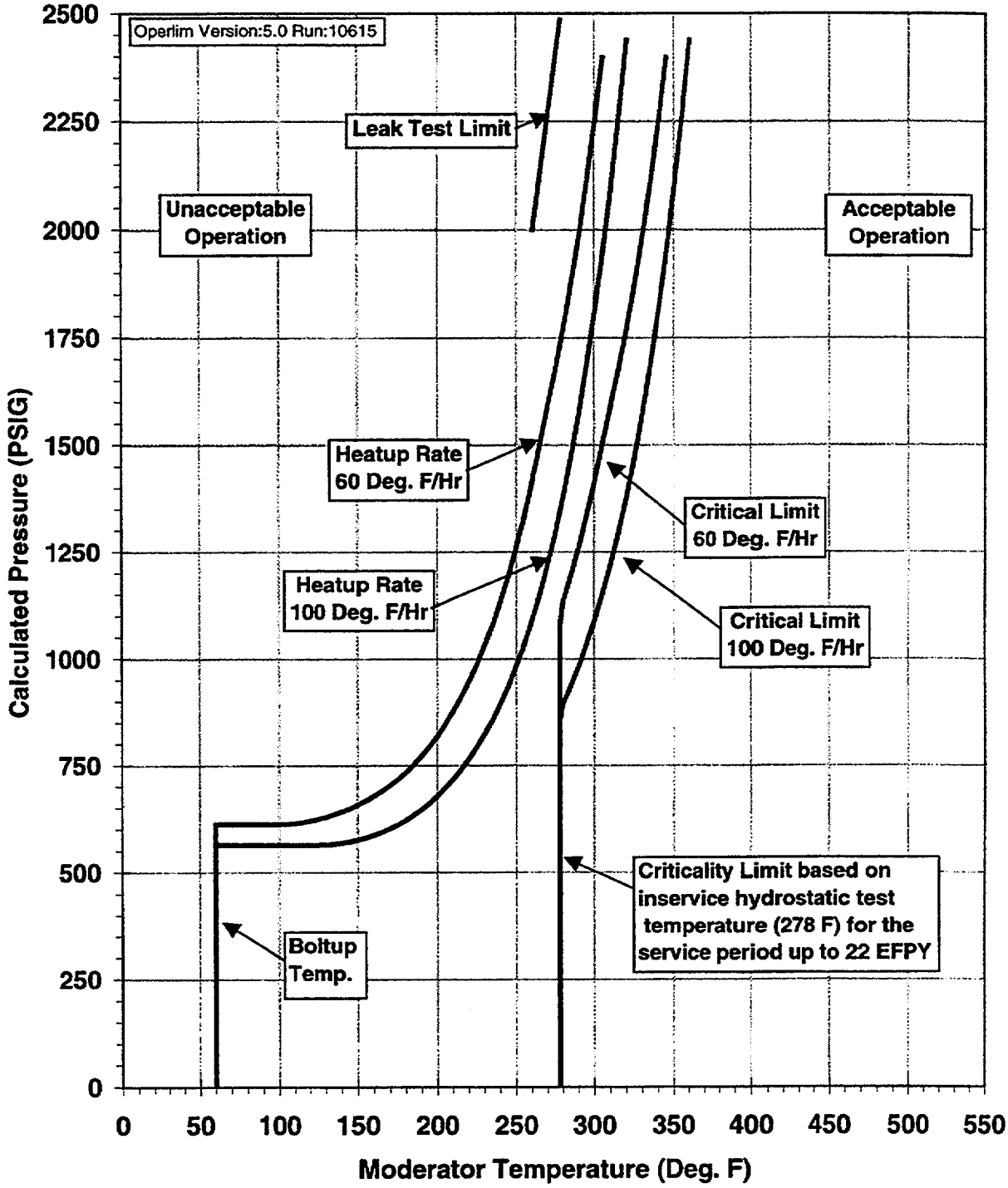

Figure 5-2 Heatup Curves for 22 EFPY, Composite (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

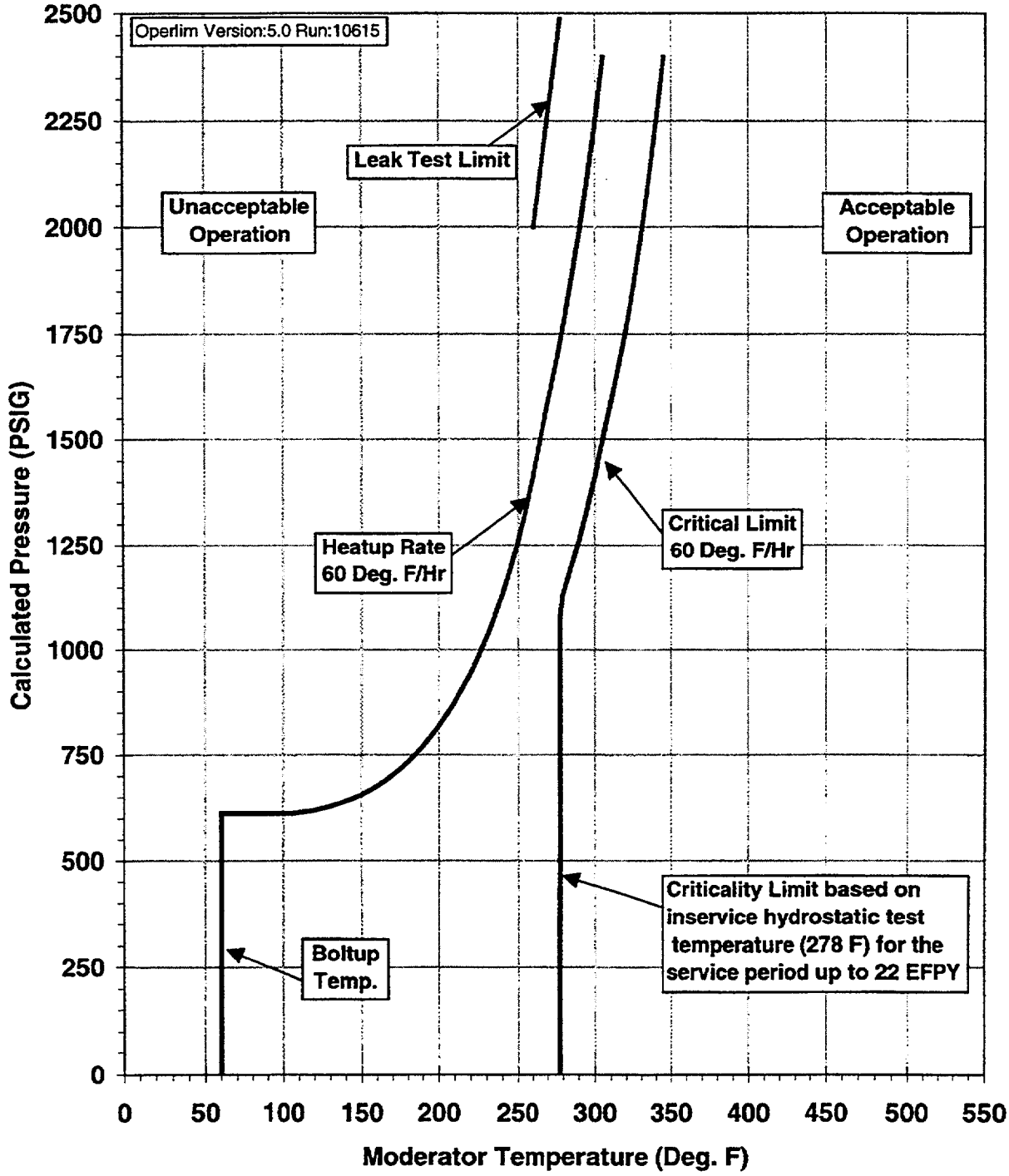

Figure 5-3 Heatup Curves for 22 EFPY, Heatup Rate of 60 Deg. F/Hr (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

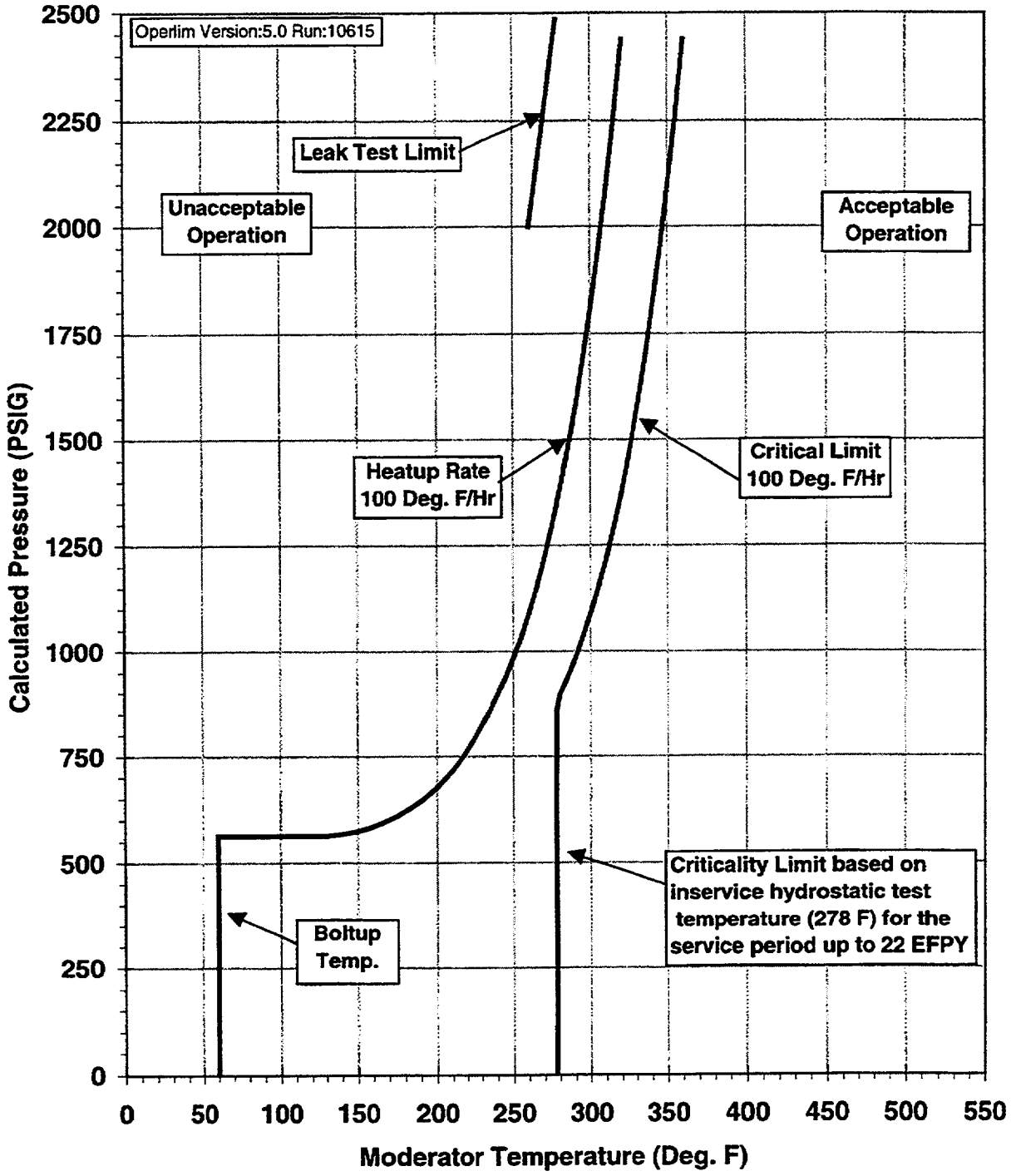

Figure 5-4 Heatup Curves for 22 EFPY, Heatup Rate of 100 Deg. F/Hr (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

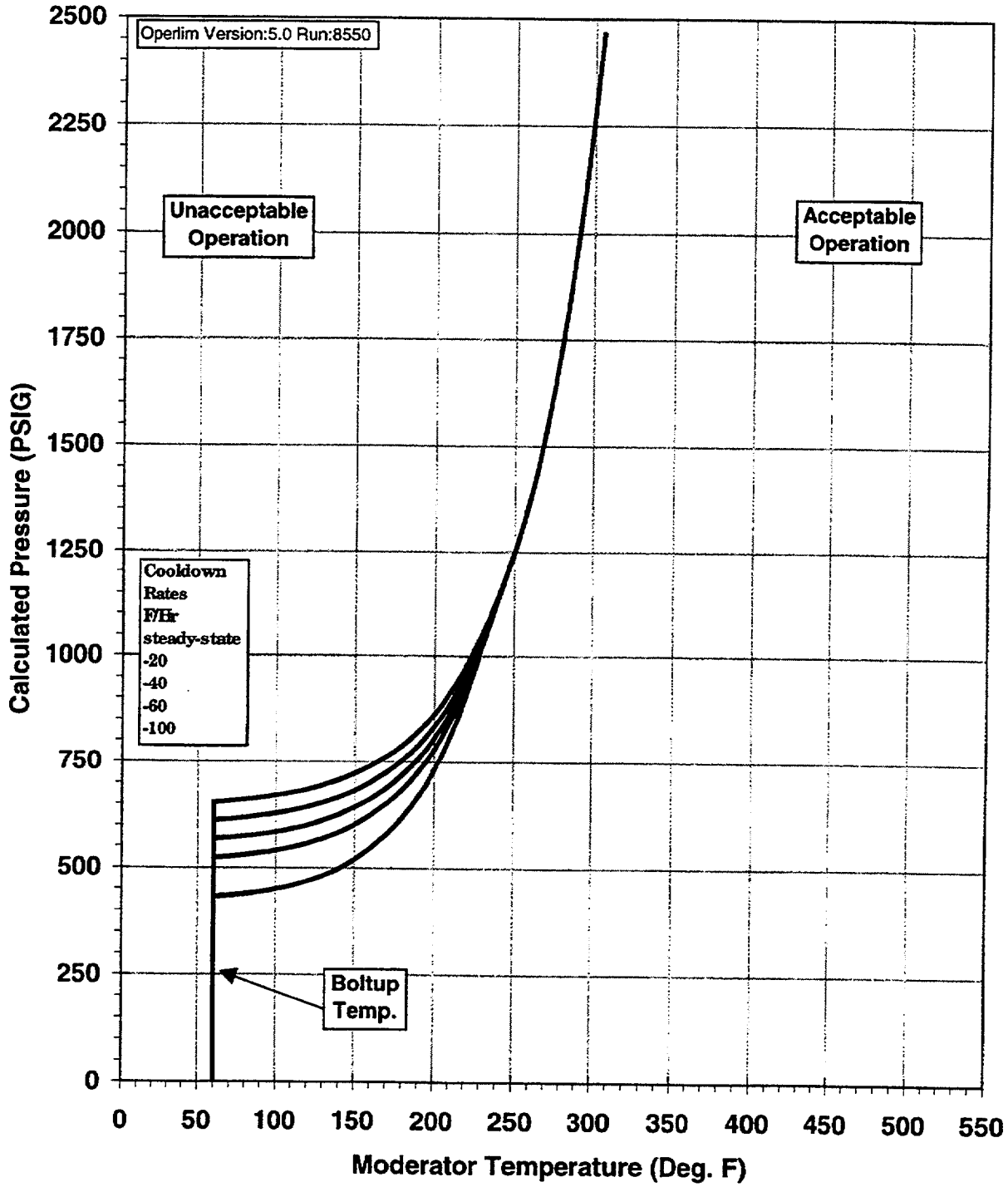

Figure 5-5 Cooldown Curves for 27.44 EFPY (ASME Code Case N-640 and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

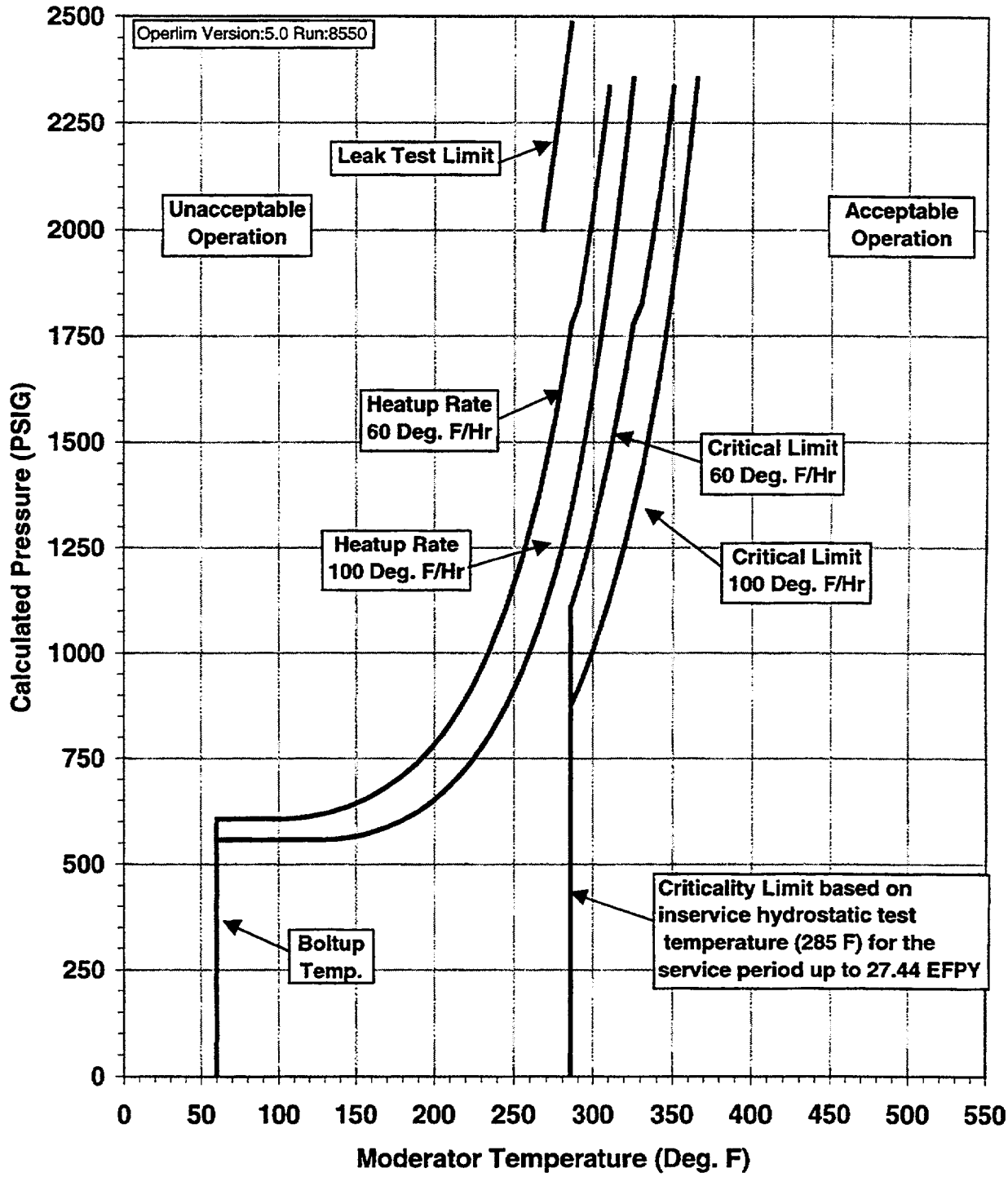

Figure 5-6 Heatup Curves for 27.44 EFPY, Composite (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

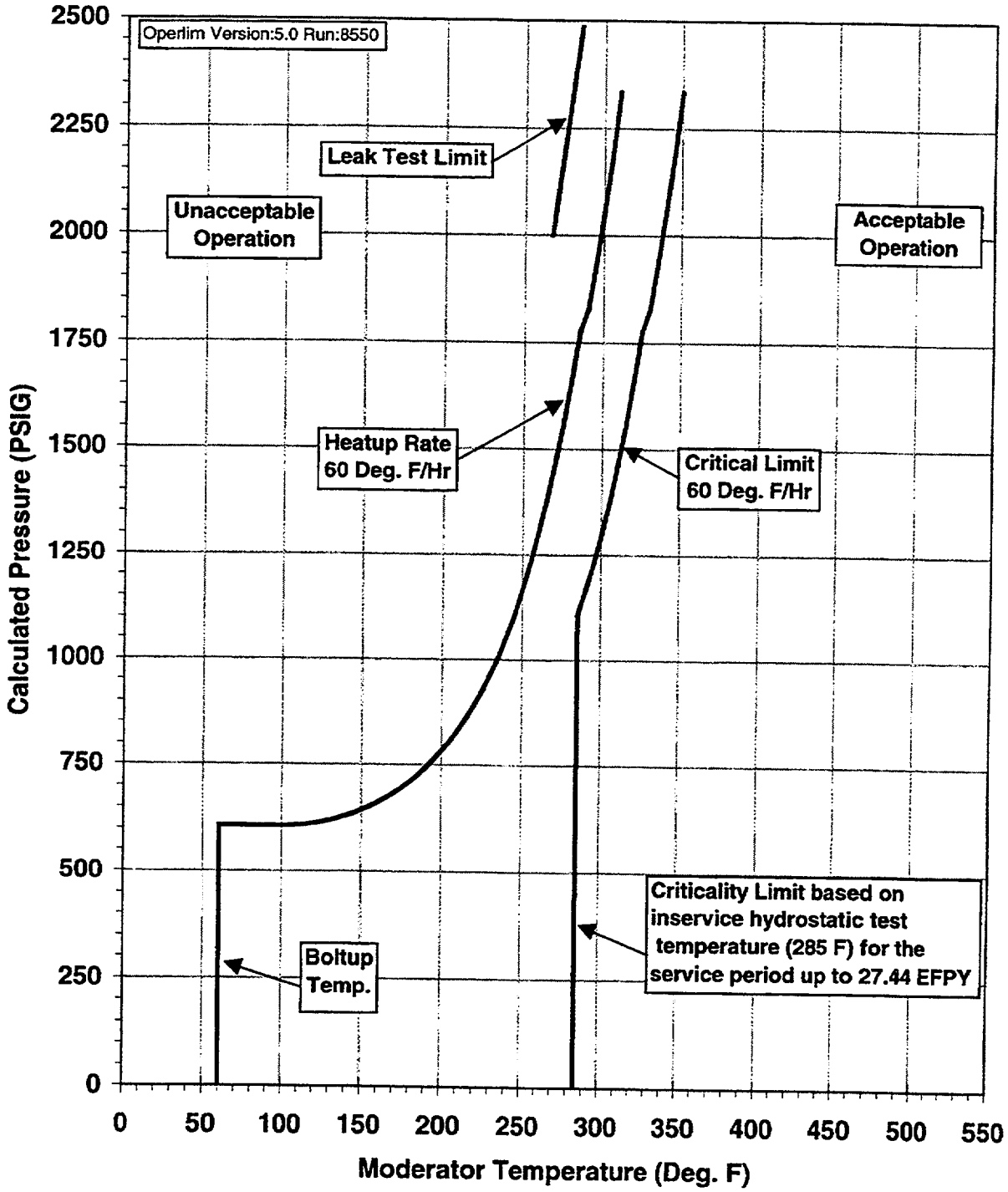

Figure 5-7 Heatup Curves for 27.44 EFPY, Heatup Rate of 60 Deg. F/Hr (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

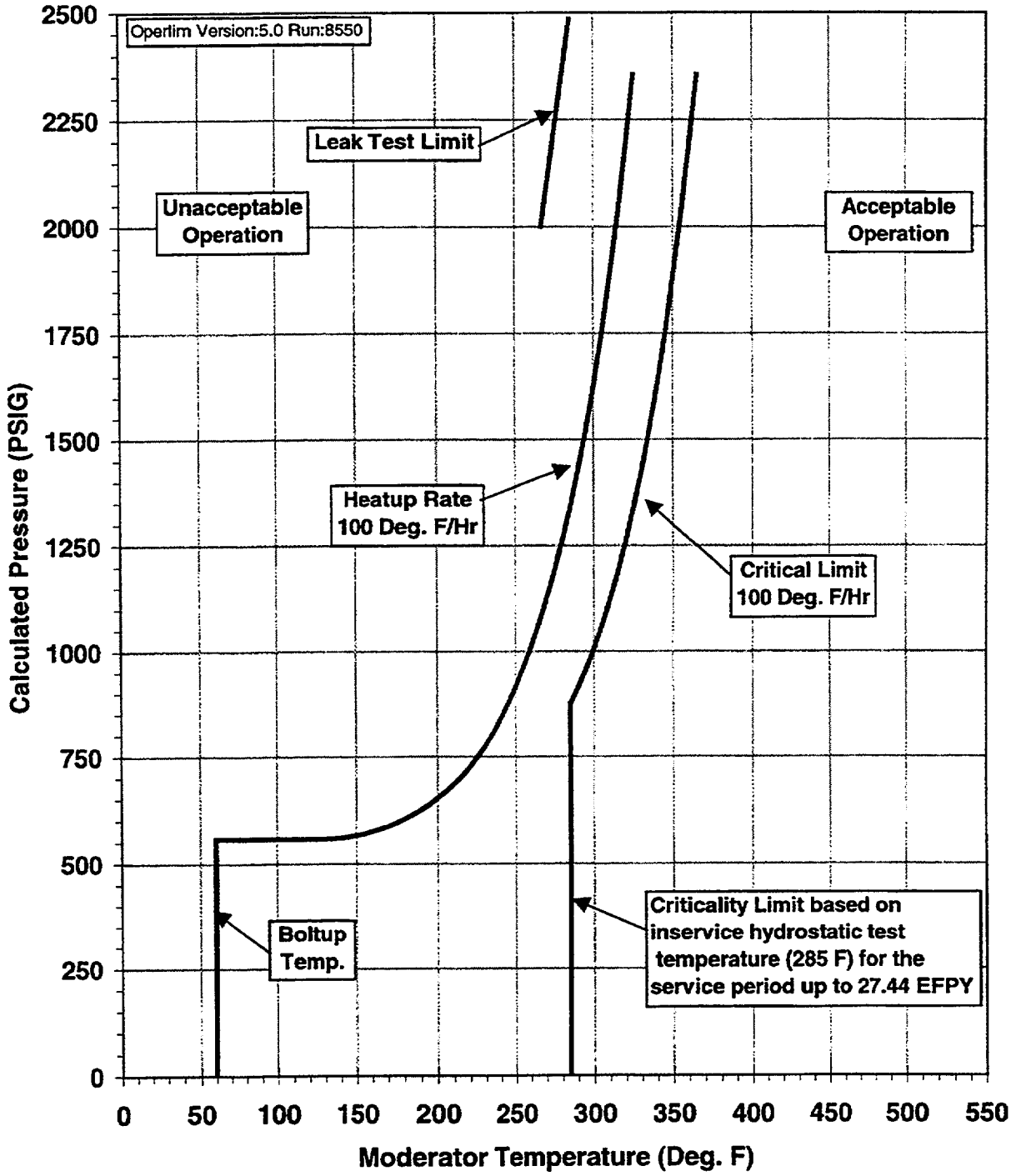

Figure 5-8 Heatup Curves for 27.44 EFPY, Heatup Rate of 100 Deg. F/Hr (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

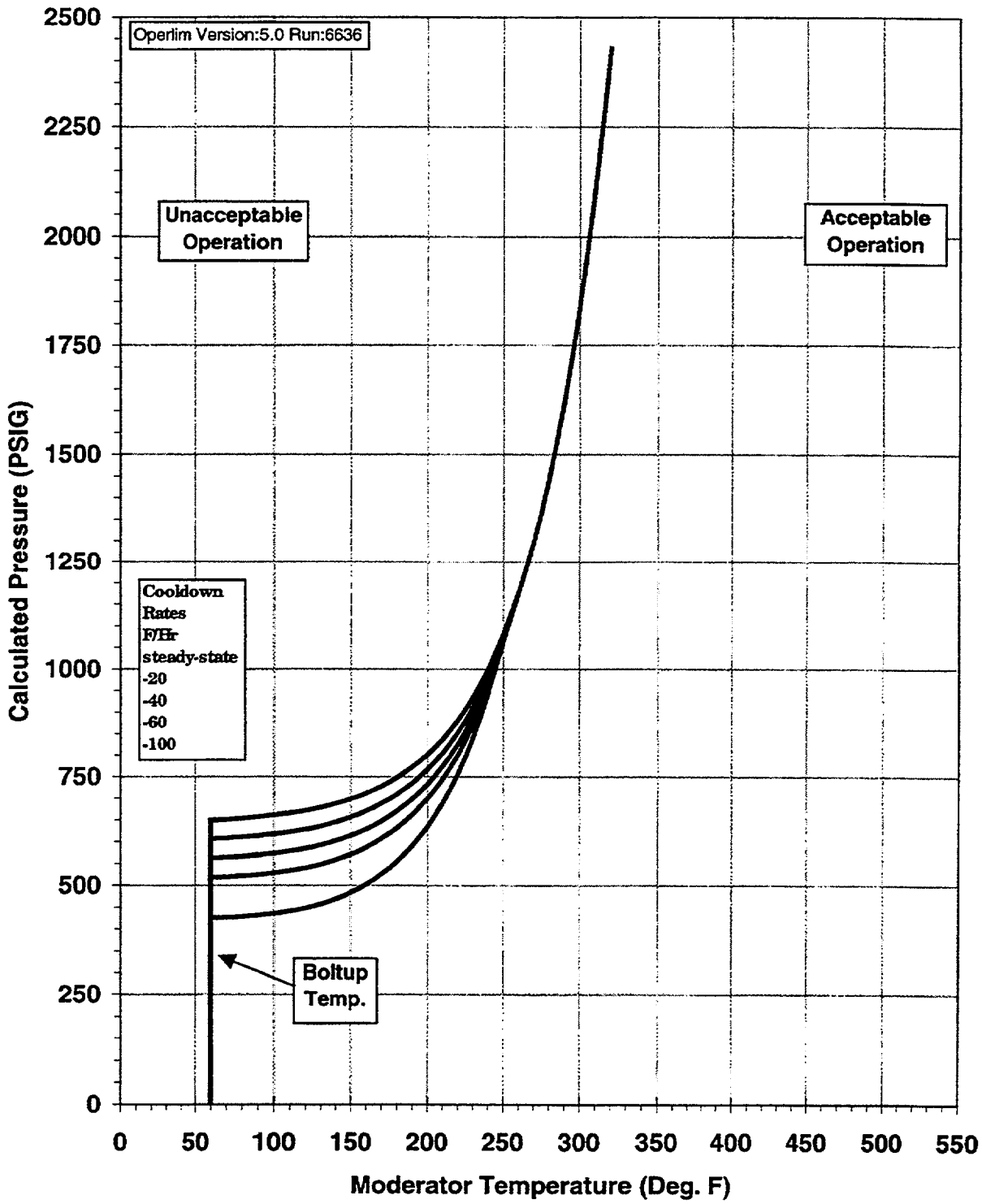

Figure 5-9 Cooldown Curves for 44.18 EFPY (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

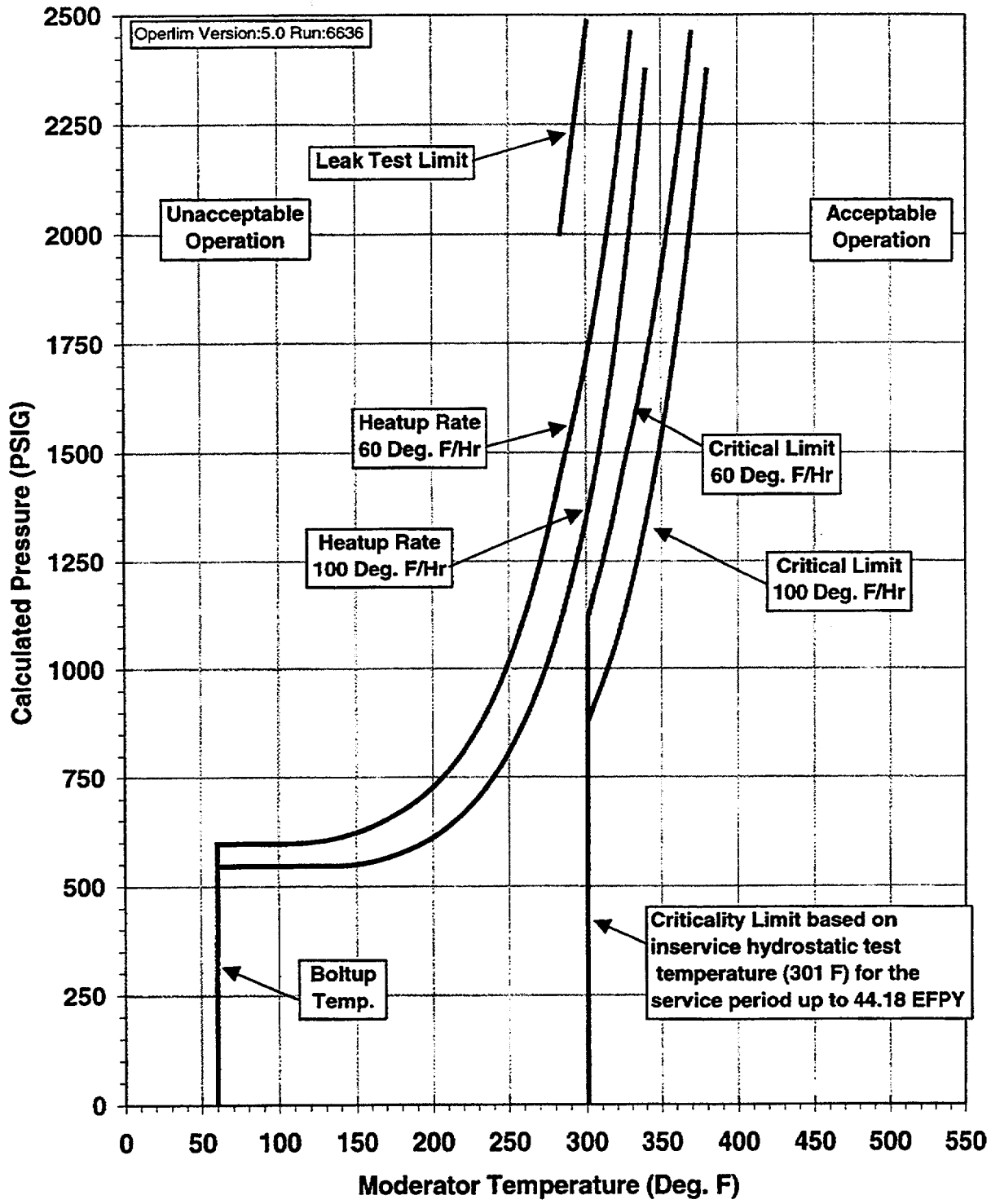

Figure 5-10 Heatup Curves for 44.18 EFPY, Composite (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

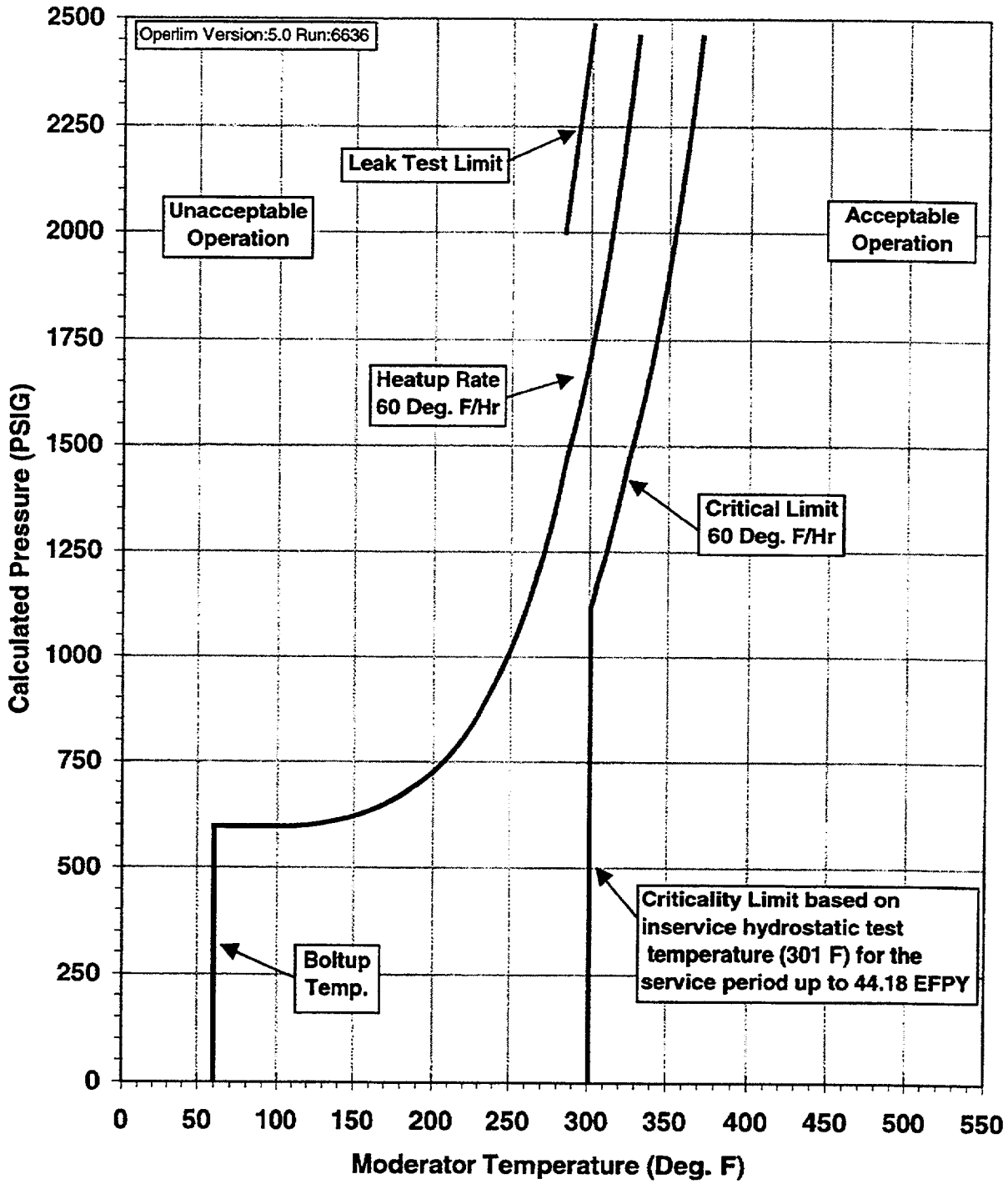

Figure 5-11 Heatup Curves for 44.18 EFPY, Heatup Rate of 60 Deg. F/Hr (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

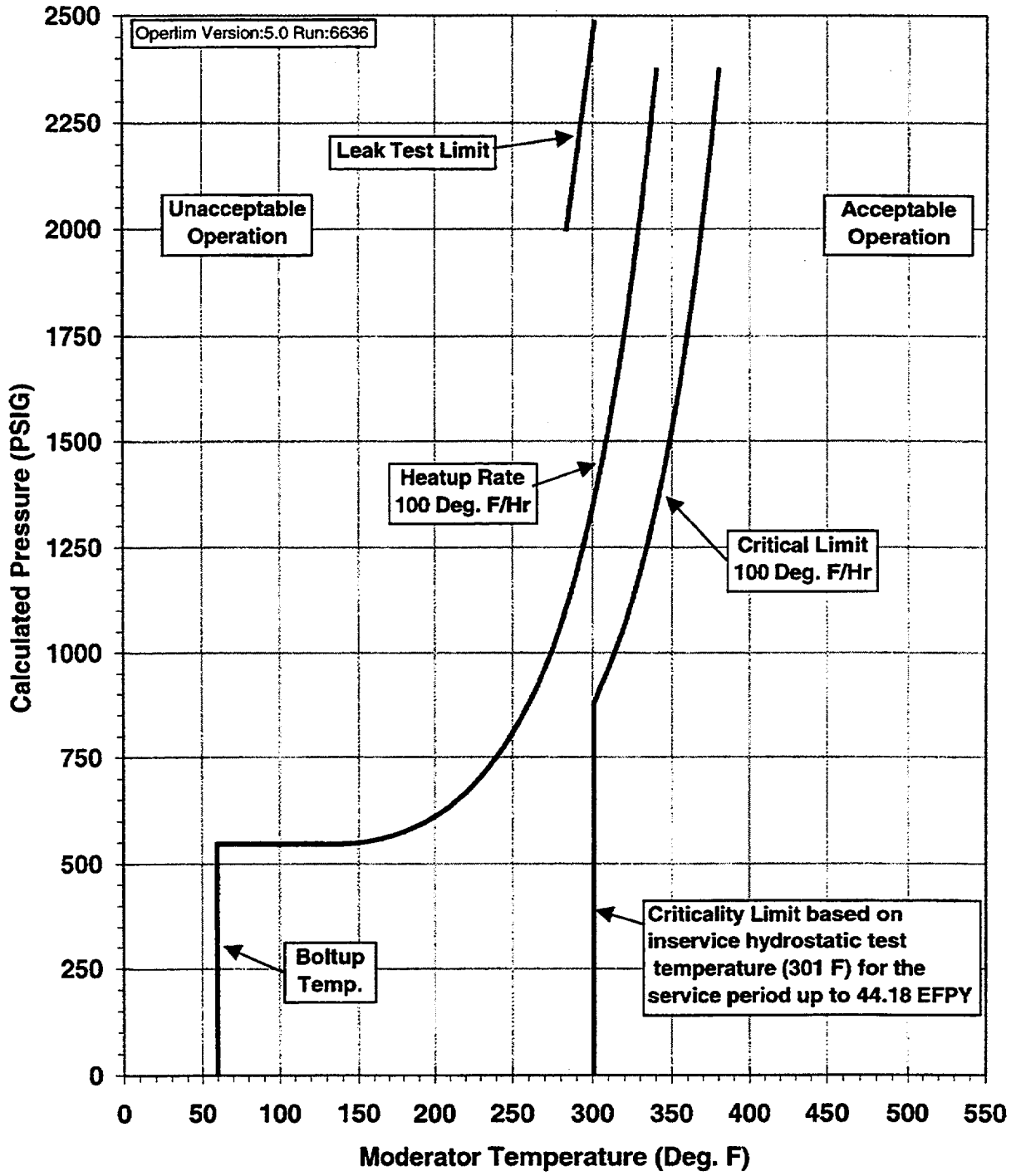

Figure 5-12 Heatup Curves for 44.18 EFPY, Heatup Rate of 100 Deg. F/Hr (Master Curve Methodology and 1996 Appendix G are Applicable) (No Uncertainties for Instrumentation Errors)

6 REFERENCES

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3. WCAP-15624, "Fracture Toughness Material Property Report for BVPS-1," W. L. Server, et al., November 2001.

4. Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," U.S. Nuclear Regulatory Commission, May, 1988.

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10. 1989 Section III, Division 1 of the ASME Boiler and Pressure Vessel Code, paragraph NB-2331, "Materials for Vessels."

11. WCAP-15571, "Analysis of Capsule Y from First Energy Company Beaver Valley Unit 1 Reactor Vessel Radiation Surveillance Program," C. Brown, et al., November 2000.

12. WCAP-15570, "Beaver Valley Unit 1 Heatup and Cooldown Limit Curves for Normal Operation," C. Brown, et al., November 2000.