Materials Reliability Program: Risk-Informed Revision of ASME Section XI Appendix G – Proof of Concept (MRP-143)

1009546

This report describes research sponsored by EPRI and the U.S. Department of Energy (Award No. DE-FC07-03ID14536).

Materials Reliability Program: Risk-Informed Revision of ASME Section XI Appendix G – Proof of Concept (MRP-143)

1009546

Technical Update, March 2005

Cosponsor
U.S. Department of Energy
1000 Independence Avenue
Washington, DC

EPRI Project Manager
S. Rosinski

Electric Power Research Institute • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Westinghouse Electric Company

XGEN Engineering

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

CITATIONS

This report was prepared by

Westinghouse Electric Company
P.O. Box 355
Pittsburgh, PA 15230

Principal Investigators
B. Bishop
N. Palm
T. Meyer
W. Bamford
Dr. R. Lott
S. Byrne
T. Laubham

XGEN Engineering
7173 Queensbridge Way
San Jose, CA 95120-4281

Principal Investigator
Dr. S. Ranganath

This report describes research sponsored by EPRI and the U.S. Department of Energy (Award No. DE-FC07-03ID14536. Task 10).

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors(s) and do not necessarily reflect the views of the Department of Energy.

The report is a corporate document that should be cited in the literature in the following manner:

Materials Reliability Program: Risk-Informed Revision of ASME Section XI Appendix G – Proof of Concept (MRP-143), EPRI, Palo Alto, CA, and U.S. Department of Energy, Washington, D.C.: 2005. 1009546.

REPORT SUMMARY

A joint research program between the EPRI Materials Reliability Program (MRP) and the Boiling Water Reactor Vessel and Internals Project (BWRVIP) has been initiated to examine the use of risk-informed methods to modify ASME Section XI, Appendix G procedures for determining pressure-temperature (P-T) limit curves for plant heat-up and cool-down. This report summarizes results for one of three proof-of-concept studies funded under this joint program. Results demonstrate that by using risk-informed methods, the current Appendix G approach can be significantly relaxed while not compromising vessel integrity.

Background

ASME Section XI, Appendix G provides procedures for determining pressure-temperature limit curves for plant heat-up and cool-down. These procedures were based on Welding Research Council Bulletin WRC-175, developed over thirty years ago. The methodology is considered to be very conservative because it contains a large margin against fracture. Under certain conditions, it produces very restrictive operating limits thereby affecting plant availability and increasing the potential for violation of operating limits. Furthermore, plant operational limits such those imposed by the Low Temperature Over Pressurization (LTOP) protection systems and the physical limitations on achievable heating and cooling rates provide additional assurances that these already conservative limits are seldom approached. Because of the significant risk margins determined from NRC and EPRI studies on Pressurized Thermal Shock (PTS) in pressurized water reactors (PWRs), it was recognized that some relaxation of the conservatisms in the current Appendix G procedure is justified for both PWRs and boiling water reactors (BWRs).

Objective

- Demonstrate that risk-informed methods can be used to relax the conservatisms included in the current methodology while maintaining adequate levels of structural integrity.

Approach

NRC Research along with the EPRI MRP has been reevaluating the current PTS rule (10CFR50.61) for the past several years. This effort has lead to significant improvements in the probabilistic fracture mechanics (PFM) code, FAVOR, for use in reactor vessel integrity analysis. It is possible to use the FAVOR code to test different assumed limiting cool-down curves and select a revised Appendix G that produces an acceptable level of risk.

Information was used from a Westinghouse feasibility study that examined the current range of plant cool-down operations in the Westinghouse NSSS fleet. The goal of the investigation was

to determine if the dynamic cool-down operating limits of the PWR systems could be relaxed. The feasibility study investigated the structural limits on the reactor vessel, NSSS control system capabilities, and reactor coolant system water chemistry. This information was used to develop limiting but realistic cool-down transients for input into the PFM evaluation.

Deterministic sensitivity studies and FAVOR code PFM runs were performed to determine the extent to which the current Appendix G parameters could be relaxed. While most of the evaluation was performed for pressurized water reactors (PWR), the effect of the proposed changes were evaluated for boiling water reactors (BWR) and other components.

Results and Conclusions
Results of this study suggest that risk-informed methods can be used to significantly relax the current ASME and NRC Appendix G requirements while still maintaining satisfactory levels of reactor vessel structural integrity. Specifically, the conservative risk analyses for initiation only have shown that three options for changing the current requirements for PWR plants are possible. These three options demonstrate the flexibility provided by the risk-informed Appendix G concept to satisfy both the needs for PWR plant operators, such as reducing cool-down time by 90 minutes, as well as the requirements of ASME code groups that would have to approve the proposed changes to Appendix G. Since the pressure test is the limiting structural conditions for BWR vessels, the proposed concept of relaxing Appendix G requirements provides significant relief for this condition. In one example, the time to obtain the required pressure test temperature following refueling can be reduced by 12 hours. The risk-informed analysis methods used for this work are the same as those used by NRC Research to support significant relaxation of the integrity requirements for Pressurized Thermal Shock (PTS) in highly embrittled vessels. This relaxation in Appendix G requirements directly translates into significant improvements in operational flexibility.

EPRI Perspective
The determination of P-T limits is the last major element of RPV integrity analysis that is being evaluated using risk-informed approaches. Results of this work will ultimately provide an integrated approach to RPV integrity assessment that will ensure safe and reliable operation for 60 years and beyond. The joint MRP/BWRVIP effort to revise the P-T limit curve methodology is currently focused on three proof-of-concept studies to investigate various risk-informed approaches and demonstrate feasibility. This report, along with the other proof-of-concept studies (1011742 and 1011691) are an important contribution in pursuit of a final risk-informed methodology.

Keywords
Reactor pressure vessel integrity
Probabilistic fracture mechanics
ASME Section XI Appendix G

CONTENTS

C.5 Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 200°F/hr Cool-down Rate after RHR Initiation C-18

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Background

ASME Section XI, Appendix G [1] provides the methodology for determining pressure-temperature limit (P-T) curves for plant heat-up and cool-down. Using this methodology, curves are designed to assure that the combination of stresses due to internal pressure and thermal gradients do not cause failure due to large postulated pre-existing flaws in the embrittled reactor pressure vessel beltline. The limit curves are based on a deterministic fracture mechanics analysis at an assumed limiting level of embrittlement. The Appendix G methodology for calculating the P-T curves is based on Welding Research Council Bulletin WRC-175 [2], which was developed over thirty years ago. The methodology is considered to be very conservative, to maintain a large margin against fracture, and under certain conditions to produce very restrictive operating limits that could limit plant availability by increasing the potential for violation of the operating limits. Furthermore, operational limits such as those imposed by the Low Temperature Over Pressurization (LTOP) protection systems and the physical limitations on achievable heating and cooling rates provide additional assurances that these already conservative limits are seldom approached. The conservative factors that are contained in the current Appendix G approach are:

- A factor of two on primary pressure stress,
- An assumed surface-breaking flaw with a depth corresponding to 25% of the vessel wall thickness,
- The use of the lower bound K_{IC} fracture toughness curve, and
- A 2-sigma margin term applied to the estimated embrittlement index (irradiated RT_{NDT}).

Objective

The objective of this report is to demonstrate (i.e., provide a “proof of concept”) that risk-informed methods, including probabilistic fracture mechanics (PFM), can be used to justify the relaxation of some of the conservative factors contained in the Appendix G methodology. The risk-informed process for justifying the relaxation of requirements could be used to support the modification of the ASME Section XI Appendix G deterministic methodology.

This proof-of-concept study utilized input and information from the following two related efforts:

NRC PTS Risk Reevaluation [3]

NRC Research along with the EPRI MRP Task Group on Reactor Pressure Vessel (RPV) Integrity Issue Task Group has been performing a risk-informed reevaluation of the current PTS rule (10CFR50.61 [4]) for the past several years. This effort has lead to significant improvements in the probabilistic fracture mechanics code FAVOR [5] which is used in the analysis of PTS transients. This code provides a risk-informed method for analyzing reactor vessel integrity based on a realistic description of flaw distributions in reactor pressure vessels, calculation of actual applied stress intensities and best estimates of the fracture toughness. The probabilistic approach utilized in the FAVOR code analyzes the effects of the input distributions and uncertainties on key parameters in calculating the probability of reactor vessel failure associated with a particular PTS transient. The FAVOR code was used to evaluate different limiting cool-down curves and select a curve determination methodology (i.e. revised Appendix G) that produces curves with an acceptable level of risk.

Study on Feasibility of Accelerated Heat-up and Cool-down (See Appendix A)

During the late 1980’s and early 1990’s, Westinghouse was involved with the evaluation of large amounts of operating plant data that utilities provided to support evaluations of thermal stratification in the surge lines and pressurizer nozzles for plant life extension. A total of 45 years of operational history from nine plants was evaluated. In general, the evaluations of the data showed that the original design assumptions about operating transients that occurred while the units were at power were conservative and bounding. The investigations also revealed that there were differences between the actual plant heat-up and cool-down operating practices and those assumed in the original design analysis. Further investigation showed that due to interpretation differences with respect to the limiting vessel heat-up and cool-down rates, there was the possibility that the plant could be operating in a regime that had not been fully evaluated. However, follow-on studies of these possible regimes have shown that no real condition adverse to plant or public safety exists due to the differences between actual operations and those assumed by designers because of the significant conservatisms in the pressure-temperature limits.

These studies also showed that there was a need for improvement in the methods used to qualify P-T limits and limiting conditions for operations and that the communication with utility operators needs to be improved. One need for improvement identified was in the plant operators’ knowledge of the basis for the limiting conditions of operations with respect to structural integrity. Another need was improvement in the analysts’ understanding of the actual operating practices during plant heat-up and cool-down operations. As a result of these needs, Westinghouse developed an “apparatus and method for monitoring pressure-temperature margins” in pressurized water reactor (PWR) systems [6].

Shortly thereafter, Westinghouse funded a technical feasibility study for applying the new method to the actual and potential range of plant heat-up and cool-down operations in the Westinghouse NSSS fleet. The goal of this study was to determine if the dynamic heat-up and cool-down operating limits of the PWR systems could be relaxed. The study addressed three technical areas as follows:

- Structural limits were evaluated with respect to fracture resistance of the reactor vessel under a wide range of actual and extended operating conditions. This portion of the investigation utilized current ASME Appendix G methods and requirements for determining the fracture limits for an expanded range of postulated pressure and temperature time histories and embrittlement (RT_{NDT}) limits in order to determine the range of practical fracture limits.
- NSSS control systems capabilities were investigated to determine the controllable dynamic range of NSSS heat-up and cool-down operations. The maximum safe controlled range of plant heat-up and cool-down operations that could be managed by operating personnel using the existing plant control systems was determined. These studies were performed using the Westinghouse NSSS plant simulator located at the Waltz Mill Site in Madison, Pennsylvania.
- The effects of a wider dynamic plant cool-down range on the control of NSSS water chemistry were investigated to determine whether or not an accelerated cool-down would be advantageous.

The overall conclusion of the feasibility study was that accelerated cool-down was technically feasible. While the goal of the current study is not necessarily to support accelerated heat-up and cool-down, the information gathered as part of this feasibility study is most helpful in determining the range of possible cool-down curves for the Westinghouse NSSS fleet.

2
APPROACH

The purpose of this study is to demonstrate that probabilistic methods can be used to relax the conservatisms currently contained in the ASME Section XI Appendix G methodology for determining P-T limit curves for reactor pressure vessel heat-up and cool-down. The approach taken in this study utilized the FAVOR PFM Code used in the NRC PTS Risk Reevaluation Program and operational data from the Westinghouse feasibility study on accelerated cool-down. For this study, the Westinghouse NSSS and RPV design were analyzed. The Westinghouse feasibility study on accelerated cool-down showed that due to the embrittlement and thick cross-section, the RPV beltline was the most limiting region of the RCS. Since it is generally recognized that cool-down is more limiting than heat-up in terms of reactor vessel integrity, only cool-down transients were evaluated.

A flow chart for developing a risk-informed Appendix G is contained in Figure 2-1. Each numbered element, or step, of the flow chart that was used for this study is described below.

1. Actual / Possible Transients - Based on the work performed from the Westinghouse feasibility study on accelerated cool-down, a range of operating conditions were determined. Utility input was obtained to augment the range of cool-down transients considered.

2. Proposed Changes to Appendix G Factors – A new set of less conservative Appendix G factors was proposed. Deterministic sensitivity studies were performed to determine the relative effects of changing the factors. These sensitivity studies, which are detailed in Chapter 3, provided the basis for the proposed set of less conservative Appendix G factors.

3. Proposed Limiting Transients – Rather than analyze all possible cool-down transients, a set of proposed limiting transients was developed based on the transients determined in step 1. This set of transients is representative of possible limiting cool-down operation at domestic units. The deterministic sensitivity studies of Chapter 3 were also used to identify which transients were limiting for use in the subsequent probabilistic fracture mechanics evaluation.

4. PTS RPV Model - The PWR reactor vessel models (FAVOR input), developed for the pilot plants of the NRC PTS Risk Reevaluation effort, were utilized. For this proof-of-concept, only the Westinghouse NSSS design was evaluated and therefore, the RPV model which was used was that for the Westinghouse pilot plant in the NRC PTS Risk Reevaluation, Beaver Valley Unit 1 after 60 effective full power years (EFPY) of operation.

5. FAVOR Evaluation PWR & BWR - The FAVOR code with the reactor vessel model input was used to determine the probability of failure for each of the proposed transients from Step 3. For the purposes of this proof-of-concept study, failure was assumed to occur with crack initiation. The effect of the proposed approach on BWR operation was qualitatively evaluated later in Chapter 7.

6. Failure Frequency < Goal - The failure frequency (i.e., frequency of initiation) was compared to an acceptance criterion. Based on the PTS Risk Reevaluation Criteria [3], a risk goal of 1E-06 per year for initiation frequency was chosen. If the frequency was less than or equal to the risk goal, the proposed transient was acceptable and passed to the next step. If the frequency for the transient was greater than the risk goal, then the proposed changes to Appendix G were re-evaluated and modified as necessary.

7. Acceptable Changes to Appendix G - If all the failure frequencies for all the proposed transients met the risk goal then the proposed changes to the Appendix G factors were considered to be acceptable.

The following two steps were not utilized in this proof-of concept study. However, these steps could be used to move towards implementation of the relaxed Appendix G methodology.

8. Actual / Possible Operating Conditions (T, t, dT/dt) - In this step, a range of actual / possible operating temperatures and rates of temperature change would be determined for all the non-limiting Hu/Cd transients.

9. Envelope of Acceptable Conditions (P, T, dT/dt) - Using the newly determined Appendix G factors, limits on pressure could be determined for each actual / possible transient. The limits on pressure combined with the temperature and time operating conditions for the limiting transients, would form a complete envelope of acceptable operating conditions.

For a complete study of a risk-informed Appendix G methodology this process could be used to evaluate Westinghouse, CE, B&W, and BWR NSSS designs and reactor pressure vessels.

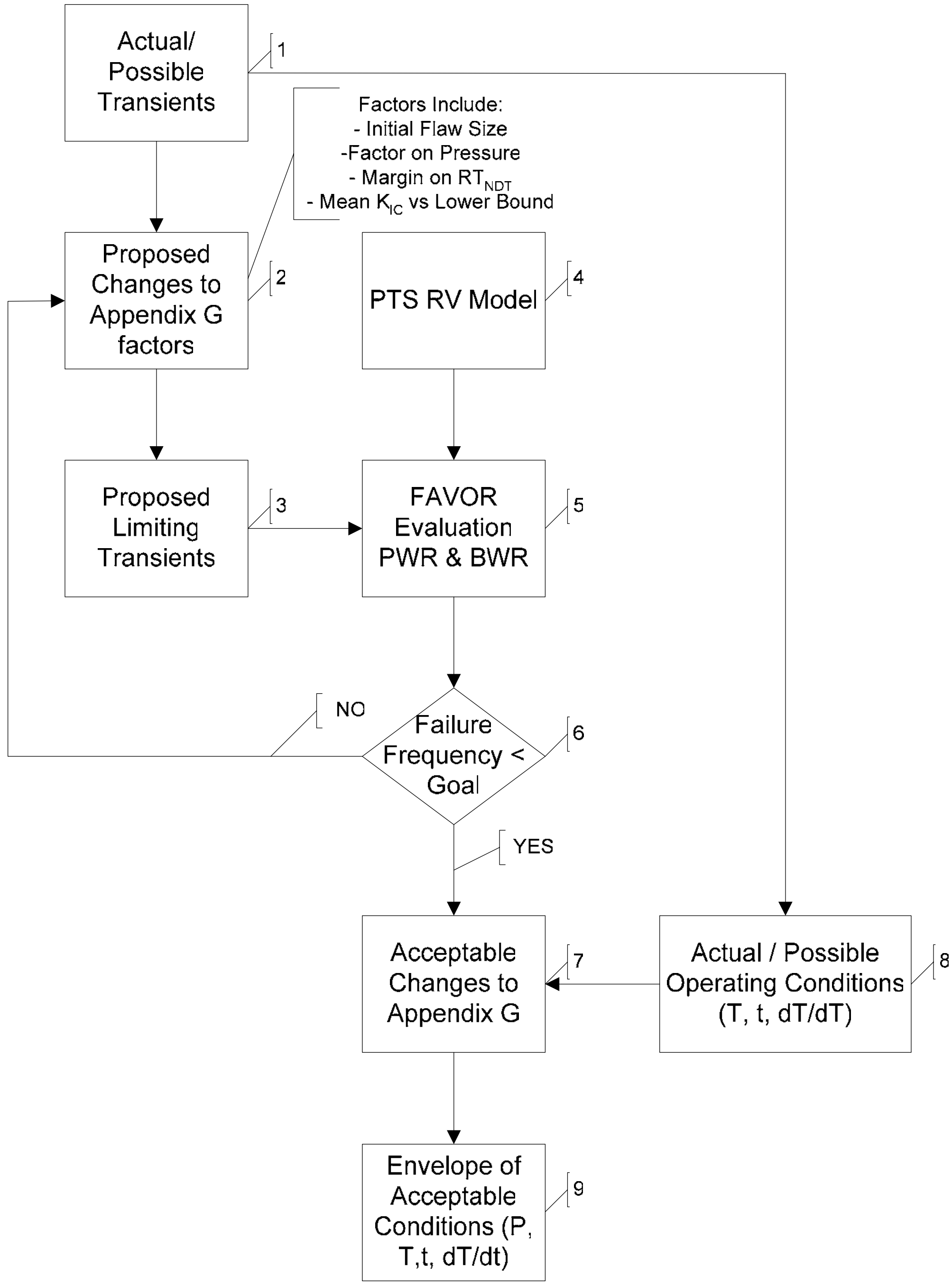


Figure 2-1
Approach for Determining Relaxed Appendix G Parameters

3 DETERMINISTIC SENSITIVITY STUDIES

Prior to performing any probabilistic evaluations of changes to the current Appendix G methodology, sensitivity studies were performed for various transients, safety factors, and margins. The purpose of these sensitivity studies was the following:

- To determine the relative effect of changing the Appendix G safety factors and margins and
- To determine which cool-down transients would be evaluated using the probabilistic FAVOR PFM Code.

Knowing that the execution of the FAVOR Code can take considerable time and computing resources, these sensitivity studies also minimized the number of probabilistic evaluations that were required.

Background

As previously mentioned, Westinghouse has performed a feasibility study on accelerated cool-down. As part of this feasibility study technical bases were developed to show that adequate safety margins exist to allow cooling rates greater than the maximum cool-down rate of 100°F/hr. A large number of cooling scenarios and material toughness conditions, in terms of RT_{NDT} (nil-ductility reference temperature), at the RPV beltline were investigated systematically to determine how fast the cooling rates can be, and how to control the cool-down curves, for safe operation.

The investigation was performed using Westinghouse deterministic fracture mechanics computer codes. These codes have been compared to the Westinghouse OPERLIM code for determining pressure-temperature limits and have been determined to produce similar results (See Appendix B). This code uses a methodology that has been accepted by the NRC for the calculation of P-T limit curves for heat-up and cool-down in accordance with the current Appendix G methodology [7]. As a result of the deterministic investigation, it was determined that from a fracture mechanics standpoint, a cool-down rate in excess of 200°F/hr was feasible even for the most highly irradiated reactor vessels.

After the fracture mechanics evaluations were performed, the accelerated cool-down rates were tested on the SNUPPS simulator at the Westinghouse Waltz Mill Site. This testing showed that a cool-down rate of 200°F/hr from normal operating temperature to 350°F was feasible from an operational standpoint. Once the temperature has reached 350°F, heat removal must be accomplished through the residual heat removal (RHR) system. This system is not capable of removing heat beyond the design rate of 100°F/hr. For this reason, a cool-down rate of 200°F/hr between normal operating temperature and RHR alignment was used for the sensitivity studies and after alignment to RHR a rate of 100°F/hr was used.

Two typical operational practices for cool-down are of note. During this study it was determined from operators' input that many Westinghouse plants hold pressure while initially decreasing temperature during cool-down. Secondly, all plants hold temperature at 350°F for approximately 30 minutes to allow for alignment to the residual heat removal system. Because these are common practices and the goal of this project is to develop more realistic heat-up and cool-down curves, these practices were considered in the sensitivity studies.

Sensitivity Studies on Effect of Changing Appendix G Factors

The first set of sensitivity studies was performed to determine the relative effect on the stress intensity factor of changing each of the Appendix G safety factors and margins. These sensitivity studies correspond to Step 2 of Figure 2-1. As part of the Westinghouse feasibility study on accelerated cool-down, various theoretical cool-down transients were postulated and analyzed in attempt to fully explore the limits for the reactor vessel. Several of the postulated transients, which were not acceptable when analyzed using the current Appendix G methodology, were chosen for the sensitivity studies on changing the Appendix G safety factors and margins.

The following changes to the Appendix G parameters were proposed for evaluation in the sensitivity studies:

- Assumption of a 1/8 T flaw rather than a ¼ T flaw – The assumption of a 1/8T flaw is more consistent with studies on flaw distributions performed for the NRC PTS Risk Reevaluation [8].
- Factor of 1 on pressure – The FAVOR code uses the actual pressure with no safety factors. To obtain correlation between the deterministic and probabilistic evaluations it would seem reasonable to eliminate the safety factor on pressure.
- Elimination of the margin term from RT_{NDT} – The FAVOR code considers uncertainties within the PFM analysis and it is therefore redundant to include a margin term in RT_{NDT}. To represent elimination of the margin term, the margin term was subtracted from various values of RT_{NDT}. 35°F was chosen as an average margin term for 32 EFPY from the NRC Reactor Vessel Integrity Database (RVID) [9] and therefore, this value was subtracted from the RT_{NDT} values used in the sensitivity studies.

The effects of the conservatism in the use of the lower bound K_{IC} fracture toughness curve instead of a mean-value curve were not evaluated or considered for change in this study. This is because there is no mean curve for fracture toughness in the ASME Code and all computer codes for the Appendix G deterministic calculations are programmed to use the lower-bound ASME curve for initiation toughness.

Evaluations were first performed by independently varying each of these proposed Appendix G parameters while holding the other two constant and then performed using combinations of the changes. These studies were performed with the limiting transients from the feasibility study discussed above at RT_{NDT} values of 70°F and 250°F. These values of RT_{NDT} were chosen based on their use in the feasibility study on accelerated cool-down and also to observe the effect of the changes at various levels of irradiation. Along with the cases run with the proposed changes, base cases were also run at these RT_{NDT} values with the existing Appendix G parameters. The output of each deterministic fracture mechanics sensitivity study was plotted as K_I and K_{IC} with respect to time. The point where K_I exceeds K_{IC} represents vessel failure per the current Appendix G methodology (i.e., crack initiation). By plotting the results in this manner it is evident if the scenario is successful and if so, how much overall margin remained between K_I and K_{IC} after changing the safety factors and margins. These evaluations showed the relative effect of changing each of the parameters.

The limiting transient from the feasibility study on accelerated cool-down which was chosen to be used in these sensitivity studies consisted of a 200°F/hr cool-down with an 80 minute hold in pressure and a 30 minute hold in temperature at 350°F. The pressure and temperature vs time plot for this transient is shown in Figure 3-1. The results of the sensitivity studies with this transient for a reactor vessel with an RT_{NDT} of 70°F are shown in Figure 3-2 to 3-5. The results for a reactor vessel with an RT_{NDT} of 250°F are shown in Figure 3-6 to 3-10.

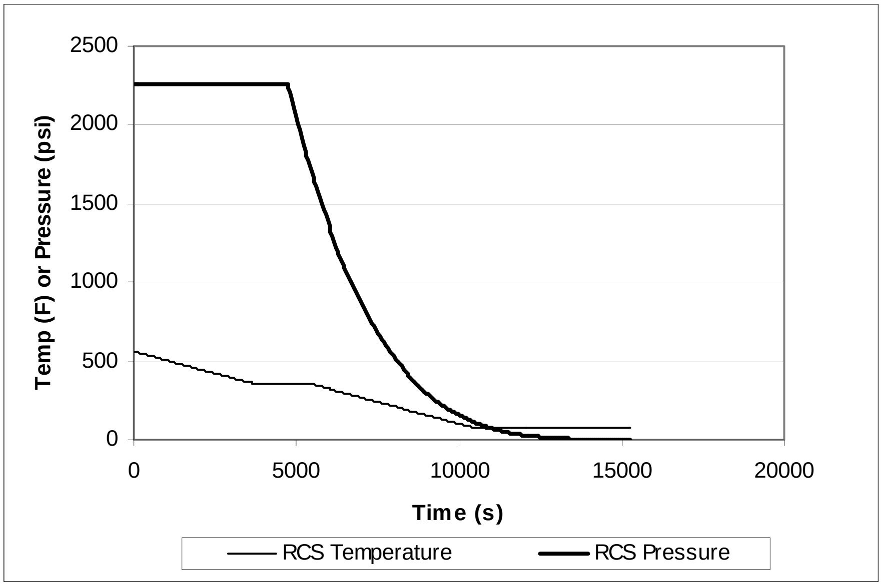


Figure 3-1
Limiting Transient Used for Sensitivity Studies

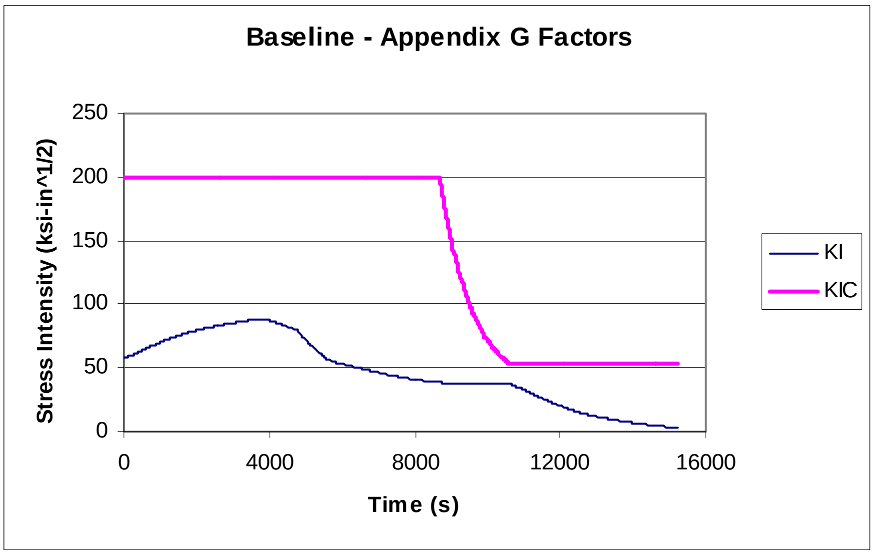


Figure 3-2
Appendix G Analysis Using Existing Factors, RT_{NDT} = 70°F

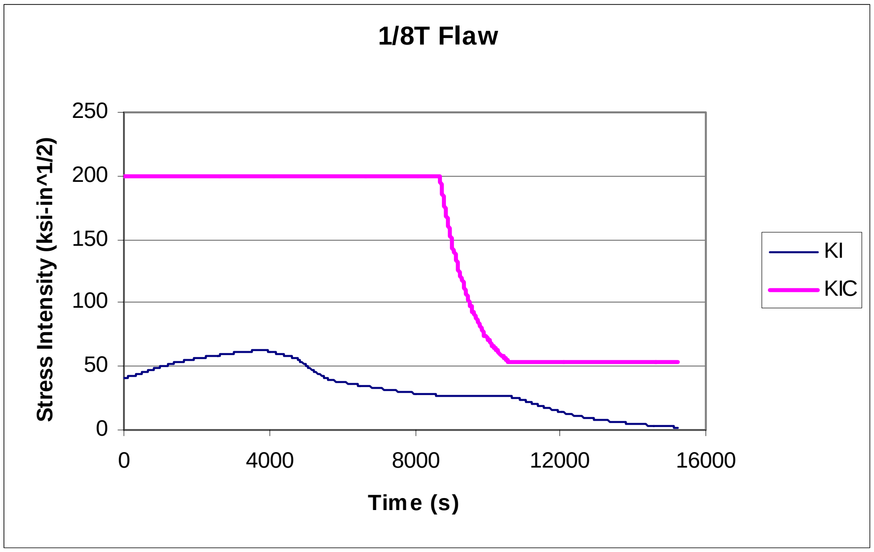


Figure 3-3
Appendix G Analysis Using a 1/8T Flaw, RT_{NDT} = 70°F

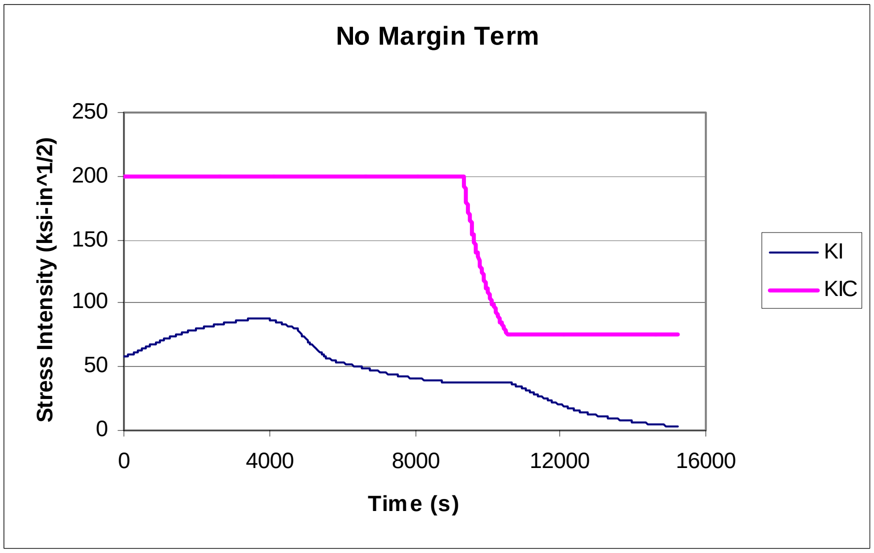


Figure 3-4
Appendix G Analysis Using No Margin Term, RT_{NDT} = 70°F

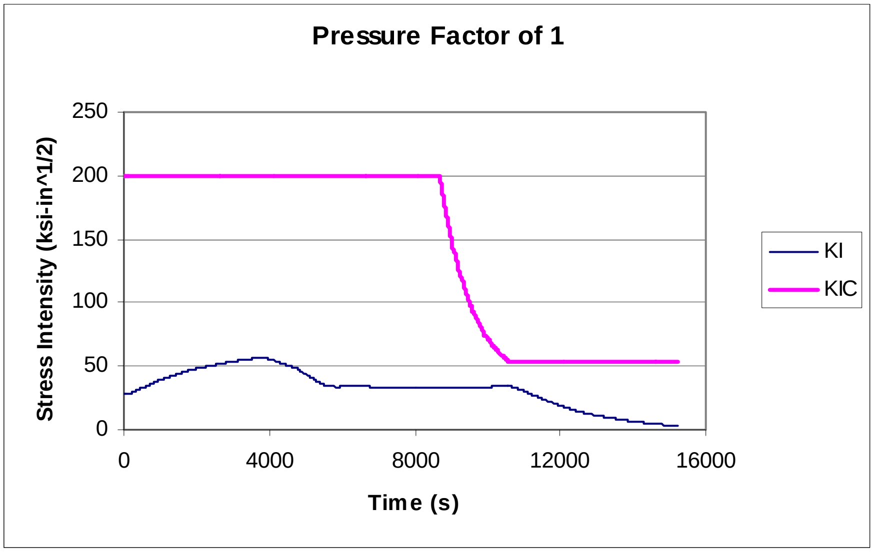


Figure 3-5
Appendix G Analysis Using a Pressure Factor of 1, RT_{NDT} = 70°F

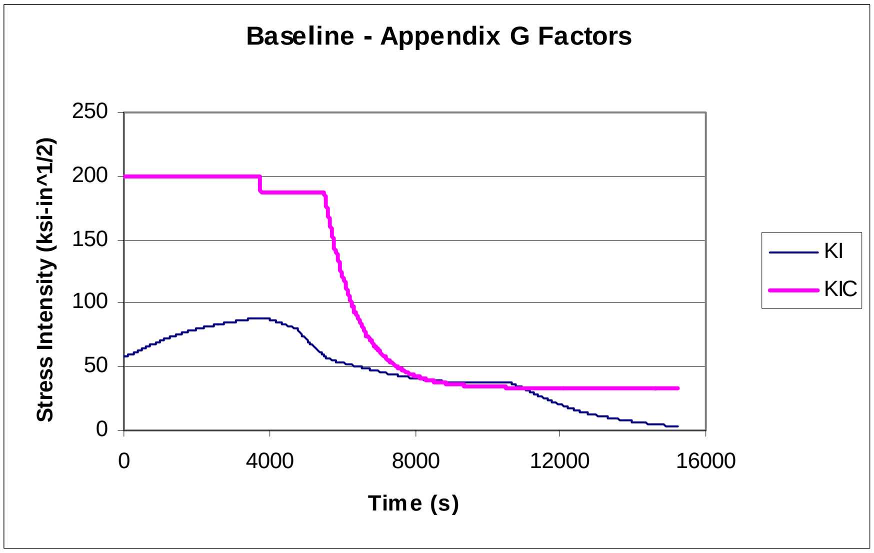


Figure 3-6
Appendix G Analysis Using Existing Factors, RT_{NDT} = 250°F

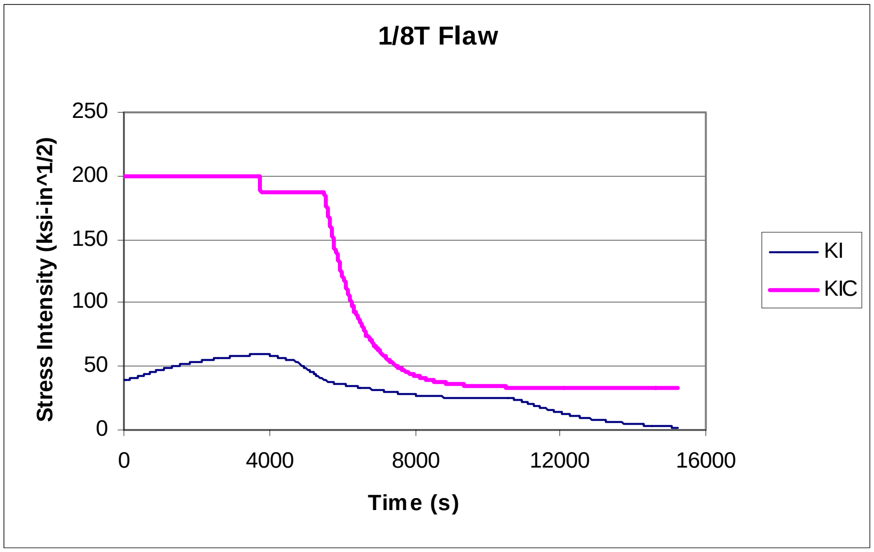


Figure 3-7
Appendix G Analysis Using a 1/8T Flaw, RT_{NDT} = 250°F

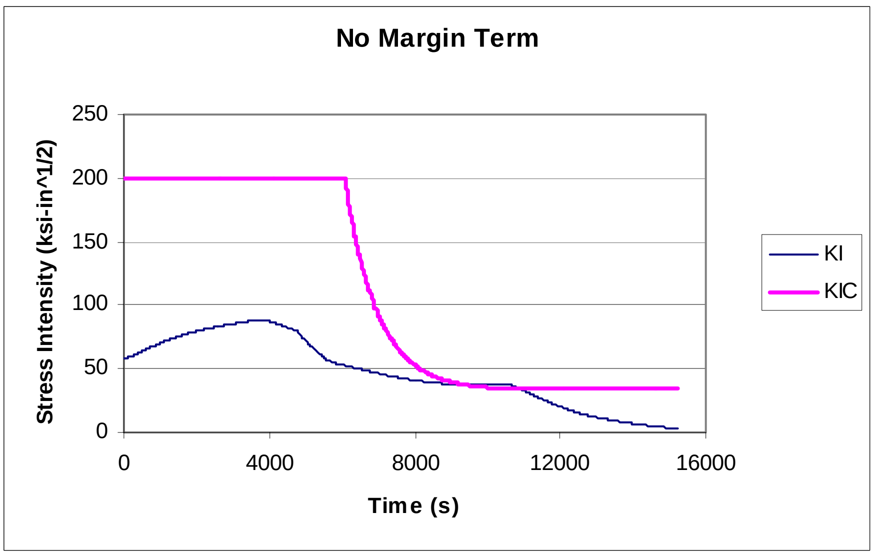


Figure 3-8
Appendix G Analysis Using No Margin Term, RT_{NDT} = 250°F

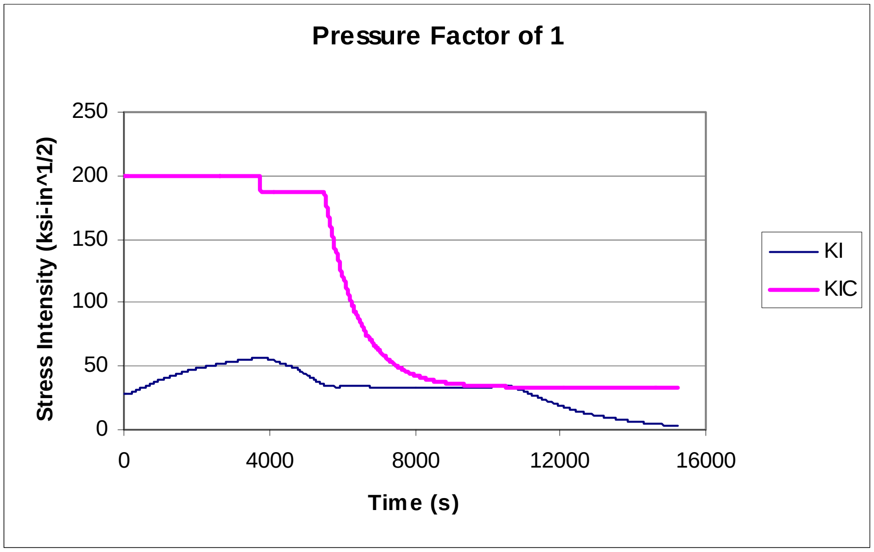


Figure 3-9
Appendix G Analysis Using a Pressure Factor of 1, RT_{NDT} = 250°F

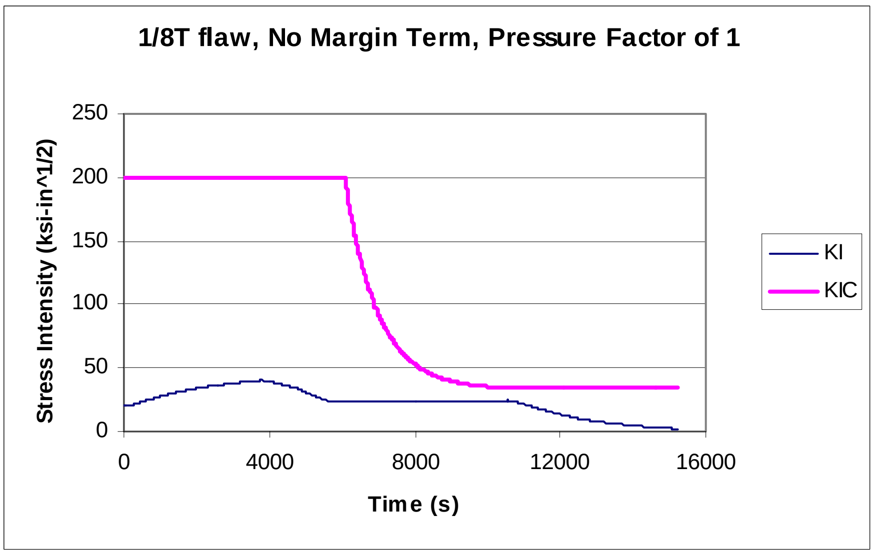


Figure 3-10
Appendix G Analysis Using All Relaxed Factors, RT_{NDT} = 250°F

The effect of changing each parameter can be seen by observing the difference between the K_I and K_{IC} lines at the point where they are closest. It is evident from Figure 3-2 through 3-10 that the parameter which has the most significant effect is the flaw depth. Assuming a 1/8 T flaw rather than a ¼ T flaw allows the RT_{NDT} =250°F case to be successful while in the baseline case, K_I exceeds K_{IC}. Reducing the factor on pressure from 2 to 1 has very little effect on the stress intensity except at the beginning of the cool-down transient. This is because the calculation of the total stress intensity for the reactor vessel is a combination of stress intensity due to thermal stresses and stress intensity due to pressure stresses. Once into the cool-down transient, the thermal stresses dominate due to the thermal gradient through the vessel wall. Furthermore, as the cool-down transient progresses the pressure is decreasing and the factor on stress is becoming less significant. While the factor on pressure affects only the pressure stress portion, the flaw size affects both the thermal and pressure portions. Finally, the point of greatest concern is typically at the end of the transient where the vessel fracture toughness is at its minimum. At this point the contribution due to the pressure stress is minimal. Therefore, for these sensitivity studies, the flaw size is controlling over the factor on pressure.

Elimination of the margin term was evaluated by subtracting 35°F from the RT_{NDT} values of 70°F and 250°F. Elimination of the margin term has a significant effect for cases where RT_{NDT} is low. For high values of RT_{NDT}, the exponential shape of the K_{IC} curve with respect to ($T - RT_{NDT}$) makes the elimination of the margin term less significant.

Sensitivity Studies on Cool-down Transients

After the sensitivity studies were performed for the Appendix G parameters, evaluations were performed to determine the limiting transients to be evaluated using the FAVOR code. These sensitivity studies correspond to Step 3 of Figure 2-1. In order to increase flexibility in cool-down operations and reflect typical operating practices, the following were considered in determining the limiting cool-down transients:

- 200°F/hr Cool-down – This has been demonstrated to be possible through the Westinghouse feasibility study and would increase operational flexibility.
- Pressure Hold at Cool-down Initiation – This is a departure from the design basis analysis but is common practice at a number of Westinghouse plants.
- Temperature Hold at 350°F – This is necessary for alignment to RHR; it is also common practice at Westinghouse plants and typically lasts at least 30 minutes.
- 375 psi Minimum Pressure for RCP Operation – This is the minimum net positive suction head (NPSH) for operation of the reactor coolant pumps (RCP) to keep cavitation from occurring.

For these sensitivity studies, it was decided to use a RT_{NDT} value that is enveloping for the fleet. The Westinghouse plant chosen for this evaluation is Beaver Valley Unit 1. This plant is being evaluated in the NRC PTS Risk Re-Evaluation Project. For 60 effective full power years (EFPY) of operation this plant is expected to have a maximum RT_{NDT} value of 332°F. The margin included in this RT_{NDT} value is 42°F. Therefore, the RT_{NDT} value used in the sensitivity studies, not including the margin term, is 290°F. The proposed Appendix G parameters identified in the sensitivity studies on changing the Appendix G parameters were also used for this sensitivity study.

Two sets of sensitivity studies were performed. The first set investigated the hold in pressure at the beginning of the cool-down transient. The second set investigated operation at elevated pressures at the end of the cool-down transient. Transients with a cool-down of 200°F/hr with a hold in temperature at 350°F were used. For the first set of sensitivity studies, the pressure was held at the beginning of the cool-down for 20, 50, or 80 minutes. The temperature and pressure vs. time plots for these transients are shown in Figure 3-11. The K_I and K_{IC} plots for these sensitivity studies are shown in Figures 3-12 to 3-15. Even with the increased cool-down rate and hold in pressure, there is still substantial margin between K_I and K_{IC}.

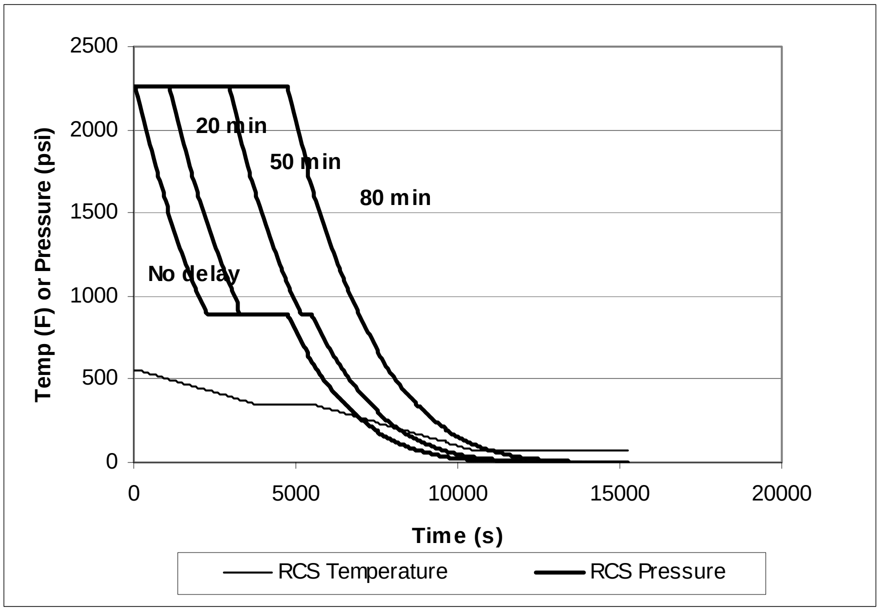


Figure 3-11
Transients for Sensitivity Studies on Pressure Hold at Beginning of Transient

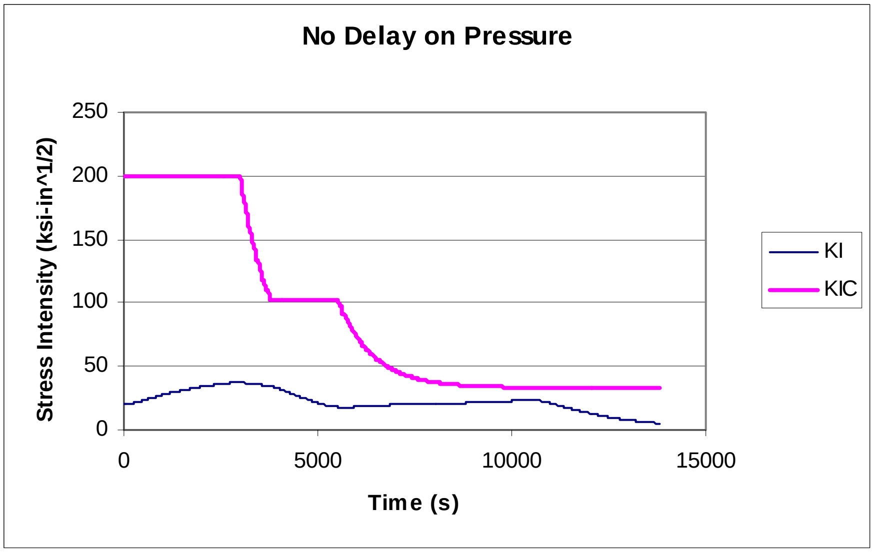


Figure 3-12
Analysis of Cool-down with No Delay on Pressure

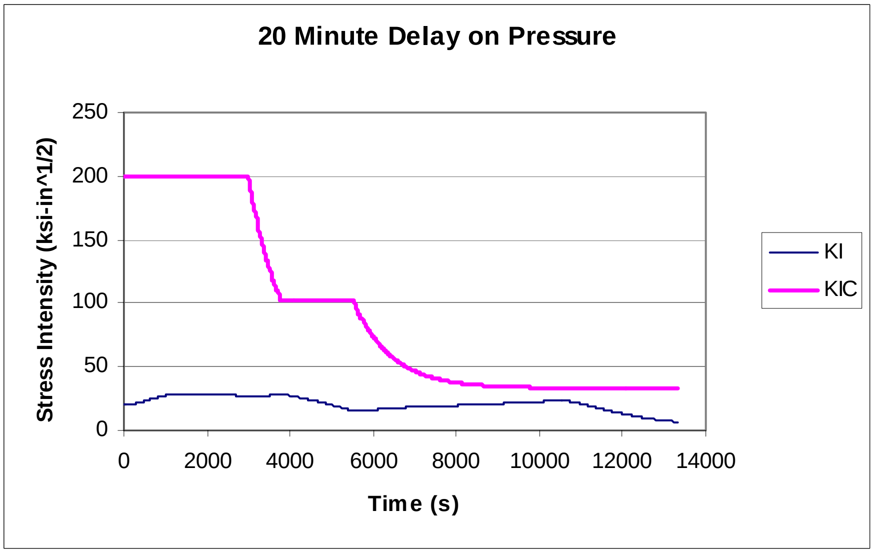


Figure 3-13
Analysis of Cool-down with 20 Minute Delay on Pressure

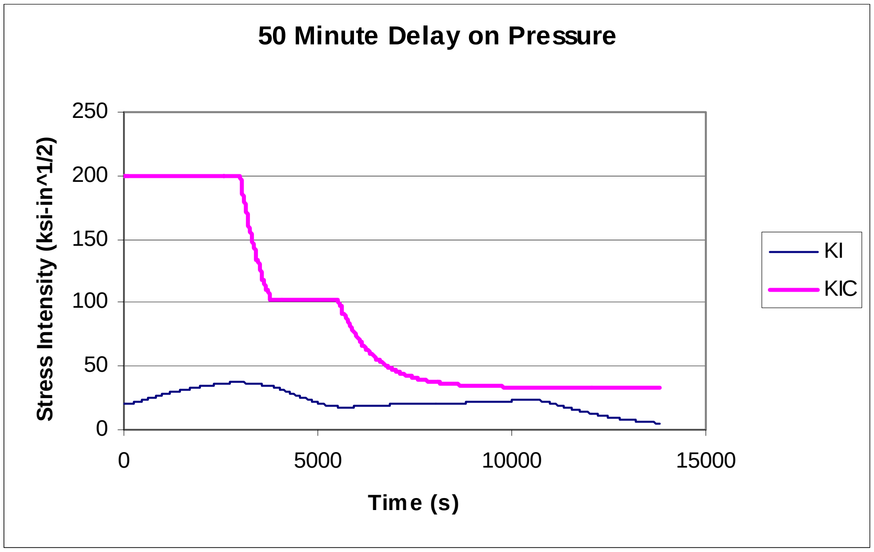


Figure 3-14
Analysis of Cool-down with 50 Minute Delay on Pressure

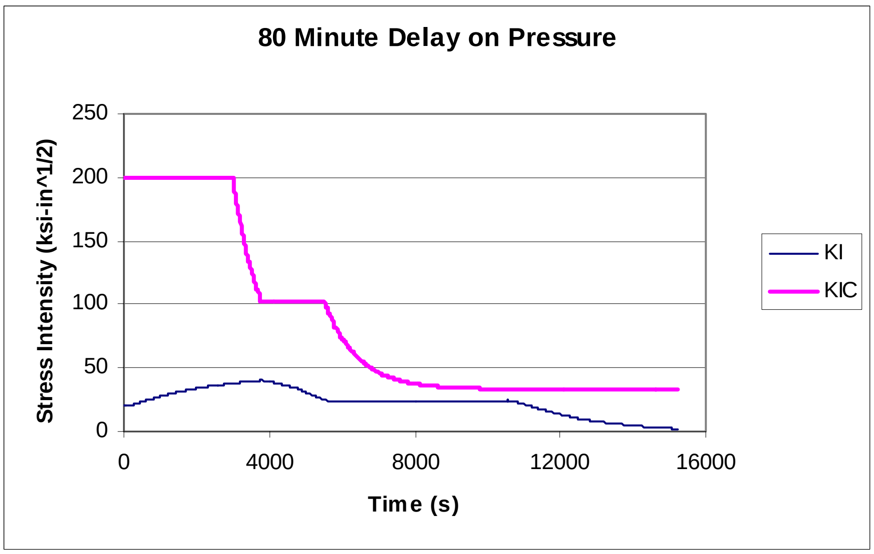


Figure 3-15
Analysis of Cool-down with 80 Minute Delay on Pressure

After the delay in pressure reduction at the beginning of the transient was investigated, a second set of sensitivity studies was performed to investigate operation at higher pressures at the end of the transient. The transients evaluated in the previous sensitivity studies used a continuous 200°F/hr cool-down and temperature hold at 350°F for alignment to RHR. However, for this set of sensitivity studies a more realistic cool-down rate of 100°F/hr was used after alignment to RHR. Furthermore, since the first set of sensitivity studies showed that an 80 minute hold in pressure was possible, an 80 minute hold was also used for this set of sensitivity studies. The sensitivity studies performed to assess the effect of changing each Appendix G parameter showed that the factor of 2 on pressure does not have a significant effect on K_I except at the beginning of the transient. Therefore, allowing for an increase in pressure by a "factor" does little to increase operational flexibility at the end of the transient.

In order to investigate operational flexibility for pressure at the end of the transient, sensitivity evaluations were performed with the pressure held at the end of the transient at 375, 760, 1160, and 1460 psi. 375psi was chosen based on being the minimum pressure for RCP operation. The other pressures are approximate multiples of 375psi. The pressure and temperature vs. time plots for these transients are shown in Figure 3-16. These transients reflect characteristics of actual operating practices while also allowing for more flexible control of pressure and cool-down rate. It was determined from this set of sensitivity studies that pressure could be held at normal operating pressure for 80 minutes and then dropped and held at any of these pressures for the remainder of the cool-down without K_I exceeding K_{IC}. This is shown in Figures 3-17 to 3-20.

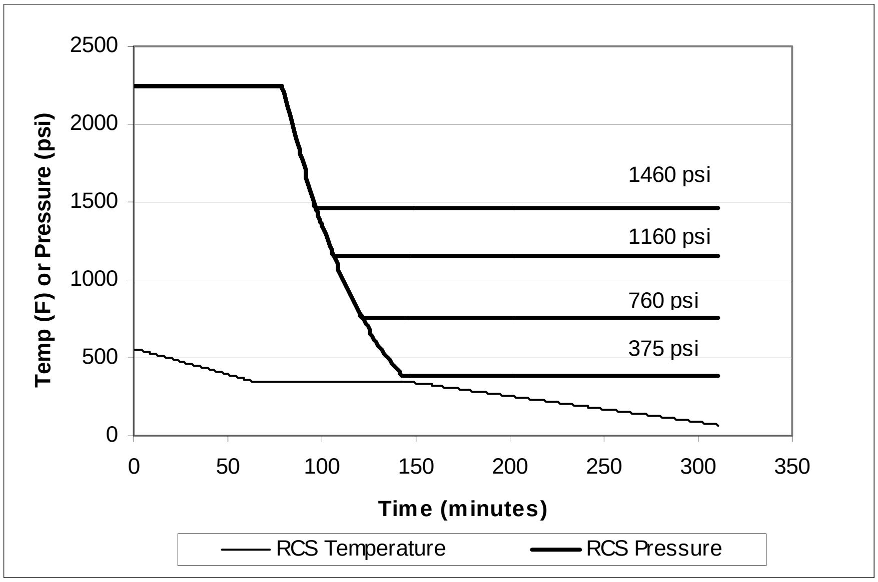


Figure 3-16
Cool-down Transients with Varying Minimum Pressures

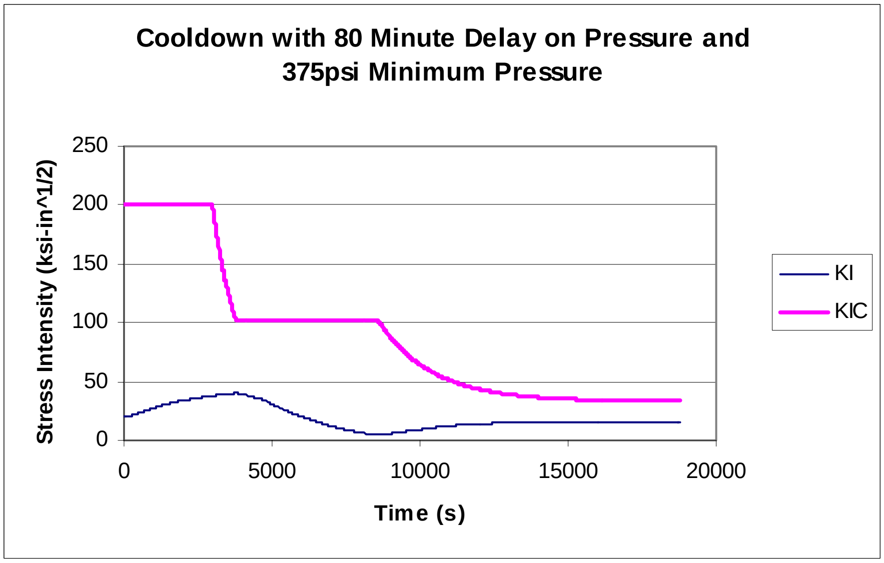


Figure 3-17
Cool-down with 80 Minute Delay on Pressure and 375 psi Minimum Pressure

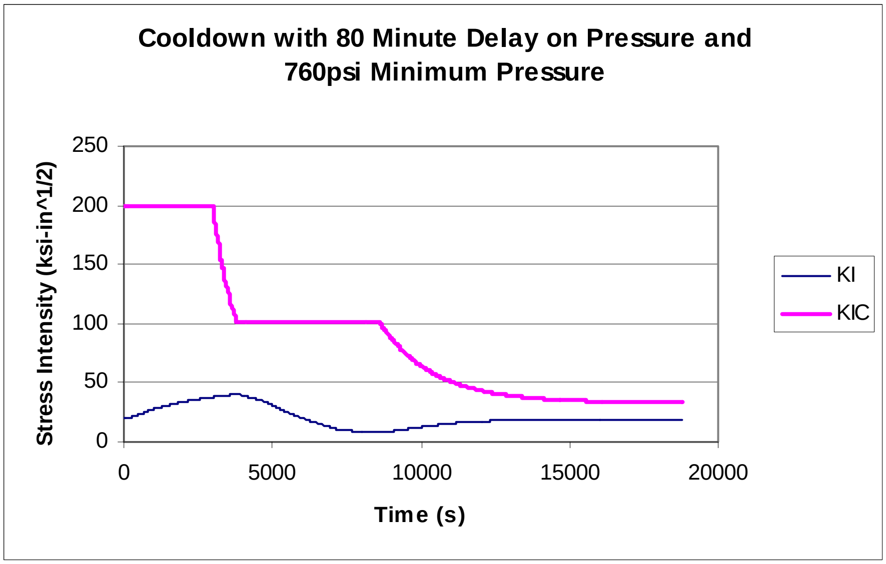


Figure 3-18
Cool-down with 80 Minute Delay on Pressure and 760 psi Minimum Pressure

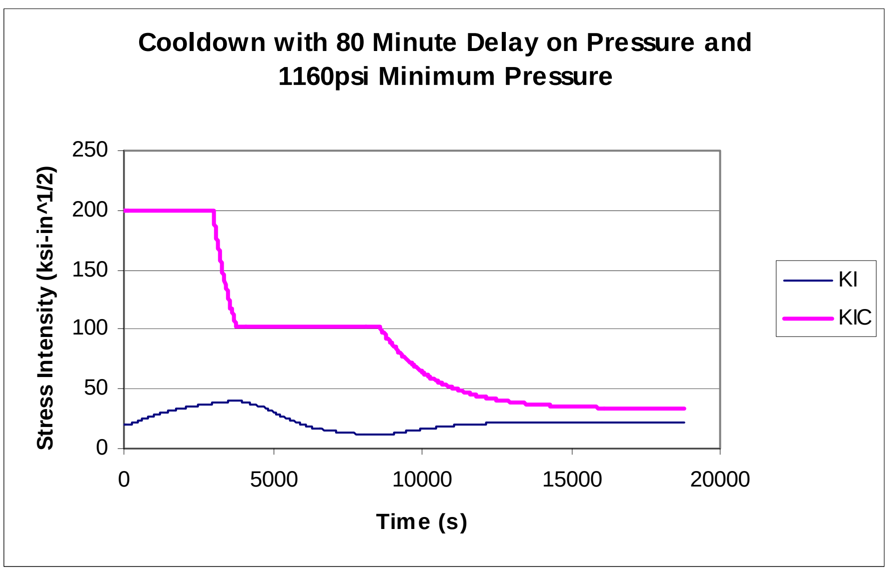


Figure 3-19
Cool-down with 80 Minute Delay on Pressure and 1160 psi Minimum Pressure

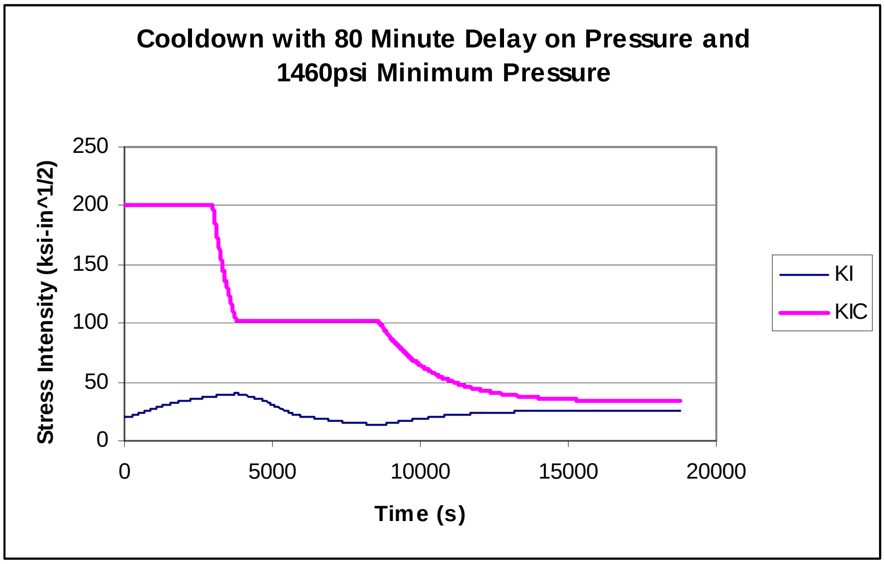


Figure 3-20
Cool-down with 80 Minute Delay on Pressure and 1460 psi Minimum Pressure

In order to be evaluated against the risk goal described in Chapter 2 (Step 6 of Figure 2-1), a transient needed to be evaluated in FAVOR that would result in a failure frequency approaching 1E-06/yr. Therefore, for input to the FAVOR Code, a transient needed to be determined for which the deterministic fracture mechanics evaluation results in K_I approaching K_{IC} but not exceeding it. It is evident in Figures 3-16 to 3-20 that even with a minimum pressure of 1460psi, approximately 7 ksi√in remains between K_I and K_{IC}. [Note: Subsequent analysis of these transients in Chapter 4 using the FAVOR code resulted in either no crack initiations or frequencies of initiation which were well below the risk goal.] It was therefore evident that in order for K_I to approach K_{IC} a more rapid cool-down after RHR initiation was necessary. While the RHR system is not capable of removing heat in excess of 100°F/hr, in order to obtain a more limiting transient for this proof-of-concept, the cool-down rate after initiation of RHR was increased to 150°F/hr, 175°F/hr, and 200°F/hr for the 375psi and 760psi hold cases. The pressure and temperature vs. time plots for these transients are shown in Figure 3-21. The results of the deterministic evaluations of these transients are shown in Figures 3-22 to 3-26. Several of the more limiting cool-down transients in these sensitivity studies were evaluated probabilistically with the FAVOR PFM code, as described in the next chapter of this report.

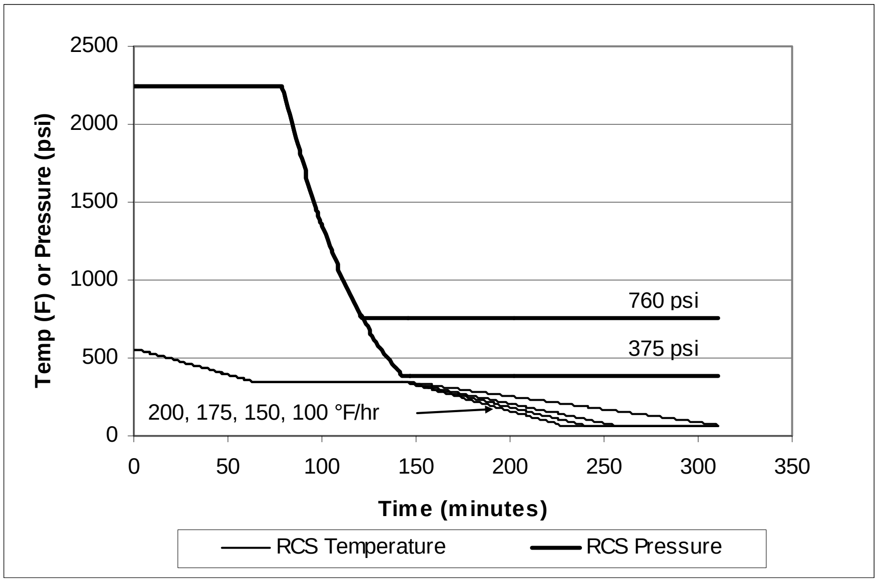


Figure 3-21
Cool-down Transients with Varying Minimum Pressures and Post RHR Initiation Cool-down Rates

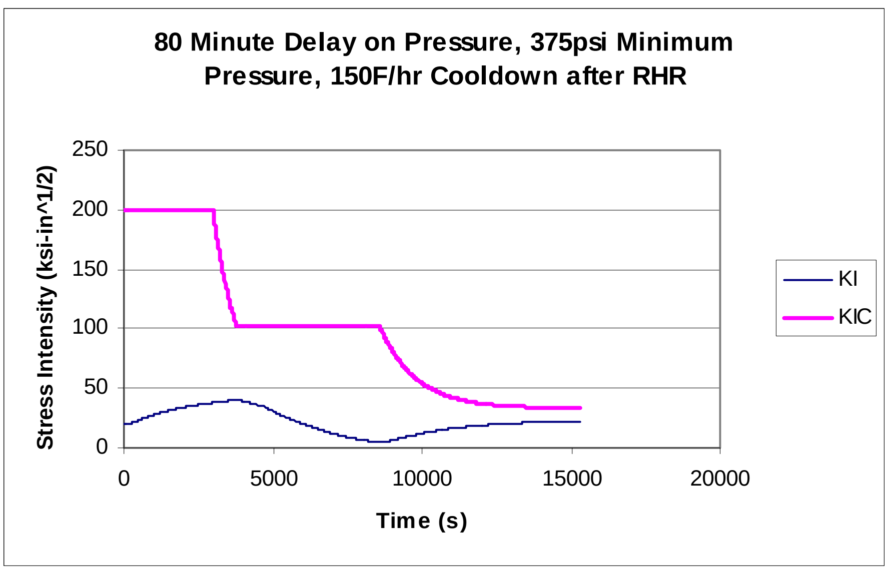


Figure 3-22
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 150°F/hr Cool-down Rate after RHR Initiation

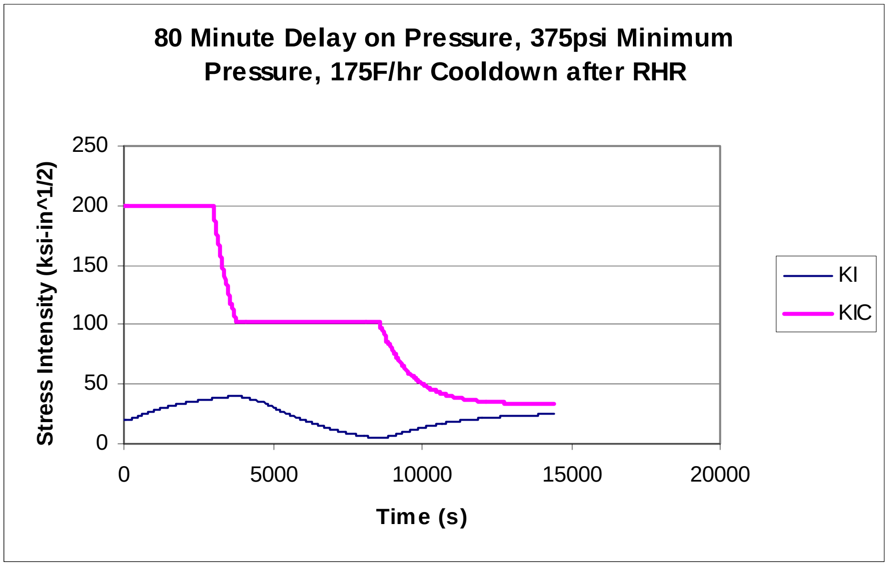


Figure 3-23
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 175°F/hr Cool-down Rate after RHR Initiation

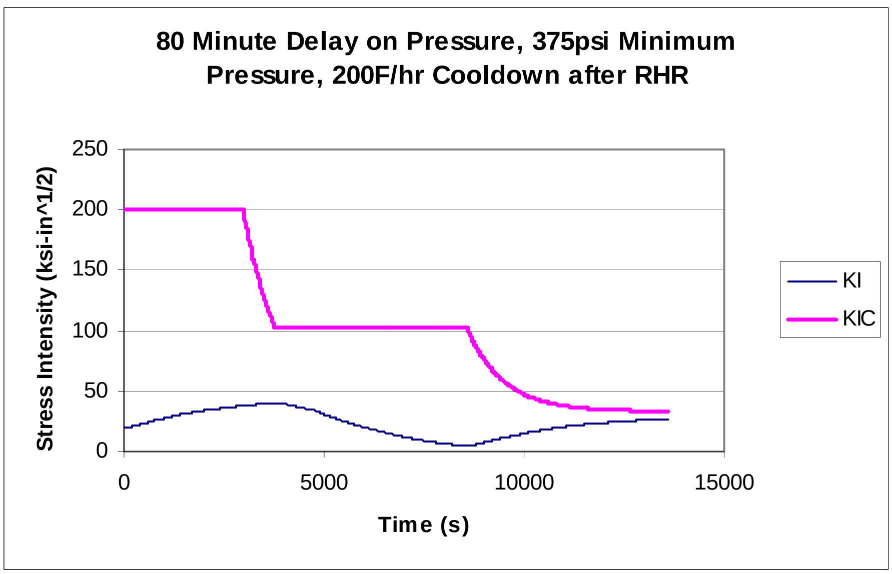


Figure 3-24
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 200°F/hr Cool-down Rate after RHR Initiation

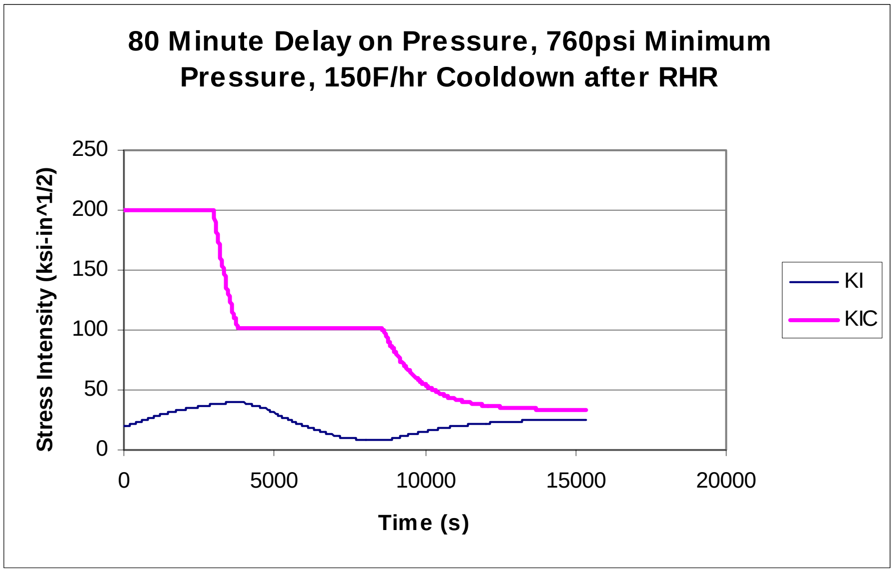


Figure 3-25
Cool-down with 80 Minute Delay on Pressure, 760 psi Minimum Pressure, and 150°F/hr Cool-down Rate after RHR Initiation

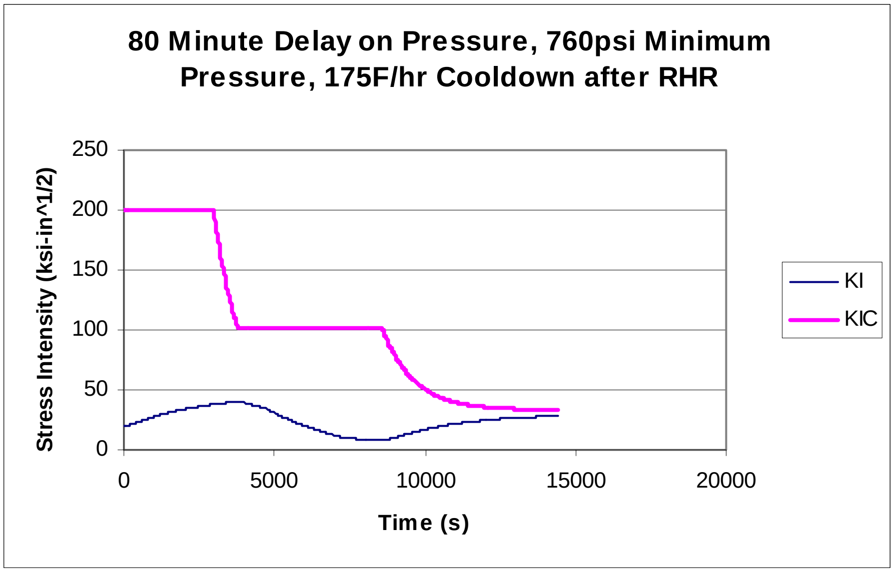


Figure 3-26
Cool-down with 80 Minute Delay on Pressure, 760 psi Minimum Pressure, and 175°F/hr Cool-down Rate after RHR Initiation

4
FAVOR PFM ANALYSES

This chapter documents the PFM analyses of the limiting transients determined in Chapter 3 and Step3 of Figure 2-1. This analysis corresponds to Step 5 of Figure 2-1. As described in Chapter 1, the FAVOR Code was used in the NRC PTS Risk Reevaluation Program for calculating the probability of reactor vessel cracking associated with a particular transient. In the case of the PTS Risk Reevaluation three representative plants, one for each of the domestic PWR NSSS designs, were analyzed relative to the frequency of reactor vessel failure due to PTS transients. For this proof-of-concept study, the PTS transients were replaced with cool-down transients and a probability of crack initiation was obtained for each transient. The FAVOR Code has undergone several revisions throughout the NRC PTS Risk Reevaluation effort. The most recently released version at the time of this analysis was 04.1. This version was utilized in this proof-of-concept study. [Note: An error has been found during the verification and validation of this version of the FAVOR code. It has been determined that this error increases the through-wall failure probability but does not affect the probability of flaw initiation. Due to the fact that the approach taken in this report utilizes the probability of crack initiation and not the probability of failure, the error does not effect the conclusions of this report.]

Code Execution

To run the FAVOR code, three modules (FAVLOAD, FAVPFM and FAVPOST) and various input files are required. This is illustrated in Figure 4-1. The first module in FAVOR is the load module, FAVLOAD, where the thermal-hydraulic time histories are input for the proposed cool-down transients. For each cool-down transient, deterministic calculations are performed to produce a load-definition input file for FAVPFM. These load-definition files include time-dependent, through-wall temperature profiles, through-wall circumferential and axial stress profiles, and stress-intensity factors for a range of axially and circumferentially oriented inner surface-breaking flaw geometries (both infinite and finite-length).

The FAVPFM module is the second module contained in the FAVOR code. This module uses the input distributions for surface flaws, weld flaws, and plate flaws, the loads for the cool-down transients from the FAVLOAD module and fluence/chemistry input data at 60 EFPY (effective full-power years) to calculate the initiation and failure probabilities for each cool-down transient.

The FAVPOST post-processor is the third module in FAVOR. It combines the distributions of initiating frequencies for the transients with the results of the PFM analysis to generate probability distributions for the frequencies of vessel crack initiation and vessel failure. This module also generates statistical information on these distributions and the distributions for the conditional probabilities of reactor vessel crack initiation and failure for each transient included in the risk analysis. For each cool-down transient, a frequency of initiation was determined for comparison to the risk goal.

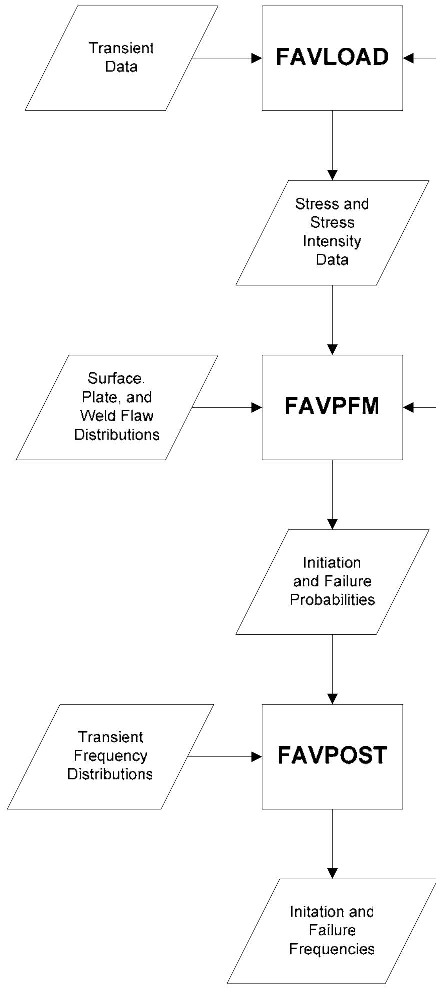


Figure 4-1
FAVOR Evaluation Process Flowchart

Inputs

The limiting transients determined deterministically in Chapter 3 were determined for the Westinghouse pilot plant for the NRC PTS Risk Reevaluation, Beaver Valley Unit 1. Therefore, the FAVOR evaluations for this proof-of-concept were also performed for Beaver Valley Unit 1.

The pilot plant FAVOR input files used in the NRC PTS Risk Reevaluation for Beaver Valley Unit 1 were electronically transmitted to Westinghouse by Oak Ridge National Laboratory at the request of NRC. The FAVLOAD input file was then modified by Westinghouse by removing the PTS transient data and replacing it with the time, temperature, pressure, and heat transfer data for the limiting cool-down transients from Chapter 3. For FAVPFM, the same fluence/chemistry input data for Beaver Valley Unit 1 as that used in the PTS Risk Reevaluation at 60 EFPY was used. The plate and embedded flaw distributions were also the same as those used for Beaver Valley Unit 1 in the PTS Risk Reevaluation.

For the PTS Risk Reevaluation, Beaver Valley Unit 1 was evaluated with no assumed surface flaws. Appendix G assumes the existence of a surface flaw. Therefore it was necessary to include surface flaws in the evaluation for this proof-of-concept study. A surface breaking flaw distribution file was generated based on the postulation of through-cladding flaws. This file was generated using the same input and computer code that were used for the PTS Risk Reevaluation, except single-pass cladding was specified instead of multi-pass cladding. For Beaver Valley Unit 1 this results in a 2% through-wall flaw. No through-cladding flaws have ever been found during reactor vessel in-service inspections, hence it is a conservative assumption to bound any vessels with single-pass cladding. The surface flaw density is approximately 1/1000th the density of plate and weld flaws. This is consistent with assumptions made for the NRC PTS Risk Reevaluation. This flaw distribution was used in the FAVPFM analysis rather than the file used in the NRC evaluation at Beaver Valley Unit 1.

The FAVPOST input files for the PTS Risk Reevaluation Program included the frequency distributions for the postulated PTS transients. For this study it was necessary to create a FAVPOST input file for the proposed cool-down transient. It was assumed that a cool-down occurs for refueling each 18 months. While current cool-down frequencies range from 12 to 18 months, it is expected that by the time 60 EFPY is achieved, the cool-down frequencies will range from 18 to 24 months. Therefore, a conservative frequency of one cool-down per 1.5 years was used. A standard deviation (sigma) of one month was also assumed. Using these assumptions, a normal frequency distribution with a mean frequency of 0.667 cool-downs per year was created and included in a FAVPOST input file. This file was used as input to the FAVPOST module to determine a frequency of crack initiation.

Results

The results of the FAVOR evaluations are presented in Table 4-1 for only those cool-down transients that resulted in any initiations in 10,000 vessel simulations (about 80 million flaw simulations). The FAVOR postprocessor output for the evaluations with non-zero initiation probabilities can be found in Appendices C.1 to C.7.

Table 4-1
FAVOR Results

Reactor Vessel Cool-down Transient	Frequency of Initiation
A.) Cool-down with 80 Minute Delay on Pressure and 1160 psi Minimum Pressure (see Figure 3-19 and Appendix C.1)	2.55E-07/yr.
B.) Cool-down with 80 Minute Delay on Pressure and 1460 psi Minimum Pressure (see Figure 3-20 and Appendix C.2)	4.33E-07/yr.
C.) Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 150°F/hr Cool-down Rate after RHR Initiation (see Figure 3-22 and Appendix C.3)	3.83E-07/yr.
D.) Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 175°F/hr Cool-down Rate after RHR Initiation (see Figure 3-23 and Appendix C.4)	8.84E-07/yr.
E.) Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 200°F/hr Cool-down Rate after RHR Initiation (see Figure 3-24 and Appendix C.5)	2.06E-06/yr.
F.) Cool-down with 80 Minute Delay on Pressure, 760 psi Minimum Pressure, and 150°F/hr Cool-down Rate after RHR Initiation (see Figure 3-25 and Appendix C.6)	1.10E-06/yr.
G.) Cool-down with 80 Minute Delay on Pressure, 760 psi Minimum Pressure, and 175°F/hr Cool-down Rate after RHR Initiation (see Figure 3-26 and Appendix C.7)	2.83E-06/yr.

From the results in Table 4-1 it is evident that the transient which results in a frequency of initiation nearest to, but not exceeding, the risk goal of 1E-06/year is reactor vessel cool-down transient "D". As shown previously in Figure 3-21, there is approximately 9 ksi√in between K_I and K_{IC} when the proposed Appendix G factors are used in a deterministic analysis for this transient. Due to the fact that the frequency of initiation for transient "F" is close to the risk goal when analyzed using the probabilistic methods, but is 9 ksi√in from failure when analyzed using the deterministic method, it is apparent that the proposed Appendix G factors have removed too much conservatism from the deterministic approach. Due to the fact that the calculated mean value for frequency of initiation is only slightly less than the risk goal, it is necessary for the deterministic approach to calculate failure for the transient analyzed.

In order for the deterministic failure to calculate failure, conservatism had to be added to the proposed Appendix G parameters. Several options were considered. These options are as follows:

- Return the factor of 2 on pressure and include the margin term on RT_{NDT} – The assumed flaw size was kept at the proposed size of 1/8T. The results of the deterministic analysis with these parameters are shown in Figure 4-2. While these parameters reduce the difference between K_I and K_{IC}, there a 3 ksi√in difference and therefore do not add enough conservatism to the deterministic method.

- Return the assumed flaw size to 1/4T – The factor on pressure was kept at 1 and the margin term was not included. The results of the deterministic analysis with these parameters are shown in Figure 4-3. The results show that the deterministic process using a 1/4T flaw, no margin term, and no factor on pressure produces failure results that are consistent with those produced using the probabilistic fracture mechanics approach near the risk goal.

- Return the factor of 2 on pressure, include the margin term on RT_{NDT}, assume a flaw size greater than 1/8T but smaller than 1/4T – In this option the deterministic analysis was iteratively performed until a flaw size was found for which the analysis resulted in K_I exceeding K_{IC}. The results of this analysis are shown in Figure 4-4. This option demonstrates that with the inclusion of the margin term on RT_{NDT} and the factor of 2 on pressure, the assumed flaw size can be reduced to 0.141T (approximately 1.125" for T = 8") and the deterministic approach will produce failure results that are consistent with those produced using the probabilistic fracture mechanics approach near the risk goal.

- Return the factor of 2 on pressure and assume a flaw size greater than 1/8T but smaller than 1/4T – This option is the same as that above with the exception that the margin term is not included. The results of this analysis are shown in Figure 4-5. This option demonstrates that with the elimination of the margin term on RT_{NDT} and the inclusion of a factor of 2 on pressure, the assumed flaw size can be reduced to 3/16T (approximately 1.5" for T = 8") and the deterministic approach will produce failure results that are consistent with those produced using the probabilistic fracture mechanics approach near the risk goal.

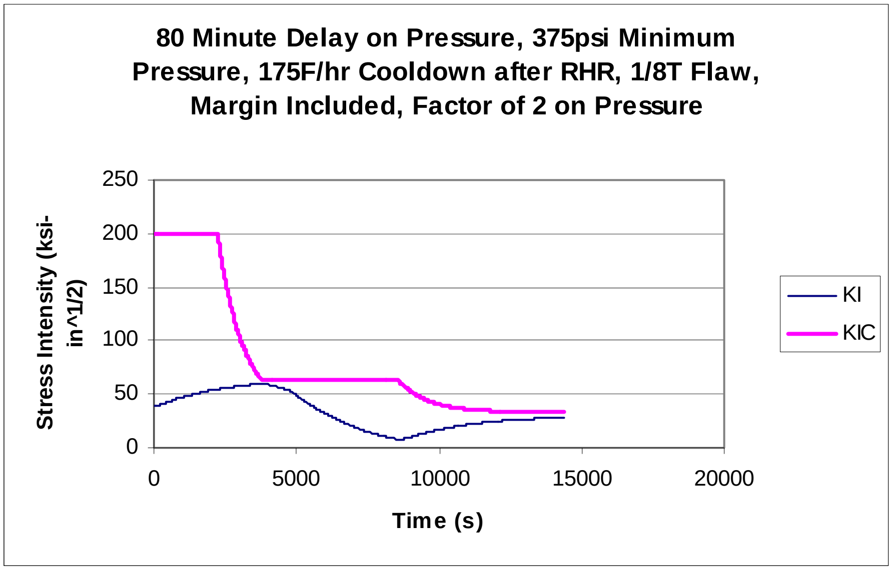


Figure 4-2
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, 175°F/hr Cool-down Rate after RHR Initiation, 1/8 T Flaw, Margin Term on RT_{NDT}, and Factor of 2 on Pressure

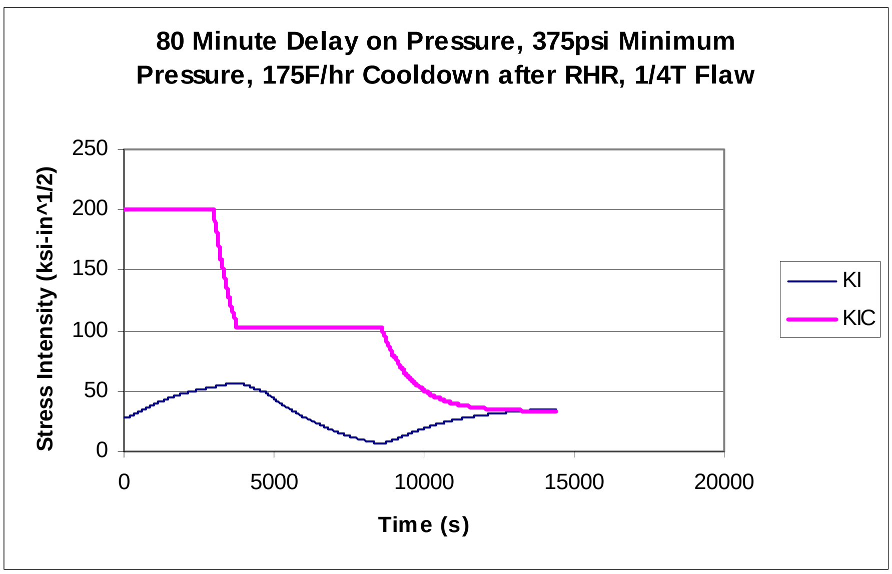


Figure 4-3
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, 175°F/hr Cool-down Rate after RHR Initiation, and 1/4 T Flaw, No Margin Term on RT_{NDT}, and No Factor on Pressure

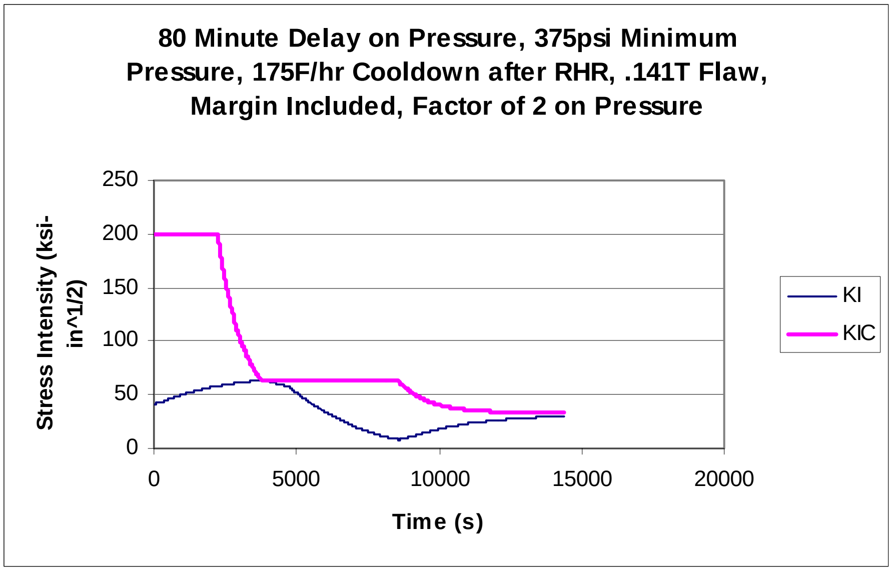


Figure 4-4
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, 175°F/hr Cool-down Rate after RHR Initiation, 0.141T Flaw, Margin Term on RT_{NDT}, and Factor of 2 on Pressure

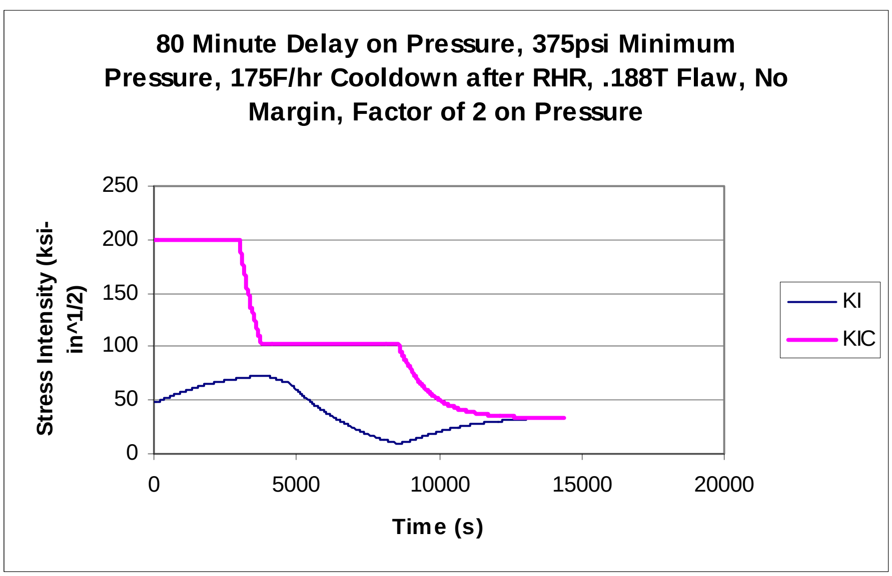


Figure 4-5
Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, 175°F/hr Cool-down Rate after RHR Initiation, 3/16T Flaw, No Margin Term on RT_{NDT}, and Factor of 2 on Pressure

5
RISK EVALUATION OF INITIAL RESULTS

It has been shown through this proof-of-concept that the conservatisms in the current Appendix G factors can be reduced and still satisfy appropriate failure probability criteria. Specifically it has been shown in Chapter 4 that it is possible to relax the Appendix G criteria in three different ways and still meet the risk goal. These are:

- Eliminate the margin term on RT_{NDT} and the factor of 2 on pressure,
- Retain the margin term on RT_{NDT} and factor of 2 on pressure and reduce the assumed flaw size from 1/4T to 0.141T (e.g. 2 inch to 1.125 inch for T of 8 inches), or
- Eliminate the margin term on RT_{NDT} and reduce the assumed flaw size from 1/4 T to 3/16T (e.g. 2 inch to 1.5 inch for T of 8 inches).

Furthermore, it has been demonstrated that even with the less conservative proposed Appendix G parameters operational flexibility can be increased by allowing for operation at higher pressures and faster cool-down rates.

As shown by the FAVOR results in Chapter 4, for a reactor vessel cool-down with an 80 minute delay on pressure, 375 psi minimum pressure, and 175°F/hr cool-down rate after RHR initiation the failure frequency is 8.84E-07/year. At an upper 2-sigma bound on frequency, this corresponds to a failure frequency of 1.02E-06/year. This frequency meets the risk acceptance criteria of 1.0E-06/year. This risk acceptance criterion is consistent with that used in the NRC PTS Risk Reevaluation with the exception that the PTS Risk Reevaluation considered reactor vessel failure to occur when a crack had propagated through the vessel wall. For this evaluation, reactor vessel failure was assumed to occur at crack initiation. In this respect, the risk acceptance for this evaluation is more conservative than that used in the NRC PTS Risk Reevaluation Program.

While this proof-of-concept has shown that relaxation of the Appendix G parameters is possible, additional analysis is required to fully determine the most appropriate approach and effect of the changes. Other considerations that need to be investigated for developing a new Appendix G methodology include the following:

- Effect of heat-up relative to cool-down – This evaluation only considered the effect of changing the Appendix G factors for cool-down. The effect of changing the factors needs to be considered for an outer diameter flaw during heat-up of the reactor vessel.
- Lower levels of reactor vessel embrittlement – This evaluation considered the Beaver Valley Unit 1 reactor vessel for which the projected RT_{PTS} at 60 EFPY is 332°F. The sensitivity studies showed that the removal of the margin term has a more significant effect on allowable cool-down rates and pressures for less embrittled reactor vessels. Therefore,

evaluations need to be performed to consider the changes on the Appendix G factors for reactor vessels with lower levels of irradiation and potentially higher margin terms.

- Effects of less frequent scenarios (e.g. overpressure transient) – This evaluation considered cool-down transients which would be considered to be normal operating conditions. Additional evaluations need to be performed to show that less frequent but more severe transients would not be significant contributors to the initiation frequencies.
- Other PWR NSSS and reactor vessel designs (CE and Babcock and Wilcox) – This evaluation considered the Westinghouse reactor vessel design. Additional FAVOR evaluations need to be performed utilizing models of other PWR reactor vessel designs.
- BWR NSSS and reactor vessel designs – Deterministic evaluations need to be performed using BWR specific data. FAVOR evaluations need to be performed with a BWR model including realistic geometry and fluence data for the limiting pressure-test transient.
- The effect of the proposed factors on plant components other than the reactor vessel – This evaluation assumed that the limiting plant component was the reactor vessel beltline. Other plant components such as the piping, pressurizer, and steam generators need to be evaluated to verify that the reactor vessel beltline is the limiting component.
- The effect of low temperature overpressure protection system limitations – Evaluations would also need to be performed to ensure that there are no conflicts with the operation of this system. It may be possible that the requirements for this system could also be relaxed.
- Tradeoff studies need to be performed to determine which Appendix G changes provide the maximum amount of flexibility to the plant operators while remaining acceptable to the ASME Code Groups that would have to approve the Code Case with the proposed changes. This investigation could also consider the benefits of using a mean K_{Ic} curve instead of the lower-bound curve currently in the ASME Code.

After these items are considered and additional analysis is performed it should be possible to develop a new Appendix G methodology that retains the current format and deterministic methods but allows for significant increases in operational flexibility.

6
APPLICABILITY TO BWR VESSELS

The previous discussions of potential concepts to reduce the excessive conservatism in Appendix G of Section XI, ASME Code addressed PWR vessels only. The concepts were first evaluated based on deterministic analysis, and were validated later by the use of risk-informed evaluations. Several options for relaxation of the Appendix G methodology were judged to be feasible based on deterministic analysis for the cool-down transient that is the governing condition for PWR vessels from a fracture mechanics viewpoint. They were then evaluated by using the FAVOR PFM Code to determine the reactor vessel crack initiation frequency. If the calculated initiation frequency is less than the acceptable risk of 1E-06/year and the deterministic analysis shows adequate margin, the concepts evaluated could be included in any future revisions to Section XI Appendix G criteria. The general conclusion of the 'proof of concept study' was that the three options for revising Appendix G were feasible for the PWR vessels and that further risk-informed probabilistic and deterministic fracture mechanics can help define the optimum approaches to revise Appendix G.

This section evaluates the applicability of relaxing Appendix G requirements for BWR vessels. BWR conditions and the governing transients are quite different and independent BWR evaluations are needed to determine the applicability and acceptability of the proposed ideas for Appendix G revisions for BWR vessels.

Background

Unlike PWR vessels, the cool-down transient in a BWR is not a limiting concept from the viewpoint of fracture margin. Heat-up is similarly not as much of a concern since the thermal stresses are compressive during heat-up. On the other hand, cool-down combines both pressure and tensile thermal stresses. However, because of the unique BWR conditions, cool-down is not a condition that combines high stress and low temperature in a BWR and is therefore not the governing transient. Some of the differences between PWR vessels and BWR vessels are:

- The BWR follows the steam saturation curve. Figure 6-1 shows the pressure as a function of temperature. It is seen that when the pressure drops to 20% of the operating pressure (~200 psi from 1050 psi) the corresponding coolant temperature is still high – approximately 400°F thus assuring that the toughness remains high.
- The irradiation-induced shift in RT_{NDT} is generally low in BWR vessels because of the large annulus of water between the core shroud and the reactor vessel which tends to reduce the fluence on the vessel inner diameter (ID) surface. The ID fluence in BWR vessels range from about $3x10^{17}$ to $5x10^{18}$ n/cm^2 at 32 Effective Full Power Years (EFPY) of operation [10]. The adjusted reference temperatures (ART) for BWR welds are in the range 60°F to 150°F at 32 EFPY. The initial weld RT_{NDT} values range from -

30°F to -70°F. At the point where the pressure is zero and the vessel coolant temperature is 212°F, the crack tip temperature (1/4 T) is still 398°F (based on Figure G-2214-2, Appendix G). Clearly the temperature is high enough to assure a K_{Ic} value of 200 ksi-√ inch.

- The pressure test is more limiting than cool-down in a BWR because the crack tip temperature is much lower during the pressure test than in the operating condition but the pressure stress is essentially the same. The temperature for the pressure test is achieved through pump heat and attaining temperatures in excess of 200°F is difficult. Also at temperatures exceeding 200°F, other requirements such as containment isolation and availability of emergency core cooling system (ECCS) apply which make pressure test temperatures in excess of 200°F difficult to maintain.

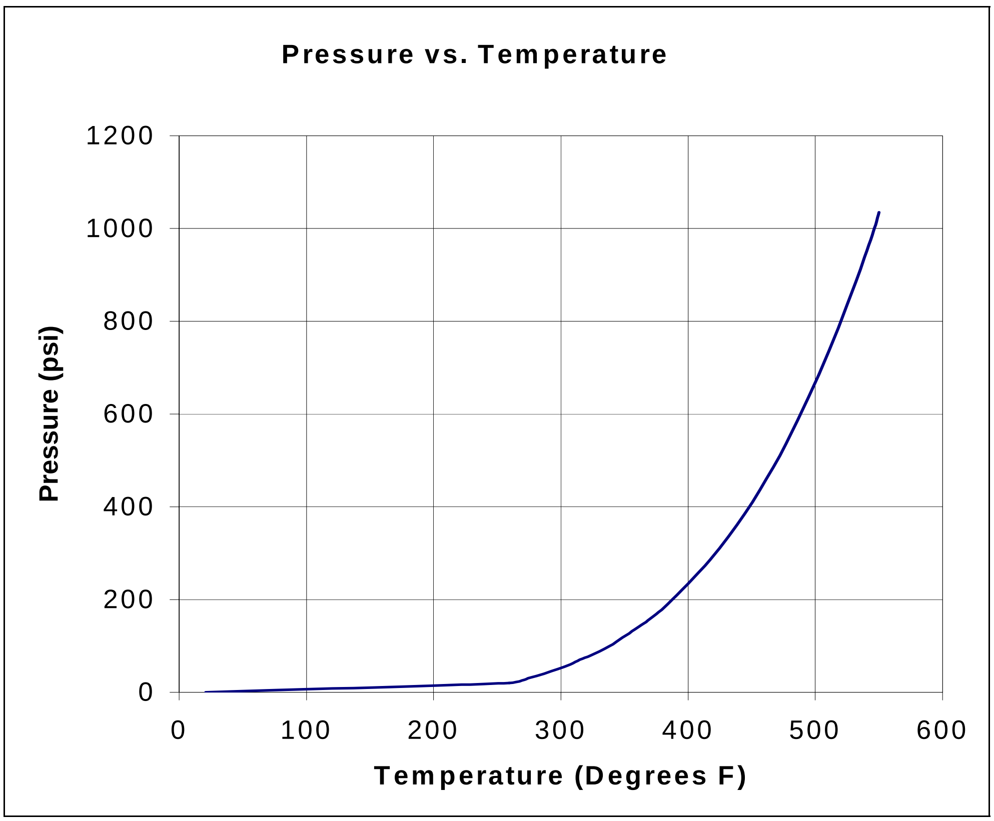


Figure 6-1
BWR Cool-down Curve

The BWR evaluations described here address cool-down issues in a manner similar to the PWR deterministic evaluations. In addition, the pressure test is also evaluated because it is the governing transient from a fracture mechanics perspective.

Cool-down Evaluation

A key issue in cool-down is the potential for implementing a cool-down rate that exceeds the traditional 100°F/hour rate. Although the RHR limitations (the inability of the RHR systems to remove the decay heat at temperatures half way through the cool-down transient) may preclude the use of higher cool-down rates (e.g. 200°F/hour) over the entire cool-down event, still it is useful to demonstrate the acceptability of higher cool-down rates from the viewpoint of fracture margin. BWR plants do experience cool-down rates in excess of 100°F/hour (e.g. after return from the loss of feedwater heater transient when the vessel may be exposed to cooler water rapidly). While this does not pose a structural concern, it is still treated as a reportable event to the regulatory authorities. Thus demonstrating that there are adequate margins at higher cool-down rates and allowing the higher rate in the technical specifications does offer advantages to BWR licensees, regardless of whether they take advantage of the higher rate in plant operation.

Similar to the evaluation of PWR vessels three options for reducing the conservatisms in the current Section XI Appendix G procedures are considered:

- Smaller postulated flaw – 1/8 T flaw instead of the ¼ T flaw
- Lower factor on pressure (one instead of two) in the cool-down analysis
- Elimination of the margin term in the irradiation shift. The margin term that is commonly used for BWR vessels is 56°F for welds, but for the BWR sensitivity analysis, the reduction will be 35°F which is based on the average margin value in the irradiated RPV material database.

Values Assumed in the Analysis

The evaluations presented here are based on the following:

- Average vessel diameter of 240 inches and thickness of 6 inches. Operating pressure of 1050 psi. The pressure test is also assumed to be at 1050 psi.
- Average weld initial RT_{NDT} of -50°F. Data ranges from -20°F to -70°F [10]
- ART of 150°F. Data ranges from 60°F to 150°F at 32 EFPY [10]
- The ID fluence at 32 EFPY ranges from $3x10^{17}$ to $5x10^{18}$ n/cm^2 at 32 EFPY. These values are not directly used in the analysis.
- Assuming an average initial RT_{NDT} value of -50°F, a bounding ART of 150°F and a margin term of 56°F are reasonable, but a conservative estimate of the fluence dependent shift at 32 EFPY is 144 °F.
- The analysis is performed for 60 EFPY to provide a conservative bound that allows for license renewal. The shift in RT_{NDT} at 60 EFPY is calculated assuming that the fluence goes up by the ratio (60/32) and using the fluence dependence $f^{(0.28\text{-}\log f)}$ [11]. Computing the higher shift associated with the higher fluence at 60 EFPY, and adding the margin term, the ID surface ART at 60 EFPY is estimated to be 181°F.

- The RT_{NDT} at the crack tip is determined by using the exp (-0.067x) relationship [11]. Based on this, the RT_{NDT} at the crack tip for a 1/4 T flaw at 60EFPY is 164.5°F. This value is used for all the BWR analyses reported here.
- The effect of cladding is conservatively neglected. The stainless steel cladding has lower thermal conductivity and effectively acts to insulate the vessel from the colder coolant temperatures. Thus, for the cool-down transients, neglecting the cladding assures that the vessel material is at lower temperature. This results in the vessel having higher thermal stress and lower toughness.

Conventional Appendix G Analysis

Figures 6-2 and 6-3 show the results of the analysis for both the 100°F/hour and 200°F/hour cool-down rates. The analysis was performed using the conventional Appendix G assumptions – 1/4 T flaw, factor of two on pressure and one on thermal stresses and the margin term of 56°F for calculating the ART [11]. The K value due to the pressure stress was determined using the procedures of A-3320 in Section XI, Appendix A [12]. As expected the required K value ($2K_{Ip}$ + K_{It}) is high at the beginning of the transient when the pressure is high, but after 90 minutes into cool-down, the pressure stress becomes small. The thermal K contribution was determined using the procedures of G-2214.3 in Section XI, Appendix G [1]. Unlike the K due to pressure, the thermal K is essentially constant during cool-down. As seen in Figure 6-2, the available toughness, K_{Ic} at the crack tip is the maximum value of 200 ksi-√inch. Even at the end of cool-down and with the assumption of the highest shift in RT_{NDT}, the crack temperature is still sufficiently high so that the maximum value of K_{Ic} value of 200 ksi-√inch is maintained. Figure 6-3 shows the results for a cool-down rate of 200°F/hour and Appendix G assumptions. The main difference is the higher thermal K value (16.8 ksi-√inch for 200°F/hour rather than 8.4 ksi-√inch for the 100°F/hour rate). The overall K value is somewhat higher for the higher cool-down rate, but still below the K_{Ic} value of 200 ksi-√inch. The results confirm that cool-down is not a limiting transient and the higher cool-down rate presents no problems in terms of fracture margin.

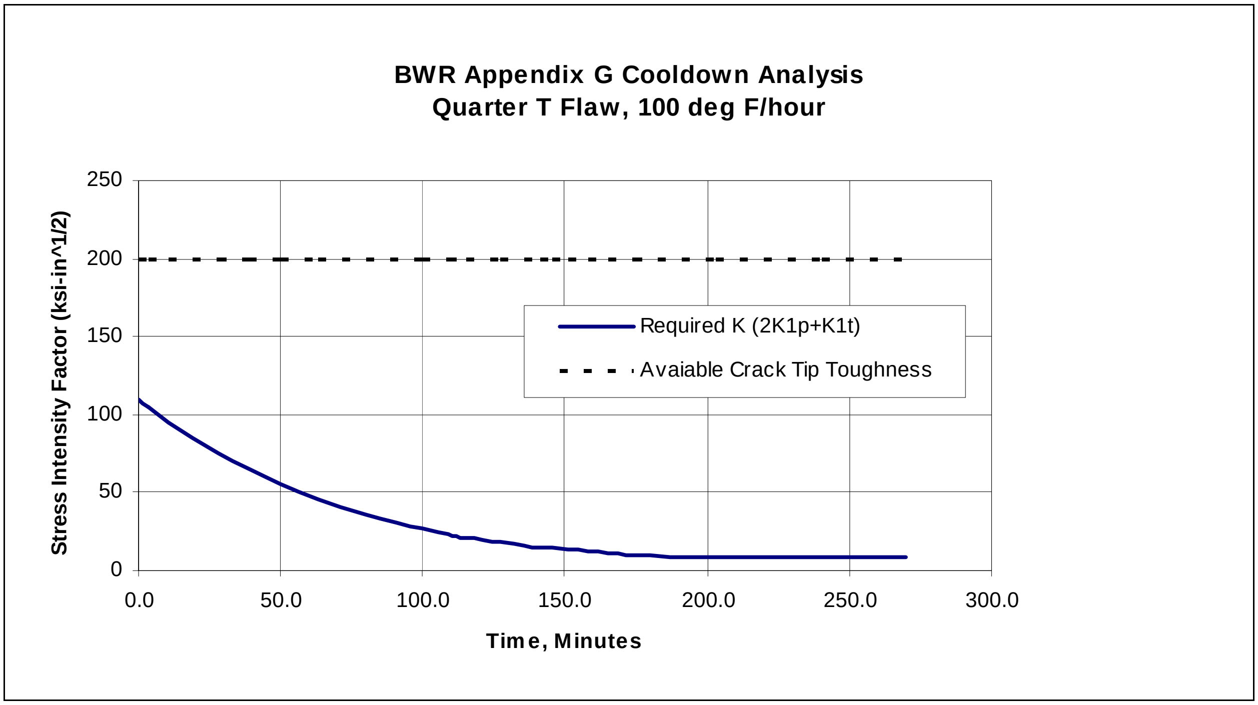


Figure 6-2
Appendix G (1/4 T flaw) Analysis for 100°F/hour Cool-down

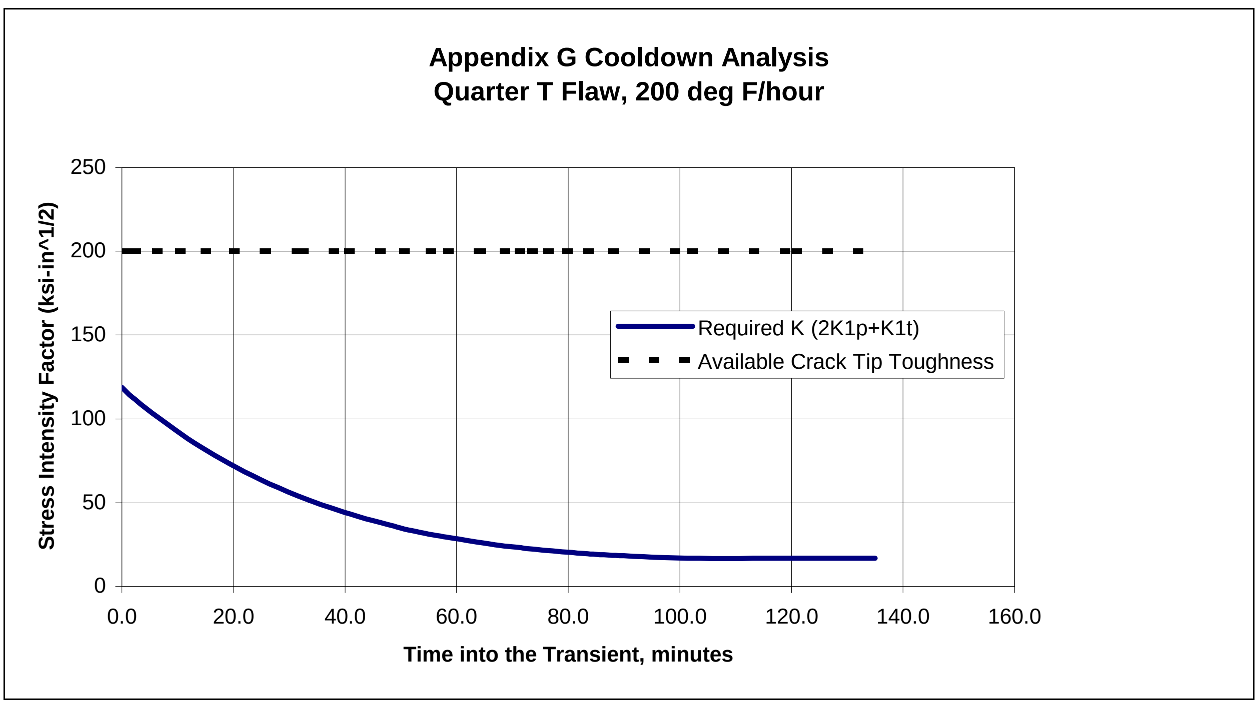


Figure 6-3
Appendix G (1/4 T flaw) Analysis for 200°F/hour Cool-down

Proposed Revisions to Appendix G

Figures 6-4 and 6-5 show the evaluation for an assumed 1/8 T flaw for the 100°F/hour and 200°F/hour cool-down rates. Other requirements such as the factor of 2 on pressure and the margin term remain the same as those in conventional Appendix G analysis. The required K is lower (approximately $1/\sqrt{2}$ compared to the ¼ T case) because of the smaller flaw but this is somewhat offset by the fact that the available crack tip fracture toughness is lower. The crack tip temperature is lower for the 1 /8 T flaw assumption because of the greater proximity to the surface. Also, the ART at the 1/8 flaw is expected to be slightly higher because of higher fluence. Thus the available K_{Ic} would be lower, but as in the conventional Appendix G analysis, the temperature is still high enough that the crack tip K_{Ic} value of 200 ksi-√inch is maintained. The conclusions on high fracture margin apply for both the 100°F/hour and 200°F/hour cool-down rates.

The other two approaches – reducing the factor on pressure stress from two to one and eliminating the margin term – were not explicitly evaluated since it is clear that the margin between the required K and the available crack tip toughness will be higher than in conventional Appendix G analysis.

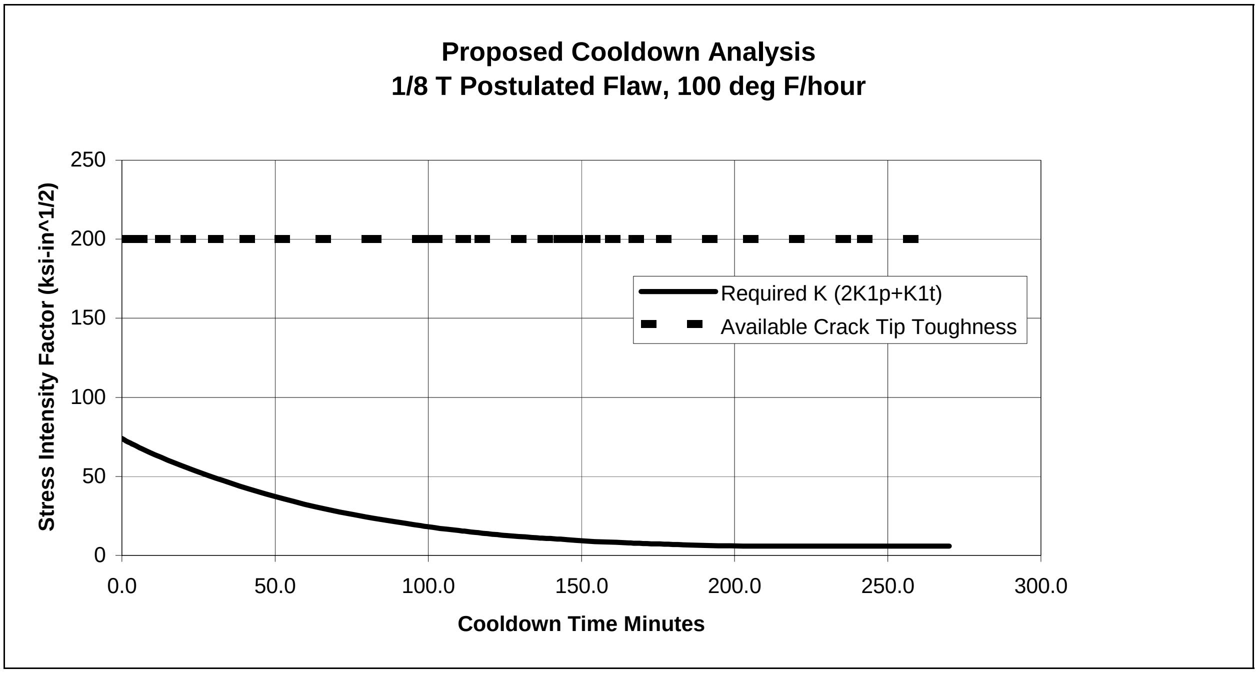


Figure 6-4
Proposed (1/8 T flaw) Analysis for 100°F/hour Cool-down

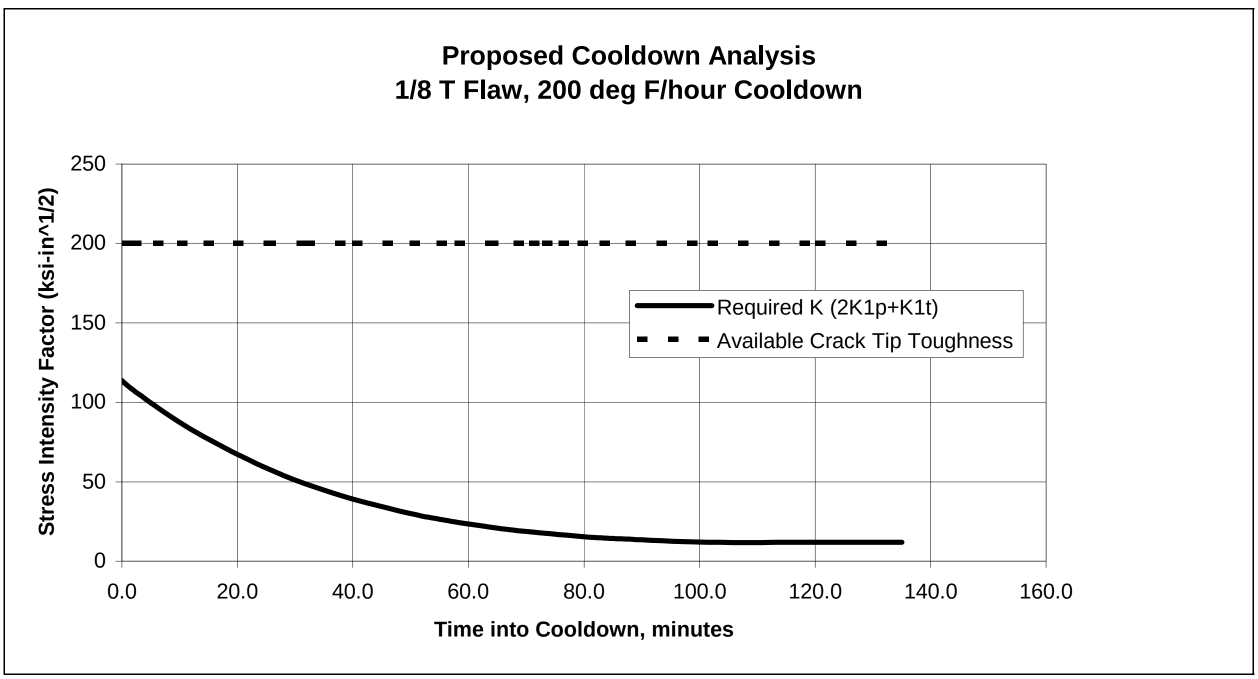


Figure 6-5
Proposed (1/8 T flaw) Analysis for 200°F/hour Cool-down

Impact of the Proposed Appendix G Changes for the Cool-down Transient

The results confirm that cool-down is not a limiting transient and the higher cool-down rate presents no problems in terms of fracture margin. So there is no overwhelming advantage from the proposed changes at least for the cool-down transient. Although the 100°/hour cool-down is not an Appendix G requirement, the analyses presented here supports the case that increasing the allowable cool-down rate to 200°F/hour is acceptable from the fracture mechanics viewpoint. This provides strong support for the inclusion of the higher cool-down rate in plant technical specifications. While many plants may not take advantage of the higher cool-down rate in their operational practice, inclusion of this in the technical specifications offers an important benefit. Many BWR vessels experience higher than 100°/hour cool-down transients (e.g. following the loss of feedwater heaters) and these events are classified as tech spec violations that are reportable to the regulatory authorities. Such transients have no structural impact but result in a minor increment in fatigue usage. Classifying this as a tech spec violation adds unnecessary regulatory burdens without any commensurate advantage in terms of plant safety.

Pressure Testing

The most limiting transient from the fracture margin viewpoint is the pressure test that is done prior to startup following vessel component assembly. The pressure test is performed directly before the plant startup and is intended to check for leaks. The temperature for the pressure test is provided by pump heat. A conservative requirement for the pressure test in Appendix G temperature leads to several concerns. In addition to taking much longer critical path time, too high a temperature (e.g. greater than 200°F) causes personnel problems during leak detection, requires containment isolation and mandates the ECCS to be operational. Thus, for a BWR the proposed changes to Appendix G that reduce some of the excessive conservatisms in the current Appendix G criteria offer important benefits.

The current Appendix G rules require the test temperature to be determined based on providing a factor of 1.5 on pressure. The other standard requirements such as the postulation of a ¼ T flaw and inclusion of the margin term remain. In order to evaluate the effect of the proposed revisions, a fracture mechanics evaluation was performed for a BWR pressure test. The following assumptions were used in the analysis:

- Pressure 1050 psi; average vessel diameter 240 inches; thickness in the core belt line region 6 inches.
- ID surface ART at 60 EFPY = 181.3°F. Crack tip ART is based on the conventional exp (-0.067x) dependence.

Table 6-1 shows the required minimum temperatures for the pressure test. The required temperature is high under the current Appendix G criteria at 60 EFPY. The three concepts for relaxation – factor of 1 on pressure, 1/8T flaw and no margin term – lead to lower pressure test temperatures in the range of 155°F to 166°F (compared to 201°F for the current Appendix criteria), a significant improvement. Implementation of all three concepts leads to virtually no controls on the minimum temperature requirement. The K required by Appendix G for the combination of all three concepts is 33.8 ksi√inch while the lower bound K_{Ic} toughness is 33.2

ksi√inch regardless of the temperature. Thus, for all practical purposes, there is no temperature restriction for this case.

Table 6-1
BWR Pressure Test Temperatures for Different Appendix G Assumptions

Analysis Parameters	Postulated Flaw size, inches	Factor on Pressure	Crack Tip ART used in the Analysis	Required Pressure Test Temperature °F
Conventional Appendix G analysis	1.5	1.5	164.5	201.0
1/8 T flaw; 1.5 on Pressure, Margin Term included	0.75	1.5	172.7	165.1
1/4 T flaw; 1 on pressure, Margin Term included	1.5	1.0	164.5	155.8
1/4 T flaw; 1.5 on pressure, No Margin (subtract 35F)	1.5	1.5	129.5	166.0
1/8 T flaw; 1 on Pressure, No Margin Term (subtract 35F)	0.75	1.0	137.7	NA

From a BWR perspective, the 1/8 T flaw assumption appears to be most promising. The pressure test temperature required by a revised Appendix G is realistic. BWR vessel inspections over the last 30 years have shown no evidence of surface cracking. Therefore the assumption of a smaller flaw is reasonable. There are other locations (e.g. in the vessel and head closure welds) where smaller than ¼ T flaws have been postulated. Also, there is a Code precedent in using a one-inch flaw in Appendix E. Finally the pressure test is conducted with the fuel not critical (all control rods are fully inserted) so the risk of core damage in the event of RPV failure is somewhat lower. In light of this, the use of a 1/8T flaw is justified for BWR pressure tests. However, a FAVOR PFM analysis of the pressure test condition is needed to validate the deterministic assessment and demonstrate that the risk is acceptable based on a probabilistic evaluation.

Conclusions

The following conclusions summarize the BWR assessment of the proposed concepts for relaxing the conservatism in Appendix G, Section XI, ASME Code.

- Unlike the PWR vessels, the cool-down transient is not the limiting condition for the BWR from a fracture mechanics standpoint. There are significant margins even with current Appendix G rules and even higher margins with the proposed concepts for relaxation of Appendix G. So there is no overwhelming advantage from the proposed changes at least for the cool-down transient. The margins are acceptable with the current criteria and with the proposed changes.
- Although the 100°/hour cool-down is not an Appendix G requirement, the analyses presented here supports the case that increasing the allowable cool-down rate to

200°F/hour is acceptable from a fracture mechanics standpoint. This provides strong support for the inclusion of the higher cool-down rate in plant technical specifications. Inclusion of the higher cool-down rates in the technical specifications provides significant regulatory advantages by eliminating unnecessary burden in reporting violations of the 100°F/hour cool-down limit.

- The pressure test is the limiting fracture mechanics condition for the BWR. The proposed concepts for relaxing Appendix G offer significant relief for the pressure test condition. In particular, the 1/8 T flaw assumption appears to be most promising. BWR vessel inspections over the last 30 years have shown no evidence of surface cracking. Furthermore, the pressure test is conducted with the fuel not critical (all control rods are fully inserted) so the core damage risk for a BWR is lower. Therefore the assumption of a smaller flaw is reasonable. As long as the FAVOR PFM analysis of the pressure test condition demonstrates that the risk is acceptable, the proposed relaxation (1/8 T flaw) offers significant plant benefits without leading to unacceptable structural margins.

7 SUMMARY AND CONCLUSIONS

Based upon the initial results of these studies it appears that risk-informed methods can be used to significantly relax the current ASME and NRC Appendix G requirements while still maintaining adequate assurance of reactor vessel structural integrity. Specifically, the conservative risk analyses for 'initiation' failure criteria have shown that three possible options for changing the current Appendix G requirements for PWR plants are:

- Eliminate the margin term on RT_{NDT} and factor on pressure,
- Reduce the assumed flaw size by almost 44 percent, or
- Eliminate the margin term on RT_{NDT} and reduce the assumed flaw size by 25 percent.

These three options demonstrate the flexibility provided by the risk-informed Appendix G concept to satisfy both the needs for PWR plant operators, such as reducing cool-down time by 90 minutes, as well as the requirements of ASME code groups that would have to approve the proposed changes to Appendix G.

Because of the large margins in the cool-down limits that already exist in Appendix G for vessels in BWR plants, the proposed changes would also be acceptable. However, inclusion of higher cool-down rates allowed by the risk-informed changes to Appendix G in the technical specifications of BWR plants provides significant regulatory advantages by eliminating the reporting and evaluation requirements for short-term violations of current cool-down limits. Since the pressure test is the limiting structural conditions for BWR vessels, the proposed concept of relaxing Appendix G requirements provides significant relief for this condition. In one example, the time to obtain the required pressure test temperature following refueling can be reduced by 12 hours.

The risk-informed analysis methods used for this work are the same as those used by NRC Research to support significant relaxation of the integrity requirements for Pressurized Thermal Shock (PTS) in highly embrittled vessels. While further analysis is required to completely justify the possible changes, it is clear that a relaxation in Appendix G requirements would directly translate into significant improvements in operational flexibility. The use of the proposed Appendix G requirements could yield the following improvements in operational flexibility:

- Fewer limitations due to higher values of RT_{NDT} – Studies in this report have shown that cool-down transients that are not acceptable based upon the current Appendix G requirements for a RT_{NDT} of 70°F would be acceptable for a RT_{NDT} of 332°F with the proposed parameters.
- Accelerated cool-down to the point of system capabilities rather than structural capabilities – Studies in this report have shown that cool-down rates of 200°F/hr, which was the limiting

cool-down rate achieved in simulator testing, are structurally possible down to 350°F. After which, a cool-down rate of 100°F/hr, beyond the capabilities of the RHR system, would not challenge reactor vessel integrity.

- Operation at increased pressures – Studies in this report have shown that the total stress intensity in the reactor vessel beltline is controlled by thermal stresses rather than pressure stresses. The effects of a hold on pressure at the beginning of the cool-down transient along with operation at elevated pressures have been investigated. Even with the accelerated cool-down rates described above, the increased pressure did not challenge reactor vessel integrity.

Such improvements in operational flexibility are an objective of industry groups including the Westinghouse Owners Group and the Materials Reliability Program RPV Integrity Issue Task Group.

The cost benefits of the proposed changes to Appendix G can be significant when implemented across the domestic fleet of PWR and BWR plants:

- For a reduction of 1.5 hours in cool-down time per operating cycle in 69 PWR plants, the cost savings range from ~$1,000,000/year for an 18-month cycle to ~$1,500,000/year for a 12-month cycle.
- For a reduction of 12 hours in pressure-test time per refueling outage in 34 BWR plants, the cost savings is ~$2,900,000/year for a 24-month operating cycle.

These cost savings were estimated using the conservative costing rate of $340,000 per 24-hour day that the Westinghouse Owners Group uses to evaluate new project authorizations. The actual fleet wide savings could be much higher.

.

8
REFERENCES

1. *ASME Boiler and Pressure Vessel Code*, Section XI, Appendix G, American Society of Mechanical Engineers, New York, NY.

2. "*PVRC Recommendations on Toughness Requirements for Ferritic Materials*," PVRC Ad Hoc Group on Toughness Requirements, Welding Research Council Bulletin WRC-175, August 1972.

3. U.S. Nuclear Regulatory Commission. *Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Criteria in the PTS Rule (10CFR50.61)* NUREG 1086, 2005.

4. Office of the Federal Register, National Archives and Records Administration. Code of Federal Regulations, 10CFR50.61, *Fracture Toughness Requirements for Protection Against Thermal Shock Events*. 2003.

5. U.S. Nuclear Regulatory Commission. *Fracture Analysis of Vessels – Oak Ridge FAVOR, v04.1, Computer Code: Theory and Implementation of Algorithms, Methods, and Correlations*, NUREG/CR-6854, issued by Oak Ridge National Laboratory, October, 2004.

6. *Apparatus and Method for Monitoring Pressure-Temperature Margins*, U.S. Patent Number 5,761,086, Cranford, III; Elwyn L., February 13, 1996.

7. WCAP-14040-A Revision 4, *Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heat-up and Cool-down Limit Curves*, May 2004.

8. F.A. Simonen, S.R. Doctor, G.J. Schuster, and P.G. Heasler, *A Generalized Procedure for Generating Flaw Related Inputs for the FAVOR Code*, NUREG/CR-6817 Rev. 1, October 2003.

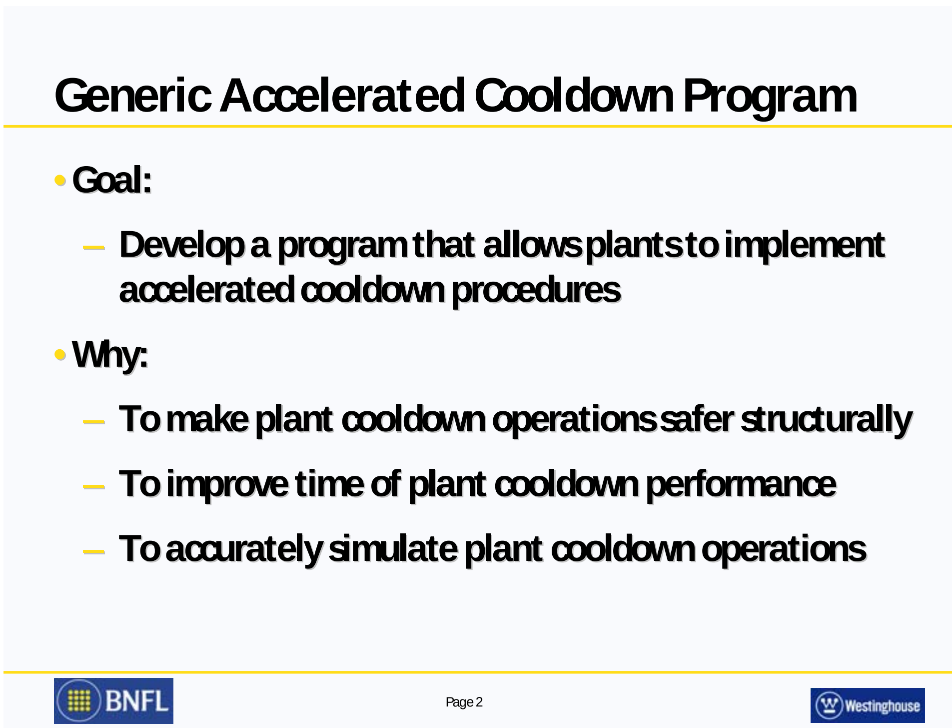
9. U.S. Nuclear Regulatory Commission, *RVID Reactor Vessel Integrity Database*, Version 2.0.1 Washington, DC, 2000.

10. "BWR Vessel and Internals Project, BWR Pressure Vessel Shell Weld Inspection Recommendations (BWRVIP-05)," EPRI Report TR-104697, September 1995.

11. "Radiation Embrittlement of Reactor Vessel Materials," USNRC Regulatory Guide 1.99 Revision 2, May 1988.

12. *ASME Boiler and Pressure Vessel Code*, Section XI, Appendix A, American Society of Mechanical Engineers, New York, NY

A
SUPPLEMENTAL INFORMATION



Generic Accelerated Cooldown Program

- Potential Obstacles:
  - Fracture
  - Fatigue
  - Radio-Chemistry
  - CVCS System capacity

BNFL Page 3 Westinghouse

Generic Accelerated Cooldown Program

- Westinghouse Efforts to date:
- Developed feasible accelerated cooldown scenarios.
- Completed fracture mechanics analyses of the critical RV regions: Belt-line, Nozzle corner, and Nozzle Safe-end Welds, with good results.
- Conducted cooldown simulation runs (SNUPPS model). Showed that 200F/ hr cooldown rates can be easily controlled.
- Time savings: Over 1.5 hrs (1 hr from 557 F to 350 F, 0.5 hrs from 350 F to 70 F)
- Completed Licensing feasibility study.
- Westinghouse was awarded a patent on "Apparatus and Method for Monitoring Pressure-Temperature Margins" (US Patent 5,761,086).

BNFL Page 4 Westinghouse

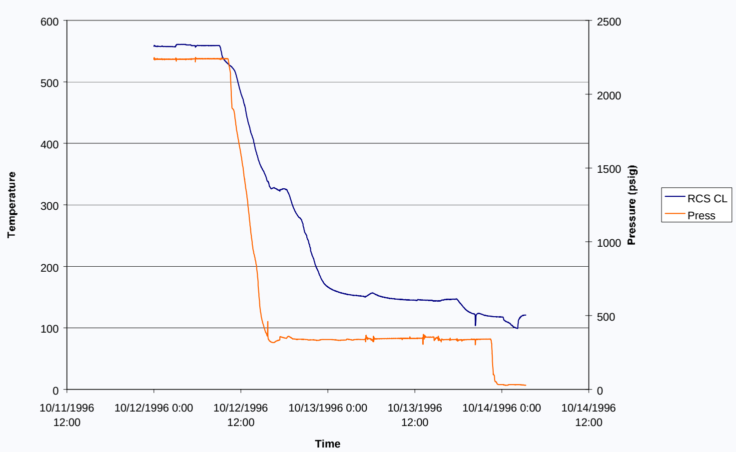
Generic Accelerated Cooldown Program

- Current practices differ widely from plant to plant, 40-50 degree cooldown rates remain common, 80 degree cooldown rates proven successful at Exelon plants.

BNFL Page 5 Westinghouse

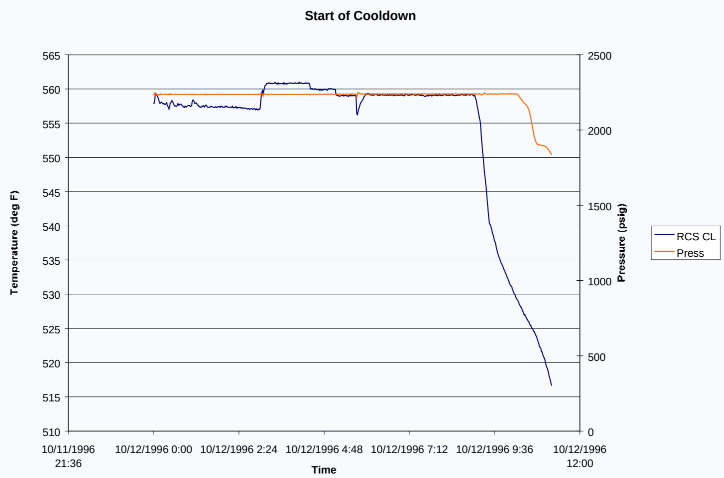
Generic Accelerated Cooldown Program

4 Loop Cooldown Plant 1



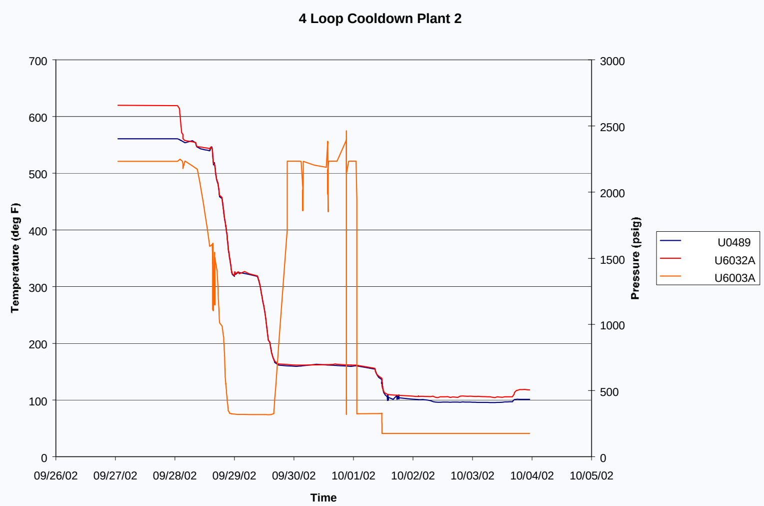
BNFL Page 6 Westinghouse

Generic Accelerated Cooldown Program



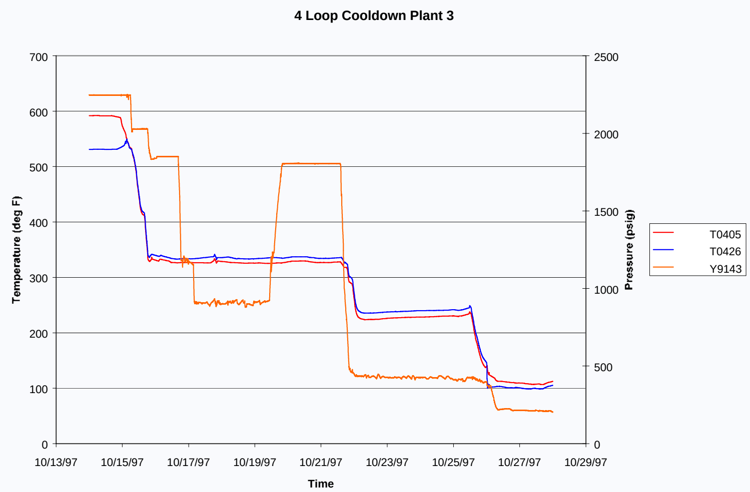
BNFL Page 7 Westinghouse

Generic Accelerated Cooldown Program



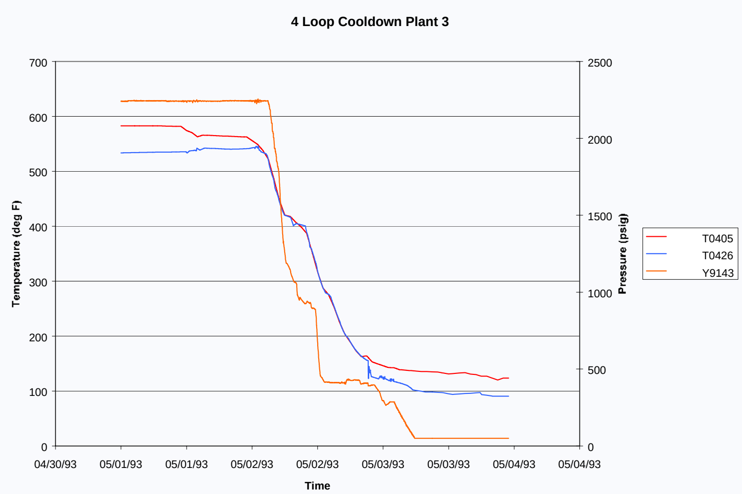
BNFL Page 8 Westinghouse

Generic Accelerated Cooldown Program



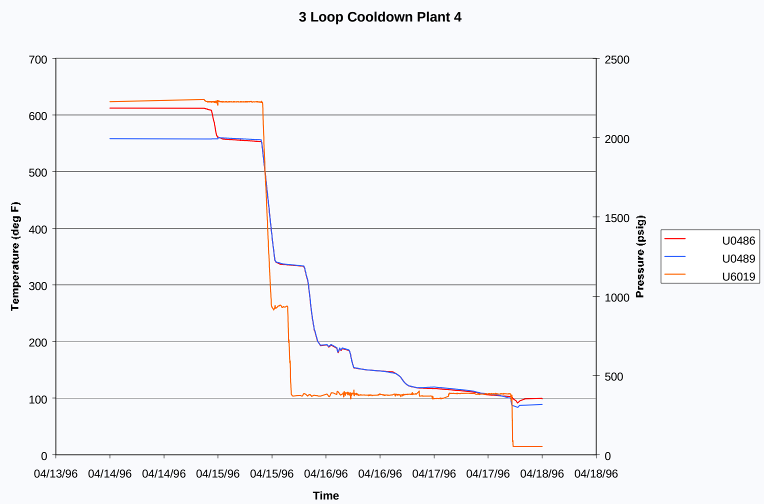
BNFL Page 9 Westinghouse

Generic Accelerated Cooldown Program



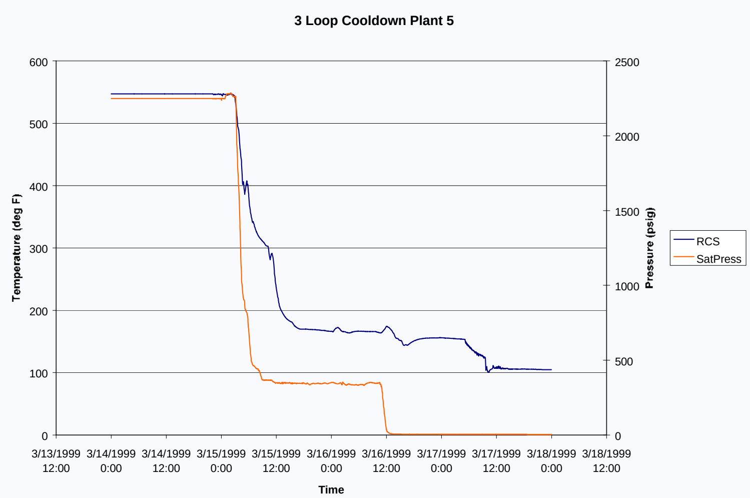
BNFL Page 10 Westinghouse

Generic Accelerated Cooldown Program



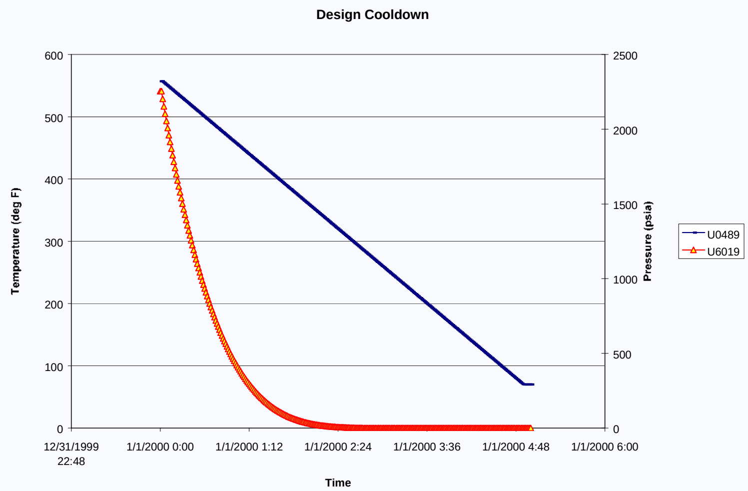
BNFL Page 11 Westinghouse

Generic Accelerated Cooldown Program



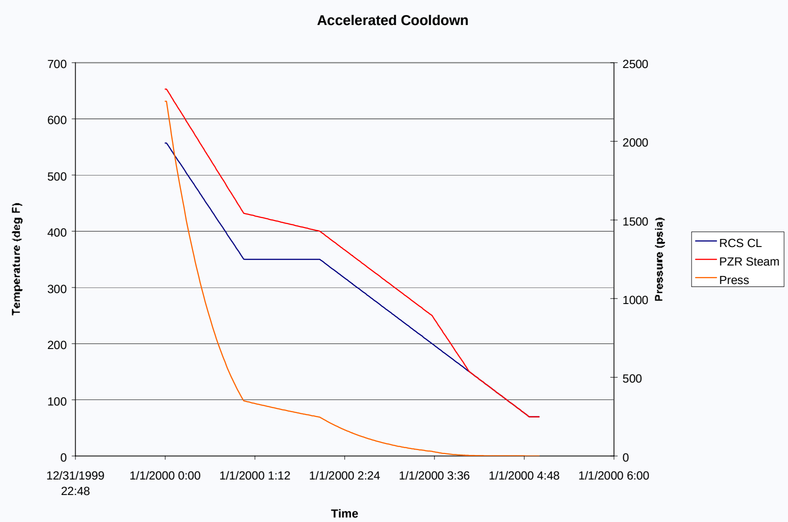
BNFL Page 12 Westinghouse

Generic Accelerated Cooldown Program



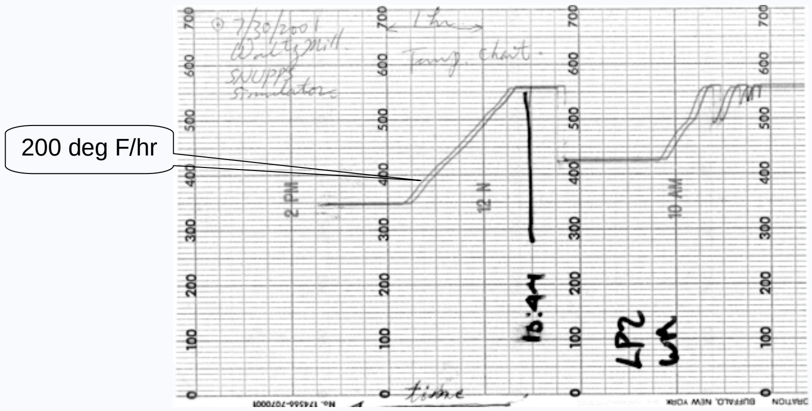
BNFL Page 13 Westinghouse

Generic Accelerated Cooldown Program



BNFL Page 14 Westinghouse

Generic Accelerated Cooldown Program



Strip Chart from SNUPPS Simulator Testing

BNFL | Page 15 | Westinghouse

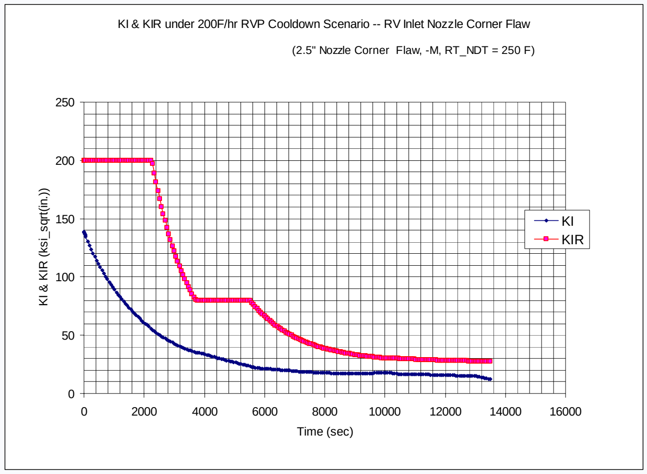
Generic Accelerated Cooldown Program

Fracture Analysis Results:

1. The feasibility study indicates that structural integrity is maintained for the proposed accelerated cooldown scenarios, 200 F/hr.
2. The fracture mechanics assessments were performed based on the upper bound RTNDT value, 250 F.
3. The fracture mechanics assessments were performed for the critical locations in the RPV, such as at belt-line where RTNDT is high, and at RV inlet nozzle corner where stress concentration is considerable.
4. Fatigue crack growth was not investigated at this time but can be evaluated if necessary.

BNFL | Page 16 | Westinghouse

Generic Accelerated Cooldown Program



BNFL Page 17 Westinghouse

Generic Accelerated Cooldown Program

- **Shutdown Chemistry Concerns**
  - **Potential Particulate Crud Release**
    - **An increase of particulates can be associated with cooldown operations, could create elevated out-of-core radiation fields**
  - **CVCS Capacities**
    - **Charging system capacity will limit ability to control inventory (make up)**

BNFL Page 18 Westinghouse

B
BENCHMARKING OF DETERMINISTIC CALCULATIONS

To benchmark the Westinghouse deterministic fracture mechanics codes used for the sensitivity studies in Chapter 3, a comparison was made against the Westinghouse OPERLIM Code. This code uses a methodology that has been accepted by the NRC for the calculation of P-T limit curves for heat-up and cool-down in accordance with the current Appendix G methodology. The Westinghouse deterministic code uses as input a transient's temperature and pressure versus time history. An Appendix G fracture mechanics evaluation is then performed to determine K_I with respect to K_{IC} for the duration of the transient. The OPERLIM code also performs an Appendix G deterministic fracture mechanics evaluation. However, OPERLIM uses an input cool-down rate and from the ASME Appendix G K_{IC} curve determines allowable pressures with respect to temperature. There are two other distinct differences between the calculations performed using the Westinghouse deterministic codes used in Chapter 3 and OPERLIM. OPERLIM computes K_{IC} based on the temperature at the crack tip whereas the Westinghouse deterministic codes compute K_{IC} based on the temperature at the reactor vessel inner radius. Furthermore, the OPERLIM code conservatively adds a margin term equal to 34°F to the reference temperature, RT_{NDT}, while the Westinghouse deterministic codes do not.

To compare the two codes, OPERLIM was used to determine allowable pressures with respect to temperature for a design basis 100°F/hr cool-down. The dimensions of the Beaver Valley Unit 1 reactor vessel (wall thickness included cladding thickness) were used along with a RT_{NDT} of 290°F. The allowable pressures from OPERLIM, and the corresponding temperature data, were then input into the Westinghouse deterministic codes to calculate K_I with respect to K_{IC} for the duration of the transient. However, in order to facilitate the two codes producing equivalent results (due to the differences in the codes), the temperature input for the Westinghouse code was changed to the crack tip temperature (as output by the OPERLIM code), rather than the fluid temperature. This change has minimal effects on the calculated K_I but is significant in determining the appropriate value for K_{IC}. After the temperature input was revised, the reference temperature input to the Westinghouse code was changed from 290°F to 324°F to reflect the addition of the margin term (34°F) within OPERLIM. After these input changes were made the transient was evaluated with the Westinghouse code. The calculated stress intensity, K_I, was then plotted for comparison to K_{IC} and is shown in Figure B-1. The results matched very well.

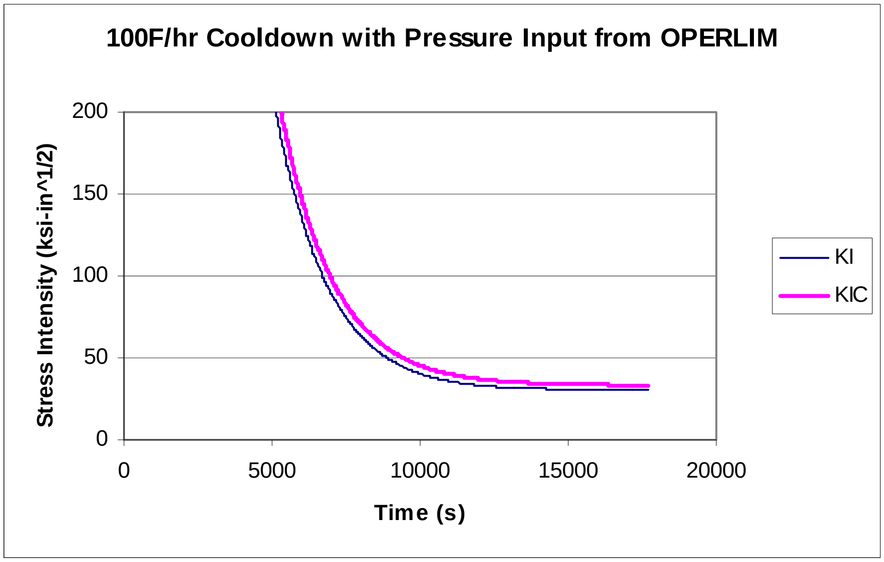


Figure B-1
Deterministic Code Benchmarking

Theoretically, by using the allowable pressures calculated by OPERLIM and the 100°F/hr cool-down rate (along with the adjustments to the input described above), the values of K_I determined by the Westinghouse code should equal K_{IC} for each point in time. As can be seen in Figure B-1, the results obtained when using the allowable pressures from the OPERLIM Code compare well to K_{IC}. Therefore, the use of the Westinghouse deterministic code is suitable for use in the evaluations for this proof of concept.

C
FAVOR OUTPUT

C.1 Cool-down with 80 Minute Delay on Pressure and 1160 psi Minimum Pressure

```
 ************************************************
*                                                *
*              WELCOME TO FAVOR                  *
*                                                *
*   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE      *
*                VERSION 04.1                    *
*                                                *
*     FAVPOST MODULE: POSTPROCESSOR MODULE       *
*  COMBINES TRANSIENT INITIAITING FREQUENCIES    *
*        WITH RESULTS OF PFM ANALYSIS            *
*                                                *
*     PROBLEMS OR QUESTIONS REGARDING FAVOR      *
*            SHOULD BE DIRECTED TO               *
*                                                *
*               TERRY DICKSON                    *
*        OAK RIDGE NATIONAL LABORATORY           *
*                                                *
*          e-mail: dicksontl@ornl.gov            *
*                                                *
************************************************

************************************************************
* This computer program was prepared as an account of     *
* work sponsored by the United States Government          *
* Neither the United States, nor the United States        *
* Department of Energy, nor the United States Nuclear     *
* Regulatory Commission, nor any of their employees,      *
* nor any of their contractors, subcontractors, or their  *
* employees, makes any warranty, expressed or implied, or *
* assumes any legal liability or responsibility for the   *
* accuracy, completeness, or usefulness of any            *
* information, apparatus, product, or process disclosed,  *
* or represents that its use would not infringe           *
* privately-owned rights.                                 *
************************************************************



     DATE: 28-Dec-2004  TIME: 14:28:21


      Begin echo of FAVPost input data deck          14:28:21   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ************************************************************************
    2    *                       FAVPost input dataset                          *
    3    *                           BEAVER VALLEY                              *
    4    *                                                                      *
    5    *    1 Beaver Valley Cool-down transients                               *
```

```
    6    *                                                                      *
    7    *    File created on 12/20/04                                          *
    8    *                                                                      *
    9    ************************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
   17    6.49E-01 17.47
   18    6.67E-01 19.74
   19    6.86E-01 17.47
   20    7.06E-01 12.10
   21    7.27E-01 6.56
   22    7.50E-01 2.78
   23    7.74E-01 0.92
   24    8.00E-01 0.30
no./col. 1.......10........20........30........40........50........60........70........80

               End echo of FAVPost input data deck          14:28:21   28-Dec-2004


              FAVPOST INPUT  FILE NAME                  = postbv.in
              FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
              FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
              FAVPOST OUTPUT FILE NAME                  = bvpostpresshold3.out



                 **********************************
                 * NUMBER OF SIMULATIONS =  10000 *
                 **********************************
```

TRANSIENT NUMBER	CONDITIONAL PROBABILITY OF INITIATION CPI=P(I|E) MEAN CPI	95th % CPI	99th % CPI	CONDITIONAL PROBABILITY OF FAILURE CPF=P(F|E) MEAN CPF	95th % CPF	99th % CPF	RATIO CPFmn/CPImn
1	3.9326E-07	0.0000E+00	0.0000E+00	2.6277E-07	0.0000E+00	0.0000E+00	0.6682

```
         NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
                CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


            ***********************************************************
            *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
            *         FOR THE FREQUENCY OF CRACK INITIATION           *
            ***********************************************************

                    FREQUENCY OF         RELATIVE    CUMULATIVE
                  CRACK INITIATION       DENSITY     DISTRIBUTION
              (CRACKED VESSELS PER YEAR)   ( %)          (%)

                      0.0000E+00         99.5000       99.5000
                      5.4307E-06          0.4300       99.9300
                      1.6292E-05          0.0200       99.9500
                      1.1404E-04          0.0100       99.9600
                      2.1180E-04          0.0100       99.9700
                      2.5524E-04          0.0100       99.9800
                      8.4175E-04          0.0100       99.9900
                      1.0698E-03          0.0100      100.0000


                      =============================================
                      ==      Summary Descriptive Statistics     ==
                      =============================================

                      Minimum                          = 0.0000E+00
```

```
          Maximum                          = 1.0753E-03
          Range                            = 1.0753E-03

          Number of Simulations            =  10000

          5th Percentile                   = 0.0000E+00
          Median                           = 0.0000E+00
          95.0th Percentile                = 0.0000E+00
          99.0th Percentile                = 0.0000E+00
          99.9th Percentile                = 1.0685E-06

          Mean                             = 2.5467E-07
          Standard Deviation               = 1.4080E-05
          Standard Error                   = 1.4080E-07
          Variance (unbiased)              = 1.9824E-10
          Variance (biased)                = 1.9822E-10
          Moment Coeff. of Skewness        = 6.6598E+01
          Pearson's 2nd Coeff. of Skewness = 5.4262E-02
          Kurtosis                         = 4.6712E+03


***********************************************************
*      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
*         FOR THE FREQUENCY OF VESSEL FAILURE             *
***********************************************************

         FREQUENCY OF         RELATIVE    CUMULATIVE
       VESSEL FAILURES        DENSITY     DISTRIBUTION
  (FAILED VESSELS PER YEAR)   ( %)          (%)

          0.0000E+00         99.5000       99.5000
          3.6695E-06          0.4500       99.9500
          6.9721E-05          0.0100       99.9600
          1.5779E-04          0.0100       99.9700
          2.0916E-04          0.0100       99.9800
          5.1740E-04          0.0100       99.9900
          7.2289E-04          0.0100      100.0000


          =============================================
          ==      Summary Descriptive Statistics     ==
          =============================================

          Minimum                          = 0.0000E+00
          Maximum                          = 7.2656E-04
          Range                            = 7.2656E-04

          Number of Simulations            =  10000

          5th Percentile                   = 0.0000E+00
          Median                           = 0.0000E+00
          95.0th Percentile                = 0.0000E+00
          99.0th Percentile                = 0.0000E+00
          99.9th Percentile                = 1.0685E-06

          Mean                             = 1.7033E-07
          Standard Deviation               = 9.3384E-06
          Standard Error                   = 9.3384E-08
          Variance (unbiased)              = 8.7207E-11
          Variance (biased)                = 8.7198E-11
          Moment Coeff. of Skewness        = 6.5987E+01
          Pearson's 2nd Coeff. of Skewness = 5.4719E-02
          Kurtosis                         = 4.6558E+03

***********************************************************
*  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
*             AND FREQUENCY OF RPV FAILURE BY             *
*                      TRANSIENT                          *
*       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
***********************************************************
```

	% of total frequency of crack initiation	% of total frequency of of RPV failure
1	100.00	100.00
TOTALS	100.00	100.00

```
**********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY PARENT SUBREGION                   *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
**********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	99.60	99.41	0.00	99.41
6	275.88	13.15	0.05	0.08	0.00	0.08
7	256.29	13.15	0.01	0.01	0.00	0.01
8	313.05	21.20	0.30	0.44	0.00	0.44
9	283.05	21.20	0.04	0.06	0.00	0.06
	TOTALS	99.98	100.00	100.00	0.00	100.00

```
**********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY CHILD SUBREGION                    *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
**********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	0.00	0.00	0.00	0.00
6	275.88	13.15	0.05	0.08	0.00	0.08
7	256.29	13.15	0.01	0.01	0.00	0.01
8	313.05	21.20	54.27	54.69	0.00	54.69
9	283.05	21.20	45.67	45.22	0.00	45.22
	TOTALS	99.98	100.00	100.00	0.00	100.00

C.2 Cool-down with 80 Minute Delay on Pressure and 1460 psi Minimum Pressure

```
*************************************************
*                                               *
*               WELCOME TO FAVOR                *
*                                               *
*   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE     *
*                 VERSION 04.1                  *
*                                               *
*     FAVPOST MODULE: POSTPROCESSOR MODULE      *
*  COMBINES TRANSIENT INITIAITING FREQUENCIES   *
*        WITH RESULTS OF PFM ANALYSIS           *
*                                               *
*     PROBLEMS OR QUESTIONS REGARDING FAVOR     *
*             SHOULD BE DIRECTED TO             *
*                                               *
*                TERRY DICKSON                  *
*        OAK RIDGE NATIONAL LABORATORY          *
*                                               *
*          e-mail: dicksontl@ornl.gov           *
*                                               *
*************************************************
```

```
***********************************************************
* This computer program was prepared as an account of     *
* work sponsored by the United States Government          *
* Neither the United States, nor the United States        *
* Department of Energy, nor the United States Nuclear     *
* Regulatory Commission, nor any of their employees,      *
* nor any of their contractors, subcontractors, or their  *
* employees, makes any warranty, expressed or implied, or *
* assumes any legal liability or responsibility for the   *
* accuracy, completeness, or usefulness of any            *
* information, apparatus, product, or process disclosed,  *
* or represents that its use would not infringe           *
* privately-owned rights.                                 *
***********************************************************
```

```
     DATE: 28-Dec-2004  TIME: 14:28:52


      Begin echo of FAVPost input data deck         14:28:53   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ************************************************************************
    2    *                       FAVPost input dataset                          *
    3    *                           BEAVER VALLEY                              *
    4    *                                                                      *
    5    *    1 Beaver Valley Cool-down transients                               *
    6    *                                                                      *
    7    *    File created on 12/20/04                                          *
    8    *                                                                      *
    9    ************************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
   17    6.49E-01 17.47
```

```
   18    6.67E-01 19.74
   19    6.86E-01 17.47
   20    7.06E-01 12.10
   21    7.27E-01 6.56
   22    7.50E-01 2.78
   23    7.74E-01 0.92
   24    8.00E-01 0.30
 no./col. 1.......10........20........30........40........50........60........70........80

               End echo of FAVPost input data deck         14:28:53   28-Dec-2004


              FAVPOST INPUT  FILE NAME                  = postbv.in
              FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
              FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
              FAVPOST OUTPUT FILE NAME                  = bvpostpresshold4p.out



                  **********************************
                  * NUMBER OF SIMULATIONS =  10000 *
                  **********************************
```

```
                CONDITIONAL PROBABILITY                     CONDITIONAL PROBABILITY
                OF INITIATION CPI=P(I|E)                     OF FAILURE CPF=P(F|E)
 TRANSIENT   MEAN          95th %        99th %        MEAN          95th %        99th %    RATIO
  NUMBER      CPI            CPI           CPI          CPF            CPF           CPF   CPFmn/CPImn
         |-------------------------------------|  |-------------------------------------|
     1    6.6774E-07    0.0000E+00    1.4874E-08    5.5802E-07    0.0000E+00    1.4874E-08  0.8357
```

```
        NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
               CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


            ***********************************************************
            *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
            *         FOR THE FREQUENCY OF CRACK INITIATION           *
            ***********************************************************

                   FREQUENCY OF          RELATIVE    CUMULATIVE
                 CRACK INITIATION        DENSITY     DISTRIBUTION
              (CRACKED VESSELS PER YEAR)   ( %)          (%)

                      0.0000E+00         98.2600       98.2600
                      8.6569E-06          1.6600       99.9200
                      2.5971E-05          0.0200       99.9400
                      4.3284E-05          0.0100       99.9500
                      2.1642E-04          0.0100       99.9600
                      3.8956E-04          0.0100       99.9700
                      4.5881E-04          0.0100       99.9800
                      1.3418E-03          0.0100       99.9900
                      1.7227E-03          0.0100      100.0000


                      =============================================
                      ==      Summary Descriptive Statistics     ==
                      =============================================

                      Minimum                          = 0.0000E+00
                      Maximum                          = 1.7141E-03
                      Range                            = 1.7141E-03

                      Number of Simulations            =  10000

                      5th Percentile                   = 0.0000E+00
                      Median                           = 0.0000E+00
                      95.0th Percentile                = 0.0000E+00
                      99.0th Percentile                = 1.0166E-08
                      99.9th Percentile                = 8.9571E-06
```

```
          Mean                               = 4.3294E-07
          Standard Deviation                 = 2.2695E-05
          Standard Error                     = 2.2695E-07
          Variance (unbiased)                = 5.1506E-10
          Variance (biased)                  = 5.1501E-10
          Moment Coeff. of Skewness          = 6.5097E+01
          Pearson's 2nd Coeff. of Skewness   = 5.7230E-02
          Kurtosis                           = 4.4951E+03


***********************************************************
*      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
*         FOR THE FREQUENCY OF VESSEL FAILURE             *
***********************************************************

         FREQUENCY OF         RELATIVE    CUMULATIVE
       VESSEL FAILURES        DENSITY     DISTRIBUTION
  (FAILED VESSELS PER YEAR)   ( %)          (%)

          0.0000E+00         98.2600       98.2600
          7.2925E-06          1.6600       99.9200
          2.1878E-05          0.0300       99.9500
          1.6773E-04          0.0100       99.9600
          3.2816E-04          0.0100       99.9700
          4.1567E-04          0.0100       99.9800
          1.0866E-03          0.0100       99.9900
          1.4512E-03          0.0100      100.0000


          =============================================
          ==      Summary Descriptive Statistics     ==
          =============================================

          Minimum                            = 0.0000E+00
          Maximum                            = 1.4439E-03
          Range                              = 1.4439E-03

          Number of Simulations              =  10000

          5th Percentile                     = 0.0000E+00
          Median                             = 0.0000E+00
          95.0th Percentile                  = 0.0000E+00
          99.0th Percentile                  = 1.0166E-08
          99.9th Percentile                  = 8.9571E-06

          Mean                               = 3.6190E-07
          Standard Deviation                 = 1.8940E-05
          Standard Error                     = 1.8940E-07
          Variance (unbiased)                = 3.5872E-10
          Variance (biased)                  = 3.5868E-10
          Moment Coeff. of Skewness          = 6.4979E+01
          Pearson's 2nd Coeff. of Skewness   = 5.7324E-02
          Kurtosis                           = 4.5022E+03

***********************************************************
*  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
*             AND FREQUENCY OF RPV FAILURE BY             *
*                      TRANSIENT                          *
*       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
***********************************************************
                      % of total         % of total
                     frequency of       frequency of
                   crack initiation    of RPV failure
            1          100.00              100.00

               TOTALS  100.00              100.00

***********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
```

```
*               RPV BELTLINE MAJOR REGION                *
*                   BY PARENT SUBREGION                  *
*                                                        *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT     *
*           TO FREQUENCY OF CRACK INITIATION AND         *
*                FREQUENCY OF RPV FAILURE                *
**********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	97.45	96.94	0.00	96.94
6	275.88	13.15	0.38	0.46	0.00	0.46
7	256.29	13.15	0.07	0.08	0.00	0.08
8	313.05	21.20	1.80	2.16	0.00	2.16
9	283.05	21.20	0.30	0.36	0.00	0.36
	TOTALS	99.98	100.00	100.00	0.00	100.00

```
**********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY             *
*               RPV BELTLINE MAJOR REGION                *
*                   BY CHILD SUBREGION                   *
*                                                        *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT     *
*           TO FREQUENCY OF CRACK INITIATION AND         *
*                FREQUENCY OF RPV FAILURE                *
**********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	0.00	0.00	0.00	0.00
6	275.88	13.15	0.38	0.46	0.00	0.46
7	256.29	13.15	0.07	0.08	0.00	0.08
8	313.05	21.20	55.47	55.56	0.00	55.56
9	283.05	21.20	44.08	43.90	0.00	43.90
	TOTALS	99.98	100.00	100.00	0.00	100.00

C.3 Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 150°F/hr Cool-down Rate after RHR Initiation

```
     ************************************************
     *                                              *
     *               WELCOME TO FAVOR               *
     *                                              *
     *   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE    *
     *                 VERSION 04.1                 *
     *                                              *
     *     FAVPOST MODULE: POSTPROCESSOR MODULE     *
     *  COMBINES TRANSIENT INITIAITING FREQUENCIES  *
     *         WITH RESULTS OF PFM ANALYSIS         *
     *                                              *
     *     PROBLEMS OR QUESTIONS REGARDING FAVOR    *
     *             SHOULD BE DIRECTED TO            *
     *                                              *
     *                TERRY DICKSON                 *
     *         OAK RIDGE NATIONAL LABORATORY        *
     *                                              *
     *           e-mail: dicksontl@ornl.gov         *
     *                                              *
     ************************************************

************************************************************
* This computer program was prepared as an account of     *
* work sponsored by the United States Government          *
* Neither the United States, nor the United States        *
* Department of Energy, nor the United States Nuclear     *
* Regulatory Commission, nor any of their employees,      *
* nor any of their contractors, subcontractors, or their  *
* employees, makes any warranty, expressed or implied, or *
* assumes any legal liability or responsibility for the   *
* accuracy, completeness, or usefulness of any            *
* information, apparatus, product, or process disclosed,  *
* or represents that its use would not infringe           *
* privately-owned rights.                                 *
************************************************************
```

```
     DATE: 28-Dec-2004  TIME: 14:31:37


      Begin echo of FAVPost input data deck         14:31:37   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ***********************************************************************
    2    *                       FAVPost input dataset                         *
    3    *                           BEAVER VALLEY                             *
    4    *                                                                     *
    5    *    1 Beaver Valley Cool-down transients                              *
    6    *                                                                     *
    7    *    File created on 12/20/04                                         *
    8    *                                                                     *
    9    ***********************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
```

```
   17    6.49E-01 17.47
   18    6.67E-01 19.74
   19    6.86E-01 17.47
   20    7.06E-01 12.10
   21    7.27E-01 6.56
   22    7.50E-01 2.78
   23    7.74E-01 0.92
   24    8.00E-01 0.30
no./col. 1.......10........20........30........40........50........60........70........80

              End echo of FAVPost input data deck          14:31:37   28-Dec-2004

             FAVPOST INPUT  FILE NAME                    = postbv.in
             FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
             FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
             FAVPOST OUTPUT FILE NAME                    = bvpost380psi150fhr.out


                **********************************
                * NUMBER OF SIMULATIONS =  10000 *
                **********************************
```

TRANSIENT NUMBER	CONDITIONAL PROBABILITY OF INITIATION CPI=P(I|E) MEAN CPI	95th % CPI	99th % CPI	CONDITIONAL PROBABILITY OF FAILURE CPF=P(F|E) MEAN CPF	95th % CPF	99th % CPF	RATIO CPFmn/CPImn
1	5.9040E-07	0.0000E+00	4.4724E-09	2.1767E-08	0.0000E+00	3.0825E-09	0.0369

```
        NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
               CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


             ***********************************************************
             *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
             *         FOR THE FREQUENCY OF CRACK INITIATION           *
             ***********************************************************

                   FREQUENCY OF         RELATIVE    CUMULATIVE
                 CRACK INITIATION       DENSITY     DISTRIBUTION
             (CRACKED VESSELS PER YEAR)   ( %)          (%)

                    0.0000E+00         98.4400       98.4400
                    7.7935E-06          1.4800       99.9200
                    2.3380E-05          0.0300       99.9500
                    1.7925E-04          0.0100       99.9600
                    3.5071E-04          0.0100       99.9700
                    3.9747E-04          0.0100       99.9800
                    1.2080E-03          0.0100       99.9900
                    1.5353E-03          0.0100      100.0000


                    =============================================
                    ==      Summary Descriptive Statistics     ==
                    =============================================

                    Minimum                          = 0.0000E+00
                    Maximum                          = 1.5431E-03
                    Range                            = 1.5431E-03

                    Number of Simulations            =  10000

                    5th Percentile                   = 0.0000E+00
                    Median                           = 0.0000E+00
                    95.0th Percentile                = 0.0000E+00
                    99.0th Percentile                = 3.0844E-09
                    99.9th Percentile                = 7.1362E-06
```

```
          Mean                               = 3.8265E-07
          Standard Deviation                 = 2.0345E-05
          Standard Error                     = 2.0345E-07
          Variance (unbiased)                = 4.1392E-10
          Variance (biased)                  = 4.1388E-10
          Moment Coeff. of Skewness          = 6.5488E+01
          Pearson's 2nd Coeff. of Skewness   = 5.6424E-02
          Kurtosis                           = 4.5435E+03


************************************************************
*      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
*         FOR THE FREQUENCY OF VESSEL FAILURE              *
************************************************************

         FREQUENCY OF         RELATIVE    CUMULATIVE
       VESSEL FAILURES        DENSITY     DISTRIBUTION
  (FAILED VESSELS PER YEAR)   ( %)          (%)

          0.0000E+00         98.4700       98.4700
          1.1468E-07          1.1700       99.6400
          3.4404E-07          0.0600       99.7000
          5.7339E-07          0.0300       99.7300
          8.0275E-07          0.0200       99.7500
          1.0321E-06          0.0100       99.7600
          1.2615E-06          0.0100       99.7700
          1.4908E-06          0.0300       99.8000
          1.7202E-06          0.0200       99.8200
          2.1789E-06          0.0100       99.8300
          2.6376E-06          0.0100       99.8400
          2.8670E-06          0.0100       99.8500
          3.3257E-06          0.0100       99.8600
          3.5550E-06          0.0100       99.8700
          3.7844E-06          0.0100       99.8800
          4.0138E-06          0.0100       99.8900
          4.2431E-06          0.0100       99.9000
          4.4725E-06          0.0100       99.9100
          4.7018E-06          0.0100       99.9200
          4.9312E-06          0.0100       99.9300
          6.5367E-06          0.0100       99.9400
          7.4541E-06          0.0100       99.9500
          8.8303E-06          0.0100       99.9600
          9.7477E-06          0.0100       99.9700
          1.0436E-05          0.0100       99.9800
          1.6628E-05          0.0100       99.9900
          2.2592E-05          0.0100      100.0000


          =============================================
          ==      Summary Descriptive Statistics     ==
          =============================================

          Minimum                            = 0.0000E+00
          Maximum                            = 2.2706E-05
          Range                              = 2.2706E-05

          Number of Simulations              =  10000

          5th Percentile                     = 0.0000E+00
          Median                             = 0.0000E+00
          95.0th Percentile                  = 0.0000E+00
          99.0th Percentile                  = 2.1689E-09
          99.9th Percentile                  = 4.5084E-06

          Mean                               = 1.4073E-08
          Standard Deviation                 = 3.6725E-07
          Standard Error                     = 3.6725E-09
          Variance (unbiased)                = 1.3487E-13
          Variance (biased)                  = 1.3486E-13
          Moment Coeff. of Skewness          = 4.1113E+01
```

```
                 Pearson's 2nd Coeff. of Skewness  = 1.1496E-01
                 Kurtosis                          = 2.0643E+03

     ***********************************************************
     *  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
     *               AND FREQUENCY OF RPV FAILURE BY           *
     *                        TRANSIENT                        *
     *       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
     ***********************************************************
                             % of total         % of total
                            frequency of       frequency of
                          crack initiation    of RPV failure
                   1         100.00              100.00

                      TOTALS  100.00              100.00

 ***********************************************************
 *    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
 *            AND FREQUENCY OF RPV FAILURE BY              *
 *               RPV BELTLINE MAJOR REGION                 *
 *                   BY PARENT SUBREGION                   *
 *                                                         *
 *       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
 *           TO FREQUENCY OF CRACK INITIATION AND          *
 *                FREQUENCY OF RPV FAILURE                 *
 ***********************************************************

                                                % of total
                % of     % of total       through-wall crack
MAJOR    RTPTS  total  frequency of            frequency
REGION   (MAX)  flaws  crack initiation  cleavage ductile total

   1    232.66   2.29        0.00         0.00     0.00     0.00
   2    232.66   2.29        0.00         0.00     0.00     0.00
   3    220.01   3.70        0.00         0.00     0.00     0.00
   4    220.01   3.70        0.00         0.00     0.00     0.00
   5    160.72  19.30       97.86        41.97     0.00    41.97
   6    275.88  13.15        0.31         8.52     0.00     8.52
   7    256.29  13.15        0.05         1.42     0.00     1.42
   8    313.05  21.20        1.54        41.69     0.00    41.69
   9    283.05  21.20        0.24         6.40     0.00     6.40

        TOTALS  99.98      100.00       100.00     0.00   100.00

 ***********************************************************
 *    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
 *            AND FREQUENCY OF RPV FAILURE BY              *
 *               RPV BELTLINE MAJOR REGION                 *
 *                   BY CHILD SUBREGION                    *
 *                                                         *
 *       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
 *           TO FREQUENCY OF CRACK INITIATION AND          *
 *                FREQUENCY OF RPV FAILURE                 *
 ***********************************************************

                                                % of total
                % of     % of total       through-wall crack
MAJOR    RTPTS  total  frequency of            frequency
REGION   (MAX)  flaws  crack initiation  cleavage ductile total

   1    232.66   2.29        0.00         0.00     0.00     0.00
   2    232.66   2.29        0.00         0.00     0.00     0.00
   3    220.01   3.70        0.00         0.00     0.00     0.00
   4    220.01   3.70        0.00         0.00     0.00     0.00
   5    160.72  19.30        0.00         0.00     0.00     0.00
   6    275.88  13.15        0.31         8.52     0.00     8.52
   7    256.29  13.15        0.05         1.42     0.00     1.42
   8    313.05  21.20       55.24        76.85     0.00    76.85
   9    283.05  21.20       44.40        13.21     0.00    13.21

        TOTALS  99.98      100.00       100.00     0.00   100.00
```

C.4 Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 175°F/hr Cool-down Rate after RHR Initiation

```
************************************************
*                                              *
*               WELCOME TO FAVOR               *
*                                              *
*   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE    *
*                 VERSION 04.1                 *
*                                              *
*     FAVPOST MODULE: POSTPROCESSOR MODULE     *
*  COMBINES TRANSIENT INITIAITING FREQUENCIES  *
*        WITH RESULTS OF PFM ANALYSIS          *
*                                              *
*     PROBLEMS OR QUESTIONS REGARDING FAVOR    *
*             SHOULD BE DIRECTED TO            *
*                                              *
*                TERRY DICKSON                 *
*        OAK RIDGE NATIONAL LABORATORY         *
*                                              *
*          e-mail: dicksontl@ornl.gov          *
*                                              *
************************************************

************************************************************
* This computer program was prepared as an account of     *
* work sponsored by the United States Government          *
* Neither the United States, nor the United States        *
* Department of Energy, nor the United States Nuclear     *
* Regulatory Commission, nor any of their employees,      *
* nor any of their contractors, subcontractors, or their  *
* employees, makes any warranty, expressed or implied, or *
* assumes any legal liability or responsibility for the   *
* accuracy, completeness, or usefulness of any            *
* information, apparatus, product, or process disclosed,  *
* or represents that its use would not infringe           *
* privately-owned rights.                                 *
************************************************************



     DATE: 28-Dec-2004  TIME: 14:48:53


      Begin echo of FAVPost input data deck         14:48:53   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ************************************************************************
    2    *                       FAVPost input dataset                           *
    3    *                           BEAVER VALLEY                               *
    4    *                                                                       *
    5    *    1 Beaver Valley Cool-down transients                                *
    6    *                                                                       *
    7    *    File created on 12/20/04                                           *
    8    *                                                                       *
    9    ************************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
   17    6.49E-01 17.47
   18    6.67E-01 19.74
```

```
   19    6.86E-01 17.47
   20    7.06E-01 12.10
   21    7.27E-01 6.56
   22    7.50E-01 2.78
   23    7.74E-01 0.92
   24    8.00E-01 0.30
no./col. 1.......10........20........30........40........50........60........70........80

               End echo of FAVPost input data deck          14:48:53   28-Dec-2004


              FAVPOST INPUT  FILE NAME                    = postbv.in
              FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
              FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
              FAVPOST OUTPUT FILE NAME                    = bvpost380psi175fhr.out



                 **********************************
                 * NUMBER OF SIMULATIONS =  10000 *
                 **********************************
```

TRANSIENT NUMBER	CONDITIONAL PROBABILITY OF INITIATION CPI=P(I|E) MEAN CPI	95th % CPI	99th % CPI	CONDITIONAL PROBABILITY OF FAILURE CPF=P(F|E) MEAN CPF	95th % CPF	99th % CPF	RATIO CPFmn/CPImn
1	1.3591E-06	0.0000E+00	3.9328E-06	2.1909E-07	0.0000E+00	3.5263E-06	0.1612

```
        NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
               CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


             ***********************************************************
             *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
             *         FOR THE FREQUENCY OF CRACK INITIATION           *
             ***********************************************************

                     FREQUENCY OF         RELATIVE    CUMULATIVE
                   CRACK INITIATION       DENSITY     DISTRIBUTION
               (CRACKED VESSELS PER YEAR)   ( %)          (%)

                      0.0000E+00         97.1500       97.1500
                      1.5006E-05          2.6500       99.8000
                      4.5018E-05          0.1100       99.9100
                      7.5031E-05          0.0400       99.9500
                      4.3518E-04          0.0100       99.9600
                      7.9533E-04          0.0100       99.9700
                      9.1538E-04          0.0100       99.9800
                      2.3260E-03          0.0100       99.9900
                      2.9562E-03          0.0100      100.0000


                      =============================================
                      ==      Summary Descriptive Statistics     ==
                      =============================================

                      Minimum                           = 0.0000E+00
                      Maximum                           = 2.9712E-03
                      Range                             = 2.9712E-03

                      Number of Simulations             =  10000

                      5th Percentile                    = 0.0000E+00
                      Median                            = 0.0000E+00
                      95.0th Percentile                 = 0.0000E+00
                      99.0th Percentile                 = 2.6138E-06
                      99.9th Percentile                 = 5.5468E-05
```

```
Mean                             = 8.8392E-07
Standard Deviation               = 3.9843E-05
Standard Error                   = 3.9843E-07
Variance (unbiased)              = 1.5875E-09
Variance (biased)                = 1.5873E-09
Moment Coeff. of Skewness        = 6.3202E+01
Pearson's 2nd Coeff. of Skewness = 6.6555E-02
Kurtosis                         = 4.2778E+03


***********************************************************
*      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
*         FOR THE FREQUENCY OF VESSEL FAILURE             *
***********************************************************

       FREQUENCY OF         RELATIVE    CUMULATIVE
     VESSEL FAILURES        DENSITY     DISTRIBUTION
  (FAILED VESSELS PER YEAR)   ( %)         (%)

         0.0000E+00        97.1800       97.1800
         4.3422E-07         1.3800       98.5600
         1.3027E-06         0.3400       98.9000
         2.1711E-06         0.1400       99.0400
         3.0396E-06         0.1500       99.1900
         3.9080E-06         0.1400       99.3300
         4.7765E-06         0.0800       99.4100
         5.6449E-06         0.1100       99.5200
         6.5134E-06         0.0700       99.5900
         7.3818E-06         0.0400       99.6300
         8.2503E-06         0.0300       99.6600
         9.1187E-06         0.0200       99.6800
         9.9872E-06         0.0200       99.7000
         1.0856E-05         0.0200       99.7200
         1.1724E-05         0.0200       99.7400
         1.3461E-05         0.0100       99.7500
         1.5198E-05         0.0100       99.7600
         1.6066E-05         0.0100       99.7700
         1.7803E-05         0.0200       99.7900
         1.9540E-05         0.0100       99.8000
         2.1277E-05         0.0100       99.8100
         2.2145E-05         0.0100       99.8200
         2.4751E-05         0.0100       99.8300
         2.6488E-05         0.0100       99.8400
         2.9961E-05         0.0100       99.8500
         3.0830E-05         0.0100       99.8600
         3.3435E-05         0.0100       99.8700
         3.5172E-05         0.0200       99.8900
         3.7778E-05         0.0100       99.9000
         4.1251E-05         0.0100       99.9100
         4.2988E-05         0.0100       99.9200
         4.4725E-05         0.0100       99.9300
         4.7330E-05         0.0100       99.9400
         5.6883E-05         0.0100       99.9500
         5.8620E-05         0.0100       99.9600
         6.0357E-05         0.0100       99.9700
         6.2094E-05         0.0100       99.9800
         6.2963E-05         0.0100       99.9900
         8.6411E-05         0.0100      100.0000


         =============================================
         ==      Summary Descriptive Statistics     ==
         =============================================

         Minimum                          = 0.0000E+00
         Maximum                          = 8.5976E-05
         Range                            = 8.5976E-05

         Number of Simulations            =  10000
```

```
                5th Percentile                     = 0.0000E+00
                Median                             = 0.0000E+00
                95.0th Percentile                  = 0.0000E+00
                99.0th Percentile                  = 2.4537E-06
                99.9th Percentile                  = 4.0161E-05

                Mean                               = 1.4402E-07
                Standard Deviation                 = 2.1566E-06
                Standard Error                     = 2.1566E-08
                Variance (unbiased)                = 4.6509E-12
                Variance (biased)                  = 4.6504E-12
                Moment Coeff. of Skewness          = 2.3801E+01
                Pearson's 2nd Coeff. of Skewness  = 2.0035E-01
                Kurtosis                           = 6.6731E+02

     ***********************************************************
     *  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
     *             AND FREQUENCY OF RPV FAILURE BY             *
     *                      TRANSIENT                          *
     *       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
     ***********************************************************
                         % of total         % of total
                        frequency of       frequency of
                      crack initiation    of RPV failure
                 1         100.00              100.00

                    TOTALS  100.00              100.00

 ***********************************************************
 *    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
 *            AND FREQUENCY OF RPV FAILURE BY              *
 *               RPV BELTLINE MAJOR REGION                 *
 *                   BY PARENT SUBREGION                   *
 *                                                         *
 *       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
 *           TO FREQUENCY OF CRACK INITIATION AND          *
 *                FREQUENCY OF RPV FAILURE                 *
 ***********************************************************

                                                  % of total
                 % of     % of total          through-wall crack
MAJOR    RTPTS   total   frequency of             frequency
REGION   (MAX)   flaws  crack initiation  cleavage ductile total

   1    232.66   2.29         0.00          0.00     0.00     0.00
   2    232.66   2.29         0.00          0.00     0.00     0.00
   3    220.01   3.70         0.00          0.00     0.00     0.00
   4    220.01   3.70         0.00          0.00     0.00     0.00
   5    160.72  19.30        86.32         15.17     0.00    15.17
   6    275.88  13.15         2.06         12.75     0.00    12.75
   7    256.29  13.15         0.52          3.22     0.00     3.22
   8    313.05  21.20         8.89         55.14     0.00    55.14
   9    283.05  21.20         2.21         13.72     0.00    13.72

        TOTALS  99.98       100.00        100.00     0.00   100.00

 ***********************************************************
 *    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
 *            AND FREQUENCY OF RPV FAILURE BY              *
 *               RPV BELTLINE MAJOR REGION                 *
 *                   BY CHILD SUBREGION                    *
 *                                                         *
 *       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
 *           TO FREQUENCY OF CRACK INITIATION AND          *
 *                FREQUENCY OF RPV FAILURE                 *
 ***********************************************************

                                                  % of total
                 % of     % of total          through-wall crack
MAJOR    RTPTS   total   frequency of             frequency
REGION   (MAX)   flaws  crack initiation  cleavage ductile total
```

1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	0.00	0.00	0.00	0.00
6	275.88	13.15	2.06	12.75	0.00	12.75
7	256.29	13.15	0.52	3.22	0.00	3.22
8	313.05	21.20	57.22	66.21	0.00	66.21
9	283.05	21.20	40.20	17.82	0.00	17.82
	TOTALS	99.98	100.00	100.00	0.00	100.00

C.5 Cool-down with 80 Minute Delay on Pressure, 375 psi Minimum Pressure, and 200°F/hr Cool-down Rate after RHR Initiation

```
          ************************************************
          *                                              *
          *               WELCOME TO FAVOR               *
          *                                              *
          *   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE    *
          *                VERSION 04.1                  *
          *                                              *
          *     FAVPOST MODULE: POSTPROCESSOR MODULE     *
          *  COMBINES TRANSIENT INITIAITING FREQUENCIES  *
          *        WITH RESULTS OF PFM ANALYSIS          *
          *                                              *
          *     PROBLEMS OR QUESTIONS REGARDING FAVOR    *
          *            SHOULD BE DIRECTED TO             *
          *                                              *
          *               TERRY DICKSON                  *
          *        OAK RIDGE NATIONAL LABORATORY         *
          *                                              *
          *          e-mail: dicksontl@ornl.gov          *
          *                                              *
          ************************************************

     ***********************************************************
     * This computer program was prepared as an account of     *
     * work sponsored by the United States Government          *
     * Neither the United States, nor the United States        *
     * Department of Energy, nor the United States Nuclear     *
     * Regulatory Commission, nor any of their employees,      *
     * nor any of their contractors, subcontractors, or their  *
     * employees, makes any warranty, expressed or implied, or *
     * assumes any legal liability or responsibility for the   *
     * accuracy, completeness, or usefulness of any            *
     * information, apparatus, product, or process disclosed,  *
     * or represents that its use would not infringe           *
     * privately-owned rights.                                 *
     ***********************************************************



          DATE: 28-Dec-2004  TIME: 14:32:29


           Begin echo of FAVPost input data deck         14:32:29   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ************************************************************************
    2    *                       FAVPost input dataset                          *
    3    *                           BEAVER VALLEY                              *
    4    *                                                                      *
    5    *    1 Beaver Valley Cool-down transients                               *
    6    *                                                                      *
    7    *    File created on 12/20/04                                          *
    8    *                                                                      *
    9    ************************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
   17    6.49E-01 17.47
   18    6.67E-01 19.74
   19    6.86E-01 17.47
```

```
   20    7.06E-01 12.10
   21    7.27E-01 6.56
   22    7.50E-01 2.78
   23    7.74E-01 0.92
   24    8.00E-01 0.30
no./col. 1.......10........20........30........40........50........60........70........80

               End echo of FAVPost input data deck          14:32:29   28-Dec-2004


              FAVPOST INPUT  FILE NAME                    = postbv.in
              FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
              FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
              FAVPOST OUTPUT FILE NAME                    = bvpost380psi200fhr.out



                 **********************************
                 * NUMBER OF SIMULATIONS =  10000 *
                 **********************************
```

TRANSIENT NUMBER	CONDITIONAL PROBABILITY OF INITIATION CPI=P(I|E) MEAN CPI	95th % CPI	99th % CPI	CONDITIONAL PROBABILITY OF FAILURE CPF=P(F|E) MEAN CPF	95th % CPF	99th % CPF	RATIO CPFmn/CPImn
1	3.1564E-06	0.0000E+00	3.4967E-05	1.1635E-06	0.0000E+00	3.2083E-05	0.3686

```
        NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
               CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


           ***********************************************************
           *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
           *         FOR THE FREQUENCY OF CRACK INITIATION           *
           ***********************************************************

                    FREQUENCY OF         RELATIVE    CUMULATIVE
                  CRACK INITIATION       DENSITY     DISTRIBUTION
              (CRACKED VESSELS PER YEAR)   ( %)          (%)

                      0.0000E+00        96.6000       96.6000
                      2.5479E-05         2.9500       99.5500
                      7.6436E-05         0.2300       99.7800
                      1.2739E-04         0.0800       99.8600
                      1.7835E-04         0.0600       99.9200
                      2.2931E-04         0.0200       99.9400
                      3.3122E-04         0.0100       99.9500
                      8.4080E-04         0.0100       99.9600
                      1.5032E-03         0.0100       99.9700
                      1.7071E-03         0.0100       99.9800
                      3.9492E-03         0.0100       99.9900
                      5.0703E-03         0.0100      100.0000


                      =============================================
                      ==      Summary Descriptive Statistics     ==
                      =============================================

                      Minimum                           = 0.0000E+00
                      Maximum                           = 5.0448E-03
                      Range                             = 5.0448E-03

                      Number of Simulations             =  10000

                      5th Percentile                    = 0.0000E+00
                      Median                            = 0.0000E+00
                      95.0th Percentile                 = 0.0000E+00
                      99.0th Percentile                 = 2.3170E-05
                      99.9th Percentile                 = 1.6861E-04
```

```
             Mean                             = 2.0646E-06
             Standard Deviation               = 6.8959E-05
             Standard Error                   = 6.8959E-07
             Variance (unbiased)              = 4.7553E-09
             Variance (biased)                = 4.7549E-09
             Moment Coeff. of Skewness        = 6.0544E+01
             Pearson's 2nd Coeff. of Skewness = 8.9818E-02
             Kurtosis                         = 3.9895E+03


   ***********************************************************
   *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
   *         FOR THE FREQUENCY OF VESSEL FAILURE             *
   ***********************************************************

           FREQUENCY OF         RELATIVE    CUMULATIVE
         VESSEL FAILURES        DENSITY     DISTRIBUTION
     (FAILED VESSELS PER YEAR)   ( %)         (%)

             0.0000E+00         96.6200      96.6200
             1.5973E-06          1.3500      97.9700
             4.7920E-06          0.3200      98.2900
             7.9867E-06          0.2000      98.4900
             1.1181E-05          0.1400      98.6300
             1.4376E-05          0.1800      98.8100
             1.7571E-05          0.1100      98.9200
             2.0765E-05          0.0900      99.0100
             2.3960E-05          0.0900      99.1000
             2.7155E-05          0.0900      99.1900
             3.0349E-05          0.0700      99.2600
             3.3544E-05          0.0500      99.3100
             3.6739E-05          0.1000      99.4100
             3.9934E-05          0.0400      99.4500
             4.3128E-05          0.0400      99.4900
             4.6323E-05          0.0500      99.5400
             4.9518E-05          0.0500      99.5900
             5.2712E-05          0.0300      99.6200
             5.5907E-05          0.0100      99.6300
             5.9102E-05          0.0100      99.6400
             6.2296E-05          0.0200      99.6600
             6.5491E-05          0.0300      99.6900
             6.8686E-05          0.0200      99.7100
             7.1880E-05          0.0200      99.7300
             7.5075E-05          0.0300      99.7600
             7.8270E-05          0.0100      99.7700
             8.1464E-05          0.0200      99.7900
             8.7854E-05          0.0100      99.8000
             9.1048E-05          0.0100      99.8100
             1.0063E-04          0.0100      99.8200
             1.0383E-04          0.0200      99.8400
             1.0702E-04          0.0100      99.8500
             1.1022E-04          0.0100      99.8600
             1.2619E-04          0.0100      99.8700
             1.3258E-04          0.0100      99.8800
             1.3897E-04          0.0200      99.9000
             1.4855E-04          0.0200      99.9200
             1.5175E-04          0.0100      99.9300
             1.5814E-04          0.0100      99.9400
             1.6453E-04          0.0100      99.9500
             1.7092E-04          0.0100      99.9600
             1.9328E-04          0.0100      99.9700
             2.1245E-04          0.0100      99.9800
             2.3481E-04          0.0100      99.9900
             3.1787E-04          0.0100     100.0000


             =============================================
             ==      Summary Descriptive Statistics     ==
             =============================================
```

```
              Minimum                           = 0.0000E+00
              Maximum                           = 3.1627E-04
              Range                             = 3.1627E-04

              Number of Simulations             =  10000

              5th Percentile                    = 0.0000E+00
              Median                            = 0.0000E+00
              95.0th Percentile                 = 0.0000E+00
              99.0th Percentile                 = 2.2027E-05
              99.9th Percentile                 = 1.4415E-04

              Mean                              = 7.6976E-07
              Standard Deviation                = 8.3892E-06
              Standard Error                    = 8.3892E-08
              Variance (unbiased)               = 7.0378E-11
              Variance (biased)                 = 7.0371E-11
              Moment Coeff. of Skewness         = 1.8551E+01
              Pearson's 2nd Coeff. of Skewness  = 2.7527E-01
              Kurtosis                          = 4.5336E+02

    ***********************************************************
    *  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
    *             AND FREQUENCY OF RPV FAILURE BY             *
    *                      TRANSIENT                          *
    *       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
    ***********************************************************
                       % of total        % of total
                      frequency of      frequency of
                    crack initiation    of RPV failure
                1         100.00            100.00

                   TOTALS  100.00            100.00

***********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY PARENT SUBREGION                   *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
***********************************************************

                                                % of total
                % of      % of total       through-wall crack
MAJOR    RTPTS  total    frequency of           frequency
REGION   (MAX)  flaws  crack initiation  cleavage ductile total

   1    232.66   2.29         0.00          0.00     0.00     0.00
   2    232.66   2.29         0.00          0.00     0.00     0.00
   3    220.01   3.70         0.00          0.00     0.00     0.00
   4    220.01   3.70         0.00          0.00     0.00     0.00
   5    160.72  19.30        65.70          6.91     0.00     6.91
   6    275.88  13.15         5.23         14.20     0.00    14.20
   7    256.29  13.15         1.71          4.64     0.00     4.64
   8    313.05  21.20        20.77         56.36     0.00    56.36
   9    283.05  21.20         6.59         17.89     0.00    17.89

        TOTALS  99.98       100.00        100.00     0.00   100.00

***********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY CHILD SUBREGION                    *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
```

```
*                FREQUENCY OF RPV FAILURE                 *
***********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency: cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	0.00	0.00	0.00	0.00
6	275.88	13.15	5.23	14.20	0.00	14.20
7	256.29	13.15	1.71	4.64	0.00	4.64
8	313.05	21.20	58.08	61.88	0.00	61.88
9	283.05	21.20	34.98	19.28	0.00	19.28
	TOTALS	99.98	100.00	100.00	0.00	100.00

C.6 Cool-down with 80 Minute Delay on Pressure, 760 psi Minimum Pressure, and 150°F/hr Cool-down Rate after RHR Initiation

```
     ************************************************
     *                                              *
     *               WELCOME TO FAVOR               *
     *                                              *
     *   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE    *
     *                 VERSION 04.1                 *
     *                                              *
     *     FAVPOST MODULE: POSTPROCESSOR MODULE     *
     *  COMBINES TRANSIENT INITIAITING FREQUENCIES  *
     *        WITH RESULTS OF PFM ANALYSIS          *
     *                                              *
     *     PROBLEMS OR QUESTIONS REGARDING FAVOR    *
     *            SHOULD BE DIRECTED TO             *
     *                                              *
     *                TERRY DICKSON                 *
     *        OAK RIDGE NATIONAL LABORATORY         *
     *                                              *
     *          e-mail: dicksontl@ornl.gov          *
     *                                              *
     ************************************************

************************************************************
* This computer program was prepared as an account of     *
* work sponsored by the United States Government          *
* Neither the United States, nor the United States        *
* Department of Energy, nor the United States Nuclear     *
* Regulatory Commission, nor any of their employees,      *
* nor any of their contractors, subcontractors, or their  *
* employees, makes any warranty, expressed or implied, or *
* assumes any legal liability or responsibility for the   *
* accuracy, completeness, or usefulness of any            *
* information, apparatus, product, or process disclosed,  *
* or represents that its use would not infringe           *
* privately-owned rights.                                 *
************************************************************



     DATE: 28-Dec-2004  TIME: 14:33:08


      Begin echo of FAVPost input data deck         14:33:08   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ************************************************************************
    2    *                        FAVPost input dataset                         *
    3    *                            BEAVER VALLEY                             *
    4    *                                                                      *
    5    *    1 Beaver Valley Cool-down transients                               *
    6    *                                                                      *
    7    *    File created on 12/20/04                                          *
    8    *                                                                      *
    9    ************************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
   17    6.49E-01 17.47
```

```
    18    6.67E-01 19.74
    19    6.86E-01 17.47
    20    7.06E-01 12.10
    21    7.27E-01 6.56
    22    7.50E-01 2.78
    23    7.74E-01 0.92
    24    8.00E-01 0.30
 no./col. 1.......10........20........30........40........50........60........70........80

               End echo of FAVPost input data deck          14:33:08   28-Dec-2004


              FAVPOST INPUT  FILE NAME                   = postbv.in
              FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
              FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
              FAVPOST OUTPUT FILE NAME                   = bvpost760psi150fhr.out



                 **********************************
                 * NUMBER OF SIMULATIONS =   6000 *
                 **********************************
```

TRANSIENT NUMBER	CONDITIONAL PROBABILITY OF INITIATION CPI=P(I|E) MEAN CPI	95th % CPI	99th % CPI	CONDITIONAL PROBABILITY OF FAILURE CPF=P(F|E) MEAN CPF	95th % CPF	99th % CPF	RATIO CPFmn/CPImn
1	1.7059E-06	0.0000E+00	1.6728E-06	6.3300E-07	0.0000E+00	1.6016E-06	0.3711

```
        NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
               CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


            ***********************************************************
            *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
            *         FOR THE FREQUENCY OF CRACK INITIATION           *
            ***********************************************************

                   FREQUENCY OF          RELATIVE    CUMULATIVE
                 CRACK INITIATION        DENSITY     DISTRIBUTION
              (CRACKED VESSELS PER YEAR)   ( %)          (%)

                      0.0000E+00         97.2500       97.2500
                      1.3221E-05          2.6000       99.8500
                      3.9664E-05          0.0500       99.9000
                      6.6107E-05          0.0333       99.9333
                      6.7429E-04          0.0167       99.9500
                      7.8006E-04          0.0167       99.9667
                      2.0493E-03          0.0167       99.9833
                      2.6311E-03          0.0167      100.0000


                      =============================================
                      ==      Summary Descriptive Statistics     ==
                      =============================================

                      Minimum                          = 0.0000E+00
                      Maximum                          = 2.6178E-03
                      Range                            = 2.6178E-03

                      Number of Simulations            =   6000

                      5th Percentile                   = 0.0000E+00
                      Median                           = 0.0000E+00
                      95.0th Percentile                = 0.0000E+00
                      99.0th Percentile                = 1.1376E-06
                      99.9th Percentile                = 5.1761E-05

                      Mean                             = 1.1036E-06
```

```
          Standard Deviation                = 4.4906E-05
          Standard Error                    = 5.7974E-07
          Variance (unbiased)               = 2.0166E-09
          Variance (biased)                 = 2.0162E-09
          Moment Coeff. of Skewness         = 5.0124E+01
          Pearson's 2nd Coeff. of Skewness  = 7.3728E-02
          Kurtosis                          = 2.6610E+03


 ***********************************************************
 *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
 *         FOR THE FREQUENCY OF VESSEL FAILURE             *
 ***********************************************************

         FREQUENCY OF         RELATIVE    CUMULATIVE
       VESSEL FAILURES        DENSITY     DISTRIBUTION
   (FAILED VESSELS PER YEAR)   ( %)         (%)

          0.0000E+00         97.2500       97.2500
          3.7891E-06          2.4333       99.6833
          1.1367E-05          0.1000       99.7833
          1.8945E-05          0.0500       99.8333
          2.6524E-05          0.0667       99.9000
          4.1680E-05          0.0167       99.9167
          5.6836E-05          0.0167       99.9333
          3.3723E-04          0.0167       99.9500
          3.6754E-04          0.0167       99.9667
          5.5700E-04          0.0167       99.9833
          7.5403E-04          0.0167      100.0000


          =============================================
          ==      Summary Descriptive Statistics     ==
          =============================================

          Minimum                           = 0.0000E+00
          Maximum                           = 7.5024E-04
          Range                             = 7.5024E-04

          Number of Simulations             =   6000

          5th Percentile                    = 0.0000E+00
          Median                            = 0.0000E+00
          95.0th Percentile                 = 0.0000E+00
          99.0th Percentile                 = 1.0899E-06
          99.9th Percentile                 = 3.5096E-05

          Mean                              = 4.1120E-07
          Standard Deviation                = 1.3751E-05
          Standard Error                    = 1.7753E-07
          Variance (unbiased)               = 1.8909E-10
          Variance (biased)                 = 1.8906E-10
          Moment Coeff. of Skewness         = 4.3855E+01
          Pearson's 2nd Coeff. of Skewness  = 8.9708E-02
          Kurtosis                          = 2.0706E+03

 ***********************************************************
 *  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
 *             AND FREQUENCY OF RPV FAILURE BY             *
 *                      TRANSIENT                          *
 *       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
 ***********************************************************
                      % of total        % of total
                     frequency of      frequency of
                   crack initiation    of RPV failure
            1         100.00             100.00

               TOTALS  100.00             100.00

 ***********************************************************
```

```
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY PARENT SUBREGION                   *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
***********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	93.43	82.27	0.00	82.27
6	275.88	13.15	0.80	2.16	0.00	2.16
7	256.29	13.15	0.27	0.73	0.00	0.73
8	313.05	21.20	4.40	11.87	0.00	11.87
9	283.05	21.20	1.10	2.97	0.00	2.97
	TOTALS	99.98	100.00	100.00	0.00	100.00

```
***********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY CHILD SUBREGION                    *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
***********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	0.00	0.00	0.00	0.00
6	275.88	13.15	0.80	2.16	0.00	2.16
7	256.29	13.15	0.27	0.73	0.00	0.73
8	313.05	21.20	58.66	64.50	0.00	64.50
9	283.05	21.20	40.27	32.61	0.00	32.61
	TOTALS	99.98	100.00	100.00	0.00	100.00

C.7 Cool-down with 80 Minute Delay on Pressure, 760 psi Minimum Pressure, and 175°F/hr Cool-down Rate after RHR Initiation

```
     ************************************************
     *                                              *
     *               WELCOME TO FAVOR               *
     *                                              *
     *   FRACTURE ANALYSIS OF VESSELS: OAK RIDGE    *
     *                 VERSION 04.1                 *
     *                                              *
     *     FAVPOST MODULE: POSTPROCESSOR MODULE     *
     *  COMBINES TRANSIENT INITIAITING FREQUENCIES  *
     *        WITH RESULTS OF PFM ANALYSIS          *
     *                                              *
     *     PROBLEMS OR QUESTIONS REGARDING FAVOR    *
     *             SHOULD BE DIRECTED TO            *
     *                                              *
     *                TERRY DICKSON                 *
     *        OAK RIDGE NATIONAL LABORATORY         *
     *                                              *
     *          e-mail: dicksontl@ornl.gov          *
     *                                              *
     ************************************************

************************************************************
* This computer program was prepared as an account of     *
* work sponsored by the United States Government          *
* Neither the United States, nor the United States        *
* Department of Energy, nor the United States Nuclear     *
* Regulatory Commission, nor any of their employees,      *
* nor any of their contractors, subcontractors, or their  *
* employees, makes any warranty, expressed or implied, or *
* assumes any legal liability or responsibility for the   *
* accuracy, completeness, or usefulness of any            *
* information, apparatus, product, or process disclosed,  *
* or represents that its use would not infringe           *
* privately-owned rights.                                 *
************************************************************



     DATE: 28-Dec-2004  TIME: 14:34:44


      Begin echo of FAVPost input data deck         14:34:44   28-Dec-2004

no./col. 1.......10........20........30........40........50........60........70........80
    1    ************************************************************************
    2    *                        FAVPost input dataset                         *
    3    *                            BEAVER VALLEY                             *
    4    *                                                                      *
    5    *    1 Beaver Valley Cool-down transients                               *
    6    *                                                                      *
    7    *    File created on 12/20/04                                          *
    8    *                                                                      *
    9    ************************************************************************
   10    CNTL  MTRAN=1
   11    ITRN ITRAN=1 NHIST=13 ISEQ=1
   12    5.71E-01 0.30
   13    5.85E-01 0.92
   14    6.00E-01 2.78
   15    6.15E-01 6.56
   16    6.32E-01 12.10
   17    6.49E-01 17.47
```

```
    18    6.67E-01 19.74
    19    6.86E-01 17.47
    20    7.06E-01 12.10
    21    7.27E-01 6.56
    22    7.50E-01 2.78
    23    7.74E-01 0.92
    24    8.00E-01 0.30
 no./col. 1.......10........20........30........40........50........60........70........80

               End echo of FAVPost input data deck          14:34:44   28-Dec-2004


              FAVPOST INPUT  FILE NAME                  = postbv.in
              FAVPFM  OUTPUT FILE CONTAINING PFMI ARRAY = INITIATE.DAT
              FAVPFM  OUTPUT FILE CONTAINING PFMF ARRAY = FAILURE.DAT
              FAVPOST OUTPUT FILE NAME                  = bvpost760psi175fhr.out


                **********************************
                * NUMBER OF SIMULATIONS =   4500 *
                **********************************
```

TRANSIENT NUMBER	CONDITIONAL PROBABILITY OF INITIATION CPI=P(I|E) MEAN CPI	95th % CPI	99th % CPI	CONDITIONAL PROBABILITY OF FAILURE CPF=P(F|E) MEAN CPF	95th % CPF	99th % CPF	RATIO CPFmn/CPImn
1	4.3587E-06	0.0000E+00	2.9616E-05	2.1813E-06	0.0000E+00	2.9286E-05	0.5004

```
        NOTES: CPI IS CONDITIONAL PROBABILITY OF CRACK INITIATION, P(I|E)
               CPF IS CONDITIONAL PROBABILITY OF RPV FAILURE, P(F|E)


            ***********************************************************
            *      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
            *         FOR THE FREQUENCY OF CRACK INITIATION           *
            ***********************************************************

                    FREQUENCY OF         RELATIVE    CUMULATIVE
                  CRACK INITIATION       DENSITY     DISTRIBUTION
              (CRACKED VESSELS PER YEAR)   ( %)          (%)

                      0.0000E+00         96.3111       96.3111
                      2.3530E-05          3.2444       99.5556
                      7.0590E-05          0.1778       99.7333
                      1.1765E-04          0.1333       99.8667
                      1.6471E-04          0.0444       99.9111
                      2.5883E-04          0.0222       99.9333
                      1.3412E-03          0.0222       99.9556
                      3.6471E-03          0.0222       99.9778
                      4.6354E-03          0.0222      100.0000


                      =============================================
                      ==      Summary Descriptive Statistics     ==
                      =============================================

                      Minimum                          = 0.0000E+00
                      Maximum                          = 4.6589E-03
                      Range                            = 4.6589E-03

                      Number of Simulations            =   4500

                      5th Percentile                   = 0.0000E+00
                      Median                           = 0.0000E+00
                      95.0th Percentile                = 0.0000E+00
                      99.0th Percentile                = 1.9731E-05
                      99.9th Percentile                = 1.8947E-04
```

```
          Mean                              = 2.8263E-06
          Standard Deviation                = 9.0729E-05
          Standard Error                    = 1.3525E-06
          Variance (unbiased)               = 8.2317E-09
          Variance (biased)                 = 8.2299E-09
          Moment Coeff. of Skewness         = 4.5171E+01
          Pearson's 2nd Coeff. of Skewness  = 9.3454E-02
          Kurtosis                          = 2.1308E+03


***********************************************************
*      PROBABILITY DISTRIBUTION FUNCTION (HISTOGRAM)      *
*         FOR THE FREQUENCY OF VESSEL FAILURE             *
***********************************************************

         FREQUENCY OF         RELATIVE    CUMULATIVE
       VESSEL FAILURES        DENSITY     DISTRIBUTION
  (FAILED VESSELS PER YEAR)   ( %)          (%)

          0.0000E+00         96.3111       96.3111
          7.8666E-06          2.5111       98.8222
          2.3600E-05          0.5333       99.3556
          3.9333E-05          0.2222       99.5778
          5.5066E-05          0.1556       99.7333
          7.0799E-05          0.0222       99.7556
          1.0227E-04          0.0444       99.8000
          1.1800E-04          0.0444       99.8444
          1.3373E-04          0.0444       99.8889
          1.6520E-04          0.0222       99.9111
          2.5960E-04          0.0222       99.9333
          7.6306E-04          0.0222       99.9556
          1.1721E-03          0.0222       99.9778
          1.5497E-03          0.0222      100.0000


          =============================================
          ==      Summary Descriptive Statistics     ==
          =============================================

          Minimum                           = 0.0000E+00
          Maximum                           = 1.5576E-03
          Range                             = 1.5576E-03

          Number of Simulations             =   4500

          5th Percentile                    = 0.0000E+00
          Median                            = 0.0000E+00
          95.0th Percentile                 = 0.0000E+00
          99.0th Percentile                 = 1.9640E-05
          99.9th Percentile                 = 1.8947E-04

          Mean                              = 1.4252E-06
          Standard Deviation                = 3.1967E-05
          Standard Error                    = 4.7654E-07
          Variance (unbiased)               = 1.0219E-09
          Variance (biased)                 = 1.0217E-09
          Moment Coeff. of Skewness         = 3.9663E+01
          Pearson's 2nd Coeff. of Skewness  = 1.3375E-01
          Kurtosis                          = 1.7150E+03

***********************************************************
*  FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATIONON   *
*             AND FREQUENCY OF RPV FAILURE BY             *
*                      TRANSIENT                          *
*       WEIGHTED BY TRANSIENT INITIATING FREQUENCIES      *
***********************************************************
                      % of total         % of total
                     frequency of       frequency of
                    crack initiation   of RPV failure
           1          100.00              100.00
```

TOTALS	100.00		100.00

```
**********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY PARENT SUBREGION                   *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
**********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	77.70	55.47	0.00	55.47
6	275.88	13.15	3.12	6.23	0.00	6.23
7	256.29	13.15	0.82	1.63	0.00	1.63
8	313.05	21.20	13.86	27.69	0.00	27.69
9	283.05	21.20	4.50	8.98	0.00	8.98
	TOTALS	99.98	100.00	100.00	0.00	100.00

```
**********************************************************
*    FRACTIONALIZATION OF FREQUENCY OF CRACK INITIATION   *
*            AND FREQUENCY OF RPV FAILURE BY              *
*               RPV BELTLINE MAJOR REGION                 *
*                   BY CHILD SUBREGION                    *
*                                                         *
*       WEIGHTED BY % CONTRIBUTION OF EACH TRANSIENT      *
*           TO FREQUENCY OF CRACK INITIATION AND          *
*                FREQUENCY OF RPV FAILURE                 *
**********************************************************
```

MAJOR REGION	RTPTS (MAX)	% of total flaws	% of total frequency of crack initiation	% of total through-wall crack frequency cleavage	ductile	total
1	232.66	2.29	0.00	0.00	0.00	0.00
2	232.66	2.29	0.00	0.00	0.00	0.00
3	220.01	3.70	0.00	0.00	0.00	0.00
4	220.01	3.70	0.00	0.00	0.00	0.00
5	160.72	19.30	0.00	0.00	0.00	0.00
6	275.88	13.15	3.12	6.23	0.00	6.23
7	256.29	13.15	0.82	1.63	0.00	1.63
8	313.05	21.20	54.94	59.33	0.00	59.33
9	283.05	21.20	41.12	32.81	0.00	32.81
	TOTALS	99.98	100.00	100.00	0.00	100.00

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, CA, and Charlotte, NC, was established in 1973 as an independent, non-profit center for public interest energy and environmental research. EPRI brings together member organizations, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of power generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents over 10% of EPRI's total R&D program.

Together…shaping the future of electricity

Export Control Restrictions
Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

1009546

Printed on recycled paper in the United States of America

Electric Power Research Institute (EPRI) • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com