# Assessment of Large-Scale Pressurized Thermal Shock Experiments Using the FAVOR Fracture Mechanics Computer Code

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## ABSTRACT

Large-scale experiments of pressure vessels performed at the Oak National Laboratory (ORNL)[1] in the mid 1980s validated the applicability of the linear-elastic fracture mechanics (LEFM) computational methodology for application to fracture analysis of reactor pressure vessels (RPVs) in nuclear power plants. The current federal regulations to insure that nuclear RPVs maintain their structural integrity, when subjected to transients such as pressurized thermal shock (PTS) events, were derived in the early-mid 1980s from a comprehensive computational methodology of which LEFM is a major element.

Recently, the United States Nuclear Regulatory Commission (USNRC) has conducted the PTS re-evaluation project that has the objective to establish a technical basis for a potential relaxation to the current PTS regulations which could have profound implications for plant license-extension considerations. The PTS re-evaluation project has primarily consisted of the development and application of an updated risk-based computational methodology that has been implemented into the **F**racture **A**nalysis of **V**essels: **O**ak **R**idge (FAVOR) computer code. LEFM continues to be a major element of the updated computational methodology.

As part of the PTS re-evaluation program, there has been an extensive effort to validate that FAVOR has an accurate implementation of the LEFM methodology. This effort has consisted of the successful benchmarking of thermal analysis, stress analysis, and LEFM fracture analysis results between FAVOR and ABAQUS, a commercial general-purpose finite element computer code that has fracture mechanics capabilities, for a range of transient descriptions. The NRC has also participated in international round-robin benchmarking exercises in which FAVOR-generated solutions to well-specified PTS problems have been compared to solutions generated by other research institutions.

A more fundamental aspect of the ongoing validation of FAVOR is demonstration that FAVOR can be used to successfully predict the results of large-scale fracture experiments. The objective of this paper is to document the FAVOR analysis of the first large-scale pressurized thermal shock experiment (PTSE) performed at ORNL. Results of these analyses provide validation that FAVOR accurately predicts the cleavage fracture initiation of a long surface breaking flaw in a large-scale thick-walled pressure vessel.

## INTRODUCTION AND DESCRIPTION OF PTSE-1 EXPERIMENT

A primary objective of NRC research sponsored at ORNL over the past three decades has been the development and validation of computational methods to predict the fracture behavior of RPVs subjected to transient loading conditions such as PTS.

These studies of the fracture behavior of large-scale specimens included three distinct phases of experiments that used thick-wall cylindrical specimens. These phases sequentially addressed the fracture of RPVs exposed to (1) pressure loads, (2) thermal transient loads, and (3) concurrent pressure and thermal transients, and have historically been referred to as Intermediate Test Vessel experiments [1−8], Thermal Shock Experiments [9−12] and Pressurized Thermal Shock Experiments [13−14]. A total of 22 thick-wall cylinder tests made up these phases and were performed from the early 1970s to the mid 1980s.

The first pressurized thermal shock experiment was performed at ORNL in 1984 [13]. It was performed on a scale that allows important aspects of fracture behavior of nuclear RPVs to be simulated. Such experiments serve as a means by which theoretical analytical models, such as LEFM, can be validated such that they can be applied to fracture analysis of RPVs in nuclear plants.

The flawed vessel was enclosed in a shroud as shown in Fig. 1. The shroud was electrically heated to bring the vessel to the desired initial temperature. The thermal transient was initiated by suddenly injecting chilled water or a methanol-water mixture into the outer vessel. The annulus between the cylindrical surfaces of the two vessels was designed to permit coolant velocities that would produce the appropriate convective heat transfer from the test vessel for a period of about 10 minutes. Pressurization on the inside surface of the test vessel was controlled independently by a system capable of increasing pressures to approximately 100 Mpa.

The decision to place the flaw on the external surface of the vessel and to thermally shock the test vessel on the outside surface rather than the inside surface, as in an overcooling accident in a RPV, was based on two factors. First, extensive analytical studies had shown that, for the shallow flaw depths to be studied, the test vessel geometry produces stress and temperature fields in the region of the flaw that well represent the fields in a RPV with an inside flaw. Second, to construct a facility for testing a thick vessel with the flaw and the thermal shock on the inside would be very expensive. Accordingly, it is important to note that the analyses performed by FAVOR reported in this paper modeled the flaw located on the inner surface of the RPV.

The scale of the PTSE was chosen large enough to attain full-scale constraint of the flawed region in the test vessel. Test conditions and materials were selected to produce stress fields and gradients around the flaw that are characteristic of RPVs and to provide realistic fracture toughness conditions. PTSE-1 incorporated a sharp surface-breaking crack that was long, sharp, and shallow as assumed in regulatory assessments at the time of the test. In the fracture analyses conducted thus far during the PTS re-evaluation, a very high percentage of postulated flaws are sharp planar embedded flaws, based on data generated from the non-destructive and destructive examination of

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[1]Managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S.Department of Energy.

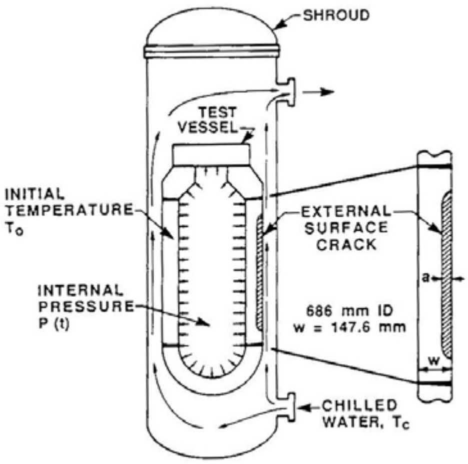


**Fig. 1. Schematic drawing of flawed test vessel inside shroud.**

actual RPV material in NRC-sponsored research at Pacific Northwest National Laboratory [15−17].

PTSE 1 consisted of three experiments. PTSE 1A did not result in fracture initiation. This paper includes a comparison of the FAVOR thermal analysis with experimental data from PTSE 1A; however, no fracture analysis was performed for PTSE 1A since it was a non-event. PTSE 1B and 1C did result in fracture initiation and are analyzed in some detail in this paper.

The vessel was extensively instrumented to give direct measurements of crack mouth opening displacement, temperature profiles through the wall, and internal pressure during the transients. Also, extensive material property tests preceded the transient test of the PTSE 1 vessel. The reader is referred to ref. 13 for more details regarding the experimental facility, material properties, instrumentation, etc., applicable to PTSE-1.

## TRANSIENT DEFINITIONS, TEST VESSEL GEOMETRY, AND MATERIAL PROPERTIES

Tables 1 and 2 specify the test vessel geometry and the thermal-elastic properties utilized in the FAVOR analyses. The material properties of the test vessel were typical of those of an RPV subjected to moderate neutron embrittlement of the wall.

Figure 2 illustrates the pressure and thermal transients for PTSE 1B and 1C.

Static fracture initiation ($K_{Ic}$) toughness data were determined from test of 25 mm compact specimens. Figure 3 shows the data together with size-effect-adjusted data and the curves used in the pretest and posttest analyses. The A curve in Fig. 3 was used in analyses made prior to execution of the first transient (PTSE 1A), and curve B was used subsequently. The initiation toughness data were obtained by the Babcock and Wilcox Research Center. The B curve was used in the FAVOR deterministic fracture analyses.

## BRIEF OVERVIEW OF FAVOR DETERMINISTIC COMPUTATIONAL METHODOLOGIES

FAVOR performs finite element thermal and stress analyses on a one-dimensional model of the vessel wall [18]. The transient heat conduction equation with temperature-independent properties is solved to produce time-varying temperature profiles through the wall. The finite-element stress analysis calculates radial displacements and then, through strain-displacement and linear-elastic stress-strain relationships, time varying axial and hoop stress profiles. These stresses include the effects of thermal and mechanical (internal pressure) loads.

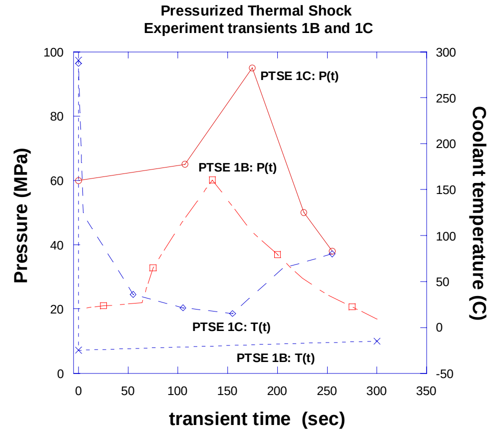


**Fig. 2. Pressure and thermal transients for PTSE 1B and 1C.**

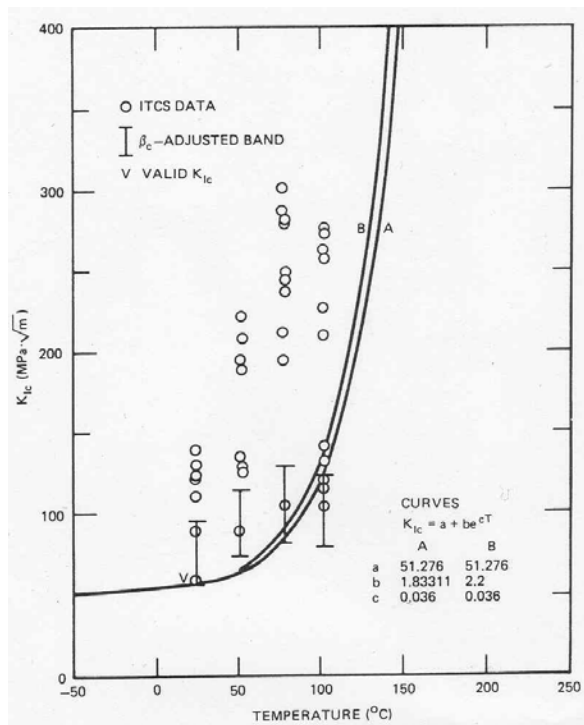


**Fig. 3. Derivation of static fracture initiation ($K_{Ic}$) toughness curve used in pretest and posttest analyses was experimentally determined from test of 25 mm compact specimens.**

For surface breaking flaws, $K_I$ is calculated in FAVOR using a weighting-function approach originally introduced by Buckner [19] and applied by other researchers. The stress-intensity factor is calculated by linear superposition technique, where instead of analyzing the cracked structure using actual loads, the analysis is performed with a distributed pressure loading applied to the crack surfaces only. This pressure is opposite in sign, but equal in magnitude and distribution to the stresses along the crack line that are calculated for the uncracked structure with the actual loads applied [18].

As part of the PTS re-evaluation program, there has been an extensive effort to validate that FAVOR has an accurate implementation of the LEFM methodology. This effort has consisted of the successfull benchmarking of thermal analysis, stress analysis, and LEFM fracture analysis results between FAVOR and ABAQUS [20], a commercial general-purpose finite element computer code that has fracture mechanics capabilities [21−24].

## COMPARISON OF THROUGH–WALL TEMPERATURE PROFILES AT VARIOUS TRANSIENT TIMES

Figures 4(a)–4(c) illustrate comparisons of through-wall temperature profiles at different transient times (before and after crack initiation) for experiments PTSE 1a, 1b, and 1c, respectively. The experimental temperature data was obtained from thermocouples located at various through-wall locations. The FAVOR thermal results were obtained by applying the thermal transients illustrated in Fig. 2 to the inner surface of the test vessel geometry.

A modified version of FAVOR was constructed to perform thermal analyses of vessels to which the thermal shock is applied to the external surface to verify that there are no significant differences obtained in the temperature through-wall profiles obtained by the version of FAVOR (utilized in these analyses) in which the thermal shock is applied to the inner surface of the vessel. The results of these analyses, as expected, did verify that the one-dimensional finite element thermal analysis methodology utilized by FAVOR generated very nearly identical through wall profiles for both cases.

The comparison of the FAVOR-generated through-wall temperature profiles with the experimental data obtained from thermocouples at various through-wall locations successfully validates that the one-dimensional finite element thermal analysis performed by FAVOR accurately predicts the through-wall temperature profiles observed in PTSE 1A, 1B, and 1C.

## COMPARISON OF FAVOR DETERMINISTIC FRACTURE ANALYSES WITH PTSE 1B AND 1C

Figures 5 and 6 illustrate the results of FAVOR deterministic fracture analyses to predict PTSE 1-B and 1-C, respectively. Table 3 provides a summary of comparisons between the FAVOR prediction and the experimental results for PTSE 1B and 1C.

In the FAVOR analysis of PTSE 1-B, the flaw is modeled as an axially oriented infinite-length inner-surface-breaking with a depth of 12.2 mm. The fracture initiation is predicted to occur at 55.4 seconds after initiation of the transient at which time there is an intersection between the FAVOR-generated applied $K_I$ curve and the $K_{Ic}$ curve (using Eq. (B) from Fig. 3) at a value of 175.0 Mpa $m^{1/2}$. The actual time of fracture initiation was 67.1 seconds at which time the applied $K_I$ was calculated to be 177.4 Mpa $m^{1/2}$.

In the FAVOR analysis of PTSE 1-C, the flaw is modeled as an axially oriented infinite-length inner-surface-breaking with a depth of 24.4 mm. The fracture initiation is predicted to occur at 137.7 seconds after initiation of the transient at which time there is an intersection between the FAVOR-generated applied $K_I$ curve and the $K_{Ic}$ curve (using Eq. (B) from Fig. 3) at a value of 277.8 Mpa $m^{1/2}$. The actual time of fracture initiation was 125.4 seconds at which time the applied $K_I$ was calculated to be 254.8 Mpa $m^{1/2}$.

The values of applied $K_I$ at actual time of initiation were determined by posttest analyses performed in 1984 with the crack modeled on the exterior surface. The loading consisted of the through-wall temperature profile (obtained from thermocouples) and internal pressure at the actual time corresponding to the fracture initiation.

FAVOR accurately predicts the cleavage fracture initiation of a long surface breaking flaw in PTSE 1-B and 1-C, especially considering the degree of uncertainty in $K_{Ic}$.

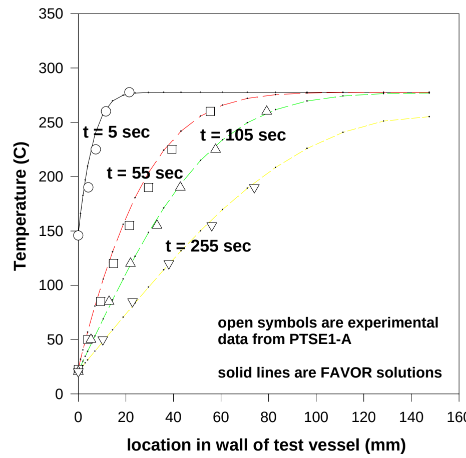


**Fig. 4(a). Validation of FAVOR thermal analysis for PTSE1-A.**

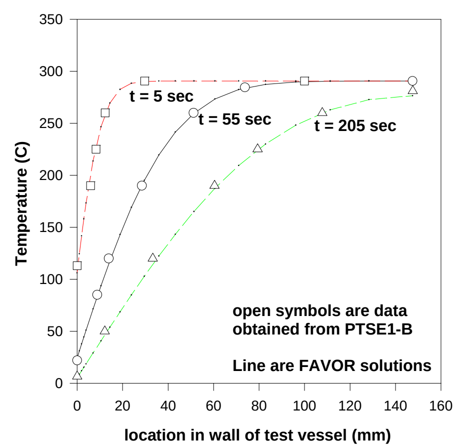


**Fig. 4(b). Validation of FAVOR thermal analysis for PTSE-1B.**

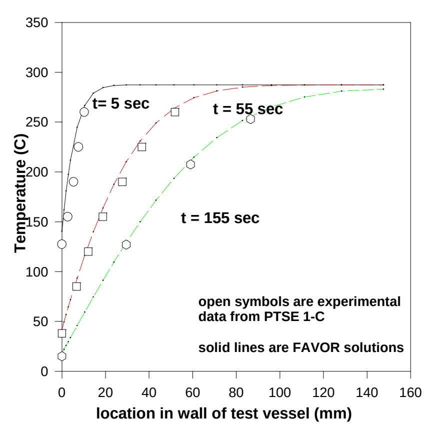


**Fig. 4(c). Validation of FAVOR thermal analysis for PTSE-1C.**

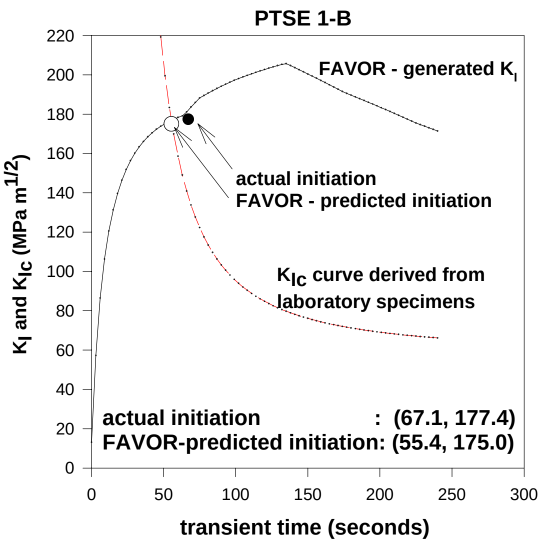


**Fig. 5. Comparison of FAVOR deterministic fracture analysis with results of PTSE 1B.**

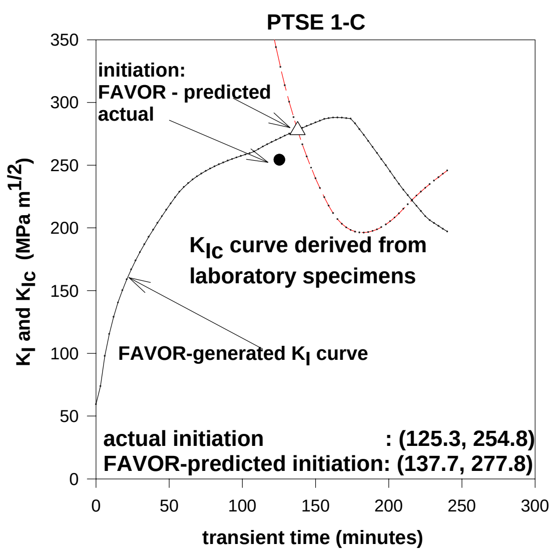


**Fig. 6. Comparison of FAVOR deterministic fracture analysis with results of PTSE 1C.**

## PROBABILISTIC CONSIDERATIONS

In the FAVOR probabilistic fracture mechanics (PFM) methodology, a deterministic fracture analysis is performed for each postulated flaw. In each deterministic analysis, a flaw geometry and crack tip $RT_{NDT}$ has been determined by sampling from appropriate probability distributions. The result of each deterministic fracture analysis is a conditional probability of crack initiation (CPI) in the closed interval (0,1). The probability is conditional in the sense that the transient is assumed to occur. During a PFM analysis, a Monte Carlo procedure is utilized in which many flaws are postulated resulting in many values of CPI; from which a probability distribution for CPI can be derived.

Given that a value of CPI is calculated for each flaw, an interesting question to propose is: what value of CPI would the FAVOR PFM methodology predict for the specific flaws (geometries and crack tip $RT_{NDT}$) associated with experiments PTSE-1B and 1C.

The deterministic fracture analysis for each postulated flaw is performed by stepping through discrete transient time steps to examine the temporal relationship between the applied Mode I stress intensity factor ($K_I$) and the static cleavage fracture initiation toughness ($K_{Ic}$) at the crack tip. A Weibull distribution, in which the parameters were calculated by the *Method of Moments* point-estimation technique, forms the basis for the statistical model of $K_{Ic}$. For the Weibull distribution, there are three parameters to estimate: the location parameter, *a*, of the random variate, the scale parameter, *b*, of the random variate, and the shape parameter, *c*. The reader is referred to ref. 18 regarding the extended $K_{Ic}$ database and mathematical procedures employed in the derivation of the Weibull distribution for $K_{Ic}$.

Figures 7 and 8 illustrate the relationship between applied $K_I$ and the stochastic characterization of $K_{Ic}$ for PTSE 1B and 1C, respectively. Each of the figures illustrate the "$K_{Ic}$ space" that resides between the Weibull a parameter (which may be thought of as the 0$^{th}$ percentile of $K_{Ic}$) and the 99$^{th}$ percentile of $K_{Ic}$, and the percentile corresponding to the actual initiation. The Weibull a parameter provides a lower bound $K_{Ic}$ curve such that the applied $K_I$ must be greater than Weibull a in order to have a non-zero CPI. If $K_I$(t) is greater than this lower bound

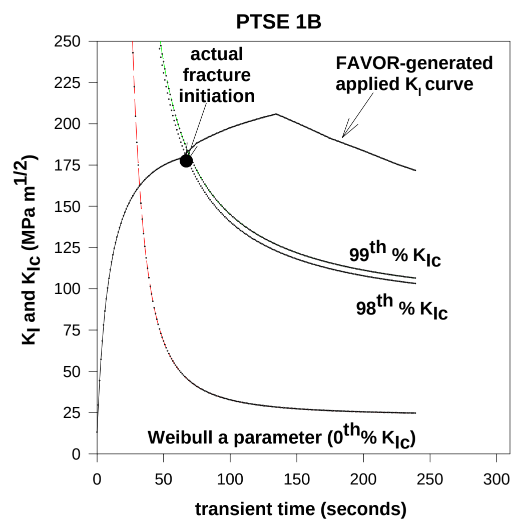


**Fig. 7. For PTSE 1B; FAVOR predicted CPI = 1.0; at actual time of initiation, the FAVOR - predicted CPI = 0.98.**

curve, the instantaneous CPI is calculated as the fractional part (percentile) of the $K_{Ic}$ space that corresponds to the applied $K_I$(t). The CPI for a flaw is simply the maximum value of instantaneous CPI during the transient. The value of CPI can be thought of as a measure of how far the applied $K_I$ penetrates into the $K_{Ic}$ space. The reader is referred to ref. 18 for more details regarding the FAVOR PFM methodology.

The FAVOR PFM model predicts a CPI of 1.0 ( since $K_I(t)$ > 99$^{th}$ % of $K_{Ic}$ distribution) for PTSE 1B and 1C, (i.e., FAVOR predicted a 100% probability that each flaw would initiate in cleavage fracture). Table 4 provides a summary of applying the FAVOR PFM model to PTSE 1B and 1C. The table specifies the transient times at which CPI becomes greater than zero (the time at which $K_I(t)$ > Weibull a parameter), the time at which applied $K_I(t)$ > 99$^{th}$ % of $K_{Ic}$, and the calculated CPI at the actual time of crack initiation.

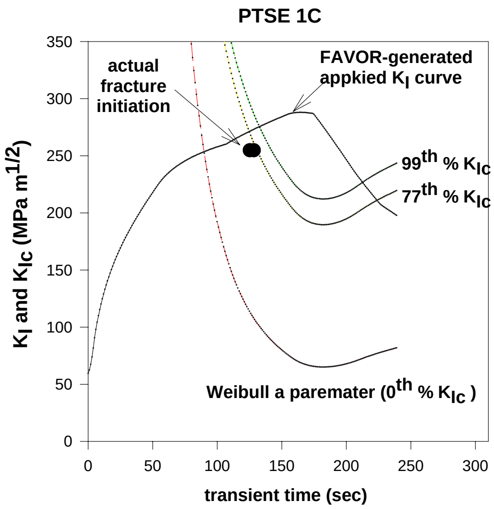


**Fig. 8. For PTSE 1C; FAVOR predicted CPI = 1.0; at actual time of initiation, the FAVOR-predicted CPI = 0.77.**

## MODIFICATIONS TO INDEX TEMPERATURE $RT_{NDT}$ IN PFM MODEL

The FAVOR PFM methodology utilizes an adjustment to values of $RT_{NDT}$ to account for the conservative bias implicit in the ASME NB-2331 definition of $RT_{NDT}$, the variety of inconsistent transition temperature metrics used to define $RT_{NDT}$, the lack of prescription in the test methods used to define $RT_{NDT}$, and the fact that the *CVN* and *NDT* values used to define $RT_{NDT}$ do not themselves measure fracture toughness. This adjustment is based on the difference between $RT_{NDT}$ values estimated using NB-2331 procedures and LEFM valid fracture toughness data. The reader is referred to reference 18 for a technical discussion regarding the adjustment to $RT_{NDT}$ data used in the FAVOR PFM methodology.

The ($RT_{NDT}$, $K_{Ic}$) data used in the derivation of the Weibull $K_{Ic}$ statistical distribution (utilized in the FAVOR PFM methodology) was adjusted to account for the conservative bias; therefore, to be consistent, the ($RT_{NDT}$, $K_{Ic}$) data for the flawed region of the test vessel should be adjusted. The $RT_{NDT}$ for flawed region of the test vessel in PTSE 1 was 91.3°C (Table 2). Applying the adjustment specified in the methodology in reference 18 results in an $RT_{NDT}$ of 77.8°C. This is the value of $RT_{NDT}$ utilized in the PFM analysis to generate the data in Table 4.

## CONCLUSIONS

The PTSE-1 experiment was re-analyzed using the FAVOR code. Results of deterministic and probabilistic fracture analyses provide validation that FAVOR accurately predicts the cleavage fracture initiation of a long surface breaking flaw in a large-scale thick-walled pressure vessel. This fundamental validation provides confidence that FAVOR can be applied in the fracture analysis of RPVs in nuclear power plants. As part of the ongoing validation of FAVOR, it is anticipated that FAVOR will continue to be validated against other earlier large-scale experiments in which the test vessel contained a surface breaking flaw and more recent small specimen experiments that contained embedded flaws.

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**Table 1. PTSE-1 Test Vessel and Flaw Geometry**

| Property | Units | PTSE 1-B | PTSE 1-C |
|---|---|---|---|
| Inside radius | inches | 13.5 | 13.5 |
| | mm | 343 | 343 |
| Wall thickness | inches | 5.81 | 5.81 |
| | mm | 147.6 | 147.6 |
| Flaw length | inches | 39.37 | 39.37 |
| | mm | 1000 | 1000 |
| Flaw depth | inches | 0.4803 | 0.9606 |
| | mm | 12.2 | 24.4 |

**Table 2. PTSE-1 Test Vessel Thermal and Mechanical Properties**

| Property | Units | Base material |
|---|---|---|
| Thermal conductivity | W/m-K | 41.54 |
| | Btu/h-ft-°F | 24.0 |
| Specific heat | J/kg-K | 502.4 |
| | Btu/lbm-°F | 0.12 |
| Modulus of elasticity | GPa | 202.24 |
| | ksi | 29341 |
| Poisson's ratio | | 0.3 |
| Thermal expansion coefficient | $K^{-1}$ | $4.49 \times 10^{-6}$ |
| | $°F^{-1}$ | $8.05 \times 10^{-6}$ |
| Density | $kg/m^3$ | 7833 |
| | $lbm/ft^3$ | 489 |
| $RT_{NDT}$ | °C | 91.3 |
| | °F | 196.3 |

**Table 3. Summary of Comparisons Between FAVOR Predictions and the Experimental Results for PTSE 1B and 1C**

| Experiment | Flaw depth (mm) | Flaw length (mm) | Actual time of fracture initiation (sec) | FAVOR predicted time of fracture (sec) | $K_I$ @ actual initiation (Mpa $m^{1/2}$)* | FAVOR $K_I$ @ predicted time of initiation (Mpa $m^{1/2}$)** |
|---|---|---|---|---|---|---|
| PTSE-1B | 12.2 | 1000 | 67.1 | 55.4 | 177.4 | 175.0 |
| PTSE-1C | 24.4 | 1000 | 125.4 | 137.7 | 254.8 | 277.8 |

* As calculated in posttest analyses for outer-surface breaking flaw.
** As calculated by FAVOR for inner-surface breaking flaw.

**Table 4. Summary of Applying FAVOR PFM Methodology to PTSE 1B and 1C.**

| Experiment | Time @ which CPI > 0* (sec) | $RT_{NDT}$ ( C ) | Time @ which CPI > 0.99 ** (sec) | CPI at time FAVOR predicted initiation | CPI at actual time of initiation |
|---|---|---|---|---|---|
| PTSE-1B | 33 | 77.8 | 81 | 0.75 | 0.98 |
| PTSE-1C | 90 | 77.8 | 157 | 0.98 | 0.77 |

* Time at which applied $K_I(t)$ > Weibull a parameter ($0^{th}$ % of $K_{Ic}$).
** Time at which applied $K_I(t)$ > $99^{th}$ % of $K_{Ic}$.