Review of Studies Regarding Risk-Informing Regulations for Normal Operating Transients

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(opinions expressed herein are those of the author and do not reflect an official position of the Nuclear Regulatory Commission)

ABSTRACT

The current regulations, as set forth by the United States Nuclear Regulatory Commission (USNRC), to insure that light-water nuclear reactor pressure vessels (RPVs) maintain their structural integrity when subjected to planned startup (heat-up) and shutdown (cool-down) transients are specified in Appendix G to 10 CFR Part 50, which incorporates by reference Appendix G to Section XI of the ASME Code. The technical basis for these regulations contains many aspects that are now broadly recognized by the technical community as being unnecessarily conservative.

During the past decade, the NRC conducted the interdisciplinary Pressurized Thermal Shock (PTS) Re-evaluation Project that established a technical basis to support a risk-informed revision to current PTS regulations (10CFR Part 50.61). Once the results of the PTS re-evaluation are incorporated into a revision of the 10 CFR 50.61 guidance on PTS, the technical basis for the fracture toughness that is required to withstand a PTS event (an accidental loading) will differ from the technical basis for the fracture toughness that is required by Appendix G to 10 CFR Part 50 for normal operating transients. The new PTS guidelines will be based on more realistic risk-informed models and inputs whereas the existing Appendix G requirements contain many known conservatisms that place unnecessary burdens on plant operation. Consequently, a goal of this project is to develop technical information supporting a risk-informed revision to the current requirements of Appendix G to 10 CFR 50 in a manner that is consistent with that used to develop a risk-informed revision to the PTS regulations.

This research has consisted of the application of the FAVOR computer code for cool-down transients associated with reactor shutdown and the development and application of the FAVOR^{HT} computer code for heat-up transients associated with reactor startup. This paper provides a brief overview of the current results of this research project.

INTRODUCTION AND PROBLEM DEFINITION

The current regulations [1] to insure that RPVs maintain their structural integrity when subjected to planned startup (heat-up) and shutdown (cool-down) transients are based on a prescriptive deterministic fracture methodology in which an allowable pressure is derive for a specified cool-down or heat-uprate. The maximum allowable cool-down or heat-up rate is 100º F / hr.

The upper bound of the allowable pressure and temperature that are permitted to occur during planned normal transients are established by converting the ASME K_{Ic} (crack initiation toughness transition curve) to coordinates of pressure and temperature by assuming a surface breaking flaw of depth one-fourth of the reactor vessel wall thickness (1/4 t) and of a 6:1 aspect ratio. In the derivation of the allowable pressure for a specified cool-down transient associated with reactor shutdown, the flaw is assumed to be an inner surface breaking flaw, whereas, in the derivation of the allowable pressure for a specified heat-up transient associated with reactor startup, the flaw is assumed to be an outer surface breaking flaw.

The prescriptive deterministic fracture methodology of ref. 1 uses the following equation to define the P-T curve for a RPV. K_{Ic} values are determined using conditions at the deepest point on the (1/4t) flaw and the applied stress intensity factors (K_{Im} and K_{It}) are determined at the same location.

$$2K_{Im} + K_{It} < K_{Ic} \tag{1}$$

where K_{Im} is the stress intensity factor produced by pressure-induced membrane loading in the RPV shell (*ksi* $\sqrt{in}$),
K_{It} is the stress intensity factor produced by a radial thermal gradient through the wall of the RPV (*ksi* $\sqrt{in}$),
K_{Ic} is the ASME crack-initiation curve described by the following equation:

$$K_{Ic} = 33.2 + 20.734 \exp\left[0.02\left(T(t) - RT_{NDT}\right)\right] \tag{2}$$

The factor of two applied to K_{Im} in Eq. (1) is the means by which allowance is made to accommodate sources of stress intensity factor not included in Eq. 1. Those sources include residual stresses in the RPV structural welds, stresses produced by pressure on the crack face, and stresses resulting from differential thermal expansion between the stainless steel cladding and the low-alloy steel RPV shell material.

Equation (1) can be re-arranged and applied as follows to derive the time-dependent allowable pressure (P_{CODE}) at a given normalized temperature ($T(t) - RT_{NDT}$), where RT_{NDT} is the maximum reference nil ductility temperature in the RPV beltline at the current time in the life of the RPV.

$$P_{CODE} = (K_{Ic} - K_{It})/(2C_P) \tag{3}$$

where C_P is the stress intensity factor at the deepest point of the 1/4*t* flaw produced by a 1 ksi pressure loading in the RPV ($ksi\sqrt{in}$ / ksi) and P_{CODE} is the allowable pressure (ksi).

PROBABILISTIC FRACTURE MECHANICS (PFM) ANALYSES OF COOL-DOWN TRANSIENTS ASSOCIATED WITH REACTOR SHUTDOWN

PFM Analyses of Currently Bounding Cool-Down Transients Associated with Reactor Shutdown

A study [2] was performed in which PFM analyses were performed with the FAVOR code [3-4] for bounding cool-down transients allowed by the current requirements of Section XI – Appendix G. The transients are considered as "bounding" because the currently maximum allowable cool-down rate of 100 ºF / hr was applied. This single rate was applied until the coolant temperature reached 70 ºF, at which time (288 min) the coolant temperature remained constant. Figure 1 illustrates the allowable pressure derived from the application of the deterministic fracture methodology described above for the 1/4*t* flaw, as well as some smaller reference flaw sizes that will be discussed below.

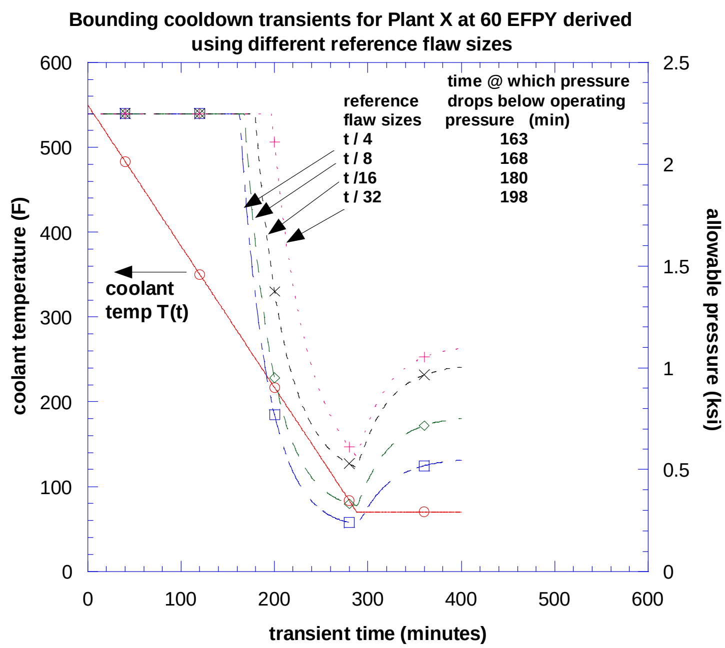

Figure 1 - Bounding cool-down pressure transients associated with reactor shutdown for Plant X at 60 EFPY; allowable pressure derived using different reference flaw sizes, assuming the currently maximum allowable cool-down rate of 100 ºF / hr. One effect of utilizing a smaller reference flaw is to increase the time duration at which the pressure is allowed to hold at steady state operating condition.

The scoping analyses for all studies discussed in this paper were performed for one of the plants, hereafter referred to as Plant X, evaluated as part of the PTS re-evaluation project [5-6]. The neutron fluence map corresponded to 60 effective full power years (EFPY). The embrittlement and flaw characterization models utilized in this study were identical to those from the PTS re-evaluation. All postulated flaws were embedded flaws. Each RPV (in the FAVOR Monte Carlo analysis) was postulated to have approximately 5000 embedded flaws uniformly distributed within the first 3/8 of the RPV wall thickness. Also, it should be noted that the PFM model, consistent with the model utilized in the PTS re-evaluation study, included through-wall weld residual stress and a clad-base material stress free temperature of 488ºF.

In all analyses reported in this paper, the convective heat-transfer coefficient was conservatively set to a constant value of 5000 Btu/hr-ft^2-°F since this is considered to be conduction limited. Conduction limited denotes a condition in which the wall conduction dominates the thermal resistance to energy flowing from the wall to the fluid. In the limit, as the convective heat transfer coefficient gets very large, the difference between the fluid and wall temperatures approaches zero, and subsequently, the fracture mechanics behavior becomes asymptotic for increasing values of h. It was determined in a previous study [7] that fracture mechanics analysis results have little sensitivity to convective heat transfer coefficient (h) for values of h equal to or greater than values that correspond to being conduction limited conditions.

Warm pre-stress (WPS) was included in the fracture model. The concept of WPS [8] is that for any flaw to have a non-zero conditional probability of initiation at any transient time step, the total applied stress intensity factor, designated as K_I, at that time step must be greater than at all previous time steps in the transient. The physical basis for WPS is well established, and the existence of the effect has been demonstrated through the testing of both laboratory specimens and scaled nuclear RPV structures [9]. The NRC has adopted WPS in the baseline models used to establish the technical basis for revision of the PTS rule.

Conclusions from the PFM analyses of currently bounding cool-down transients associated with reactor shutdown were as follows [2]:

(1) The thru-wall crack frequency (TWCF) for the bounding cool-down transient (that complies with the current requirements of Section XI – Appendix G) is below the proposed new acceptance criteria for PTS of 1 x 10^{-6} failed RPVs per reactor operating year for currently anticipated lifetime of 60 EFPY, assuming approximately one or two reactor shutdowns per operating year.

(2) Figure 1 illustrates that one effect of using a reference flaw shallower than the ASME ¼ -T flaw is to allow the pressure to hold at steady state operating pressure to a later time in the transient before it must be reduced. Specifically, as illustrated in figure 1, reducing the reference flaw size from t/4 to t/8, t/16, and t/32 increases the time at which the pressure can be held at steady state operating pressure from 163 to 168, 180, and 198 minutes, respectively.

(3) Similar to the results in Figure 1, the removal of the factor of two on pressure in equations 1 and 3 increased the permissible pressure hold time from 163 to 186 minutes.

In both items (2) and (3) above, the longer permissible pressure hold time **did not** increase the probability that the RPV would experience cleavage fracture during shutdown since all crack initiations and through-wall failures were predicted to occur within the first 142 minutes of the transient, which is before changes to either the reference flaw size or the pressure safety factor had any influence on the derived allowable maximum pressure.

PFM Analyses of Parameterized Transients Associated with Reactor Shutdown

Bishop et al. performed PFM analyses for a number of parameterized cool-down transients in which more than one cooling rate is used, i.e., the coolant temperature is assumed to decrease at a constant rate until it "plateaus" for a period of time for alignment to the residual heat removal (RHR) system [10]. After the plateau, the coolant temperature is further decreased at a constant rate until ambient temperature, assumed to be 70º F, is reached. Pressure is also assumed to decrease in a multi-linear fashion as will be illustrated below. Figure 2 illustrates temperature-and-pressure-related parameters, respectively, associated with parameterized cool-down transients as utilized in this paper, which were motivated by the work of Bishop et al [10]. Descriptions of the coolant temperature and pressure-related parameters associated with the parameterized cool-down transients are as follows.

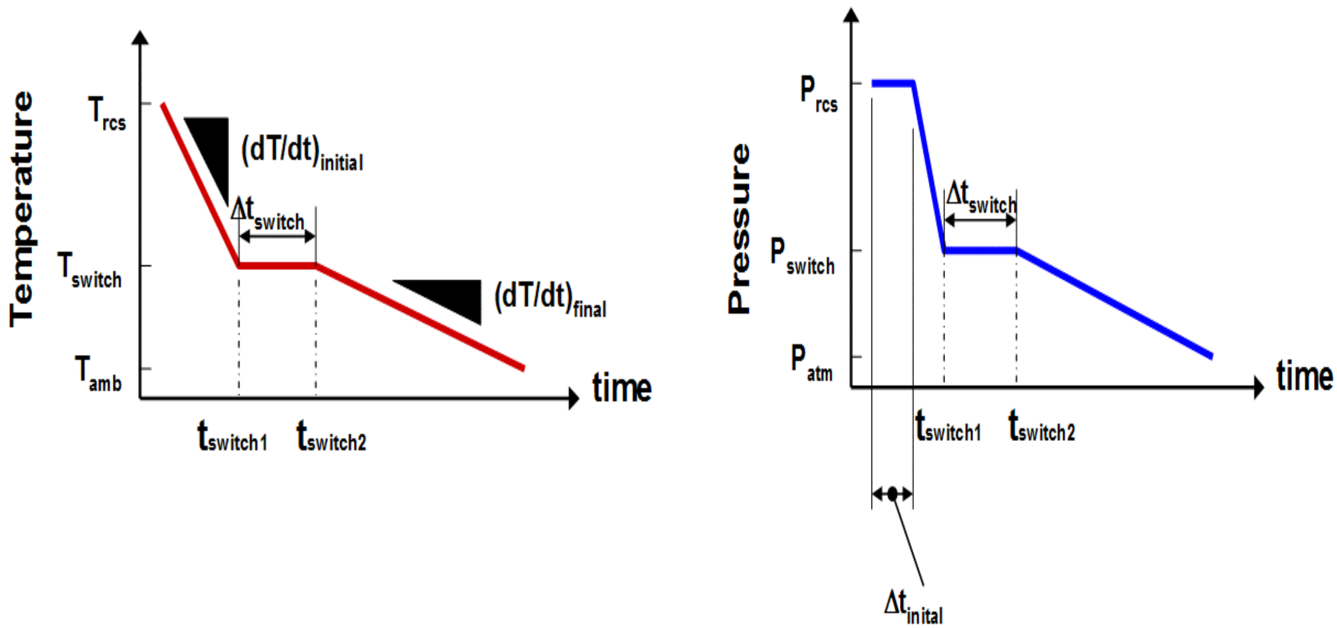

Figure 2 – Temperature-and pressure related variables for parameterized cool-down transient associated with reactor shutdown.

Temperature-related cool-down parameters

1) $(dT/dt)_{initial}$ is the initial cool-down rate of the coolant from the steady-state operating temperature which is assumed to be 550 ºF.

2) T_{switch} is the coolant temperature plateau associated with switchover to shutdown cooling, i.e., the temperature at which the $(dT/dt)_{initial}$ rate terminates. $t_{switch1}$ is the transient time at which the coolant temperature reaches $T_{switch.}$

3) Δt_{switch} is the time interval at which the coolant remains at the plateau temperature T_{switch}. The coolant temperature arrives at the plateau temperature T_{switch} at $t_{switch1}$ and remains there until $t_{switch2}$; therefore, $\Delta t_{switch} = t_{switch2} - t_{switch1}$.

4) $(dT/dt)_{final}$ is the final cool-down rate at which the coolant temperature decreases from the plateau T_{switch} to ambient temperature (T_{amb}) which is assumed to be 70 ºF. Parametric values of 60 and 100 ºF / hr were utilized for $(dT/dt)_{final}$ in this study.

Pressure-related cool-down parameters

1) $\Delta t_{initial}$ is the pressure "hold time", i.e., the time after the start of the cool-down transient at which the pressure begins to drop from steady state operating pressure, which is assumed to be 2.25 ksi in this study.

2) P_{switch} is the value of pressure at which the pressure plateaus after it drops from operating pressure. In these analyses the pressure is assumed to remain at the plateau pressure as long as the temperature remains at the plateau temperature of T_{switch}, i.e., the pressure arrives at P_{switch} at $t_{switch1}$ and remains there until $t_{switch2}$; at which time it decreases to atmospheric pressure (assumed to be 0.014 ksi) at a transient time of 300 minutes.

A previous analysis [11] of parameterized cool-down transients associated with reactor shutdown focused on a range of values of $(dT/dt)_{initial}$ between 100 and 400 ºF / hr. This previous scoping analysis also assumed a value of P_{switch} of 1.0 ksi. In this paper, our intent is to perform PFM analyses over a range of parameters that are more consistent with actual reactor operating procedures. Based on discussions with nuclear industry representatives, a value of 200 ºF / hr was identified as a reasonable upper-bound for initial cool-down rate. Therefore, the analyses reported in this paper used values of $(dT/dt)_{initial}$ of

100, 125, 150, 175, and 200 ºF / hr. Also, a value of P_{switch} = 0.40 ksi, which is more consistent with actual reactor operating practices, was used for the analyses reported in this paper.

Both the analyses reported herein and the results of our previous analyses [11] demonstrate that when WPS is included in the model, the PFM solutions are invariant with respect to both Δt_{switch} and $(dT / dt)_{final}$. This occurs because, for all conditions investigated to date, both Δt_{switch} and $(dT / dt)_{final}$ occur at times in the transient after the time at which the peak stress intensity factor (K_{Ipeak}) has occurred (under WPS conditions the time of K_{Ipeak} signals the latest time in the transient at which crack initiation probability is accumulated [3]). Operationally, this finding has an important implication. To the extent that the conditions modeled in these analyses accurately represent service conditions, these results suggest that the post-switchover rate (i.e., $(dT /dt)_{final}$) may be as fast as 100 ºF / hr without having any effect at all on vessel integrity. Post-switchover rates are now, in many cases, restricted to much slower rates. Thus these results indicate a relaxation in requirements having (simultaneously) no safety detriment and potentially a large operational benefit.

Beyond these potential operational implications, our results also suggest that it is possible to parameteize the PFM solutions as a function of five variables: embrittlement level, P_{switch}, $(dT / dt)_{initial}$, T_{switch}, and $\Delta t_{initial}$ (in the analyses reported herein both embrittlement level and P_{switch} are held fixed). There is a complex interaction between $(dT / dt)_{initial}$, T_{switch}, and $\Delta t_{initial}$ that determines the time of peak loading, designated as t_{peak}, and the magnitude of peak loading $K_I(t_{peak})$. t_{peak} is sensitive to $\Delta t_{initial}$; therefore, when WPS is included in the model, the PFM solutions are also very sensitive to $\Delta t_{initial}$.

Figure 3 provides the results of the PFM analyses for Plant X at 60 EFPY for various values of $(dT / dt)_{initial}$ as a function of the pressure hold time $\Delta t_{initial}$. Specifically, the mean value of the conditional probability of crack initiation, designated as CPI_{mean}, is plotted as a function of pressure hold time $\Delta t_{initial.}$ for various values of initial cool-down rate $(dT / dt)_{initial.}$ Each discrete value of CPI_{mean} is the mean value of a distribution generated by FAVOR during a Monte Carlo PFM analysis.

Table 1 summarizes the combinations of operating temperature and pressure within which Plant X, operating at 60 EFPY, can be shutdown and remain below the limit of $CPI_{mean} = 1 \times 10^{-6}$. In this table, the cool-down transients are parameterized in terms of $(dT / dt)_{initial,}$ $T_{switch,}$ and $\Delta t_{initial.}$ All PFM solutions in Figure 3 and Table 1 were generated with P_{switch} = 0.40 ksi.

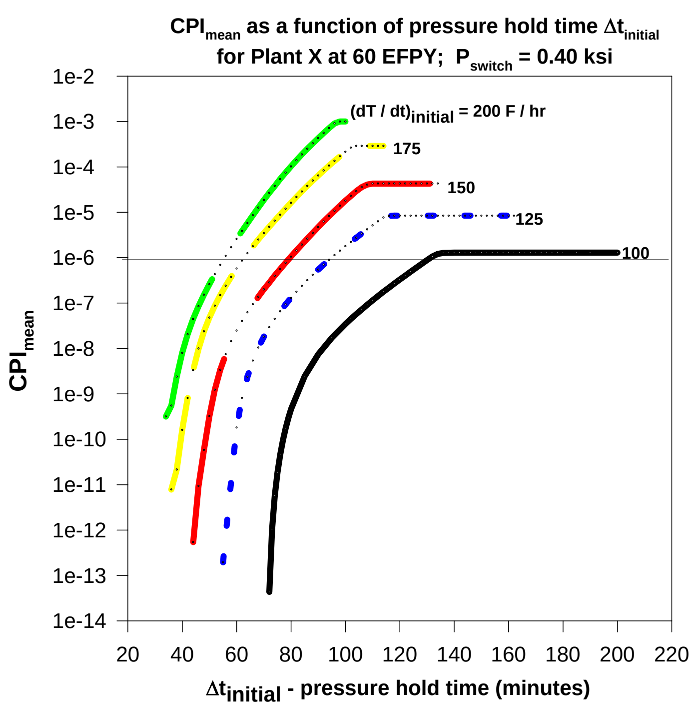

Figure 3 –Mean value of the conditional probability of crack initiation (CPI_{mean}) as a function of pressure hold time $\Delta t_{initial}$ for a range of initial cool-down rates $(dT / dt)_{initial}$. Each discrete value of CPI_{mean} is the mean value of a distribution of CPI generated by FAVOR during a Monte Carlo PFM analysis.

Table 1 – Intervals of pressure hold time ($\Delta t_{initial}$) which result in CPI_{mean} and $CPF_{mean} < 1.0 \times 10^{-6}$

$(dT / dt)_{initial}$ °F / hr	Maximum $\Delta t_{initial}$ interval for which $CPI_{mean} = 0$ (minutes)	Maximum $\Delta t_{initial}$ interval for which $CPI_{mean} < 1.0 \times 10^{-6}$ (minutes)	Maximum $\Delta t_{initial}$ interval for which $CPF_{mean} < 1.0 \times 10^{-6}$ (minutes)	T_{switch} ($\Delta t_{initial}$) at which $CPI_{mean} \sim 1.0 \times 10^{-6}$ (°F)
100	$\Delta t_{initial} < 72$	$\Delta t_{initial} < 131$	all $\Delta t_{initial}$	332
125	$\Delta t_{initial} < 55$	$\Delta t_{initial} < 95$	$\Delta t_{initial} < 101$	352
150	$\Delta t_{initial} < 44$	$\Delta t_{initial} < 79$	$\Delta t_{initial} < 84$	353
175	$\Delta t_{initial} < 36$	$\Delta t_{initial} < 63$	$\Delta t_{initial} < 67$	367
200	$\Delta t_{initial} < 34$	$\Delta t_{initial} < 56$	$\Delta t_{initial} < 60$	363

Figure 4 uses some of the data from Table 1 to illustrate a relationship between $(dT/dt)_{initial}$, $\Delta t_{initial}$, and CPI_{mean} for fixed values of embrittlement and P_{switch}. In figure 4, combinations of $(dT/dt)_{initial}$ and $\Delta t_{initial}$ below the curves have values of CPI_{mean} below the stated value, while combinations of $(dT/dt)_{initial}$ and $\Delta t_{initial}$ above the curves have values of CPI_{mean} above the stated value. Once the functionality of these curves with embrittlement level and P_{switch} are defined, they would provide one means to establish acceptable cool-down parameters for normal operating transients in a manner consistent with the way PTS screening limits were determined [6,12].

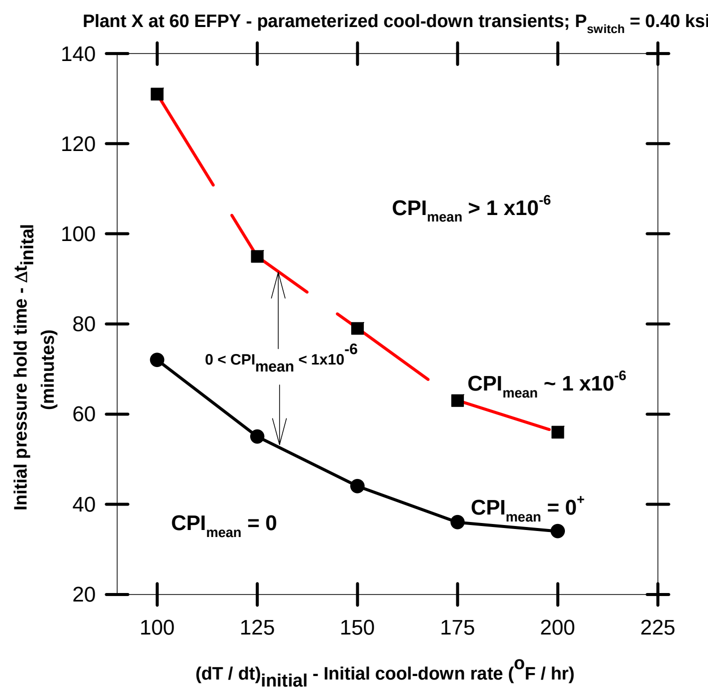

Figure 4 – Illustration of parameterized cool-down transients that satisfy a risk informed criteria for normal operating transients for Plant X at 60 EFPY assuming P_{switch} = 0.40 ksi.

PFM ANALYSES OF HEAT-UP TRANSIENTS ASSOCIATED WITH REACTOR STARTUP

Previous versions of the FAVOR computer code have been designed specifically to perform deterministic and PFM analyses of RPVs subjected to cool-down transients. Cool-down transients, where the coolant in contact with the RPV inner surface decreases with time, produce time-dependent stresses that are tensile on and near the RPV inner surface, thus generating Mode I opening driving forces that act on inner surface-breaking or embedded flaws located near the inner surface of the RPV wall. Heat-up transients, where the temperature of the coolant in contact with the inner surface of the RPV wall increases with time, produce time-dependent stresses that are tensile on and near the RPV outer surface, thus generating

Mode I opening driving forces that act on outer surface-breaking or embedded flaws located near the outer surface of the RPV wall.

Development And Application Of The FAVOR^{HT} Computer Code

The FAVOR^{HT} computer code (13-14) has been developed to perform deterministic and PFM analyses of RPVs subjected to heat-up transients, such as those associated with reactor start-up. The FAVOR^{HT} code has been designed specifically to perform deterministic and PFM analyses of embedded flaws that reside in the outer 3/8 of the RPV wall thickness.

A PFM analysis was performed for the currently limiting heat-up transient allowed by for Plant X at 60 EFPY. The result of this analysis was a CPI_{mean} of 7.0 x 10^{-11} due to cleavage fracture, which is several orders of magnitude lower than for the currently limiting cool-down transient associated with reactor shutdown, as previously discussed. The FAVOR^{HT} code also checks for crack extension due to ductile tearing as an initiating mechanism. No ductile tearing was predicted.

FAVOR^{HT} will continue to be applied to support a risk-informed approach to 10CFR 50 Appendix G. It is anticipated that a technical case can be developed such that for a given initial cool-down / heat-up rate, cool-down transients will always be more limiting, thereby, reducing the scope and complexity of future analyses.

SUMMARY AND CONCLUSIONS

A goal of our investigation is to develop technical information supporting a basis for a risk-informed revision to the current requirements for transients associated with normal reactor operation in a manner that is consistent with that used to develop the risk-informed revision to the regulations for accidental PTS transients. The FAVOR and FAVROR^{HT} computer codes were applied for normal operation transients for the most limiting of the three domestic commercial pressurized water reactors analyzed in the PTS re-evaluation at 60 EFPY. As in the PTS re-evaluation, all flaws for this RPV were assumed to be embedded.

PFM analyses for bounding cool-down transients, associated with reactor shutdown, that were defined based on current ASME code requirements were performed. These transients are bounding in so far as the maximum allowable cool-down rate of 100 ^{o}F / hr was applied. This bounding cool-down transient is in compliance, and is therefore consistent with, the proposed new acceptance criteria for PTS of 1 x 10^{-6} failed RPVs per reactor operating year. Our analyses also showed that if ASME code requirements are modified by either: (1) using a smaller reference flaw in the derivation of the allowable pressure, or (2) elimination of the factor of two used in the derivation of the allowable pressure, no changes to the estimated conditional probabilities of crack initiation of RPV failure occurs. This is the case because neither of these potential Code changes alters the allowable cool-down transients before the time (t_{peak}) at which the peak load $K_I(t_{peak})$ occurs.

PFM analyses of parameterized cool-down transients in which the operating temperature and pressure time histories are represented in a multi-linear fashion were performed over a range of parameters that are believed to be representative of operating conditions that currently occur in PWRs. Based on these analyses, the following conclusions are drawn.

1. For the conditions analyzed to date, the PFM solutions are invariant with respect to both Δt_{switch} and $(dT/dt)_{final}$. This occurs because both Δt_{switch} and $(dT/dt)_{final}$ occur at times in the transient after the time at which the peak stress intensity factor has occurred (under WPS loading the time of peak loading signals the latest time in the transient at which crack initiation probability is accumulated). To the extent that the conditions modeled in these analyses accurately represent service conditions, these results suggest that the post-switchover cool-down rate may be as fast as 100 ^{o}F / hr without any effect at all on RPV integrity. Post-switchover cool-down rates are now, in many cases, restricted to much slower rates. Thus, these results indicate a possible relaxation in requirements having (simultaneously) no safety detriment and a potentially large operational benefit.

2. By using PFM analyses, there is a potential to develop parametric relationships between the following four variables: embrittlement level, P_{switch}, $(dT/dt)_{initial}$, and $\Delta t_{initial}$.

For the high embrittlement conditions analyzed herein, our results indicate that initial cooling rates exceeding the current limit of 100 ^{o}F / hr can be allowed if certain achievable restrictions are placed on the initial pressure hold time $\Delta t_{initial}$.

PFM analyses performed to date for heat-up transients, associated with reactor startup, indicate that the probabilities of fracture are several orders of magnitude lower than that for a cool-down transient, associated with reactor shutdown, with the same (but opposite) coolant temperature initial rate of change.

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