SENSITIVITY TO T_{MIN} IN TRACE/PARCS ANALYSIS OF ATWS WITH INSTABILITY

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ABSTRACT

In a companion paper [1], the results of TRACE/PARCS [2, 3] calculations for representative anticipated transient without SCRAM (ATWS) events leading to core instability (ATWS-I) were presented. In that analysis, fuel damage was predicted as a result of oscillatory power and flow leading to conditions of failure of the cladding surface to rewet. A review of the results indicated that the mechanism leading to this failure involved first, incidence of incremental cladding surface temperature increase during periods of dryout until, eventually, the cladding surface temperature exceeds the minimum stable film boiling temperature (T_{min}). Once the cladding hot-spot temperature exceeds T_{min}, TRACE/PARCS predicts that the cladding surface becomes locked in an inverted annular film boiling heat transfer regime with low heat transfer. Cladding surface temperature then increases above 1478 K [2200 °F], thus indicating fuel damage.

In the current work, sensitivity calculations were performed to study the impact of T_{min} on the fuel damage consequences of ATWS-I. The TRACE T_{min} correlation (i.e., Groeneveld-Stewart) predicts a lower value compared to an alternative T_{min} correlation (i.e., Shumway). This difference is primarily due to consideration of cladding material properties. If zircaloy material properties are taken into account, the Shumway correlation predicts a higher T_{min} compared to that for stainless steel of about 100 K [180 °F] to 150 K [270 °F] [4]. The regulatory purpose of the current work is to study the sensitivity of TRACE/PARCS analysis results to a higher value of T_{min}. Given that different analysis methods may utilize alternative correlations for T_{min}, such a study assists in comparing those method's results with confirmatory TRACE/PARCS results.

The current TRACE/PARCS sensitivity analysis results demonstrate a subtle sensitivity of major plant parameters to the change in T_{min} value (e.g. steam flow rate, core flow rate, pressure, etc.). However, the predicted incidence of fuel damage was shown to be highly sensitive to T_{min}. With a sufficiently high analysis value of T_{min}, fuel temperature increase is limited by continued, periodic rewet of the cladding surface through the entire oscillatory phase of the event, and no sustained cladding heat-up is predicted.

KEYWORDS
ATWS BWR MELLLA+ PARCS TRACE

1. INTRODUCTION

1.1. Background

TRACE/PARCS has been assessed for the application of analyzing ATWS events for BWRs operating at MELLLA+ conditions and determined to be applicable with reasonable prediction results [5]. Based on TRACE/PARCS calculations described in a companion paper [1], the potential for peak cladding temperature (PCT) to exceed 1478K [2200 °F] during ATWS scenarios that result in instability (ATWS-I) has been identified. While 1478K is not a regulatory limit for ATWS events, this informal metric serves as a gauge for the potential of fuel damage to impact core coolability. In other words, long term core coolability can be demonstrated by ensuring that the PCT remains below 1478K as this would preclude fuel damage. During beyond design basis events, such as ATWS, some degree of fuel failure may occur as a result of other mechanisms (e.g., dryout, excessive cladding strain, burst, etc.) but perforated fuel pins may still remain in a coolable geometry.

The results of the analysis in the companion paper have identified the mechanism for extreme and prolonged fuel heat-up during ATWS-I. During the oscillatory phase of an ATWS-I, the power and, more importantly, the flow undergo large amplitude oscillation [1]. When the flow rate becomes small during an oscillation, the fuel will go into dryout. During this short period of dryout the cladding temperature increases. However, the flow oscillates, and as such, will increase over a short period subsequent to the dryout. At first, the cladding experiences periodic cycles of dryout and rewetting.

As the oscillation magnitude increases, approaching a non-linear limit cycle, the cladding temperature increase during the low-flow portion of the oscillation increases. During the upsurge of flow that follows, the rewetting of the cladding becomes insufficient to remove all of the thermal energy deposited during the previous low-flow portion of the oscillation. During this stage, the fuel cladding temperature "ratchets" higher.

At a certain point in the event, the fuel cladding temperature during a period of low-flow increases above the minimum stable film boiling temperature. At this stage, the cladding surface "locks" into a film boiling regime. Subsequent increases in flow are insufficient to rewet the cladding surface. Once the cladding surface enters film boiling, the cladding temperature increases to high levels, in many cases above 1478K.

Two calculation cases of interest are ATWS-I events initiated by turbine trip from the MELLLA+ low flow corner (85 percent of rated flow) on the 100 percent rated power (or 120 percent of originally licensed thermal power) line. Calculations were performed at the beginning of cycle (BOC) and at the peak-hot-excess (PHE) exposure point.

In the current sensitivity analysis, the nominal calculation results are compared to sensitivity calculation results performed with a higher, fixed minimum stable film boiling temperature.

1.2. Regulatory Purpose

The regulatory purpose of the current work is to assess the sensitivity of plant and fuel response during ATWS-I to assumptions regarding the minimum stable film boiling temperature (T_{min}). The specific regulatory purpose is the assistance in the quantitative comparison of reference results to those generated using alternative methodologies that may rely on different correlations for predicting T_{min}.

1.3. Methodology

To conduct these calculations, a special version of TRACE was developed. This special version of TRACE is referred to as TRACE-TMIN. TRACE-TMIN is essentially identical to Version 5 Patch 3 with only one difference, where TRACE-TMIN adds a "nameslist" variable called TMINNL that allows the user to input a fixed, constant value to be assumed for the T_{min}.

As in [1], the BWR/5 model is divided into two parts, the first being the TRACE systems model. This part of the overall model simulates the thermal-hydraulic and thermo-mechanical response of the plant and core. The second part of the model is the PARCS neutronic model. The PARCS part simulates the kinetic behavior of the core in response to changing conditions of the coolant and fuel. The two models are connected through a mapping interface that associates thermal-hydraulic channels with neutronic nodes. The core is modeled with 382 TRACE CHAN components representing 764 fuel assemblies. Additional descriptive details are provided in the companion paper [1].

The sensitivity calculations are performed in two phases. In the first phase, the nominal case is rerun with TRACE-TMIN without invoking the TMINNL variable. This generates the same results as the calculations shown in [1]. This step is performed in part to demonstrate that the code version produces same results and also so that the comparisons between calculation results are based on the same code version.

The nominal case calculation requires four steps. In the first step, a TRACE standalone calculation is performed to initialize the plant conditions. In the second step, a TRACE/PARCS coupled steady-state calculation is performed to initialize the conditions in the core and determine the steady-state power distribution. In the third step, a PARCS standalone calculation is performed to determine the harmonic shape for subsequent use in the transient calculation. In the fourth step, a TRACE/PARCS coupled transient calculation is performed. This four step approach is identical to that used in the companion paper [1].

In the second phase, the sensitivity calculation is performed. The sensitivity calculation only updates the value of T_{min}, and therefore, only the transient input is changed relative to the nominal case. Therefore, all of the necessary restart files from the first phase are used and only a transient calculation is performed in the second phase with a modified transient restart deck.

Aside from updating the T_{min}, some minor changes were made to the transient restart input deck to add additional signal variables to make plotting output variables simpler.

2. T_{MIN} SENSITIVITY STUDIES OF TURBINE TRIP EVENTS

Two sensitivity calculations were performed as part of the current study. These calculations consider two different points in the reference, equilibrium cycle: the peak hot excess (PHE) exposure point and beginning of cycle (BOC). In each calculation, the T_{min} was changed to a fixed value of 900K and the results were compared to the nominal calculation results. The sensitivity calculation is performed with a T_{min} of 900 K because this value is consistent with, albeit slightly conservative relative to, the prediction of the Shumway correlation [4] at 7 MPa of pressure at low flow and high void fraction with a zircaloy alloy cladding (~930 K). The nominal calculation utilizes the models described by the companion paper [1] and, in particular, calculates T_{min} according to the Groeneveld-Stewart correlation.

The PHE point is of interest generally owing to the higher fission cross-section typical at this point; which generally makes the out-of-phase more dominant as the subcritical mode reactivity is inversely proportional to the fission cross-section [6]. Previous studies also indicate that a strong out-of-phase bi-modal oscillation develops in the PHE case [1]. Further, the previous studies have indicated that the calculated PCT is highest for the PHE reference case [1].

The BOC point is of interest from an instability perspective owing to the downward peaked axial power shape. Generally, a downward peaked axial power shape is destabilizing for two reasons. Firstly, a downward peaked axial power shape tends to increase the axially averaged void fraction and secondly, the void perturbations begin at a low axial point in the core, which increases the delay time before that void exits the active region of the core [6]. Previous studies [1] have indicated that while the PHE point may be more limiting, large amplitude power oscillations develop for the BOC case with appreciable fuel heat-up.

2.1. Steamline Flow

Figure 1a provides a comparison of the steamline flow rate for the PHE nominal case and the case with a fixed T_{min} of 900 K; Figure 1b provides an analogous comparison for the BOC point in cycle. The comparison indicates that the early part of the transient shows essentially no difference in the results. This is to be expected as the calculations should predict identical behavior prior to fuel heat-up since the T_{min} has no influence on the calculation.

The general steamline flow behavior in the early transient is driven by the closure of the turbine stop valve at 10 seconds, causing the large decrease in flow. This closure causes a pressurization of the reactor pressure vessel; however, when the turbine bypass valves begin to control pressure the steamline flow rate rapidly increases to relieve that increased pressure. The steamline flow rate then decreases during the period of about 11 seconds to 75 seconds in response to a decrease in reactor core power level over the same period. Some oscillation is observed after 100 seconds, which corresponds to the onset of power instability (and hence core void production oscillation). As the turbine bypass system is sized for 100 percent steam flow, the safety/relief valves are not predicted to open.

Some subtle differences are observed between 100 and 125 seconds for both exposures. These small differences coincide with the timing of the onset of large amplitude power oscillations, and therefore, the onset of periodic fuel dryout and rewet. However, one observes that the differences at this stage of the transient are very minor.

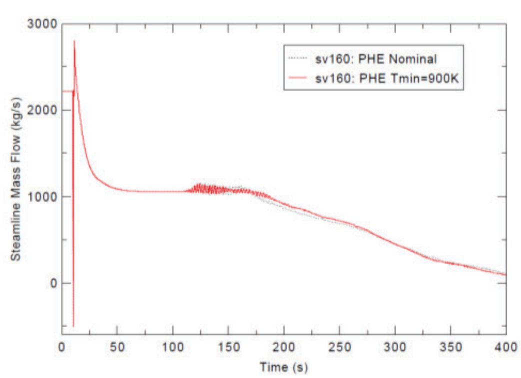

Figure 1a. PHE Steamline Flow Rate.

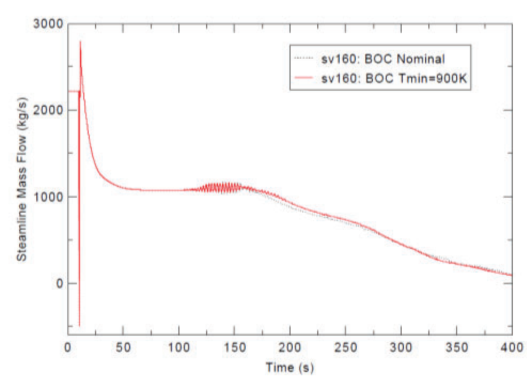

Figure 1b. BOC Steamline Flow Rate.

The only notable difference between the nominal and T_{min}=900K cases is the steamline flow after approximately 175 seconds. In the T_{min}=900K case, the steamline flow remains slightly higher when compared to the nominal case from about 175 seconds to about 300 seconds. As discussed in Section 2.2, the T_{min}=900K case predicts higher reactor power over this period (on average) and this contributes to higher steam production, and therefore, slightly higher steamline flow during this period.

2.2. Core Power and Dome Pressure

Figure 2 compares the nominal and T_{min}=900K reactor power response cases. The nominal and T_{min}=900K cases indicate identical predictions of the power during the early transient through the onset of instability. The initial power pulse is in response to pressurization following closure of the turbine stop valves. The power pulses and declines in response to a combination of the opening of the turbine bypass valves to reduce reactor pressure as well as a reduction in core flow rate following automatic trip of the recirculation pumps.

After about 25 seconds at both times in cycle, Figure 2 illustrates a steady increase in the reactor power leading up to the onset of instability. This power increase is caused by cooler core inlet flow. The turbine trip isolates the flow of extraction steam to the feedwater heat cascade, in response, the feedwater flow becomes cooler, and consequently, the core inlet flow becomes cooler. Reactor power increases to compensate for the cooler inlet flow to maintain a critical void condition within the core under conditions of natural circulation.

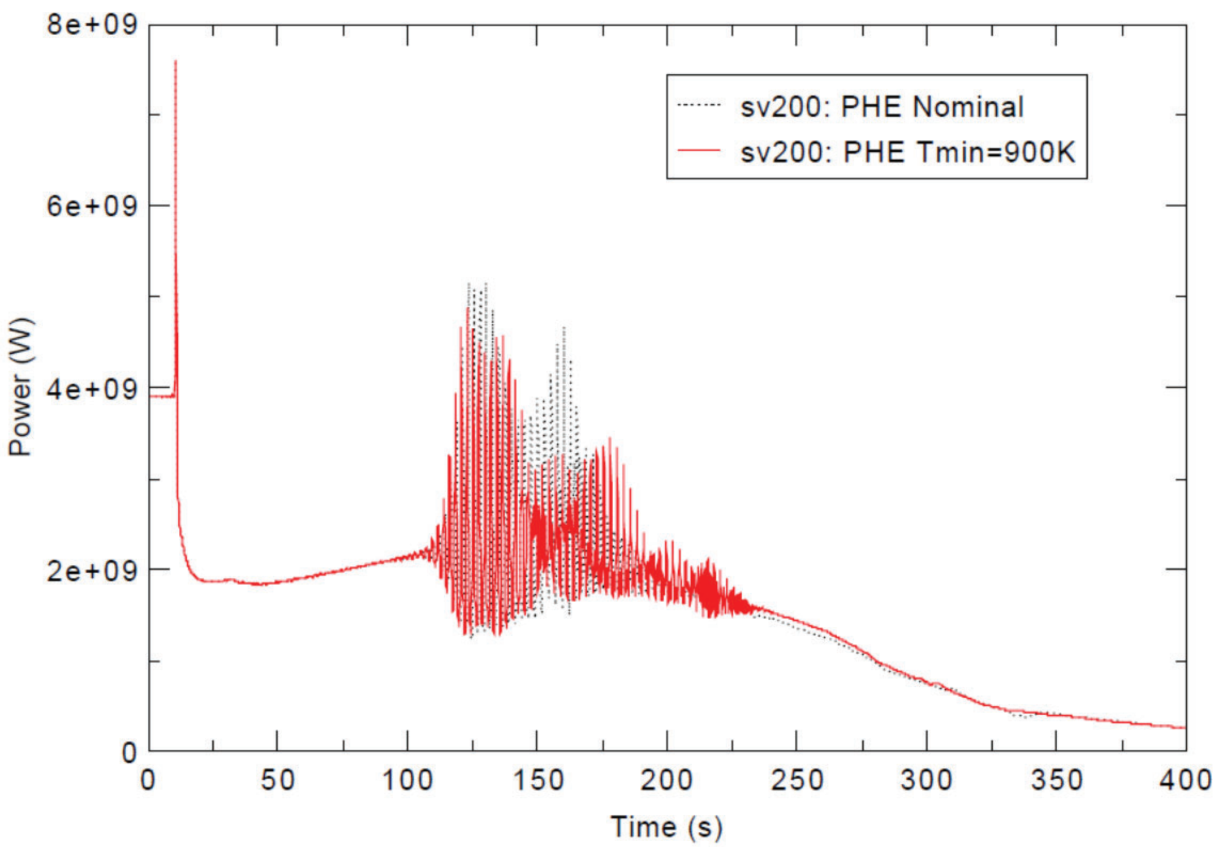

Figure 2a. PHE Reactor Power.

At PHE, the oscillations begin around 100 seconds with a frequency of 0.44 Hz. The oscillations grow in magnitude until reaching a limit cycle around 120 seconds. During this limit cycle, the power oscillates with a frequency of 0.48 Hz based on the observed time between successive power peaks. The frequency is the same in both the nominal and T_{min}=900K cases. The frequency increases to 0.81-0.82 Hz around 150 seconds, as observed in Figure 2a, due to non-linear effects. The frequency increase is ~6 seconds later in the T_{min}=900K case as compared to the nominal case.

At BOC, the oscillations begin around 100 seconds and exhibit a frequency of 0.41 Hz based on the observed timing of successive peaks prior to the limit cycle (see Figure 2b). During the limit cycle, the BOC cases show a frequency of 0.40 Hz before increasing to ~0.75-0.80 Hz during the non-linear phase after ~150 seconds.

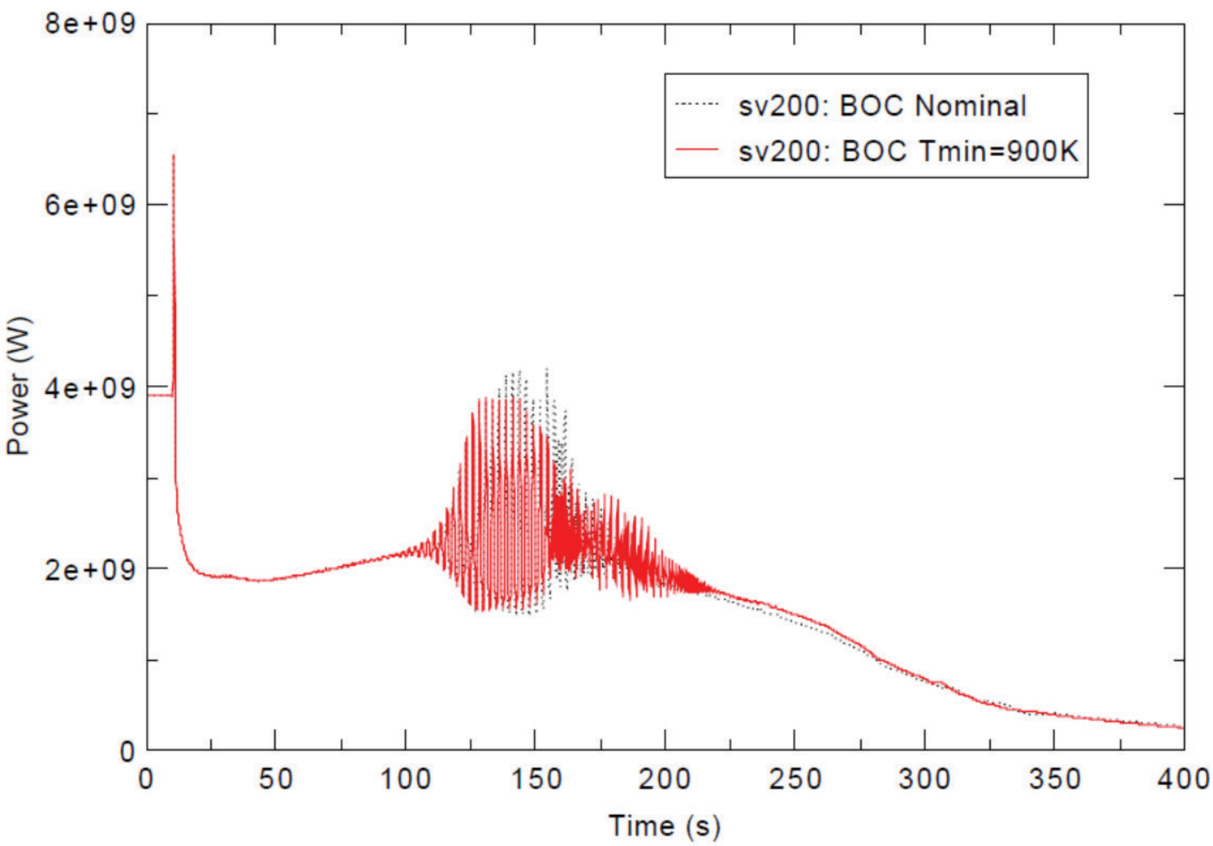

Figure 2b. BOC Reactor Power.

Some differences are observed in the power response following the instability onset. Both calculations exhibit nearly identical power oscillation magnitude growth, however, the nominal calculation appears to slightly higher oscillation magnitude around 125 seconds. Further, all calculations appear to indicate the development of non-linear, bi-modal coupled oscillations, as evidenced by frequency doubling of the power oscillation around 150 seconds.

Figure 3 provides a comparison of the dome pressures. The nominal and T_{min}=900K results are in generally good agreement. The pressure is controlled by the turbine bypass system according to a fixed boundary condition. Variations in the response are driven by the subtle variations in average core power. When the pressure is fixed at the end of the steamline, as in the current calculations, the dome pressure is dictated by the balance of steam production in the reactor core and steam exhaust through the turbine bypass. Therefore, the differences in dome pressure response that appear between 150 and 300 seconds mirror the subtle differences in steamline flow rate and are driven by the differences in the average reactor power response.

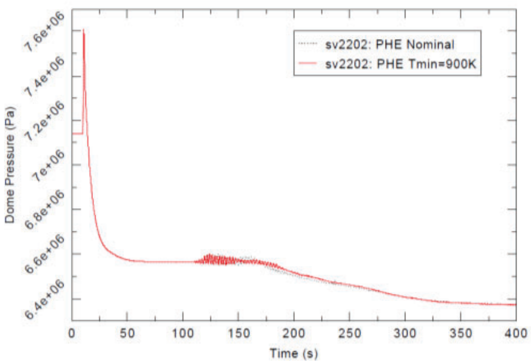

Figure 3a. PHE Dome Pressure.

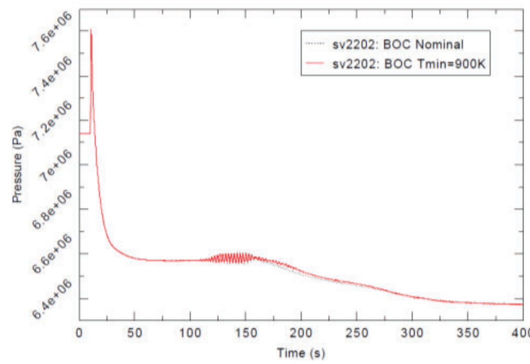

Figure 3b. BOC Dome Pressure.

The differences in steamline flow and dome pressure are most noticeable between 175 and 225 seconds. During this period, the transient power response shown in Figure 2 indicates that the average power is slightly higher in the T_{min}=900K case compared to the nominal case. The difference in the transient reactor power response can be tied to the difference in the transient Doppler reactivity effect.

Figure 4 provides a plot comparing the total reactivity dynamic response in both cases for both times in cycle. The total reactivity is a combination of several effects, including the void condition in the core, fuel temperature, and boron concentration. The reactor power will adjust to "chase" a critical condition during the ATWS. However, a notable difference can be observed in examining the Doppler reactivity component, shown in Figure 5.

Figure 5 compares the Doppler reactivity worth for both cases for both times in cycle. Starting around 120 seconds, the nominal and T_{min}=900K curves diverge with the T_{min}=900K case predicting a more positive Doppler reactivity compared to the nominal cases. This is easily explained in terms of the heat-up behavior of the fuel. As discussed in greater detail in Section 2.7 (see Figure 11), a failure to rewet occurs in the nominal case around this time of interest (about 120 seconds). At this point, the nominal cases predict an increase in fuel temperature and a corresponding increase in negative Doppler reactivity. This explains the downward trend in the nominal case Doppler reactivity when compared to the T_{min}=900K cases, which do not predict extreme fuel heat-up. The larger amplitude power oscillations observed in the nominal case during the period between 120 and 200 seconds appear to be caused by larger amplitude oscillations in fuel temperature and Doppler worth.

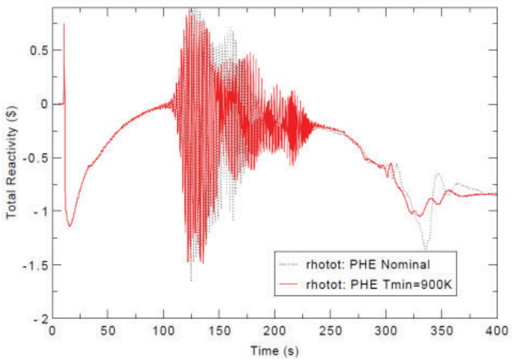

Figure 4a. PHE Total Reactivity

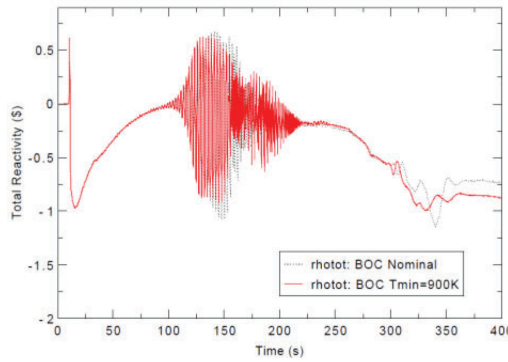

Figure 4b. BOC Total Reactivity.

The longer term average power predicted in the T_{min}=900K cases is slightly higher (after about 175 seconds). This is when the Doppler reactivity differences become largest, implying that to achieve a critical condition, this positive Doppler reactivity must be compensated by an increase in reactor core power and the associated increase in void production.

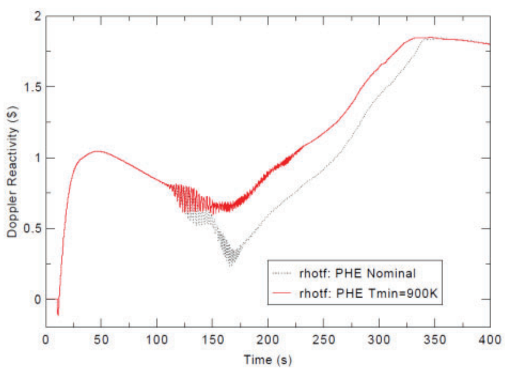

Figure 5a. PHE Doppler Reactivity.

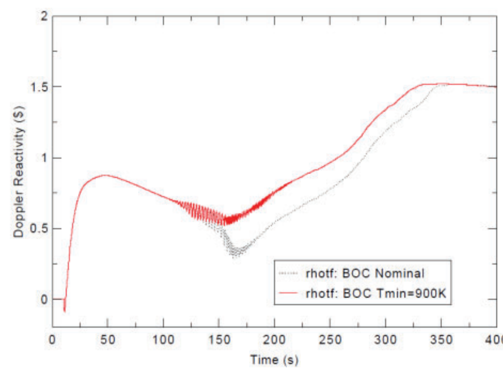

Figure 5b. BOC Doppler Reactivity.

Figure 5 shows that the nominal and T_{min}=900K cases predict different Doppler reactivity through about 325 seconds. Figure 11 illustrates, at least for the hot spot, the fuel temperature in the nominal case is decreasing over this same period. As the nominal case fuel temperature decreases and comes into better agreement with the T_{min}=900K case, the difference in Doppler reactivity should also decrease. This is the observed trend in the results.

2.3. Core Flow

A comparison of the core flow rates is shown in Figure 6. The results of both cases at both times in cycle indicate nearly identical core flow responses. While reactor power and hence void production is slightly higher in the T_{min}900K case, owing to a more positive Doppler reactivity, the impact on the core pressure drop is very minor. This is because the introduction of additional void to the active core flow has two competing effects in terms of pressure drop. The introduction of additional void tends to increase the buoyancy of the flow (reducing pressure drop) while at the same time increasing the two-phase flow friction pressure losses (increasing pressure drop). Under conditions of natural circulation these two competing effects are of similar magnitude.

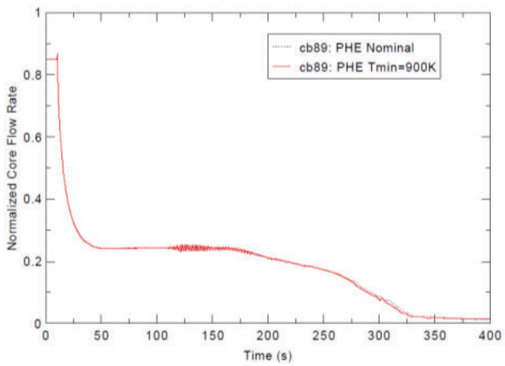

Figure 6a. PHE Core Flow Rate.

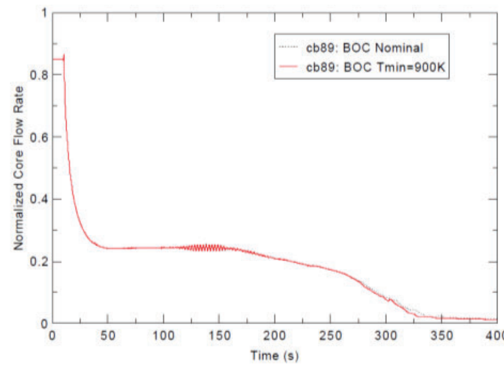

Figure 6b. BOC Core Flow Rate.

Since the core flow is dictated by a combination of the core pressure drop characteristics (which are very similar in both cases) and the natural circulation driving head provided by the downcomer water level (which is controlled to the same level in both cases), the similarity in the core flow rate response between the two cases is expected.

2.4. Feedwater Flow and RPV Water Level

Figure 7 shows the predicted feedwater flow rate response in both cases at both times in cycle. The feed flow is essentially the same throughout the transient with only a small difference observable between about 200 and 250 seconds. In the T_{min}=900K cases, the reactor power is slightly higher during this period. This higher power leads to slightly higher steam production, and hence, slightly higher inventory loss through the steamline (see Figure 1). To compensate for this higher steamline flow rate, the feedwater flow rate is slightly larger to control the downcomer water level to the same setpoint.

Figure 8 compares the level responses, which shows that the two cases predict nearly identical level responses through about 250 seconds at both times in cycle. A very slight difference can be seen after this point with the nominal case water level slightly higher than the T_{min}=900K case. However, at this stage of the transient the power oscillations have been suppressed and the difference in level response at this point in the calculation is not considered significant.

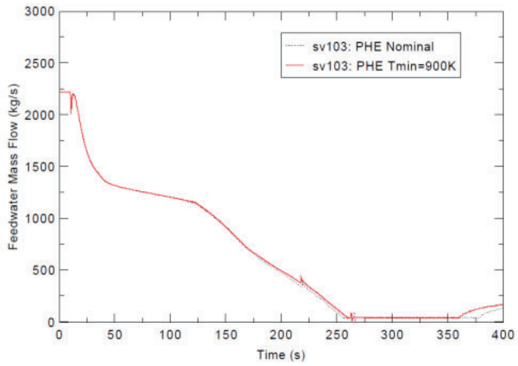

Figure 7a. PHE Feedwater Flow Rate.

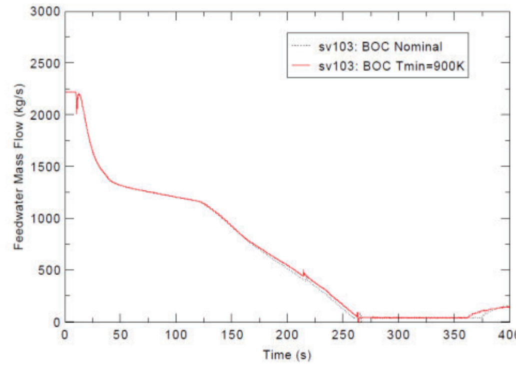

Figure 7b. BOC Feedwater Flow Rate.

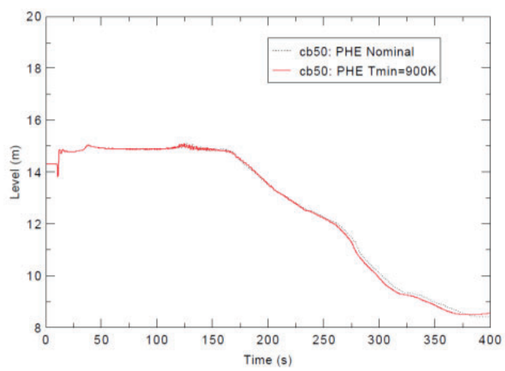

Figure 8a. PHE Reactor Water Level.

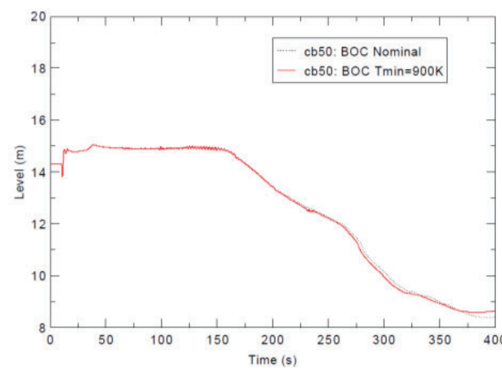

Figure 8b. BOC Reactor Water Level.

2.5. Boron Inventory in the Core

Figure 9 compares the integrated boron inventory near the active core region. This figure of merit serves as a gauge for the effectiveness of the standby liquid control system to deliver an adequate quantity of soluble boron to the core to shutdown the reactor. The boron accumulation in the core is a strong function of the core flow rate. Despite differences in power, and hence void production, the core flow rate (as discussed in Section 2.3) is nearly identical. The similarity in core flow rate between the nominal and T_{min}=900K cases explains the nearly identical trends in core boron inventory observed throughout the calculation.

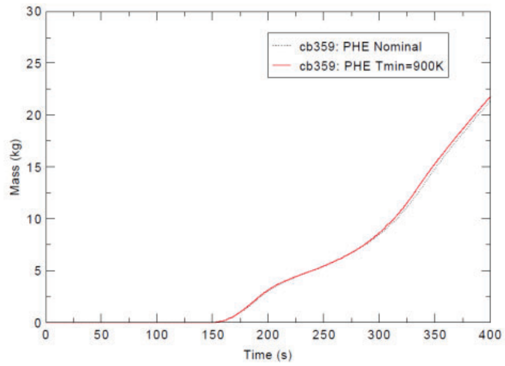

Figure 9a. PHE Core Boron Inventory.

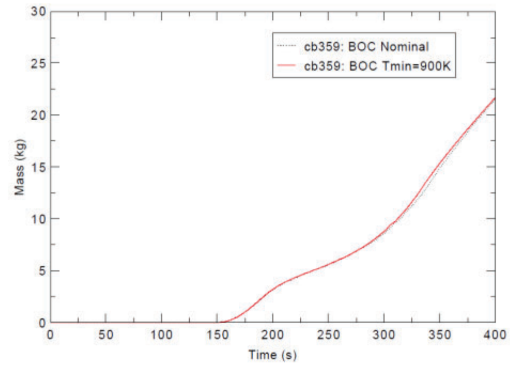

Figure 9b. BOC Core Boron Inventory.

2.6. Liquid Subcooling of Core Flow

Figure 10 provides a comparison of the inlet subcooling response. After about 200 seconds, the subcooling is higher in the T_{min}=900K cases. This may be attributable to the slightly higher power in the T_{min}=900K case during the same period of the transient. With slightly higher core exit quality, the return flow rate of saturated liquid to the downcomer over this period is slightly lower compared to the nominal case. As the core flow rate is essentially the same, this difference in liquid flow is compensated in the T_{min}=900K case by a slightly larger flow of cooler feed. This slightly higher feed flow is observed over the same period in Figure 7. The combination is a slightly cooler inlet flow for the T_{min}=900K case compared to the nominal case.

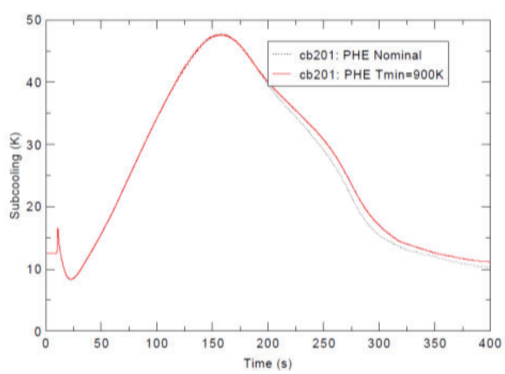

Figure 10a. PHE Core Inlet Subcooling.

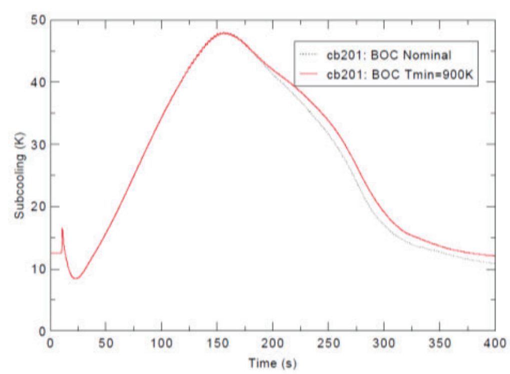

Figure 10b. BOC Core Inlet Subcooling.

2.7. Fuel Rod Cladding Temperature

Most parameters discussed to this point for the PHE and BOC calculations have been only slightly sensitive to the T_{min}. However, the differences in the plant responses can be directly tied to the differences in the onset and degree of fuel heat-up. This affects the power response through the Doppler reactivity feedback. Figure 11 shows the most significant difference in the calculation results by plotting the peak cladding temperature response for the nominal and T_{min}=900K cases at both times in cycle.

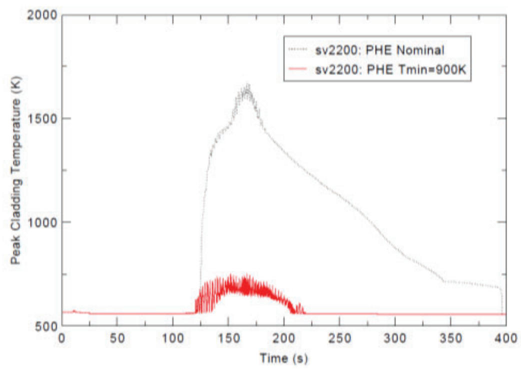

Figure 11a. PHE PCT.

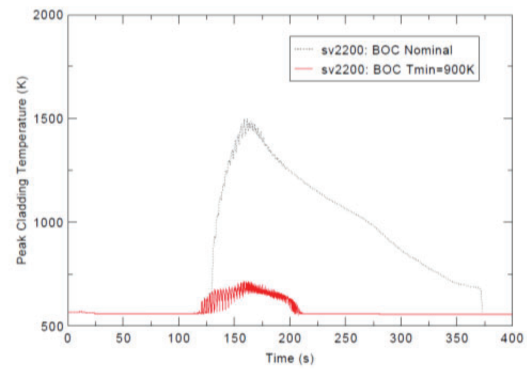

Figure 11b. BOC PCT.

In the nominal case, after the onset of large amplitude power instability, the cladding surface goes through a few cycles of dryout and rewet with a failure to rewet predicted around 125 seconds. This failure to rewet corresponds to the cladding hot spot achieving an outer surface temperature equal to that predicted by the Groeneveld-Stewart T_{min} correlation. After this failure to rewet, the fuel heats up to high temperatures in excess of 1500K.

The T_{min}=900K case, however, shows different behavior. Periodic dryout and rewet are observed in both cases; however, in the T_{min}=900K case, the cladding surface temperature during any dryout/rewet oscillation does not heat-up above the T_{min}. As such, there is no predicted failure to rewet the surface and transition boiling heat transfer limits cladding temperature in the period between 125 and 200 seconds. This dramatically changes the predicted PCT response, with the T_{min}=900K case showing only a moderate heat-up to about 700-750K both at PHE and BOC. This result is expected because the large PCT calculated in the nominal case is a direct consequence of a failure to rewet during a single oscillation; which is determined directly by the T_{min}.

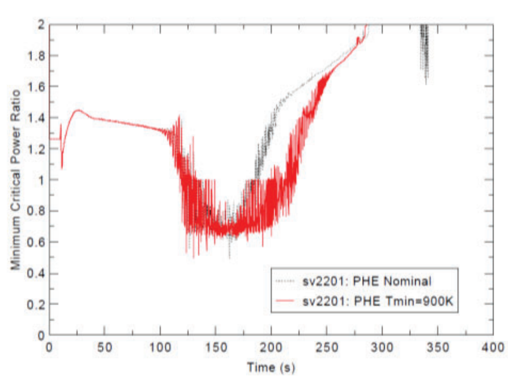

Figure 12a. PHE MCPR.

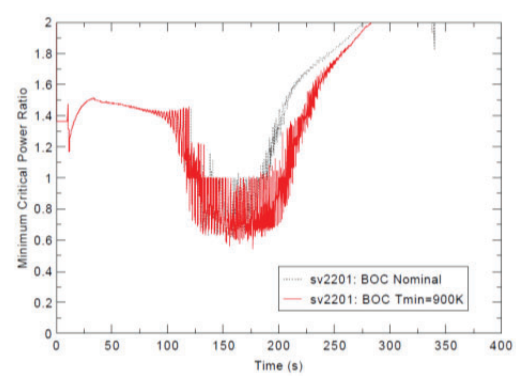

Figure 12b. BOC MCPR.

Figure 12 shows a comparison of the minimum critical power ratio (MCPR). As can be seen up to about 150 seconds, the T_{min}=900 K sensitivity cases predict periods of rewetting during the oscillation. There is an interval around 150 seconds where the nominal and T_{min}=900K calculations indicate that the MCPR remains below 1.0 (indicating dryout conditions), but the heat-up has already progressed to high temperatures in the nominal case. During this analogous period in the T_{min}=900 K cases, Figure 11 shows that the hot spot PCT does not return to pre-critical-heat-flux temperatures, but also does not go into extreme heat-up.

After 175 seconds, the nominal cases indicate that the MCPR recovers more rapidly compared to the T_{min}=900K cases. This is likely attributable to the higher reactor power in the T_{min}=900K case compared to the nominal case. At the hot assembly and hot spot location, the fuel temperatures predicted in the nominal case are much higher, meaning that the local power would be even further suppressed than what is indicated by the total core power response shown in Figure 2. As the two temperature predictions come into closer agreement between 200 and 300 seconds, the predicted MCPR margin also comes into better agreement.

2.8. Summary

The results of this study indicate that the PCT prediction is sensitive to the assumptions regarding the minimum stable film boiling temperature. When a higher T_{min} is applied in the calculation, extreme and prolonged fuel heat-up is not predicted. With a higher T_{min}, the cladding surface is likely to rewet during the oscillatory stage and does not encounter a failure to rewet with subsequent "locking" into the film boiling heat transfer regime.

This effect on the fuel heat-up has subtle effects on the overall plant response, but these sensitivities are much smaller. The difference in predicted heat-up affects Doppler reactivity worth in the core. The Doppler reactivity effect is compensated by void reactivity leading to several consequential effects in terms of oscillation magnitude, steamline flow rate, and core inlet subcooling. However, the overall plant response remains largely similar and the primary effect is on the prediction of PCT.

3. CONCLUSIONS

Sensitivity calculations were performed at two cycle exposure points of interest from a stability standpoint, PHE and BOC. These sensitivity calculations varied the assumed behavior of the minimum stable film boiling temperature. The two exposure cases yielded very similar observed trends in the transient responses. The following observations were inferred from the calculation results.

1. With a higher T_{min}, prolonged and extreme cladding heat-up is not observed in either the PHE or BOC cycle-exposure studies. This is explained by the rewetting of the cladding surface during the oscillatory phase in the sensitivity calculations. With a higher value of T_{min}, the cladding surface does not "lock" into a film boiling heat transfer regime. Good heat transfer conditions persist during the oscillatory phase leading to an extended period of cyclic dryout and rewet of the cladding surface at the core hot spot. PCT remains much lower in the sensitivity calculations with high T_{min} compared to the nominal cases.
2. In the sensitivity cases, since fuel heat-up is limited compared to the nominal case, the reactivity detriment from Doppler worth is compensated by increased void reactivity, leading to slightly higher average core power in the sensitivity cases. With a higher T_{min}, the reactor core average power is slightly higher. This effect is subtle compared to the effect on PCT.

3. A higher core power in the high T_{min} cases contributes to higher steamline flow and higher dome pressure compared to the nominal case. The core produces slightly more steam in the high T_{min} cases, which necessitates a higher dome pressure to exhaust that steam production through the turbine bypass. This effect is subtle compared to the effect on PCT.
4. A higher steamline flow rate in the high T_{min} cases contributes to a higher feedwater flow rate to maintain the same level response. A controller in the calculation simulates operator actions to maintain level. In the sensitivity calculations, the level response is essentially the same since feedwater flow compensates the change in steamline flow in the calculation. This effect is subtle compared to the effect on PCT.
5. A higher feedwater flow in the high T_{min} cases contributes to a slightly cooler core inlet temperature in the sensitivity cases. This is caused by a slightly lower liquid return flow rate from the separators (which is at saturation temperature) and a slightly higher feed flow rate (which is at a lower temperature). This effect is subtle compared to the effect on PCT.
6. Core flow rate is essentially unaffected by T_{min}. The core flow rate is a function of pressure drop during the natural circulation phase of the event. Since two-phase friction losses are largely compensated by buoyancy effects under natural circulation conditions, the slightly higher void in the high T_{min} case does not contribute to a noticeable change in core pressure drop. The result is essentially identical core flow rates.
7. The boron accumulation in the core is a strong function of the core flow rate. Since the core flow rate is unaffected by the change in T_{min}, the boron inventory response is also largely unaffected.

In conclusion, it was observed that a higher T_{min} has a subtle effect on overall plant transient response; however, a higher T_{min} translates to a significant reduction in the PCT depending on whether the fuel heats up to T_{min} during the oscillatory phase, or not. In the current sensitivity calculations, prolonged fuel heat-up was precluded as the peak cladding temperature did not reach 900K.

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