USNRC Office of Nuclear Regulatory Research

Applicability of TRACE/PARCS to MELLLA+ BWR ATWS Analyses – Revision 1

Applicability of TRAC-RELAP Advanced Computational Engine (TRACE) and Purdue Advanced Reactor Core Simulator (PARCS) codes to Maximum Extended Load Line Limit Analysis Plus (MELLLA+) Boiling Water Reactor (BWR) Anticipated Transients without SCRAM (ATWS) Analyses

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ENCLOSURE 2

Executive Summary

The maximum extended load line limit analysis plus (MELLLA+) domain has been proposed for boiling water reactors (BWRs) that have extended power uprates (EPUs). The MELLLA+ domain would allow operation at high reactor thermal power (up to 120 percent of originally licensed thermal power (%OLTP)) at reduced reactor core flow (as low as 80 percent of rated core flow (%RCF)). The high power-to-flow state point (120 %OLTP / 80 %RCF) introduces new safety concerns related to the consequences of anticipated transient without SCRAM (ATWS) events initiated from this state.

The TRAC-RELAP Advanced Computational Engine (TRACE) and Purdue Advanced Reactor Core Simulator (PARCS) codes have previously been applied to analyze and study complex BWR transients. This report summarizes the outcome of a determination regarding the applicability of these codes to analyze particular ATWS scenarios relevant to MELLLA+ operation. These transients include: ATWS with core instability (ATWSI) and ATWS with emergency depressurization (ATWSED).

In undertaking this applicability determination, the RES staff relied on generic evaluation model development guidance, in particular, the code scaling, applicability, and uncertainty (CSAU) methodology and the evaluation model development and assessment process (EMDAP) described in NUREG/CR-5249, “Quantifying Reactor Safety Margins,” December 1989, and Regulatory Guide (RG) 1.203, “Transient and Accident Analysis Methods,” December 2005, respectively. In keeping with these processes, the RES staff: (1) identified the plant class and transient scenarios, (2) identified and ranked the important phenomena, (3) determined code requirements, (4) established an assessment matrix, and (5) determined the TRACE/PARCS code applicability.

TRACE/PARCS was found to represent all highly important phenomena with either reasonable or excellent agreement over the range of interest for ATWS at MELLLA+ conditions. Therefore, TRACE/PARCS was deemed applicable to analyze the two ATWS scenarios of interest.

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1 Introduction

This report documents the applicability determination for TRACE/PARCS to analyze anticipated transient without SCRAM (ATWS) events for boiling water reactors (BWRs) operating with a maximum extended load line limit analysis plus (MELLLA+) expanded operating domain. It is the intent to use TRACE to simulate postulated MELLLA+ ATWS events to study plant transient response, consequences, and effectiveness of mitigating actions.

The applicability determination process was based on the Code Scaling, Applicability, and Uncertainty (CSAU) methodology and the Evaluation Model Development and Assessment Process (EMDAP) (Ref. 12 and 13). CSAU and EMDAP provide for specific methodological steps and acceptance criteria for establishing the applicability of an analysis method to adequately simulate a given scenario. These processes include similar steps and these are reflected in the current applicability determination.

First, a specific plant type or class of plants has been identified; BWRs operating at MELLLA+ conditions. Section 2 of this report describes MELLLA+ BWR plants. Briefly, the MELLLA+ domain allows operation at high power levels coincident with low core flow rates.

Second, specific transient or accident scenarios were identified. Section 3 describes two ATWS scenarios of particular concern for MELLLA+ BWRs. The first scenario is a postulated ATWS event with core instability and the second scenario is a postulated ATWS event with emergency depressurization.

Third, the specific figures of merit were identified. Section 4 describes these figures of merit. In general, ATWS events are analyzed to gauge consequences, quantify safety margins, and to evaluate the effectiveness of mitigating actions to bring the plant to a stable, cold condition. For any particular scenario, the figures of merit are tied to specific limits and system performance.

Fourth, important phenomena relating to the ATWSI and ATWSED scenarios were identified. This step is referred to as the phenomena identification and ranking table (PIRT) process. Not all phenomena contribute equally to the progression or consequences of a postulated event. The PIRT process identifies the important phenomena that must be considered in the evaluation. Section 5 describes how previously developed BWR PIRTs were used to build a PIRT relevant to MELLLA+ ATWS. This section also provides the results of the PIRT and lists all of the highly important phenomena.

Fifth, a capability review was performed to ensure TRACE had sufficient models and functions to simulate all of the identified, important phenomena. Section 6 correlates the specific capabilities of TRACE to the highly important PIRT phenomena.

Sixth, an assessment matrix was established. The assessment matrix considers all of the highly important phenomena and collects relative separate effects and integral effects test (SET/IET) data and corresponding TRACE comparisons. The purpose of the assessment matrix is to identify a sufficient assessment basis to fully cover all of the important phenomena. Once the matrix is established, a review of comparisons between TRACE calculations and experimental results was conducted. Section 7 describes the assessment matrix and assessment review. TRACE was determined to adequately simulate all of the highly important phenomena.

Section 7.3 addresses special considerations for core and plant model nodalization. Section 9 describes the conclusions of the applicability determination. It was found that TRACE is applicable to evaluate MELLLA+ ATWS events relative to specific figures of merit.

2 Maximum Extended Load Line Limit Analysis Plus Operation

The MELLLA+ operating domain utilizes a flow control window (FCW) at high reactor power. It is very similar to the MELLLA concept, except, this FCW is utilized at extended power uprate (EPU) power levels. Figure 1 illustrates the FCW concept as it applies to the MELLLA domain (Ref. 1). At rated thermal power, the reactor may be maneuvered along the FCW to compensate for reactivity changes through cycle depletion. The FCW has two notable advantages for licensees. First, the FCW offers flexibility in controlling reactivity by providing an alternative to control blade pattern swaps. Second, the FCW allows operation at high power to flow ratio. At the high power to flow state point, high void fraction in the upper portion of the core promotes the production of plutonium. The enhanced plutonium conversion owing to the harder spectral conditions confers some fuel cycle economic benefits.

For reference, Figure 2 provides a typical power/flow operating map depicting the MELLLA+ upper boundary (Ref. 1). The MELLLA+ domain expands allowable operation at EPU power levels down to low core flow rates (as low as 80 percent of rated core flow (%RCF)). The operation at the low flow point along the MELLLA+ upper boundary at EPU power levels (shown as Point D in Figure 2) introduces new safety concerns relative to normal EPU operation (between Points A and B in Figure 2). In particular, these issues are associated with the consequences of postulated ATWS events initiated from Point D.

Figure 3 illustrates a typical plant trajectory following a postulated ATWS event (Ref. 1). From Point D, the reactor power decreases in response to a dual recirculation pump trip (2RPT). The 2RPT is an automated plant response intended to reduce the gross reactor thermal power. As shown in the figure, the power is reduced, however, begins to climb again as flow rate approaches the natural circulation line. The increase in reactor power is in response to a loss of extraction steam to the feedwater heater (FWH) cascade. For example, if the postulated initiating event is a turbine trip (TT), the closure of the turbine stop valve (TSV) results in a loss of extraction steam to the FWH cascade. The FW temperature starts to decrease in response. The reactor core responds to the reactivity insertion associated with elevated core inlet subcooling and power increases.

If left unmitigated, the plant will evolve to a state point where the reactor achieves a critical void fraction similar to the normal operating condition at relatively high power and natural circulation flow. The power to flow ratio following the 2RPT is shown for a hypothetical MELLLA+ plant and for a plant operating at normal EPU conditions in Figure 3. As can be seen, the reactor power under natural circulation conditions is much higher for a MELLLA+ plant.

The higher thermal load present following 2RPT for postulated ATWS events introduces two clear safety concerns. First, the reactor evolves to a very high power to flow condition, and specifically to a region of the power/flow map where unstable power oscillations are likely to occur. The occurrence of these power oscillations, if left unmitigated, may result in fuel damage. Additionally, the violence of the power oscillations may hamper the effectiveness of mitigation strategies. For example, ATWS events are typically mitigated through the injection of dissolved neutron absorber through the standby liquid control system (SLCS); the occurrence of oscillation induced core inlet flow reversal may reduce the rate at which this soluble absorber is delivered to the active region of the reactor core.

Second, since the 2RPT at MELLLA+ is less effective in reducing the reactor core power, the containment must absorb additional energy during the mitigation period. This additional thermal load may exhaust available pressure suppression capacity of the containment wet-well, which would prompt an emergency depressurization according to standard emergency operating procedures. The emergency depressurization raises several concerns. In particular, the manual initiation of the emergency depressurization implies that: (1) the reactor has undergone a beyond design basis event, and fuel damage may have occurred, (2) the pressure suppression capacity of the containment has been exhausted, and (3) the reactor coolant pressure boundary has been bypassed by manually opening the automatic depressurization system (ADS) valves. Under these conditions, two of the three primary fission product barriers may be compromised.

Based on these safety considerations particular to MELLLA+ operation, the primary scenarios of interest for evaluation are ATWS events with either: (1) core instability or (2) emergency depressurization.

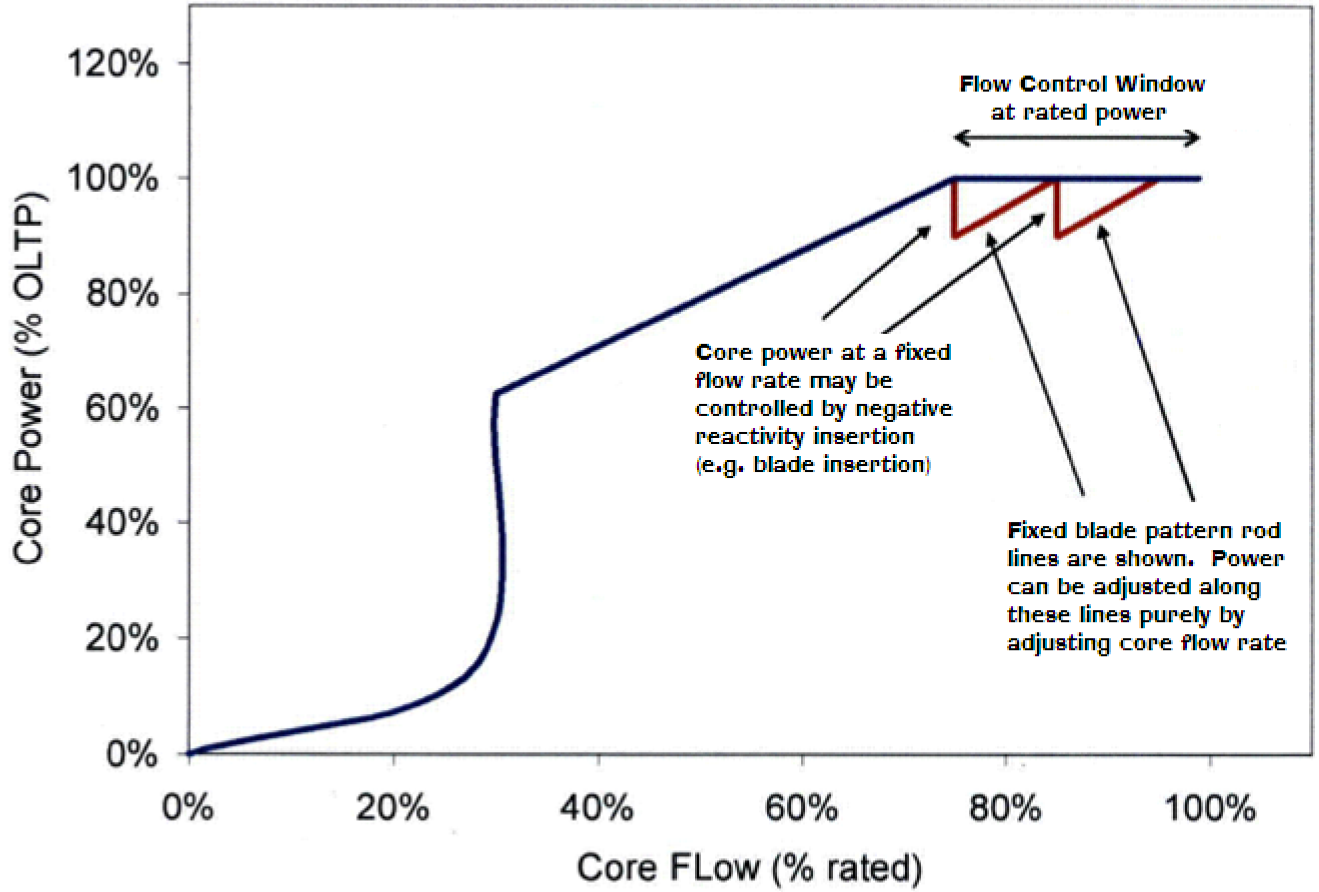

Figure 1: Illustration of a Flow Control Window[1]

[1] Ref. 1

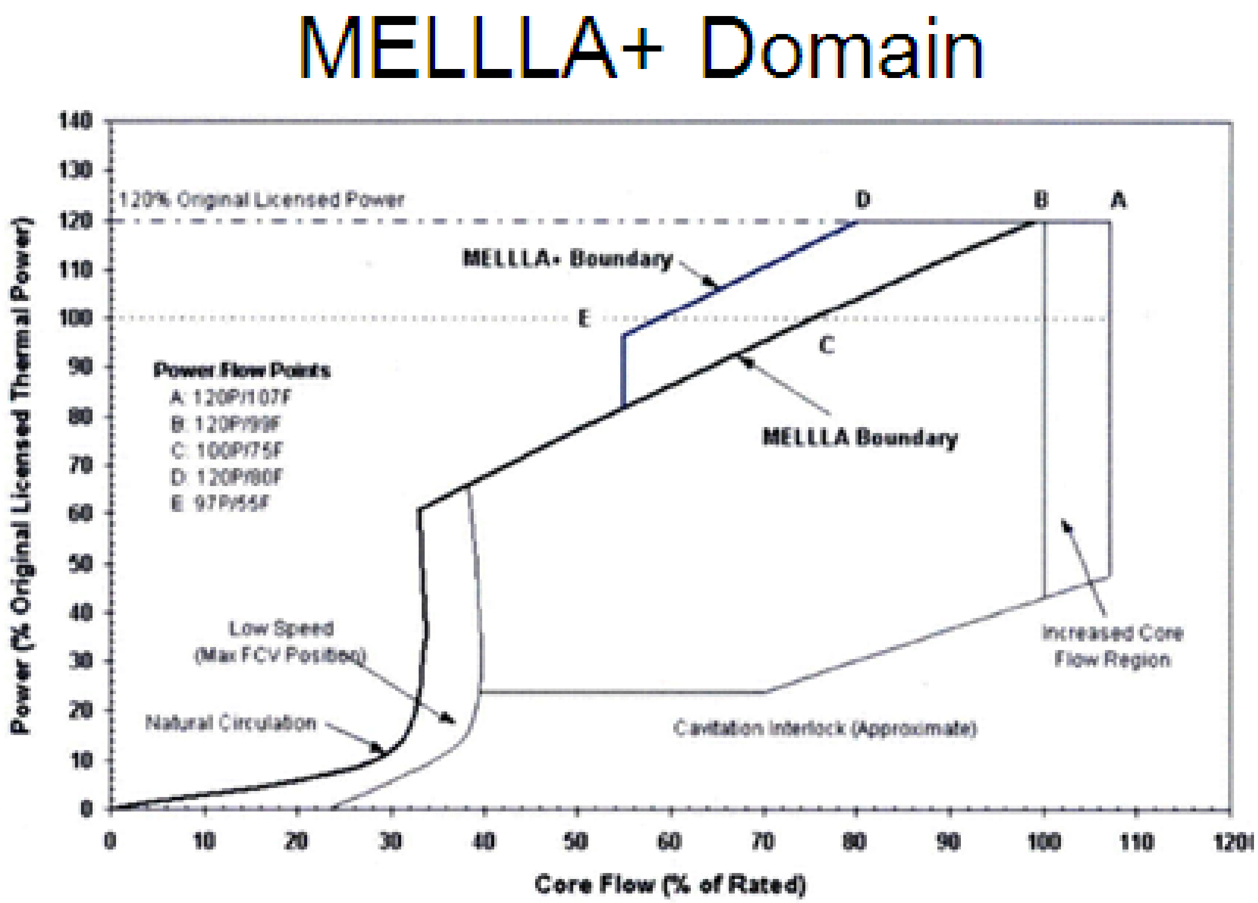

Figure 2: Boundaries of the MELLLA+ Operating Domain[2]

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[2] Ref. 1

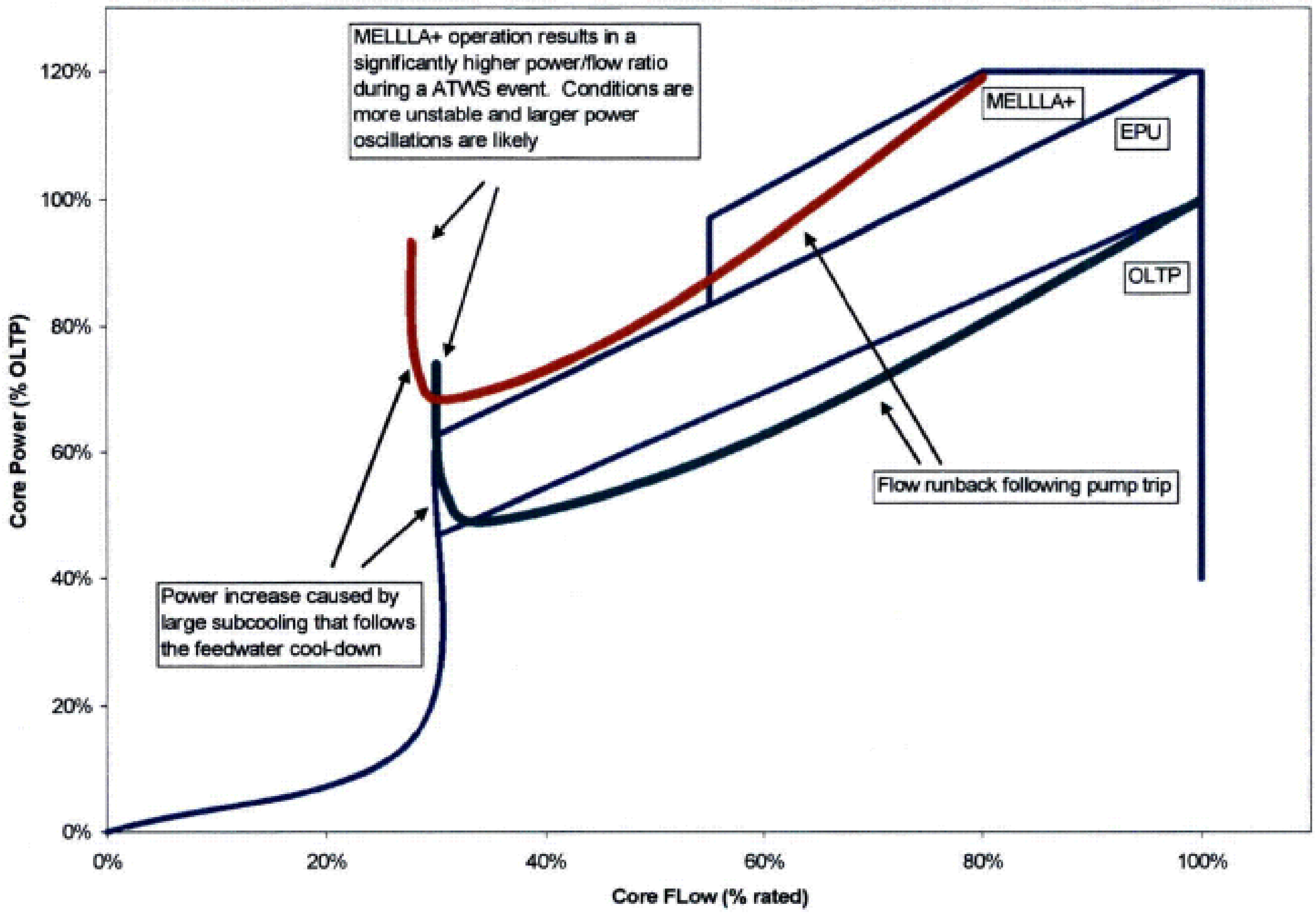

Figure 3: Natural Circulation Conditions Following Dual Recirculation Pump Trip[3]

[3] Ref. 1

3 Anticipated Transients without SCRAM Scenario Selection

Following the processes described by the CSAU and EMDAP, specific event scenarios have been selected. The first scenario is a postulated ATWS event with core instability (ATWSI). The second scenario is a postulated ATWS event with emergency depressurization (ATWSED). The specifics of each scenario are discussed in turn below.

3.1 ATWS with Core Instability

The likelihood of unstable power oscillations following a 2RPT initiator has previously been studied by both the nuclear industry and the staff. However, the introduction of MELLLA+ operating conditions may exacerbate the consequences of such an event relative to those conditions previously studied. Figure 4 depicts the relative power/flow conditions following a 2RPT for a plant operating at originally licensed thermal power, MELLLA, and MELLLA+ (Ref. 1). As can be seen from this figure, MELLLA+ may exacerbate the consequences of a 2RPT. For MELLLA operation, unstable power oscillations may occur, but become increasingly likely during the FW temperature (FWT) reduction stage, where the plant is slowly evolving to the point marked “MELLLA” in Figure 4. For MELLLA+ plants, the early onset of power oscillations may occur without the requisite decrease in FWT.

To understand the expected transient conditions for analysis, it is valuable to review previous studies of potential ATWSI events occurring from the MELLLA upper boundary. These transients were studied by the BWR Owners’ Group (BWROG) using the TRACG analysis code. Figure 5 depicts the transient scenario considered using a power/flow state point trajectory (Ref. 2).

Figure 6 shows a plot of predicted core power response to the transient (Ref. 2). As can be seen, within approximately one minute large, irregular power oscillations were observed. Based on these studies, the BWROG developed recommended mitigation strategies to address the occurrence of these large, irregular power oscillations.

The onset of the power oscillations is tied to the transient reduction in FWT following isolation of the steam supply to the FWH cascade. As the core inlet subcooling increases, the reactor power increases and shifts downward in the axial direction. The downward shift reduces the single phase to two phase pressure drop ratio in the fuel channels, making these channels more susceptible to density wave oscillations. The onset of these oscillations is accompanied by a period of rapid growth. After two minutes, the BWROG TRACG calculations indicate the onset of non-linear instability with large and irregular power spikes.

Large amplitude power oscillations may lead to fuel damage if the cladding goes into dryout and heats up above the minimum stable film boiling temperature. If the cladding temperature exceeds the minimum stable film boiling temperature then rewet is precluded. When rewet is precluded, the additional heat deposition during power pulses will result in higher cladding temperatures, potentially exceeding limits and resulting in fuel damage.

This event was studied by the BWROG to develop recommended mitigation strategies as previously stated. In the current work, it is necessary to address the applicability of TRACE to not only simulate these power oscillations, but to also simulate the plant response to the manual actions taken, according to emergency procedure guidelines (EPGs), to suppress the oscillations and mitigate the event.

The BWROG recommended two operator actions in particular to suppress the power oscillations. First, the injection of soluble boron through the SLCS is intended to shutdown the reactor. Second, lowering the reactor water level below the FW inlet sparger allows the FW to mix with steam in the reactor pressure vessel (RPV) and heat up prior to reaching the core inlet. The second action has the effect of reducing the core inlet subcooling, which will have a stabilizing effect.

The scenario of interest is therefore a postulated ATWS event, initiated from the MELLLA+ upper boundary at low-flow. The event is terminated through a combination of RPV water level reduction and SLCS injection. The initiating event and plant condition, however, require additional consideration. The postulated event is a turbine trip with the turbine bypass available. The turbine trip initiator will isolate the steam flow to the FWH, thus introducing a destabilizing effect in terms of core inlet subcooling. The availability of turbine bypass prevents pressurization of the RPV during the ATWS. With the RPV near nominal pressure, the neutronic/thermal-hydraulic coupling is enhanced relative to higher pressures. These conditions are expected to produce the worst combination of plant parameters in terms of core stability.

Therefore, the specific event of interest is a turbine trip with bypass available ATWS scenario in which manual operator actions are considered to reduce reactor water level and inject soluble boron through the SLCS. For the balance of this report, the term ATWSI will specifically refer to this scenario.

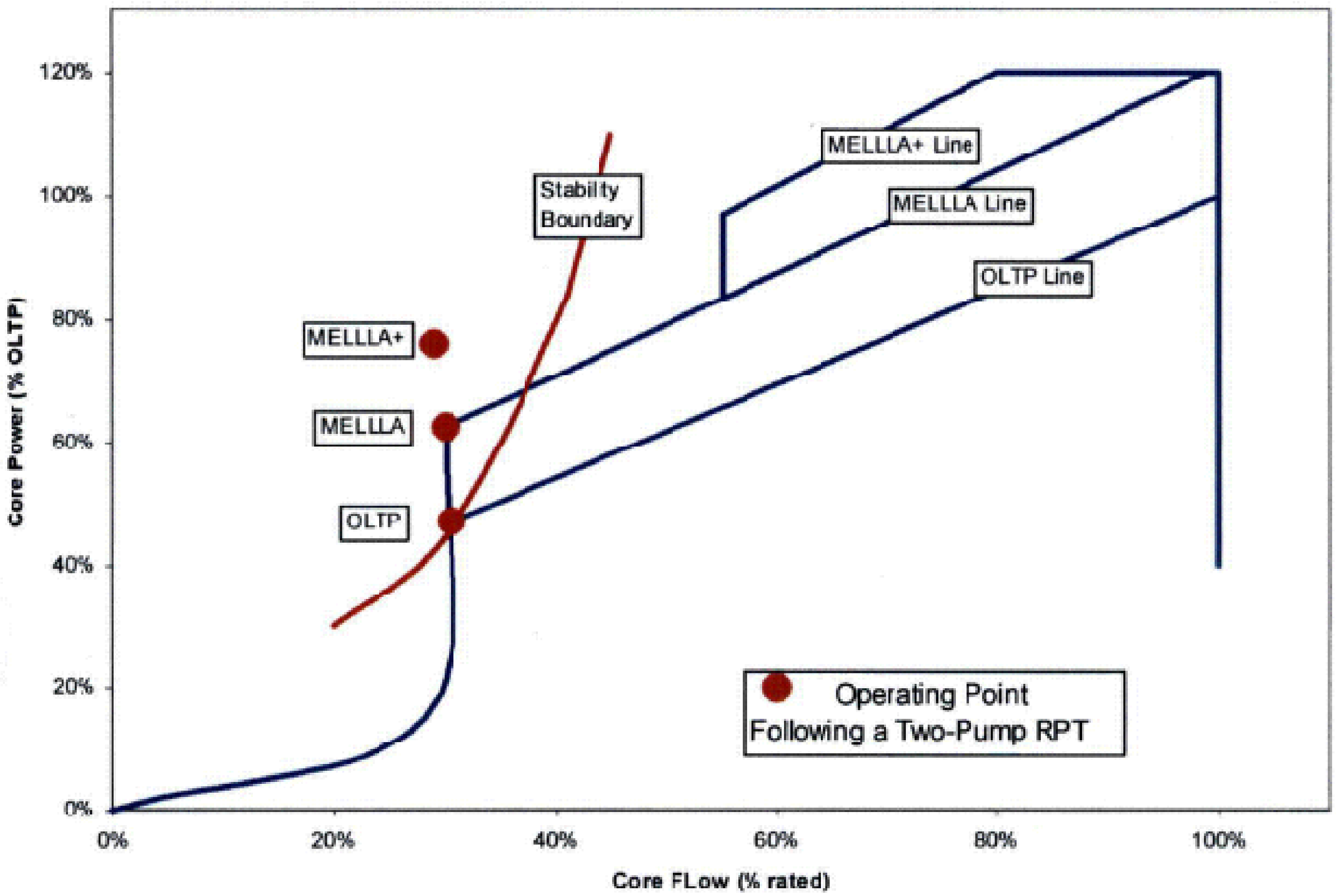

Figure 4: Influence of MELLLA+ Operation on Reactor Stability[4]

[4] Ref. 1

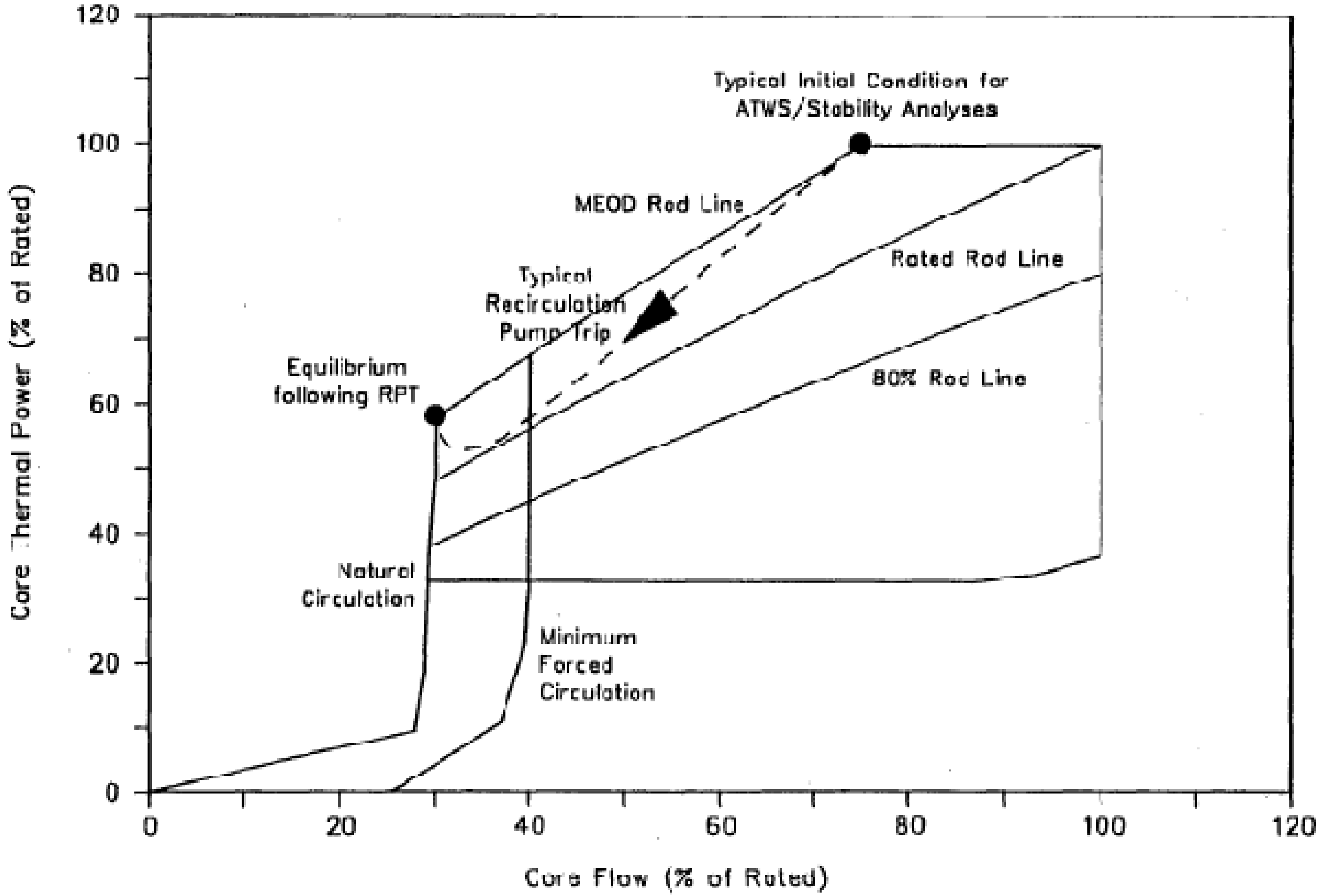

Figure 5: Plant Response to Dual Recirculation Pump Trip from MELLLA Operating Domain[5]

[5] Ref. 2

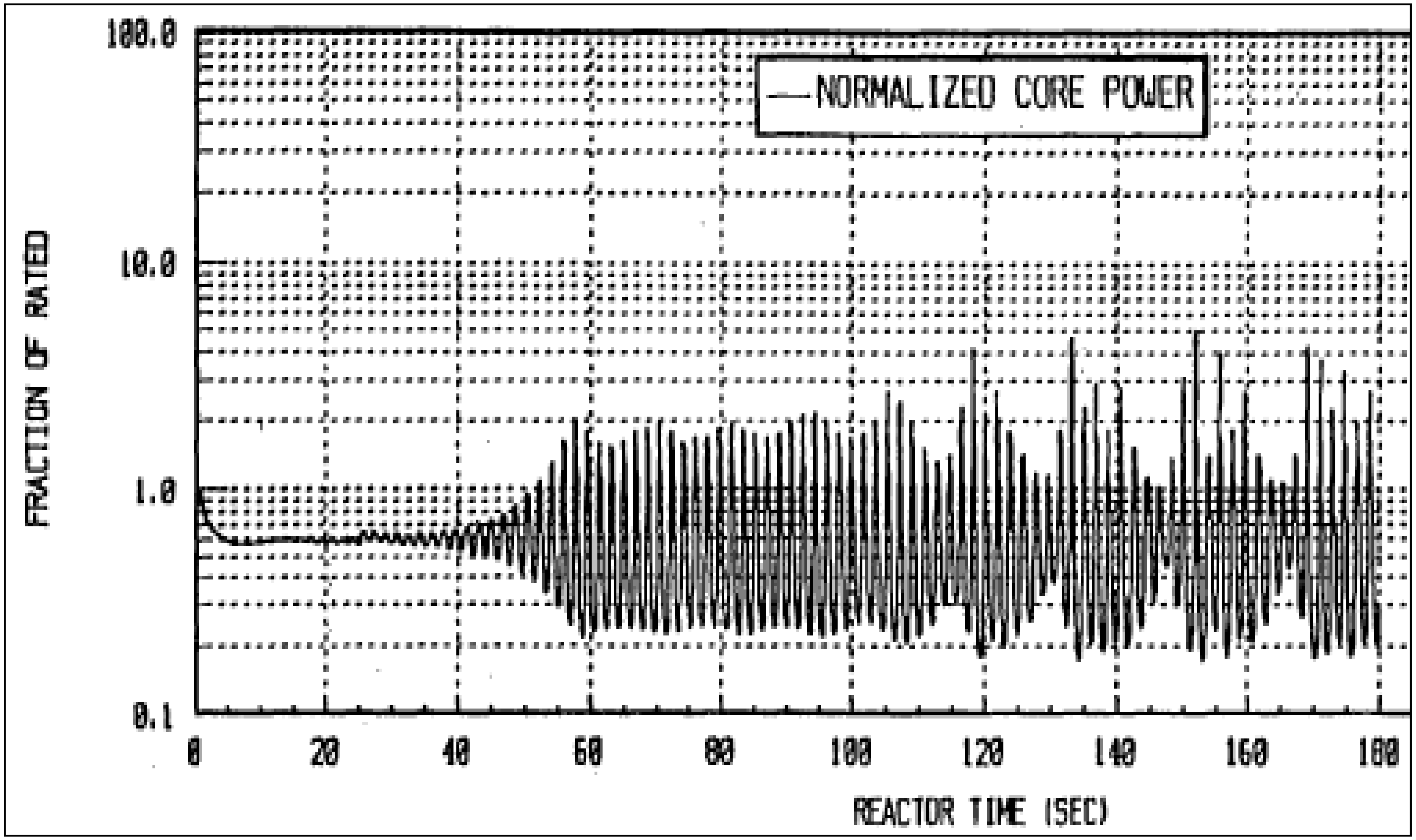

Figure 6: Transient Core Power During ATWSI[6]

[6] Ref. 2

3.2 ATWS with Emergency Depressurization

Following a 2RPT from MELLLA+ low-flow operating conditions, the reactor stabilizes at a relatively high power under natural circulation conditions (see Figure 3). If a vessel isolation event is the postulated initiator for the ATWS scenario, the containment must absorb a higher steam load during the event relative to a similar scenario initiated from full flow conditions. In a main steam isolation valve closure (MSIVC) ATWS scenario, the 2RPT will reduce the reactor power somewhat, however, following the reduction in FWT, the reactor power remains quite high. The steam produced in the core will be relieved through safety relief valves (SRVs) and absorbed in the wet-well of the containment. Reactor operators will attempt to further reduce the gross reactor power by lowering the RPV water level to reduce the natural circulation flow rate.

The containment wet-well (or suppression pool) is designed to condense the steam and thereby prevent an increase in containment pressure. Under MSIVC ATWS conditions initiated from the MELLLA+ low-flow point, however, the high thermal power may exhaust the pressure suppression capacity of the wet-well.

The heat capacity temperature limit (HCTL) refers to the temperature of the suppression pool, above which, it cannot fully condense all of the steam in the RPV. The rate at which the wet-well reaches the HCTL is directly related to the thermal power level of the reactor following the 2RPT and level reduction. Therefore, under MELLLA+ conditions, it is expected for MSIVC ATWS that the reactor will rapidly approach the HCTL. If the HCTL is challenged during the event, the EPGs direct the reactor operators to initiate an emergency depressurization.

Emergency depressurization refers to manual actuation of the automatic depressurization system (ADS). The ADS is an emergency core cooling system that is designed to reduce RPV pressure in the event of a loss-of-coolant-accident so as to allow the injection of coolant to the RPV using low pressure injection systems. The ADS opens several SRVs to relieve RPV steam to the wet-well. The intent of this step in the EPGs is to ensure that RPV pressure is relieved before the suppression capacity of the wet-well is exceeded.

An isolation ATWS event requiring activation of the ADS is referred to as ATWS with emergency depressurization (ATWSED). The ATWSED is postulated to occur while the plant is operating at the low-flow state point along the MELLLA+ upper boundary following a closure of the MSIVs. The MSIV closure isolates the RPV and steam generated in the core pressurizes the RPV until this pressure exceeds the lift pressure for the SRVs. The reactor steam is exhausted to the containment wet-well where the liquid quenches the steam. As the wet-well pool temperature increases, the wet-well eventually reaches the HCTL prompting manual actuation of the ADS.

In response to the MSIVC itself, the reactor power may increase dramatically resulting in the failure of some fuel rods since RPS has failed to mitigate the event with blade insertion. Further, the ATWSED event is postulated to require the manual actuation of the ADS, which results in a bypass of the reactor coolant system (RCS). Therefore, it is postulated that two of the three primary fission product barriers have been compromised. Additionally, since the emergency operating procedures require ADS manual action once the wet-well HCTL has been reached, the suppression pool will always reach its maximum temperature limit in those conditions. Should any additional, unexpected heat load be provided to the containment, the containment pressure is subject to rapid increase because the suppression pool cannot condense any additional steam.

The primary safety concern associated with ATWSED is the incidence of recriticality and a return to power. If the reactor is postulated to become recritical and power increases, it is likely that such a power increase would result in a pressure-power excursion. This excursion is driven by the positive neutronic feedback. As power and pressure increase the steam produced is exhausted to the containment and the containment may reach pressure limits as the suppression capacity has already been exhausted. This is of particular concern since two of the three primary fission product barriers are presumed to have been compromised.

Recriticality may occur due to two identified mechanisms. The first mechanism is characterized by a pressure increase following the occurrence of choking in the ADS SRVs. As pressure decreases in the RPV, the density difference between vapor and liquid increases, and the heat of vaporization decreases. An increased volumetric rate of steam (at a given power level) may temporarily exceed the capacity of the SRVs to discharge this steam to the containment. Choking may occur and the RPV pressure will increase as vapor generation rate exceeds the vapor exhaust rate. The pressure increase may initiate a pressure-power excursion if sufficient reactivity is added to overcome any negative reactivity worth of injected boron. Power oscillations may ensue as the higher pressure may allow a higher mass flow rate to pass through the SRVs. However, any heat generated during this stage of the transient would be presumed to increase the containment pressure because choking is more likely to occur at lower RPV pressure, when the suppression pool temperature is already high.

The NRC performed a transient calculation using TRACE for a postulated pressure regulator failure open (PRFO) ATWS event for a large BWR/4 reactor. The PRFO event is similar to MSIVC in that it will eventually result in RPV isolation. Figure 7 and Figure 8 depict the reactor pressure and reactor power response, respectively (Ref. 1). It was found that following emergency depressurization at 600 seconds, that a recriticality event could occur and an ensuing power-pressure excursion was observed in the results. Eventually the injection of boron is sufficient to shutdown the reactor.

The second mechanism is characterized by boron dilution. In order to mitigate the ATWS event, operators will inject soluble boron into the RPV through the SLCS. The boron will add negative reactivity to the core, reducing reactor power, and eventually ensuring a cold shutdown condition. However, the SLCS mass flow rate is generally small (less than 100 gpm). If emergency depressurization occurs early in the event, the inventory of boron in the core may be small. Additionally, operators attempt to reduce reactor power by decreasing and maintaining the reactor water level at a fixed set point (e.g. at the top of active fuel). At low level conditions, the reactor flow rate is low and injected boron may settle into the RPV lower head instead of becoming entrained in the core flow and entering the active region of the core. Therefore, early in the event the boron inventory in the core may be quite small.

Following actuation of ADS, the RPV pressure declines and the density of saturated liquid water increases. In order to maintain the RPV level, operators will control the FW system, and thereby, will maintain essentially a constant volume of water in the RPV. However, since the density is increasing the mass of water in the RPV will be increasing as more water is added to maintain level. If the mass injection of fresh water exceeds the injection of boron, the boron concentration in the reactor may actually decrease. The reduction in boron concentration here is referred to as dilution. A postulated occurrence of dilution may add sufficient positive reactivity to bring the reactor to a critical condition. If reactor power increases in response to the dilution and causes significant void generation, then a pressure-power excursion may likewise occur.

Both mechanisms require that the occurrence of manual emergency depressurization be early enough into the event that SLCS has not delivered a substantial quantity of negative reactivity to the active core region. For BWR/5-6 configurations, the SLCS delivers boron through the high pressure core spray (HPCS) sparger directly above the core region. Such an injection system is likely to provide negative reactivity regardless of core flow rate. However, BWR/3-4 configurations inject boron into the lower plenum. At low core flow rates, the boron may not be entrained and may settle in the RPV lower head. For this reason, it is likely that recriticality during ATWSED is more likely for BWR/3-4 configurations (or lower plenum injection configurations).

Therefore, the primary case of interest for ATWSED analysis is a plant configured for lower plenum SLCS injection. However, there are a number of other plant conditions and configurations that must be considered in determining the limiting conditions for the scenario. These include: (1) assumptions for out-of-service (OOS) SRVs, and (2) reactor water level control strategy (RWLCS). As for the former, it is common for plant Technical Specifications (TS) to allow a certain number of SRVOOS , typically two. As for the latter, EPGs may direct the operators to control and maintain reactor water level at various points, e.g. TAF or TAF plus five feet (TAF+5) or TAF minus two feet (TAF-2) (Ref. 1).

For the ATWSED analysis, it is necessary to model the natural circulation phase of the ATWS event as well as the stage where the reactor is depressurized through ADS. The staff considered two possible scenarios: (1) The SRVOOS are the lowest pressure setpoint SRVs, and (2) the SRVOOS are higher pressure setpoint SRVs, but part of ADS. The objective is to identify which of the two cases will yield the most conservative results for the ATWSED analysis.

For the situation where the two SRVOOS are low pressure setpoint SRVs (Case 1), during the natural circulation phase the reactor pressure will hang at the pressure of the lowest operable SRV opening pressure, which will be the second bank opening pressure. The second bank opening pressure is higher than the opening pressure setpoint of the two SRVOOS. A high reactor pressure will suppress void formation. During ATWS events, the reactor remains critical, therefore, the power level will stabilize during the natural circulation phase at the power level required to generate a critical core average void fraction. If the pressure is high, in order to maintain the critical void fraction, the reactor will stabilize at a high thermal power during the natural circulation phase. The high thermal power results in a high thermal load on the suppression pool. When ADS is manually actuated, the depressurization will occur rapidly because the available flow area is large – but this will occur relatively early because the wet well will approach HCTL at a high rate owing to high thermal power.

If it is assumed that the two SRVOOS are ADS valves (Case 2), then during the natural circulation phase the reactor power is low because the reactor pressure is lower. This will yield a lower thermal load to the suppression pool relative to Case 1. The suppression pool will approach the HCTL at a slower rate. It is likely that the vessel inventory of boron will be higher when ADS is manually initiated owing to a slower heat up rate of the suppression pool. It is also likely that the time to depressurize the vessel may be longer because there are fewer ADS valves in-service; however, this is partially compensated by the fact that the reactor is already at a lower pressure than in Case 1.

Therefore, the staff concluded that the conservative analysis assumption is for the two low pressure setpoint SRVs to be assumed OOS.

For RWLCS, there are several considerations. It is difficult to identify a clearly limiting or, for that matter, a clearly appropriate RWLCS. There is a strong competing effect in the influence of RWLCS on the potential for recriticality. For a lower plenum injection plant, a high level RWLCS, e.g. TAF+5, promotes a higher core flow rate under natural circulation conditions. The higher flow rate will aid in the entrainment of injected borated solution and provide more boron to the active region of the core. Therefore a higher level RWLCS appears to be advantageous; however, at a higher natural circulation core flow rate, the reactor power is higher. The higher reactor power will deliver a higher thermal load to the containment and accelerate the need for emergency depressurization. Since the likelihood of recriticality is greater the earlier the emergency depressurization, a higher level RWLCS appears disadvantageous. These competing phenomena have prompted to staff to analyze a variety of RWLCSs that include TAF-2, TAF, and TAF+5.

In summary, the ATWSED event for consideration is a postulated MSIVC event with a failure of the RPS to SCRAM the reactor. The operators are presumed to control the reactor water level to: TAF-2, TAF, or TAF+5. During the event, the wet-well reaches the HCTL prompting the operators to undergo emergency depressurization with the ADS. All ADS valves are presumed in service, but two low pressure SRVs are presumed OOS.

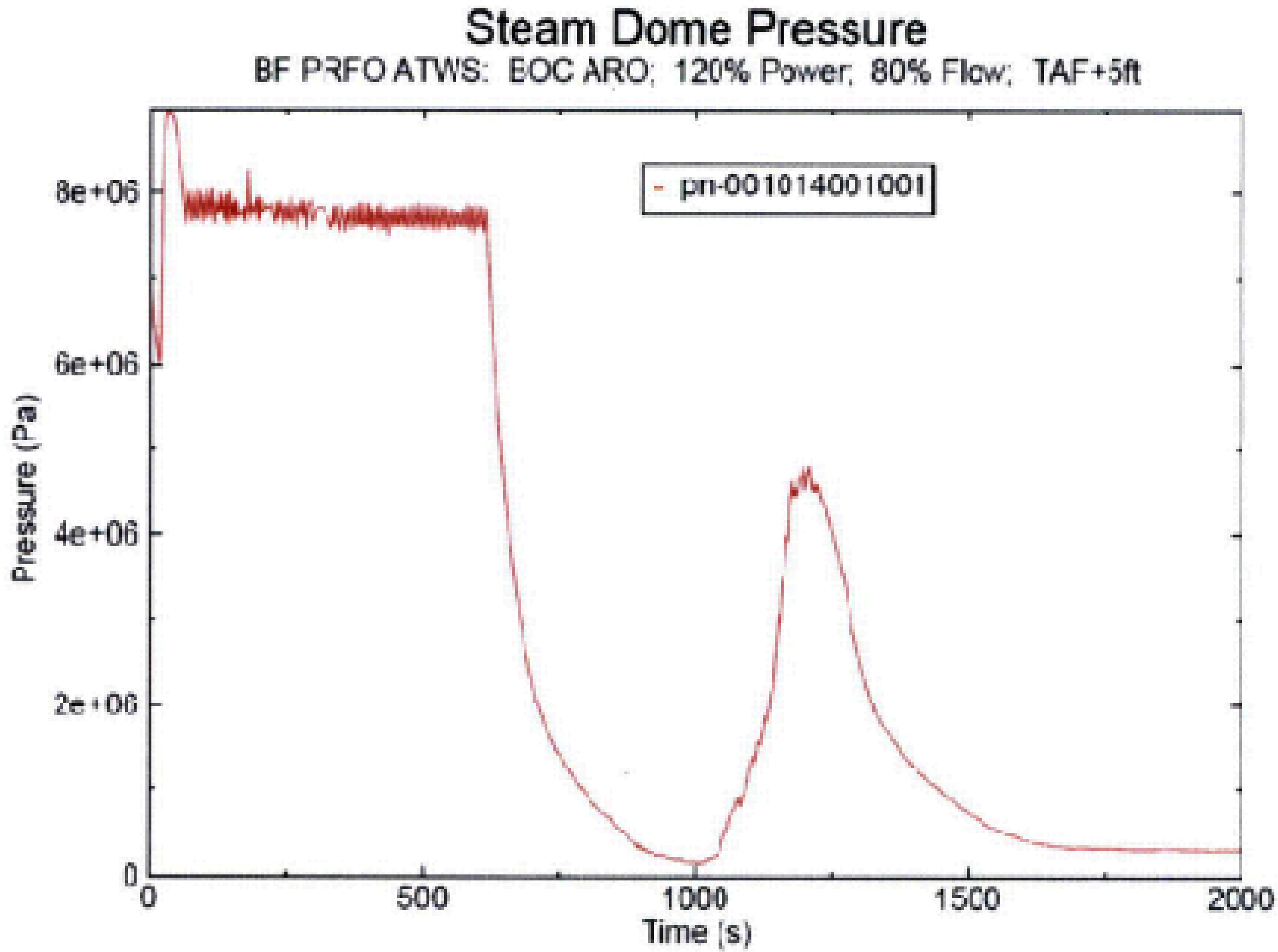

Figure 7: Dome Pressure During PRFO ATWS TAF+5 RWLCS from MELLLA+ Conditions[7]

[7] Ref. 1

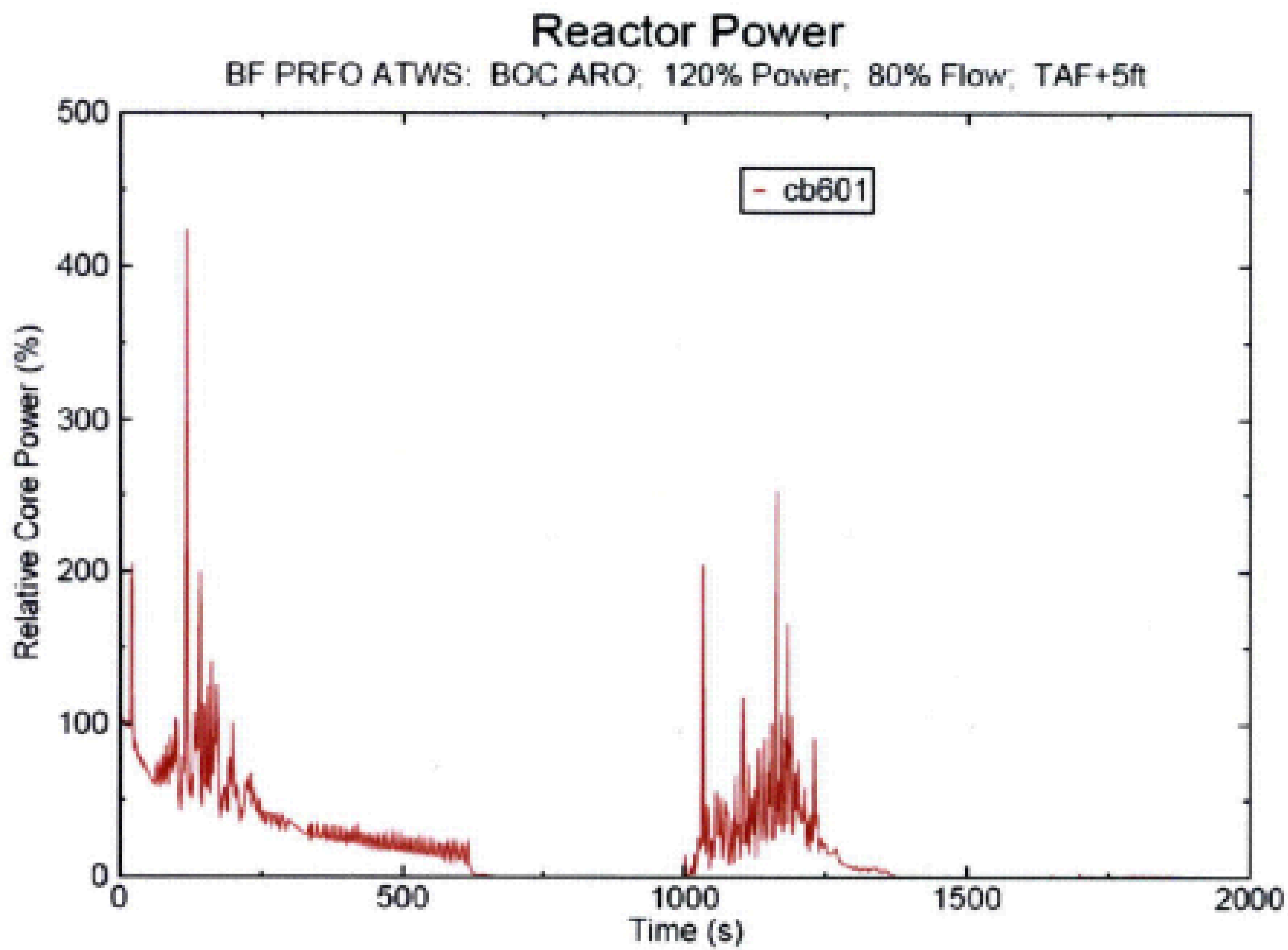

Figure 8: Reactor Power During PRFO ATWS TAF+5 RWLCS from MELLLA+ Conditions[8]

[8] Ref. 1

4 Figures of Merit

Two postulated events are under consideration for this applicability report: ATWSI and ATWSED. Figures of merit for ATWS events in general are dictated by the Standard Review Plan Section 15.8 (Ref. 15). These criteria include:

1. 10 CFR [Title 10 of the Code of Federal Regulations] 50.62 (the ATWS rule), as it relates to the acceptable reduction of risk from ATWS events via (a) inclusion of prescribed design features and (b) demonstration of their adequacy

2. 10 CFR 50.46, as it relates to maximum allowable peak cladding temperatures, maximum cladding oxidation, and coolable geometry

3. General Design Criterion (GDC) 12, found in Appendix A to 10 CFR Part 50, as it relates to ensuring that oscillations are either not possible or can be reliably and readily detected and suppressed

4. GDC 14, as it relates to ensuring an extremely low probability of failure of the coolant pressure boundary

5. GDC 16, as it relates to ensuring that containment design conditions important to safety are not exceeded as a result of postulated accidents

6. GDC 35, as it relates to ensuring that fuel and clad damage, should it occur, must not interfere with continued effective core cooling, and that clad metal-water reactor must be limited to negligible amounts

7. GDC 38, as it relates to ensuring that the containment pressure and temperature are maintained at acceptably low levels following any accident that deposits reactor coolant in the containment

8. GDC 50, as it relates to ensuring that the containment does not exceed the design leakage rate when subjected to the calculated pressure and temperature conditions resulting from any accident that deposits reactor coolant in the containment

Since two specific ATWS events are the subject of the current work, those figures of merit specific to each event are discussed in the following sections.

4.1 ATWS with Core Instability

In analyzing an ATWSI event, the objective is to determine the effectiveness of the manual operator actions to suppress the unstable power oscillations. These actions include the reduction in reactor water level and the injection of soluble boron through SLCS. In the analysis, the reactor power oscillations will be observed and the effectiveness of the mitigating actions will be determined by the prediction of oscillation suppression. Therefore, the key figure of merit is the decay ratio. This is to be differentiated from the limit-cycle oscillation magnitude or growth ratio. Previous analyses have demonstrated the onset of irregular power oscillations that are classified as “non-linear” owing to large changes in core reactivity. While these types of oscillations are expected to be predicted, the exact magnitude of these oscillations is not a fundamental figure of merit in assessing the effectiveness of the operator actions. Rather, the reactor is expected to become stable, presuming that the actions are effective, and the power oscillations magnitude should show a decline over time. The effectiveness of the operator actions can then be demonstrated by observing a decay ratio less than one in the transient power response.

4.2 ATWS with Emergency Depressurization

For ATWSED, the objective of the analysis is to determine the likelihood of recriticality during the event. On one hand, the occurrence of recriticality can be observed directly from the transient response should a power excursion be predicted. On the other hand, if a recriticality is not observed, it is difficult to arrive at a figure of merit related to the “margin” to recriticality. One such figure could be the negative reactivity present in the core. This direct measure of core subcriticality must be considered. However, it is advantageous to consider other figures of merit that may be related to the phenomena of recriticality in the form of precursors. Identification of precursors to recriticality allows the analysis to gauge a more fundamental margin to the onset of an event that might result in recriticality. A useful gauge for this purpose is choking or the margin to choking in the ADS valves to account for the first identified recriticality mechanism, i.e. pressurization following ADS valve choking. A second useful gauge is the minimum boron concentration during the depressurization stage. To fully analyze the ATWSED event and to make an assessment as to the potential for recriticality, it is suggested that the analysis figures of merit include: core reactivity, ADS choking, and boron concentration.

5 Phenomena Identification and Ranking

Phenomena Identification and Ranking Tables (PIRTs) are part of the CSAU and EMDAP processes and are used to identify and rank the important phenomena affecting the progression of any event. Not all phenomena affect transient progression in the same way. The PIRT process is used in the applicability determination as a means for selecting those phenomena of the highest importance. It is important for any transient analysis method to acceptably capture all of the highly important phenomena.

Much work has previously been done developing PIRTs for BWR transients. The staff has elected to use this previous work as a starting point for the current applicability report and not to reproduce previous efforts. Two PIRTs were used as references, combined herein, and updated accordingly for the specific events under consideration. Reference 3 is a PIRT that was developed to address ATWSI events for high burnup fuel and Reference 4 is a generic BWR PIRT that includes transients, such as ATWS.

The first step in generating the PIRT for MELLLA+ ATWS is to collect the high ranked phenomena identified in References 3 and 4. Second, the ranking, where necessary, was updated to reflect the specific scenarios considered (i.e. ATWSI and ATWSED). Third, in many cases similar phenomena were identified with different nomenclature, and a consistent index was established to relate the phenomena according to a consistent nomenclature. The collection of the highly important phenomena is used to establish an appropriate assessment matrix.

After collecting these rankings, and adjusting as necessary, several highly important phenomena were identified. Table 3 provides a summary of these phenomena. This table also provides the common index for cross-reference between the Reference 3 and 4 PIRTs. A complete discussion of the specific phenomena as well as the basis for their importance rankings is provided in the associated references. The rationale for the selection of the phenomena in Table 3 was determined as follows.

Reference 4 is a generic PIRT and addresses a number of different scenarios. Neither ATWSI nor ATWSED were explicitly considered as a class of transient in the generic PIRT. However, by selecting similar transients it is possible to ensure that all of the relevant phenomena are included in the MELLLA+ ATWS PIRT. Those scenarios most applicable to ATWSI and ATWSED include: depressurization transients, instability transients, and ATWS transients. These specific scenarios were selected and have been identified in Table 1 as “D,” “I,” and “ATWS,” respectively.

The approach taken in the current applicability determination is to identify the highly ranked phenomena for the three classes of events (D, I, and ATWS) and to consider the net ranking for any phenomenon as the highest ranking for any of these classes. This approach, therefore, simultaneously considers ATWSED and ATWSI. Therefore, the net ranking shown in Table 1 should not be construed as to mean that all of the highly ranked phenomena are highly important to both ATWSED and ATWSI. The benefit of this global approach to the PIRT is that the highly ranked phenomena would have to be combined in the subsequent step of the applicability determination, which combines all of the highly ranked phenomena to establish the assessment matrix.

This work uses a standard importance ranking metric of: high (H), medium (M), or low (L). In terms of ranking, the previously established phenomena rankings have been preserved unless specific considerations have prompted a revision for the current work. In these cases, the specific phenomenon and rationale is discussed herein. Table 1 list the phenomena from Reference 4 along with the ranking associated with each transient category. The net ranking is the highest ranking for any of the transient types considered. Only the phenomena with a high net ranking have been listed. In this work, four phenomena warranted special consideration and different rankings were assigned. These phenomena include: (1) flow: natural circulation, (2) reactivity: SCRAM, (3) Stability: neutronic/thermal-hydraulic, and (4) 3-D T/H effect (lower plenum).

For flow: natural circulation (index: CNC), the power level during ATWS is a strong function of the flow rate under natural circulation conditions. Therefore, this phenomenon was assigned a high ranking. For the case of reactivity: SCRAM, a low ranking was assigned as the events under consideration are ATWS events and the RPS is presumed to fail. Since SCRAM does not occur, the phenomenon was reassigned a ranking of low. For stability: neutronic/thermal-hydraulic (index: CSNTH) the ranking was assigned as high given the importance of this phenomenon to ATWSI events. For 3-D T/H effect (index: LP3D), the phenomenon was assigned a ranking of high as the thermal hydraulic conditions in the lower plenum tend to dictate the transport of boron in the reactor pressure vessel. Assumptions regarding these conditions and the analysis of these conditions have a strong bearing on the impact of boron injection to mitigate a postulated ATWS event. This is particularly relevant to the ATWSED scenario where lower plenum SLCS injection was deemed to be the limiting scenario.

The identified phenomena and rankings from Reference 4 were combined with the results of an ATWSI PIRT detailed in Reference 3. As stated before, the nomenclature is somewhat different, but similar phenomena have been given a consistent index as shown in Table 3. Table 2 summarizes the PIRT from Reference 3 as well as some minor modifications made to address the specific event scenarios under consideration. One distinction between References 3 and 4 is the importance ranking metric. Reference 3 quantifies the phenomenon's importance in terms of an importance rank (IR) which ranges from 0 to 100. For the current purpose, an IR between 68 and 100 is deemed "H," an IR between 33 and 67 (inclusive) is deemed "M," and an IR of 32 or less is deemed "L."

In this case, two exceptions were noted. First, counter current flow limitation (index: CCFL) in the core region had been ranked as medium. For BWR/5-6 configurations, SLCS injection is into the separator dome above the reactor core. The penetration of the borated solution into the active core region may be retarded by CCFL considerations at the upper tie plate (UTP) or top of the rodded zone in the fuel assemblies. Therefore, as this phenomenon may restrict the transport of boron into the active core region, the ranking was revised to high. Second, mixing and thermal stratification (index: LP3D) was assigned a higher rank (i.e. H) given that the thermal-hydraulic condition in the lower plenum have a strong influence on the transport of boron for lower plenum injection configurations (i.e. BWR/3-4).

The reference PIRTs consider only the phenomena relevant to the reactor systems. However, in ATWS analysis (and in particular ATWSED) the plant response depends on the interaction between the reactor system and the containment. The specific interaction is the absorption and suppression of reactor steam in the containment wet-well when the reactor coolant system is isolated, as would be the case for an MSIVC event. In this instance, the plant response will be sensitive to the heat up of the containment wet-well. The only important phenomena here are suppression (i.e. the collapse of reactor steam to liquid due to quenching in the liquid in the containment) and heat up (i.e. the associated bulk temperature increase as a result of suppression). These phenomena are well understood and directly related to the integrated mass and energy released from the reactor system combined with fluid properties. Therefore, the relevant phenomena are captured by consideration of flow into the main steam line and from the main steam line through the safety relief or automatic depressurization system valves. Given the simplistic nature of the coupling between the reactor system and containment required by ATWS calculations in this current work, no specific consideration was given to the ranking and assessment of containment phenomena.

Table 1: PIRT from Reference 4 as Modified for MELLLA+ ATWS

Category	D[9]	I[10]	ATWS[11]	Notes	Net[12]	INDEX
Component/Phenomenon						
Core/						
Boiling: film	L	H	H*	Film boiling is likely to occur during ATWS events and will affect the prediction of peak cladding temperature	H	CBF
Boiling: subcooled	M	H	M		H	CBS
Control rod pattern/movement	L	H	L		H	CRP
Dryout	L	H	H*	Dryout is likely to occur during ATWS events and will affect the prediction of peak cladding temperature	H	CD
Feedback: fuel temperature	M	H	H		H	CDOP
Feedback: void	H	H	H		H	CVRC
Flow: coastdown	L	H	H		H	CFLC
Flow: natural circulation	L	H	L*	For long term ATWS, the core power level is a function of the flow rate achievable under natural circulation conditions. While ranked high for instability reasons, the ATWS ranking should also be considered high for the current events under consideration	H	CNC
Flow: multi-channel T/H effect	H	H	H		H	CCHAN
Fuel: burnup	L	H	M		H	CBURN
Fuel: design/type	L	H	M		H	CFUEL
Heat conductance: fuel-clad gap	M	H	H		H	CHGAP

[9] D stands for depressurization events
[10] I stands for instability events
[11] ATWS stands for anticipated transients without SCRAM
[12] The net ranking for any phenomenon is the highest ranking for the D, I, or ATWS events

Category	D[9]	I[10]	ATWS[11]	Notes	Net[12]	INDEX
Interphase shear	H	H	H		H	CIS
Power distribution: axial	L	H	L		H	CAPS
Power distribution: radial	L	H	L		H	CRPS
Pressure drop	H	H	H		H	CDP
Reactivity: SCRAM	L	H*	H*	SCRAM reactivity was ranked high for ATWS. However, SCRAM is postulated not to occur. Therefore, this ranking should likely be reduced to L for ATWS. It was ranked high for instability, however, since only ATWS events are under consideration, the total ranking was reduced to L	L	
Stability: neutronic/thermal-hydraulic	L	H	L*	Stability effects were ranked low in the original PIRT for ATWS because pressurization events were considered to be limiting. In the subject work, the combination of ATWS with core instability is important when events are initiated from MELLLA+ minimum flow conditions. Therefore, the ATWS ranking was increased to H to match the instability ranking	H	CSNTH
Subcooling: coolant	M	H	M		H	CCSC
Void: collapse	L	M	H		H	CVCOL
Void: distribution	H	H	H		H	CVD
Void: subcooled liquid	H	H	H		H	CSCL
3-D kinetics effects	M	H	H		H	C3DK
Bypass/						
Pressure drop	H	H	H		H	BDP
Lower plenum/						
Pressure drop	H	H	H		H	LPDP

Category	D[9]	I[10]	ATWS[11]	Notes	Net[12]	INDEX
3-D T/H effect	L	H	L*	The conditions in the lower plenum affect the propensity for boron mixing and remixing for BWR plants with a standby liquid control system configured to inject into the lower plenum. Therefore this phenomenon should be ranked high for ATWS.	H	LP3D
Downcomer/						
Interphase shear	H	H	H		H	DCIS
Void: collapse	N/A	N/A	H		H	DCVCO
Void: distribution	H	H	H		H	DCVD
2-phase level	H	H	H		H	DC2F
Upper plenum/						
Pressure drop	H	H	H		H	UPDP
Separators/						
Carry-under	H	H	H		H	SCU
Pressure drop	H	H	H		H	SDP
Dryers/						
Pressure drop	L	H	L		H	DRDP
Jet pumps/						
Flow: forward	H	H	H		H	JPFF
Pressure drop	H	H	H		H	JPDP
Steam line/						
Pressure wave propagation	H	L	H		H	MSLPW
Flow: critical	H	L	H		H	MSLCF
Pressure drop	M	M	H		H	MSLDP
Recirculation pumps/						
Coastdown	H	H	H		H	RCPC

Table 2: PIRT from Reference 3 as Modified for MELLLA+ ATWS

Subcategory	Component	Phenomenon	IR	RANK	INDEX	Notes
Calculation of power history during event	Core	Moderator feedback	100	H	CVRC	
	Core	Fuel temperature feedback	100	H	CDOP	
	Core	Delayed-neutron fraction	67	M		
	Core	Fuel cycle design	100	H	CFUEL	
Calculation of the pin fuel enthalpy increase during event	Core	Heat resistances in high-burnup fuel, gap, and cladding (including oxide layers)	100	H	CHGAP	
	Core	Heat capacities of fuel and cladding	100	H	CCP	
	Core	Fractional energy deposition in pellet	42	M		
	Core	Pellet radial power distribution	50	M		
	Core	Pin peaking factors	93	H	CRPS	
	Core	Metal water reaction heat addition	57	M		
Calculation of fuel to coolant heat transfer	Core	Single-phase convection	42	M		
	Core	Subcooled boiling	100	H	CBS	
	Core	Nucleate boiling, bulk boiling, and forced convection vaporization	90	H	CNB	
	Core	Dryout	100	H	CD	
	Core	Film boiling over a wide void fraction range	93	H	CBF	
	Core	Rewet	100	H	CREW	
Calculation of core and system hydraulics	Bypass	Flow fraction	44	M		
	Bypass	Void fraction due to direct moderator heating	86	H	BDMH	
	Core	Void distribution including subcooled boiling	89	H	CVD	
	Core	Frictional pressure drop	88	H	CDP	

Subcategory	Component	Phenomenon	IR	RANK	INDEX	Notes
	Core	Form pressure drop	100	H	CDP	
	Core	Acceleration pressure drop	43	M		
	Core	Direct moderator heating	64	M		
	Core	Counter current flow limitation	60	M	CCFL	Ranking considered as H to address boron ingress to the core through CCFL breakdown at the UTP for BWR/5/6 configuration
	Core	Flow blockage	81	H	CFB	
	Downcomer	Void distribution	0	L		
	Downcomer	Condensation heat transfer	79	H	DCHTX	
	Downcomer	Mixing and thermal stratification	42	M	LP3D	Ranking considered as H to address boron stratification and remixing
	Downcomer	Jet pump or internal pump loss	100	H	JPDP	
	Downcomer	Friction and form loss	0	L		

Table 3: High Ranked Phenomena and Index Labels

Index	Component	Phenomenon Description
BDMH	Bypass	Void fraction due to direct moderator heating
BDP	Bypass	Pressure drop
C3DK	Core	3-D kinetics effects
CAPS	Core	Axial power distribution
CBF	Core	Film boiling
CBS	Core	Subcooled boiling
CBURN	Core	Fuel burnup
CCFL	Core	Counter current flow limiting
CCHAN	Core	Multi-channel T/H flow effect
CCP	Core	Heat capacities of fuel and cladding
CCSC	Core	Coolant subcooling
CD	Core	Dryout
CDOP	Core	Fuel temperature reactivity feedback
CDP	Core	Pressure drop
CFB	Core	Flow Blockage
CFLC	Core	Flow coastdown
CFUEL	Core	Fuel design/type
CHGAP	Core	Fuel-clad gap heat conductance
CIS	Core	Interphase shear
CNB	Core	Nucleate boiling, bulk boiling, and forced convection vaporization
CNC	Core	Natural circulation
CREW	Core	Rewet
CRP	Core	Control rod pattern/movement
CRPS	Core	Radial power distribution
CSCL	Core	Void in subcooled liquid

Index	Component	Phenomenon Description
CSNTH	Core	Stability: neutronic/thermal-hydraulic
CVCOL	Core	Void collapse
CVD	Core	Void distribution
CVRC	Core	Void reactivity feedback
DC2F	Downcomer	2-phase level
DCHTX	Downcomer	Condensation heat transfer
DCIS	Downcomer	Interphase shear
DCVCO	Downcomer	Void collapse
DCVD	Downcomer	Void distribution
DRDP	Dryer	Pressure drop
JPDP	Jet pump	Pressure drop
JPFF	Jet pump	Forward flow
LP3D	Lower plenum	3-D T/H effect including stratification
LPDP	Lower plenum	Pressure drop
MSLCF	Steam line	Critical flow
MSLDP	Steam line	Pressure drop
MSLPW	Steam line	Pressure wave propagation
RCPC	Recirculation pumps	Coastdown
SCU	Separator	Carry-under
SDP	Separator	Pressure drop
UPDP	Upper plenum	Pressure drop

6 Capability Review

Table 3 provides a list of the highly important phenomena. To establish the applicability of TRACE/PARCS, it is first necessary to ensure that TRACE/PARCS has, functionally, the capability to simulate all of the highly ranked phenomena. The capability matrix review process associates the highly ranked phenomena with specific code capabilities.

TRACE/PARCS is a code system with thermal-hydraulic and thermo-physical phenomena predicted by TRACE with the kinetics phenomena predicted by PARCS. For each of the highly ranked phenomena, if the phenomenon is thermal-hydraulic or thermo-physical, the staff identified those specific features in TRACE that capture it. Table 4 provides this summary for the highly ranked PIRT and for completeness; the staff generated similar results for the medium phenomena, which are listed in Table 5. These tables list each phenomenon and provide a short description of the approach taken in TRACE to simulate the phenomenon and, lastly, provide a reference to the specific section of the TRACE theory manual (Ref. 7) that describes that specific feature.

In many instances the phenomenon is treated with closure relationships. Closure relationships refer to empirical or semi-empirical models and correlations that are used to predict the associated phenomena. In several instances, a specific closure relationship has been developed to cover only a portion of the entire range of application and to fully address the subject phenomenon a series of closure relationships are required. In Table 4 and Table 5 the notes regarding the details of the capability will list an example of one of the set of correlations or closure relationships used to capture the subject phenomenon.

In instances where the phenomenon is treated inherently by the PARCS nodal diffusion solver or supporting features of PARCS, this has been noted in the tables. The PARCS nodal solver, kinetics capability, and decay heat model are sufficient to model all phenomena related to reactivity feedback, transient power, and power distribution. The PARCS neutronic methods are described in detail in Reference 8. As applicable the table includes references to specific sections of the PARCS theory manual, which is a separate document.

In other instances the phenomenon is treated with explicit user controller inputs. In these cases, no reference is made to a specific section of the TRACE or PARCS theory manuals.

One feature that the staff notes with regard to core coolant subcooling (index: CCSC) is that this phenomenon does depend on boundary conditions applied to the plant model in terms of inlet feedwater temperature. Steady state and transient feedwater temperature conditions are modeled using control systems to emulate the feedwater system based on plant data and its effect on this phenomenon is considered as part of the system boundary condition.

For all of the high and medium ranked PIRT phenomena the capability to model the phenomenon is present in TRACE/PARCS with one exception. The 3-D T/H effect including thermal stratification in the lower plenum was singled out as TRACE/PARCS does not have a complete capability, inherently, in this regard. While TRACE has sufficient thermal-hydraulic simulation capability to model the 3D T/H effects, TRACE does not have a sufficiently robust boron transport capability to simulate the phenomenon of borated solution stratification. This is denoted in Table 4 with “Y*.” Throughout this report, the term “boron transport” will refer collectively to the phenomena of entrainment, diffusion, stratification, mixing, and remixing.

However, to overcome this shortcoming in TRACE, the staff developed a boron transport methodology that makes use of control system and component features in TRACE to capture the effects of injected boron mixing, stratification, and remixing with a modeling approach. This methodology is based on scaled experimental test data collected at both the Vallecitos Nuclear Center (VNC) and University of California Santa Barbara (UCSB). The details of the boron transport methodology are proprietary and documented in Reference 9. Using this methodology, TRACE is capable of capturing the effects of mixing, stratification, and remixing of borated solution in the lower plenum. Therefore, the staff determined that, overall, TRACE/PARCS is fully capable of modeling the important phenomena for MELLLA+ ATWS events.

Table 4: Capability Matrix for High Ranked PIRT Phenomena

Index	Component	Phenomenon	Capability Exists in TRACE/PARCS	Capability Details	TRACE Theory Manual Reference
BDMH	Bypass	Void fraction due to direct moderator heating	Y	Field equations, Interfacial shear, and PARCS power factors	Chapter 1, Field Equations; Chapter 4, Interfacial Drag
BDP	Bypass	Pressure drop	Y	Field equations	Chapter 1, Field Equations
C3DK	Core	3-D kinetics effects	Y	PARCS nodal method	See Chapter 4 of Reference 8
CAPS	Core	Axial power distribution	Y	PARCS nodal method	See Chapter 4 of Reference 8
CBF	Core	Film boiling	Y	Dispersed flow film boiling is modeled as a superposition of radiative and convective components with the heat transfer equivalent of a two-phase multiplier on the convective term	Chapter 6, Post-CHF Heat Transfer
CBS	Core	Subcooled boiling	Y	Closure relation - e.g. Lahey, mechanistic	Chapter 6, Pre-CHF Heat Transfer
CBURN	Core	Fuel burnup	Y	PARCS input and CHAN input (rod group axial burnup)	N/A
CCFL	Core	Counter current flow limiting	Y	Closure relation - e.g. Bankoff	Chapter 7, Countercurrent Flow

Index	Component	Phenomenon	Capability Exists in TRACE/PARCS	Capability Details	TRACE Theory Manual Reference
CCHAN	Core	Multi-channel T/H flow effect	Y	Field equations, 1D/3D component interface	Chapter 1, Field Equations
CCP	Core	Heat capacities of fuel and cladding	Y	Material properties	Chapter 12, Structural Material Properties
CCSC	Core	Coolant subcooling	Y	Field equations	Chapter 1, Field Equations
CD	Core	Dryout	Y	Closure relation - e.g. Biasi	Chapter 6, Critical Heat Flux
CDOP	Core	Fuel temperature reactivity feedback	Y	PARCS nodal method	See Chapter 4 of Reference 8
CDP	Core	Pressure drop	Y	Field equations	Chapter 1, Field Equations
CFB	Core	Flow Blockage	Y	Dynamic Gap Conductance Model with Elastic & Plastic Deformation (Clad Rupture) (NFCI=3)	Chapter 8, Fuel Rod Models
CFLC	Core	Flow coastdown	Y	Field equations	Chapter 1, Field Equations
CFUEL	Core	Fuel design/type	Y	CHAN input	N/A
CHGAP	Core	Fuel-clad gap heat conductance	Y	CHAN input (gas composition), Material properties, and Closure relation - e.g. Modified NFI	Chapter 8, Fuel Rod Models

Index	Component	Phenomenon	Capability Exists in TRACE/PARCS	Capability Details	TRACE Theory Manual Reference
CIS	Core	Interphase shear	Y	Field equations	Chapter 4, Interfacial Drag
CNB	Core	Nucleate boiling, bulk boiling, and forced convection vaporization	Y	Closure relation - e.g. Basu et al.	Chapter 6, Pre-CHF Heat Transfer
CNC	Core	Natural circulation	Y	Field equations	Chapter 1, Field Equations
CREW	Core	Rewet	Y	Closure relation - e.g. Groeneveld-Stewart	Chapter 6, Minimum Stable Film Boiling
CRP	Core	Control rod pattern/movement	Y	PARCS input	N/A
CRPS	Core	Radial power distribution	Y	PARCS nodal method	See Chapter 4 of Reference 8
CSCL	Core	Void in subcooled liquid	Y	Field equations	Chapter 4, Interfacial Drag
CSNTH	Core	Stability: neutronic/thermal-hydraulic	Y	Field equations, closure relations, semi-implicit numerics, and PARCS nodal method	Chapter 1, Field Equations
CVCOL	Core	Void collapse	Y	Field equations	Chapter 1, Field Equations; Chapter 4, Interfacial Drag
CVD	Core	Void distribution	Y	Field equations	Chapter 1, Field Equations; Chapter 4, Interfacial Drag

Index	Component	Phenomenon	Capability Exists in TRACE/PARCS	Capability Details	TRACE Theory Manual Reference
CVRC	Core	Void reactivity feedback	Y	PARCS nodal method	See Chapter 4 of Reference 8
DC2F	Downcomer	2-phase level	Y	Level tracking	Chapter 7, Level Tracking
DCHTX	Downcomer	Condensation heat transfer	Y	Closure relation - e.g. Kuhn, Schrock and Peterson	Chapter 6, Condensation Heat Transfer
DCIS	Downcomer	Interphase shear	Y	Field equations	Chapter 1, Field Equations; Chapter 4, Interfacial Drag
DCVCO	Downcomer	Void collapse	Y	Field equations	Chapter 1, Field Equations; Chapter 4, Interfacial Drag
DCVD	Downcomer	Void distribution	Y	Field equations	Chapter 1, Field Equations; Chapter 4, Interfacial Drag
DRDP	Dryer	Pressure drop	Y	Field equations	Chapter 1, Field Equations
JPDP	Jet pump	Pressure drop	Y	Field equations	Chapter 1, Field Equations
JPFF	Jet pump	Forward flow	Y	Closure Relation, e.g. Idel'Chik	Chapter 10, Jet Pump (JETP)
LP3D	Lower plenum	3-D T/H effect including stratification	Y*	Field equations with the boron transport modeling approach	Chapter 1, Field Equations
LPDP	Lower plenum	Pressure drop	Y	Field equations	Chapter 1, Field Equations

Index	Component	Phenomenon	Capability Exists in TRACE/PARCS	Capability Details	TRACE Theory Manual Reference
MSLCF	Steam line	Critical flow	Y	Closure Relation - e.g. Burnell	Chapter 7, Critical Flow
MSLDP	Steam line	Pressure drop	Y	Field equations	Chapter 1, Field Equations
MSLPW	Steam line	Pressure wave propagation	Y	Field equations	Chapter 1, Field Equations
RCPC	Recirculation pumps	Coastdown	Y	PUMP input - pump curves and inertia	Chapter 10, Pump (PUMP)
SCU	Separator	Carry-under	Y	SEPD input	Chapter 10, Separator (SEPD)
SDP	Separator	Pressure drop	Y	Field equations	Chapter 1, Field Equations
UPDP	Upper plenum	Pressure drop	Y	Field equations	Chapter 1, Field Equations

Table 5: Capability Matrix for Medium Ranked PIRT Phenomena

Component	Phenomenon	Capability Exists in TRACE/PARCS	Capability Details	TRACE Theory Manual Reference
Bypass	Flow fraction	Y	User Input - Leakage loss coefficients	N/A
Core	Acceleration pressure drop	Y	Field Equations	Chapter 1, Field Equations
Core	Direct moderator heating	Y	User Input - PARCS power factors	N/A
Core	Metal water reaction heat addition	Y	Closure Relation - e.g. Cathcart	Chapter 8, Metal-Water Reaction
Core	Single-phase convection	Y	Closure Relation - e.g. Dittus-Boelter	Chapter 6, Pre-CHF Heat Transfer
Core	Fractional energy deposition in pellet	Y	User Input - PARCS power factors	N/A
Core	Pellet radial power distribution	Y	User Input - CHAN component	N/A
Core	Delayed-neutron fraction	Y	6-group model	See Chapter 2 of Reference 8

7 Assessment Matrix and Review

According to the CSAU and EMDAP processes, the applicability determination cannot be made without comparison of the method to appropriate separate effects and integral effects test (SET/IET) data. The PIRT is used to guide the assessment matrix determination process. It is essential in the applicability determination to ensure that the capabilities of the code with regard to all highly ranked PIRT phenomena are assessed against SET/IET data over the full range of application.

TRACE/PARCS has been extensively assessed and the staff has relied heavily on this previous assessment base as well as relying on a number of new assessments to populate an assessment matrix. The assessment matrix is designed to identify those test data that either fully or partially capture the highly ranked phenomena. By developing and populating the assessment matrix, one can determine those particular phenomena for which, potentially, additional assessment test data must be gathered.

The TRACE assessment was expanded for MELLLA+ ATWS to include comparison to test data from FIST, BFBT, FRIGG, Christensen, Peach Bottom, and Ringhals. The new IET/SET assessments are documented in Reference 11 and the plant data assessments are documented in Reference 10. The Reference 11 assessments were performed using TRACE V5.333, which corresponds to TRACE V5 Patch 2. The Reference 10 assessments were performed using TRACE V5.405, which is based on V5 Patch 2 with a small number of enhancements and modifications to correct identified programming deficiencies These new cases compliment the extensive assessment documented in the TRACE V5.0 assessment manual (Ref. 6). These assessment reports document the tests, the results of the TRACE calculations, and a determination of the adequacy of the assessment. The reader is directed to these references for additional details regarding specific assessments.

Table 6 summarizes the assessment matrix. The matrix shows all of the high ranked PIRT phenomena and the corresponding assessment cases that capture each phenomenon. The matrix classifies each assessment as: (1) fully (F) capturing the phenomenon, (2) partially (P) capturing the phenomenon, and (3) fully capturing the phenomenon when considered in a collection of SET/IET tests (C).

Some of the phenomena are only partially assessed. These instances are highlighted in Table 6. Each of these phenomena are discussed in Section 7.1. In certain cases the partial assessment has to deal with the fluid dynamics of thermo-physical phenomena that are indirectly assessed. For example, the fuel thermal conductivity model in TRACE is derived from FRAPCON, which is independently assessed. Additionally, the LP3D phenomenon is considered as only partially assessed owing to a lack of boron transport data in the TRACE assessment base.

Given the assessment matrix, the staff reviewed the quality of the assessment to determine the degree of agreement between the test data and the TRACE calculations. The agreement was ranked as being: (1) excellent (E), (2) reasonable (R), (3) minimal (M), or (4) insufficient (I). These terms were established as part of the EMDAP with specific definitions to facilitate a consistent and meaningful ranking of the assessment case agreement. In order for TRACE to be found adequate the ranking of the assessment cases in the matrix must be either reasonable or excellent. The definition for each agreement ranking is as follows:

- “Excellent Agreement” (E) applies when the code exhibits no deficiencies in modeling a given behavior. Major and minor phenomena and trends are correctly predicted. The calculated results are judged to agree closely with data.
- “Reasonable Agreement” (R) applies when the code exhibits minor deficiencies. Overall, the code provides an acceptable prediction. All major trends and phenomena are predicted correctly. Differences between calculated values and data are greater than are deemed necessary for excellent agreement.
- “Minimal Agreement” (M) applies when the code exhibits significant deficiencies. Overall, the code provides a prediction that is not acceptable. Some major trends or phenomena are not predicted correctly, and some calculated values lie considerably outside the specified or inferred uncertainty bands of the data.
- “Insufficient Agreement” (I) applies when the code exhibits major deficiencies. The code provides an unacceptable prediction of the test data because major trends are not predicted correctly. Most calculated values lie outside the specified or inferred uncertainty bands of the data.

Table 7 summarizes the review of the assessment matrix. For each phenomenon, the associated assessment cases have been ranked using the above rankings of E, R, M, or I. Since the assessments have been documented in various reference reports, the reference is also provided with the associated ranking in the table. Of particular interest are those phenomena that are not either E or R. In the predominance of instances, the TRACE assessment indicates either excellent or reasonable agreement between TRACE and assessment case data for the highly ranked phenomena. There are certain exceptions. These exceptions are discussed in Section 7.2.

7.1 Partially Assessed Phenomena

The assessment matrix shown in Table 6 denotes several phenomena that are only partially assessed. These phenomena include: Bypass: Void Fraction due to direct moderator heating (index: BDMH); Core: Heat capacities of fuel and cladding (index: CCP); Core: Flow Blockage (index: CFB), Core: Fuel-clad Gap heat conductance (index: CHGAP); Lower plenum: 3D T/H effect including stratification (index: LP3D); and Recirculation pumps: coastdown (index: RCPC). For BDMH, the assessment is only considered partial because the assessment cases do not include integral assessments that would capture the effects of neutron heating. For CCP and CHGAP, the TRACE assessment does not address these phenomena since they are assessed indirectly. The effect of stratification in the lower plenum is a phenomenon that covers the dynamics of borated solution transport, and is therefore, considered to be only partially assessed since the existing TRACE assessment does not consider boron transport. Finally, recirculation pump coastdown is reported to be only partially assessed by the integral FIST and TLTA tests (Ref. 6).

7.1.1 Bypass: Void Fraction due to Direct Moderator Heating

Bypass void fraction due to direct moderator heating refers to the phenomenon, specifically of radiation to directly deposit fission energy in the liquid water in the bypass flow around the fuel assembly channels and within the internal water channels (for modern fuel designs). The heat deposition in the coolant itself is predominantly deposited by neutrons as the fast fission neutrons slow down. TRACE/PARCS evaluates this heat deposition based on user input and, based on the bypass hydraulic conditions, predicts the void fraction. TRACE void predictions are well assessed. For this phenomenon, however, TRACE has not been assessed completely in that all direct energy deposition mechanisms are not considered.

Direct energy deposition is controlled by user input to establish the fraction of core power deposited as direct energy in the coolant. Therefore, this phenomenon is controlled by user input (see Table 4). The fractions are calculated external to TRACE. These factors are generally calculated using a highly detailed coupled neutron/gamma transport code.

While lattice physics codes generally provide calculated direct energy deposition data, general practice is to generate detailed Monte Carlo based models as a validation and verification exercise for the lattice physics code outputs. These ancillary calculations to the standard lattice calculations are generally used to generate direct energy parameter inputs for TRACE/PARCS since utilizing coupled neutron/gamma transport calculations in lattice depletion may result in unacceptably long run times.

Monte Carlo methods are accurate methods for predicting neutron and gamma transport for arbitrary geometric configurations. Monte Carlo codes such as MCNP and KENO have been extensively qualified, particularly against criticality and flux measurements in critical experiments. MCNP in particular is recognized as an industry standard for transport code verification and validation. When direct energy deposition factors are externally calculated using a qualified method such as MCNP, the results are considered to be adequate for best-estimate analyses such as ATWS. Therefore, no additional assessment for TRACE was deemed necessary.

It is worthy to note that TRACE/PARCS can only apportion direct energy using core average input parameters. In reality, the relative deposition of bypass heat is sensitive to local conditions, such as in-channel void and bypass void fraction. This is a limitation on the TRACE/PARCS code system. Selection of the appropriate direct energy factors for core analysis requires judicious selection of Monte Carlo transport calculations and averaging techniques to adequately capture core average behavior.

7.1.2 Core: Heat Capacities & Fuel-Clad Gap Heat Conductance

The fuel thermal properties, including heat capacity and gap conductance are modeled in TRACE using a combination of material property inputs and models. The models relied on for MELLLA+ ATWS evaluations are derived from FRAPCON (Ref. 14). FRAPCON can be used to calculate fuel thermal-mechanical properties, such as gap gas composition, and these data are input into TRACE. Additionally, aspects such as fuel thermal conductivity are calculated in TRACE using models that were developed for use in FRAPCON.

Therefore, while the TRACE assessment base does not address fuel thermal-mechanical properties, the basis for the associated models and capabilities of those models has been address by integral assessment of the FRAPCON 3.4 code. This assessment is documented in Reference 14. For thermal predictions (which include these highly ranked PIRT phenomena), the FRAPCON models are reasonable (Ref. 14).

The TRACE thermo-physical models have been indirectly assessed through the FRAPCON assessment and have been found to agree reasonably well with assessment data. Therefore, TRACE is adequately, albeit indirectly, assessed to simulate these phenomena. The results of the assessment additionally indicate that the TRACE capability is acceptable.

7.1.3 Flow Blockage

Flow blockage refers to a reduction in flow area due to geometry changes arising from clad ballooning and fuel-rod deformation. Flow blockage is determined according to correlation reported in Reference 18. Even though the degree of flow blockage associated with cladding rupture has been considered an area with a great deal of uncertainty (Ref. 3); the recommendations in Reference 18 for flow blockage correlations have been widely adopted. Since the TRACE model is based on the survey of empirical data and derived from these data, the model has been judged to be adequately assessed against available data for the current purposes.

7.1.4 Lower Plenum: 3D T/H Effect Including Stratification

The FIST small break loss-of-coolant-accident, SSTF, PBTT, and Ringhals assessment bases cover the 3D T/H effect in the lower plenum apart from the phenomenon of borated solution stratification. Stratification, mixing, and remixing phenomena are considered part of the overall 3D T/H effect in the lower plenum for the purpose of this applicability determination. As previously stated, TRACE does not include an explicit boron transport capability. Consequently, TRACE predictions have not been compared against boron transport qualification data.

In order to address the phenomena associated with boron transport a specific boron transport methodology was developed for TRACE (Ref. 9). The boron transport methodology uses a combination of TRACE components and control systems to simulate the transport of boron in the reactor coolant system. The parameters that dictate the performance of these components and systems is based on integral testing performed at VNC and UCSB (Ref. 9). Therefore, while TRACE has not been assessed, the physical phenomena are captured implicitly by the boron transport methodology, which is tuned to match experimental data. Therefore, the assessment relative to LP3D is deemed appropriate.

7.1.5 Recirculation Pumps: Coastdown

Recirculation pump coastdown is a phenomenon that is predominantly dictated by the inertia of the recirculation pump. Generally, for a plant specific analysis, the coastdown is simulated according to recirculation pump inertia input supplied by a licensee or vendor. The inertia is generally based on experimental test data, or integral plant operational data that is not part of the TRACE assessment basis. However, since the phenomenon is captured according to empirically determined parameters for a given analysis, the phenomenon will be modeled with a reasonable degree of agreement with the supplied data.

Table 6: Assessment Matrix[13]

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
BDMH	Bypass	Void fraction due to direct moderator heating																	P											
BDP	Bypass	Pressure drop	F																											
C3DK	Core	3-D kinetics effects										F	F																	
CAPS	Core	Axial power distribution										P	F																	
CBF	Core	Film boiling	F	F					F		F																			F
CBS	Core	Subcooled boiling	P	C	C		C	C	F	C	C	C	C															F		
CBURN	Core	Fuel burnup										P	F																	
CCFL	Core	Counter current flow limiting	F	F	F	F			F									P												
CCHAN	Core	Multi-channel T/H flow effect				F						F	F													F				
CCP	Core	Heat capacities of fuel and cladding																												
CCSC	Core	Coolant subcooling	C	C	C		C	C	C	C	C	P	F															F		
CD	Core	Dryout	F	F	F				F		F											F				F	F			

[13] In this table, “F” denotes fully capturing the phenomenon, “P” denotes partially capturing the phenomenon, and “C” denotes fully capturing the phenomenon when considered in a collection of SET/IET tests

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CDOP	Core	Fuel temperature reactivity feedback										F	F																	
CDP	Core	Pressure drop	F						F		F			F																
CFB	Core	Flow Blockage																												
CFLC	Core	Flow coastdown	F	F																										
CFUEL	Core	Fuel design/type										P	F																	
CHGAP	Core	Fuel-clad gap heat conductance																												
CIS	Core	Interphase shear	C	C	C		C	C	C	C	C	C	C																	
CNB	Core	Nucleate boiling, bulk boiling, and forced convection vaporization	F						F		F											F				F	F			
CNC	Core	Natural circulation	F	F					F																					
CREW	Core	Rewet									F							F		F	F	F				F	F			
CRP	Core	Control rod pattern/movement										P	F																	
CRPS	Core	Radial power distribution										F	F																	

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CSCL	Core	Void in subcooled liquid	F	C	C		C	C	C	C	C	F	F																	
CSNTH	Core	Stability: neutronic/ thermal-hydraulic							F			F	F																	
CVCOL	Core	Void collapse	F	C	C		C	C	C	C	C	F	F																	
CVD	Core	Void distribution	F	C	C		C	C	F	C	F															P				F
CVRC	Core	Void reactivity feedback										F	F																	
DC2F	Down-comer	2-phase level	F	P	C		C	C	C	C	C	C	C				F													F
DCHTX	Down-comer	Condensation heat transfer																					F	F	F				F	
DCIS	Down-comer	Interphase shear	C	C	C		C	C	C	C	C	C	C																	
DCVCO	Down-comer	Void collapse										F																		
DCVD	Down-comer	Void distribution							F		F																			
DRDP	Dryer	Pressure drop	P	P										F																
JPDP	Jet pump	Pressure drop	F	P										F																
JPFF	Jet pump	Forward flow	F	P																										
LP3D	Lower plenum	3-D T/H effect including stratification	P			P						P	P																	

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
LPDP	Lower plenum	Pressure drop												F																
MSLCF	Steam line	Critical flow	F	F											F	F														
MSLDP	Steam line	Pressure drop												F																
MSLPW	Steam line	Pressure wave propagation										F	F																	
RCPC	Recirc. pumps	Coastdown	P	P																										
SCU	Separ-ator	Carry-under	P	F								F	F																	
SDP	Separ-ator	Pressure drop												F																
UPDP	Upper plenum	Pressure drop												F												F				

7.2 Insufficient or Minimal Agreement Cases

Table 7 summarizes the review of the assessment cases and reports the ranking of the agreement between TRACE and data for all cases within the assessment matrix. For several phenomena, a ranking of minimal or insufficient has been reported. Table 7 indicates these phenomena, and the specific assessment case, with shading. Six phenomena were indentified and include: Core: Subcooled Boiling (index: CBS); Core: Dryout (index: CD); Core: Nucleate boiling, bulk boiling, and forced convection vaporization (index: CNB); Core: Rewet (index: CREW); Core: Stability: Thermal-hydraulic/neutronic (index: CSNTH); and Downcomer: Condensation Heat Transfer (index: DCHTX).

7.2.1 Core: Subcooled & Bulk Boiling

According to Reference 11, TRACE agreement with subcooled and bulk boiling assessment cases was insufficient for several cases. In particular for subcooled boiling, many FRIGG cases and the Christensen case were reported to have insufficient agreement. This is in contrast to the wider set of cases that forms the assessment matrix. Reasonable or excellent agreement is reported for cases such as BFBT, THTF, and TLTA.

The Christensen test is a square tube channel and is not as applicable to rod bundles representative of BWR fuel assemblies. Therefore, this applicability determination focused on the rod bundle test data. While Reference 11 reports that certain assessment cases demonstrated insufficient agreement, a closer inspection of the assessment demonstrates reasonable agreement for the cases most directly applicable to BWR applications. Figure 10 is taken from Reference 11 and compares TRACE predictions of axial void fraction to FRIGG measurement data for typical BWR conditions. The cases shown in the figure consider a range of inlet subcooling. For the high inlet subcooling cases, TRACE predicts a void fraction that is consistent with the FRIGG measurements in the subcooled region. A somewhat large difference in subcooled void fraction (approximately 10 percent) was observed in only one case, Test 613013. While the agreement is not excellent, the data are predicted well and the trends are captured, warranting a ranking of “reasonable.”

For bulk boiling, the integral assessment basis includes IET and plant data which includes FIST, TLTA, Ringhals, and Peach Bottom. The integral data comparisons as well as plant comparisons indicate good agreement. As reported in Reference 10, steady state power distribution measurements and calculations were reportedly in excellent agreement. Due to tight coupling between void fraction and power distribution, the integral assessments indicate at least a “reasonable” ranking for bulk boiling predictions.

Tests such as FRIGG and BFBT for an instrumented rod bundle also indicate overall reasonable agreement. Reference 11 reports reasonable agreement between TRACE and BFBT data for bulk boiling. However, Reference 11 also reports a range of agreement relative to FRIGG with several cases deemed to be of insufficient agreement. As for the case with subcooled boiling, axial void predictions and measurements for typical BWR conditions indicate reasonable agreement (see Figure 10). The degree of agreement between FRIGG data and TRACE shown in Figure 10 is typical of most cases. The TRACE predictions are not within the measurement error of the FRIGG measurements. However, the data are predicted well and overall trends in axial void distribution are captured. The FRIGG tests would indicate in the bulk boiling region a ranking of “reasonable.” The performance for FRIGG is consistent with performance for the other integral assessments.

When the FRIGG and BFBT assessments documented in Reference 11 are closely scrutinized, the agreement between TRACE and the test data for typical and transient BWR conditions appears to warrant a ranking of “reasonable” for subcooled and bulk boiling. This ranking is consistent with the performance of TRACE for integral test and plant data measurements that capture the subcooled and bulk boiling phenomena. When considered together, the TRACE assessment basis demonstrates, overall, reasonable agreement. Reasonable agreement is sufficient to deem TRACE applicable to model these phenomena.

7.2.2 Core: Dryout & Rewet

Dryout refers to the incidence of a departure from nucleate boiling. Such conditions are expected to occur when the fuel rod heat flux is sufficiently high relative to the cooling capacity of the coolant that void forms in the fluid film around the cladding and blankets the cladding surface. A marked reduction in heat transfer occurs and fuel cladding heat up occurs. Rewet refers to a restoration of cooling to rods that have experienced heat up.

These phenomena were ranked as highly important as the incidence of prolonged dryout (without rewet) may lead to fuel damage if excessive cladding temperatures are encountered. Previous studies of ATWSI events indicated that if the event is not mitigated that core power level may increase and result in periods of significant and extended heat up (Ref. 2).

The assessment cases reported in Reference 11 indicate reasonable TRACE agreement with test data collected at FIST and FRIGG in terms of dryout and at BFBT in terms of both dryout and rewet. The range of agreement reported for the BFBT data is between poor (or insufficient) and reasonable (Ref. 11). The reason for this is that the Biasi and CISE correlations available in TRACE generate different results. When the Biasi correlation is used, the TRACE predictions are in reasonable agreement with the BFBT dryout and rewet test data.

Further, the TRACE assessment manual (Ref. 6) reports minimal TRACE agreement with test data collected at RBHT in terms of predicted rewet. RBHT, however, was conducted at low pressure and flow conditions that are not representative of fluid conditions during BWR ATWS events. The predicted dryout and rewet at THTF are more relevant and the assessment indicates reasonable agreement for these cases (Ref. 6). On the basis of the performance for the FIST, FRIGG, BFBT and THTF assessments the TRACE agreement appears to be reasonable.

Based on the reasonable agreement of TRACE with experimental data, TRACE was found to be applicable to model the phenomena of dryout and rewet when the Biasi critical heat flux correlation is used.

7.2.3 Core: Stability

Reference 11 reports that when TRACE was compared to instability power limit test data from FRIGG that the agreement was minimal to insufficient. For test 601210 in particular, TRACE did not predict the onset of flow oscillations whereas the test indicated flow instability under these test conditions. Reference 11 attributes the poor agreement in the predicted power threshold for instability to a higher predicted mass flux in the TRACE assessment case relative to test data. However, the FRIGG stability assessment was performed using an axial nodalization that is largely uniform through the CHAN component representing the test section. It is likely that the selected nodalization contributed to numerical damping of the system. For stability evaluations it is important to maintain Courant limit near unity to avoid excessive numerical damping (see Section 7.3). Therefore, this particular assessment case was not judged to fully apply to the current applicability determination. A sensitivity study presented in Appendix F of Reference 11 demonstrates the effect of renodalization and the use of semi-implicit numerics. With these adjustments and adjustment of the exit loss-coefficient, much better agreement with the instability data was demonstrated.

The integral assessment performed in Reference 10 includes a direct comparison of calculated and measured decay ratios for a full core model. The assessment report describes the axial nodalization adopted for the assessment. The channel components were modeled using varying axial node sizes to maintain Courant limit near one. The results of this integral assessment indicate excellent agreement with test data.

A similar integral assessment performed in Reference 16 evaluates the TRACE predictions of decay ratio, natural frequency, and transfer function for the Peach Bottom low-flow stability tests. The TRACE agreement with stability measurements from this assessment was reasonable.

Given that the Reference 10 and 16 assessment models include appropriate features to address numerical damping, and the agreement with experimental data ranges from reasonable to excellent, it was determined that the TRACE capability to model the Stability: neutronic/thermal-hydraulic (index: CSNTH) is at least reasonable.

7.2.4 Downcomer: Condensation Heat Transfer

According to the TRACE assessment manual, the agreement between TRACE and assessment data ranges from excellent to insufficient. Section 5 of Reference 6 provides a succinct summary of the results of the condensation assessment. The UCB and Debhi test data indicate reasonable to excellent agreement. For the U. Wisc. Condensation test, TRACE under-predicts the degree of condensation heat transfer at high steam velocities (3 m/sec). The U. Wisc. Condensation test included tests to specifically investigate the phenomena of wall condensation for containment heat structures to study loss-of-coolant-accident conditions. The nature of the test and the flow range where TRACE indicates less than reasonable agreement differs from those analysis conditions important to MELLLA+ ATWS.

The condensation heat transfer phenomenon was ranked as highly important for the downcomer component. During ATWS events the flow rate in the downcomer is quite low, and level is dropped below the feedwater sparger. Condensation of steam is likely to occur in the downcomer once the feedwater spargers are uncovered. The low flow conditions that are analyzed as part of the transient analysis are more representative of the Debhi or UCB tests where TRACE indicates reasonable agreement with the data.

It has been a standard practice to utilize the TRACE three-dimensional level tracking feature in the downcomer for BWR applications to accurately track the liquid/vapor interface at the top of the level. However, in ATWS calculations, this approach may result in the under-prediction of condensation heat transfer in the downcomer following uncovery of the feedwater sparger. With the level tracking feature active, TRACE will calculate condensation heat transfer according to a fixed interfacial area that is given by the geometric configuration of the downcomer. In reality, the feedwater sparger is comprised of a number of small nozzles attached to a common distribution header and will inject liquid into a steam atmosphere in a series of jets once the sparger uncovers. Figure 9 illustrates typical feedwater sparger geometry. When level tracking is employed it is likely that TRACE will underpredict the interfacial area for the calculation of condensation heat transfer, leading to a bias in the calculated heat transfer.

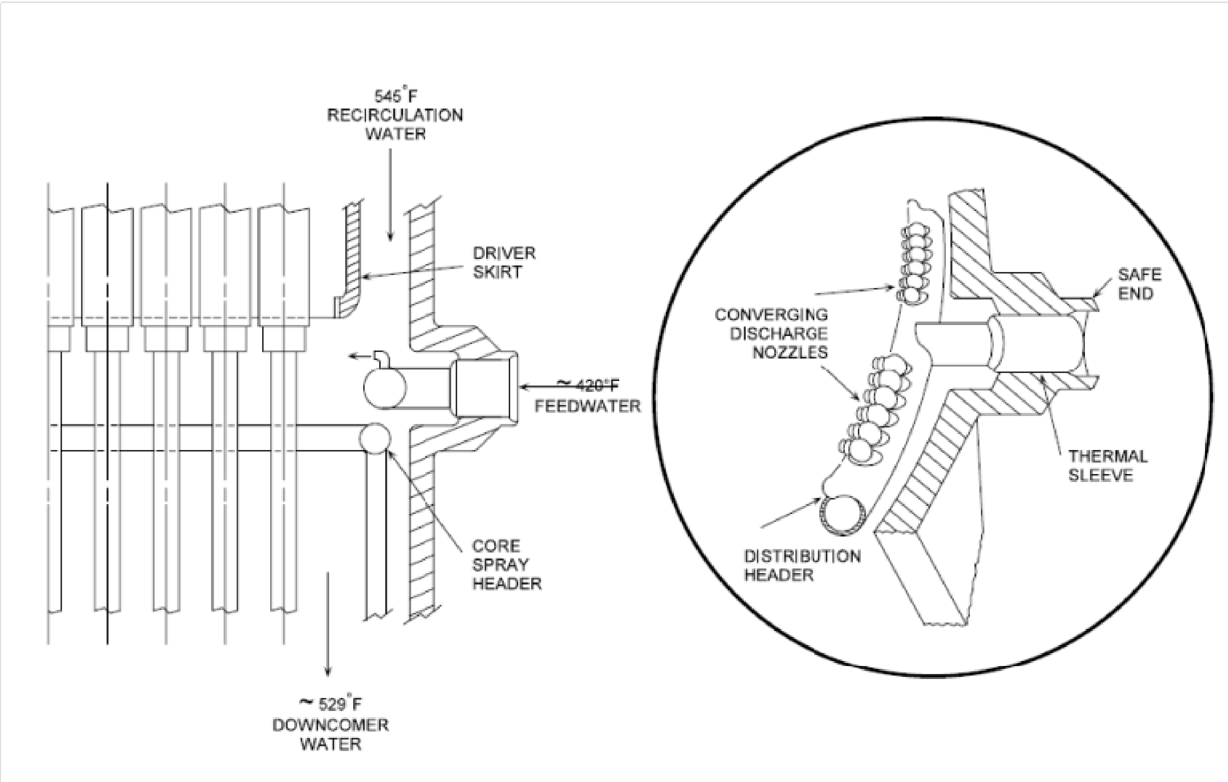

Figure 9: Typical Feedwater Sparger Geometry[14]

Since condensation heat transfer is an important phenomenon dictating core power response during ATWS events, the user should employ caution when specifying optional level tracking within the vessel component. Additionally, depending on the specific application and assumptions regarding the feedwater system, TRACE may not accurately capture the appropriate interfacial area. For instance, the feedwater injection is typically modeled with a singular feed injection source in TRACE as opposed to a multitude of small injection nozzles. At the current time TRACE does not include a special model to calculate condensation heat transfer for feed injection through a typical sparger configuration. Therefore, even without level tracking, the calculated interfacial area must be analyzed to ensure calculated downcomer liquid temperatures are realistic for ATWSI and ATWSED analyses.

[14] From Reference 17

For the specific use of TRACE in the context of MELLLA+ ATWS analysis, the TRACE assessment indicates reasonable agreement over the range of application. However, given the complexity of typical feedwater sparger geometries and intricacies of level tracking options, the user must evaluate the calculation results to ensure they are realistic.

Table 7: Agreement Review and Adequacy of the Assessment[15]

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
BDMH	Bypass	Void fraction due to direct moderator heating																	E [6]											
BDP	Bypass	Pressure drop	R [11], R [6]																											

[15] In this table, E denotes “excellent,” R denotes “reasonable,” M denotes “minimal,” and I denotes “insufficient” with regard to the agreement between TRACE and the associated assessment data.

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
C3DK	Core	3-D kinetics effects										R [5], E[10]	R [5], E[10]																	
CAPS	Core	Axial power distribution										E [10]	E [10]																	
CBF	Core	Film boiling	R [5], R [6]	R [5], R [6]					R to E [6]		N/A																			R [6]

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CBS	Core	Subcooled boiling	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	I to E [11], R [5]	R [5]	E [5]	R [5], E [10]	R [5], E [10]															I [11]		
CBURN	Core	Fuel burnup										E [10]	E [10]																	
CCFL	Core	Counter current flow limiting	R to E [6]	R to E [6]	R to E [6]	R to E [6]			R to E [6]									R to E [6]												

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CCHAN	Core	Multi-channel T/H flow effect				R [5], R [6]						R [5], E [10]	R [5], E [10]													R [6]				
CCP	Core	Heat capacities of fuel and cladding																												
CCSC	Core	Coolant subcooling	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	R [5]	R [5]	E [5]	R [5], E [10]	R [5], E [10]															N/A		

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CD	Core	Dryout	R [11], R[5], R [6]	R [5], R [6]	R [5]				R [11]		I to R [11][16]											R [6]				R [6]	R [6]			
CDOP	Core	Fuel temperature reactivity feedback										R [5], E [10]	R [5], E [10]																	

[16] This assessment is considered to be purely in “Reasonable” agreement when only the Biasi critical heat flux correlation is considered.

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CDP	Core	Pressure drop	R [11], R [6]						R [11]		R [11]			E [5]																
CFB	Core	Flow Blockage																												
CFLC	Core	Flow coastdown	R [5], R [6]	R [5], R [6]																										

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CFUEL	Core	Fuel design/type										E [10]	E [10]																	
CHGAP	Core	Fuel-clad gap heat conductance																												
CIS	Core	Interphase shear	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	R [5]	R [5]	E [5]	R [5], E [10]	R [5], E [10]																	

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CNB	Core	Nucleate boiling, bulk boiling, and forced convection vaporization	R [11], R [6]						I to R [11]		R [11]											R [6]				R [6]	R [6]			
CNC	Core	Natural circulation	R [11], R [5], R [6]	R [5], R [6]					R [11]																					
CREW	Core	Rewet									R [11]							R to E [6]		R to E [6]	M [6]					R [6]	R [6]			

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CRP	Core	Control rod pattern/ movement										E [10]	E [10]																	
CRPS	Core	Radial power distribution										E [10]	E [10]																	
CSCL	Core	Void in subcooled liquid	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	R [5]	R [5]	E [5]	R [5], E [10]	R [5], E [10]																	

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CSNTH	Core	Stability: neutronic/ thermal-hydraulic							I [11]			R [16]	E [10], R [5]																	
CVCOL	Core	Void collapse	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	R [5]	R [5]	E [5]	R [5], E [10]	R [5], E [10]																	
CVD	Core	Void distribution	R [11], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	R [11], R [5], R to E [6]	R [5]	E [5], R [11]	R [5], E [10]	R [5], E [10]													R [6]				R [6]

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
CVRC	Core	Void reactivity feedback										R [5], E [10]	R [5], E [10]																	
DC2F	Downcomer	2-phase level	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5], R to E [6]	R [5], R to E [6]	R [5]	E [5]	R [5], E [10]	R [5], E [10]				R to E [6]													R [6]
DCHTX	Downcomer	Condensation heat transfer																					R [6]	E [6]	I to E [6]				R [6]	

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
DCIS	Downcomer	Interphase shear	R [5], R [6]	R [5], R [6]	R [5]		E [5]	E [5]	R [5]	R [5]	E [5]	R [5], E [10]	R [5], E [10]																	
DCVCO	Downcomer	Void collapse										E [10]																		
DCVD	Downcomer	Void distribution							R to E [6]		N/A																			

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
DRDP	Dryer	Pressure drop	R [6]	R [6]										E [5]																
JPDP	Jet pump	Pressure drop	R [11], R [6]	R [6]										E [5]																
JPFF	Jet pump	Forward flow	R [11], R [6]	R [6]																										

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
LP3D	Lower plenum	3-D T/H effect including stratification	R [5], R [6]			R [5], R [6]						R [5], E [10]	R [5], E [10]																	
LPDP	Lower plenum	Pressure drop												E [5]																
MSLCF	Steam line	Critical flow	E [11], R [5], R [6]	R [5], R [6]											R [5], R [6]	R [5], R [6]														

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
MSLDP	Steam line	Pressure drop												E [5]																
MSLPW	Steam line	Pressure wave propagation										R [5], E [10]	R [5], E [10]																	
RCPC	Recirc. Pumps	Coastdown	R [6]	R [6]																										

			Assessment Case																											
Index	Component	Phenomenon Description	FIST SBLOCA	TLTA LBLOCA	THTF Mixture Level/Uncovery Test	SSTF	CISE Adiabatic Tube Test	Wilson Bubble Rise Test	FRIGG	GE Level Swell	BFBT	Peach Bottom 2	Ringhals 1	Single-phase and Two-phase Wall Friction Development Assessment	Marviken	Super Moby Dick	RBHT Mixture Level	GOTA Reflood	GOTA Radiation	FLECHT-SEASET Reflood	RBHT Reflood	RBHT Steam Cooling	UCB Condensation	Dehbi Condensation	U. Wisc. Condensation	SCTF	CCTF	Christensen	UPTF	THTF
SCU	Separator	Carry-under	R [5], R [6]	R [5]								R [5], E [10]	R [5], E [10]																	
SDP	Separator	Pressure drop												E [5]																
UPDP	Upper plenum	Pressure drop												E [5]												R [6]				

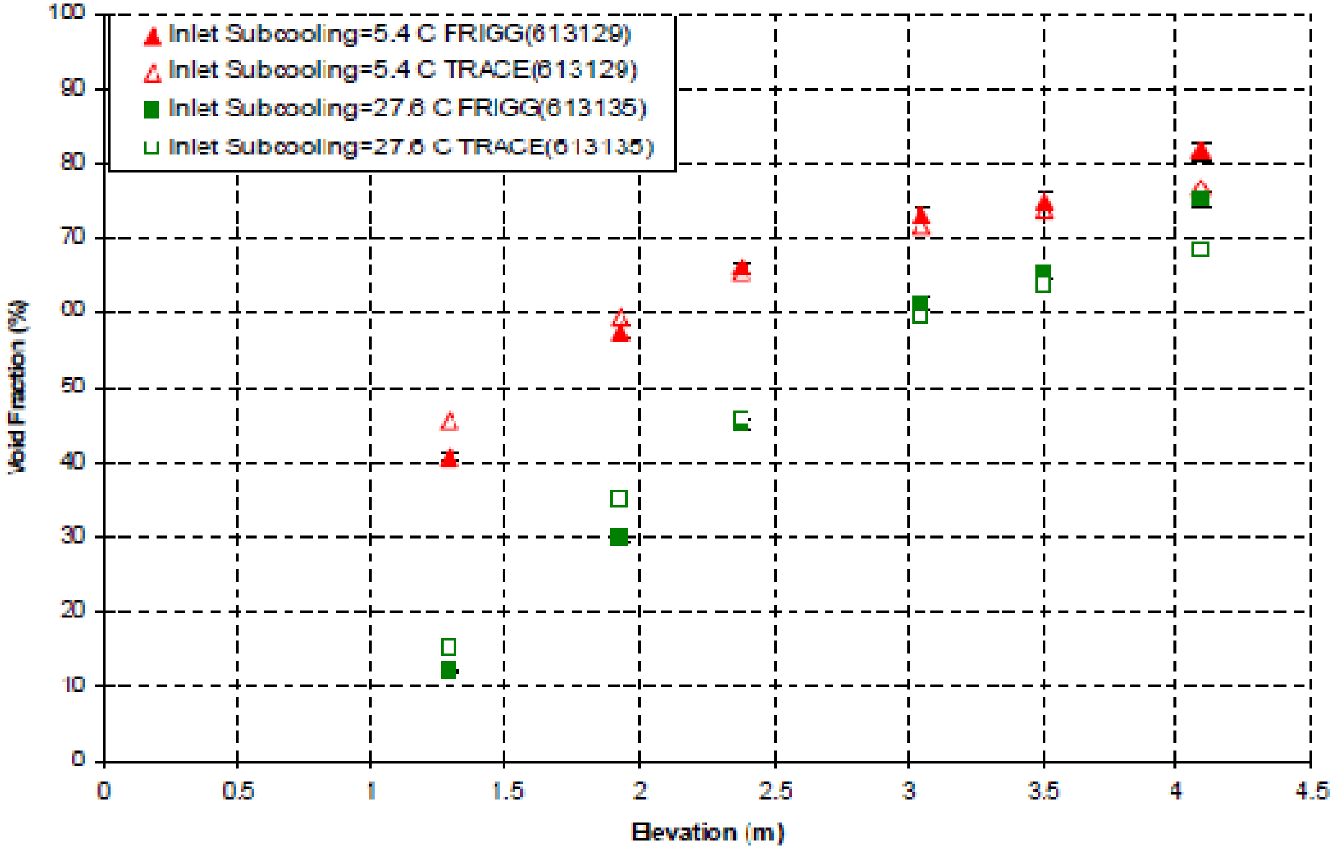

Figure 10: TRACE Axial Void Predictions for FRIGG (P=7.0 MPa, w=12 kg/s, Q=4.5 MW)[17]

[17] Ref. 11

7.3 Assessment Matrix Review Conclusions

A thorough review of the TRACE assessment matrix indicates that all relevant high ranked PIRT phenomena have been assessed either directly or indirectly. Certain phenomena are treated through explicit modeling assumptions and are tuned to empirical data (e.g. boron transport and recirculation pump inertia). Therefore, the physical basis for all required models is justified based on data.

The assessment basis includes SET/IET as well as plant data to support its applicability. When compared to these assessment data, TRACE indicates at least reasonable agreement for all high ranked PIRT phenomena. Reasonable agreement is sufficient to justify the applicability of TRACE to simulate the subject phenomena.

8 Nodalization

Plant model nodalization is aimed at achieving a balance between resolution of highly important phenomena and computational cost for any analysis. The CSAU process identifies the selected plant nodalization as a potential source of uncertainty in the analysis. Both CSAU and EMDAP recommend consistent nodalization between assessment and production analyses (Ref. 12 and 13). ATWSI and ATWSED analyses introduce additional nodalization considerations relative to standard practice for BWR transient and accident evaluations.

One important phenomenological consideration for ATWSI is the modal kinetic behavior. Generally, BWR core models make use of channel grouping techniques in order to reduce model size by using a single channel component to represent several channels in the reactor core. On a fundamental level, a quadrant symmetric core loading may be simulated by grouping four symmetric partner channels in a TRACE model. This approach is generally applicable for most transients, however, during ATWSI, it is expected that higher harmonic modes of the flux shape will be excited and contribute to the contour of the power oscillations. A simple case to consider is the first azimuthal harmonic (also known as the regional mode or out-of-phase mode). When this harmonic mode is excited the local power may oscillate out-of-phase between two sides of the core. If a four-to-one channel grouping (i.e. quarter core) strategy is employed, then TRACE will not predict the excitation of the higher harmonic mode. Therefore, for ATWSI the channel grouping must take special consideration of the likelihood of higher harmonic mode power oscillations in ATWSI. TRACE and PARCS may be used in a coupled manner to calculate the first harmonic shape, which is useful in establishing an acceptable channel grouping. Reference 10 demonstrates this approach for developing an appropriate two-to-one channel grouping (i.e. half core) that will allow TRACE to predict regional mode power oscillations.

Aside from nodalization constraints related to phenomena resolution, the nodalization must additionally balance numerical effects that can influence calculation results. Numerical effects here refer to the potential for artificial diffusion during transient calculations. These effects can significantly distort ATWS analysis results unless managed through careful consideration of the nodalization.

ATWSI analyses must select a core nodalization to reduce the effect of numerical damping in order to accurately predict the onset of core instability. The Ringhals stability assessment reported in Reference 10 provides additional details of the influence of Courant number on core decay ratio predictions. Figure 11 illustrates an optimized core axial nodalization as well as a sensitivity study relating core decay ratio predictions to integration time. The Courant number is given by the ratio of the product of the time integration step size and velocity to the node size. To maintain a consistent Courant number within the core, it is necessary to vary the node size axially. As the figure shows, deviating from Courant number near unity has an artificial stabilizing effect on the calculations. Additionally, the figure shows that the channel components should have a more refined nodalization in the lower portion of the core than the top of the core.

ATWSI and ATWSED calculations will both require the calculation of boron transport. For lower plenum injection plants (i.e. BWR/3-4), the lower plenum axial nodalization must be modeled according to the guidelines documented in the boron transport methodology (Ref. 9). To accurately simulate the effects of boron stratification and remixing it is necessary to include additional refinement of the lower plenum nodalization to control borated water flow as well as to prevent excessive numerical diffusion of boron through the RPV. The nodalization guidelines are documented in Reference 9.

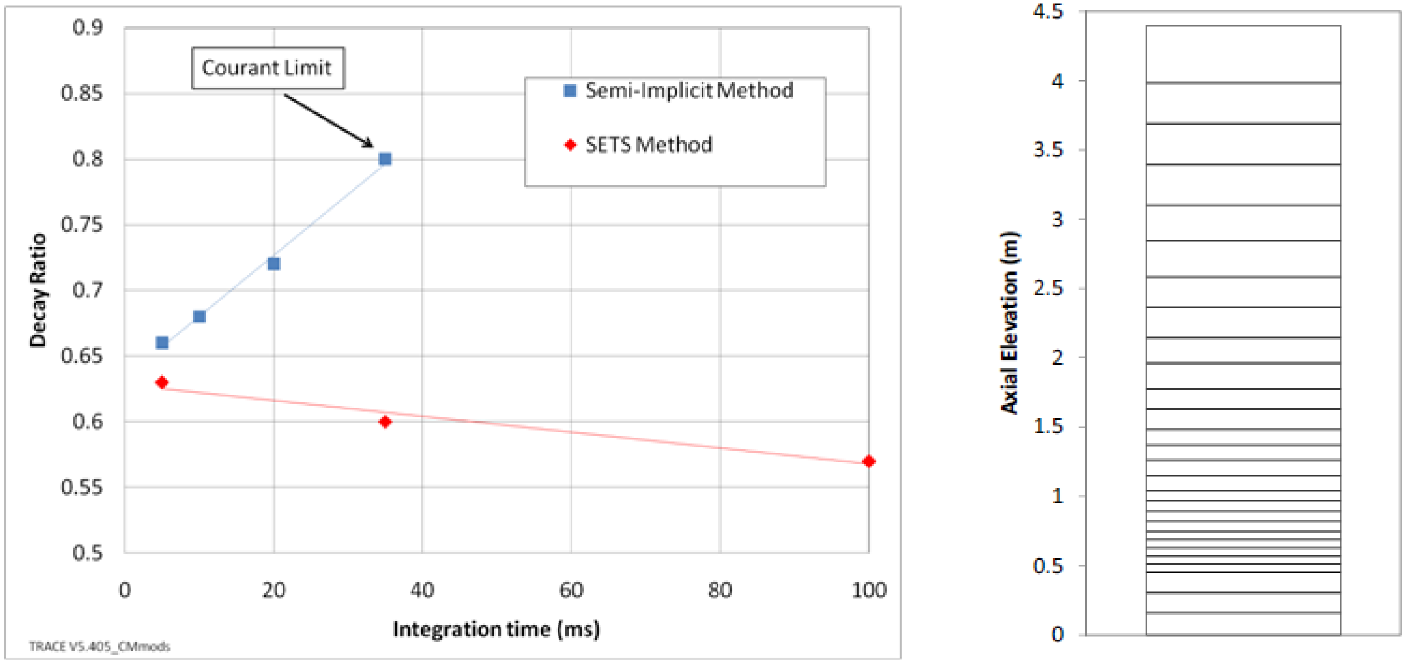

Figure 11: Decay Ratio as a Function of Integration Time and Axial Nodalization[18]

[18] Ref. 10

9 Conclusions

The applicability of TRACE to perform ATWSI and ATWSED analyses for MELLLA+ BWR plants has been evaluated. The applicability determination follows the CSAU and EMDAP processes. These processes rely on the identification and ranking of phenomena for specific transient and accident scenarios. For the ATWSI and ATWSED scenarios, many highly ranked PIRT phenomena were considered. An assessment matrix was constructed that adequately covered the highly ranked phenomena. Comparison of TRACE results to assessment case data indicated, generally, reasonable agreement. All highly ranked phenomena were represented by TRACE with reasonable or excellent agreement when compared to experimental data over the range of conditions of interest for ATWS analyses. Based on these findings, TRACE was deemed adequate for ATWSI and ATWSED analyses for MELLLA+ BWR plants.

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