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ABSTRACT

A TRACE/PARCS model has been developed to analyze ATWS in a BWR operating in the expanded operating domain called MELLLA+. The TRACE model incorporates features that facilitate the simulation of ATWS events in a BWR/5 housed in a Mark II containment. It includes control logic to initiate operator actions to mitigate the ATWS events, such as water level control, emergency depressurization, and injection of boron via the standby liquid control system. Separate banks of safety relief valves are modeled to capture the potential of vessel repressurization due to valve choking. A boron transport model, using control system components in TRACE, has been developed to calculate the effective boron concentration delivered to core flow after accounting for boron stratification and remixing. A BWR ATWS initiated at MELLLA+ operating conditions has been analyzed to demonstrate the plant response and the effectiveness of automatic and operator actions during the event. The scenario studied is initiated by main steam isolation valve closure and leads to heat up of the suppression pool and emergency depressurization. The event is mitigated successfully by a combination of automatic recirculation pump trip and operator actions that depressurize the reactor, and reduce power by water level control and injection of boron.

KEYWORDS
ATWS BWR MELLLA+ PARCS TRACE

1. INTRODUCTION

In recent years, the operating power of boiling water reactors (BWRs) has been increased, sometimes to 120% of their original licensed thermal power (OLTP). This places them in an expanded operating domain in the power-flow operating map. One option being pursued, viz, maximum extended load line limit analysis plus (MELLLA+), utilizes a flow control window (FCW) at high reactor power [1]. It is very similar to the MELLLA concept, except, this FCW is utilized at extended power uprate (EPU) levels of 120% of the OLTP. One safety issue that becomes more important when operating in the MELLLA+ domain is the response of the plant to an anticipated transients without scram (ATWS) and this is the motivation for the U.S. Regulatory Commission (NRC) to undertake the present study. This study uses the TRACE/PARCS code package [2, 3], to perform a coupled neutronics/thermal hydraulics analysis of an ATWS initiated by a main steam isolation valve closure (MSIVC) that requires emergency depressurization (ATWS-ED). Previously the performance of the ESBWR in an MSIVC ATWS had been analyzed using another reactor system code, TRACG [4].

A couple of safety considerations particular to an isolation ATWS in BWRs are emergency depressurization (ED) and recriticality [5]. In an MSIVC ATWS scenario, the steam produced in the core will be relieved through safety relief valves (SRVs) and absorbed in the wetwell 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 additional thermal load may exhaust available pressure suppression capacity of the containment wetwell, which would prompt an ED according to standard emergency operating procedures. If there had been any fuel damage from the ATWS, two of the three primary fission product barriers may be compromised. Should any additional, unexpected heat load be imposed on the containment, the containment pressure would be subject to a rapid increase because the suppression pool cannot condense any additional steam. This leads to a safety concern associated with the incidence of recriticality and return to power. Recriticality may occur due to two identified mechanisms. The first mechanism is due to repressurization of the reactor if choking occurs in the SRVs. The second mechanism is characterized by boron dilution due to the injection of water to maintain water level overpowering the injection of boron-and the increase in coolant density as a result of a lower system pressure after the ED.

A TRACE/PARCS model has been developed to analyze ATWS in a BWR operating in the MELLLA+ domain. The primary focus is to assess the effectiveness of operator actions in mitigating an ATWS-ED by way of reducing reactor power during the early phase and for the long term, keeping the reactor sub-critical. The reactor and the balance of plant systems contain unique features (e.g., stratification and remixing of boron in the lower plenum is the one emphasized in this paper) to provide quantitative information during an ATWS-ED. The calculations employ different plant conditions and/or modeling assumptions. This includes different water level control strategies and different initial core flow rates at three different exposure points during a typical fuel cycle; beginning-of-cycle (BOC), peak-hot-excess-reactivity (PHE), and end-of-full-power-life (EOFPL). It also includes looking at a different location for injection of soluble boron into the RPV.

2. METHODOLOGY

The methodology utilizes TRACE/PARCS [2, 3], a code system with thermal-hydraulic and thermo-physical phenomena predicted by TRACE and reactor kinetics phenomena predicted by PARCS. The code package has been assessed for its applicability to MELLLA+ BWR ATWS [5], and additional studies with the current model [6, 7, 8 and 9] provide insights into its capability. The TRACE/PARCS coupled code system has also been applied to study BWR out-of-phase oscillations [10]. The development of models used in the current analysis is documented in [6, 7] and summarized in [11, 12]. The following discussion provides a brief description of the TRACE system model and the PARCS core model. A new methodology to model boron transport in the reactor vessel is then discussed in more detail. The boron transport model is necessary for a more realistic simulation of boron injection in the lower plenum because TRACE does not have a mechanistic model capable of explicitly simulating the mixing, stratification, and remixing of boron. Figure 1 is a node diagram providing the component view of the complete model.

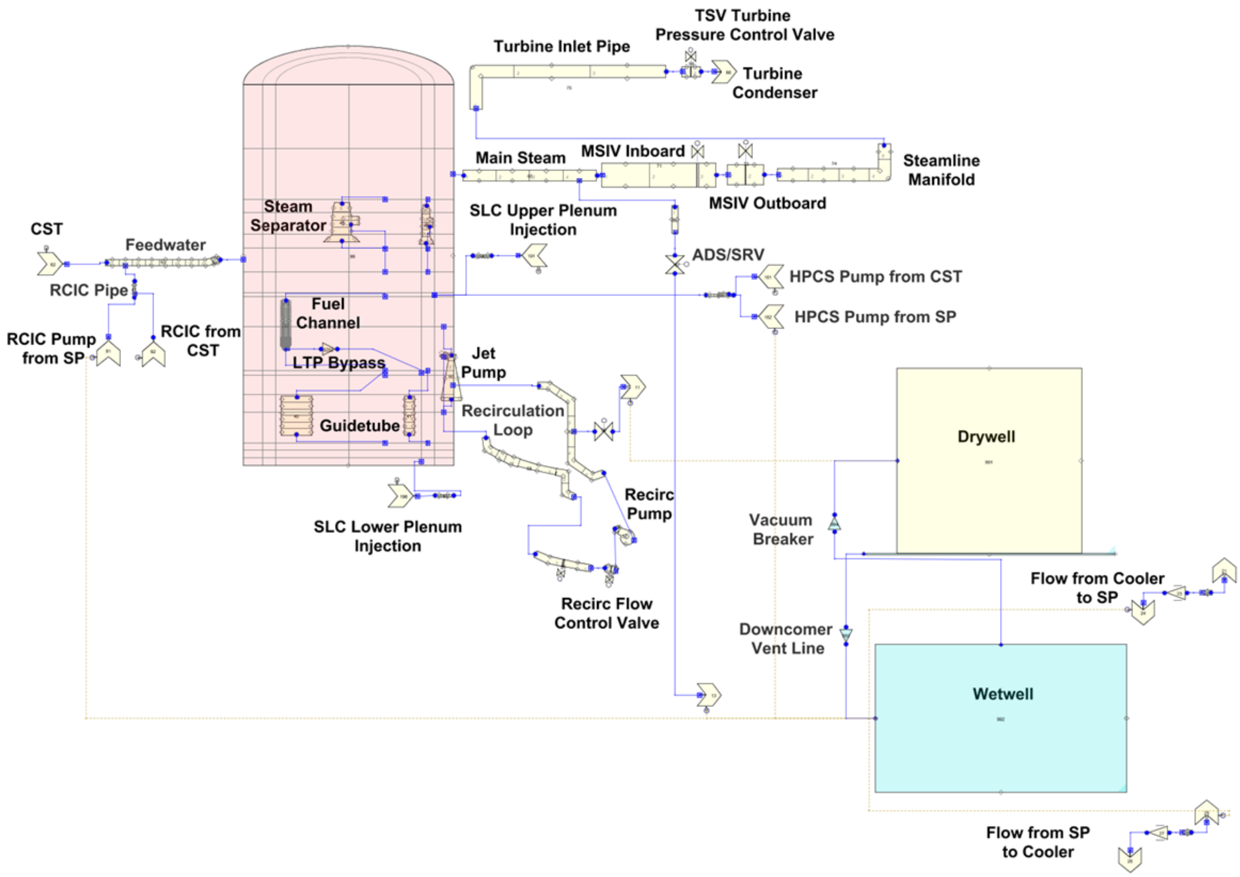

Figure 1 Component View of the BWR/5 Plant for ATWS Simulations.

2.1 TRACE System Model

The TRACE model is for a BWR/5 plant and consists of hydraulic components and heat structures. The reactor is represented by a VESSEL component with three radial rings, 17 axial levels, and one azimuthal segment. The core and the steam separators are in rings 1 and 2 while the downcomer is in the 3rd (outer-most) ring. Fuel assemblies are modeled with CHAN components. Five rod types are defined in the CHAN component representing full-length fuel rod, part-length fuel rod, gad rod (fuel rod with integral gadolinia burnable poison), the hot rod and water rod. The CHAN model incorporates three TRACE options: dynamic gas-gap conductance, modified Nuclear Fuels Industries (NFI) correlation for fuel thermal conductivity, and metal-water reaction. These optional models use burnup information together with the gadolinia content in a fuel rod. The gap-gas composition and initial oxide thickness on the clad are determined from FRAPCON results [6, 7].

A POWER component identifies CHANs for coupling with PARCS. Besides the VESSEL component (with internals consisting of one jet pump, two control rod guidetubes, and two steam separators), the model also has one recirculation loop with recirculation pump and flow control valve, a feedwater line, a reactor core isolation cooling system (RCIC) line with option to draw from the condensate storage tank (CST) or the suppression pool, two standby liquid control system (SLCS) lines (for lower plenum and upper plenum injection), a main steamline with in-board and out-board main steam isolation valves (MSIVs) and five side-branches to four banks of safety/relief/automatic depressurization system valves (SRVs and ADS), turbine control valve (TCV), and a Mark II primary containment (drywell and wetwell) with suppression pool cooler and passive heat structures (structural components). Plant configuration options are included to simulate BWR/4-like SLCS injection into the lower plenum of the vessel and this is the configuration being considered for the ATWS-ED analysis. Control systems consisting of signal variables, control blocks and trips complete the TRACE model. A three-element feedwater (FW) controller is included in the model to maintain reactor water level (RWL) at the desired level setpoint based on the following controller inputs: FW flow, steam flow, and RWL. Adjusting the RWL input to the controller allows simulation of operator actions to control level according to different strategies. The adjustment is in the form of a bias which represents the difference between the nominal level setpoint and the target water level. The RWL input to the controller is the sum of the actual RWL and the bias.

2.2 PARCS Core Model

The core requires detailed attention and each fuel assembly is represented in the PARCS neutronics model, albeit multiple assemblies share the same thermal-hydraulic channel in the TRACE model. The model is based on an equilibrium core of 764 GE14 assemblies. Each assembly is a 10x10 fuel bundle consisting of:

- Full-length fuel rods without gadolinia (with natural uranium top and bottom blankets)
- Full-length fuel rods with gadolinia (with natural uranium bottom blankets only)
- Partial-length fuel rods without gadolinia (with natural uranium bottom blankets only)
- Two water rods

Fuel enrichment varies from rod to rod, and gadolinia concentration changes for different rod types and axial level. The PARCS core model includes multiple planar regions with unique materials, representing two reflectors (top and bottom), and several distinct axial segments in the active fuel region. The cross sections used by PARCS were generated with SCALE/TRITON [13] in accordance with the cross section generation guidelines found in [14]. PARCS core models are essentially identical for each of the three different exposure points in the cycle considered: BOC, PHE, and EOFPL. The three models differ in the nodal exposure and moderator density history information contained in the depletion (*.dep) file, and the position of the control rod banks.

The internal coupling between TRACE and PARCS is facilitated by mapping, a process to define the correspondence between neutronic nodes and hydraulic volumes/heat structures. For ATWS-ED, the core response is expected to be fairly uniform, allowing a coarse TRACE representation.

The grouping is based on geometrical and fuel cycle considerations. This is possible because in a core with an EPU, the power shape is flattened and reload fractions are high [1], so position-based grouping is similar to power grouping. A clear advantage of this position-based approach is that the grouping works for all points in the cycle. The result is a TRACE model with 27 channels, with mapping shown in Figure 2. Each group of fuel assemblies that share the same TRACE hydraulic channel is indicated by a different color or shade. A ‘0’ indicates a fresh fuel location at the BOC condition. The stars in the figure indicate control rod positions where the blades are “significantly” inserted (more than 10 steps) during cycle depletion (either for BOC or PHE). Two hydraulic channels are assigned for the four fuel assemblies adjacent to each of these “significantly” inserted control rods, one channel for the two fresh assemblies and one for the two burned assemblies. A more refined grouping using 382 channels (half-core symmetry) has also been developed [6]. Steady-state results from the 27 and 382 channel models indicate that the two models give almost identical radially averaged axial power distributions and very close axially averaged radial power distributions with a maximum RMS of 0.05 for the difference. These results confirm that the 27 channel grouping is acceptable for core-wide transients over the full range of exposures considered [7].

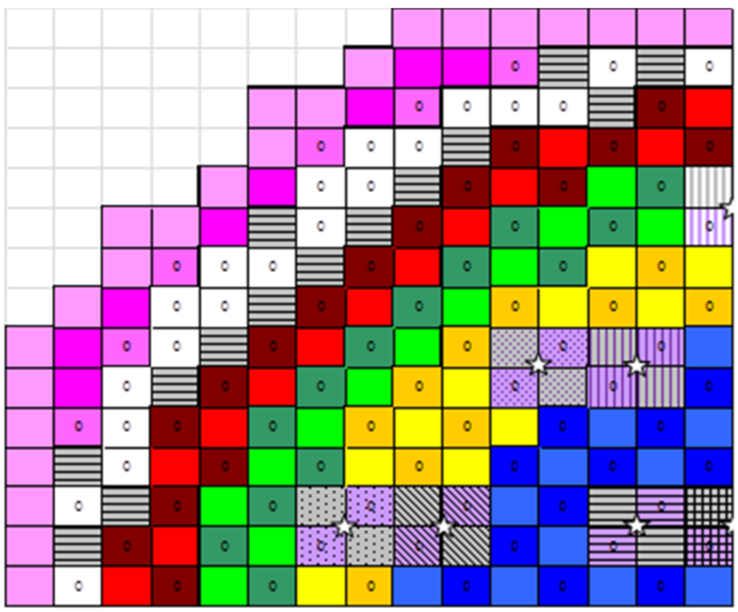

Figure 2 Mapping Strategy – 27 Channel Model.

2.3 Boron Transport Model

An assessment of the applicability of TRACE/PARCS to BWR ATWS analysis notes that TRACE does not have a sufficiently robust boron transport capability to simulate the phenomenon of boron solution stratification [5]. The term “boron transport” refers collectively to the phenomena of entrainment, diffusion, stratification, mixing, and remixing. However, to overcome this shortcoming in TRACE, a new boron transport methodology was developed. The methodology is based on scaled experimental test data collected at both the Vallecitos Nuclear Center (VNC) [15, 16] and University of California Santa Barbara (UCSB) [17] and it makes use of control system and component features in TRACE to capture the effects of injected boron mixing, stratification, and remixing.

The model simulates the SLCS using a combination of a FILL component and a PIPE component. A control system, based on the new boron transport model, determines an effective boron concentration in the SLCS injection flow. The control logic accounts for boron mixing and remixing, using empirical parameters that are core flow dependent.

Depending on core flow conditions, boron injected through the SLCS may either mix or become stratified. When fully mixed, the boron injected into the vessel is completely entrained in the core flow and becomes available to circulate to the core. Under reduced core flow conditions the mixing is not 100% efficient and the boron solution will stratify or settle to the bottom of the reactor vessel, removing some of the injected boron from circulation to the core. The removal of the boron from the core flow due to stratification can be simulated by reducing the concentration of the source boron. Conceptually the source boron once in the vessel is split into two streams, entrained and stratified. The fractional split between the two streams is denoted by an empirical factor γ, the mixing coefficient. Thus,

$$\text{Boron in entrained stream} = \gamma C_{SLCS} W_{SLCS} \tag{1}$$

$$\text{Boron in stratified stream} = (1-\gamma) C_{SLCS} W_{SLCS} \tag{2}$$

where, C_{SLCS} is the nominal value of boron concentration in the SLCS, and W_{SLCS} is the mass flow rate of boron solution in the SLCS. When entraining conditions exist, the mixing coefficient is unity, and when the core flow rate is below a threshold value and the solution is presumed to stratify, the mixing coefficient is equal to 0.

A second phenomenon that affects boron transport in the reactor vessel is remixing. Remixing occurs when the core flow rate is sufficiently high to entrain borated solution that has stratified in the bottom of the lower plenum (BLP). This is characterized by a flow-dependent remixing coefficient θ. The boron delivered by this remixing stream is given by,

$$\text{Boron in remixing stream} = \theta C_{BLP} W_{BLP} \tag{3}$$

where, C_{BLP} is the boron concentration in the bottom of the lower plenum, and W_{BLP} is the liquid mass flow rate of core flow that egresses the lower plenum.

The boron transport model is designed to keep track of the delivery of entrained boron into the core due to mixing and remixing. An effective injection concentration can then be calculated according to the following equation, which sums all sources of newly entrained boron and the two sources represented by equations (1) and (3).

$$C_{FILL} W_{SLCS} = \gamma C_{SLCS} W_{SLCS} + \theta C_{BLP} W_{BLP} \tag{4}$$

where, C_{FILL} is the effective injection concentration. The splitting of source boron into two streams, mixing and remixing, is similar to the development described in [15].

The time dependent, average concentration of stratified boron in the lower plenum, C_{BLP}, is calculated by doing a mass balance for the stratified boron in the lower plenum, as shown in equation (5).

$$M_B(t) = C_{BLP} \int_{BLP} \rho \, dV = \int_{t'=0}^{t} [(1-\gamma) C_{SLCS} W_{SLCS} - \theta C_{BLP} W_{BLP}] dt' \qquad (5)$$

where, M_B is the mass of stratified, soluble boron in the lower plenum; ρ is the liquid density in the BLP; V is the liquid volume in the BLP, and t is time.

Only the stratified mass is considered because TRACE will internally track entrained boron. This continuity equation is fully generalized and may be used to account for conditions such as prompt stratification (i.e., stratification of the flow as it is injected into the vessel) and remixing occurring simultaneously. Equation (5) tracks the addition of boron to the lower plenum through stratification (first term inside the time integrand) and the removal of boron from the lower plenum due to remixing (second term inside the integrand).

In equations (4) and (5) W_{BLP} represents the "sweeping" flow through the bottom of the lower plenum and it is based on the mass flow calculated by TRACE. The control volume for the BLP is defined to be the cells occupying axial levels L1, L2 and L3 in rings 1 and 2 of the BWR/5 TRACE VESSEL component, for a total of six cells. The lower plenum sweeping flow rate W_{BLP} is then defined as the positive liquid mass flow exiting this control volume at the interface between axial levels three and four in rings 1 and 2. W_{BLP} has two components, a ring 1 (R1) and a ring 2 (R2) contribution, and they are summed to give the net contribution. The respective contribution is set to zero if the axial liquid flow between L3 and L4 in a ring is negative, i.e., flow enters the control volume from axial level 4.

The boron transport model implemented in the TRACE input model for the BWR/5 is a set of control components that solves for C_{FILL} and C_{BLP} using the continuity equations expressed in Equations (4) and (5). Specifically the control system calculates the following two parameters.

$$C_{FILL} = (\theta C_{BLP} W_{BLP}) / W_{SLCS} + \gamma C_{SLCS} \qquad (6)$$

$$C_{BLP} = M_B / M_{BLP} \qquad (7)$$

In equation (7) M_B is obtained from the time integration indicated in equation (5) while M_{BLP} is the mass of liquid in the BLP. M_{BLP} is evaluated by summing the liquid inventory in the six cells of the BLP control volume. Lower plenum boron injection is directed radially inward at the outer face of ring 3 of the VESSEL just beneath the jet pump outlet nozzle.

The core is modeled in TRACE with a large number of fuel channels and tracking the boron inventory in each fuel channel is therefore, burdensome. A simplified approach has been developed to track the boron inventory in a control volume around the core. This control volume includes one vessel node below the active core and two vessel nodes above the active core. Considering this control volume, there are only eight available flow paths for boron ingress and egress. These flow paths include: (1) the high pressure core spray (HPCS) sparger, (2) the upper plenum SLCS injection line, (3) the ring 1 (R1) separators, (4) the ring 2 (R2) separators, (5) the R1 control rod guide tubes (CRGTs), (6) the R2 CRGTs, (7) the R1 lower plenum, and (8) the R2 lower plenum.

A control system is set up to integrate the boron continuity equation for the control volume. The integration is over the rate of boron exchanges at the interfaces. Integrating this equation would allow the inventory with a volume slightly larger than the active core to be calculated. The core boron inventory as a function of time is then evaluated by integrating the continuity equation, assuming $B_c(0)=0$.

$$B_C(t) = \sum_{i=1}^{8} S_i \int_0^t W_{l,i} B_i \, dt \quad (8)$$

where, B_c is the boron inventory in the core; $W_{l,i}$ is the water mass flow rate in the ith flow path; B_i is the boron concentration in the donor cell, and S_i is a directional index, +1 for ingress and -1 for egress.

3. RESULTS

The TRACE/PARCS BWR/5 model has been applied to analyze MELLLA+ BWR ATWS events initiated by turbine trip [19] and MSIV closure [20]. Additional discussions of the ATWS-ED transient summarized in [20] are presented here to highlight the effects of some of the special modeling features implemented in the TRACE/PARCS model. The discussions are illustrated by the use of one of the exposure points (BOC) analyzed by the model, however, the general progression of the transient and the conclusions are applicable to all cases analyzed [7, 9, 20].

The ATWS-ED transient of interest is a BOC case with the reactor at120% OLTP (3988 MWt) and a core flow of 85% rated flow (11,620 kg/s or 25,560 lb/s). The scenario includes several system trips and operator actions. The ATWS is initiated by an MSIV closure and the recirculation pumps are tripped (2RPT) on a high RPV pressure signal. Initial water level control to the top of active fuel (TAF) is followed by a level restoration later in the transient. Boron injection is initiated at 200 s into the transient and an emergency depressurization is initiated when the suppression pool temperature reaches the heat capacity temperature limit (HCTL) of 344 K (160°F). The sequence of events for the ATWS-ED case is given in Table I to illustrate the general progression of the transient.

Figure 3 shows the reactor responding initially to the MSIV closure with a power pulse due to the collapse of void in the core. The peak power is limited by fuel temperature feedback but void feedback also has a role after sufficient time has elapsed for heat transfer to the coolant. The reactor power then drops rapidly in response to the 2RPT and lifting of SRVs to about 50% of the initial power. The RPV pressure oscillation is observed in Figure 4, a result of SRVs cycling open and close in banks.

An operator action to reduce water level to TAF commences at 130 s. On receiving the new water level demand signal the feedwater controller decreases flow to the reactor. The rapid decline in water level is observed in Figure 5 and the corresponding decrease in core flow is seen in Figure 6.

Table I. Sequence of events – ATWS-ED

Time (s)	Event
0.0	• Null transient simulation starts
10.0	• Null transient simulation ends • MSIV closure starts • Reactor trip due to MSIV closure fails
13.4	• High RPV pressure trips recirculation pumps (2RPT)
13.8	• First lift of SRVs
14.5	• MSIVs completely closed
130	• Initiation of reactor water level control to TAF
137	• Maximum peak clad temperature of 646 K (703°F)
211	• Initiation of boron injection
~248	• Boron starts accumulating in core
349	• Emergency depressurization initiated
538	• Drywell reaches maximum pressure of 0.162 MPa (23.5 psi)
2180	• Water level restoration over 100 s begins
2208	• Suppression pool reaches maximum temperature of 359 K (187°F)
2500	• Simulation ends.

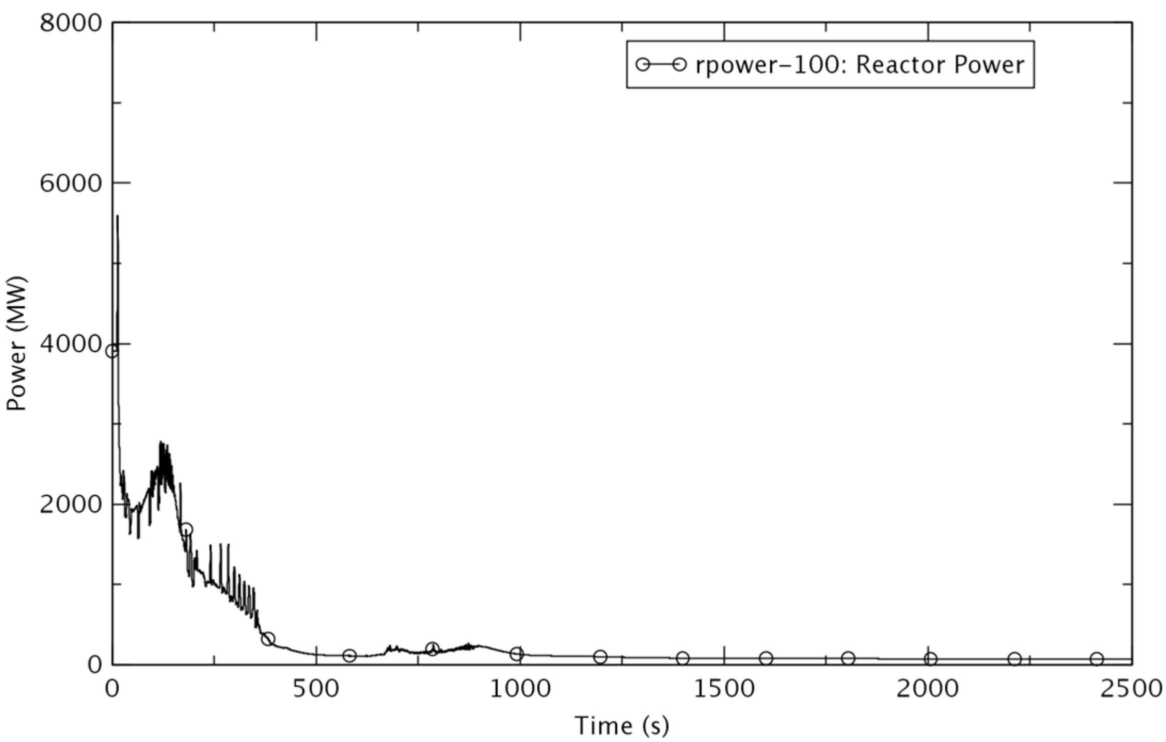

Figure 3 Reactor Power.

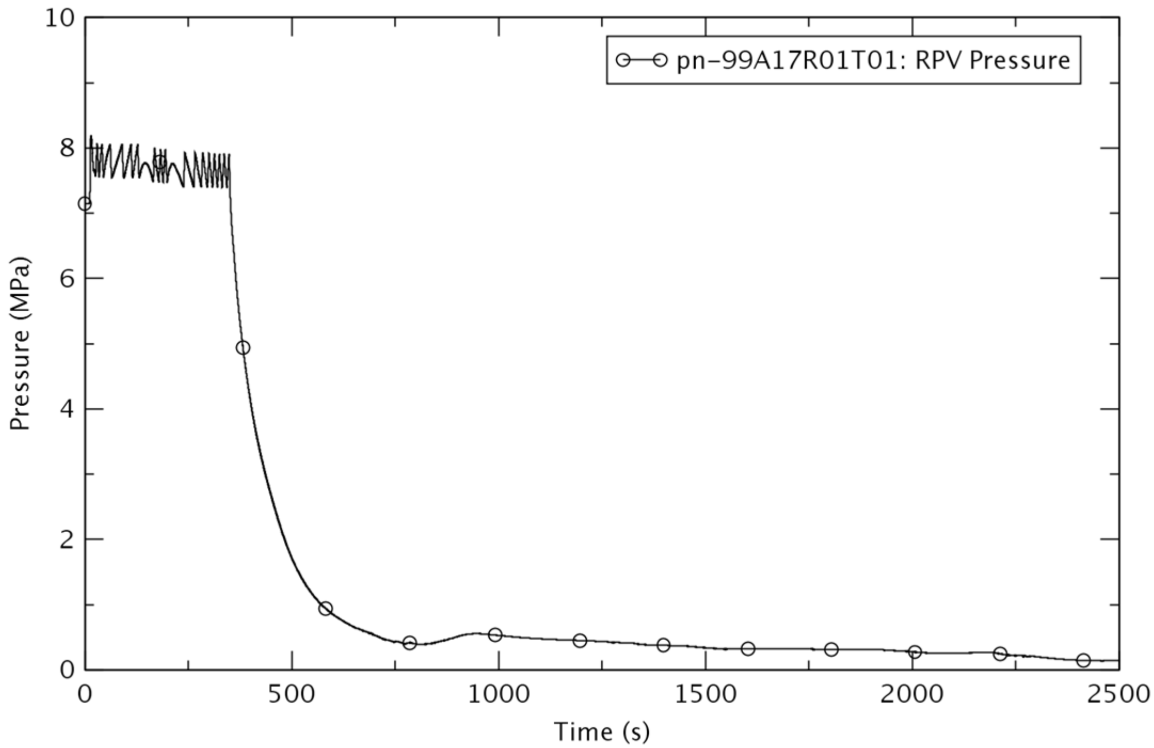

Figure 4 RPV Pressure.

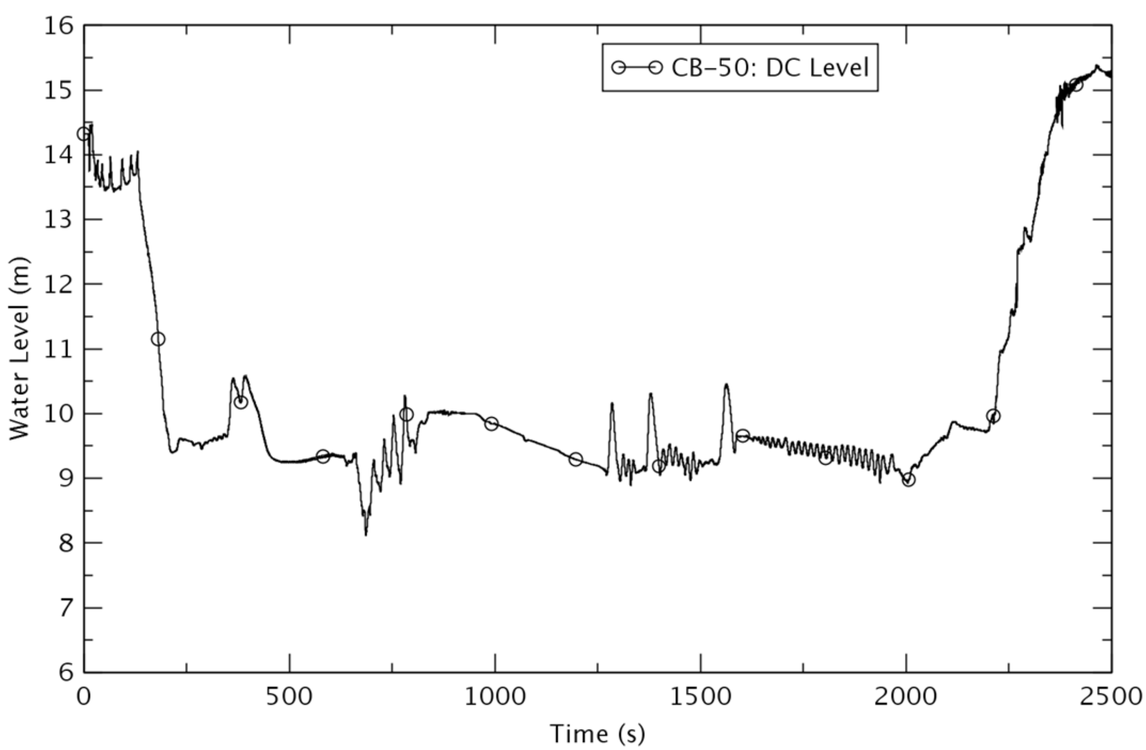

Figure 5 Reactor Water Level.

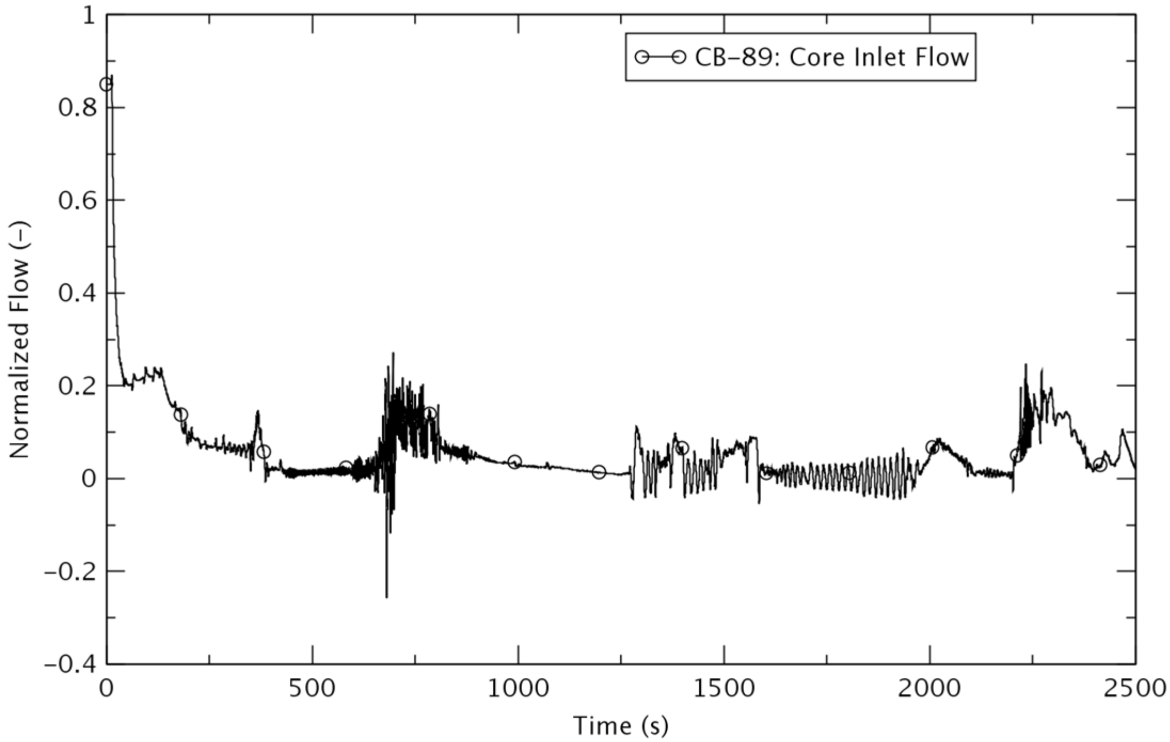

Figure 6 Core Flow (Normalized).

The TRACE analysis demonstrates that reactor power does respond to 2RPT and water level control as designed and a quasi-steady-state is approached with the steam being relieved to the suppression pool through SRVs. As indicated in Table I the peak clad temperature does not pose any challenge to the fuel integrity. However, due to the high power following the 2RPT, the heatup of the suppression pool causes the containment to approach the HCTL. At that point the operators are assumed to manually actuate the ADS to depressurize the RPV. The effect of the ED is most visible in the rapid decrease in reactor pressure (Figure 4) at 350 s. The most significant impact on the core thermal-hydraulics due to the ED is the flashing of the coolant in the core and, to a lesser extent, in the lower plenum. An example is the slight drop in water level around 700 s as water from the downcomer completes the refilling of the vessel lower plenum. The decrease in water level then signals the controller to increase feedwater flow leading to an increase in the core flow. Between 600 s and 1000 s the core power exhibits some fluctuations due to perturbations in core flow and downcomer water level as the feedwater control system, modeled in TRACE to simulate operator action, attempts to maintain water level to TAF. After 1000 s, perturbations in core flow and water level, due to periodic flashing in the core region as a result of the core inlet temperature hovering around saturation, have little effect on reactor power as the depressurization together with boron injection shuts down the reactor and the total power level drops to decay power level (Figure 3).

Boron injection is an important operator action to mitigate reactor power in an ATWS-ED transient. In the TRACE model, boron is injected to the lower plenum of the VESSEL component with an effective concentration that accounts for mixing and remixing. The boron inventory in the core region is shown in Figure 7 as a function of time. The injection starts at

211 s, and it takes 30-40 s for the boron to reach the core region. The buildup of boron in the core appears to level off at about 400 s. This is due to the boron concentration at the injection point becoming zero as shown in Figure 8. The reduction in boron concentration at the injection point is a feature of the boron transport model when boron stratification is predicted. The model keeps track of the stratified boron for later delivery into the coolant when the flow condition again supports remixing of boron. A later increase in boron inventory at about 700 s coincides with the refilling of the lower plenum along with rising downcomer water level from increased feedwater flow causing an increase in core flow. An increase in boron inventory is also observed after water level recovery commencing at 2180 s. Raising the water level causes a surge in core flow (Figure 6) and provides the sweeping flow through the lower plenum to remix the stratified boron in the coolant. As expected the enhanced remixing of boron is reflected in an increase in the injection boron concentration (Figure 8) at the time of level recovery.

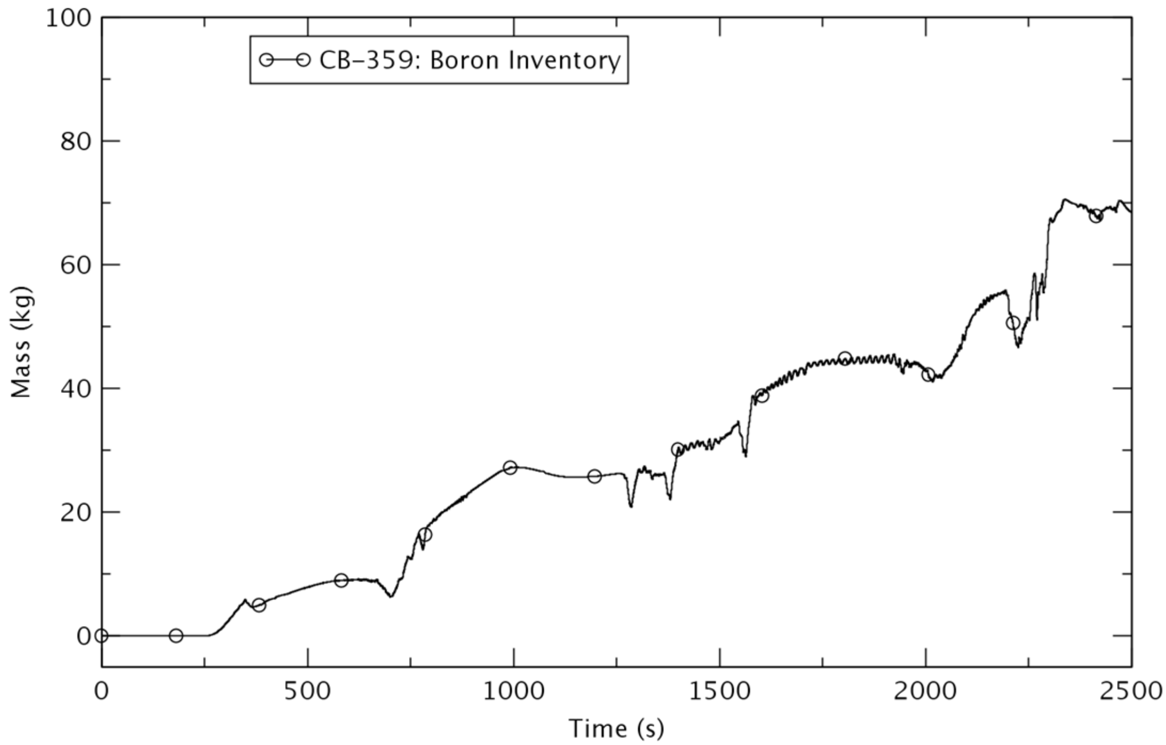

Figure 7 Boron Inventory in the Core Region.

Reactivity components (including total, fuel temperature (T_f or Doppler), moderator density (dm), and boron) as calculated by PARCS for this ATWS-ED transient are shown in Figure 9. The net reactivity of the core stays negative after around 1000 s and this is indicative of sufficient buildup of negative boron reactivity to sustain a reactor shutdown. It is observed in the figure that restoration of water level at 2180 s causes a positive increase in the moderator density reactivity but that is more than compensated for by a corresponding increase in the negative contribution from the boron reactivity. This increase in boron reactivity is a direct consequence of the boron transport model that correctly predicts, under increasing core flow condition, remixing will increase the delivery of boron to the core.

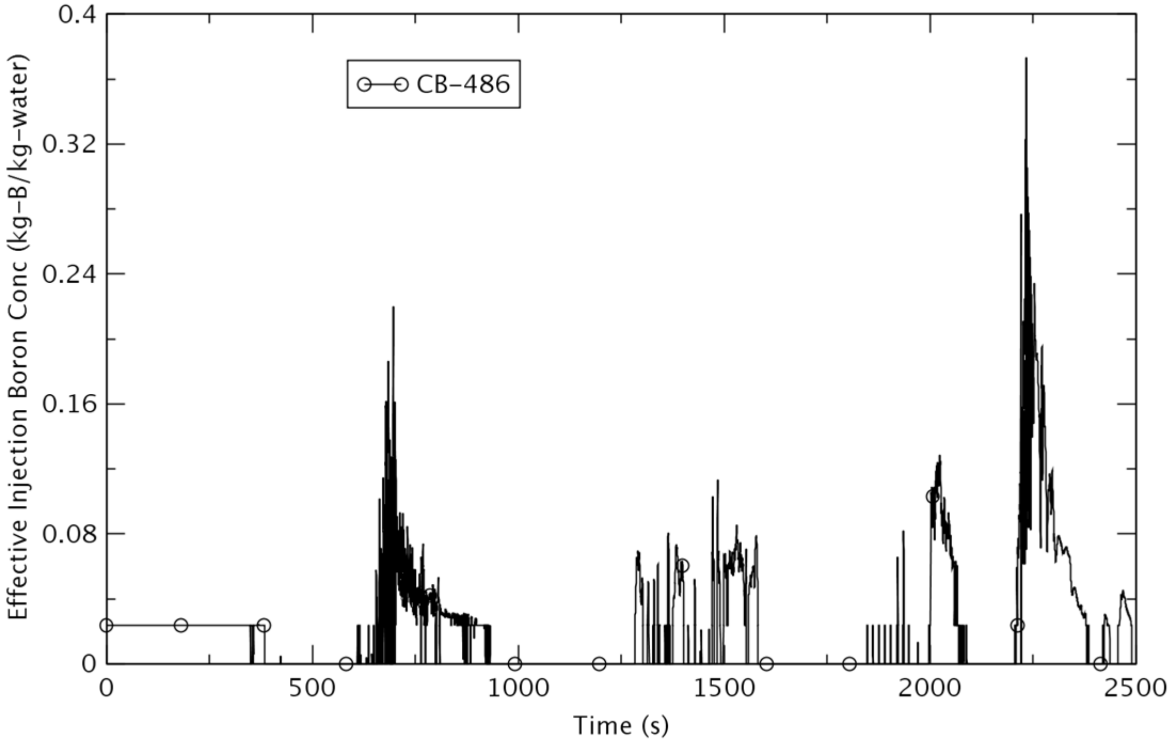

Figure 8 Effective Injection Boron Concentration.

The TRACE calculation shows that there is no recriticality due to either choking in the SRVs or dilution of boron in the coolant. The steam flow through the SRVs is choked but the SRVs are of sufficient capacity that no significant repressurization of the RPV is observed.

One of the potential causes of recriticality is the dilution of boron concentration in the core. This can be the result of boron stratification in the lower plenum due to low flow rate and/or an increase in water density due to ED and addition of feedwater. The TRACE calculation does not indicate any instance of recriticality. Therefore, the TRACE analysis demonstrates that the effects of ED and feedwater injection are not sufficient to cause recriticality due to boron dilution. The effect of boron dilution is only observed briefly between 500 s and 700 s in Figure 9. During that period the boron reactivity shows a positive slope indicating a decrease in boron reactivity.

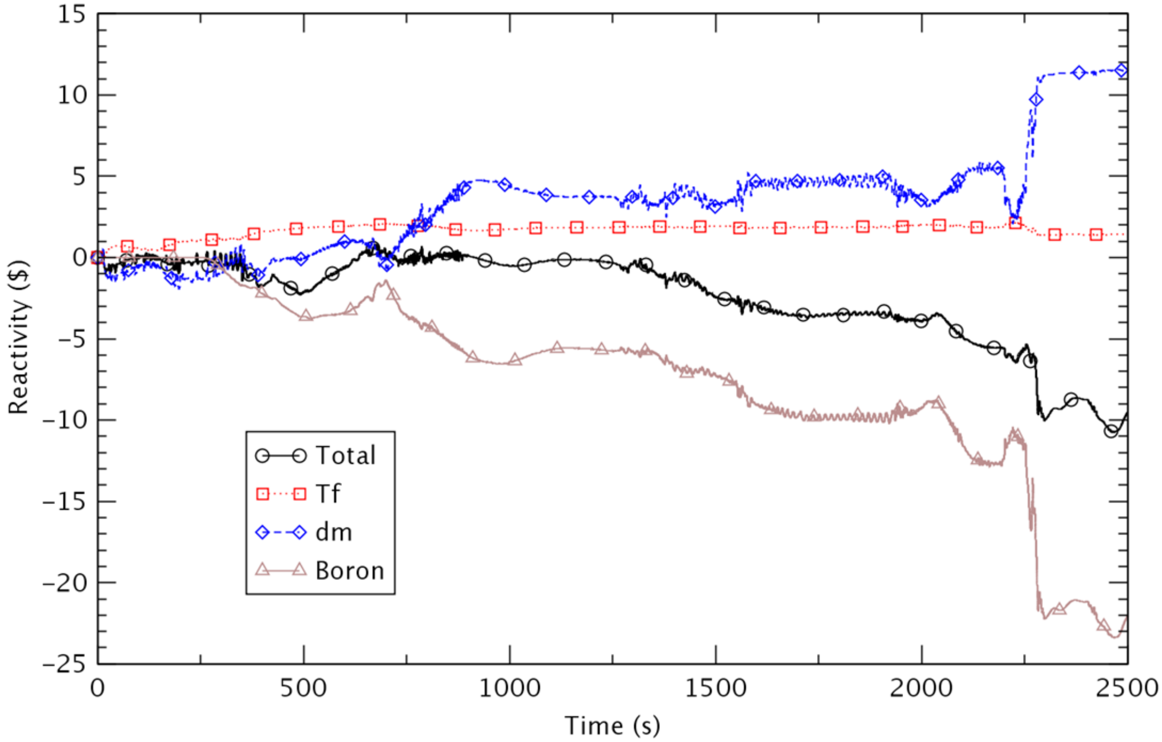

Figure 9 Core Reactivity.

4. CONCLUSIONS

A TRACE/PARCS BWR/5 model has been developed with active and passive components and features that capture operator actions to mitigate an ATWS. These features include control systems to model boron transport in the bottom of the lower plenum, reactor water level control and operation of SRVs in banks. The boron transport model is noteworthy because it allows for stratification and remixing and not just simple entrainment as normally modeled. A detailed PARCS core model treats each fuel assembly explicitly. A mapping scheme that is applicable to the three exposures considered maps the 764 assemblies to 27 TRACE hydraulic channels.

The effectiveness of passive and active components and operator actions in mitigating an ATWS requiring emergency depressurization, starting from MELLLA+ conditions, has been demonstrated. The plant response shows that the fuel integrity and the pressure suppression capability of the containment are not challenged in an ATWS initiated by an MSIV closure. Once sufficient boron has accumulated in the core, the reactor stays sub-critical and the negative boron reactivity is more than sufficient to overcome positive reactivity introduced by decreasing fuel temperature and increasing moderator density. The boron transport methodology implemented in the TRACE BWR model is shown to be capable of simulating the phenomena of boron stratification and remixing in the lower plenum of the reactor vessel.

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