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INTRODUCTION

A TRACE model has been developed for using the TRACE/PARCS computational package [1, 2] to simulate anticipated transients without scram (ATWS) events in a boiling water reactor (BWR). The model represents a BWR/5 housed in a Mark II containment. The reactor and the balance of plant systems are modeled in sufficient detail to enable the evaluation of plant responses and the effectiveness of automatic and operator actions to mitigate this beyond design basis accident.

The TRACE model implements features that facilitate the simulation of ATWS events initiated by turbine trip and closure of the main steam isolation valves (MSIV). It also incorporates control logic to initiate actions to mitigate the ATWS events, such as water level control, emergency depressurization, and injection of boron via the standby liquid control system (SLCS). Two different approaches have been used to model boron mixing in the lower plenum of the reactor vessel: modulate coolant flow in the lower plenum by a flow valve, and use control logic to modulate boron concentration according to coolant flow rate.

SYSTEM MODEL

The TRACE model of the BWR/5 plant consists of a number of hydraulic components and heat structures and is modified from a model provided by the U.S. Nuclear Regulatory Commission. Fuel assemblies are modeled with CHAN components. A POWER component identifies CHANs for coupling with PARCS. Figure 1 is a node diagram providing the component view of the complete model. The model consists of a BWR vessel (with internals consisting of one jet pump, a lower plenum flow control valve, two control rod guidetubes, and two steam separators), 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 SLCS lines (for lower plenum and upper plenum injection), a main steamline with in-board and out-board main steam isolation valves (MSIVs) and a branch to safety/relief/automatic depressurization system valves (SRVs and ADS), turbine control valve (TCV), and a primary containment (drywell and wetwell) with suppression pool cooler and passive heat structures (structural components). Plant configuration options are included to allow the model to simulate BWR/4-like SLCS injection into the lower plenum of the vessel. Control systems consisting of signal variables, control blocks and trips complete the TRACE model.

MODEL FEATURES

Development of the model and its application to ATWS events initiated by turbine trip and MSIV closure have been documented in [3] and [4]. The following discussion highlights some of the more significant features of the TRACE model.

Vessel

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. Slab heat structures are used to represent the vessel wall, core shroud, and internal support structures. The bottom head of the vessel is divided into three axial levels to enable a more realistic simulation of boron mixing in the lower plenum.

In one version of the model, a lower plenum valve (LPV), located in Ring 2 at the top of axial level 3, was used to emulate the effect of boron stratification and mixing/remixing in the bottom of the lower plenum (BLP). The LPV controls coolant flow through the BLP as the jet pump discharge is above the LPV. Below the stratification core flow rate setpoint, the LPV closes to isolate the lower regions of the lower plenum and prevent effective entrainment of borated water into the active core region. When the core flow rate increases above the remixing threshold the LPV opens with a flow rate based area-curve to simulate increased remixing effectiveness.

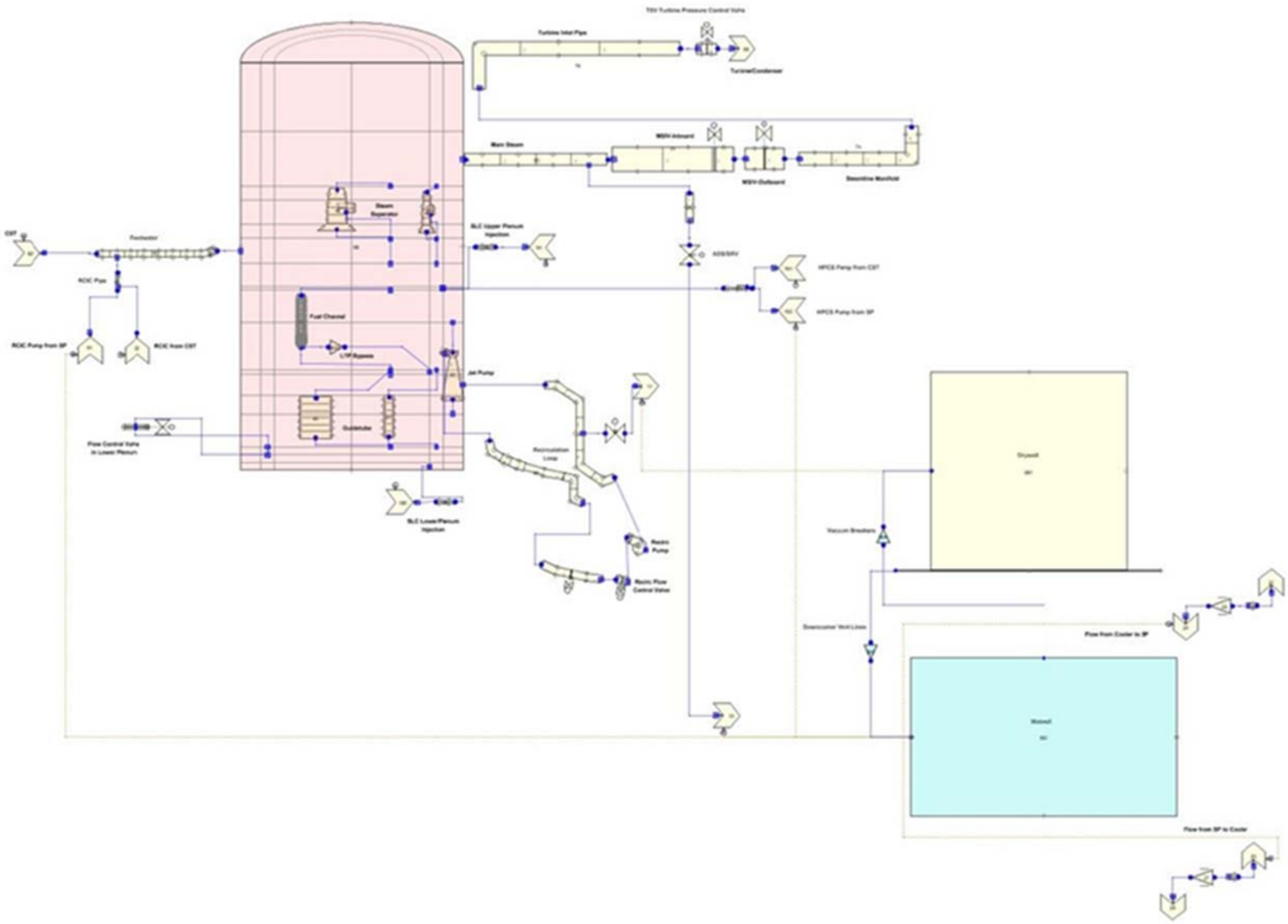

Figure 1 Component View of the BWR/5 Plant for ATWS Simulations

The boron transport model was later replaced by another approach discussed in the next section.

Based on user experience, stable core flow is achieved when 3D level tracking is turned on only in the downcomer region and the vessel region outside the two steam separators. It is noted that these two regions are the only parts of the VESSEL where a free surface exists and thus it is logical to apply 3D level tracking only in these two regions. The strategy is later modified by disabling level tracking in the vessel Ring 3 for all nodes starting at the feedwater injection sparger and below, until reaching a node near the level control strategy area (e.g. top of active fuel). This is intended to overcome the under-estimation of interfacial heat transfer area when level tracking is on.

The guidetubes in Rings 1 and 2 of the VESSEL are each modeled with one effective guidetube in each Ring. Each guidetube is modeled with a PIPE component penetrating the core support plate with inlet in axial level 3 and outlet in axial level 7. The guidetubes are used to model core bypass flow through the core support plate and they also provide an alternative flow path for the borated coolant to flow from the core bypass region (volume outside the channel box) allowing the settling (stratification) of the boron solution in the lower plenum of the vessel.

Boron Transport Model

TRACE does not have a mechanistic model capable of simulating the mixing, stratification, and remixing of boron explicitly but it has a solute-tracking option (ISOLUT=1) that will track entrained boron. While testing the LPV implementation of the boron mixing model it was found that transport of boron in the BLP was sensitive to the time step size and the choice of the numerical scheme, i.e. SETS or semi-implicit (SI). The use of SI limits numerical diffusion and is attributed to significant differences in the predicted axial distribution of boron in the BLP. Since the calculation is sensitive to the time step size, and TRACE internally controls the time step size, it is possible for TRACE to predict different transient progressions based on factors such as computing platform. This was not considered robust and therefore, an alternate approach, different from the use of the LPV for boron transport, was developed.

An alternative boron transport model was developed to approximate the expected behavior of the borated solution once injected into the BLP. The new model captures the key phenomena of interest: stratification, entrainment, remixing, and circulation. The model simulates the SLCS injection using a combination of a FILL and PIPE component that inject at a specified time dependent flow rate and an effective boron concentration that accounts for boron mixing and remixing. The effective boron concentration is evaluated during a transient by control logic.

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 that enters the vessel is split into two streams, entrained and stratified. The fractional split between the two streams is characterized by an empirical factor γ, the mixing coefficient. Qualitatively when entraining conditions exist, γ is unity, and when the core flow rate is low and the solution is presumed to stratify, γ 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 BLP. Conceptually boron stratified in the BLP can be split into two streams characterized by an empirical factor θ, the remixing coefficient, that is flow dependent. Depending on the flow rate of the coolant sweeping through the BLP a fraction (θ) of this flow delivers the boron for remixing.

The boron transport model is implemented in TRACE by use of control logic to evaluate C_{FILL}, the effective boron concentration for injection into the vessel. C_{FILL} is determined from the contribution of boron from two streams, the entrained stream (γ stream) and the remixed stream (θ stream). The concentration of boron in the entrained stream is taken to be the same as the actual boron concentration in the SLCS tank. The concentration of boron in the entrained stream is calculated from the mass balance for the stratified boron in the BLP. The continuity equation for the mass balance has a source from the (1-γ) stream and a sink from the θ stream.

To simulate the total delivery of entrained boron into the core due to both mixing and remixing, the SLCS injection is simulated as occurring upstream of both the SLCS injection sparger and the lower plenum. The proposed injection location is directly beneath the jet pump outlet nozzle. Further, TRACE is known to not conserve momentum for vessel cells with a zero velocity boundary condition along the flow direction, as is the case at the bottom of the downcomer. To partially offset the momentum loss at this location, the SLCS injection is directed radially inward at the outer face of Ring 3. While the momentum addition and momentum loss will not fully cancel each other, this approach aims to minimize the numerical impact of the SLCS injection on total momentum. Furthermore, the injection temperature and mass flow rate are set to be equal to the nominal values for the SLCS to preserve mass and energy.

Core Model

There are 764 fuel assemblies in the core and they are associated with the two inner radial rings in the VESSEL component, 616 assemblies in Ring 1 and 148 assemblies in Ring 2. Ninety-two of the fuel assemblies in Ring 2 are identified as peripheral assemblies because they are located on the outer edge of the core next to the core shroud. Each fuel assembly has 92 fuel rods and two water rods arranged in a 10x10 array with each water rod occupying four grid positions. There are three types of fuel rods, full length, partial length and gad rod (rods with integral gadolinia burnable poison) and they are grouped together as separate rod groups in the CHAN component. A fourth and fifth rod group represent the hot rod in an assembly and the water rods respectively.

The core model has two different configurations, a 27 CHAN core and a 382 CHAN core [3, 4]. For the 27 CHAN core the grouping is based on geometrical and fuel cycle considerations. The logic considers burnup and proximity to control blades. It also accounts for different inlet orifice loss in the peripheral assemblies. The 382 CHAN core takes into account the half core symmetry and is used for instability analysis in an ATWS transient.

The CHAN model incorporates three TRACE options: dynamic gas-gap in the fuel rod, modified 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 [3, 4].

Reactor Core Isolation Cooling System

The RCIC system supplies coolant to maintain the reactor water level between levels L3 and L8 (these are water level setpoints and are different from the axial levels in the VESSEL component) when the reactor is isolated, in particular after the MSIV closure. The RCIC, with its steam-driven pump, will take suction first from the condensate storage tank (CST) until the depletion of the reserve and then from the suppression pool (SP). Control logic for the RCIC has been incorporated to account for net positive suction head, low pressure operation, and condensate storage tank capacity.

Feedwater and Reactor Water Level Control

A three-element feedwater (FW) controller is included in the BWR/5 TRACE model to maintain reactor water level (RWL) at the desired level setpoint based on the following controller inputs: FW flow, steam flow, and reactor water level (RWL). Adjusting the RWL input to the controller allows simulation of operator actions to control RWL 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 controller input is the sum of the actual RWL and the bias.

Safety Relief Valve Model

The BWR/5 plant model has a total of 18 safety relief valves (SRVs) arrayed in five banks and seven of these valves in two banks also belong to the auto-depressurization system (ADS). In an initial simplified model a single valve was used to represent all the open valves. The fractional opening of this lumped valve was determined by a control system that makes use of the trip status of each bank of SRVs. The trip status is a function of the lift and reset pressures for each bank and the main steam line pressure. The single-valve model failed to recognize that while the lumped valve is only partially open, some of the lower pressure banks are already fully open. In a revised model, each bank of the operable SRVs is modeled with a separate valve. The opening and closing of the valves are controlled by logic that reflects the two functional modes of the SRVs, the relief mode and the auto-depressurization mode. This revised model provides a more accurate representation of the pressure loss in a partially open SRV.

Containment Model

The CONTAN component in TRACE is used to model the two compartments in a Mark II containment, the drywell and the wetwell.

A suppression pool cooler is modeled to emulate the suppression pool cooling mode of the residual heat removal system (RHR). The code version used for this study did not allow a control system to activate and deactivate the CONTAN component cooler. In order to enable the activation of suppression pool cooling with control logic, a scheme was developed to remove energy from the suppression pool water by feed and bleed (remove warm pool water and replenish with cold water). There are two parts to the scheme, a source to supply the feed and a sink to receive the bleed. The connections to the wetwell are modeled with two BREAK components. The required mass flow to remove a certain amount of energy from the suppression pool is calculated by noting the heat removal capacity of the RHR heat exchanger.

For calculations where the heat capacity of the containment is important, as in the case of an ATWS requiring emergency depressurization (ED), the presence of containment heat structures provides heat sinks and increases the heat capacity of the suppression pool. Heat structures added to the CONTAN model include walls of the wetwell (SP plus the airspace) and the reactor pedestal in the wetwell.

CONCLUSIONS

A TRACE BWR/5 model has been developed for applications that include the simulation of beyond design basis accidents, such as ATWS events initiated by turbine trip and MSIV closure. The model includes active and passive components and also has features that capture operator actions to mitigate an ATWS. Control systems were developed to model boron transport in the bottom of the lower plenum and reactor water level control.

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REFERENCES

1. "TRACE V5.0 Theory Manual," ML120060218, U.S. Nuclear Regulatory Commission, June 4, 2010.
2. T. Downar, et al., "PARCS: Purdue Advanced Reactor Core Simulator," *Proc. PHYSOR 2002*, Seoul, Korea, October 7-10, 2002.
3. L-Y. Cheng et al., "BWR Anticipated Transients Without Scram in the MELLLA+ Expanded Operating Domain – Model Development and Events Leading to Instability," BNL-97068-2012, Brookhaven National Laboratory, March 30, 2012. To be issued as a NUREG/CR, 2013.
4. L-Y. Cheng et al., "BWR Anticipated Transients Without Scram in the MELLLA+ Expanded Operating Domain –Events Leading to Emergency Depressurization," BNL-98584-2012, Brookhaven National Laboratory, November 27, 2012. To be issued as a NUREG/CR, 2013.