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INTRODUCTION

Anticipated transients without scram (ATWS) in a boiling water reactor (BWR) were simulated in order to understand reactor response and determine the effectiveness of automatic and operator actions to mitigate this beyond-design-basis accident. The events of interest herein are initiated by a turbine trip when the reactor is operating in the expanded operating domain MELLLA+ [maximum extended load line limit plus]. In these events the reactor may initially be at up to 120% of the original licensed thermal power (OLTP) and at flow rates as low as 80% of rated.

For these (and similar) ATWS events the concern is that when the reactor power decreases in response to a dual recirculation pump trip, the core will become unstable and large amplitude oscillations will begin. The occurrence of these power oscillations, if left unmitigated, may result in fuel damage, and the amplitude of the power oscillations may hamper the effectiveness of the injection of dissolved neutron absorber through the standby liquid control system (SLCS).

METHODOLOGY

The methodology utilizes TRACE/PARCS [1, 2], coupling thermal-hydraulics and thermal-mechanical modeling of all relevant reactor components by TRACE and the modeling of neutronics in the core by PARCS. The code package has been assessed for its applicability to ATWS [3], and additional studies with the current model [4, 5] provide insights into its capability. The model is capable of simulating different phases of ATWS events with instability (ATWS-I) from inception of instability through growth, transition, and decay.

The development of the models used in the current analysis is documented in [4]. Reactor systems and components for a BWR/5 that are modeled are:

- the steamline, including turbine bypass and stop valves, safety/relief valves, and main steam isolation valves
- the recirculation loop, including recirculation pumps
- feedwater and reactor water level control
- reactor core isolation cooling with options to draw from the condensate storage tank or the suppression pool
- standby liquid control system (SLCS)
- primary containment (drywell and wetwell) with pool cooler, and
- the vessel, including core, steam separator/dryer, and jet pumps.

The core requires special attention during ATWS-I simulations and therefore each fuel bundle is represented individually in the PARCS neutronics model, albeit two bundles share the same thermal-hydraulic channel in the TRACE model. Nuclear data for each nuclear node are a function of thermal-hydraulic variables and the presence of control blades or soluble boron. Models for three different exposures in the equilibrium cycle are available: beginning of cycle (BOC), peak hot excess reactivity (PHE, close to the middle of the cycle), and end-of-full-power life (EOFPL, close to the end of cycle). Each TRACE channel incorporates five rod groups, four to simulate different fuel rod groups and one for the internal water rods.

RESULTS

The base ATWS-I case starts at 120% OLTP (3988 MWt) and 85% of rated flow (11,620 kg/s or 25,560 lb/s) at PHE with the assumption of 100% turbine bypass being available.

Other sensitivity cases were run to assess the effect of:

- initial core flow rate
- turbine bypass capacity
- time in cycle
- gap conductance

For gap conductance a low limit of 5,000 W/m^2-K (881 BTU/hr-ft^2-°F) [6], a high limit of 161,000 W/m^2-K (28,400 BTU/hr-ft^2-°F) [6] and a variable quantity

determined by a dynamic model within TRACE were considered.

The sequence of events for the base ATWS-I case is given in Table I. A turbine trip results in turbine stop valve (TSV) closure and reactor trip is assumed to fail. The turbine trip signal also initiates a trip of the recirculation pumps (2RPT). Turbine bypass is simulated by reopening the TSV to its initial 100% flow area. The dual recirculation pump trip results in a ramp-down of forced recirculation flow as the pumps coast down and natural circulation flow develops in the vessel. Isolation of the turbine results in a steady decrease in feedwater (FW) temperature because extraction steam feed to the FW heater cascade has been stopped.

Under natural circulation conditions with increased core inlet subcooling due to decreased FW temperature, the core becomes unstable and power oscillations occur. Manual operator actions reducing reactor water level and injecting boron are simulated to gauge the effectiveness of these actions in suppressing power oscillations and reducing power.

Table I. Sequence of Events – Base ATWS-I Case

Time (s)	Event
0.0	• Null transient simulation starts.
10.0	• Null transient simulation ends. • TSV closure is initiated by turbine trip. • Recirculation pumps are tripped on the turbine trip. • Feedwater temperature starts decreasing.
10.1	• TSV closes completely and starts opening again to simulate 100% turbine bypass.
11.1	• TSV (bypass) completes opening.
~11.4	• Steam flow starts decreasing.
~12.3	• Feedwater flow starts decreasing.
~95	• Power oscillation above noise level is apparent (instability onset).
120	• Water level reduction (WLR) is initiated by reducing the normal water level control system setpoint linearly to top of active fuel (TAF) over 180 s.
130	• Boron injection is initiated and linearly ramped to full flow at 190 s.
~144	• Bi-modal oscillation of the core power is observed.
~160	• Boron starts accumulating in the core.
~163	• Downcomer water level begins decreasing. • Peak cladding temperature of ~1700 K occurs.
~240	• Power oscillation ends.
400	• Simulation ends.

Figure 1 shows the reactor core power during the event. Power increases suddenly when the TSV closes at 10 s. This is caused by the sudden rise of the system pressure, which results in collapsing voids (increasing moderator density) and positive reactivity feedback.

As power increases, the fuel temperature also increases and the Doppler feedback effect adds negative reactivity. Upon opening of the turbine bypass valve the system pressure starts to decrease suddenly. This together with the significant reduction in core flow due to the 2RPT results in voiding in the reactor pressure vessel (RPV). The negative reactivity feedback due to void causes the power to decrease.

The power then settles to a level consistent with natural circulation flow. Next, the reactor enters into a period of slow power increase (from approximately 30 s to 95 s), responding to an increase in core inlet subcooling.

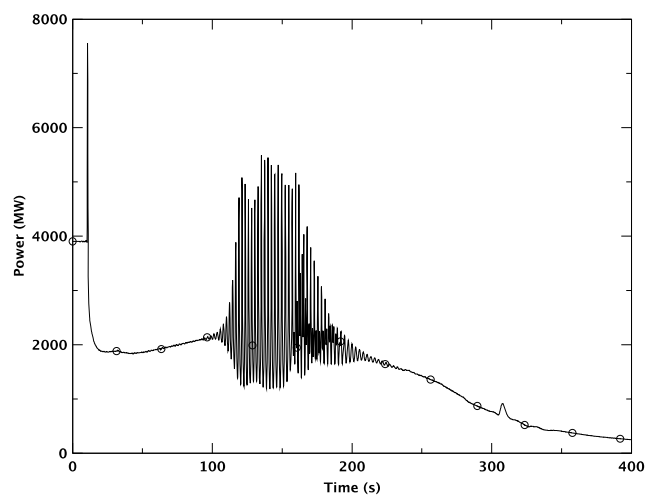

Figure 1. Reactor Core Power – Base ATWS-I Case

Oscillations in power are observed from around 95 s through 240 s. The reactor instability is dictated by a combination of effects. The power remains substantial (>50% of initial power) while core flow is dictated by natural circulation; hence resulting in a high power to flow ratio. Additionally, the power becomes heavily bottom peaked in response to high inlet subcooling. These two effects are destabilizing. After 160 s, boron starts to accumulate in the core and the oscillations become damped and eventually total power decreases to decay heat level.

The amplitude of the power oscillation grows after initiation until around 120 s when the oscillation reaches a limit cycle. The peak power between subsequent pulses varies, indicating that bifurcation of the power oscillation has likely occurred. The core power amplitude remains near this limit cycle value until around 160 s and then reduces when boron is introduced.

Around 144 s the power oscillation evolves into a bi-modal mode with both a core wide and regional component. The oscillation contour begins to develop a regional (or out-of-phase) component. The evolution of a coupled bi-modal oscillation contour indicates non-linear harmonic coupling. The non-linearity is also evident in the accompanying frequency doubling.

Figure 2 shows the power contours, axially averaged bundle powers, at 152 s when bi-modal oscillation becomes recognizable and clear. The colors blue and dark red indicate low and high power, respectively. As mentioned above, the core is represented by 764 fuel assemblies in the PARCS neutronics model while half-core symmetry is assumed for the TRACE hydraulic model (382 channels). As shown in Figure 1, the bi-modal oscillation starts around 144 s. Initially the amplitude of the oscillation is very small, but as the event progresses, it gets larger and becomes recognizable in the total power at around 152 s. The bi-modal power fluctuation appears to oscillate about the harmonic plane, or the y=0 plane in Figure 2.

The 2-to-1 mapping between neutronic nodes (fuel assemblies) and thermal-hydraulic channels is a limitation of the coupled model which can have an impact on the contour of the oscillations. Higher harmonic modes are degenerate insofar as equivalent, symmetric harmonic shapes exist for the higher order modes. This degeneracy allows certain degrees of freedom if higher order harmonic modes are excited in the overall oscillation contour. The 2-to-1 channel mapping does not allow the calculation to resolve the degenerate symmetric harmonic shapes, which would potentially allow the rotation of the oscillation contour azimuthally around the core [7]. However, imposing a half core symmetry is likely to be conservative, at least as far as the hot spot is concerned, in the sense that for a "real" core response (without the half core symmetry restriction) the rotation of the contour will relocate the hot spot with the peak local oscillation magnitude which would not be the case with the half core symmetry assumption imposed. The fuel assembly subject to the highest local power oscillation magnitude will have some time to recover (or cool down) from the power pulses if the model allows the higher harmonic modes to rotate around the core.

CONCLUSIONS

The objective of this work was to use TRACE/PARCS simulations to understand reactor response and determine the effectiveness of automatic and operator actions during a BWR ATWS initiated at MELLLA+ operating conditions. The scenarios studied are initiated by a turbine trip and lead to large amplitude core instability. The calculations were done at nominal initial conditions and assumptions for three cycle exposures during an equilibrium cycle and with

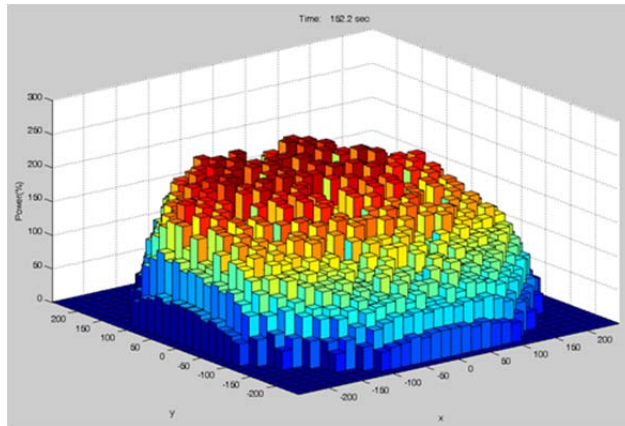

Figure 2. Radial Power Showing Bi-Modal Oscillation

different turbine bypass fraction, initial core flow rate, and gap conductance.

The most significant observations from analyzing the overall transients are:

- Operator actions to reduce water level and start the SLCS in order to get soluble boron into the core are effective in mitigating power oscillations in ATWS-I transients and help to keep power low and eventually shut down the core.
- Power oscillations are more severe at PHE relative to BOC and non-existent at EOFPL. The relative stability at EOFPL is attributed to several factors: a relatively lower core power after the 2RPT, a lower liquid subcooling at the core inlet, and an axially top-peaked core power shape.
- The sensitivity study has demonstrated the effects of turbine bypass capacity and initial core flow on the ATWS instabilities in a BWR. It is thus prudent, for each plant-specific application, to model each plant with its proposed licensed limiting condition.
- The calculated peak clad temperature (PCT) for several cases was greater than 1,478 K (2200°F). The PCT excursion is due to a failure to rewet once local power oscillations have resulted in cladding temperature exceeding the minimum stable film boiling temperature (Tmin). The peak temperatures reached are sensitive to correlations for Tmin, transition boiling and film boiling. High quality data for code assessment at conditions encountered in the ATWS-I calculations is scarce resulting in a large uncertainty in the prediction.

The most significant observations from analyzing the behavior when the reactor is unstable are:

- The determination of core stability cannot be based on the core average power alone. In analyzing the power oscillations the transition from fundamental to harmonic modes may result in a decrease in the average core power, suggesting an approach to a more stable state. However, higher mode

oscillations, the first harmonic in particular, have been observed to exhibit sustained oscillations in individual channels (or fuel bundles) with growing amplitude. The space-time kinetics analysis conducted with the TRACE/PARCS code system provides the additional spatial element to delineate the effects of regional and out-of-phase oscillations. Visualization tools, such as computer animation, are best suited to analyze the complex spatial detail of the calculation results.

- The current assumption of half-core symmetry in the mapping of hydraulic channels may not be adequate to resolve higher harmonic modes in the core response. This is particularly true for regional oscillations that manifest in different azimuthal modes which have been observed in plant events and other calculations [5].
- A figure-of-merit (FoM) was defined for each of eight phases of instability events. The FoMs that show expected behavior are (approximately) power-to-flow during the approach to the onset of instability and the growth ratio (or decay ratio) during the phase from onset through normal growth. In general, reactor instability becomes more severe when the power is higher and a higher growth ratio leads to more severe power oscillations.

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