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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 closure of the main steam isolation valves (MSIVs) 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.

In these cases, the concern is the amount of energy being placed into containment during the mitigation period. This thermal load may exhaust available pressure suppression capacity of the containment wetwell, which would prompt an emergency depressurization (ED) according to standard emergency operating procedures. The emergency depressurization raises several concerns: 1) the reactor has undergone a beyond-design-basis event, and fuel damage, e.g. clad perforation, 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 valves.

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 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 (SRVs), 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)
- automatic depressurization system (ADS)
- primary containment (drywell and wetwell) with pool cooler, and
- reactor pressure vessel (RPV), including core, steam separator/dryer, and jet pumps.

The core requires special attention and each fuel bundle is represented in the PARCS neutronics model, albeit multiple bundles share the same thermal-hydraulic channel in the TRACE model. The resulting model with 27 channels has been shown to reproduce the steady state power distribution obtained with 382 channels [4]. Nuclear data for each nuclear node are a function of thermal-hydraulic variables and the presence of control blades or soluble boron. TRACE/PARCS models [4] for three different exposures in the equilibrium cycle were developed: 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.

Several manual operator actions are treated in the ATWS-ED analysis:

- Water level control to top of active fuel (TAF), TAF plus five feet (TAF+5) or TAF-2.
- Boron injection to the lower plenum.
- Emergency depressurization (ED). Operator actuation of the ADS is triggered by the heat capacity temperature limit (HCTL) of the suppression pool.
- Water level recovery to normal water level.

Water level control is simulated by sending a biased signal to the feedwater controller. The biased water level signal is the sum of the current level and the bias which is the difference between the nominal level setpoint and the desired water level.

Boron transport in the lower plenum is simulated by using a control system to determine the effective concentration of the boron solution injected into the reactor. The model captures key phenomena of interest: stratification, entrainment, remixing, and circulation [4].

RESULTS

The base ATWS-ED case starts at 120% OLTP (3988 MWt) and 85% of rated flow (11,620 kg/s or 25,560 lb/s). Calculations have been performed [4, 5] to analyze the parametric effects of:

- time in the fuel cycle (BOC, PHE, and EOFPL)
- initial core flow rate (75%, 85%, and 105% of rated flow)
- reactor water level strategy (to top-of-active-fuel (TAF) and TAF-2 and TAF+5)
- SLCS injection location

SLCS injection locations refers to the option to model injection in the lower plenum as in the BWR/4 design or injection in the upper plenum as would be the case for a BWR/5.

The sequence of events for an ATWS-ED base case is given in Table I to illustrate the general progression of the transient. This case starts at BOC and assumes water level control is to the top-of-active-fuel (TAF) with SLCS injection into the lower plenum.

The reactor power until 1500 s (after which there are only small changes) is shown in Figure 1. In response to the pressurization of the RPV following the MSIV closure there is an increase in power due to the collapse of steam void in the core. The pressurization also leads to a drop in water level in the downcomer and a trip of both recirculation pumps (2RPT). The reactor power decreases in response to primary flow coastdown following the 2RPT. In the meantime steam pressure is relieved as steam flows to the suppression pool through the safety relief valves (SRVs). As the core flow shifts to natural circulation the water level begins to recover due to increased feedwater (FW) flow. The increased FW flow combined with a steady decrease in FW temperature (due to the stoppage of extraction steam feed to the feedwater heater cascade) causes the core inlet subcooling to increase, accompanied by a corresponding increase in reactor power.

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

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
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.

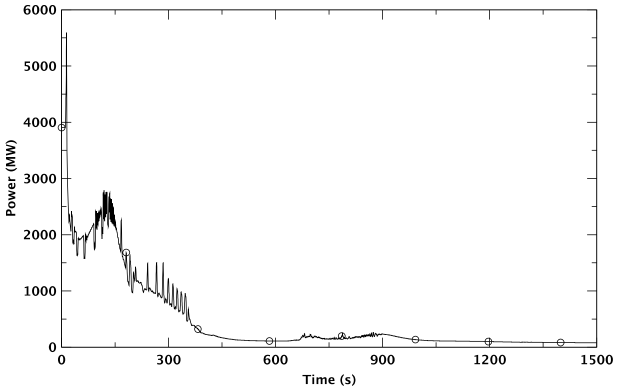

Figure 1. Reactor Core Power –ATWS-ED Base Case

The reactor power remains relatively high (roughly 50% of initial power) at the reduced core flow rate. The water level control strategy is successful in bringing the reactor power on a downward trend. After the initiation of boron injection there is some delay while the boron concentration builds up in the core sufficiently to mitigate the ATWS event and eventually shut down the reactor. Once the heat capacity temperature limit (HCTL) is reached in the suppression pool, emergency depressurization is simulated by tripping the ADS. This causes a momentary water level swell in the downcomer. In response to the depressurization, the reactor power decreases to near decay heat level and voiding is observed in the lower plenum of the reactor vessel. The subsequent refilling of the lower plenum, with coolant drawn from the downcomer, causes the water level to drop below the desired elevation, in this case the TAF. In response, the level control system increases the feedwater flow raising the water level and increases the core flow, resulting in a temporary and small increase in reactor power.

The operation of the turbine driven reactor core isolation cooling system (RCIC) is hampered significantly by the depressurization of the RPV. The periodic voiding and refilling of the lower plenum and the corresponding responses of the feedwater flow lead to perturbations in water level and core flow. However, negative reactivity introduced by boron entrained in the core flow maintains the reactor at low power level. Towards the end of the simulation the water level is restored by operator action to its normal level. The accompanying positive reactivity addition due to increases in core flow and core inlet subcooling are effectively controlled by the enhanced delivery of boron to the core and as a result the core power remains at the decay heat level.

In an ATWS event the reactor power is controlled by auxiliary shutdown systems, such as the standby liquid control system, and other operator actions, such as water level control and emergency depressurization. However there are phenomena that might lead to recriticality during the later phase of the transient such as,

- Choking in the safety/relief valves (SRVs) that leads to a pressure/power excursion later in the transient.
- Decrease in boron concentration with approximately constant boron mass while the coolant density increases.

Choking in the ADS valves and coolant density increase are observed in the calculations. However, the boron concentration accumulated in the core resulted in more than sufficient negative reactivity to suppress positive reactivity changes during the ATWS-ED transients.

The transient results indicate that the containment pressure and the suppression pool water temperature both stay low enough as not to challenge the containment integrity and its pressure suppression capability. The pool cooler is shown to be successful in mitigating excessive temperature increases due to the steam from the SRVs.

The timing and magnitude of the maximum peak clad temperature (PCT) is different for the various ATWS-ED cases. When PCT is reached early in the transient, it occurs either right after the MSIV closure or shortly after initiation of water level reduction when reactor power is still ~50%. When late, it happens after the ED when the core is nearly voided and the reactor power is at or near decay heat level. The high void condition usually results in more limiting PCT even though the reactor may be at a lower power level than the case with a higher core flow. However, all of the predicted PCTs are below 1478 K (2200°F).

In all cases analyzed, there is no overheating of the clad, no recriticality predicted, and no overheating of the wetwell observed.

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 MSIV closure and lead to heat up of the suppression pool and emergency depressurization. The calculations were done at nominal initial conditions and assumptions for three exposures during an equilibrium cycle and with different reactor water level control strategies and different initial core flow rates.

Some of the most significant observations from analyzing these ATWS-ED transients are:

- In all cases considered, the event is mitigated successfully by a combination of automatic recirculation pump trip (2RPT) and operator actions that depressurize the RPV using the ADS, and reduce power by water level control and injection of boron using the SLCS.
- Early action to lower downcomer water level is effective in mitigating a power increase.
- The cycling of SRVs before the emergency depressurization causes power oscillations. No sustained power oscillations related to density-wave oscillations (and core instability) are observed.
- After 2RPT, lowering water level reduces reactor power through a decrease in core flow that results in more voiding in the core.
- Emergency depressurization (ED) results in decreasing reactor power towards the decay heat level.
- The rate of depressurization is a function of the steaming rate, i.e., the reactor power. Higher power generally leads to slower depressurization rate.
- Subsequent to the ED, oscillations in core flow and water level are due to periodic voiding and refilling of the core and the cycling of the feedwater system in an attempt to maintain water level.
- In all cases analyzed there is no re-pressurization, and the reactor stays sub-critical after sufficient boron has built up in the core.
- Injection of boron is effective in overcoming positive reactivity effects due to fuel temperature decreasing, and moderator density increasing.
- There is about 30 s to 50 s delay for the injected boron to reach the core. The delivery of boron is consistent with the boron transport model implemented in the TRACE BWR/5 model [4].

- An increase in liquid water density due to ED or addition of feedwater has no observable impact on the dilution of the boron concentration.
- Boron stratification in the lower plenum due to low core flow is the principal cause of reduction in boron reactivity during the ATWS-ED transient.
- Restoring the water level to its normal elevation results in substantial increase in boron inventory in the core.
- The implementation of two-loop cooling and passive heat sinks in the wetwell of the containment is effective in mitigating the heat-up of the suppression pool and prevents boiling.
- The drywell pressure in all cases is low compared to the design pressure of a typical BWR/5 containment.
- The magnitude and timing of the PCT are sensitive to the initial conditions (exposure and core flow rate) and the reactor water level control strategy.
- In comparing the results of different locations for boron injection (upper and lower plena), the following is observed:
    - o The initial buildup of entrained boron in the core is a little bit faster when the injection is into the upper plenum. However, there is little noticeable difference in the transient response between the two cases.
    - o With the slightly earlier arrival of boron in the core the ED occurs about three seconds later for the case with upper plenum injection.
    - o The maximum PCT, maximum suppression pool temperature, and the maximum drywell pressure are basically identical for the two cases with different locations for boron injection.

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