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Technical Evaluation Review of TRACG Applications to ESBWR ATWS

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Abstract – The application of TRACG to ESBWR ATWS is reviewed in this report and discussed in terms of the thermal-hydraulic and neutronics modeling. Areas of concern are identified and discussed. Some of the RAIs have been addressed by GEH, the remaining RAIs will be addressed at a later date. TRACG has all of the models required to simulate ESBWR ATWS. However, in terms of the mixing and transport of borated solution in the core bypass, core, and lower plenum, it has not been demonstrated that TRACG is conservative.

Abbreviations

AOO	Anticipated Operational Occurrences
ARI	Alternate Rod Insertion
ATWS	Anticipated Transient Without Scram
BWR	Boiling Water Reactor
CCFL	Counter-Current Flow Limiting
CRD	Control Rod Drive
CSAU	Code Scaling, Applicability and Uncertainty
EOP	Emergency Operating Procedures
ESBWR	Economic Simplified Boiling Water Reactor
FMCRD	Feedwater Motion Control Rod Drive
GEXL	GE boiling length dryout correlation
IC	Isolation Condenser
LRNB	Load Rejection Without Bypass
MCNP	Monte Carlo N-Particle
MCPR	Minimum Critical Power Ratio
MOC	Middle of Cycle
MSIVC	Main Steamline Isolation Valve Closure
PCT	Peak Clad Temperature
PIRT	Phenomena Identification Ranking Table
RAI	Request for Additional Information
RCPB	Reactor Coolant Pressure Boundary
RPV	Reactor Pressure Vessel
RPS	Reactor Protection System
RWCU	Reactor Water Cleanup
SCRRI	Select Control Rod Run-In
SDC	Shutdown Cooling
SLCS	Standby Liquid Control System
SRP	Standard Review Plan
SRV	Safety Relief Valve
TCV	Turbine Control Valves
TGBLA	Neutron transport and diffusion coupled computer code for fuel lattice design (Toshiba)

1.0. Introduction

TRACG application to ESBWR Anticipated Transient without scram (ATWS) (i.e. pressurization events, depressurization events, cold water events, and level transient events) was reviewed[1]. The main areas of review for TRACG as applied to ESBWR ATWS are: accident scenario, PIRTs, assessment, and uncertainties. The applicability and uncertainty of TRACG as applied to ATWS follows the CSAU methodology in Ref. 4. Because of the low probability associated with an ATWS event the propagation of errors statistical approach is used. The propagation of errors statistical approach is expected to be conservative.

Section 2.0 of this report identifies the scenarios in which GEH is to apply the TRACG code and associated methodology in Reference 1. Section 3.0 includes a review of GEH's PIRT. Section 4.0 discusses the TRACG thermal-hydraulic modeling. Section 5.0 discusses the TRACG 3-D transient neutronics modeling. Conclusions are in Section 6.0 and References are in Section 7.0.

2.0. Scenario Specifications

ESBWR design[2,3] has 1132 bundles at a reactor power of 4500 MWt. The base line analysis model is based on an equilibrium core of GE14 10x10 fuel. GE14 10x10 fuel assembly has 92 fuel rods and 2 water rods. The 92 fuel rods include 78 full length rods and 14 partial length rods. The active core height is 3.048m (10 ft).

The important safety parameters for ATWS analysis are:

1) Primary system – Reactor pressure vessel (RPV) is limited by the maximum primary stress within the reactor coolant pressure boundary (RCPB) to the emergency limits as defined in the ASME Code Section III,
2) Fuel integrity – peak cladding temperature not exceed 1473 K and local oxidation of the cladding not exceed 17% of the total cladding thickness,
3) Containment integrity – containment pressure is limited by design pressure of the containment structure and suppression pool temperature to the wetwell design temperature,
4) Long-term shutdown cooling – following an ATWS, the reactor shall be brought to a safe shutdown condition and be cooled and maintained in a cold shutdown condition.

ESBWR features that mitigate ATWS are:

1) Alternate rod insertion (ARI) system that is independent of the Reactor Protection System (RPS).
2) Automatic standby liquid control system (SLCS).
3) Electrical insertion of the fine motion control rod drive (FMCRD)s.
4) Automatic feedwater runback under conditions indicative of an ATWS.

AOOs for the ESBWR design can be grouped into the following categories:

1. Pressurization events, including: turbine trip, generator load rejection, main steam line isolation valve closure.
2. Depressurization events, including: opening of one control or turbine bypass valve.
3. Cold water events, including: loss of feedwater heating and inadvertent high pressure coolant injection.
4. Level transient events such as partial or complete loss of feedwater.

These scenarios were reviewed by GEH in terms of the ATWS severity and the following were found to be highest in severity in terms of ATWS (i.e. category I):

1. Closure of all Main Steam Isolation Valves (MSIVC) – Based on generic studies this transient produces maximum values for neutron flux, heat flux, vessel pressure, peak cladding temperature (PCT), and suppression pool temperature.
2. Loss of Condenser Vacuum – Turbine trips on low condenser vacuum and bypass valves are available for a short period time and then close on low condenser vacuum. In long term this AOO scenario is similar to MSIVC. This AOO is included in the severe ATWS category to ensure that short term peak vessel pressure and clad temperature are not limiting.
3. Loss of Feedwater Heating – ESBWR mitigation for loss of feedwater heating is Select Control Rod Run-In (SCRRI). For ATWS, this event is analyzed without SCRRI. This event is included in the high ATWS severity category because of the potential for limiting peak clad temperature (PCT). It is not limiting for vessel pressure or suppression pool temperature, because the turbine bypass valves are available.

The following accident scenarios were included in category II (i.e. less severe than category I):

1. Generator Load Rejection with a Single Failure in the Turbine Bypass System – Pressurization and energy addition to the pool is less severe than MSIVC.
2. Loss of Grid Connection – Response is similar to Load Rejection with bypass.
3. Loss of All Feedwater Flow – Loss of feedwater flow results in reactor power decrease. MSIVC will occur at a low water level. Because of the reduced reactor power, MSIVC ATWS will be more severe than this accident scenario.

The third category of ATWS scenarios covers those cases that have only minor impact to the reactor vessel and containment:

1. Closure of Turbine Control Valve (TCV) – Because other TCVs and bypass valves are available, the pressurization rate is less severe than MSIVC, and the energy addition to the pool is less severe than MSIVC.
2. Generator Load Rejection with Bypass – Pressurization and energy addition to the pool is less severe than MSIVC.
3. Turbine Trip with Bypass - Pressurization and energy addition to the pool is less severe than MSIVC.
4. Turbine Trip with Single Failure in the Turbine Bypass System – Half of the bypass valves are available, therefore pressurization and energy addition to the pool is less severe than MSIVC. Similar to generator load rejection event with a single failure in the bypass system, that is already in category II.
5. Closure of One Main Steam Isolation Valve – Three main steam lines are still available, therefore pressurization rate and energy addition to the pool is less severe than MSIVC.
6. Loss of Shutdown Cooling Function of Reactor Water Cleanup / Shutdown Cooling System (RWCU / SDC) system – Only a concern when reactor is subcritical. When reactor is critical other heat sinks are available.
7. Inadvertent Isolation Condenser Initiation – Results in a moderator temperature decrease and a slow insertion of positive reactivity into the core. Reactor power will settle out at a new steady-state.
8. Runout of one Feedwater Pump – Event is bounded by Loss of Feedwater Heating with SCRRI failure.
9. Opening of One Control or Turbine Bypass Valve – Mild decrease in pressure that is compensated by the control system closing other valves.
10. Loss of Unit Auxiliary Transformer – Results in a fast transfer of the buses and no scram or pressurization.

3.0. Phenomena Identification Ranking

The critical safety parameters for ESBWR ATWSs are reactor pressure vessel (RPV) pressure, peak fuel clad temperature (PCT), containment pressure and suppression pool temperature. Ref. 1 presents the Phenomena Identification Ranking Table (PIRT) for ESBWR ATWSs. The PIRT was developed for 5 phases of the ATWS transient:

1. Short term pressurization, neutron flux increase, and fuel heatup. Void and Doppler reactivity feedback limit the power increase. Safety valve opening limits the vessel pressure. The important phenomena and uncertainties are similar to ESBWR AOO.

2. Feedwater runback, water level reduction. Water level reduction reduces the reactor power. The important phenomena and uncertainties are similar to ESBWR AOO.
3. Boron injection, mixing, and negative reactivity insertion. This phase includes boron transport and mixing.
4. Post Shutdown Suppression Pool Heatup. This phase involves those phenomena that affect decay heat and cooling of the suppression pool. Note the isolation condenser has been designed to terminate steam flow to the pool once the core is subcritical, therefore this phase of the accident is of limited importance.
5. Depressurization of the reactor. Although the ESBWR EOPs have not been developed, they may direct the operator to depressurize the reactor during an ATWS and this is considered in the ESBWR ATWS analysis. If the suppression pool is calculated to reach the heat capacity temperature limit, the energy added to the pool by manual SRV opening is included in the analysis.

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The high importance phenomena for ESBWR ATWS should at a minimum include the high importance phenomena for ESBWR AOO, since ATWS is an AOO without a scram. The list given above includes the ESBWR AOO high importance phenomena, as well as the phenomena associated with the transport, mixing, and reactivity of the boron injected into the system.

4.0. Thermal-Hydraulic Modeling

TRACG is a two-fluid 1D and 3D thermal-hydraulic simulation tool that also includes the capability to do coupled thermal-hydraulic/3D transient neutronics analysis[8]. The TRACG solution of the conservation equations (i.e. mass, energy, and momentum) provide the code capability to address global processes. TRACG correlations and models provide code capability to model and scale dominant phenomena for ESBWR applications. TRACG numerics, structure, and nodalization provide the capability to model plant geometry and calculate specific safety parameters within a known level of accuracy.

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During an ATWS accident, the shutdown of the reactor is accomplished by the Standby Liquid Control System (SLCS) which injects borated solution from two accumulators through four feeder pipes each of which has four nozzles at different elevations. The nozzles penetrate through the shroud wall and discharge directly into the peripheral region of the bypass. Each nozzle has two discharge ports, so the injected liquid forms two jets, pointing at angles estimated to be 60 degrees on either side of a line through the nozzle centerline to the core center.

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_____]] It is not obvious whether or not [[_____]] is conservative or non-conservative. Higher initial velocity results in a longer submerged jet and more dilution before the injected borated solution becomes a buoyant plume. More dilution may or may not be conservation. More dilution implies reduced boron concentration, which implies a smaller macroscopic cross-section for the diluted mixture. However, more dilution implies a larger fraction of the core affected by the borated solution. In addition, for the buoyant plume analysis, more dilution implies a less buoyant plume, which can be more easily swept from the core if core bypass velocities are upward.

If the liquid velocity in the periphery of the bypass is down, then the buoyant plume of borated solution will not be swept up and out of the core bypass. In

Ref. 1, it is stated that during the borated solution injection phase, the liquid velocity in the periphery of the bypass is down. Therefore, the buoyant plume analysis is important for determining the dimension of the blocked off theta sector in terms of the reducing the dilution of the borated solution in the periphery of the core bypass and for the density difference of the borated solution as it transports across the core bypass. However, it is not clear that a [[_____]] with upward flow of gas and downward flow of liquid, which involve phase change (i.e. condensation if liquid is subcooled) is appropriate for heavy liquid over a light liquid. In addition, [[_____
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For the [[_____
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TRACG numerics are known to be diffusive and depending upon the noding, transport borated solutions faster than turbulent or molecular diffusion. [[____
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_____]] The impact of this modeling approach is to reduce the dilution of the injected borated solution. Again it is not obvious whether or not this is conservative in terms of the theta flow areas. If the borated solution is allowed to transport within the [[_____]] more of the borated solution may stay in the periphery of the bypass rather than transport into the center of the core. [[_____
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However, the [[_____]] used determine the theta size for cells [[_____]] solution temperature with a [[_____]].

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_____]] Therefore, higher order differencing methods can be used to significantly [[_____
_____]] This approach would allow a conservative calculation in which no numerical diffusion, turbulent diffusion, or molecular diffusion is included. Rapid transport of borated solution into the center of the core would not occur. In addition, models for settling of boron into guide tubes and the lower plenum could be developed and applied conservatively. [[_____

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The [[_____
_____]] includes a number of implied assumptions about the flow field in the core, core bypass, and lower plenum:

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It is not obvious this assumed flow field will be the valid for all ATWS accident scenarios. For example, if the EOPs call for operator depressurization of the reactor pressure vessel and the depressurization starts before the SLCS has shutdown the reactor, the assume flow field in the core may no longer be valid. [[_____
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GEH TRACG calculations of SLCS system from a normal operating state indicate that the SLCS system shutdowns the reactor with a significantly smaller peak pool temperature. Therefore, uncertainties in flow field assumptions for shutdown from a normal operating state are not that important because of the large margin in terms of the peak pool temperature. [[_____

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The SLCS system in the ESBWR consists of two accumulators, each pressurized to 17.2 MPa, which adiabatically expand upon opening the valves to inject the hot shutdown volume of 10.8 m3 at an approximate vessel pressure of 8.6 MPa. [[_____
_____]] As the accumulators expand, the driving pressure in the accumulators will decrease. The flow rate from the accumulators to the core bypass will depend upon the accumulator time dependent pressure and the pressure in the core bypass and the geometry and length of piping between the accumulators and the core bypass. If the pre-determined SLCS injection rate is based on a vessel pressure of 8.6 MPa, it is not clear how this will be conservative for ATWS accident scenarios. [[_____
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Therefore, for this accident scenario, an assumption of a vessel pressure of 8.6 MPa is conservative.

There was a concern about how [[_____
_____]] Specifically, was the precipitate treated as solid particles in the liquid field and continued to transport with the liquid phase or plated out on the structure surfaces of the fluid cell where the boron concentration reached the saturation limit. [[_____
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_____]] From a neutronics standpoint, the effect of the boron is based on the total boron concentration within a given fluid cell including both the boron in solution and the boron that has plated out.

Normally, during an ATWS calculation the boron concentration required to shutdown the core is on the order of 5,000 ppm of elemental, natural boron, while the saturation limit is on the order of 25,000 ppm. Therefore, during core shutdown the saturation limit is not approached. Only late in the post-shutdown phase of the ATWS transient, if significant boil-off in the core occurs will the boron concentration approach the saturation limit.

On page 5-30 of Ref. 1, item C15, it is indicated that the vapor-side interfacial heat transfer in the dispersed flow regime is based a bubble diameter based on a critical Weber number. For the dispersed flow regime, the appropriate interface is between droplets of liquid and steam. Therefore a bubble diameter based critical Weber number is not appropriate. In addition, it is not obvious how the uncertainty in the Sun-Gonzalez-Tien heat transfer coefficient would be the same as the uncertainty in the Dittus-Boelter heat transfer coefficient for steam cooling conditions. Dittus-Boelter for steam cooling models the heat transfer across a single phase thermal boundary layer between the wall and the bulk steam temperature. For dispersed flow film boiling, droplet flow is present and in some cases depending upon the flow regime inverted annular flow (i.e. liquid core surrounded by steam blanket). Therefore, the Sun-Gonzalez-Tien heat transfer coefficient, at a minimum, attempts to address the effect that droplets have on the thermal boundary layer at the hot fuel rod surface. GEH addressed this concern in Ref. 18. The uncertainty included in the Dittus-Boelter type heat transfer, plus uncertainty in the radiation heat transfer and interfacial heat transfer [[_____]].

[[_____]] Therefore, it would not be appropriate to apply this non-conservative bias of [[_____]]

[[_____]]

5.0. Transient 3D Neutronics Modeling

The important neutronics parameters for ESBWR ATWS are void coefficient reactivity feedback, Doppler reactivity feedback, boron reactivity, and 3-D kinetics. The void coefficient determines the power spike given a void collapse due to pressurization event or cold water event. The void coefficient and Doppler reactivity feedback reduces the reactor power as the fuel heats up. The boron reactivity provides for shutdown of the neutron power. The 3D kinetics determines the transient power distribution for the ESBWR fuel assemblies.

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The three different void fractions [[_____]] are all in-channel void fractions with the water rod and core bypass assumed to be non-voided.
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There are a number of operating plant transients that have been successfully analyzed by TRACG that indicate that TRACG neutronics models can simulate void collapse and cold water AOO transients. These include[11]:

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3) _____
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4) _____
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These operating BWR events are not expected to be the same as AOOs in an ESBWR. However, similar phenomena must be modeled accurately to simulate these AOOs in operating plants as well as in ESBWR (i.e. power response to void collapse, pressure response to TCV closure or MSIV closure, etc.).

6.0. Conclusions

TRACG as applied to ESBWR ATWS was reviewed. The boron mixing and transport model in TRACG appears to be conservative when compared to 3D boron mixing data scaled for BWR-5 and BWR-6, with boron injection into the upper plenum. This data shows a similar flow pattern as predicted by the TRACG model for the ESBWR and comparison to the scaled results indicate that the TRACG model [[_____]] is conservative. [[_____
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