MAAP APPLICATIONS TO SHUTDOWN PSA AND SAMG DEVELOPMENT, AND INSIGHTS FROM SAMPLE CALCULATIONS

Chan Y. Paik[1], Paul McMinn[1], and Eugene van Heerden[1]

[1] *Fauske & Associates, LLC: 16W07083rd Street, Burr Ridge, Illinois, 60527, paik@fauske.com*

The Modular Accident Analysis Program (MAAP)[1] is a computer code that is used for integrated severe accident analysis. The latest MAAP5 version [1] has a detailed Reactor Coolant System (RCS) model and has the capability to model all shutdown conditions. This paper describes comparisons between the latest RCS model in MAAP5 and RELAP5 calculations for POS 3 for a Combustion Engineering type reactor. A few sample calculations are presented that model various operator actions for several different conditions for a typical Westinghouse type four loop plant. The MAAP5 results are in general agreement with RELAP5 results with some MAAP5 results being somewhat conservative compared to the RELAP5 calculations. When the reactor system is in shutdown conditions without any openings to containment (pressurizer and steam generator manways are closed), the effectiveness of injection into one or multiple steam generators was investigated and the results showed that one steam generator can remove the decay heat and prevent core uncovery. Another alternative operator action during an extended loss of AC power (ELAP) without any mobile equipment available is gravity-driven injection from the Refueling Water Storage Tank (RWST). The effectiveness of gravity injection from the RWST depends on various plant conditions such as whether the pressurizer manway or steam generator manway is open, whether the containment is isolated or not, whether the containment vent is available or not, and whether an external makeup supply to the RWST is available or not. These calculations demonstrate that MAAP5 can be used as a tool to perform shutdown PSA analysis and to develop plant specific Severe Accident Management Guidelines (SAMG) for shutdown conditions.

I. INTRODUCTION

MAAP5, the latest generation of the MAAP code, has new models and improvements compared to MAAP4: 1) calculation of forced and natural circulation inside a RCS with a more detailed nodalization, 2) capability to calculate fission power with point kinetic and 1-D neutronics models, 3) detailed steam dump logic in the PWR code so that the code can calculate initial RCS and steam generator responses after a reactor scram, 4) lower plenum debris model to address in-vessel retention phenomena plus improvements in the ex-vessel cooling model, 5) improvements in core modeling, 6) and various improvements in containment phenomena. In addition, MAAP5 has improved models for shutdown states such as mid-loop operation and conditions with the reactor head open with the vessel submerged under the refueling water pool.

Since the Fukushima accidents, many improvements were made in the MAAP5 code to calculate realistic core debris location and composition for Fukushima Daiich units 1, 2, and 3. Key improvements were made in the following areas:

- BWR RCS and core thermal hydraulics,
- BWR specific core geometry, core melt progression, and core material relocation paths to the lower plenum,
- Detailed CRD modeling in the lower plenum (radial and axial nodalization of CRD tubes) and heat transfer calculation between CRD tubes outside of the vessel and the pedestal wall,
- Detailed multi-layer lower plenum debris model (instead of a single oxidic debris pool, multiple layers (up to 100) can be modeled to track the history of corium relocation, material composition, and interaction with lower plenum water),
- Containment thermal stratification model,
- Turbulent deposition of fission product aerosols in piping in containment,
- Sump drain corium flow calculations between pedestal sumps and drywell sumps in BWR containments,
- Molten-core concrete interactions:
    - Mechanistic convective heat transfer coefficient calculation between the molten pool and crusts

---

[1] The MAAP code is owned by the Electric Power Research Institute (EPRI).

  - Full erosion shape calculation
  - Corium stratification (light metal at the top or heavy metal at the bottom)
- CO removal by Passive Autocatalytic Recombiners (PAR), and
- Hydrogen generation in containment water pools due to radiolysis.

For a PWR reactor coolant system (RCS), MAAP5 employs more sophisticated nodalization schemes compared to that of MAAP4. MAAP5 evaluates the individual response of each coolant loop and steam generator and considers coupling of the secondary sides of multiple steam generators through the steam header. One of the key improvements in MAAP5 is the ability to accommodate the independent coolant loop responses for PWR designs. The nodalization for a typical Westinghouse-type 4 loop plant is shown in Figure 1. In addition to individual loops, MAAP5 models RCS designs with two reactor coolant pumps (RCPs) per steam generator (i.e., those designs with two cold legs for each hot leg). This enables an analyst to evaluate the system response when one pump is shut down and the other RCP is operating, including the calculation of back flow in the idle loop. In each node, the mass and energy of water and gases (steam, N_2, O_2, H_2, CO and CO_2) are tracked and pressure and temperature are calculated.

Similar improvements were made for the BWR reactor coolant system in MAAP5.04 [2]. The new RCS nodalization scheme for BWR plants with jet pumps is shown in Figure 2. Similar to the PWR code, flows between nodes are calculated based on the pressure differences and the code has the capability to calculate reverse flows during a loss of coolant accident or transients with one recirculation pump off. In addition to the pressure driven unidirectional flow, single and two-phase counter current flows between nodes are also calculated when heavy fluid is above light fluid. For each node, boron and salt mass (in the BWR code only) can be tracked.

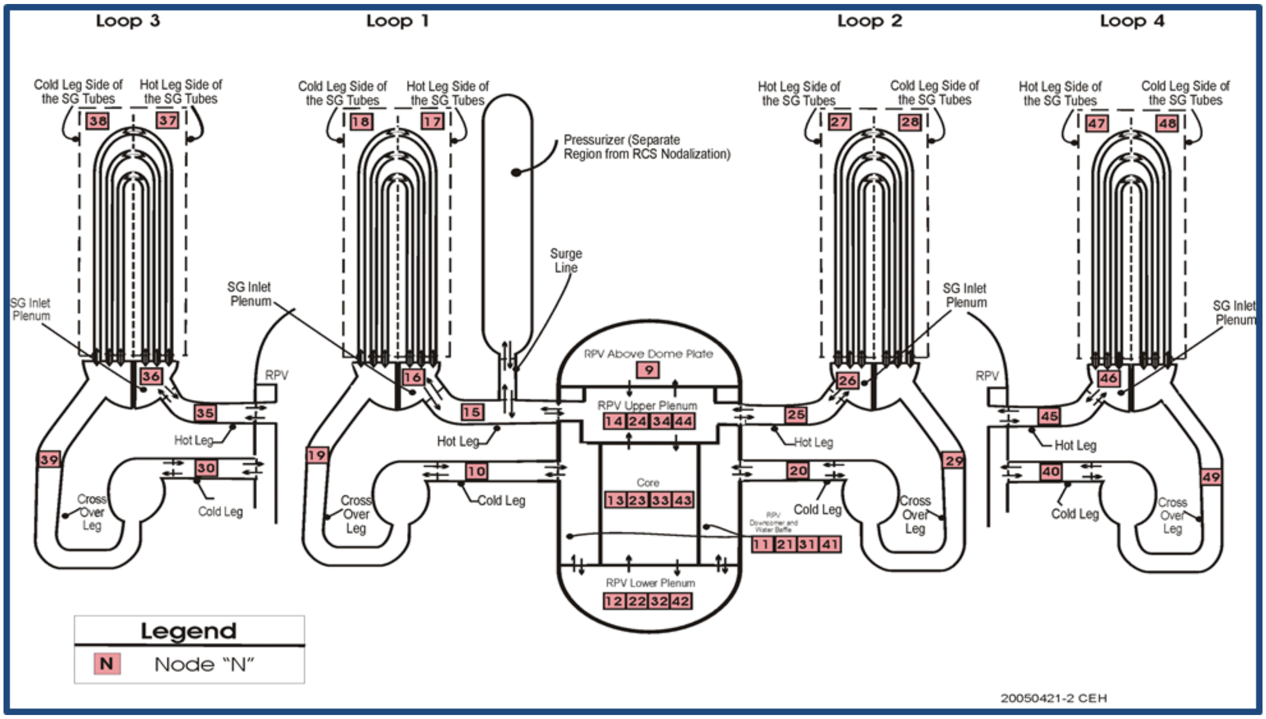

Fig. 1. RCS nodalization for a typical Westinghouse 4-loop plant.

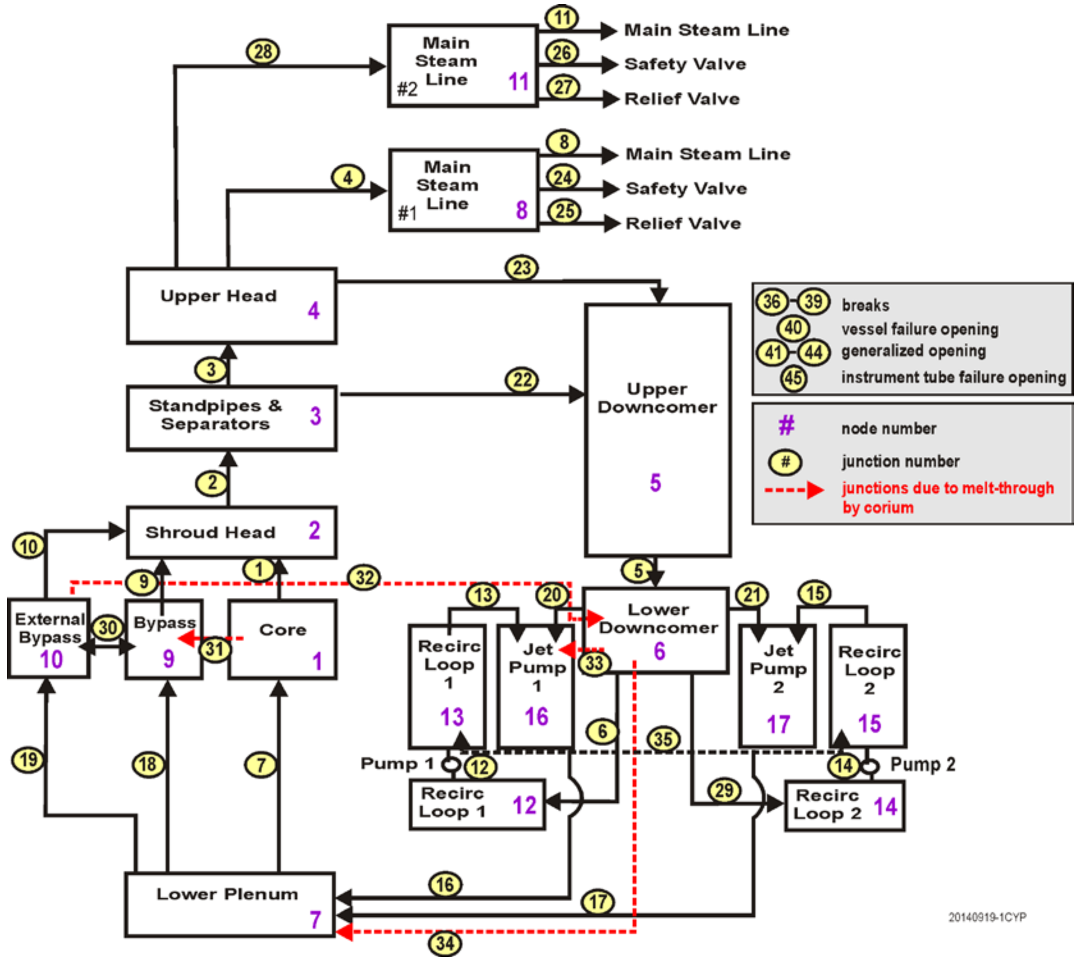

Fig. 2. RCS nodalization for BWR design with jet pumps.

II. MAAP5 MODELING CAPABILITIES FOR SHUTDOWN SEQUENCES

For the MAAP5 PWR code, plant shutdown conditions for all modes can be modeled including mid-loop conditions and reactor head open cases with water in the refueling pool. Air or nitrogen injection into the pressurizer during initial shutdown conditions can also be modeled. Additionally, nozzle dams can be placed in each loop. For the BWR code, the capability to model shutdown conditions has recently been added with the detailed RCS model in MAAP5.04. Similar to the PWR code, it can model shutdown conditions including the reactor head open condition with water in the refueling pool. Each main steam line can be plugged or not plugged.

Until now, MAAP has been widely used for Level I success criteria and Level II analysis at power. With the new capabilities added in MAAP5, it can be used to perform similar calculations for shutdown conditions. Users can specify the initial conditions of the reactor coolant system, pressurizer, and steam generators at any POS. Air or nitrogen injection into the pressurizer or vessel during initial shutdown conditions can also be modeled. Conditions with the reactor head open (PWR and BWR), nozzle dams installed (PWR), and main steam line plugging (BWR) can be modeled. Users can also specify the closure of certain junctions between nodes via the input file. With these capabilities, MAAP5 can be used at shutdown conditions:

- To identify dominant accident sequences and initiators,
- To identify vulnerable plant states,
- To evaluate the effectiveness of operator actions,
- For Level I success criteria runs, and
- For Level II sequences to calculate:
    - Time to boil and time of core uncovery,
    - Time to core damage and time to containment failure, and

  - Consequences of core damage and the source term release.

These calculations can aid in the development of SAMG for shutdown conditions and evaluate the effectiveness of operator actions through sensitivity study.

III. MAAP5 AND RELAP5 COMPARISONS

MAAP5 results have been compared to the RELAP5 results for a Combustion Engineering type reactor from POS 2 to 12 for Level I success criteria and operator action timing analysis. In this paper, the results of two sets of POS 3 sequences are compared to the equivalent RELAP5 results. The initial conditions of the POS3 cases are as follows:

- POS3A-Base:
  - 32.9 hours after reactor scram
  - RCS pressure: 3.02 MPa
  - Cold Leg Temperature= 418 K
  - Pressurizer Level: Normal operation level
  - Steam Generator: Wet lay-up level with MSIV closed
  - Loss of Shutdown Cooling at sequence initiation
- POS3A-Base + Stuck open Low Temperature Overpressure Protection (LTOP) valve
  - Initial conditions identical to POS3A-Base
  - Loss of Shutdown Cooling at sequence initiation
  - LTOP valve stuck open at sequence initiation

The results of the comparisons for these two cases are shown in Figures 3 to 8. For the POS3A-Base case, MAAP5 calculated much faster pressurization after the loss of shutdown cooling than that of RELAP5. For these comparisons, RELAP5 decay heat is used as an input for MAAP5 calculations instead of the MAAP calculated decay heat. Once the RCS pressure reached the LTOP valve opening pressure, the LTOP valve was opened and primary system coolant was lost through the valve. The LTOP valve has a dead band and variable opening area based on the RCS pressure. Since the LTOP valve was opened earlier in MAAP5 than RELAP5, the core uncovery calculated by MAAP5 was earlier than that of RELAP5 as shown in Figure 5.

For the case with the stuck-open LTOP valve, the comparisons were much better. The RCS pressure, water temperature, and the core collapsed level calculated by MAAP5 were similar to those of RELAP5. The MAAP5 results were in general good agreements with RELAP5 results:

- all major trends were captured,
- timings are generally slightly conservative, and
- the pressurization predicted by MAAP is generally faster than that predicted by RELAP
  - It was not clear why MAAP5 calculated faster pressurization. It is possible that this is due to the difference in the initial steam generator conditions and the heat transfer rate to the steam generators from the primary system.

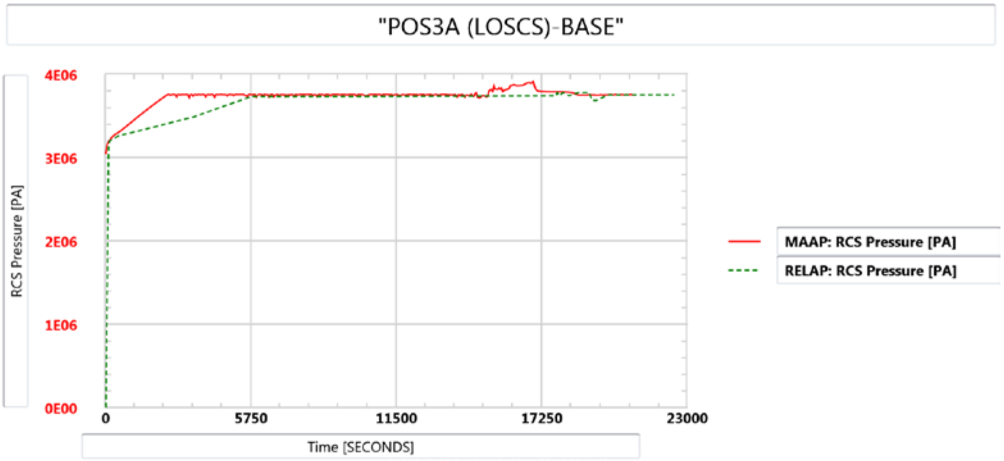

Fig. 3. Comparison of RCS pressure between MAAP5 and RELAP5 for POS3 case.

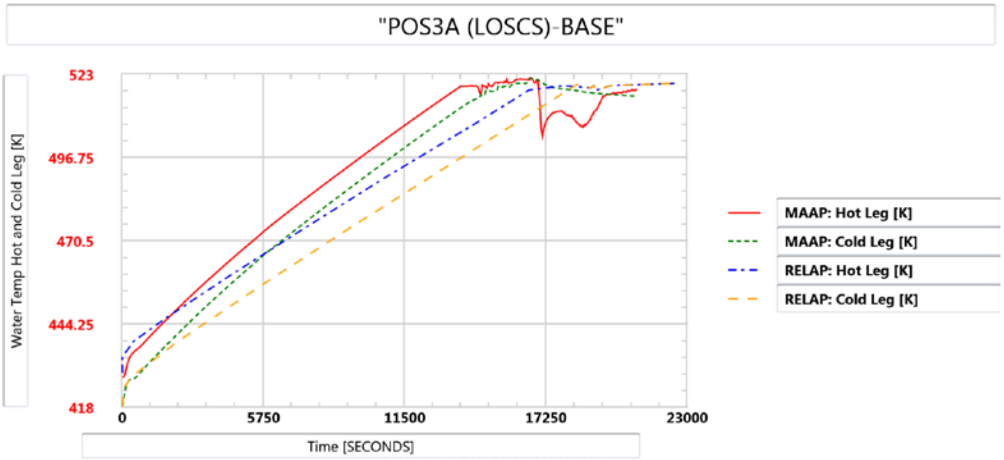

Fig. 4. Comparisons of water temperatures in loop 1 hot leg and cold leg between MAAP5 and RELAP5 for POS3 case.

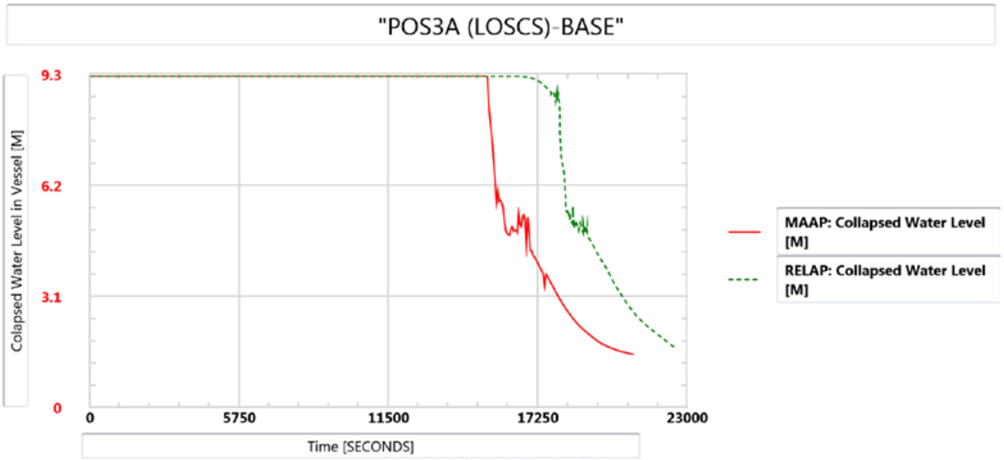

Fig. 5. Comparison of collapsed water level in the core between MAAP5 and RELAP5 for POS3 case.

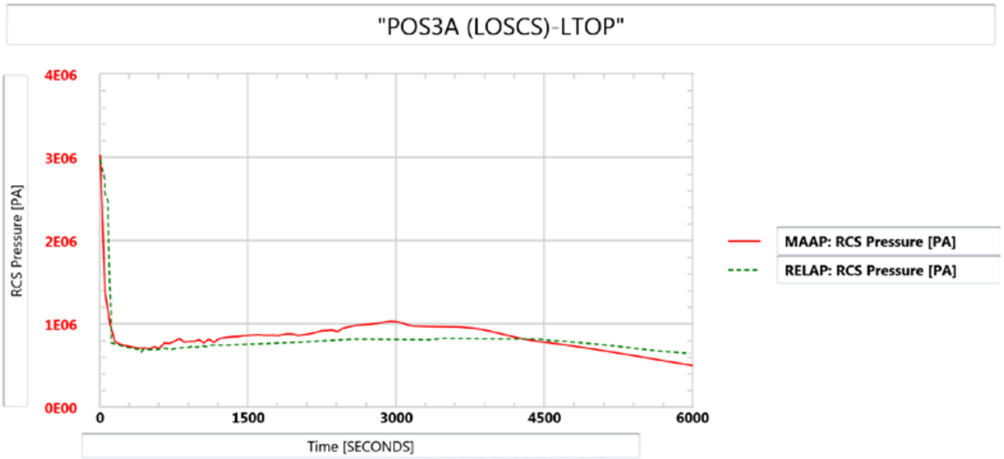

Fig. 6. Comparison of RCS pressure between MAAP5 and RELAP5 for POS3 case with stuck open LTOP valve.

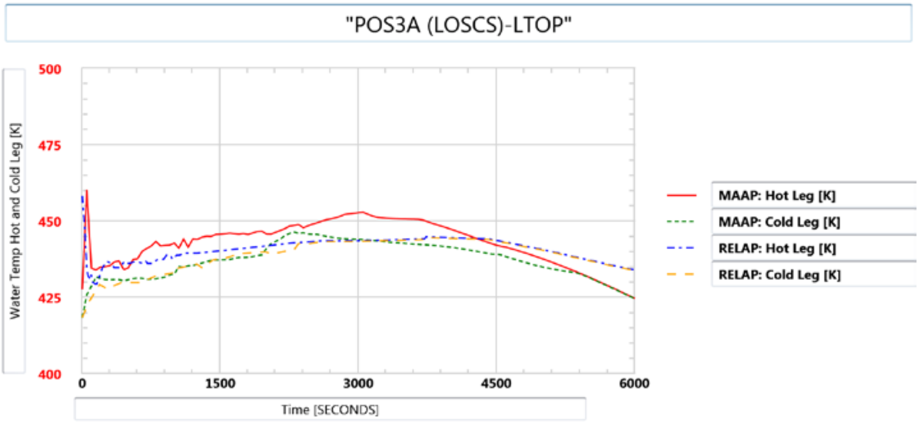

Fig. 7. Comparisons of water temperatures in loop 1 hot leg and cold leg between MAAP5 and RELAP5 for POS3 case with stuck open LTOP valve.

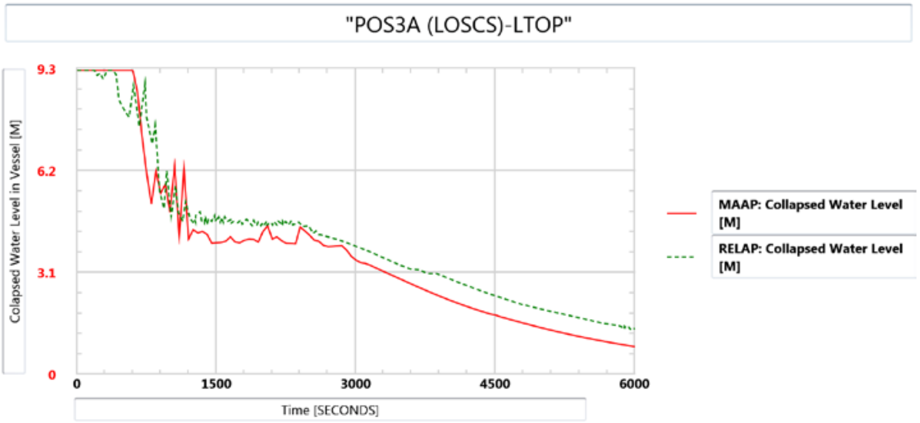

Fig. 8. Comparison of collapsed water level between MAAP5 and RELAP5 for POS3 case with stuck open LTOP valve.

IV. SAMPLE CALCULATIONS FOR SHUTDOWN CONDITIONS

Severe accident management consists of mitigation actions before and after core damage has occurred. During shutdown conditions, the severe accident progression is not very sensitive to the initial water level in the vessel except with regard to the time of core uncovery and core damage. However the following thermal hydraulic conditions in the primary system, steam generators, and containment can affect the SAMG actions and progression of the accident:

- Whether the primary system is closed or opened,
- Whether the pressurizer manway or steam generator manway is open,
- Whether the steam generators are depressurized or not,
- Whether the reactor vessel head is open or not,
- Whether the fuel is in the vessel or not, and
- Whether containment is open or closed (or able to be isolated).

Because of limited automatic equipment operation and the short time window to core uncovery during mid-loop operation, operator actions become more important than during at power conditions even though the decay heat is much lower than that at power.

During a loss of shutdown cooling, mobile equipment can be used, if available, to inject water into:

- Steam generators if steam generators are depressurized or an atmospheric dump valve is available,
- Reactor coolant system if the RCS is open or depressurization capability is available, and
- Containment.

Typically, core damage can be avoided if mobile equipment is available for injection. When the RCS is open to the containment, injection into the steam generator will not be effective and only RCS injection can prevent core damage. When mobile equipment is used to inject water into the RCS, core damage can be prevented as long as the injection is maintained. However, containment flooding and containment venting can be important issues for long term injection. For these shutdown conditions with available injection and the RCS open to the containment, it is important to have coupled RCS and containment models because the containment pressure will govern the RCS pressure. Failure to account for concurrent containment pressurization could result in an overprediction of injection capabilities.

If mobile equipment is unavailable for an extended loss of AC power (ELAP) during shutdown conditions with an open RCS (pressurizer or steam generator manways are open), establishment of gravity injection from the RWST into the RCS can be an important operator action. Some important factors for successful gravity injection are the elevation of RCS opening (pressurizer manway or steam generator manway) relative to the suction elevation in the RWST and the availability of containment heat removal or containment venting.

In this paper, a few example calculations are shown for how MAAP5 can be used for shutdown SAMG development. Three types of sample calculations are included:

1. RCS closed and SG injection available to 1 steam generator
2. Gravity injection from the RWST during an Extended Loss of AC Power
3. External injection using a fire pump for a case when the gravity injection has failed

IV.A. Steam Generator Injection Available

To test the effectiveness of steam generator injection to only one steam generator, two shutdown cases were run with the following assumptions:

- Time after reactor scram = 3 days,
- RCS initial pressure is 1 bar and the cold leg water temperature is initially at 333 K,
- Assume RCS is intact without any open manways,
- Case 1: RCS is full with a normal pressurizer water level,
- Case 2: RCS is in low-level operation condition with pressurizer man-way closed.

For the two different RCS initial conditions analyzed, the core was covered throughout the transient, showing that the injection into one steam generator was able to remove the decay heat. Figure 9 shows the RCS and steam generator pressures for both cases. Figure 10 shows the decay heat and the heat removal to the loop 1 steam generator. For case 1, with the normal pressurizer water level and the RCS full of water, boiling did not occur in the core. For case 2, boiling occurred in the core and two-phase water was pushed into the loop 1 steam generator tubes because of the pressure imbalance between loops. In case 2, water and heat sink temperatures were higher than those of case 1 resulting in higher heat loss to the containment and lower heat transfer to the loop 1 steam generator. Because of the limited initial water inventory, steam condensation occurred in the loop 1 steam generator tubes. Figure 11 shows the void fractions in the loop 1 and 2 steam generator tubes in case 2. In loop 2, the void fraction in the hot tube side (node 27) is ~ 0.93 and there was no water in the cold side steam generator tubes. When injection is available to two steam generators, the peak RCS pressure calculated was lower than that of the one steam generator injection case.

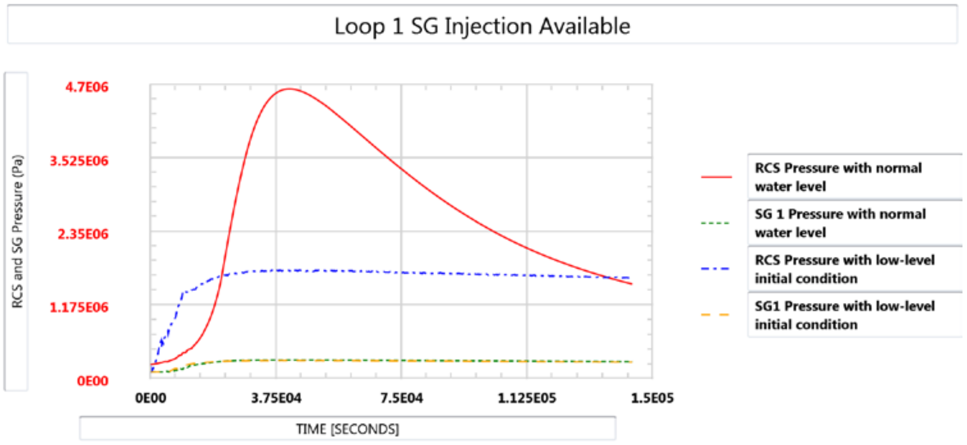

Fig. 9. RCS and loop 1 steam generator pressures for normal water level and mid-loop water level cases with injection into the loop 1 steam generator.

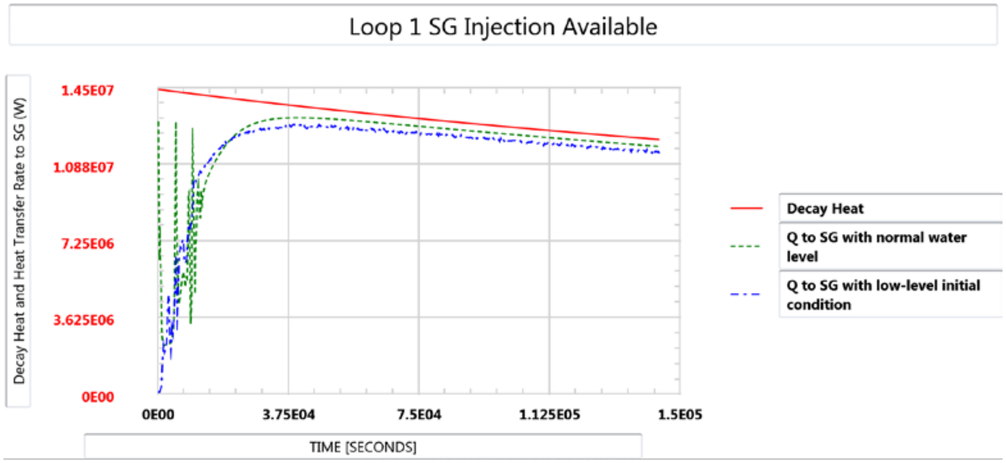

Fig. 10. Comparison of decay heat and total heat transfer rate to steam generators for normal water level and mid-loop water level cases with injection into the loop 1 steam generator.

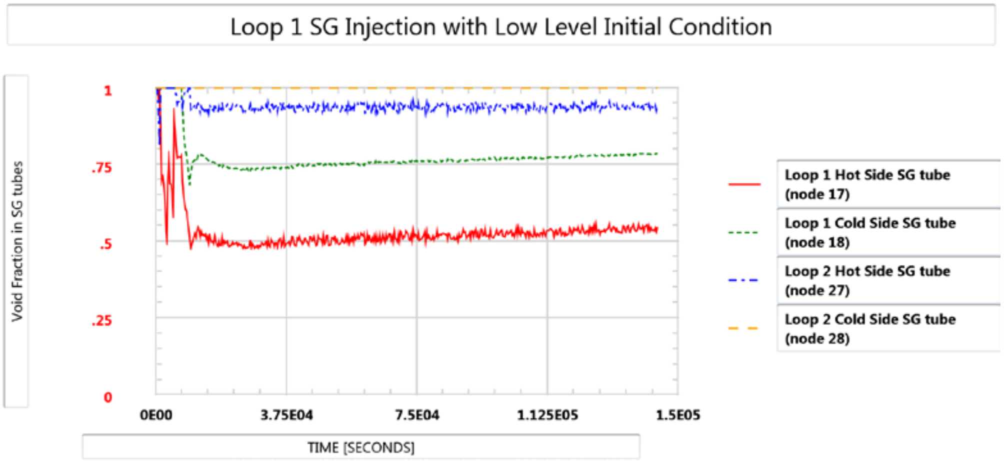

Fig. 11. Void fraction profiles in loop 1 and 2 steam generator tubes with mid-loop initial water level.

IV.B. Gravity Injection During an Extended Loss of AC Power (ELAP)

An alternative operator action during an extended loss of AC power (ELAP) without any mobile equipment available is a gravity feed from the Refueling Water Storage Tank (RWST) or from the Condensate Storage Tank (CST). The effectiveness of gravity injection from the RWST or CST depends on various plant conditions such as whether the pressurizer manway or steam generator manway is open, whether the containment is isolated or not, whether the containment vent is available or not, and whether an external makeup supply to the RWST is available or not.

MAAP5 can be used to calculate time to boil, time to core uncovery, time for containment venting, and time to core damage without any operator actions and can also be used to evaluate several SAMG actions including an RWST gravity feed strategy following an extended loss of AC power (ELAP) event during POS 5 and 6 conditions. In this paper, a few example calculations with potential SAMG actions are presented to simulate the transient that includes the feedback between the RWST, RCS, and containment.

In the sample calculations, the following assumptions and inputs are used:

- Time after reactor scram = 3 days,
- RCS and containment initial pressures are assumed to be at 1 bar and the cold leg water temperature is initially at 320 K,
- RCS is in mid-loop condition (water level at the center line of the hot leg),
- Pressurizer man-way (16” diameter) is open,
- The bottom of the RWST is at the same elevation as the center of the hot leg,

- RWST drain is modeled as a simple junction between the RCS and RWST with a single discharge coefficient representing all losses in the pipe. One injection line with a 5” diameter pipe is assumed as a base case,
- RWST gravity injection is initiated 30 minutes from the time of AC loss,
- RWST external makeup (9.46 kg/s, 150 GPM) is available between RWST water levels of 10 m and 14 m. Without makeup, the gravity injection strategy will only work initially when the water level in the RWST is high.

Three sample MAAP runs were performed for this scenario:

- One 5” gravity injection line without any containment heat removal and without containment vent,
- One 5” gravity injection line with containment vent (8” vent line opened at 1.22 bar (3 psig) and left open), and
- Two 5” gravity injection lines with containment vent.

The RWST is modeled as a containment node in the MAAP calculation and the gravity injection line is modeled as a generalized opening between the RCS and the containment. The runs were stopped when the core exit temperature exceeded 1200 °F.

After the loss of RHR cooling, the core temperature reached the saturation temperature soon and boiling occurred in the core. The boiling in the core pushed two-phase water into the hot leg and the pressurizer. As a result, the water level in the pressurizer increased as shown in Figure 12. Without the containment vent, the gravity injection soon stopped because of the high containment pressure and high water level in the pressurizer. With the containment vent available, the high pressurizer level and up to 3 psig of containment back pressure shuts off the gravity injection from time to time resulting in core uncovery in both cases with one and two injection lines. Figure 13 shows the mixture water level in the core. When the injection flow stopped, the core was uncovered and the mixture level decreased enough to reduce the steaming rate and the two-phase carry-over to the pressurizer. In most conditions, the pressurizer surge line is flooded and water drainage from the pressurizer to the hot leg is prevented. However, the pressurizer level decreased from time to time due to counter-current water drainage when the core was uncovered. Figure 14 shows the containment pressure. Without the containment vent, high containment pressure prevented gravity injection. For the other two cases, an 8” containment vent line was opened at 3 psig and remained open throughout the remainder of the sequence. Figure 15 shows the hottest core node temperature. The number of lines used for gravity injection made some difference in the pressurizer water level and timing of core uncovery. However, the general responses between two cases were similar. For the case with two injection lines, the run was stopped because the core exit temperature exceeded 1200 F.

The success of gravity injection during an ELAP with the pressurizer man-way open depends on several plant specific factors:

- Elevation difference between the RWST and RCS and the water level in the RWST,
- Availability of external RWST makeup,
- Containment vent (or containment heat removal) available or not,
- Number of injection lines, size, and the discharge coefficient of the piping, and
- Decay heat

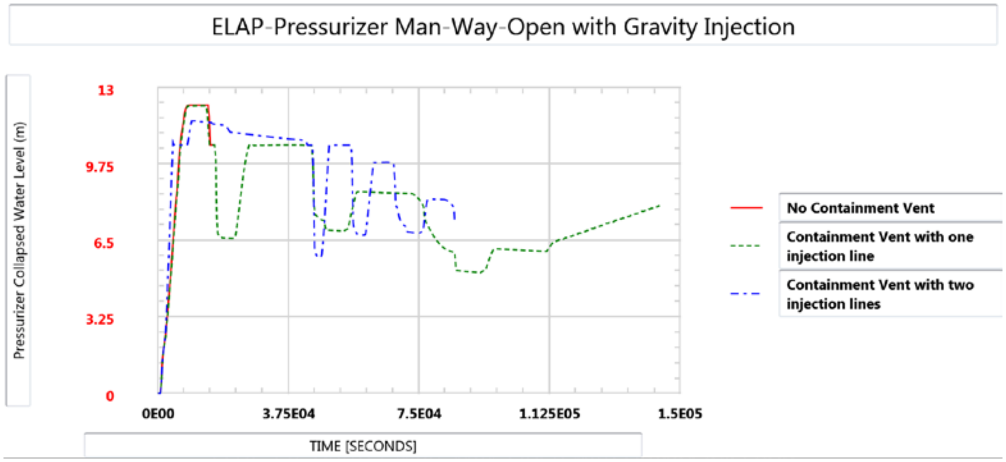

Fig. 12. Pressurizer water levels (m) for cases 1) without containment vent and one injection line, 2) with containment vent and one injection line, and 3) with containment vent and two injection lines.

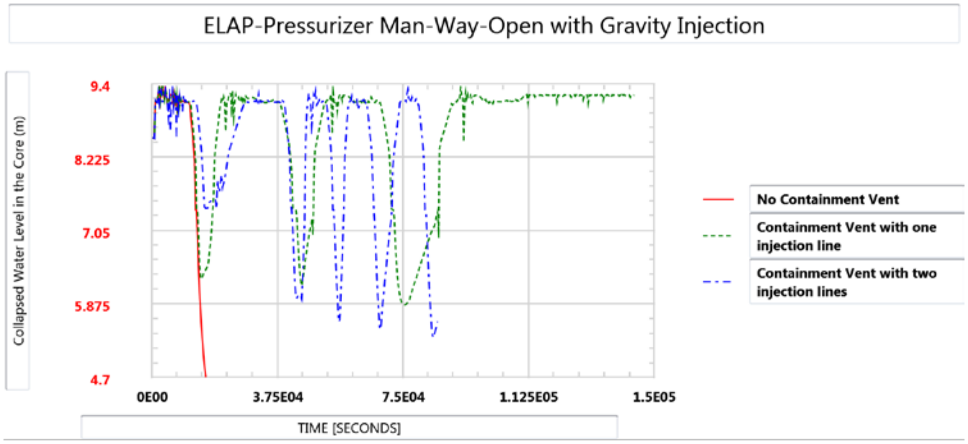

Fig. 13. Collapsed water levels in the core (m) for cases 1) without containment vent and one injection line, 2) with containment vent and one injection line, and 3) with containment vent and two injection lines.

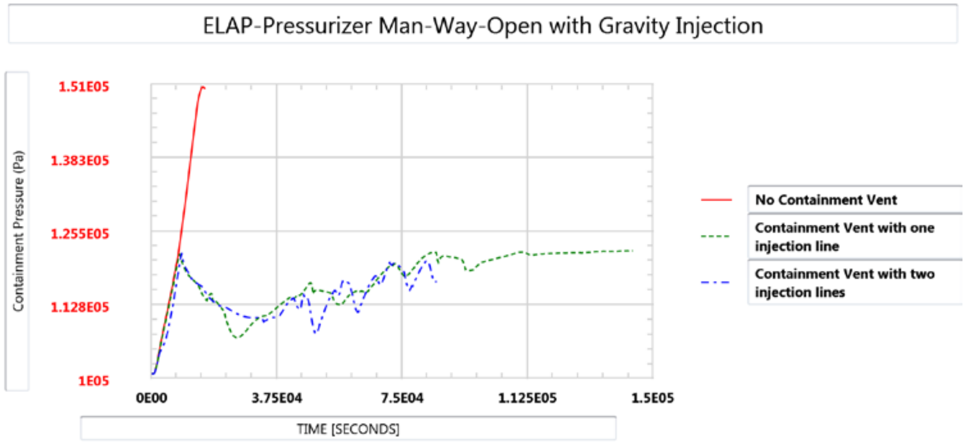

Fig. 14. Containment pressures (Pa) for cases 1) without containment vent and one injection line, 2) with containment vent and one injection line, and 3) with containment vent and two injection lines.

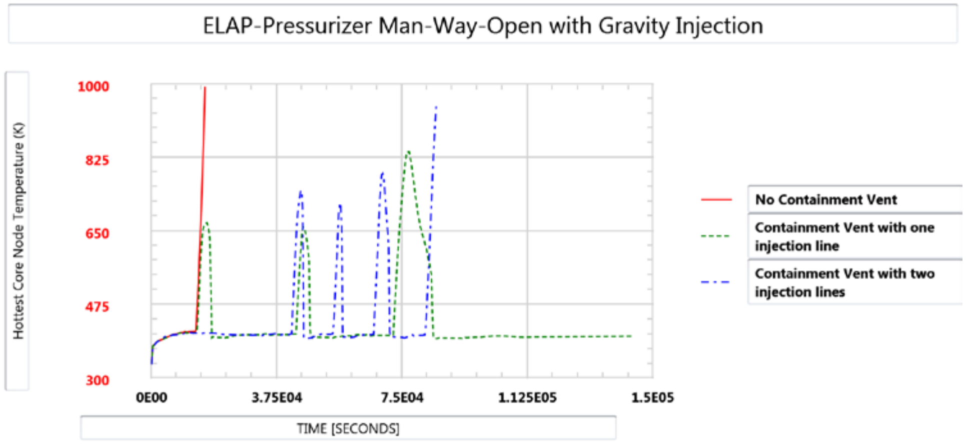

Fig. 15. Temperatures of hottest core node (K) for cases 1) without containment vent and one injection line, 2) with containment vent and one injection line, and 3) with containment vent and two injection lines.

One additional case was run with injection control for strategy consideration purposes. To avoid gravity feed shutoff due to high pressurizer water level, gravity feed line control valve operation based on the hot leg water level was assumed. For this case, the pressurizer water level remained low (< 2.2 m) and the core was covered throughout the transient. Figure 16 shows the core mixture level and the injection flow rate when the injection was controlled based on the hot leg collapsed water level.

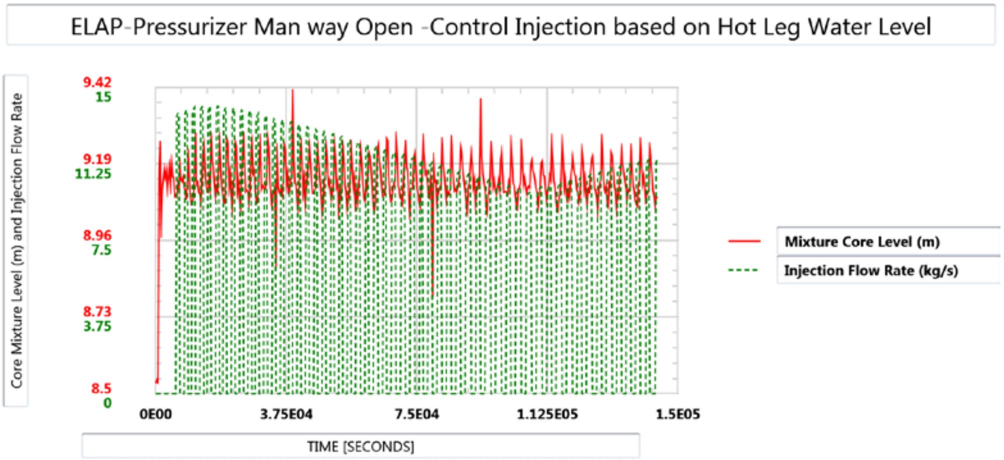

Fig. 16. Core mixture level and injection flow rate with injection control (on/off control) based on hot leg collapsed water level.

IV.C. Fire Pump Injection with Pressurizer Manway Open During an Extended Loss of AC Power

When mobile equipment such as a fire pump is available during ELAP with the RCS open to containment, injection into the RCS will prevent core uncovery. However, containment pressurization can be a problem. Two sample cases with the pressurizer manway open were run with and without containment vent. It is assumed that fire pump injection at a rate of 200 GPM (~ 12.6 kg/s) is available after 30 minutes from the time of AC loss. Once the injection started, water level reached the pressurizer man-way soon resulting in two-phase flow out of the pressurizer man-way. In these cases, the core remained covered as long as the injection was available. Figures 17 and 18 show the containment pressure with and without the containment vent and the water levels in the pressurizer, the cavity and the lower compartment with the containment vent. The water level responses are similar in both cases. Without containment venting, the pressure in the containment reached 3.3 bar at 24 hours and continued to increase. If the external injection continues for many days, containment flooding can be a long term issue.

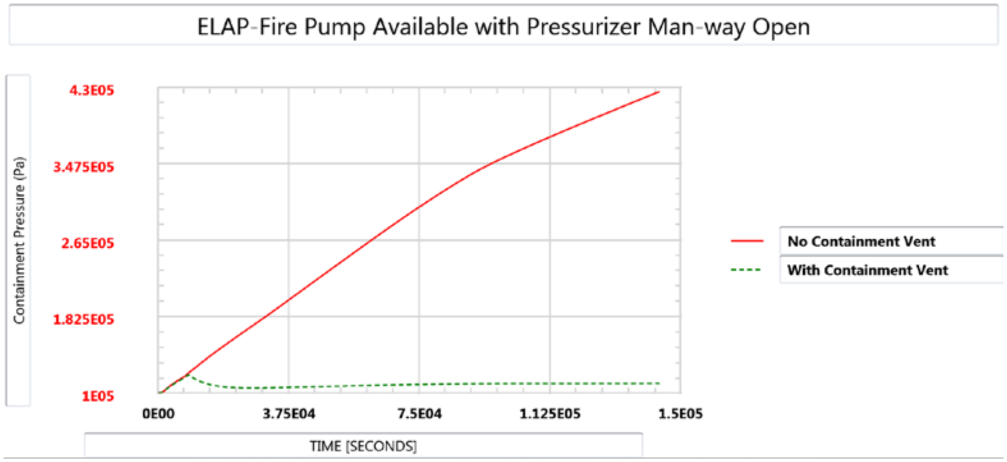

Fig. 17. Containment pressure with and without containment vent for cases with fire pump injection into RCS.

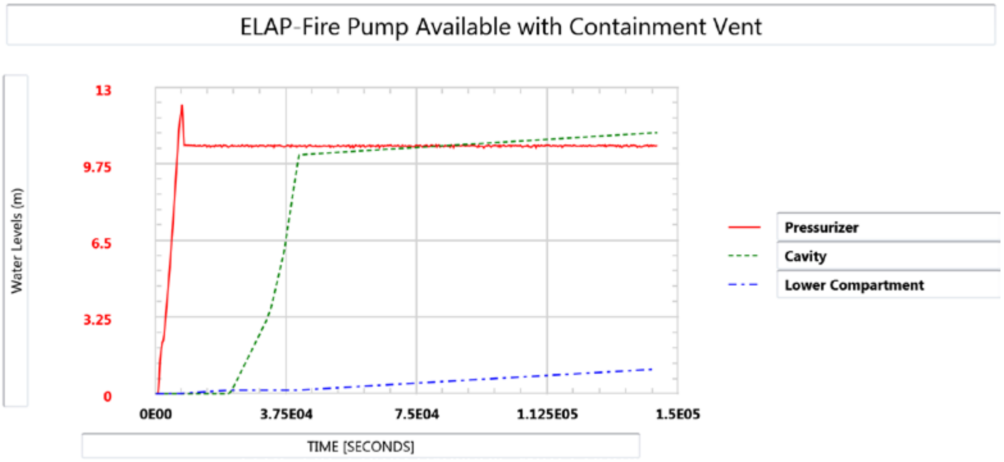

Fig. 18. Water levels in the pressurizer, cavity, and lower compartment for the case with containment vent.

V. SUMMARY

The MAAP5 PWR and MAAP5.04 BWR codes have the capability to model various POS conditions during shutdown. The MAAP5 PWR results are in general agreement with the RELAP5 results with some MAAP5 results being somewhat conservative compared to the RELAP5 calculations in terms of the core uncovery time. MAAP5 can be used to determine the effectiveness of steam generator injection and various operator actions. When there is no RCS opening, injection into one steam generator is sufficient to remove decay heat. When the RCS is open with gravity injection available, MAAP5 can be used to calculate thermal hydraulic responses in the RCS and the containment to determine timings of events such as timing of core uncovery and time to vent the containment. MAAP5 results can also be used to determine the required size of the containment vent. These sample case calculations demonstrated that MAAP5 is a tool capable of performing shutdown PSA analyses. The insights from plant specific MAAP5 calculations similar to the sample calculations can be used to guide SAMG development.

REFERENCES

1. Electric Power Research Institute, *MAAP5 Modular Accident Analysis Program for LWR Power Plants, Transmittal Document for MAAP5 Code Revision MAAP5.03*, EPRI, August, 2015.
2. Electric Power Research Institute, *MAAP5 Modular Accident Analysis Program for LWR Power Plants, Transmittal Document for MAAP5 Code Revision MAAP5.04 Beta*, EPRI, March, 2016.