TRACG Application on BWR/2 LOCA

G. Li, L. Klebanov, P. Sharpe, K. Muftuoglu, C. Heck
GE Hitachi Nuclear Energy
3901 Castle Hayne Road, Wilmington, NC, 28401, USA
Guangjun.Li@GE.com, Lev.Klebanov@GE.com, Phil.Sharpe@GE.com,
Kurshad.Muftuoglu@GE.com, Charles.Heck@GE.com

ABSTRACT

TRACG is a GE Hitachi Nuclear Energy Company (GEH) proprietary version of the Transient Reactor Analysis Code (TRAC). It is a best-estimate code for boiling water reactor (BWR) transient analysis, based on a multi-dimensional two-fluid model for reactor thermal-hydraulics, and a three-dimensional neutron kinetics model for the reactor core. TRACG has been qualified extensively against separate effects test data, component performance tests, integral system effects tests and plant data. NRC has reviewed in detail the TRACG qualification records and approved several applications of TRACG covering BWR/2s through BWR/6s, ABWR, and ESBWR designs.

The large break Loss-Of-Coolant-Accident (LOCA) for a non-jet pump plant (for example, the General Electric BWR/2) has unique characteristics. For these plants, a large recirculation line break is effectively a “bottom break” for the vessel inventory and the core cannot be reflooded. Control of core heatup relies exclusively on the core spray systems and break boundary conditions. The governing phenomena for these types of plants are therefore different from jet pump plants whose LOCA response is characterized by rapid vessel refill.

In this paper, TRACG LOCA is applied to a typical BWR/2 plant. This analysis was performed in accordance with Nuclear Regulatory Commission (NRC) requirements for Emergency Core Cooling system (ECCS) LOCA. The peak cladding temperatures (PCTs) versus different break sizes (break spectrums) are reported. The focus of this paper is placed on the effect of break boundary conditions on the core PCTs at different break locations. Although the containment atmosphere is predominately steam following the LOCA, and remains so until containment spray cooling is applied in the realistic scenario, any remaining air (or nitrogen) in containment plays an important role for the realistic LOCA scenarios. It has been found that the core PCT is significantly impacted by the existence of the noncondensible gas in the core, which is infiltrated into the core through the break. With the noncondensible gas existing in the core, the core thermal-hydraulic conditions due to reduction in steam condensation are then changed so that the heat transfer from the bundle cladding to its surrounding becomes reduced, thus generating higher PCT’s than a case with full steam boundary conditions. Furthermore the sensitivity of the amount of noncondensible gas on the core PCT behavior is also provided.

KEYWORDS
TRACG LOCA, BWR/2, best estimate, PCT, Condensation, Air Infiltration

1. INTRODUCTION

TRACG is the GE-Hitachi Nuclear Energy Americas (GEH) proprietary version of the Transient Reactor Analysis Code (TRAC). TRACG uses realistic one-dimensional and three-dimensional (3D) models and numerical methods to simulate the phenomena that govern the operation of boiling water reactors (BWRs). GEH currently performs Emergency Core Coolant System/Loss-of-Coolant Accident (ECCS/LOCA) licensing calculations for operating plants using an Nuclear Regulatory Commission (NRC)-approved set of computer codes and methods (the "SAFER/GESTR" methodology) that does not include TRACG. However, TRACG analyses have been used historically to support ECCS/LOCA licensing applications by comparing TRACG and SAFER calculations for both jet pump (JP) and non-jet pump plant LOCAs [1] [2]. The existing TRACG code documentation, consisting of a model description licensing topical report (LTR) [3], a qualification LTR [4] and a user's manual [5], is fully supportive of application to ECCS/LOCA. The TRACG Qualification LTR [4] includes comparisons of TRACG calculations with data from separate effects, component performance and integral system effect tests that are directly supportive of its use for BWR LOCA analyses. The NRC has approved the application of TRACG for ECCS/LOCA analyses of the Economical Simplified Boiling Water Reactor (ESBWR) reactor pressure vessel (RPV) and containment [6]. In non-LOCA analysis categories, NRC approvals have been granted for the generic (BWR/2-6) application of TRACG for analyses of anticipated operational occurrences (AOOs) [7] [8] and anticipated transient without scram (ATWS) overpressure transients [9], for ESBWR stability analysis [10] and for specific BWR/2-6 stability calculations [11] [12].

TRACG evolved from TRAC, originally developed for pressurized water reactor (PWR) analysis by Los Alamos National Laboratory and the initial PWR version was named TRAC-P1A [13]. The development of the BWR version of TRAC started in 1979 as a cooperative effort between General Electric (GE) and the Idaho National Engineering Laboratory (INEL). The primary objective of this activity was the development of a version of TRAC for simulation of BWR LOCAs. The main tasks were refinement of the basic TRAC models for BWR applications and the development of models for specific BWR phenomena and components. This work culminated in the mid-1980s with the parallel development of TRACB04 at GE and the very similar TRAC-BD1/MOD1 at INEL. In the earlier stages, GE, the NRC and the Electric Power Research Institute (EPRI) jointly funded the development of the code. A detailed description of these earlier versions of TRAC for BWRs is contained in References [14], [15] and [16].

GEH has submitted TRACG04 in 2011 [17] for review and approval by the US NRC as an alternative tool and methodology for LOCA licensing evaluations. GEH TRACG LOCA methodology uses previously approved methods for analyzing and demonstrating compliance with licensing limits for ECCS/LOCA in BWR/2-6 plants. TRACG calculates the PCT, local oxidation and core-wide oxidation. Thus, conformance with Criteria 1 through 3 of 10 CFR 50.46 is demonstrated by the TRACG analysis results. As discussed in Reference [18], conformance with Criterion 4 (coolable geometry) is demonstrated by conformance to Criteria 1 and 2. The bases and demonstration of compliance with Criterion 5 (long-term cooling) are also documented in Reference [18] and do not need to be evaluated as part of the TRACG ECCS/LOCA analysis. The application methodology based upon TRACG for BWR ECCS/LOCA analyses conforms to the guidance provided in Regulatory Guide 1.157 [19] and are consistent with the Core Scaling Applicability and Uncertainty (CSAU) analysis methodology [20].

As discussed and defined in Reference [17], GEH TRACG LOCA process contains the following steps:

1. The process begins with preparation of the plant-specific TRACG input basedeck. Major inputs to this step are plant specific geometry data, licensing operating parameters for LOCA/ECCS performance evaluation, analysis initial conditions, fuel-specific TRACG channel model, and fuel performance data.

2. The next major step in the analysis process is the break spectrum studies. The primary goal of this step is to determine the limiting break for further uncertainty analysis. The break spectrum studies are primarily centered on the recirculation line breaks for external pump and jet pump type plants.

The appropriate single failure assumption depending on the break analyzed is applied. Additional studies are carried out, if needed, to verify that no other single failure, break location and size, and combination of uncertainty contributors will result in a higher PCT than the limiting break case.

3. The final step oncludes uncertainty analysis, with the purpose being to quantify the uncertainties associated with the analysis, and determination of the parameters due to licensing requirement PCT, local oxidation and core wide oxidation.

In this paper, the TRACG LOCA application is applied to a typical BWR/2 plant. This analysis is focused on the second step above. The peak cladding temperatures (PCTs) versus different break sizes (break spectrum) are reported. The focus of this paper is placed on the effect of break boundary conditions on the core PCTs at different break locations. Although the containment atmosphere is predominately steam following the LOCA, and remains so until containment spray cooling is applied in the realistic scenario, any air (or nitrogen) in containment plays an important role for the realistic LOCA scenarios. Furthermore the sensitivity of the amount of noncondensible on the core PCT behavior is also provided.

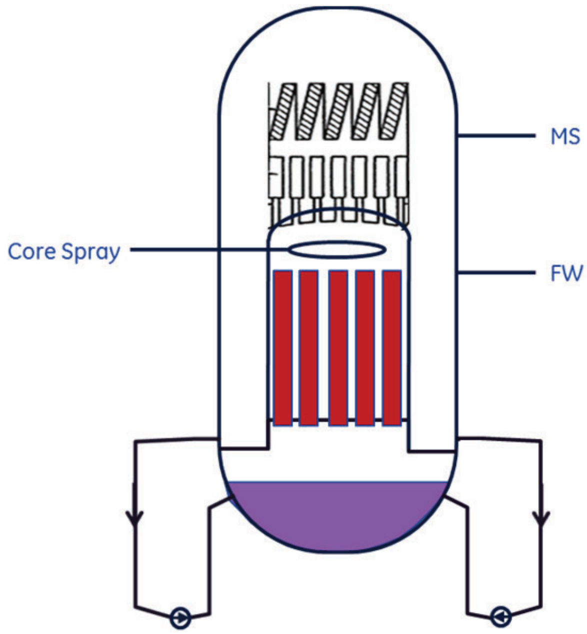

Figure 1. Schematic of a Typical BWR/2 Core and Recirculation System.

2. TYPICAL CONDITIONS FOR A NON-JET PUMP PLANT

2.1. Typical BWR/2 Plant

A typical GEH BWR/2 type plant (schematically shown in Figure 1) forms the basis for the analyses in this paper. Figure 1 show a schematic for a typical GEH BWR/2 system. The core flow is driven by a five loop of recirculation system, taking suction from the downcomer, and discharging into the lower plenum. The flow is then flowing through the core region, being heated by the energy generated by each fuel bundle. Part of liquid will be converted into steam and the two-phase mixture is flowing into the upper plenum. Most of the liquid in the two phase mixture is separated in the separators, and flowing back to the downcomer, where it mixes with colder feedwater, and is used by the recirculation system for the core flow. Before flowing into the main steam line, and then into the steam turbine for power generation, the steam leaving the steam separators, referred as wet steam with moisture, is flowing through steam dryers, where the moisture in the steam is extracted.

The large break LOCA for a non-jet pump plant has unique characteristics. For these plants, a large recirculation line break (break of one recirculation loop out of typically 5 loops) is effectively a “bottom break” for the vessel inventory and the core cannot be reflooded, as shown in Figure 1. Control of core heatup relies exclusively on the core spray systems and break boundary conditions. The governing phenomena for this type of plants are therefore different from jet pump plants whose LOCA response is characterized by rapid vessel refill.

2.2. BWR/2 ECCS and Single Failure

ECCS configuration for the sample BWR/2 is shown in Figure 2, which is different from typical later BWR ECCS system, where core injections (either at high pressure or low pressure) are provided. There are two loops of ECCS system, with two pumps in each loop for core spray. There are total of 2 Isolation condensers for delay heat removal. In performing the ECCS performance analysis the postulated failure of a single active component will never result in less than certain minimum combinations of remaining operable systems.

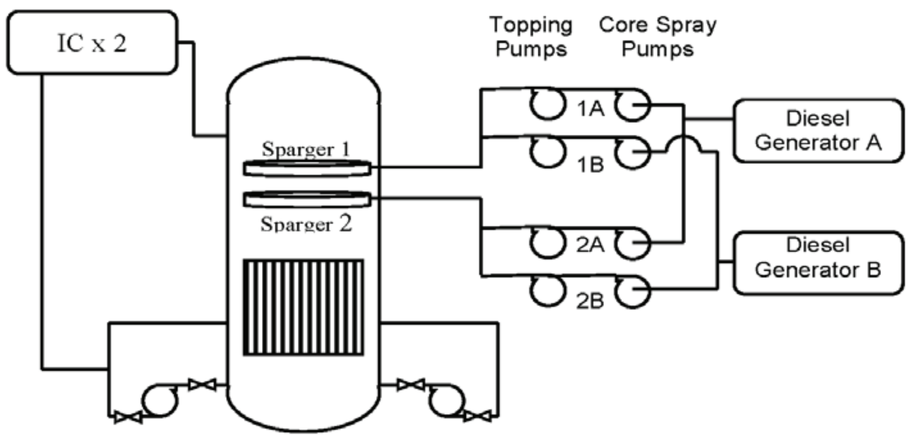

Figure 2. A Typical BWR/2 ECCS Configuration.

For an assumed single failure of an Isolation Condenser (IC), it is conservatively assumed that the unfailed ICs are connected to the broken recirculation loop so that no ICs remain available. This single failure assumption is bounded by never crediting the ICs regardless of what other single failures are postulated. This approach supports the NRC premise that the ICs which have no ability to make up lost inventory have minimal impact in mitigating a large break LOCA. For the scenario where the assumed single failure is one of the diesel generators, at least 2 Core Spray trains (2 sets of CS pump and booster pump) will remain available out of 4 CS trains shown in Figure 2. Any other single failure related to the CS pump, booster pump, CS lines, or sparger would still result in a minimum of two functional 2 CS trains

For the calculations presented in this paper, a single failure resulting in the loss of the Isolation Condenser is postulated. The available ECCS consists of two CS and three ADS valves.

2.3. TRACG Modeling and Break Boundary Conditions

GEH TRACG04 is used to model the BWR/2 system, which includes all the details within the RPV vessel pertinent to a LOCA application, and contains the steam lines, recirculation lines and feedwater lines. The recirculation lines are modeled to allow for the simulation of pipe breaks on the suction and discharge sides of the recirculation pumps. Double-ended (DE) and split breaks can be simulated with this configuration of the recirculation piping with boundary conditions established by ambient drywell pressure and gas properties (all steam, all air or air-steam mixture).

The BWR/2 core is modeled using the proprietary parameters of the GE fuel product line.

3. BREAK SPECTRUM

A recirculation line break spectrum analysis, consisting of a set of LOCA calculations for a range of break sizes up to and including the double-ended guillotine break (DEGB), was performed for the BWR/2. Additional analyses were performed for double-ended breaks in a main steam line, CS line and a feedwater line [17]. It has been found that the breaks for those non-recirculation breaks are bounded by the recirculation line break and therefore their results are not discussed in this paper. The calculations were performed with the plant operating at normal conditions. Loss-of-offsite power, causing a trip of the recirculation pumps, was assumed at the event beginning. The scram time is obtained from the earlier of the High Drywell Pressure[1] or instrument signals of the water level in the downcomer between the core barrel and the reactor vessel. Main Steam Isolation Valve (MSIV) closure was initiated on L1. For break sizes larger than approximately 0.01 m^2, the High Drywell Pressure signal occurs before the downcomer water level decreases below the instrument signal setpoint. For breaks smaller than 0.01 m^2, the scram is caused by the water level signal.

The break sizes investigated in this study are from 0.0046 m^2 to a double-ended guillotine break (DEGB) (0.33 m^2 on each side). All breaks smaller than the DEGB are modeled as split breaks, with flow from both sides of the recirculation line feeding the break flow.

For the small-to-intermediate break small-to-intermediate breaks ranging from 0.0046 to 0.037 m^2, following the MSIV closure on low water level, the RPV pressure increases for smaller breaks until the Auto Depressurization System (ADS) valves open. The ADS actuation is also on low water level with a timer delay of 120 s. For the smallest break, there is relatively less significant heatup in the core until the flashing due to the ADS subsides. As the break size increases, an earlier heatup is seen as the core inventory begins to deplete before the start of the depressurization. This early heatup is quenched by the lower plenum flashing-induced core flow. A second period of cladding heatup begins after the ADS depressurization rate subsides. This later heatup determines the PCT for the transient.

For intermediate-to-large breaks ranging in break area from 0.037 to 0.185 m^2, the RPV pressure remains close to turbine-controlled pressure following MSIV closure. The downcomer level drops to the elevation of the suction of the recirculation line before the ADS valves open. The uncovery of the recirculation line suction leads to vapor discharge from the reactor vessel and a faster depressurization rate. The depressurization rate increases further as the ADS valves open. The timing of the ADS is earlier as the break size increases but ADS actuation is of less importance for the intermediate breaks (as compared with the small breaks) because of the early depressurization following the break uncovery. The earlier depressurization for the larger breaks mitigates the core inventory loss before ADS activation and earlier activation of the CS limits the core heatup.

---

[1] Since containment is not explicitly modeled. The high drywell pressure is calculated based on break sizes in current analysis.

As the break size increases beyond 0.185 m^2, the effect of the ADS diminishes. For large breaks the reactor vessel depressurizes rapidly without a need for the ADS valves to supplement the blowdown. The reactor vessel depressurizes earlier because of the loss of fluid through the break. When the earlier activation of the CS is more important than the increased rate of inventory loss, the PCT will decrease as the break size increases. For the larger breaks, however, the CS flow addition cannot compensate for the increased break flow and a late heatup occurs. The large loss of inventory dominates the temperature rise. Slightly earlier activation of the CS is not sufficient to offset the early heatup and the PCT increases with break size. For the large breaks, a first peak PCT also occurs early in the transient because of the mismatch between the power and core flow. The first peak PCT is not limiting and is partially quenched by the lower plenum flashing that follows the uncovery of the break.

Both the break spectrums for recirculation suction line and for recirculation discharge line are provided in this paper. The break spectrums with air boundary conditions are shown in Figure 3 (noncondensible is air in this case). For small-to-intermediate break sizes, discharge breaks resulted in higher PCT than suction breaks of the same size. For larger break sizes, the suction breaks are higher than the corresponding discharge breaks. For the DBA DEGB, discharge DBA DEGB resulted in significantly higher PCT than the suction DBA. The break spectrum for BWR/2, with quite different ECCS system and plant geometry, is also very different from the break spectrum for a typical BWR/4 system [21]. Comparing Figure 3 to BWR/4 break spectrum in [21], there are a few major differences regarding the break spectrum in Figure 3.

1. For BWR/2, DEGB is bounding; intermediate break is bounding for BWR/4.
2. The bounding case for PCT is the recirculation discharge break (DSCG) with double-ended guillotine break (DE-GB). Compared to the same break area split break, PCT for DEGB is higher than the same area split break.
3. For larger suction line break (SUCT), the PCTs are higher than the corresponding DSCG break size. Surprisingly it is found that the PCT for DEGB for SUCT is much lower than the same-area split break, which is opposite to the DSCG break.

Those questions have forced us to think deeper for BWR/2 LOCA. Further studies have made and the findings are presented in the following section.

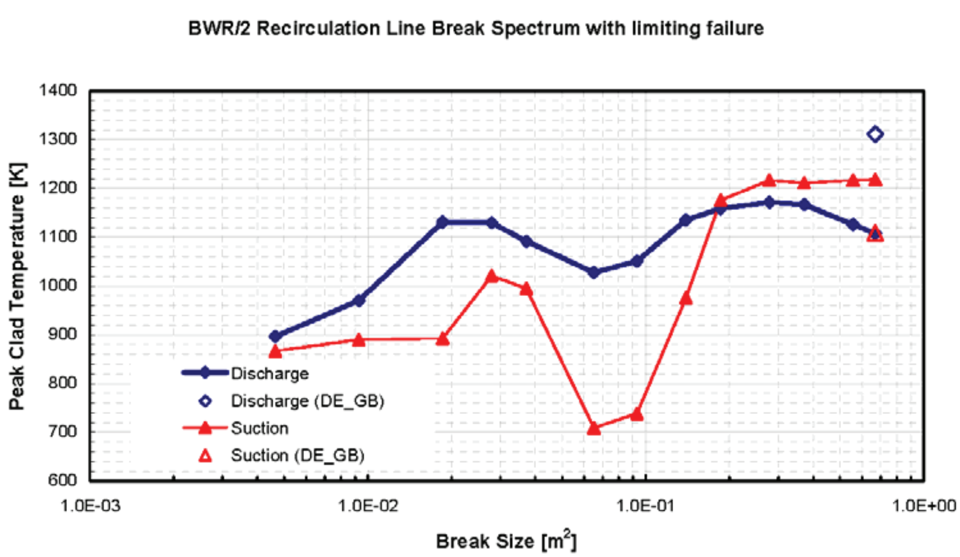

Figure 3. Break Spectrum for BWR/2 Discharge and Suction Side Breaks with Air Break Boundary Conditions.

4. SENSITIVITY STUDIES

Previous studies on TRACG LOCA for a BWR/4 or a BWR/6 plant have not reported the similar observation as discussed in the previous section [21]. The PCTs for DEGB are usually very similar to those from the same area split break. Since both BWR/4 and current BWR/2 used the similar boundary conditions, it is speculated that the behavior of BWR/2 is attributed to the BWR/2 peculiar geometry and the interaction of BWR/2 peculiar geometry with boundary condition and BWR/2 core thermal hydraulic conditions. In the following sections, the results from those studies are discussed and reported.

4.1. Break Boundary Conditions

For the results presented in Section 3, it is found that the RPV pressure can be at sub-ambient condition when CS is initiated. After the RPV pressure is below the CS pressure permissive following a large LOCA (or ADS), the introduction of large amount of cold water into RPV upper plenum (steam-water environment) will quickly lead to the condensation of steam, and the RPV pressure is significantly reduced. When the RPV pressure is lower than the break boundary condition, the gas at the break (air for Section 3 cases) will be infiltrated into the RPV. With the presence of air in the core and/or in the upper plenum, the heat transfer will be deteriorated, which would elevate the core PCT.

In the first study, the boundary condition is changed from non-condensable to all steam. For large break, all steam condition is actually a realistic boundary condition as the air initially in the drywell will be pushed into the containment wetwell through BWR vent due to a large LOCA. The DSCG break spectrum at steam boundary conditions is shown in Figure 4, together with the break spectrum with air boundary conditions. The comparisons showed that the PCTs at steam boundary condition are significantly lower than that from air boundary condition. The impact of the boundary condition is only observed for the larger breaks. As expected, the PCT for the smaller breaks is not impacted. The RPV pressure for the smaller break is always larger than the ambient pressure (break boundary pressure) and therefore the content of the break have no impact. For larger break, the rapid steam quenching due to the CS initiation can reduce the RPV pressure lower than the ambient pressure, which “suck” the break boundary gas into the system. For steam boundary condition, the heat transfer in the core and in the upper plenum would not be significantly impact. For air boundary condition, the condensation heat transfer is deteriorated and higher PCT is obtained.

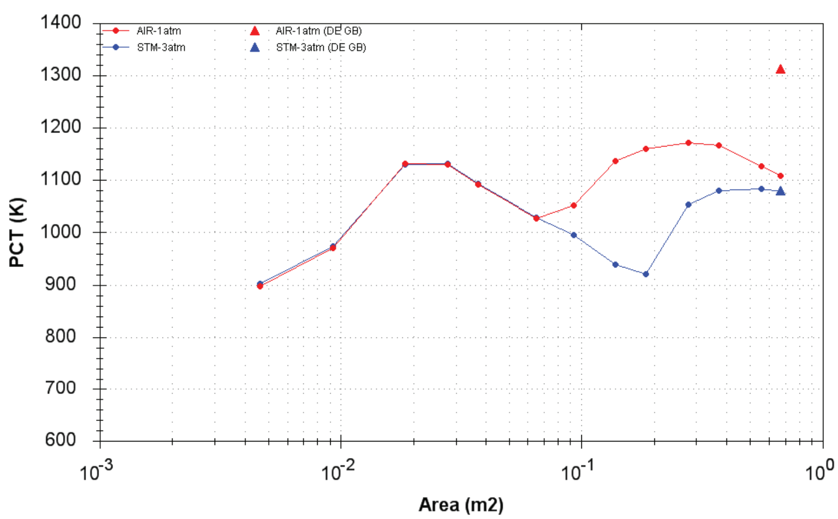

Figure 4. Effect of BWR/2 Containment Boundary Conditions.

Furthermore the difference in PCT between DEGB and the same-area split is not observed for the steam boundary condition. Similar results are for suction breaks. It is therefore concluded that the difference in BWR/2 discharge break PCT's between the DEGB and the same area split break as shown in Figure 3 is attributed to the noncondensible gas infiltration into the RPV.

4.2. DEGB versus Split for a Discharge Line Break (DSCG)

The PCT time histories for those two cases (called DEGB and Split hereafter) are shown in Figure 5.a. It is observed that the PCT's for both breaks behaves the same for the first 160 seconds, but they take different path after this time. The reason for this first PCT deviation for these two breaks is due to the air infiltration in the RPV (Air Pressure in the RPV upper plenum is shown in Figure 5.b). According to Figure 5.b, the air is present at upper plenum about 200 seconds earlier for the DEGB case than for the split case. The presence of air in the upper plenum interferes with the steam condensation (core spray), reducing the driving force for the steam flow, thus driving the PCT higher. The small amount of air in the upper plenum for the split break also drives the PCT higher, but in a much less severe manner compared to DEGB.

For BWR/2 discharge break, air could possibly enter the RPV through two paths. One is from the break in the RPV side, and the other is from the break in the pump side (through the suction line). For DEGB case, the air goes into the RPV through these two paths. It is observed, however, the air can only enter the RPV through the RPV side break after around 250 seconds for the split break because the pump side becomes water sealed after 250 seconds for the split break (Figure 5.c). Therefore for the split break, the air goes into the lower plenum through the vessel side break, and propagates upwards into the channel, bypass region and then the upper plenum. On the contrary for DEGB case, the air can go into the RPV via these two paths, but mainly goes into the upper plenum by way of the downcomer from the pump side recirculation line. The heat flux at the channel is then different (Figure 5.d for cladding heat flux). The PCT's for these two cases then behave differently due to the air content, the air flow path, and the timing of air infiltration. It is noted that the water level in the RPV, which is stabilized in the RPV lower plenum for the discharge break, plays less important role in the core PCT's than that for the BWR/2 suction break, as discussed below.

Therefore, it is speculated, for BWR/2 discharge break, that the PCT for the split break should be very similar to that for DEGB if the pump side recirculation line was not blocked by water and air could go into the system freely, just as the air does for the DEGB case. A hypothetical case is therefore examined, in which the air is introduced manually into the RPV at around 160 seconds when pump side recirculation line starts to be blocked. By doing this, it is assumed that the pump side recirculation line was not blocked and the air can freely go into the system as it does for DEGB case. The PCT time histories for the original DEGB case and this hypothetical case (called Split with Vent in this figure) are shown in Figure 6. It can be seen from this figure that the PCT for this hypothetical split case behaves essentially the same as the original DEGB case.

In summary, the PCT differences for DEGB and the same area split break as shown in Figure 3 for BWR/2 discharge break is due to the blockage of air path in the pump side recirculation line for the split break. Due to this blockage, the air amount, air path into the RPV are different for those two breaks, which then impact the channel heat-up differently, thus generating different PCT's for these two cases.

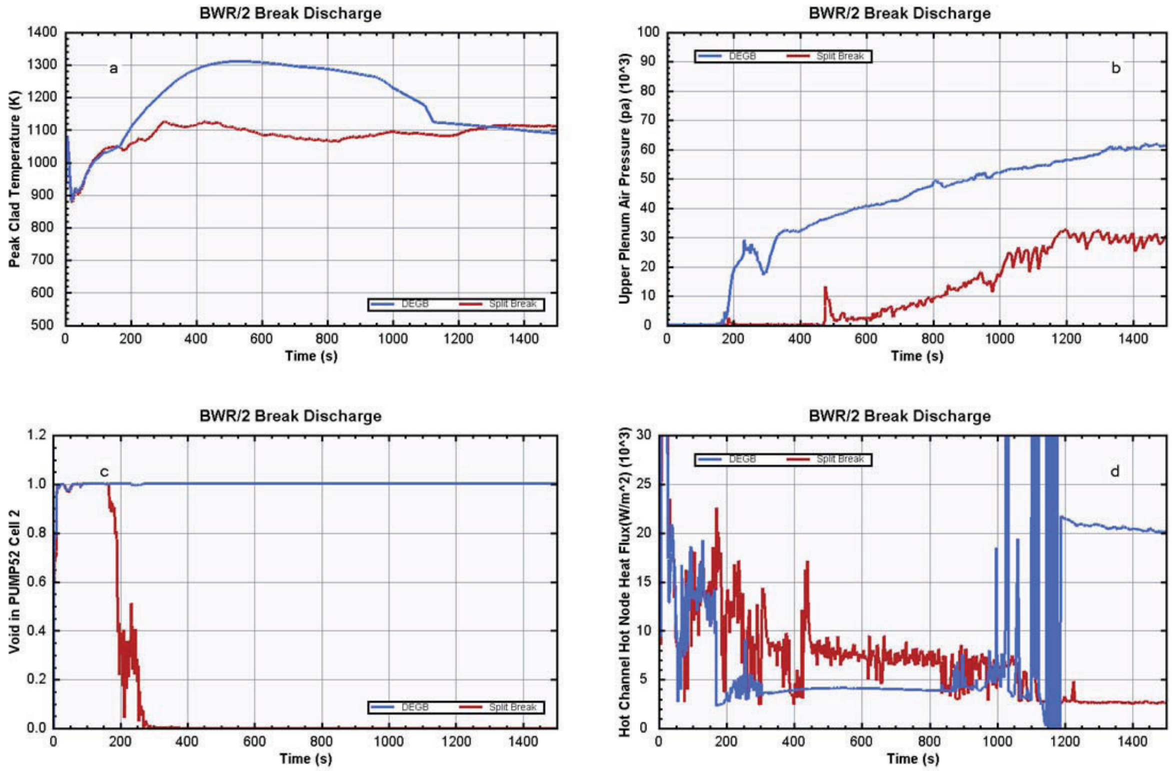

Figure 5. Comparisons for BWR/2 Discharge Splitting break and DE-GB.

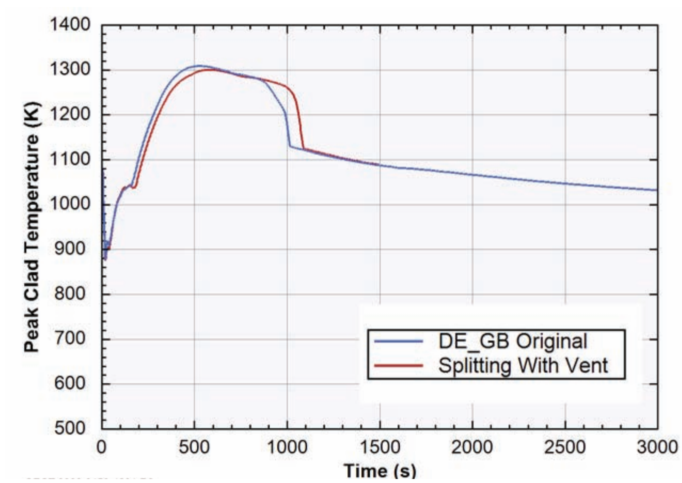

Figure 6. PCT's for BWR/2 discharge original DE GB and Split break with vent at 160 seconds.

4.3. DEGB versus Split for the Suction Line Break (SUCT)

Like BWR/2 discharge break, the difference in BWR/2 suction break PCT's between DEGB and the same area split break as shown in Figure 3 is also attributed to the noncondensible infiltration in the RPV (air in this case), but in a different manner (to be discussed below). The results for the steam boundary condition have shown that the DEGB produced almost the same PCT's as that for the same area split break.

The PCT time histories for those two suction break cases (also called DEGB and Split) are shown in Figure 7.a. It is observed that the PCT's for these two breaks behave very similar for the first 500-600 seconds, but they takes different path after this time. For DEGB case, PCT is then gradually decreasing; but it is gradually increasing, reaches the peak and then decreases for the split break. For the split break, the core PCT is about 100K higher than the DEGB case. This is different from the observation for the discharge break, where PCT for DEGB is about 200K higher than that for the split break as discussed above.

The reason for this PCT deviation for these two suction breaks is due to the amount of air in the RPV and the condition at the bottom of the core. Total air mass in the RPV is shown in Figure 7.b. According to Figure 7.b, the amount of air in the RPV is similar for those two cases until around 550 seconds. However, after this time, air continues flowing into the RPV for the DEGB case, but remains constant for the split case. In the other words, there is no air going into the system for the split break case after this time. With reference to the results in Figure 7.a, it seems that the case with a larger air quantity (DEGB) has lower core PCT.

Besides the amount of air for BWR/2 suction break in the RPV, the water level in the RPV (downcomer and core region) can be very important in the core heatup. For the BWR/2 suction break, after the initial blow down is finished and the core spray is initiated, core spray water flows into the core, then lower plenum and goes out of the RPV through either side of the suction line break. The discharge side recirculation line is totally filled with water for the suction break cases. For the RPV side suction pipe, the water flows out, and at the same time the air flows in. The water level would be stabilized so that water air counter current flow is established. This is observed for DEGB case. On the contrary for the split break, the water level in the downcomer continues going up until it is above the suction line and then stabilized. For this case, the air then ceases going into the system. This is what is observed for the split case. Figure 7.c shows the downcomer water levels for those two cases. For the split case, the core bottom is then "flooded" due to the high water level the downcomer and in the core region (Figure 7.d), which reduces the steam cooling for the channel and then generates the higher core PCT.

Therefore, it is speculated, for BWR/2 suction break, that the PCT for the split break should be very similar to that for DEGB if the air continued flowing in the system freely, just as the air does for the DEGB case. A hypothetical case is therefore run, in which the air is introduced manually into the RPV at around 125 seconds when the air is first observed in the RPV (Figure 8). The PCT time histories for the original DEGB case and this hypothetical case (called Split with Vent in this figure) are shown in Figure 8. It can be seen from this figure that the PCT for this hypothetical split case behaves essentially the same as the DEGB case.

In summary, the PCT differences for DEGB and the same area split break as shown in Figure 3 for BWR/2 suction break is due to the blockage of air path in the RPV side recirculation line (suction) for the split break. Due to this blockage for the split break, the water level in the RPV downcomer and in the core region is so high that the bottom of the core is "flooded" or "plugged", which reduces the steam cooling for channels, thus producing higher core PCT than the DEGB case.

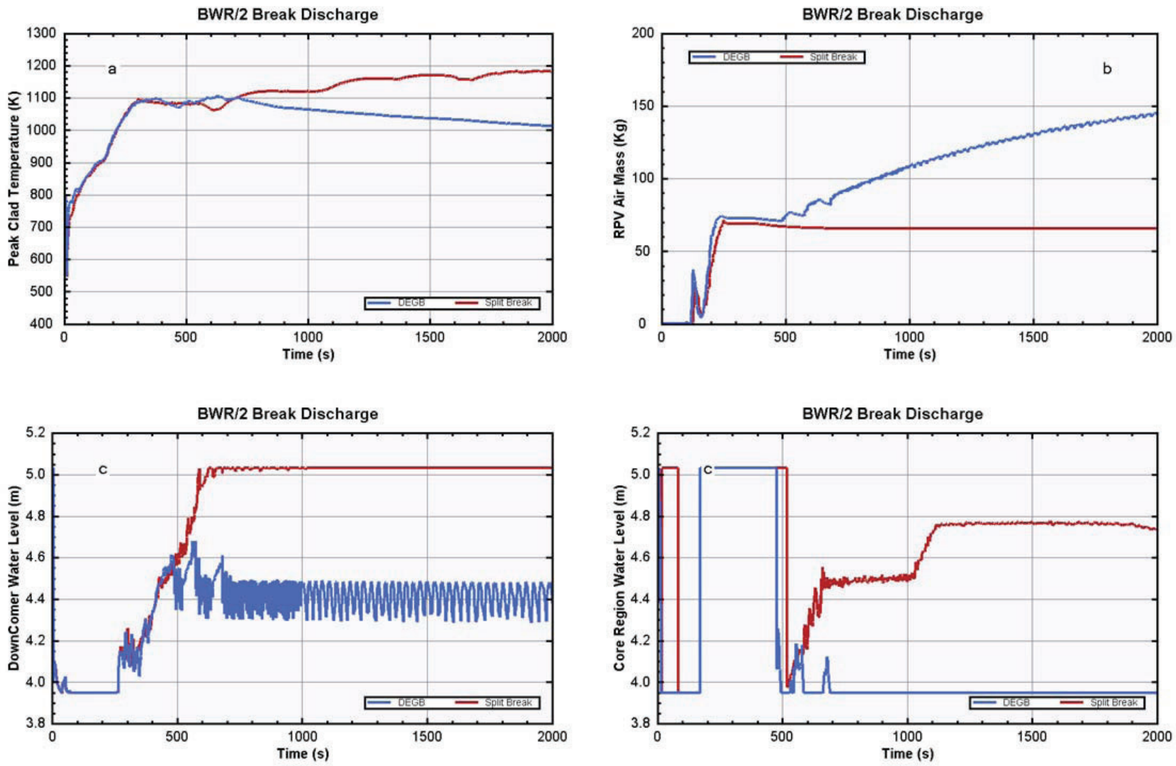

Figure 7. Comparisons for BWR/2 Suction DE GB and the same break area Split break.

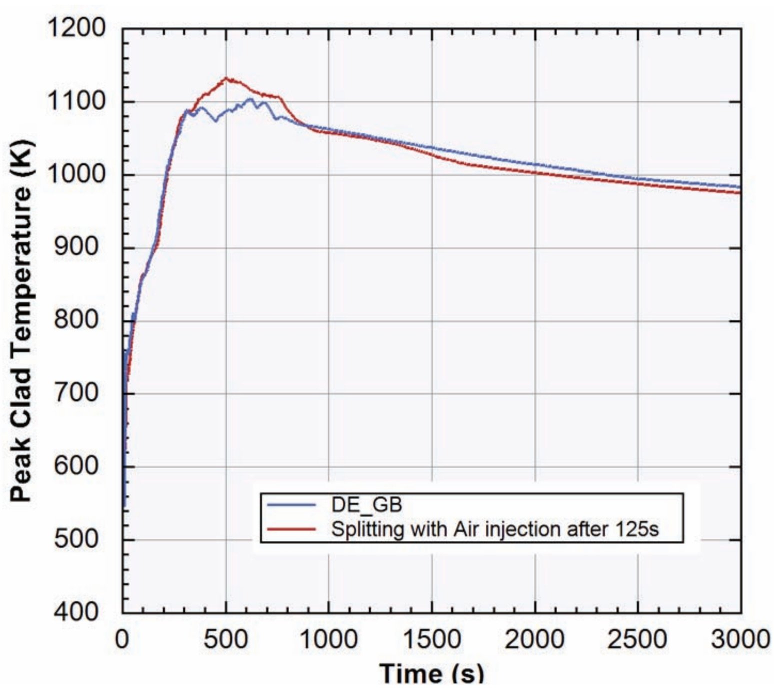

Figure 8. PCT's for BWR/2 suction original DE GB and Split break with vent at 125 seconds.

4.4. Effects of the Boundary Gas Mixture Content

Further studies are made by investigating the effect of break boundary gas mixture content. The boundary condition is changed from 100% air (or 0% steam) to 100% steam (or 0% air). The calculations are made for both DEGB and the same area split break. The PCTs for those cases are shown in Figure 9 for DSCG DEGB and Split breaks and in Figure 10 for SUCT DEGB and Split breaks.

For the BWR/2 discharge break, the limiting break is the DEGB, with a core PCT that is about 120K higher than the limiting split break. For this DEGB break, the core PCT is not sensitive to the air content in the break when air content in the break is greater than 5%.

For BWR/2 suction break, the limiting break is the maximum area split break, which is not sensitive to the air content in the break when air content in the break is greater than 1%.

These results together with the sensitivity studies show that even relatively small amounts of ingested air result in the higher PCTs and that these values are not sensitive to the amount of air beyond a small lower threshold provided that the air is not blocked from reaching the core because of the break geometry.

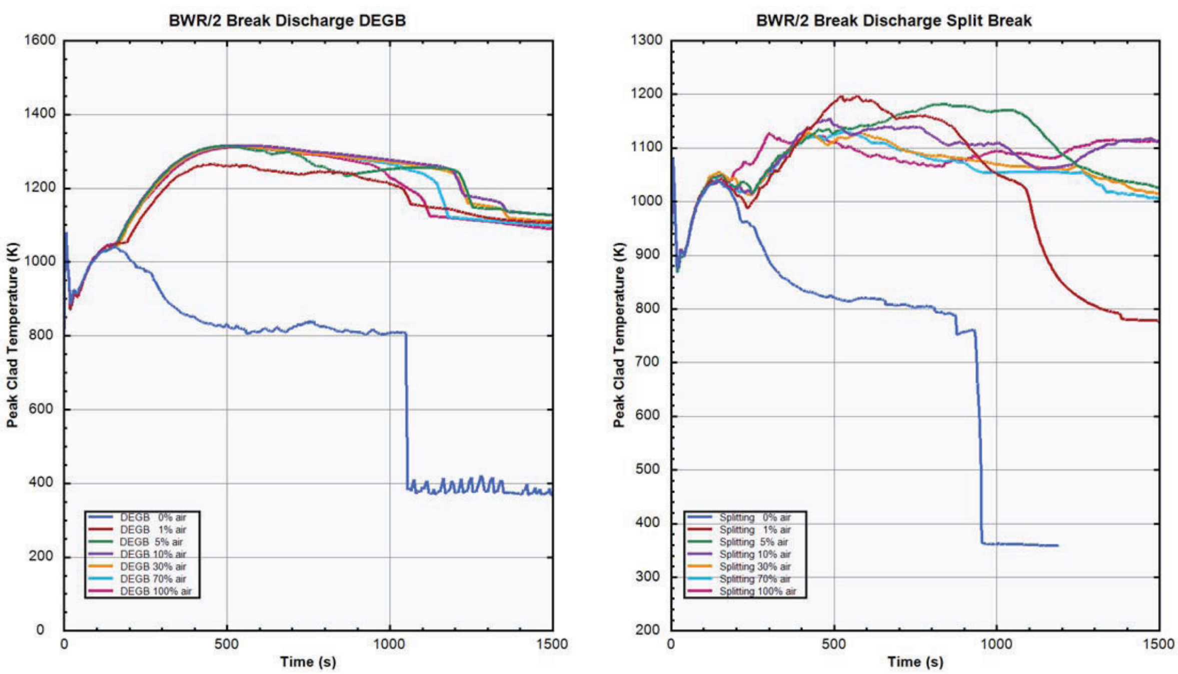

Figure 9. PCTs for different Break boundary conditions for DSCG.

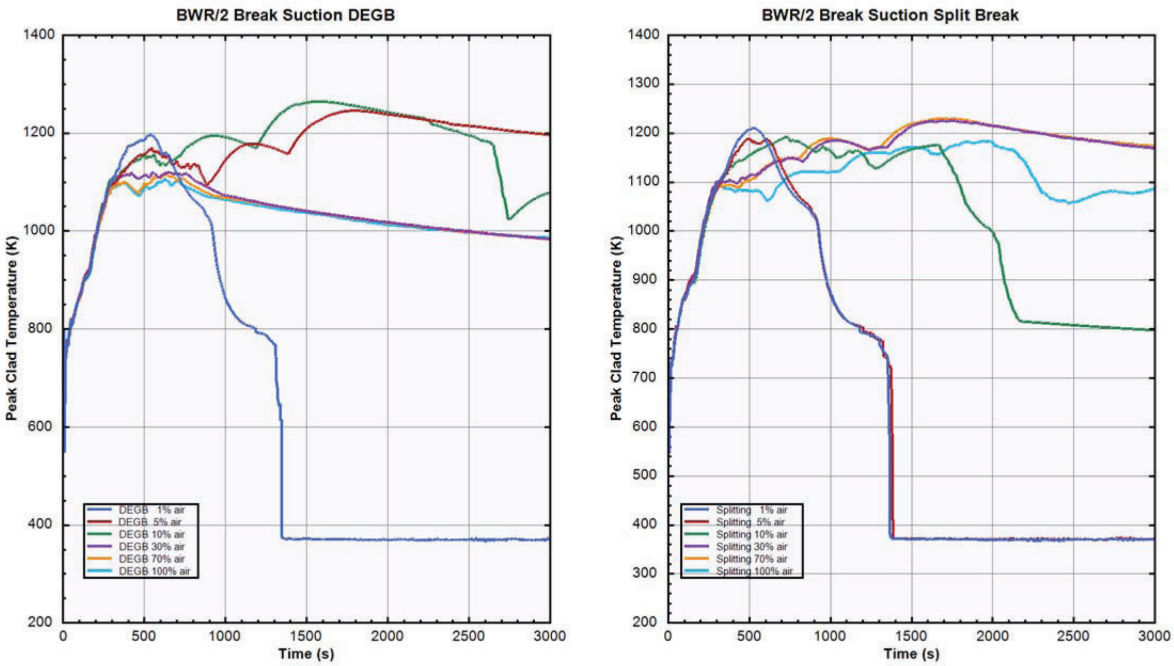

Figure 10. PCTs for different Break boundary conditions for SUCT.

4.5. BWR/2 Break Locations

The PCT difference for the BWR/2 limiting break between the DEGB and the same area split break is due to the difference in the air infiltration into the reactor vessel and core conditions. For the split break, the pump side recirculation line is filled with water and the air is blocked by the water in the recirculation line, which prevents the air from going into the vessel, and consequently the calculated PCT is lower.

Additional calculations were performed by moving the break to the lowest location in the recirculation line. For the initial calculations the break was located at the safe end of the recirculation discharge line defined by the end of the nozzle off the reactor pressure vessel. By relocating the split break to the lowest location in the recirculation line, the blockage of the pump side pipe by water is reduced and air ingested at the break can more easily flow into the vessel. For the DEGB, the impact is expected to be small as the pump side pipe empties quickly even when the discharge break is at the initial location. The results show that the break location change has insignificant impact on the PCT of the DEGB (PCT of 1308K for the initial break location versus 1298K for the break at the lowest location of the recirculation line); however, it has significant impact on the PCT of the split break, as expected. The PCT is increased to 1225K when the break is at the lowest location of the recirculation location, versus 1114K for the initial break location. It is further noted that this PCT from the split break, although increased significantly due to the break location change, is still well bounded by the PCT value calculated for the DEGB at the initial location.

5. CONCLUSIONS

LOCA responses of a typical BWR/2, being different from later BWR type in ECCS system and recirculation system, are quite different from LOCA responses of BWR/4 or BWR/6 systems. In BWR/2, a large recirculation line break is effectively a “bottom break” for the vessel inventory and the core cannot be reflooded. The BWR/2 LOCA response is totally dependent on core spray capacity, break boundary condition and thermal hydraulic condition in the core. The results have shown the air content at the break boundary has significant impact on the core PCT behavior for larger breaks. The difference in air pathway into the vessel between suction and discharge break lead to different PCT for double-ended guillotine breaks.

Sensitivity studies on break air content and break locations have been performed. It is found that the air presence, rather than the amount of air content, plays a key role in predicting the core PCT for BWR/2 LOCA. The core heatup behavior is changed by changing the break location for splitting break since the air infiltration characteristic for such breaks also changes. However, it has insignificant impact on the bounding break for BWR/2, which is the DEGB of recirculation discharge line. For the discharge DEGB, changing the break location does not significantly change the air infiltration from the break, and therefore the core heatup characteristics are not noticeably affected the air infiltration has been maximized

ACKNOWLEDGMENTS

In addition to the authors, the following people made significant contributions toward the development of LOCA modeling software and the accumulation of understanding of LOCA phenomena that are represented in this paper: Jens Andersen, Francis T. Bolger, James R. Fitch, Daniel Rock, Baris Sarikaya, B.S. Shiralkar, and Feibiu D. Shum.

REFERENCES

1. J. A. Findlay, et al., "*SAFER Model for Evaluation of Loss-of-Coolant Accidents for Jet Pump and Non-Jet Pump Plants Volume II: SAFER Application Methodology for Non-Jet Pump Plants*," NEDO-30996-A, March 1988.
2. F. D. Shum, et al., "*SAFER Model for Evaluation of Loss-of-Coolant Accidents for Jet Pump and Non-Jet Pump Plants, Volume I, SAFER – Long Term Inventory Model for BWR Loss-of-Coolant Analysis*," NEDO-30996-A, March 1988.
3. J. G. M. Andersen, et al., "*TRACG Model Description*," NEDO-32176, Revision 4, January 2008.
4. J. G. M. Andersen, et al., "*TRACG Qualification*," NEDO-32177, Revision 3, August 2007.
5. D. T. Rock and C. L. Heck, "*TRACG04P User's Manual*," December 2011.
6. B. S. Shiralkar and Y. K. Cheung, "*TRACG Application for ESBWR*," NEDO-33083-A, October 2005.
7. J. G. M. Andersen, et al., "*TRACG Application for Anticipated Operational Occurrences Transient Analysis*," NEDO-32906-A, Revision 3, September 2006.
8. "*Migration to TRACG04 / PANAC11 from TRACG02 / PANAC10 for TRACG AOO and ATWS Overpressure Transients*," NEDO-32906 Supplement 3-A, Revision 1, April 2010.
9. F. T. Bolger and M. A. Holmes, "*TRACG Application for Anticipated Transient Without Scram Overpressure Transient Analysis*," NEDO-32906 Supplement 1-A, November 2003.
10. B. S. Shiralkar, et al., "*TRACG Application for ESBWR Stability Analysis*," NEDO-33083, Supplement 1-A, Revision 2, September 2010.
11. C. R. Lehmann, et al., "*Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology for Reload Applications*," NEDO-32465-A, August 1996.
12. "*DSS-CD TRACG Application*," NEDO-33147-A, Revision 4, August 2013.
13. R. J. Pryor, et al., "*TRAC-P1A, An Advanced Best Estimate Computer Program for PWR LOCA Analysis*," Los Alamos Scientific Laboratory, NUREG/CRA-0665, May 1979.
14. J. Spore et al., *"TRAC-BD1: An Advanced Best Estimate Compute Program for Boiling water Reactor Loss-of-Coolant Analysis,"* NUREG/CR-2178, October (1981)
15. D. D. Taylor, et al., "*TRAC-BD1/MOD1: An Advanced Best Estimate Program for Boiling Water Reactor Transient Analysis*," Volumes 1-4, NUREG/CR-3633, Idaho National Engineering Laboratory, April 1984.
16. J. A. Borkowski, et al., "*TRAC-BF1/Mod1 Models and Correlations*," NUREG/CR-4391, Idaho National Engineering Laboratory, August 1992.

17. “*Licensing Topical Report TRACG Application for Emergency Core Cooling Systems / Loss-of-Coolant-Accident Analyses for BWR/2-6*” NEDO-33005, January 2011.
18. J. Duncan and P. W. Marriott, “*General Electric Company Analytical Model for Loss-of-Coolant Analysis in Accordance with 10 CFR 50 Appendix K*,” NEDO-20566-A Volumes I, II and III, September 1986.
19. U.S. NRC, “*Best-Estimate Calculations of Emergency Core Cooling System Performance*,” Regulatory Guide 1.157, May 1989.
20. B. Boyack, et al., “*Quantifying Reactor Safety Margins: Application of Code Scaling, Applicability, and Uncertainty Evaluation Methodology to a Large-Break, Loss-of-Coolant Accident,*” NUREG/CR-5249, December 1989.
21. J.G.M., Andersen et al., “Realistic Assessment of Break Size in Simulated BWR Loss-of-Coolant Accidents,” NURETH-13, Kanazawa City, Ishikawa Prefecture, Japan, September 27-October 2, 2009.