NURETH14-594

SYSTEM LEVEL PHENOMENA OBSERVED IN THE WESTINGHOUSE FULL SPECTRUM™ LOCA METHODOLOGY

M.A. Shockling, C. Frepoli, and K. Ohkawa
Westinghouse Electric Company LLC

Abstract

In this paper, the ability of the Westinghouse FULL SPECTRUM™ LOCA (FSLOCA™) best-estimate code to adequately capture the phenomena most important and dominant for small, intermediate, and large breaks of the cold leg is demonstrated for a three-loop Westinghouse pressurized water reactor (PWR). Nominal scenarios, in which typical values are assumed for uncertainty parameters, illustrate the influence of break size on the important system-level phenomena predicted by the code. The relatively more limiting predictions of peak cladding temperature for larger breaks confirm the analysis margin achieved for small breaks by analyzing in a best-estimate manner.

Introduction

Historically, loss-of-coolant accident (LOCA) analyses have considered large and small breaks separately. Differing important phenomena for the two classes of postulated events led to the use of separate safety analysis codes, each with its own set of important phenomena, validation basis, and analysis methodology. Since the mid-1990's, best-estimate methodologies specific to large breaks have been developed and implemented by Westinghouse and others to better capture the plant response to a postulated break and to gain analysis margin. Recently, Westinghouse has developed the FULL SPECTRUM™ LOCA (FSLOCA™) methodology to address postulated breaks in a best-estimate manner ranging from the smallest to the largest break sizes. [1]

Regulatory Guide 1.203 [2] describes a process for developing and assessing evaluations models "used to analyze transient and accident behavior that is within the design basis of a nuclear plant," the Evaluation Model Development and Assessment Process (EMDAP). In developing the FSLOCA methodology, Westinghouse has followed such a process. The first step of the process identifies the purpose (LOCA analysis over the full spectrum of postulated break sizes), the transient class (best estimate plus uncertainty accident analysis), and the power plant class (three-loop Westinghouse PWR). Step 2 specifies figures of merit, which for a LOCA analysis are the 10 CFR 50.46 criteria related to peak cladding temperature and cladding oxidation, but also require the evaluation model (EM) to demonstrate conservatisms related to important phenomena that influence the prediction of cladding temperatures and oxidation.

Step 3 and 4 of the EMDAP process involve the identification of systems, components, phases, geometries, fields and processes that should be modeled, and indentify and rank the phenomena and processes that are deemed relevant. A Phenomena Identification and Ranking Table (PIRT) process is used to list processes of importance and indicate at what times in the transient each process occurs. A single Phenomena Identification and Ranking Table (PIRT) has been developed for the FSLOCA methodology, following the approach outlined in [3], as discussed by [4].

Westinghouse has previously developed both large break and small break LOCA PIRTs, and these PIRTs were the subject of NRC review (for the large break LOCA PIRT) and independent peer review (for the small break LOCA PIRT). Relative rankings in the recently developed FSLOCA PIRT were assigned using the following criteria:

H = The process is considered to have high importance. Accurate modeling of the process during the particular period is considered to be crucial to correctly predict the transient.

M = The process is considered to have medium importance. The process must be modeled with sufficient detail to obtain accuracy in the simulation; however, the process is expected to have less impact on the overall results than those ranked high.

L = The process is not considered to be very important during the transient. The phenomena needs to be modeled in the code (or accounted for in the methodology), but inaccuracies in modeling these processes are not considered likely to have a significant impact on the overall transient results.

N/A = The process is considered insignificant, or does not occur at all. This process need not be modeled or be taken into consideration, as it has an insignificant impact on results.

This paper focuses on the observation of a few of the highly ranked phenomena in the context of typical small break (SB), intermediate break (IB), and large break (LB) LOCA transients postulated to occur in the cold leg of a typical 3-loop Westinghouse pressurized water reactor (PWR). A systematic evaluation of the code's capability in accurately modelling the phenomena is provided in [1] and is beyond the scope of this paper. Because a full demonstration of the PIRT process is an extensive process, here only a high-level demonstration is provided regarding the system-level behaviour, examining several of the highly ranked phenomena.

1. Transient Specifications

An element of the EMDAP process is to specify the transient periods of interest to identify the relevant phenomena for each. A realistic code intended to analyze the full spectrum of breaks must be capable of predicting the major phenomena that influence the system response and bring about the main characteristics of the transient. These characteristics differ quite significantly over the postulated range of break sizes, and the importance of phenomena varies throughout the transient as well. In this section, the periods for small, intermediate, and large break LOCAs are defined.

1.1 Small Break LOCA (SBLOCA) Periods

Blowdown: Upon initiation of the break, there is a rapid depressurization of the primary side of the reactor coolant system (RCS). Reactor trip is initiated on a low pressurizer pressure setpoint (approximately 1860 psia). Loss of condenser steam dump effectively isolates the steam generator (SG) secondary side, causing it to pressurize to the safety valve setpoint (approximately 1100 psia) and release steam through the safety valves. A safety injection (SI) signal occurs when the primary pressure decreases below the pressurizer low-low pressure setpoint (approximately 1760 psia), and SI begins after some delay time. The RCS remains nearly liquid solid for most of the Blowdown period, with phase separation starting to occur in the upper head, upper plenum, and hot legs near the end of this period. During the Blowdown period, the break flow is single-phase liquid. Eventually, the entire RCS saturates, the rapid depressurization ends, and the RCS reaches a pressure just above the SG secondary side pressure. Some phenomena ranked 'H' during this phase of a SBLOCA include the prediction of single- and two-phase critical flow through the break and the decay heat in the core, since they influence directly the rate of inventory loss and depressurization and drive the cladding heatup, respectively.

Natural Circulation: At the end of the Blowdown period, the RCS pressure reaches a quasi-equilibrium condition that can last for several hundred seconds, during which the SG secondary side acts as a heat sink. During this period, the system drains from the top down with voids beginning to form at the top of the SG tubes and continuing to form in the upper head and top of the upper plenum regions. There is still adequate liquid to allow significant natural circulation two-phase flow around the loops; decay heat is removed through condensation in the SGs during this time. Significant coolant mass depletion continues from the RCS, and vapor generated in the core is trapped within the upper regions by liquid plugs in the loop seals (the u-shaped section in the cold leg between the steam generator outlet plenum and the reactor coolant pump inlet), while a low quality flow still exits the break. Critical flow at the break remains a highly ranked phenomena during this phase, as it influences the rate of inventory depletion.

Loop Seal Clearance: When the liquid level in the downhill side of the pump suction piping is depressed to the bottom of the loop seal, steam previously trapped in the RCS can be vented to the cold leg break. The break flow, previously a low quality mixture, transitions to primarily steam. Prior to loop seal venting, the static head balances within the RCS can cause the vessel collapsed mixture level to depress into the core, potentially allowing the cladding to heat up. Following the venting, the vessel level recovers to about the cold leg elevation, as the imbalances throughout the RCS are relieved. Some phenomena ranked ‘H’ during this phase include the prediction of horizontal stratification and interfacial drag in the loop seal, since they influence the timing of the loop seal clearance.

Boiloff: Following loop seal venting, the vessel mixture level continues to decrease due to the boiloff of the remaining liquid inventory since the RCS pressure is generally still too high to allow sufficient ECCS injection by the high pressure SI pumps. The mixture level will reach a minimum, in some cases resulting in core uncovery, before the RCS has depressurized to the point where the break flow is less than the rate at which ECCS water is delivered. The prediction of voids and mixture level in the core is important during this phase for reasonable prediction of cladding temperature excursions related to core uncovery.

Core Recovery: The vessel mass inventory is replenished from its minimum with ECCS water and the core recovers. The transient is terminated once the entire core is quenched and the pumped SI flow exceeds the break flow. Typically the vessel inventory depletion will end once the RCS depressurizes to the accumulator check valve pressure, at which point the insurge of cold liquid quenches the rods.

1.2 Intermediate Break LOCA (IBLOCA) Periods

Blowdown/Depressurization: Following an IBLOCA, the RCS depressurizes to the pressurizer low-pressure setpoint, actuating a reactor trip signal, and the control rods insert. System pressure continues to decrease as RCS inventory is lost through the break. The cold legs will reach saturation conditions, and two-phase flow at the break will lead to a reduction in the break flow rate. The break flow remains in a critical flow condition throughout this phase. As core inventory is lost, the core may heat up during this phase due to decay heat generation. As in the small break LOCA, critical flow at the break is a highly ranked phenomenon during this period.

Accumulator Injection: Once the primary side has depressurized sufficiently, accumulator injection is initiated. The accumulator injection phase is characterized by a rapid refill of the downcomer and of the core that will typically terminate any heatup initiated during the Blowdown phase. Most important during this period of the transient is the prediction of the accumulator flowrate and the flow at the break, since the mitigation of vessel liquid inventory during this period can keep the core adequately covered.

Safety Injection: As the accumulator empties, nitrogen will surge from the accumulator to the reactor coolant system. During this last phase, only pumped SI flow will be available to maintain core cooling. A second heatup may occur if SI flow is not sufficient to match decay heat and the mass inventory decreases. Nitrogen in the system may affect the system response. This phase and the transient are considered complete when SI flow consistently exceeds break flow and the core is quenched. Therefore, here the prediction of critical break flow is ranked 'H.'

1.3 Large Break LOCA (LBLOCA) Periods

Blowdown: The Blowdown period extends from the initiation of the break until the primary side depressurizes sufficiently that emergency core cooling (ECC) water can start to penetrate the downcomer. The flow out of the break is high, but limited by critical flow phenomena. Boiling and flashing occur in the core as the flow reverses, shutting down the fission process. The hot fuel rods quickly exceed the critical heat flux, as the core flow reverses, resulting in a sharp reduction in heat transfer to the coolant. The cladding temperature rises rapidly as the initial stored energy in the fuel pellets is transferred to the cladding. Within the next several seconds, coolant in all regions of the vessel and loops begins to flash. The break flow becomes saturated, and is substantially reduced. This reduces the depressurization rate, and may also lead to a short period of positive (upward) core flow as the intact loop pumps continue to supply coolant to the vessel. Cladding temperatures may be reduced, and some portions of the core may rewet. Two-phase conditions in the pumps reduce their effectiveness, and the core flow again reverses. Significant core cooling occurs as the fission process is shutting down, and the main heat source becomes decay heat generated in the fuel rods. Some system-level phenomena of high importance during this period include the prediction of break flow, the relative break path resistances to either the pump- or vessel-side of the break, and the prediction of flow reversal/stagnation in the core.

Refill: At approximately 10 to 15 seconds after the break, the RCS pressure decreases to the point where accumulators begin injecting cold water into the cold legs. As this water flows into the downcomer, it is initially swept out of the vessel and into the broken cold leg by the continuing high flow of steam from the core. Approximately 20 to 30 seconds after the break, the RCS has depressurized to a level approaching that of the containment, and refill begins. The ECC water from the accumulators and the pumped safety injection penetrates the steam upflow in the downcomer, refilling the lower plenum within a few seconds. As the coolant enters the core, the reflooding process begins. Prediction of three-dimensional effects in the downcomer is a highly ranked phenomena, since bypass of ECC water can delay the end of refill and thus prolong cladding heatup.

Reflood: The flow into the core is oscillatory, as cold water rewets the hot fuel rods, generating steam. This steam, and the water it entrains, must pass through the vessel upper plenum, the broken loop hot leg, the steam generator, and the pump before it can be vented out the break. Entrained water that enters the steam generators is also vaporized, increasing the flow path resistance. Because of the relatively low flow during this time period, cladding temperatures continue to slowly increase until the water level in the core reaches several feet. After about two to four minutes, the cladding temperatures in the higher regions of the core begin to decrease due to heat transfer to the dispersed droplet flow. Eventually, the entire core rewets and the long-term cooling phase begins. During this period, the predictions of steam binding in the steam generators and the containment backpressure are highly important, since they influence the rate at which the core inventory can be replenished, and thus, the cladding heatup that can occur during reflood.

2. SBLOCA Demonstration

A proxy for determining the periods of a SBLOCA transient is the system pressure. Typically, the RCS pressure will quickly reduce immediately following the break initiation during blowdown. The end of blowdown is evident from a stabilization of pressure over a significant amount of time, during natural circulation. Loop seal clearance marks the beginning of the boiloff period, marked by a monotonically reducing system pressure. As core recovery occurs, the pressure stabilizes to a new quasi-equilibrium dictated by the flow resistances in the system and at the break. Figure 2-1 shows the prediction for cold leg breaks ranging from 2.0 to 8.0 inches in diameter.

To demonstrate the prediction of highly ranked phenomena, the 3-inch break is explored here in further detail. Figure 2-2 shows the predicted pressurization of the steam generator secondary side, and the depressurization of the RCS, within the first ~20-50 seconds of the transient. A quasi-equilibrium is sustained for around 1000 seconds during the natural circulation phase, where the SG secondary side remains below the RCS pressure, indicating that it is a heat sink. Until the loop seal clearance occurs and a vapour vent path is established, the break flow remains two-phase (Figure 2-3). For this demonstration, a Homogeneous Non-equilibrium Relaxation critical flow model [5] was used to predict break flow and pressure losses, which, as described in the previous section, is a highly ranked phenomenon.

A realistic LOCA evaluation model intended to analyze SBLOCA must address the phenomenon of loop seal clearance. Loop seal clearance has been demonstrated to be a highly variable event characterized by “phenomenological uncertainty” [6] associated with flow stratification, interfacial drag, flow slugging, and instabilities caused by small differences among the intact and broken loops. For very small breaks, either no loop seals will clear or the broken loop will clear “preferentially due to its proximity with the break.” [6] Relatively large breaks will exhibit multiple loop seal clearance, a process associated with oscillations, and the loops that do clear tend to be random. Such a situation is observed for the 3-inch break, shown in Figure 2-4; the two intact loops exhibit full loop seal clearance (indicated by a differential pressure near zero, constant after ~1000s), while the broken loop only partially clears. Although not shown here, it was apparent through other transients that the phenomenological uncertainty described by [6] is generally observed with the FSLOCA code.

As shown in Figure 2-3, the break flow after loop seal clearance is single-phase vapour, and during this phase the prediction of single-phase critical flow is important in predicting inventory loss and core uncovery. Although the establishment of a vapour vent path reduces the liquid entrainment from the RCS, and hence the total mass flow, the safety injection flow remains low due to the RCS pressure, which remains high (Figure 2-1). As a result, the RCS inventory continues to deplete (Figure 2-5) throughout the boiloff phase until the accumulator check valve pressure is reached, around 2200s after the break as shown by the sudden and measurable increase in total injection flow in Figure 2-6. Because the accumulator injection begins the recovery, the depressurization rate is important in determining the severity in terms of core uncovery and cladding temperatures. Condensation of vapour in the proximity of the safety injection can influence this rate.

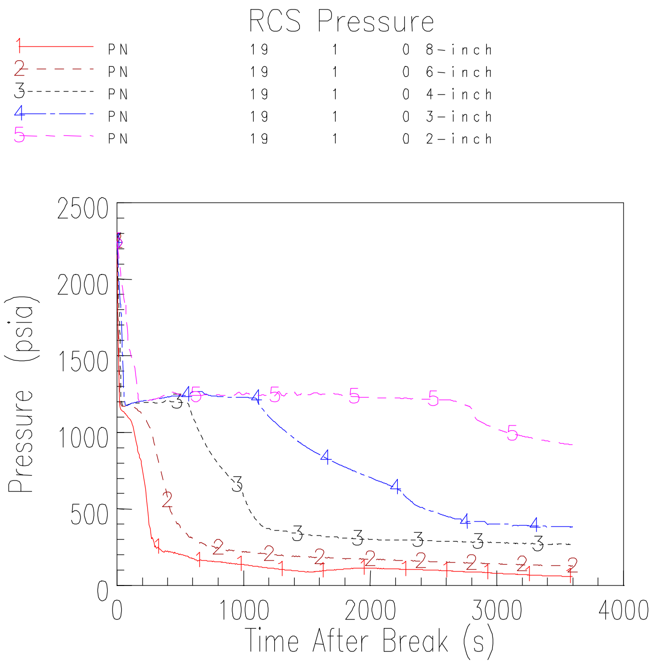

Figure 2-1 - RCS Pressure for Small Breaks

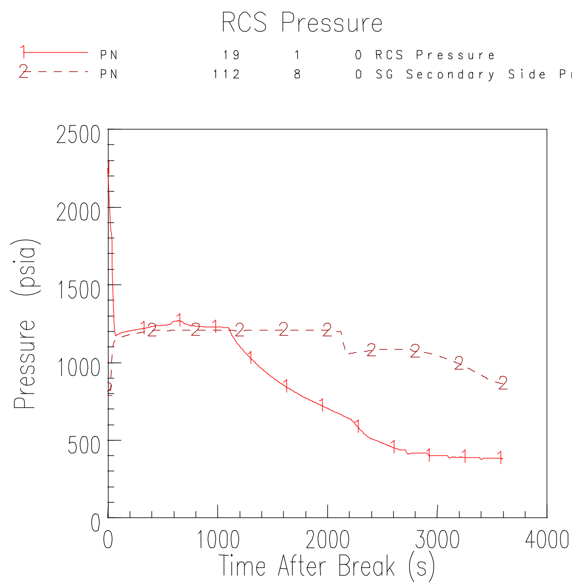

Figure 2-2 - RCS and Secondary Side Pressure for 3-inch SBLOCA

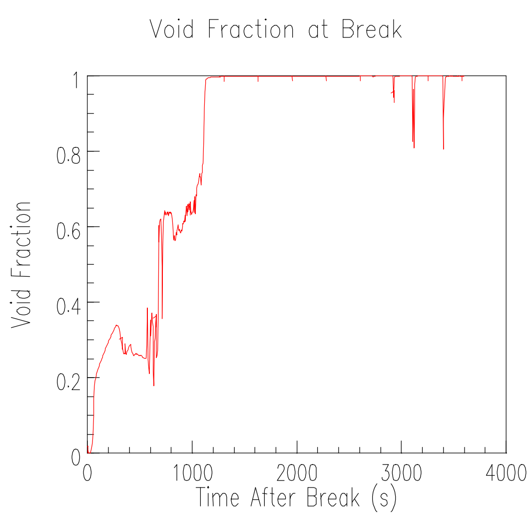

Figure 2-3 - Break Void Fraction for 3-inch SBLOCA

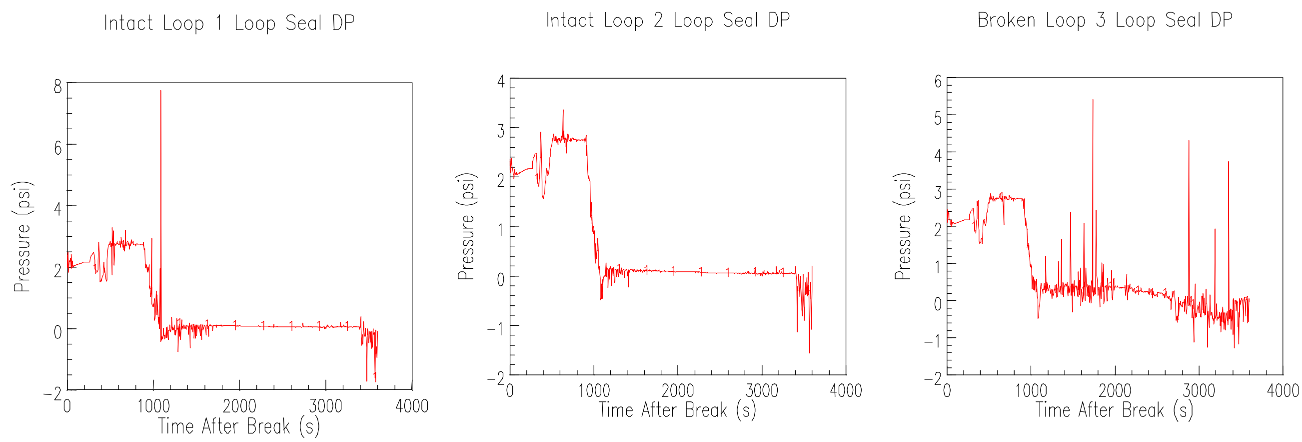

Figure 2-4 - Loop Seal Clearance Prediction (Differential Pressure) for 3-inch SBLOCA

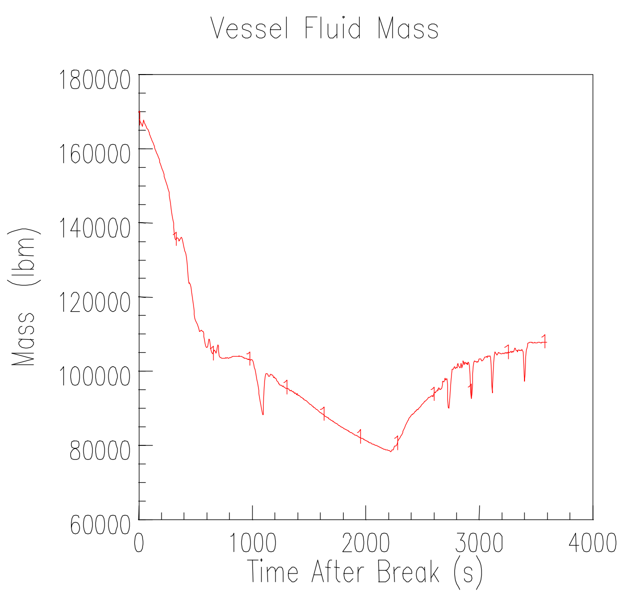

Figure 2-5 - RCS Fluid Inventory for 3-inch SBLOCA

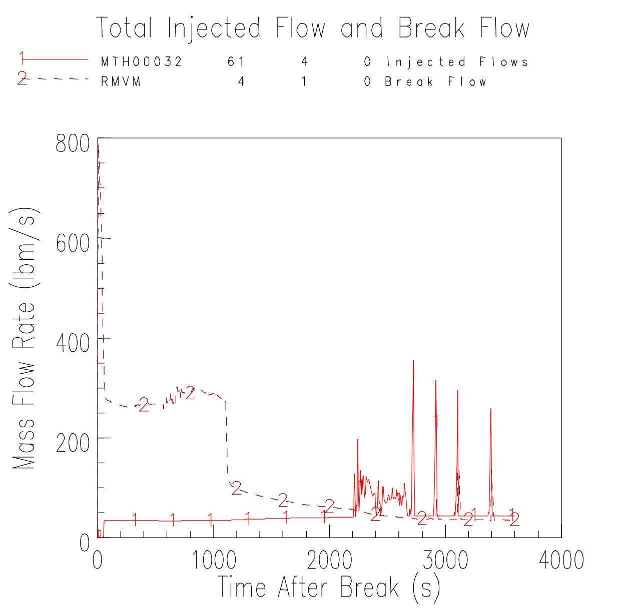

Figure 2-6 - Safety Injection for 3-inch SBLOCA

3. IBLOCA Demonstration

As shown in Figure 3-1, showing the RCS pressure response for split breaks in the cold leg ranging from 8.0 to 16.0 inches in diameter, intermediate breaks are characterized by an RCS pressure transient that does not exhibit a significant natural circulation period, but that does progress more slowly than a typical large break LOCA. Because break flow is sufficiently large, a quasi-steady natural circulation phase does not persist, and pressure falls to the accumulator check valve pressure relatively quickly in comparison with the SBLOCA transients. The 12-inch break is explored in further detail here.

As the RCS liquid becomes saturated, and flashing occurs, the transition to two-phase break flow leads to a reduction in break massflow, shown in Figure 3-2. When this occurs, the depressurization rate also reduces (Figure 3-1). The accumulator injection rapidly refills the vessel, shown in Figure 3-3, as the RCS pressure is still too high to allow for appreciable safety injection. After the accumulator has emptied, approximately 160 seconds after the break in Figure 3-4, over 200 seconds pass in which the safety injection is less than the break flow, allowing for inventory depletion (Figure 3-3). Recovery occurs as safety injection exceeds break flow.

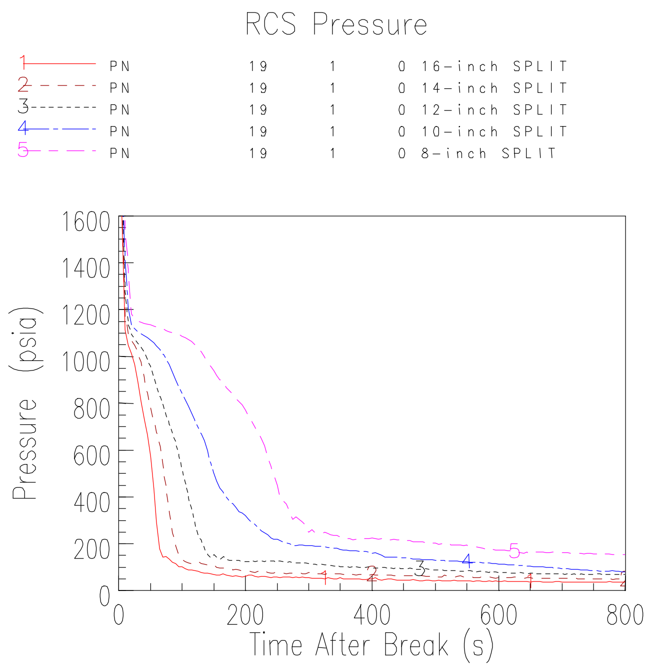

Figure 3-1 - RCS Pressure for Intermediate Breaks

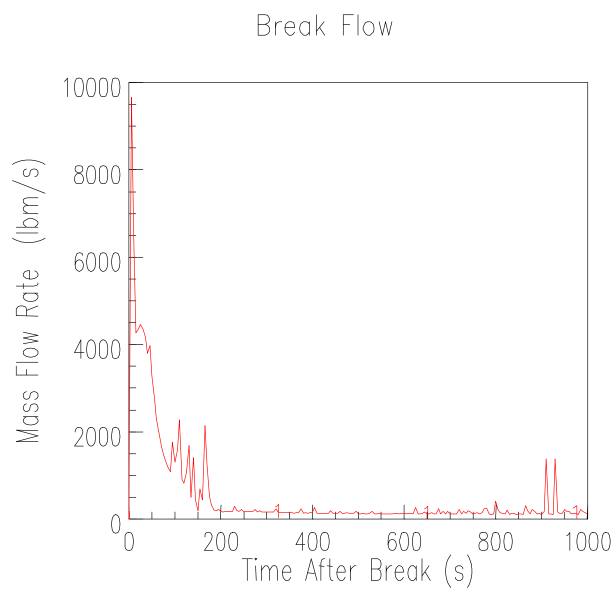

Figure 3-2 - Break flow for 12-inch IBLOCA

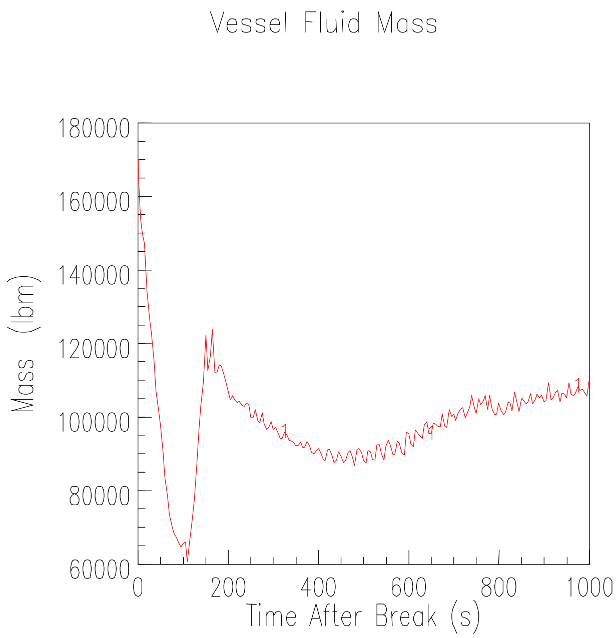

Figure 3-3 – RCS Fluid Inventory for 12-inch IBLOCA

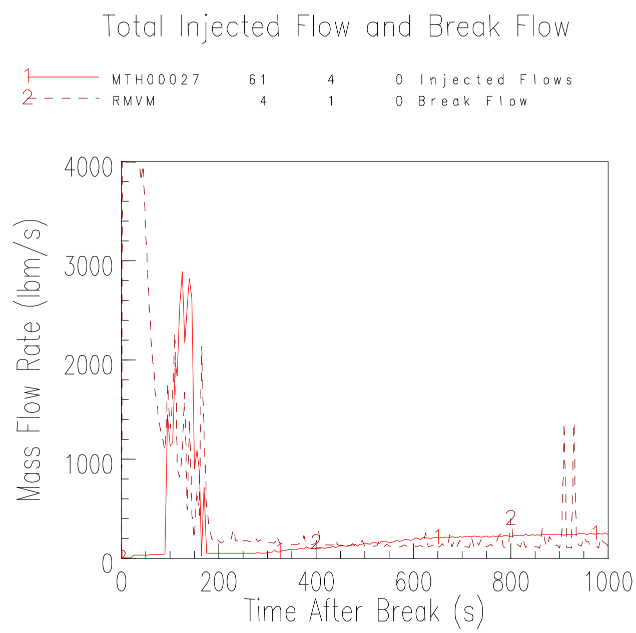

Figure 3-4 – Safety Injection for 12-inch IBLOCA

4. LBLOCA Demonstration

Following a large break LOCA, the RCS depressurizes very quickly. In Figure 4-1, the RCS pressure is shown for break sizes ranging from effective break flow area (EFA) of 1.0 to 2.8, defined by the total break area divided by the cold leg area. To achieve EFA=2.8, a numerical discharge coefficient of 1.4 is applied to the vessel- and pump-side break plane. The EFA=2.0 case, a nominal double-ended guillotine break of the cold leg (DEGCL), will be explored further here.

Figure 4-2 shows the vapour flow behaviour in the core during blowdown. A period of positive flow persists for approximately 10 seconds after the break. Shortly thereafter, flow reversal toward the break is apparent. By 20 seconds after the break, the vessel has depressurized and the net vapour flow is very small. It is this flow reversal and stagnation that was identified in Section 1.3 as being important in determining cladding heatup during the blowdown period.

The accumulator check valve pressure is reached approximately 10 seconds after the break, and the accumulator begins its blowdown (Figure 4-3). As described by [7], although localized flooding can be described by conventional correlations (Kutateladze, etc.), the system-level phenomenon of ECC bypass is 3-dimensional in nature. Adequate prediction of ECC bypass is validated in FSLOCA through comparison with the Upper Plenum Test Facility (UPTF) and other integral effect tests. Due to flooding phenomena in the downcomer and the resulting ECC bypass, vessel inventory continues to be lost through the break after the accumulator injection has started until the inventory reaches a minimum around 20 seconds (Figure 4-4) after the break, coincident with the RCS pressure reaching the containment pressure (Figure 4-1). The refill of the vessel continues after the end of ECC bypass, and the lower plenum liquid is replenished by the time the accumulator injection is complete (Figure 4-5).

The bottom-up reflood commences, driven by pumped safety injection into the cold leg, refilling the downcomer. As shown in Figure 4-6, the limiting elevation remains near the top of the active fuel (here, the fuel is 12 ft. tall). During reflood, as the quench front progresses upward, the upper elevations are cooled primarily by single phase vapour and any liquid droplets entrained upward from the quench front, [8] so it is expected that higher elevations would be more limiting. A period of approximately 150 seconds passes between the end of refill and the time when the quench front reaches the most limiting elevation, ending the transient around 200 seconds after the break.

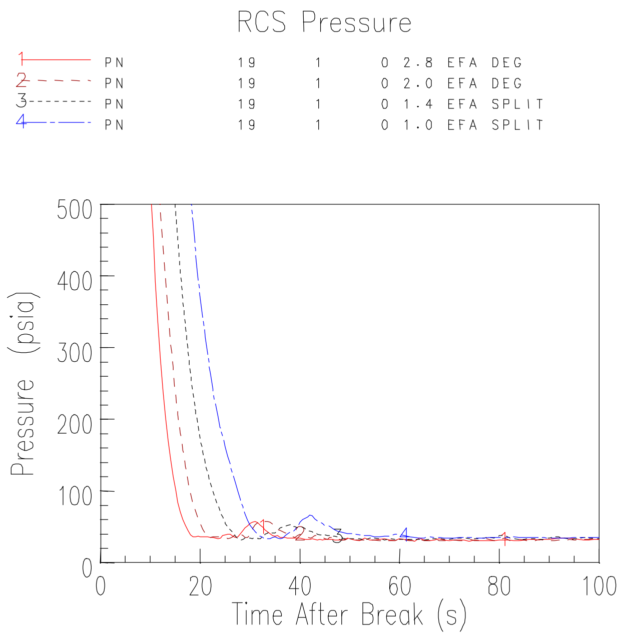

Figure 4-1- RCS Pressure for Large Breaks

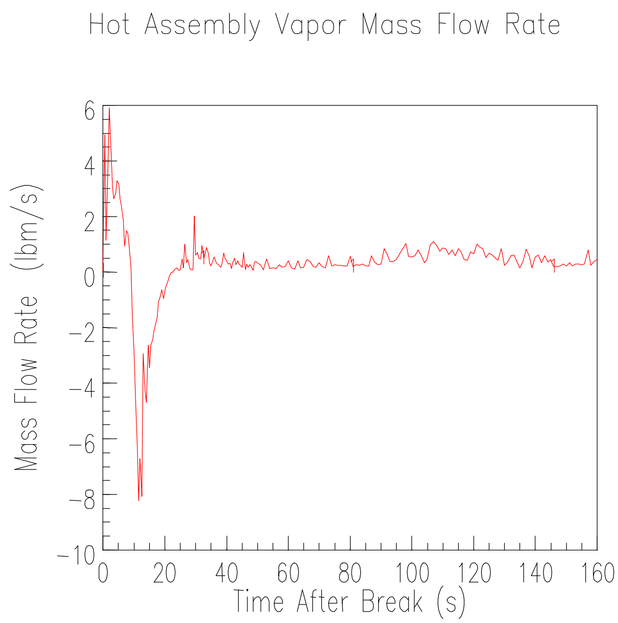

Figure 4-2 - Vapor Mass Flow Rate in Core for DEGCL

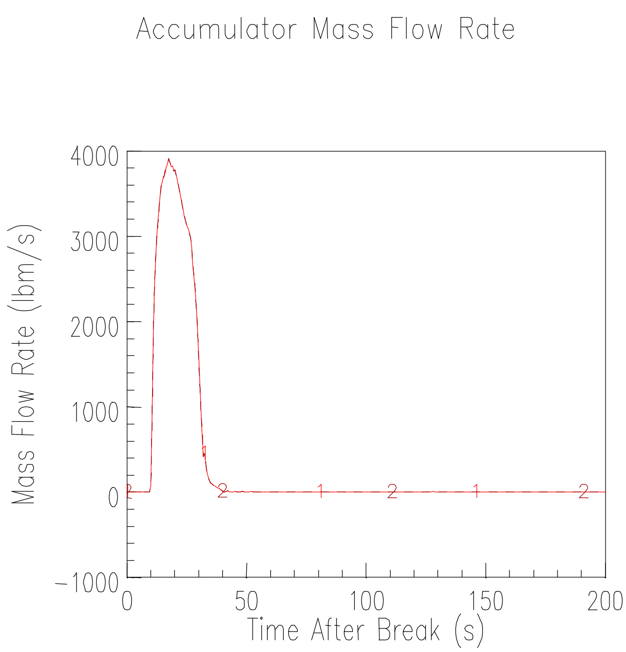

Figure 4-3 - Accumulator Flow for DEGCL

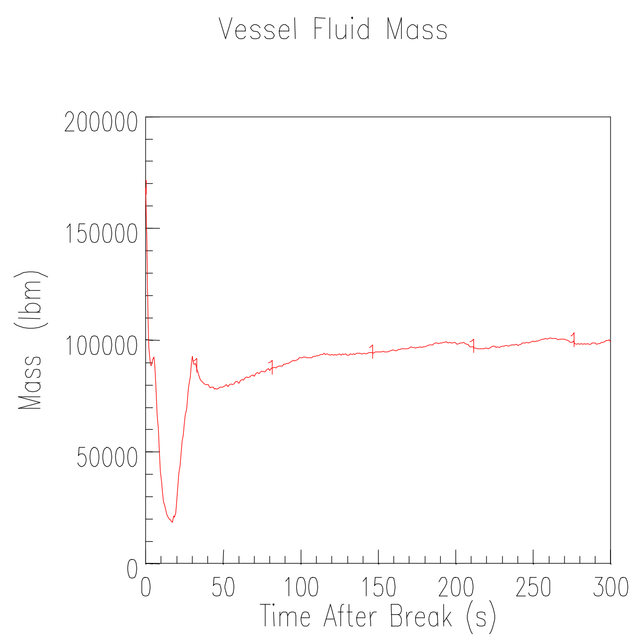

Figure 4-4 - RCS Fluid Inventory for DEGCL

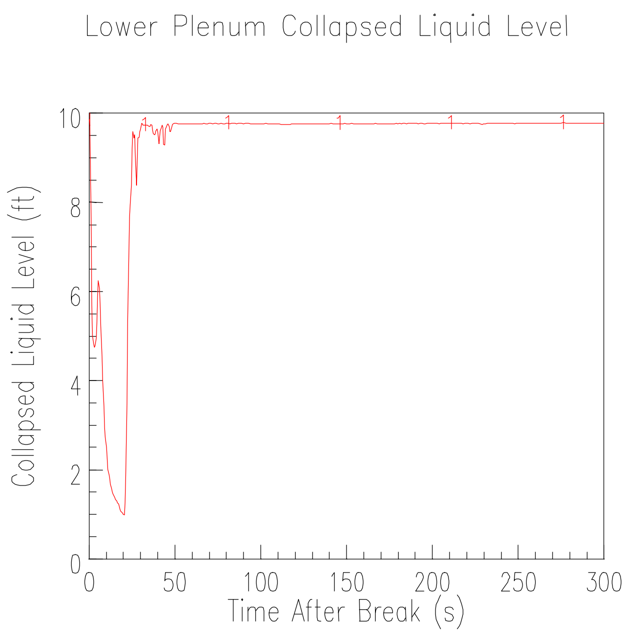

Figure 4-5 - Lower Plenum Liquid Level for DEGCL

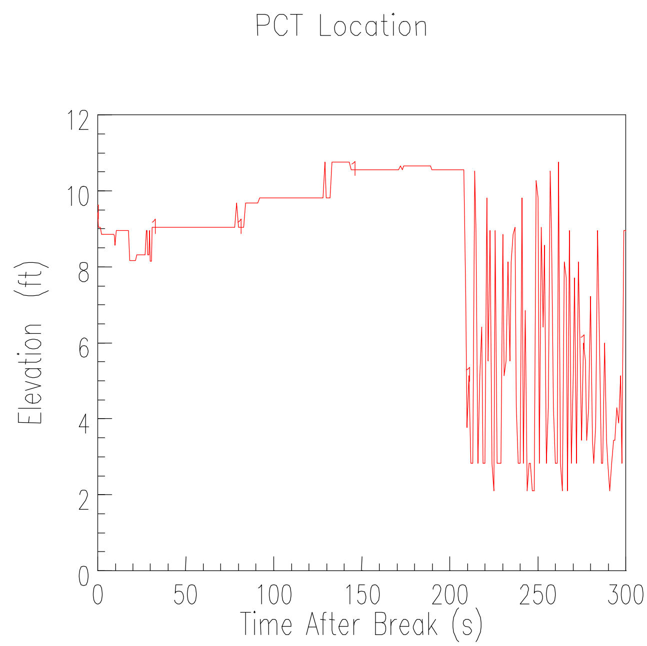

Figure 4-6 - Peak Cladding Temperature Location for DEGCL

5. Full Spectrum Results

For the purposes of comparison, Figure 5-1 shows the normalized (as a ratio of the maximum calculated) peak cladding temperature (PCT) over the full spectrum of break sizes, plotted against the effective break area. At $A/A_{CL} = 2.0$, the maximum PCT is calculated to occur for the double-ended guillotine break. Note that the effective break area also considers the influence of a discharge coefficient applied at the break plane; those points in Figure 5-1 with A/A_{CL} greater than 2.0 are double-ended guillotine breaks with discharge coefficient greater than 1.0 on each side of the break.

Consistently with the current Westinghouse best-estimate large break LOCA analysis methodology [9], both split breaks and double-ended guillotine breaks are considered (all intermediate and small breaks are split breaks); note that the two points in Figure 5-1 with $A/A_{CL} = 2.0$ represent one of each. When assuming nominal uncertainty parameters, the large breaks result in higher PCT than small and intermediate breaks.

A full analysis requires quantification of the uncertainties, which may vary in nature and magnitude for different break sizes. The treatment of uncertainties is addressed in [1].

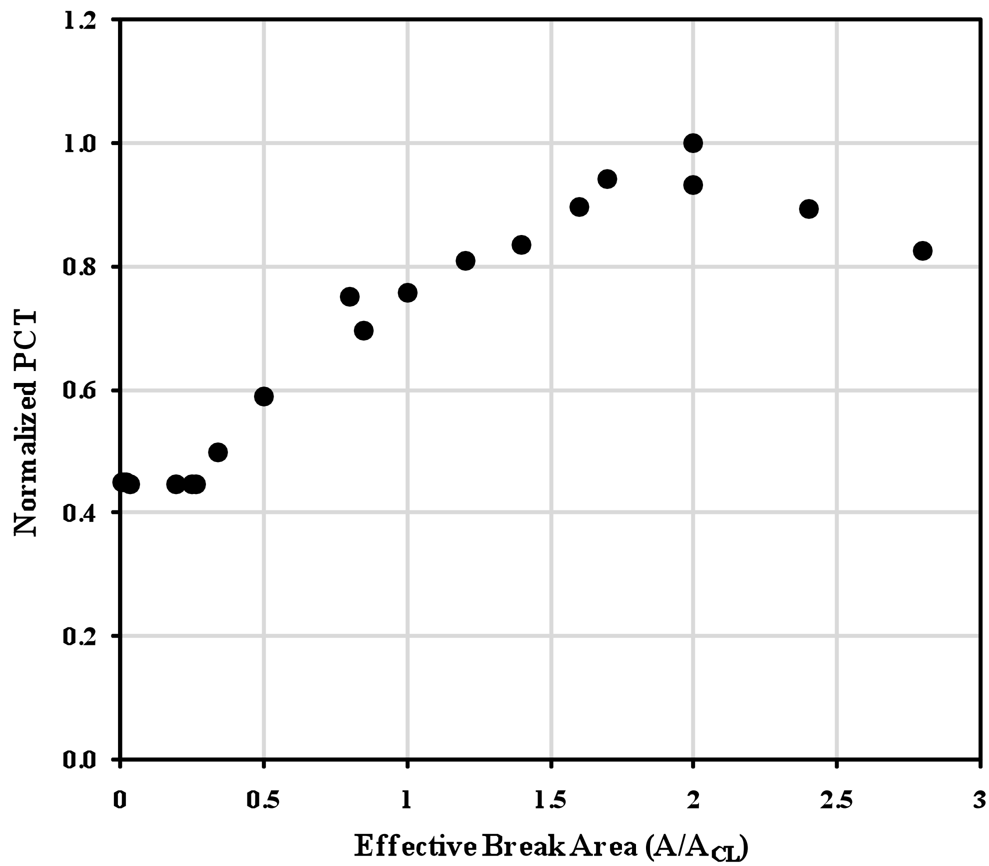

Figure 5-1 – Normalized Peak Cladding Temperature Prediction over Full Spectrum of Break Sizes

6. Summary

A system-level demonstration of the recently developed FSLOCA methodology has been provided over the full range of postulated break sizes. The important phenomena for small, intermediate, and large breaks are shown to be adequately modelled in [1], and here a summary has been provided through the observation of system-level predictions.

For small breaks, the important phenomena of two-phase critical flow, horizontal stratification and loop seal clearance, and core mixture level have been illustrated. For intermediate breaks, the phenomena related to break flow and accumulator injection have been shown. And for large breaks, the phenomena related to blowdown flow reversal/stagnation, ECC bypass, and steam binding have been illustrated.

It has been shown that, when modelling in a realistic fashion, nominal small and intermediate breaks tend to be less limiting than large breaks for this illustrative plant example.

7. References

[1] Frepoli, C., Ohkawa, K., et al., "Realistic LOCA Evaluation Methodology Applied to the Full Spectrum of Break Sizes (FULL SPECTRUM™ LOCA Methodology)," WCAP-16996-NP, Revision 0, November 2010. (ADAMS Accession Number ML103610227)

[2] Regulatory Guide 1.203, "Transient and Accident Analysis Methods." December 2005. (ADAMS Accession Number ML053500170)

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[4] Frepoli, C., "Need of a Coherent and Consistent Phenomena Identification and Ranking Table (PIRT) to Address Small, Intermediate, and Large Break LOCA in PWRs," Transactions of the American Nuclear Society, Albuquerque, NM, Nov. 12-16, 2006.

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