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EVALUATION OF THE EFFECTS OF INITIAL CONDITIONS ON TRANSIENTS IN PUMA

Yüksel Parlatan, Jae Jo, and Upendra S. Rohatgi
Brookhaven National Laboratory
Department of Advanced Technology
Upton, New York, 11973, USA

ABSTRACT

A Simplified Boiling Water Reactor (SBWR) is the latest Boiling Water Reactor (BWR) designed by the General Electric (GE). Major differences between the SBWR and the currently operating BWRs include the use of passive gravity-driven systems in the SBWR for emergency cooling of the vessel and containment. In order to investigate the phenomena expected during a Loss of Coolant Accident (LOCA), Nuclear Regulatory Commission (NRC) has sponsored an integral scaled-test facility, called Purdue University Multidimensional Integral Test Assembly (PUMA). The facility models all the major safety-related components of SBWR.

Two PUMA initialization calculations were performed to assist the Purdue University in establishing test initialization procedures. Both calculations were based on the initial conditions obtained from SBWR LOCA simulation. In the base case, a complete separation between vapor and liquid was assumed, with all the water in the lower part of the Reactor Pressure Vessel (RPV) and all the vapor above it. In the sensitivity case, the water inventory was distributed in the vessel in the same way as in the SBWR at 1.034 MPa, which is the initial pressure for PUMA facility. Purdue University plans to initialize the PUMA tests as in the base case. The sensitivity calculation is performed to provide assurance that this mode of initialization is adequate. It also provides information on possible differences in the progress of transients. For example, these calculations will indicate whether there will be more or less entrainment of liquid (if any) through the breaks in the beginning of the test.

The conditions outside of the vessel (e.g., containment, PCCS and GDCS) were identical for both cases prior to initiation of the accident. In general, calculated results appear to be very close. No substantial entrainment is observed in either calculation. Initial differences in the water level generally become undistinguishable in about 10 seconds and the Automatic Depressurization System (ADS) and Gravity Driven Cooling System (GDCS) were initiated at about same times for both cases. The differences in the first 10 seconds are caused by the development of two-phase distribution in the base case. The paper will discuss the differences in the early part of the transient. The conclusion from this study will also apply to many integral facilities which simulate the reactor transients from the middle of the transient.

INTRODUCTION

GE has developed an advanced light water reactor design called SBWR. The primary thermal-hydraulic features that distinguish the SBWR from existing BWRs are the natural circulation inside the RPV during normal operation, the GDCS for emergency core cooling, and the PCCS to reject the decay heat from the containment during the long-term phase of LOCA. To provide a driving force for the recirculation of the coolant in the vessel with the absence of jet pumps, a longer chimney is provided. Figure 1 shows a schematic of SBWR (GE, 1992)

Emergency core cooling provides water by gravity forces into the reactor pressure vessel in a LOCA. The GDCS tanks provide large amounts of water to RPV near containment pressure. However, for this concept to work the vessel needs to be depressurized so that the static head of the water residing in the elevated GDCS tanks inside the drywell overcomes the pressure differential between the drywell and RPV. The depressurization of the RPV is initiated by a low water level signal in the downcomer, and accomplished by the ADS. This system opens in tandem several safety relief valves and depressurization valves (DPV) located near the RPV steam dome.

The suppression chamber is the main system that limits the initial pressure rise in the containment by condensing large amounts of steam that escapes from the primary system and cooling off the nitrogen initially present in the inerted atmosphere of the drywell. However, the long term decay heat removal from the containment is provided by passive condensers. These PCCS heat exchangers are located on top of the drywell inside huge tanks filled with water. Hot steam/noncondensable mixture present in the drywell rises into these condensers where the steam is condensed and the nitrogen is cooled. The condensate is returned to the GDCS tanks and then to RPV, and the noncondensable gas is vented to the suppression chamber. The PCCS operation is expected to be of a self-regulating kind: when the pressure rises in the drywell, the rate of steam condensation increases which in turn decreases the pressure.

In addition to the PCCS, SBWR employs another set of heat exchangers, IC, to limit the overpressurization of the RPV during various transients including LOCA. ICs are directly connected to the RPV steam dome and condense the steam with the same mechanism as PCCS. However, ICs become nonoperational in long term during LOCA transients since noncondensable gases are expected to enter and clog them with no passive venting system available and stall the condensation process.

The performance of these safety systems under a LOCA is a major concern. Since the emergency cooling systems are driven by the buoyancy forces, interaction between the safety systems are important. The safety systems and various natural circulation phenomena in SBWR are different from those in currently operating BWRs. To investigate the performance of new safety systems and their interactions, a scaled integral test facility is built by Purdue University for the USNRC in support of test program of the SBWR.

PUMA FACILITY AND INITIALIZATION

The dimensions of the PUMA facility was determined after a detailed scaling analysis by Ishii et al (1995). PUMA is a reduced height and full pressure facility. It has a height scaling of 1/4 and a volume scaling of 1/400. The power and mass flow rates between components are scaled by 1/200. The velocity and time are scaled by 1/2.

The PUMA facility has all the major safety related components along with the RPV and its internals, containment including upper and lower drywells and suppression chamber, passive heat removal systems; IC and PCCS, and passive emergency cooling system GDCS. For instrumentation purposes, the PUMA containment does not surround the RPV as in SBWR. The RPV, DW, SPC and GDCS are made of separate tanks with proper piping between them. These tanks are heat insulated to limit the heat losses. Figure 2 shows a schematic of PUMA that illustrates the layout of the facility.

The PUMA facility will be able to simulate various SBWR transients, but only below 1.034 MPa (150 psia). Therefore, the initial conditions of the PUMA facility need to be determined at this pressure. These conditions should resemble the conditions of an SBWR at 1.034 MPA following a LOCA. For this purpose, we have utilized RELAP5 in determining the initial conditions in PUMA. RELAP5 models are developed for SBWR, and various LOCA transients are analyzed. The initial conditions for PUMA are then determined from these SBWR calculations (Parlatan et al, 1994).

Initial conditions required for proper simulation include the mass and internal energy of water, steam and noncondensable gas in each component. Temperature of the structures and water pools are also needed. The SBWR parameters are scaled properly for PUMA. For example, the initial water mass in PUMA RPV is 1/400 of the water mass in SBWR at 1.034 MPa.

A major concern during the planning of the initialization of the PUMA tests is the simulation of kinematic conditions. In the SBWR, the conditions at 1.034 MPa are not static. There will be flows between each component as well as recirculating flows inside a component. Furthermore, the water inventory in the RPV will swell and a void profile will be present in the downcomer and chimney, because of vapor generation from flashing, decay heat and stored energy released from the structures.

The possible effects of these initial flows and void distribution on the transient need to be investigated. The effect of initial flow rates between components is not important, since it will take a short time, of the order of one second, to establish similar mass flow rates, provided that the vapor generation rate in RPV is simulated correctly. For the initial RPV void distribution concern, there are two possibilities for initialization. In the first case, base case, all the water inventory is placed in the lower part of the vessel and all the vapor above it. In the second case, sensitivity case, the water inventory is distributed in the vessel in the same way as in the SBWR at 1.034 MPa.

To achieve the void distribution conditions in PUMA, similar to that in SBWR, requires a complicated procedure which involves blowing steam from the RPV immediately before the opening the valves that simulate the break. Furthermore, since the initial mass inventory in the RPV is deduced from pressure transducers, the uncertainty of the mass will be large. In the second method, on the other hand, the initialization procedure is straightforward. The water in the RPV will be heated up to the 1.034 MPa, and the break valves will be opened to start the transient.

The effects of the initialization methods on the transient behavior have been analyzed using a system code. Two code calculations were performed and compared to assess the impact of the initialization method. The overall goal is to determine the initialization method to be used in PUMA.

RELAP5/MOD3 AND PUMA MODEL

The RELAP5 hydrodynamic model is a one-dimensional, transient, two-fluid model for flow of a two-phase steam-water mixture that can contain noncondensable gases in the steam phase. RELAP5 code is solved by a semi-implicit numerical scheme to permit calculation of system transients. For more information on RELAP5 and its models see Carlson (1990). The version of RELAP5 used in this study is MOD3.1.2.

The RELAP5 input model for the PUMA facility includes models for all the components. The input deck contains approximately 250 volumes and junctions to model the hydrodynamic behavior of the PUMA facility and about 100 heat structures for the solid structures. There are several control variables and trips to model the control logic of the transient.

We had two different cases as described above: the base case where all the water is placed in the bottom of the vessel and the steam above it, and the sensitivity case where the void distribution obtained from a previous SBWR calculation. In both cases, we have used the same input deck. The initial conditions in the RPV were different for these cases. The initial conditions in containment and elsewhere were identical for both cases.

The initial water inventory and the temperature in the RPV and containment were determined from RELAP5 analysis of SBWR for similar transient. The SBWR and PUMA input deck models were developed concurrently and their nodalizations are consistent. Following a hypotethical Main Steam Line Break Accident (MSLB), the pressure in the RPV steam dome drops to 1.034 MPa at 202 seconds in SBWR time, which corresponds to 101 seconds in PUMA according to the scaling criteria developed by Ishii et al. (1995).

The mass inventory for steam and water and the number of moles of noncondensable gas are then appropriately scaled for PUMA for each component. Both the sensitivity and base case for PUMA have the same mass of water and steam, and same number of moles of air.

RESULTS

We have simulated the transient behavior of the PUMA with two different initial conditions in the RPV to assess the impact of initial conditions on the transient behavior. An MSLB accident has been analyzed for this purpose.

The simulation lasted for 1000 seconds in PUMA time scale, which is half of the SBWR time scale. The first 101-second period is the period where the RPV pressure decrease from 7.1 MPa to 1.034 MPa, which is predicted by SBWR model. The sequence of events for both the base and sensitivity cases are similar: ADS signal was set at around 325 seconds and the GDCS started injecting water to the RPV around 400 seconds. The calculations required a total of about 25 cpu-hours on an IBM 590 workstation.

Overall results of the base and sensitivity calculations are very similar, including the sequence and timing of events. Figure 3 shows the pressure in the RPV for both cases following the transient starting at 1.034 MPa and 101 seconds. The pressures for the base and sensitivity cases are indistinguishable. Figure 4 shows that the break flow rates for both cases are very similar for the first 400 seconds. Thereafter, the break flow rate is small and oscillatory due to low vapor generation rate in the RPV. The liquid inventory is shown in Figure 5. It decreases steadily until the GDCS injection starts, and then it increases. The agreement between the base and sensitivity cases are again very good. These figures demonstrate that the initial void distribution in the RPV do not affect the transient behavior of RPV.

Figure 6 shows the containment pressure as a function of time. The pressure in the drywell and suppression chamber are plotted for the base and sensitivity cases. The pressure in the containment stays nearly constant until the GDCS injection starts, and after then the steam generation ceases in the RPV. Continued condensation in the PCCS causes a pressure drop in the drywell, which leads to the opening of vacuum breakers, valves that connect the SC gas space with drywell. Redistribution of the noncondensable gas due to the opening of vacuum breakers reduces the SC pressure. This process continues until the condensation in DW ceases or the steam generation in the RPV starts again. When the steam generation starts again in the RPV, the pressure will rise since PCCS will not function efficiently in the presence of noncondensables. The agreement between the two cases are very good. Therefore, it is concluded that the initial void distribution in the RPV do not affect the transient behavior in containment.

DISCUSSION

The method of initialization may have an impact on the amount of mass flow rate through the break, and therefore, alter the behavior of the transient. The mass discharge rate through the break will be higher if there is substantial and different amounts of liquid entrainment through the break for the cases analyzed here. Liquid entrainment was expected to be higher for the sensitivity case, since the two-phase water level is higher and therefore, is closer to the break. Our analysis showed that there is only a negligible amount of liquid entrainment during the first 10 seconds following the transient. Figure 7 illustrates the liquid entrainment (in terms of the volumetric fraction of liquid) for the first 25 seconds following the transient. SBWR calculation at 1.034 MPa also indicated that there is no liquid entrainment during this period. Since both PUMA calculations also showed no substantial entrainment, it was concluded that, during MSLB in PUMA, the liquid entrainment do not affect the transient behavior.

Another concern is the timing of events, e.g. timing of ADS and GDCS activation, and if they are affected by the initialization method. Activation of ADS and GDCS is based on a water level measurement in the downcomer. The Wide Range (WR) measurement provides a collapsed water level between two pressure taps which are located near the MSL and near the bottom of chimney. When the WR reading is below a certain set-point (Level 1) continuously for 5 seconds, the timers for the ADS and GDCS mechanisms are activated. Therefore, the void distribution in the downcomer is important for the timing of events.

Figure 8 shows the WR water level prediction for the first 25 seconds following the accident initiation in PUMA for the two cases. In the first 10 seconds there are some numerical oscillations. The water level in the base case is initially lower than that in the sensitivity case. Since all the water in the base case is in the lower part of the vessel, the water level between the two WR pressure taps is smaller compared to sensitivity case. However, the WR level predictions for the two cases converge after 10 seconds. Since the water level is above Level 1 for both cases, the ADS signal was not set inadvertently due to initialization differences. Actually, the ADS signal was set much later (about 400 seconds) for both cases.

The water level in the base case increases, and that in the sensitivity case decreases in about 5 seconds to an asymptotic value. In the base case, the level swells due to the flashing and void generation and bubble rise in the RPV. On the other hand, the flashing and the void generation are not sufficient to maintain the initial water level in the sensitivity case. Figure 9 shows the void fraction in the RPV downcomer as a function of elevation from the bottom of the vessel. The void fractions are shown at 3 different times in addition to the initial void distribution: 1, 10 and 20 seconds after the transient initiation. The solid line represents the base case, and the dotted line the sensitivity case. The level swell in the base case and the level collapse in the sensitivity case are illustrated in this figure. One second after the initiation, level swell is clearly seen in the base case, and after 10 seconds the void profiles for both cases are close. The void distributions are established in about 10 seconds, which is same order as the time required for a bubble to travel 2 m with bubble rise velocity.

The level collapse in the sensitivity case is partly due to the smaller flashing and void generation rates in the PUMA. The energy inventory for the fluid and heat structures in PUMA are smaller than those in SBWR. In SBWR blowdown, the fluid temperature and the average RPV wall temperature are generally higher than the saturation temperature that corresponds to the pressure of the steam dome. In PUMA RPV, the fluid and wall temperature will be equal to the saturation temperature of the steam dome. Therefore, the initial internal energy inventory in RPV is slightly lower for PUMA. Consequently, the initial vapor generation rate in PUMA will be lower than that in SBWR, and the initial level in PUMA will not be sustained.

CONCLUSIONS

The effect of the two initialization methods for the PUMA facility transients starting at 1.0134 MPa (150 psia) are analyzed using RELAP5/MOD3. In the base case, all the water was placed at the bottom of the vessel. In the sensitivity case, the initial void profile was obtained from the analysis of MSLB in SBWR. The results of the base and sensitivity cases were compared.

The overall transient behavior of the PUMA seems very similar for both cases. There were some small differences in the first 20 seconds, after that the transients are very similar. The sequence and timing of events differ at the most by three seconds. There was very little liquid entrainment in the break for both cases early in the transient. The water level swelled in the downcomer in the base case, and collapsed in the sensitivity case in about 10 seconds to an asymptotic value. It was concluded that the method of initialization does not affect the subsequent transient behavior for an MSLB accident scenario.

The water level development in the downcomer, a level swell in the base case and a collapse in the sensitivity case, is due to the different void generation rates arising from the discrepancies in the stored energy of walls and the fluid between the SBWR and PUMA.

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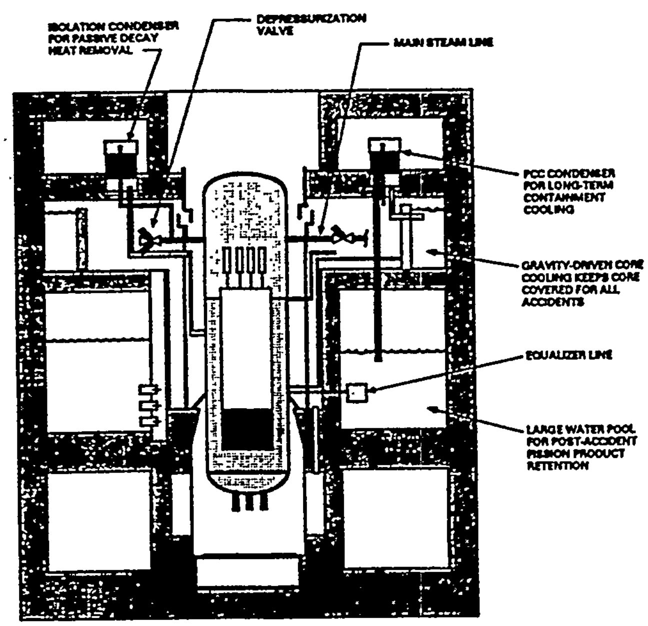

FIGURE 1: SBWR PASSIVE SAFETY SYSTEMS

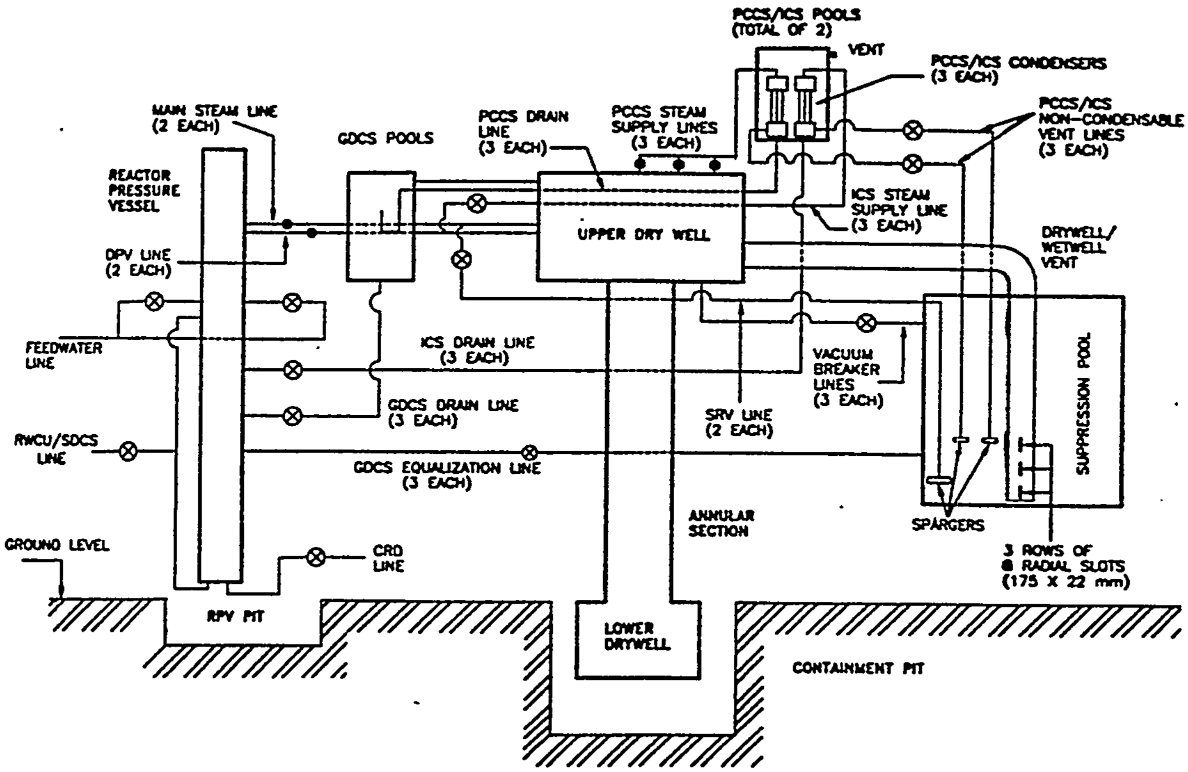

FIGURE 2: A SCHEMATIC OF PUMA FACILITY

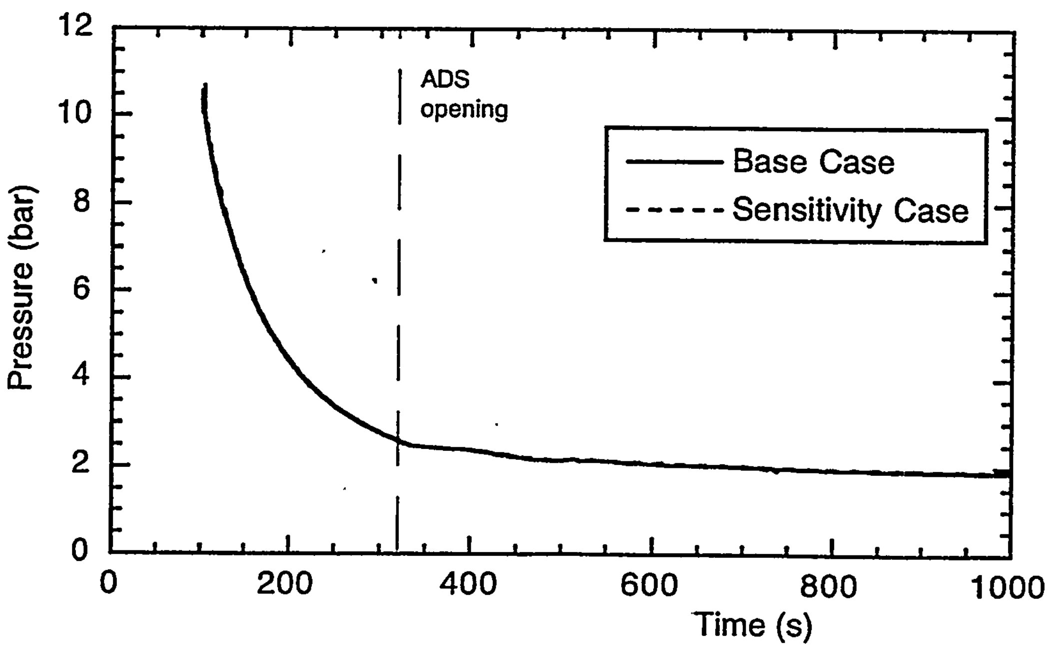

FIGURE 3: RPV PRESSURE FOR BASE AND SENSITIVITY CASES

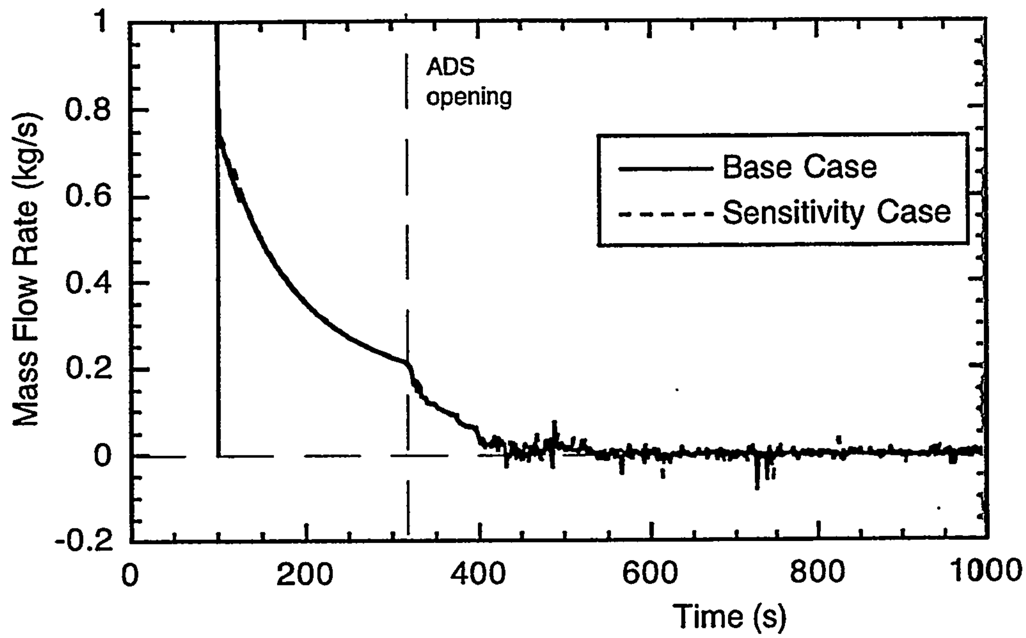

FIGURE 4: BREAK FLOW RATE FOR BASE AND SENSITIVITY CASES

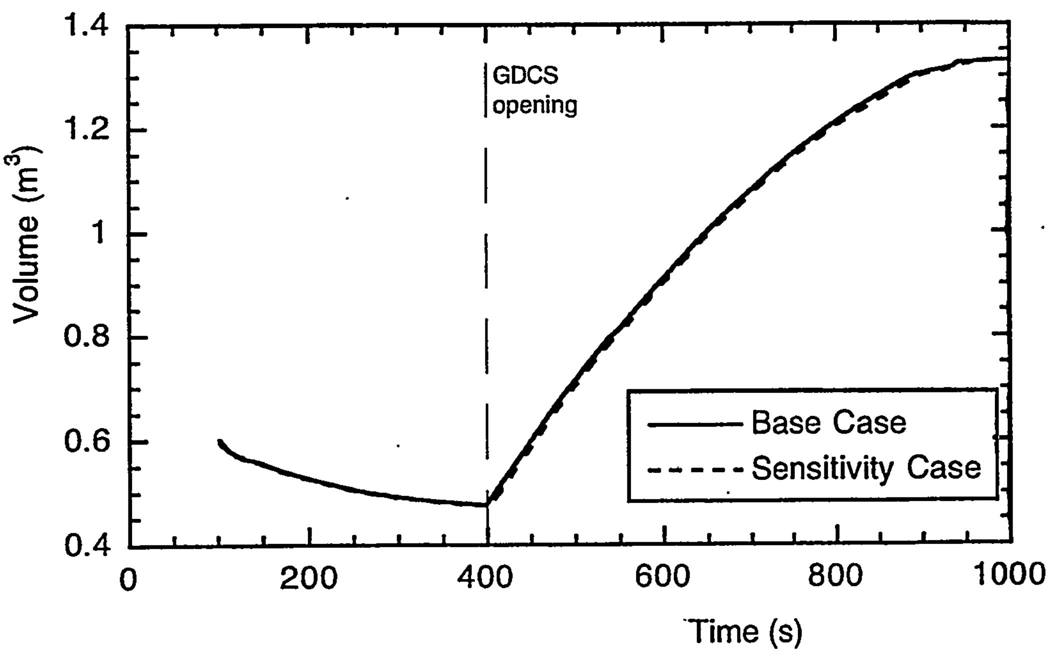

FIGURE 5: LIQUID VOLUME IN RPV FOR BASE AND SENSITIVITY CASES

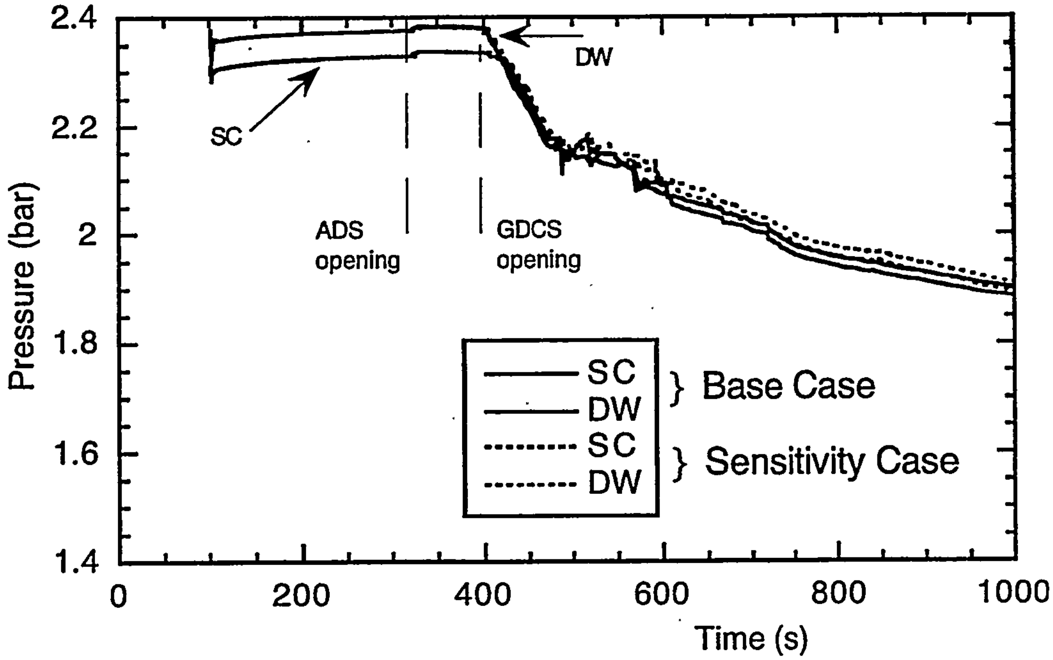

FIGURE 6: CONTAINMENT PRESSURE FOR BASE AND SENSITIVITY CASES

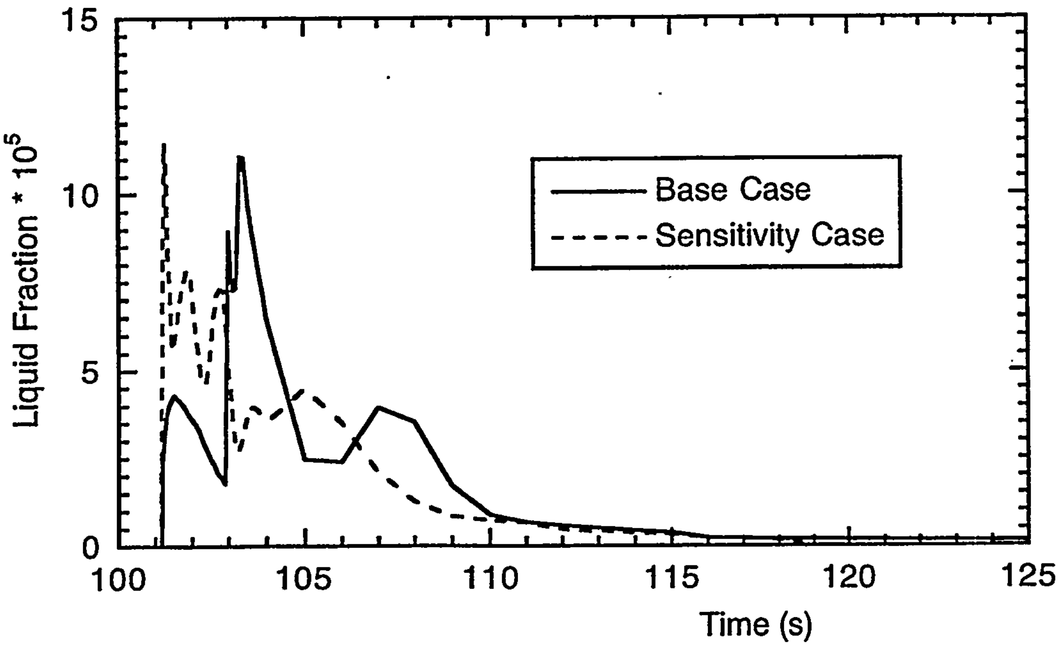

FIGURE 7: LIQUID ENTRAINMENT FOR BASE AND SENSITIVITY CASES

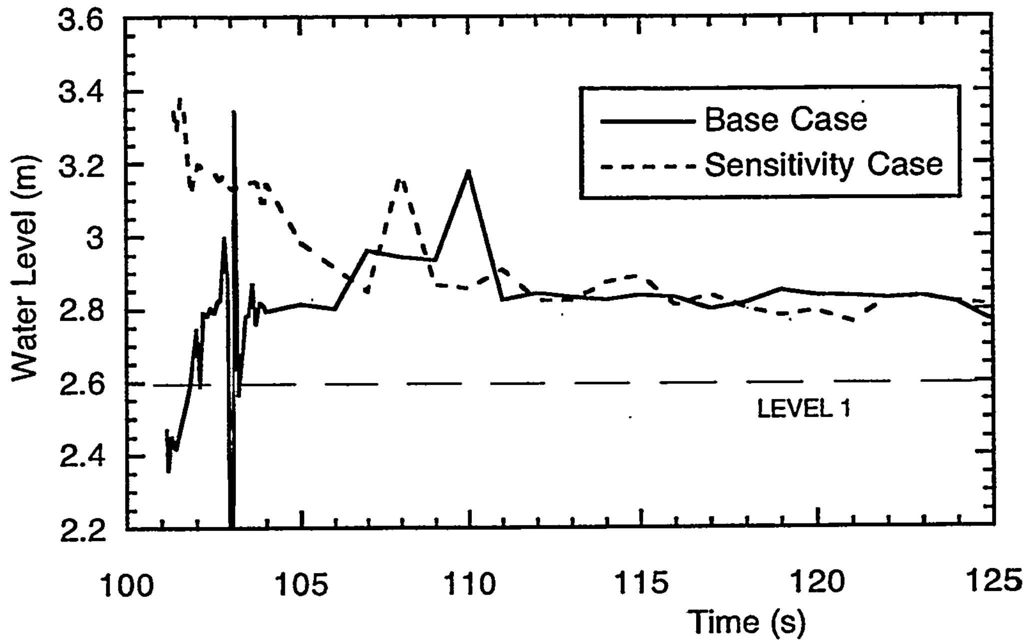

FIGURE 8: WIDE RANGE WATER LEVEL FOR BASE AND SENSITIVITY CASES

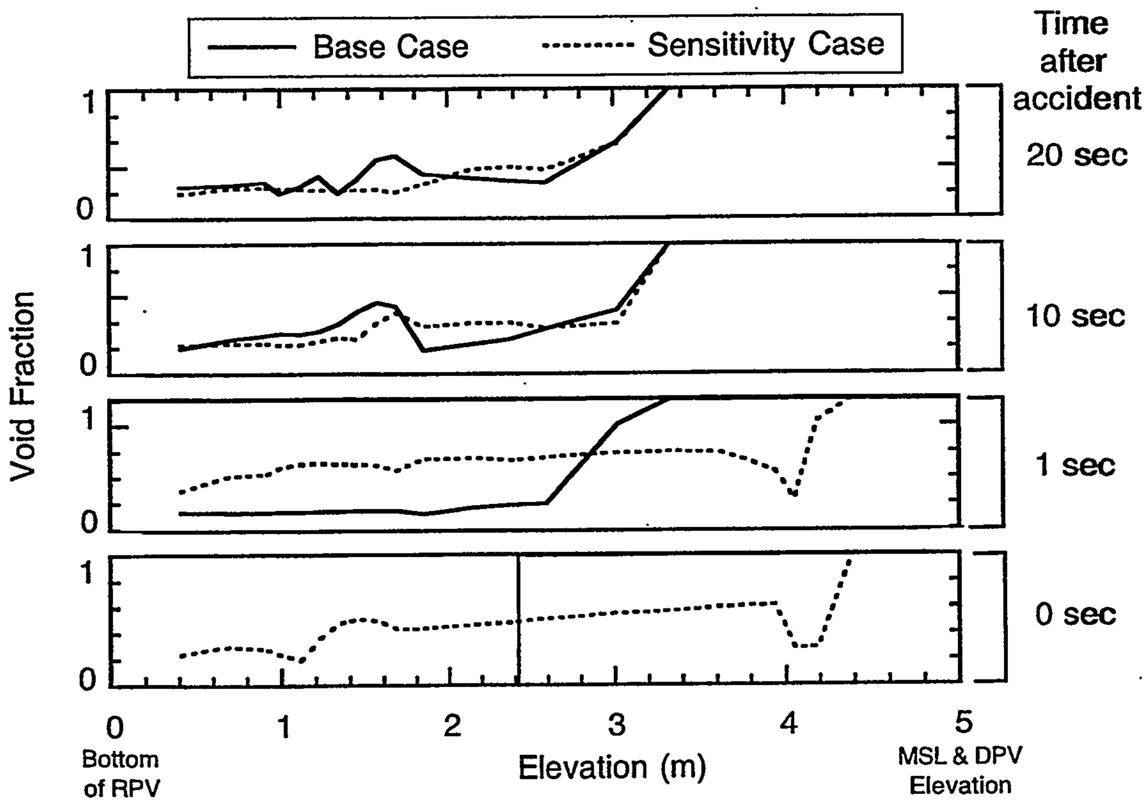

FIGURE 9: VOID FRACTION IN RPV DOWNCOMER FOR BASE AND SENSITIVITY CASES