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Confirmatory Calculations of the Donald C. Cook Sump Water Level

Technical Evaluation Report

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EXECUTIVE SUMMARY

The Nuclear Regulatory Commission (NRC) issued a Confirmatory Action Letter to the American Electric Power Company (AEP) on September 19, 1997 regarding concerns raised by an NRC Architect and Engineering (AE) inspection team about safety-related cooling systems at the D. C. Cook nuclear power plant. Calculations showed uncertainty about the volume of available water for long-term cooling under certain conditions. Following a loss-of-coolant-accident (LOCA), about 320,000 gallons of water could be trapped in the annular compartment of the containment that does not drain to the containment sump. This trapped water would not be available to the emergency core cooling systems (ECCS) during the recirculation mode. In selected LOCA scenarios, such a situation may lead to sump water level being lower than the minimum level required to prevent vortexing and could render both the ECCS and the containment spray systems inoperable. To compensate for trapped water, the licensee requested amendments to the Technical Specifications (TS) to increase the minimum required ice from 2.37 to 2.59 million pounds which when reduced by a sublimation allowance leaves 2.11 and 2.43 million pounds, respectively. The licensee also requested change to the basis for the technical specification to reflect the fact that water from the melted ice, the accumulators, and from the RCS would be used to calculate sump water level in addition to the RWST inventory. The current TS basis only discusses the water inventory of the RWST and ignores water from other sources. Analyses were performed by AEP to demonstrate adequate sump water level during the recirculation mode to prevent vortexing. Since these analyses included melt water drainage from the ice condensers, the predicted sump water level was dependent upon the rate of ice melt. SEA performed confirmatory containment response calculations focusing on the rate of ice melting and the resulting sump water level.

A simple balance of water volumes shows that with all 2.43 millions pounds of ice melted, the excess water volume was only about 39800 gallons with accumulator actuation and 12300 gallons without the accumulators. The excess volume is the water volume over and above the volume needed to fill the dead-ended volumes (e.g., reactor cavities and annular region), the in-transit water volume, and the volume of water required to fill the sump to the minimum safe level for pumping. These excess volumes correspond to a margin of safety of 1.5 and 0.5 ft of water, respectively. Note that using the existing TS ice mass of 2.11 million pounds would result in water level being approximately one-foot below the minimum safe level without water from the accumulators. Thus, increasing the ice mass, as proposed in the TS amendment, to 2.43 million pounds would result in the sump water level being higher than the safe level when all the ice melts (with or without accumulators). The concerns then are whether or not all the ice would melt, and the rate at which ice melts.

The primary focus of the SEA analyses was to predict thermal and hydraulics conditions that exist in the containment following a LOCA, and their impact on melting of ice. These calculations were performed using NRC developed accident analysis code MELCOR, which has been thoroughly validated for similar accident scenarios.

The primary source of containment geometrical data for the MELCOR calculations was the MAAP4 code input model supplied by the licensee. The sources of water considered in these calculations included the RWST, the accumulators when activated, and the ice. RCS water was not modeled in detail. Dead-ended volumes where water could be trapped and thus not returned to the sump included the annular compartment, the reactor cavity, and the floor of the refueling pool (below the drain entrance). Water in transit, i.e., piping, vapor, droplets, was considered as well.

The MELCOR analyses did not model RCS response to a postulated LOCA. Instead break flow data obtained from both NOTRUMP analyses and MAAP4 analyses was provided as input to the MELCOR. The effluence from the postulated break was introduced into each calculation as time-dependent mass and energy sources into the control volume containing the postulated break.

The accident scenario was started with ECCS pumps injecting water from the RWST into RCS piping and the break effluents released into the containment. During injection mode, the RWST water temperature of 105 °F was used. Containment spray pumps started upon a high containment pressure signal of 2.9 psig. The spray flow was distributed within the containment using the FSAR distribution fractions. When the RWST was predicted to empty, the MELCOR input model began to remove water from the containment sump at a rate equivalent to the sum of the containment spray and break flow. Determining when the switchover occurred was accomplished by integrating both the break and spray flows during the injection mode and comparing the total to the inventory of water available for injection. Following the switchover, MAAP4 calculated spray temperatures were used. Once a containment spray pump started, it was assumed to operate until the containment pressures dropped below 1.5 psig again. The containment recirculation fans were always on. All these systems response was consistent with FSAR data and the EOPs.

The ice condenser was divided into three equal vertical volumes to better simulate the cooling of the upward flowing gases through the condenser. This configuration allows each volume to have its own pool and gas temperatures and gas compositions, i.e., warmer gases with a higher vapor fraction would be expected in the bottom volume rather than in the top volume. Except for a single parameter sensitivity calculation, the total ice mass of 2.43×10^6 lbm from the MAAP4 input model was used for all calculations. Water from ice melting was added to the sump as described in the FSAR as well as the MAAP4 input model.

To account for modeling uncertainties associated with MELCOR modeling of ice condenser response, two sets of calculations were performed. The first set of calculations used 'realistic' code parameters that were found to produce best agreement with the existing experimental data (e.g., PNL ice-condenser experiments). Note that these parameters were recommended for use by the CONTAIN and MELCOR development staff. Although the ice melt in an actual plant may be reasonably well represented by the PNL ice-condenser experiments, this assumption is by no means certain, particularly in light of the limited data available to study the ice melt progression. To address this eventuality, a second set of calculations was performed using conservative modeling parameters that were judged to provide lower bound for ice melt rate.

Two sizes of pipe breaks were examined in these calculations, i.e., 2 and 6 inch pipes. A 2-inch break was considered possible for both the lower and annular compartments but a 6–inch was not possible for the annular compartment since no RCS pipes of this size exist in the annular compartment. Also, following a 6-inch break, accumulators would empty; but not following a 2-inch break.

The 6-inch break scenarios all showed a containment water level well above the minimum safe level, even in the calculation that assumed the most conservative ice melt parameters. In this conservative calculation, the minimum calculated water level was three feet above the minimum safe level, despite the fact that approximately 30% of the ice remained when the calculation was terminated at 40 hours. The 6-inch calculation benefited from the break being in the lower compartment where the break effluence poured directly into the sump, the accumulators dumped their water into the RCS, and the containment sprays were turned off relatively early. The containment sprays were turned off at 5.6 hours when the containment pressure dropped below 1.5 psig. Note that a 6-inch break was not possible in the annular compartment, as there are no 6-inch pipes in that compartment. As a result of the sprays being turned off, the annular compartment and the reactor cavity were only partially filled.

The results for the 2-inch break calculations were quite different, however, because the break was postulated to occur in the annular compartment where most of the effluence drained into this dead-ended volume, the accumulators were assumed to not dump, and the sprays ran continuously throughout the calculations. A 2-inch break is possible in both the lower and annular compartments; however, a break in the annular compartment can be shown to be the worst case scenario. The sprays were not switched off during the calculation because the containment

pressure remained slightly above the 1.5 psig turnoff setpoint. Whether or not the pressure would actually stay above 1.5 psig is difficult to determine since the pressure was so close; however, leaving the sprays running during the 2-inch break calculations was conservative.

Similar to the 6-inch break calculations, when the calculations were run using either the MELCOR or the CONTAIN recommended ice melt parameters (i.e., realistic parameters), the containment water level remained above the safe level. On the other hand, when the 2-inch calculations were run using the conservative ice melt parameters, the water level dipped well below the minimum safe level. The lowest level was 3 feet below the safe level. However, this may not pose a serious threat to ECCS operability because:

1. The minimum safe level (approximately 7-foot above the suction elevation) was established to eliminate concerns regarding vortexing and air-ingestion corresponding to ECCS design flow rate of 15,600 GPM. Following a 2-inch break, the total ECCS flow rate is less than 8000 GPM. As a result of this reduced flow rate, potential for air ingestion due to lower water level is found to be very low.
2. The calculations are based on very conservative set of assumptions regarding ice melt models and operator response. The more realistic assumptions minimize the likelihood of water level being lower than the safe level.

Alternate scenarios were run to verify that the worst case scenarios were determined. Calculations were run with a single spray train to verify that the two-train calculations represented more severe scenarios than did the one-train scenarios. In general, more containment cooling implies a slower melting of the ice. A 2-inch break in the lower compartment was compared to a 2-inch break in the annular compartment to verify that the annular compartment break was the most severe. The sensitivity of the containment water level to the ice melt parameters was examined.

In conclusion, the worst case scenario was determined to be a small break in the annular compartment, where break effluence would tend to fill this dead-ended volume, with both containment spray trains operating continuously. Using ice melt modeling parameters that successfully simulated the PNL ice condenser experiments, and were subsequently recommended by the MELCOR and CONTAIN code development staffs, the sump water level was found to remain above the minimum safe water level.

1.0 OBJECTIVE

The Nuclear Regulatory Commission (NRC) issued a Confirmatory Action Letter [1] to the American Electric Power Company (AEP) on September 19, 1997 regarding concerns raised by an NRC Architect and Engineering (AE) inspection team about safety-related cooling systems at the D. C. Cook nuclear power plant. Calculations showed uncertainty about the volume of available water for long-term cooling under certain conditions. Following a loss-of-coolant-accident (LOCA), about 320,000 gallons of water could be trapped in the annular compartment of the containment that does not drain to the containment sump. This trapped water would then not be available to the emergency core cooling systems (ECCS) during the recirculation mode following such an accident and insufficient water flow could render both the ECCS and the containment spray systems inoperable. Analyses were performed by AEP to demonstrate adequate sump water level during the recirculation mode to prevent vortexing. Since these analyses included melt water drainage from the ice condensers, the predicted sump water level was dependent upon the rate of ice melt. SEA performed confirmatory containment response calculations focusing on the rate of ice melting and the resulting sump water level.

2.0 APPROACH

These confirmatory calculations were performed using the NRC developed severe accident analysis code, MELCOR [2]. The need for a rapid response of this issue and a relatively modest level of effort limited and defined the modeling effort of these calculations. Specifically, the containment details and dimensions were not drawn from plant data (drawings, etc.) and the RCS and the ECCS systems were not modeled with MELCOR. The primary source of data for the MELCOR calculations was a MAAP4 code [3] input model [4] and presentation materials [5] supplied to SEA by AEP.

The MELCOR input model was developed using geometry data from the MAAP4 input model, i.e., volumes, areas, thicknesses, elevations, etc. Most importantly, all data controlling the sump water level geometry was adapted from the MAAP4 model and was not verified or validated. The minimum sump water level (at the plant elevation of 602 ft 10 in) required to prevent vortexing came from AEP supplied data and was not verified.

The MELCOR input model included the containment geometry and the containment pressure suppression systems. Rather than model the reactor coolant system (RCS), the effluence from the postulated pipe break was sourced into the containment at the postulated break location. Rather than model the ECCS piping and heat exchangers, the temperature of the containment sprays, when operating in the recirculation mode, was supplied to the MELCOR containment spray model. Thus, the MELCOR predicted sump water levels are dependent upon the accuracy of these source terms.

The primary difference then between the MELCOR and the MAAP4 calculations would then be the code models that predict the melting of the ice. Since ice melt models are generally parametrically based, i.e., require the code user to select values for parameters that are not well known, and the models have only been validated on relatively limited experimental data, their predicted rates for melting ice have some uncertainty attached to them. (Note that a description of the MAAP4 code ice melt model was not available to SEA.) Therefore, the use of conservative parameters was needed to reduce uncertainty associated with predicting the sump water level. Parameter values that delay the melting of the ice would predict lower sump water levels.

3.0 DESCRIPTION OF MELCOR CODE

The MELCOR code developed at Sandia National Laboratories for the U. S. Nuclear Regulatory Commission is a fully integrated computer code that models the progression of severe accidents in light water reactor nuclear power plants. The entire spectrum of severe accident phenomena, including the reactor coolant system and the containment thermal-hydraulic response; nuclear core heatup, degradation and relocation; and fission product release and transport, is treated in MELCOR in a unified framework for both boiling and pressurized water reactors. MELCOR was designed to facilitate sensitivity and uncertainty analyses. MELCOR was subjected to a peer review in 1992 [6] and has been subjected to model validation studies throughout its development.

The thermal-hydraulic behavior is modeled with a lumped sum approach using control volumes connected by flow paths. Each volume is defined spatially by its volume versus altitude, may contain a gravitationally separated pool of single or two-phase water, and an atmosphere consisting of any combination of water vapor, suspended water droplets or noncondensible gases. The pool and the atmosphere are each individually treated by equilibrium thermodynamics such that they have equal pressures but may have unequal temperatures. Noncondensible gases are modeled as ideal gases with temperature dependent specific heat capacities.

The flow paths connect volumes and define paths for moving hydrodynamic materials. Flow within the paths is treated as adiabatic but not, in general, isotropic. Materials do not reside within the flow paths, and do not transfer heat within the flow path. The flow paths may represent either a pipe-like connection in a tank-and-tube model or a cell boundary in a finite-difference model, allowing considerable modeling flexibility.

The governing thermal-hydraulic equations are the equations of conservation of mass, momentum, and energy. As is typical of lumped-parameter codes, the kinetic energy term in the energy equation and the momentum flux term in the momentum equation are omitted on the assumption that MELCOR calculations will model volume-averaged flows in the far subsonic range making these terms unimportant here. Component models exist for special flow conditions such as two-phase flow momentum exchange and phase separation. Critical flow models are included to predict critical flows at such locations as pipe breaks.

The transfer of heat between control volume atmospheres and pools and their surrounding surfaces are modeled using heat structures. These heat structures can include reactor system components such as pressure vessels, internal support structures, pipes, and steam generator tubes and containment components such as walls, floors, beams, and equipment. Heat transfer within a heat structure is modeled as one-dimensional heat conduction. Many options are available to model surface heat transfer.

The MELCOR code contains packages of models that were not needed or used herein. These packages included core meltdown and core debris transport and interaction models, models to predict the transport and behavior of radionuclide vapors and aerosols, hydrogen combustion models, and a model for fan coolers. Code packages containing unneeded models were not activated.

4.0 INPUT MODEL DESCRIPTIONS

4.1 Containment Input Model

The containment model subdivides the containment free volume into several regions designated as nodes or control volumes in the lumped parameter thermal-hydraulic calculations, i.e., the thermal-hydraulic conditions in each node is defined with one pressure, one temperature for gases, another temperature for pooled water, etc. The MELCOR input model, shown in Figure 1, used the same method of nodalization as did the MAAP4 model with the exception that the ice condenser region in the MELCOR model was subdivided into three vertical regions to facilitate modeling the ice condenser. The control volumes were numbered in increments of ten, i.e, 10, 20, etc., as shown in Figure 1. The lower portion of the containment was subdivided into five volumes corresponding to the lower compartment, annular compartment, reactor cavity, pressurizer enclosure, and the steam generator enclosures, respectively. The upper portion of the containment was subdivided into three volumes designated the upper dome, the lower dome, and the cylindrical section. The ice condenser was subdivided into four vertical volumes, three for the ice baskets and one for the upper plenum, respectively.

The elevations and sizes of the control volumes are illustrated in Figure 2 which shows their actual elevations as a function of their relative size, i.e., the width represents their cross-sectional area at that elevation. Figure 2 shows the control volume data that was actually used by the code. Also shown in Figure 2, are the overflow elevations for water overflowing the annular compartment weir into the lower compartment and for water overflowing the lower compartment into the reactor cavity, and the elevation specified as the sump minimum safe level in the lower compartment. The volumes controlling the sump water level were 319,213 and 117,819 gallons of water to fill the annulus and the reactor cavity, respectively. The volume of water in the lower compartment below the minimum safe level for pumping was 116,154 gallons. These volumes/elevations replicate the MAAP4 input model. The control volume specifications are listed in Table 1. All volumes were initialized at 14.79 psia, zero relative humidity, and no standing water. The total containment free volume was 1.27×10^6 ft^3.

In the calculations, flow moved from one control volume to the next by means of flow paths, also referred to as flow junctions. The flow path connections to the control volumes are shown in Figure 1 (referred to by number) and their specifications are listed in Table 2. These paths essentially replicate the MAAP4 input model with the following exceptions: (1) additional paths associated with subdividing the ice condenser were required, and (2) containment failure or leakage was not modeled, as was done in the MAAP4 model.

Four constant volumetric flow fans were included in the model, i.e., the recirculation fan and three hydrogen skimmer fans. The recirculation fan moves air from the upper to the lower compartments, thereby forcing air through the ice condensers following completion of RCS decompression. The three hydrogen skimmer fans pull low flows of air from the pressurizer and steam generator enclosures and the containment dome to prevent a localized buildup of hydrogen following postulated core damage. All of these fans exhaust into the annular compartment. The capacities of these fans are listed in Table 3.

Some flow can bypass the ice condenser, i.e., move from the lower to upper compartments without going through the ice condenser. Flow paths representing the refueling pool drains and leakage bypassed the ice condenser (paths 3 and 7, respectively).

The ice condenser model contains flow paths allowing air and steam to flow up through the ice condensers past the baskets containing ice. Both the entrance and the upper plenum outlet have doors that open with a very minor pressure differential to flow in only one direction. Other paths allow melt water to flow downward and out of the ice condenser. Melt water leaves the ice condensers by one of two flow paths and enters the lower compartment and sump (not the annular compartment). The main drain path consists of 21 12-inch drains with flapper valves

requiring 1.5 ft head to open. The smaller drain consists of 1.5-inch lines in the bottom of each main drain that are always open.

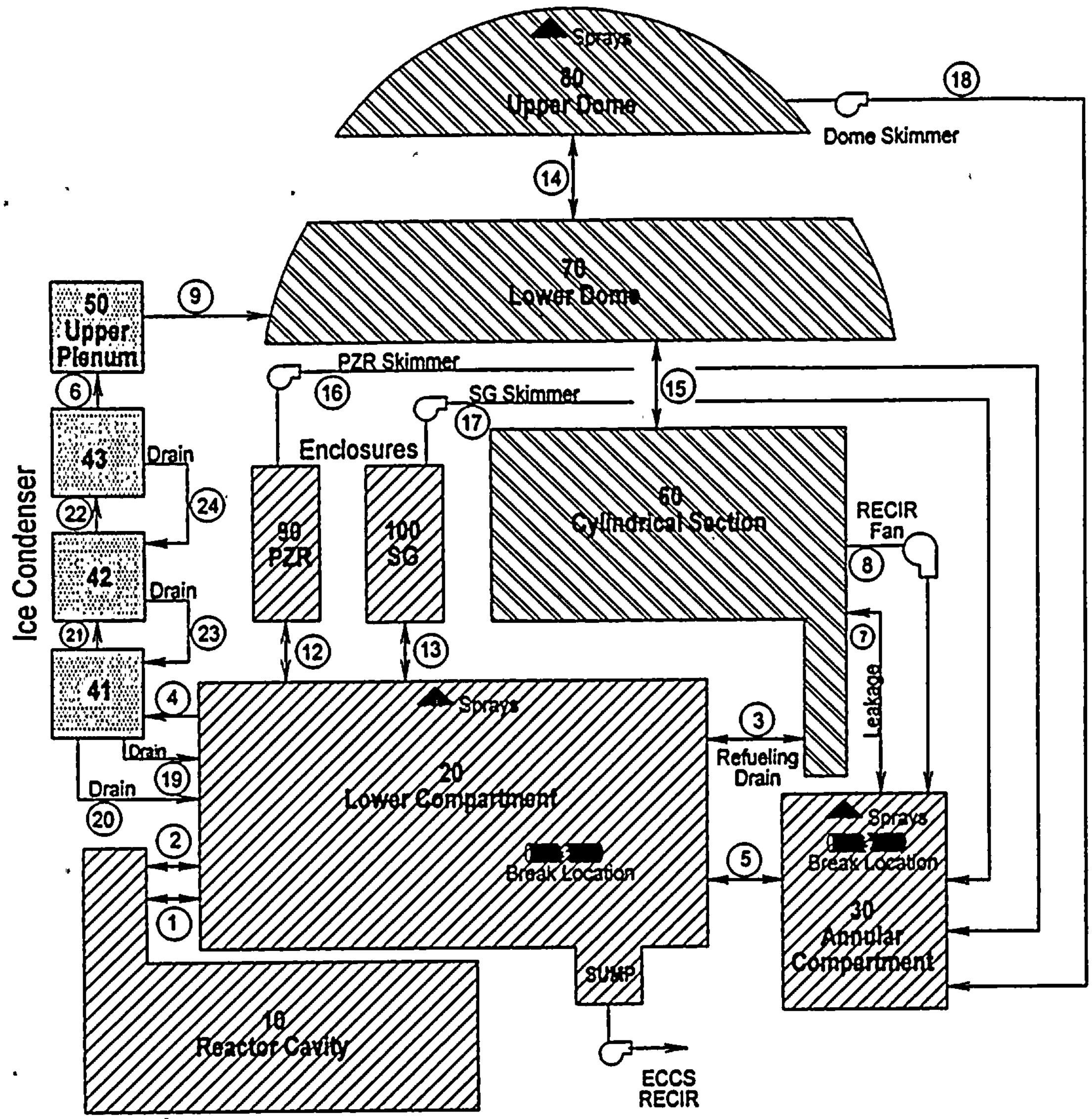

Figure 1: D. C. Cook Containment Model

There are two flow paths connecting the reactor cavity to the lower compartment volumes. One path simulates the cavity's instrument tunnel and the other path simulates the annular gap between the reactor vessel and the shield wall. Since the tunnel path is lower than the annular gap pathway, water overflow from the lower compartment flows through the tunnel path. Furthermore, the tunnel path was assumed to open vertically into the lower compartment that falling water droplets enter the tunnel.

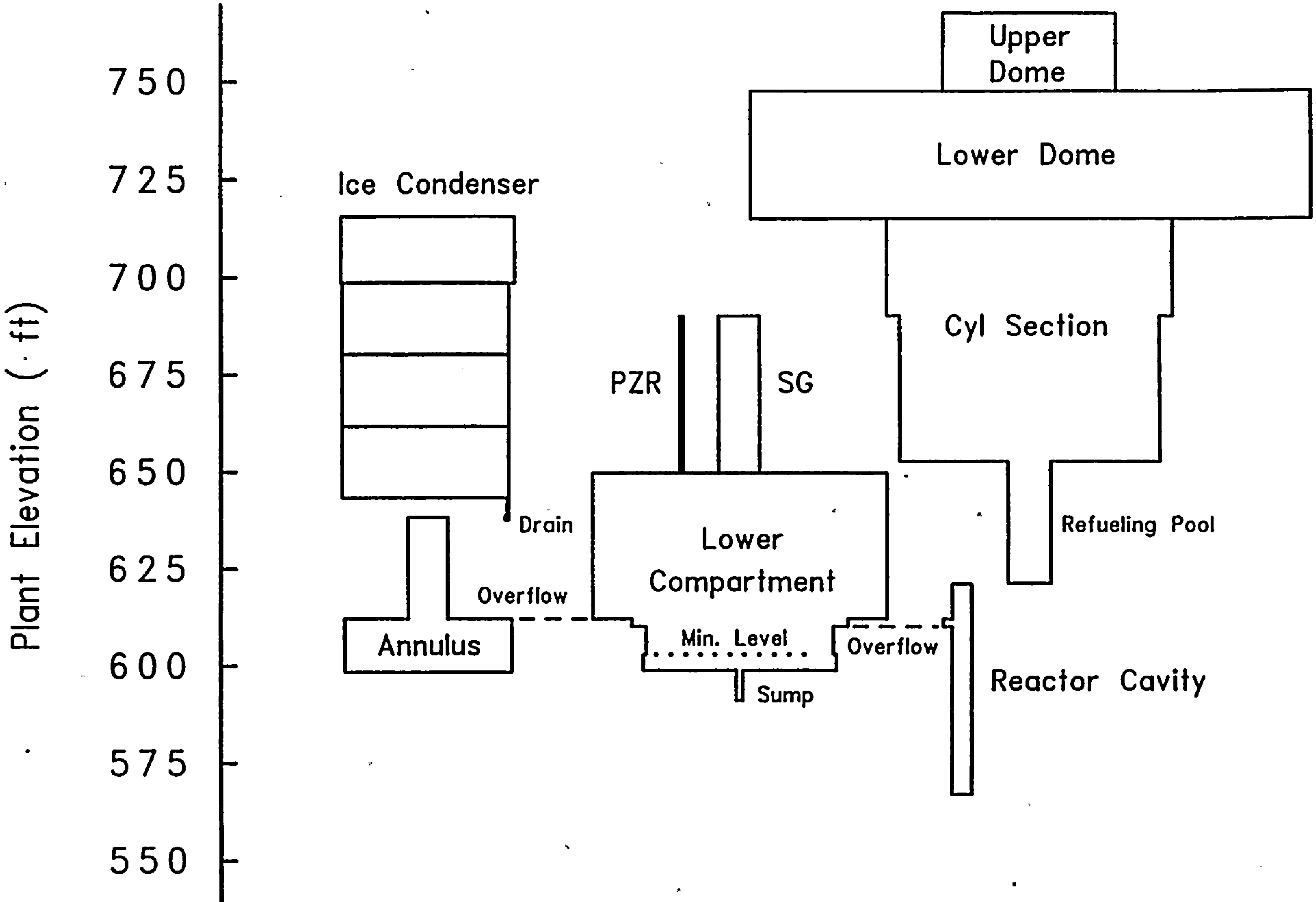

Figure 2: Containment Control Volume Diagram

Table 1: Control Volume Parameters

No.	Name of Volume	Initial Temp	Floor Elevation*	Largest Area	Free Volume
		(°F)	ft	ft^2	ft^3
1	Cavity	120	0.0	284	20000
2	Lower Compartment	120	31.8	3730	254800
3	Annular Compartment	120	31.3	3300	61300
4	Ice Condenser Compartment	15	70.6	2940	108700
5	Ice Condenser Upper Plenum	15	131.6	1330	55000
6	Upper Comp. – Cyl. Section	100	54.0	6240	336700
7	Upper Comp. – Lower Dome	100	148.6	10400	334300
8	Upper Comp. – Upper Dome	100	181.0	5970	63900
9	Pressurizer Enclosure	120	85.6	100	2700
10	Steam Generator Enclosure	120	85.6	1260	31000
	* Relative to Reactor Cavity Floor				

The refueling pool drain flow path was adjusted to trap 9500 gallons prior to spill over into the drain line. This feature was adapted from the MAAP4 input model.

Concrete and steel structures within the containment absorb and/or release heat during a LOCA accident scenario, thereby affecting the containment thermal-hydraulic response, and subsequently, the performance of the ice condensers. Again, the data for these structures were directly adapted from the MAAP4 input model.

The parameters for the concrete structures are listed in Table 4. The concrete structures were modeled with one-dimensional heat conduction. Four of these structures represented floor and therefore, were modeled with a horizontal orientation; the remainder modeled as vertical walls. Seven of the structures were internal to the containment, meaning that both faces were available for heat transfer. The other eight structures had one surface facing inside the containment, but the second face was external to the containment. External surfaces were modeled as having a constant temperature corresponding to the outer environment. Four of the surfaces were lined with 3/8-inch thick steel and the gap resistance was specified at 0.054 ft^2-hr-°F/Btu.

The parameters for the steel structures, i.e., piping, ladders, gratings, etc., are listed in Table 5. The steel structures were essentially modeled using lumped capacity heat transfer, i.e, the entire mass exists at one temperature. The largest mass of steel was located in the lower compartment. Smaller masses were found in upper compartment.

Table 2: Flow Path Parameters

No.	Flow Path Name	Type	Elevation*	Loss Coff.	Hyd. Diameter	Length	Area
			ft		ft	ft	ft^2
1	Cavity-Tunnel	Open	16.7	2	12.7	26.3	170
2	Cavity-Bypass	Open	44.9	5	1.3	3.5	16
3	Refuel-Drains	Open	37.8	3	1	17.7	2.2
4	Lower Ice Compartment Door	1 Way Door	77.1	3	1	3.0	1000
5	LC/Annulus Opening	Open	44.5	1	56.4	1.0	300
6	Upper Plenum Entrance	Open	131.7	3	1	0.1	2940
7	Annular Compartment Leak	Open	70.9	2	1	0	2.8
8	Recirculation Fan	Fan	62.0	1	1	4.5	1
9	Upper Ice Plenum Door	1 Way Door	148.6	1	19.7	0	1330
12	LC/PZR Connection	Open	82.7	1	11.2	2.9	54.3
13	LC/SGs Connections	Open	82.7	1	17.1	2.9	576
14	Lower to Upper Dome	Open	181.0	0	77.1	0	5970
15	Lower Dome to Cyl Section	Open	148.6	0	102	0	10400
16	PZR H2 Skimmer	Fan	122.9	1	0.3	56.5	0.1
17	SG H2 Skimmer	Fan	122.9	1	0.3	56.5	0.1
18	Dome H2 Skimmer	Fan	201.0	1	0.3	135	0.1
19	Large Ice Box Drain Line	Check Valve	70.6	2	1	1	13
20	Small Ice Box Drain Line	Open	70.6	2	0.1	1	2.1
21	Ice Box Divider	Open	94.8	3	1	16.4	1960
22	Ice Box Divider	Open	113.2	3	1	16.4	1960
23	Ice Melt Water Drain	Pool First	94.8	0.1	32	0.3	5
24	Ice Melt Water Drain	Pool First	113.2	0.1	32	0.3	5
	* Relative to Reactor Cavity Floor						

Table 3: Fan Capacities

No.	Flow Path Name	Volumetric Flow
		(CFM)
8	Recirculation Fan	39000
16	PZR H2 Skimmer	500
17	SG H2 Skimmer	1000
18	Dome H2 Skimmer	1000

Table 4: Parameters for Concrete Structures

No.	Name	Lined	Orient	Face Volume 1	Face Volume 2	Lowest Elevation*	Height	Thickness	Face Area
						ft	ft	ft	ft2
1	Cavity Floor	No	Hor.	10	-	0	-	12.5	664
2	Cavity Wall	No	Vert.	10	-	0	15.0	12.5	1940
3	Lower Bio Shield	No	Vert.	10	20	31.8	11.0	11.0	2750
4	Upper Bio Shield	No	Vert.	60	20	54.1	16.0	5.6	3510
5	PZR Enclosure	No	Vert.	90	60	85.1	7.7	2.0	1500
6	SG Enclosures	No	Vert.	100	60	85.1	7.7	2.0	8720
7	LC Floor	No	Hor.	20	-	31.8	-	12.5	3730
8	Crane Wall	No	Vert.	20	30	31.8	27.0	3.0	12300
9	Annular Floor	No	Hor.	30	-	31.3	-	12.5	3300
10	Annular Outer Wall	Yes	Vert.	30	-	31.3	27.0	3.5	12760
11	Ice Inner Wall	No	Vert.	60	50	132	8.5	3.0	3690
12	Ice Outer Wall	Yes	Vert.	50	-	132	8.5	3.5	4570
13	UC Op Deck	No	Hor.	60	20	85.1	-	2.9	6240
14	Lower UC Dome	Yes	Vert.	70	-	149	16.2	3.0	17340
15	Upper UC Dome	Yes	Vert.	80	-	181	10.0	3.0	7230
	* Relative to Reactor Cavity Floor								

Table 5: Parameters for Steel Structures

No.	Location	Volume	Mass	Surface Area
			lbm	ft^2
1	Lower Compartment	20	4.3E+06	65600
2	Upper Compartment - Cyl. Section	60	109000	19200
3	Upper Compartment - Lower Dome	70	109000	19200

4.2 Pipe Break

The effluence from the postulated break was introduced into each calculation as time-dependent mass and energy sources into the control volume containing the postulated break. Two sizes of pipe breaks were examined in these calculations, i.e., 2 and 6 inch pipes and two break location were considered, i.e., the lower and annular compartments, as illustrated in Table 6. A 2-inch break was considered possible for both the lower and annular compartments but a 6–inch was not possible for the annular compartment since no RCS pipes of this size exist in the annular compartment.

Table 6: Locations of Postulated Pipe Breaks

Break Size	Break Location	
	Lower Compartment	Annular Compartment
2-inch	Possible	Possible
6-inch	Possible	Not Possible

The mass flow and energy rates for the 2-inch and 6-inch breaks are shown in Figures 3 and 4, respectively. For the 2-inch break, MAAP4 data supplied to SEA [7] was used for the first 50,000 seconds. For the 6-inch break, NOTRUMP data was used for the first 1500 seconds [5] then the MAAP4 data [7] was used until 50,000 seconds. Data from the NOTRUMP code was deemed the most appropriate and used because the NRC validated NOTRUMP. Beyond 50,000 seconds, the mass flow rates were held constant and the break energy rates were decreased per declining core decay power.

4.3 Recirculation Switchover

The containment sprays and the ECCS initially inject water from the refueling water storage tank (RWST). When the RWST was predicted to empty, the MELCOR input model began to remove water from the containment sump at a rate equivalent to the sum of the containment spray and break flow. Thus, the total water inventory inside the containment remained constant from the point of switchover from the injection mode to the recirculation mode.

Determining when the switchover occurred was accomplished by integrating both the break and spray flows during the injection mode and comparing the total to the inventory of water available for injection. The water available for injection included both the RWST (295,000 gallons) and the accumulator (27,500 gallons) volumes, when activated, reduced by an amount (8500 gallons) to account for water in transit such as in piping. Thus, the injection inventory was either 286,500 or 314,000 gallons, depending upon accumulator activation. When the integrated total exceeded the injection inventory, the end of the injection mode was signaled and recirculation from the sump commenced. The 8500 gallons was the number estimated by AEP for water holdup.

Actually, it is the rate of ECCS injection into the RCS that should be integrated to determine recirculation switchover; however, this would require that the RCS be modeled. The implication of the method used is that the inherent assumption that the RCS retains its initial water inventory. This is conservative when calculating the sump water level.

The D. C. Cook accumulators, according to MAAP4 input, have an initial pressure 636.2 psi and the RCS pressure must drop below this pressure for the accumulators to activate. However, their activation could not be modeled in the MELCOR calculations without first modeling the RCS. Herein, it was assumed that the accumulators would activate following the 6-inch break but not for the 2-inch break.

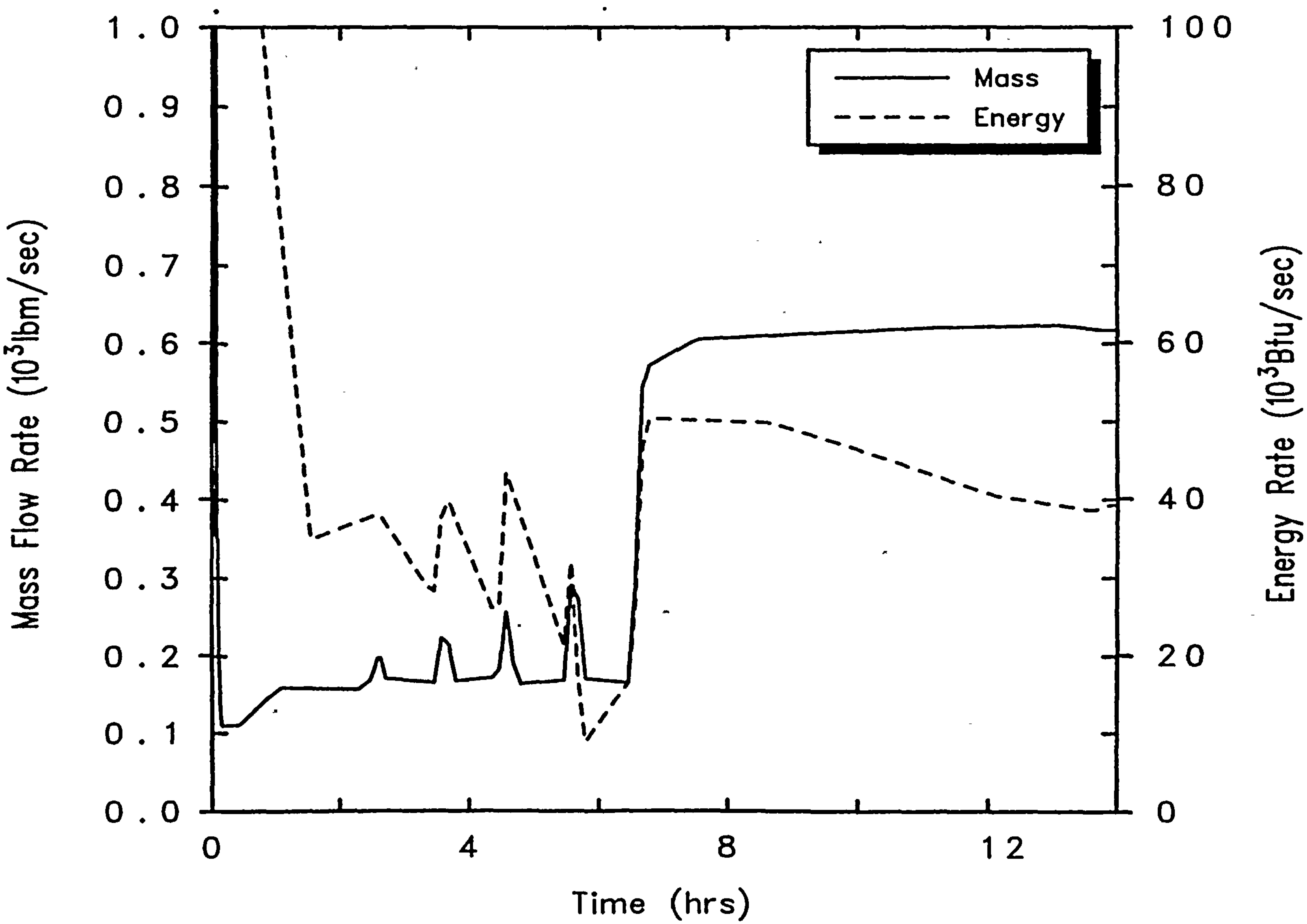

Figure 3: Break Source Term for 6-inch LOCA

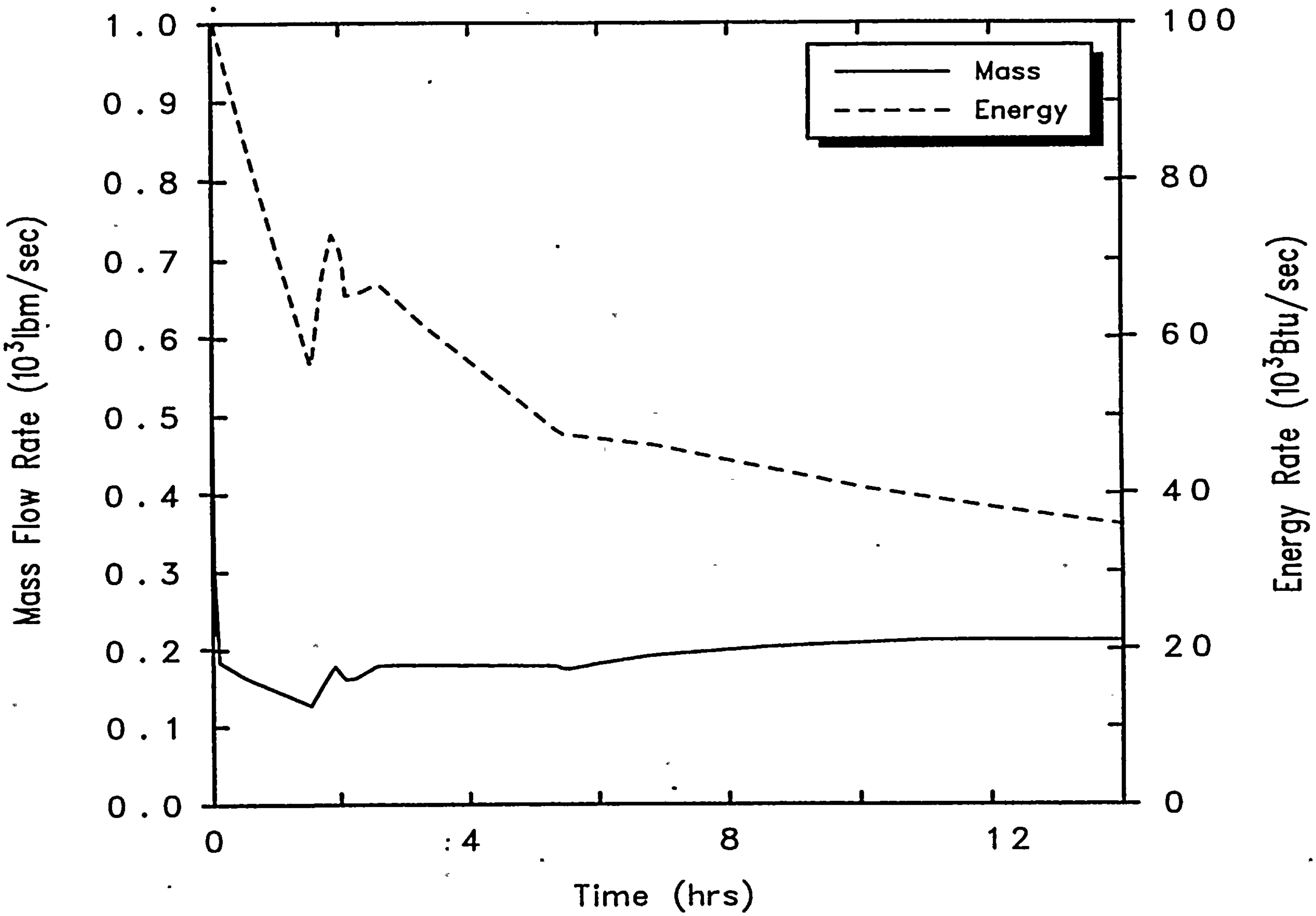

Figure 4: Break Source Term for 2-inch LOCA

4.4 Containment Sprays

The containment sprays are a primary method of removing heat from the containment and reducing containment pressures. Correct modeling of the sprays is necessary for determining the ice melt time. The total flow of water to the sprays, as modeled for both spray trains, was 6400 GPM. Alternately, 3200 GPM was used for 1 spray train. The spray flow was distributed within the containment using the MAAP4 distribution fractions, i.e.,

- 62.5% to the upper compartment,
- 31.25% to the lower compartment, and
- 6.25% to the annulus.

Subsequently, based on the assumption that some of the lower compartment spray flow would fall into the reactor cavity, 4.5% of the 31.25% (1.41%) was redirected into the reactor cavity. This 4.5% was based on the flow junction area to the reactor cavity divided by the lower compartment floor area.

Comments in the MAAP4 input model states that a small portion of the upper compartment spray flow would fall through stairwells into the annulus compartment. The MAAP4 input apparently assumed 45 GPM flowed to the annulus given a total spray flow rate of 3600 GPM. Herein, 80 GPM of the upper compartment spray flow (6400/3600*45=80) was redirected to the annulus.

The temperature of the water sprays is important to the determination of the temperatures of gasses passing through the ice condenser. During injection mode, the RWST water temperature of 105 °F from the MAAP4 input was used. During the recirculation mode, the spray temperature depends upon the water temperature being pumped from the sump, the effectiveness of the spray heat exchangers, and the heat exchanger cooling water temperature. Temperatures for the sprays operating in the recirculation mode, as calculated by MAAP4, were provided to SEA [7] for the 2-inch break. The spray temperatures used herein are shown in Figure 5a.

Both containment spray pumps (i.e., one pump for each spray train) are started upon a high containment pressure signal of 2.9 psig. If a pumps starts, then it will continue to operate until the containment pressures drops below 1.5 psig again. Hysteresis control logic was used in the MELCOR input model to simulate these pump actuation setpoints.

The sprays as modeled do not directly impact containment surfaces other than compartment floors. As spray droplets fall out of the atmosphere, the droplets were deposited into the pool associated with that particular control volume. For control volumes not capable of forming a pool, the temporarily formed pool would flow into a lower volume until a volume capable of supporting a pool was reached.

4.5 Ice Condenser

The Westinghouse ice condenser containment system was designed to suppress the pressure rise within a containment arising from a LOCA. The design consists of a large volume of subcooled ice that acts as a passive heat sink. The primary flow path from the lower compartment housing the RCS to the upper compartment is through the ice compartment. The ice, in granulated form, is contained in perforated metal baskets approximately 1 ft diameter, stacked about 50 ft high. Steam readily condenses on the ice surfaces. Most of the flow is around the outside of the baskets so little or no entrainment of ice or condensate occurs.

The rate of steam condensation is governed by the rate of heat transfer to the ice. Ice condenser models generally calculate heat transport to vertically oriented one-dimensional cylindrical structures representing the ice filled baskets. Both convective and radiant heat can be exchanged between the ice baskets and the surrounding gases. The surface heat transfer, as modeled in MELCOR, is illustrated by the following equation.

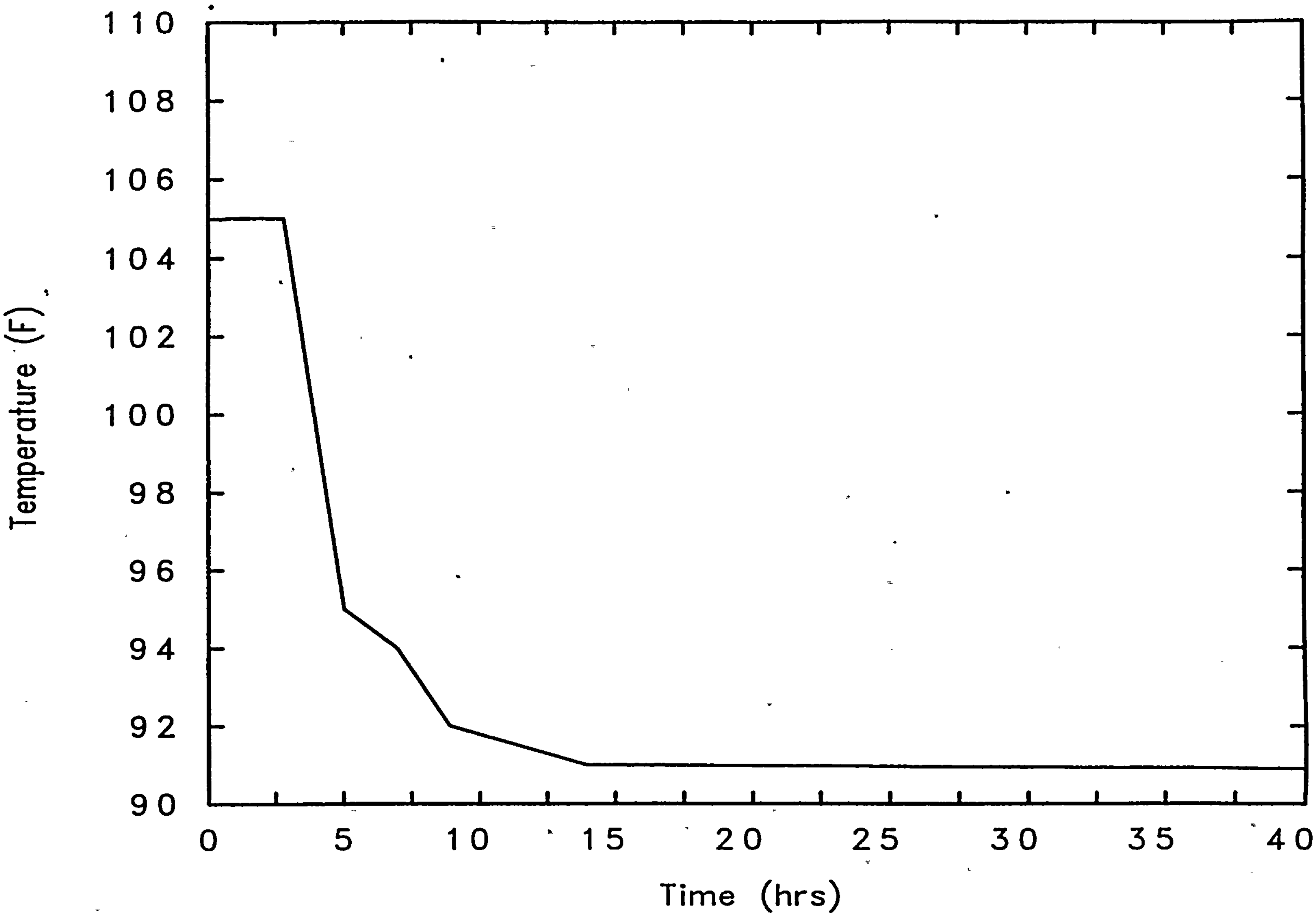

Figure 5a: Spray Temperature in Recirculation Mode

$$Q_{ice} = h_{conv} \cdot A(V_{ice}) \cdot (T_{bulk} - T_{ice}) + F \cdot \sigma \cdot A(V_{ice}) \cdot (T_{bulk}^4 - T_{ice}^4)$$

Where Q_{ice} = the rate of heat transferred,
h_{conv} = the convective heat transfer coefficient,
$A(V_{ice})$ = the heat transfer area as a function of ice volume remaining,
T_{bulk} = the temperature of the bulk gases,
T_{ice} = the temperature of the ice surface,
F = an effective radiative exchange factor, and
σ = the Stefan-Boltzmann constant.

As the ice melts, its surface area decreases at a rate that depends upon the shifting and relocation of the remaining ice. Generally, the ice at the bottom of the columns will preferentially melt faster than the ice at the top because the gases enter at the bottom. Experiments have shown ice shifting downward in the baskets to fill voids created by the melting thus leaving vacant space in the tops of the baskets. Experiments have also shown the granulated ice freezing in place essentially forming a standing column of ice that melts radially inward. The PNL experiments [8] illustrated both types of ice melt behavior. During the initial preheat phase, ice melted at the bottom was replaced by falling ice leaving the upper portion devoid of ice but, at some point, the ice melt changed to a radially oriented melt such that the ice in the lower (~2/3) disappeared at about the same time.

Two types of ice melt models have been used in the simulations of the experiments. The experiments were simulated using the CONTAIN [9, 10] code using a linear surface area model, i.e., the area simply changed with the height of the remaining column of ice, as illustrated by the following equation.

$$A = A_o \cdot \left(\frac{V}{V_o}\right)$$

Where A_o = the initial area of the ice,
V = the current volume of remaining ice, and
V_o = the initial volume of ice.

Given, a constant cross-sectional area within the ice basket, the ice volumes are proportional to the ice column heights.

The experiments were also simulated using the MELCOR code [11]; however, the MELCOR simulation assumed that the ice melted radially inward per the following equation.

$$A = A_o \cdot \left[0.25 + (0.75) \cdot \left(\frac{V}{V_o}\right)^{0.5}\right]$$

The 25% offset number in the equation pertained to radionuclide deposition modeling. It was used to account for radionuclide deposition on the wire basket that remains in place after the ice has melted. (The reason for this approach, as opposed to simulating the baskets themselves as a structure, was not made clear.)

A comparison of these two approached is shown in Figure 5b. As clearly shown, the radial model generally calculated a higher heat transfer area than the linear (axial) model.

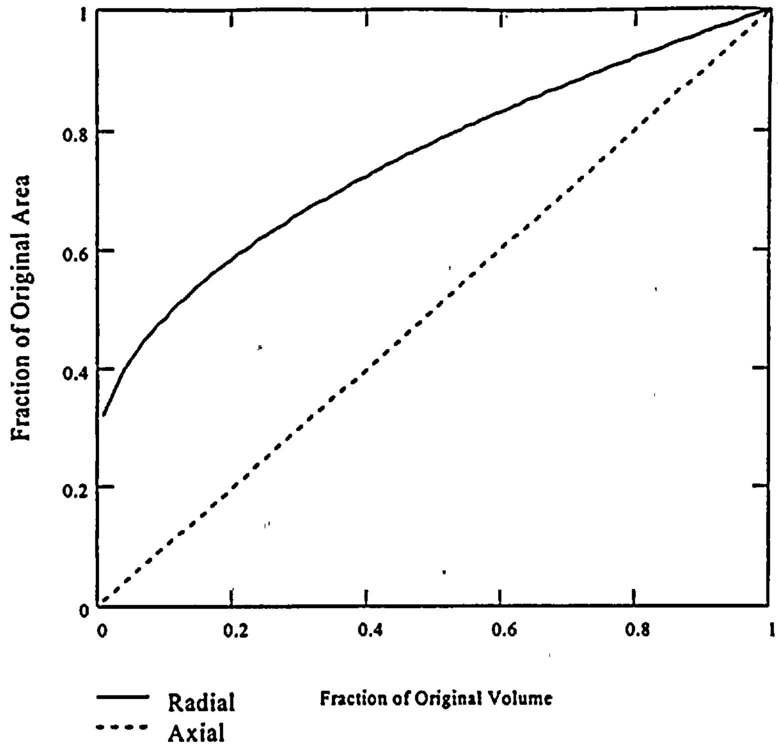

Figure 5b: Comparison of Ice Melt Geometry Models

The surface area equation as coded in MELCOR is as follows.

$$A = A_0 \cdot \left[\alpha + (1 - \alpha) \cdot \left(\frac{V}{V_0} \right)^{\beta} \right]$$

Where A_o = the initial area of the ice,
V = the current volume of remaining ice,
V_o = the initial volume of ice, and
α, β = user specified parameters.

The ice melt models in both the MELCOR and the CONTAIN codes included a user specified multiplier applied to the convective Nusselt number to account for roughness in the ice columns. This multiplier was adjusted in the CONTAIN and MELCOR simulations of the PNL ice-condenser experiments to produce reasonable reproductions of the experimental temperatures. Note that the ice melt conditions in the experiments were deduced from the experimental temperatures. Since the two simulations used considerably different ice melt geometry models, it would be expected that the two simulations would not arrive at the same multiplier. The CONTAIN code user selected multiplier that best simulated the experiments and was recommended for other code users was 5.0. Contrast this number to the 1.2 recommended by the MELCOR code staff. Actually, the MELCOR simulations for some portions of the experiments seemed to work better at higher multipliers, up to 3.8, but their recommendation for future users was 1.2.

The ice melt model parameters that were varied in the calculations in this study included the Nusselt number multiplier and the two user specified parameters, α and β. The primary combinations of these parameters are listed in Table 7.

Table 7: Primary Combinations of Ice melt Model Parameters

Ice Melt Model	Nusselt Multiplier	User Specified Parameter α	User Specified Parameter β
CONTAIN Recommendation	5.0	0.05	1.
MELCOR Recommendation	1.2	0.25	0.5
Conservative	1.2	0.05	1.

Calculations performed using either of the CONTAIN or the MELCOR recommended parameters would be expected to produce ice melt rates characteristic of the PNL ice-condenser experiments. Note that, although the value α recommended by the CONTAIN staff was apparently zero, a value of 0.05 was used herein as a precaution to prevent any numerical problems that sometimes crop up when a parameter such as an area goes to zero. The impact of this 5% was expected to have only a minor effect on the calculational results.

Although the ice melt in an actual plant may be reasonably well represented by the PNL ice-condenser experiments, this assumption is by no means certain, particularly in light of the limited data available to study the ice melt progression. Potential differences between experiments and plants could include flow conditions, type of ice, etc. Therefore, wherever possible, the use of conservative parameters is desirable. The conservative model parameters in Table 7 essentially reflect the area of a cylinder that is constantly reduced in height as the ice melts with only a small enhancement to account for the surface roughness of ice.

Radiant heat transfer between the ice and the surrounding gases was modeled in these calculations. It was expected that radiant heat transfer could play a significant role during the early portion of the accident when live steam passed through the ice condenser. At later times, that role would be considerably reduced as containment gasses cooled. The radiant exchange factor, F, was computed internally by MELCOR and was a function of gas and surface emissivities and absorptivities.

The ice condenser was divided into three equal vertical volumes to better simulate the cooling of the upward flowing gasses through the condenser. This configuration allows each volume to have its own temperatures and gas compositions, i.e., warmer gases with a higher vapor fraction would be expected in the bottom volume than in the top volume. Except for a single parameter sensitivity calculation, the total ice mass of 2.43×10^6 lbm from the MAAP4 input model was used for all calculations.

Modeling the ice melt process is difficult because the ice has voids, melts away, changes geometry, and conducts heat. The ice melt models were implemented into MELCOR by piggy backing the model onto the existing heat structures models, i.e., one-dimensional heat conduction in a cylinder. However, this heat conduction model does not consider gases flowing through the ice granules or the loss of entire conduction nodes as the ice melts. Therefore, certain modeling rules were established to best simulate the ice melt. Each ice basket was simulated as a one-foot diameter solid cylinder using only two heat conduction nodes. Using only two nodes forced the ice to have a relatively uniform temperature across the cylinder. The heat capacity associated with an initial ice temperature below that freezing was subsumed into the heat of fusion. This heat was assumed to be absorbed by the ice over a user selected temperature range (274 to 284 °K). As the ice temperature passed through this temperature range, it was predicted to melt, i.e., no melting at 274 °K but complete melting at 284 °K.

5.0 WATER INVENTORY

5.1 Water Sources to Containment

The sources of water to the containment sump included the available RWST, the accumulators, the RCS, and the ice. Water lost from the RCS would contribute to the available sump water; however, the determination of the net water lost from the RCS requires the modeling of the RCS and ECCS pumping systems which were not included in the scope of these analyses. The accumulators may or may not inject their water into the RCS depending upon the size of the pipe break. Water from melted ice would flow from the ice condenser into the lower compartment contributing to the available water. The volumetric capacities of these water sources based on a total ice mass of $2.43X10^6$ lbm and their total (with and without the accumulators) are shown in Table 8.

Table 8: Capacities of Water Sources

Source	Capacity (Gallons)
RWST	295,000
Ice	291,470
RCS	Not Credited Herein
Subtotal	**586,470**
Accumulators	27,500
Total	**613,970**

5.2 Net Containment Water Volume

The safe operation of the spray and ECCS pumps is ensured by supplying the containment with a surplus of water above the level needed to guarantee the safe operation of the spray and ECCS pumps with all dead-ended spaces filled. The surplus volume is defined as the water volume over and above the volume needed to fill the dead-ended volumes, the in-transit water, and the water required to fill the sump to the minimum safe level for pumping. Dead-ended volumes where water could be trapped, and thus not returned to the sump included the annular compartment, the reactor cavity, and the floor of the refueling pool (below the drain entrance). Water in transit, i.e., piping, vapor, droplets, was considered as well. The capacities of these volumes are listed in Table 9.

Table 9: Containment Water Volumes

Location	Capacity (Gallons)
Annular Compartment	319,210
Reactor Cavity	117,820
Piping and In-Flight Water	8,500
Refueling Pool Floor	9,500
Vapor and Droplets	3,000
Minimum Safe Level	116,150
Total	**574180**

The surplus water capacities are listed in Table 10, along with their corresponding depth above the minimum safe level. Note that the difference between the total ice mass in the old TS and the new requested TS of $3.2X10^5$ lbm less ice is equivalent to about 1.5 ft of depth. Thus using the old TS ice mass of $2.11X10^6$ lbm would result in water level being approximately one-foot below the minimum safe level without the accumulators.

Table 10: Surplus Containment Water

Accumulator Actuation	Surplus Volume (Gallons)	Surplus Depth (ft)
With Accumulators	39790	1.5
Without Accumulators	12290	0.5

The containment water level after all the ice has melted will therefore be adequate given the TS increase in ice mass. The concern then becomes whether or not the ice would melt fast enough to keep the sump water level above the minimum safe level. Several 6 and 2-inch break scenarios were evaluated to determine the time-dependent containment water levels.

6.0 LOCA SCENARIOS

A total of 19 LOCA scenarios, listed in Table 11, were evaluated. The parameters varied included:

- the break size,
- the break location,
- accumulator actuation,
- recirculation fans operating or not,
- one or two containment spray trains,
- Ice melt model parameters, and
- the initial ice melt.

Table 11: LOCA Scenario Simulations

Case	Break		System Status			Ice Melt Model		Initial Ice Mass	Results	
	Size	Loc.	Accum-ulators	RECIR Fans	Spray Trains	Nusselt Mult.	Area Model		Min Level[1]	Melt Time
	(in)							(10^6 lbm)	ft	(hr)
6base	6	LC	Yes	On	2	1.2	Linear	2.43	3.08	> 40
6a	6	LC	Yes	On	2	5	Linear	2.43	6.90	14.5
6b	6	LC	Yes	On	1	1.2	Linear	2.43	6.62	> 40
6c	6	LC	Yes	On	2	1.2	Radial	2.43	7.24	9.6
6d	6	LC	Yes	Off	2	1.2	Linear	2.43	2.25	> 40
Bench	6	LC	Yes	On[2]	1[2]	1.2	Linear	2.43	7.19	> 40
2base	2	AC	No	On	2	1.2	Linear	2.43	-3.51	> 40
2a	2	AC	No	On	1	5	Linear	2.43	0.84	7.4
2b	2	AC	No	On	1	1.2	Linear	2.43	-1.08	30.0
2c	2	AC	No	On	2	5	Linear	2.43	-0.30	17.9
2d	2	AC	No	On	2	1.2	Radial	2.43	0.07	15.7
2e	2	AC	No	On	2	2.4	Radial	2.43	0.58	10.7
2f	2	AC	No	On	2	3.6	Radial	2.43	0.58	9.0
2g	2	AC	No	On	2	2.4	Linear	2.43	-2.00	31.3
2h	2	AC	No	On	2	3.6	Linear	2.43	-1.04	22.8
2i	2	AC	No	On	2	1.2	Radial	2.11	-0.87	12.5
2j	2	AC	No	Off	2	1.2	Radial	2.43	-11.75	----[4]
2k	2	LC	No	On	2	1.2	Linear	2.43	-1.60	40.0
2l	2	AC[3]	No	On	2	1.2	Radial	2.43	-0.63	24.7

1. Lowest Sump Water Level During First 40 Hours
2. During Injection Mode Only
3. Break Submerged
4. Sump Pumped Dry at 3.2 hours

Base case 6 and 2-inch scenarios were simulated with the MECLOR code assuming the recirculation fans and both spray trains operating, a total of 2.43 x 10^6 lbm of ice, and conservative ice melt parameters. As previously discussed, the accumulators were always

activated during the 6-inch breaks but not during the 2-inch breaks. One calculation (Case Bench), in which both the fans and the sprays were deactivated upon completion of the injection phase, was run in an attempt to reproduce the results of one of the MAAP4 calculations. Two scenarios (Cases 6d and 2j) were run without the recirculation fans, although these fans would normally operate continuously during these scenarios, to illustrate their important impact on melting the ice. Both spray trains were normally activated whenever the containment pressure exceeded 2.9 psig and then turned off if the containment pressure subsequently dropped below 1.5 psig. Three sensitivity calculations were run with only one spray train for comparison. One calculation was run with the ice mass reduced to 2.11 x 10^6 lbm to illustrate the impact of not increasing the TS total ice mass. Other calculations varied the ice melt parameters to determine their impact on the sump water level.

6.1 Benchmark with MAAP4

A 6-inch cold leg break scenario that was simulated with MAAP4 was also simulated with MELCOR as a means of comparing the ice melt models of these two codes. Little information was provided to SEA regarding the assumptions implemented in the MAAP4 analysis for this scenario but a review of the four available output figures indicated that the containment sprays and probably the recirculation fans were both turned off at the end of the injection phase. The injection phase ended at about one hour corresponding to only one spray train being activated. The MELCOR and MAAP4 containment responses for this scenario are compared in Figure 6 through 9. These figures show:

- the fraction of ice remaining,
- the upper compartment containment pressure,
- the active sump water level, and
- the annulus water level, respectively.

These comparisons illustrate qualitative agreement between the two codes. The most significant differences appear to be associated with flow conditions from the break. Note that the break flow conditions used in the MELCOR simulation were digitized from hardcopy plots, and therefore, a certain amount of difference was introduced into the break flows. The MELCOR containment pressure remained much higher than the MAAP4 pressure for the first couple of hours. It was likely that the digitized break source terms (the source terms were digitized from poorly scaled plots) resulted in a slightly higher break enthalpy than was predicted by MAAP4 which in turn generated some steam in the MELCOR simulation that was not present in the MAAP4 simulation. This extra steam would also account for the faster melt rate in the MELCOR simulation. The annulus water level in the MELCOR simulation continued to gradually increase after the sprays were turned off due to the accumulation of condensate and droplet fallout whereas the MAAP4 level did not. This indicates a difference between containment response models between the two codes.

The two codes produced qualitatively comparable results with the most significant differences attributable to errors introduced into the MELCOR break source terms by the digitizing process. Other code model differences were also likely.

6.2 Six-inch LOCA Scenarios

The containment response to a 6-inch cold leg LOCA is illustrated by the containment water levels run with the conservative ice melt parameters (Case 6base) shown in Figure 10. In this scenario, the accumulators dumped, both containment spray trains were activated upon high containment pressure of 2.9 psig, and the recirculation fans ran continuously. Figure 10 shows the active sump water level in the lower compartment, the water level in the reactor cavity, and the water level in the annular compartment. Also shown are the levels where water overflows from the annular compartment into the lower compartment; where water overflows from the lower compartment into the reactor cavity; and the minimum safe level for pumping from the sump. The

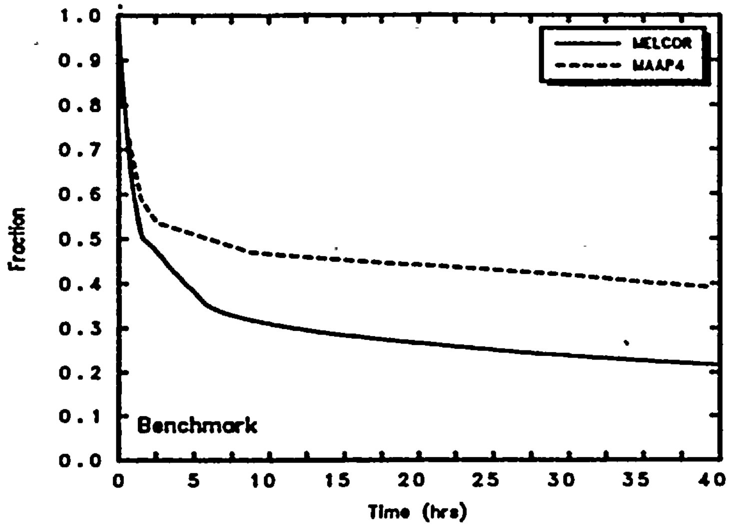

Figure 6: Fraction of Ice Remaining

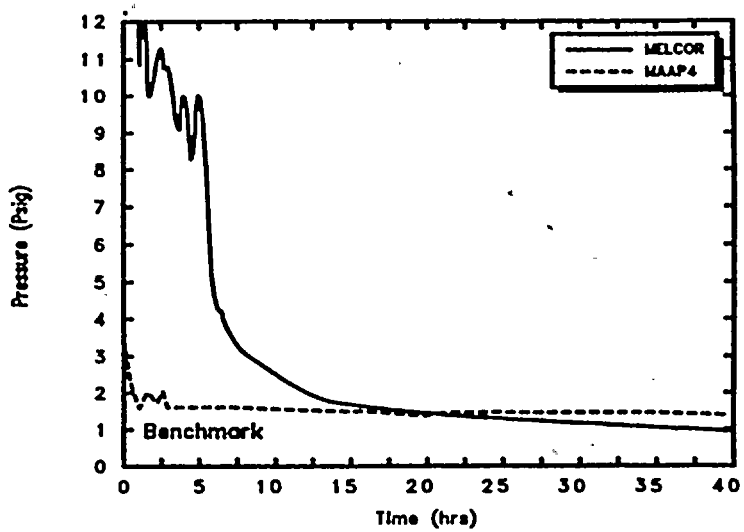

Figure 7: Upper Compartment Pressure

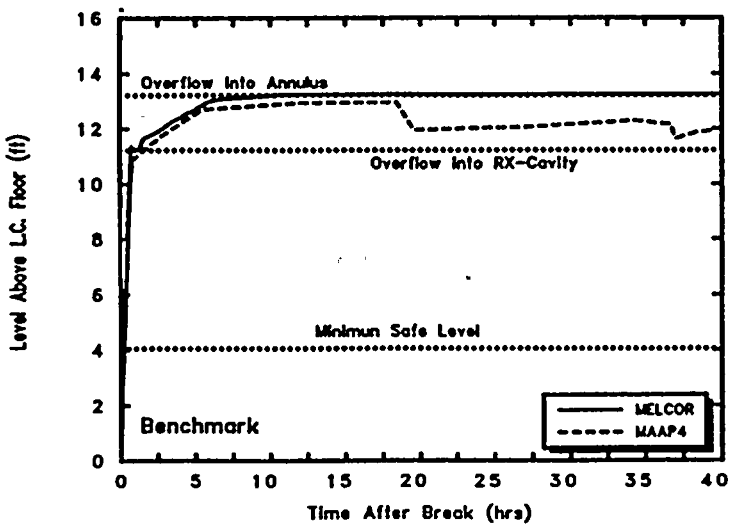

Figure 8: Active Sump Water Level

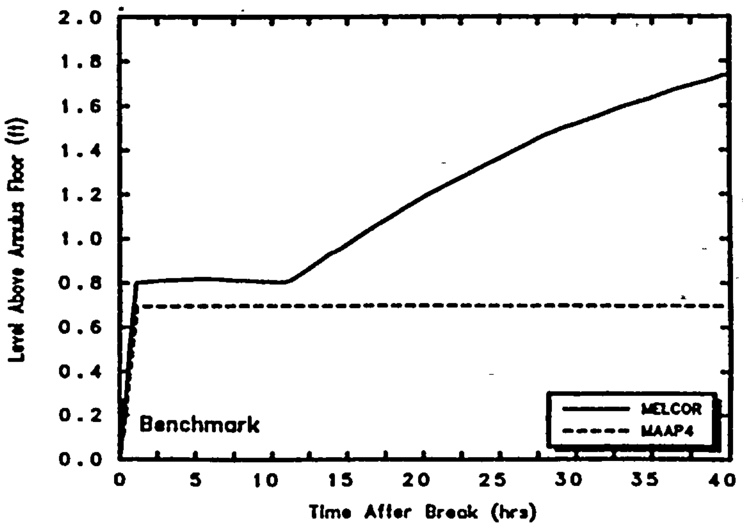

Figure 9: Annulus Water Level

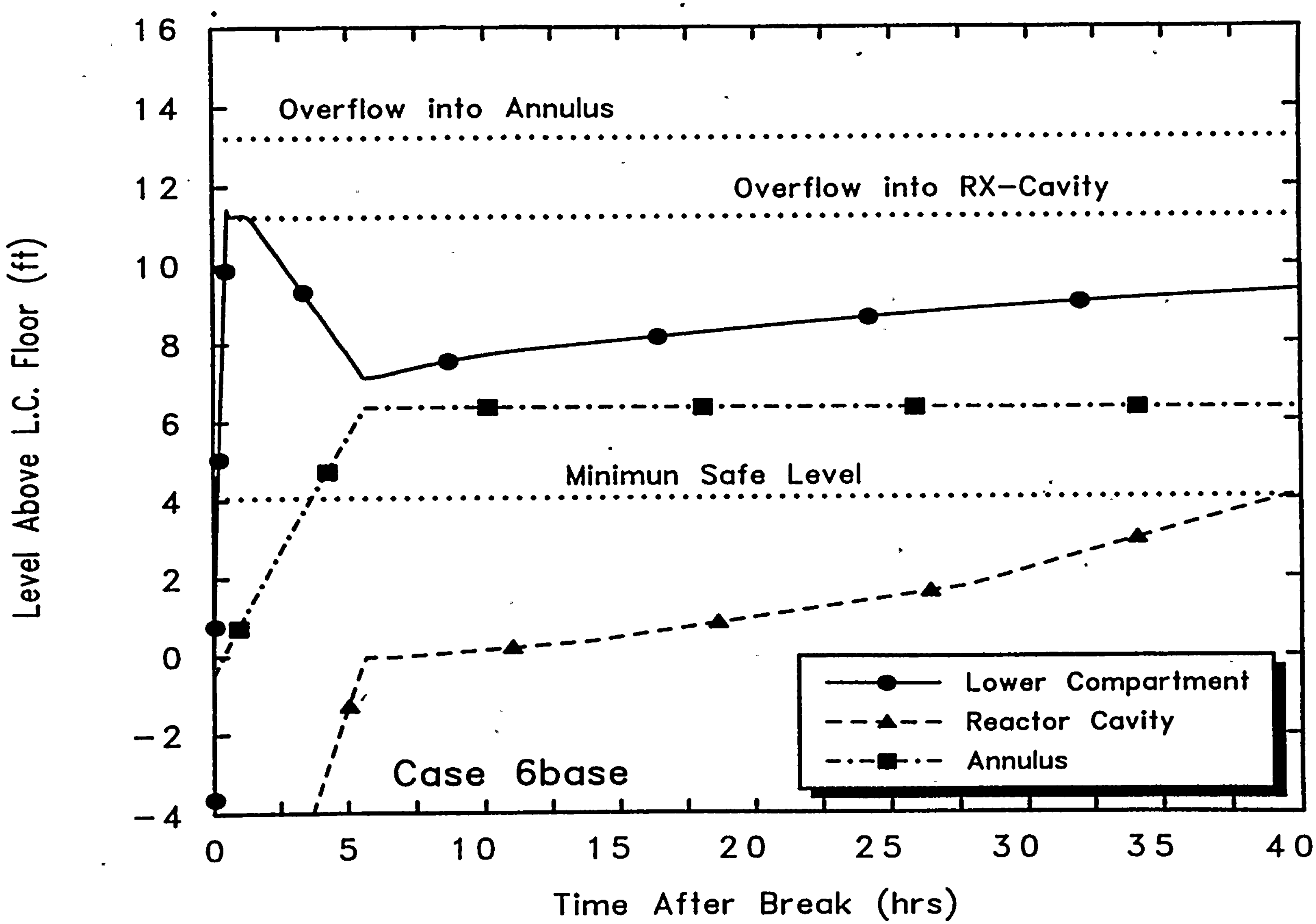

Figure 10: 6-inch LOCA Water Levels (Conservative)

sump level initially increased rapidly due to the accumulation of break flow directly into the lower compartment and to containment sprays draining to the lower compartment. In fact, water had started to overflow into the reactor cavity when the injection mode ended and pumps began to take water from the sump. Recirculation pumping then lowered the sump water level until the containment sprays stopped due to low containment pressure at 5.6 hours. Thereafter, the sump level increased again due to the accumulation of ice melt water. Water accumulated in both the annular compartment and the reactor cavity due to the containment sprays (when active) and then due to condensate and water droplet fallout. The lowest sump was still three feet above the minimum safe level even when using the conservative ice melt parameters.

The variations performed on the 6-inch LOCA scenario are illustrated by the fractions of ice remaining for each of the 6-inch cases as shown in Figure 11. First of all, the ice melted much faster when the MELCOR and CONTAIN code recommended ice melt parameters were used (Cases 6a and 6c) as opposed to the conservative parameters (Cases 6base, 6b, and 6d). In fact, when using the conservative parameters, considerable ice remained at 40 hours where the calculations were terminated. Secondly, the ice melt is compared for one versus two spray trains using the conservative parameters and for recirculation fans turned-off versus turned-on. The ice melted faster when only one spray train was active because less heat was removed from the containment resulting in slightly higher containment temperatures, therefore calculations run with both spray trains active are conservative. Although the recirculation fans would normally be operated during a LOCA scenario, their impact on the ice melt rate can be examined by comparing Case 6base (fans on) with Case 6d (fans off). Ice would melt slower without the fans because less air moves through the ice condenser. The corresponding sump water levels for these five cases are shown in Figure 12.

The containment pressure and temperature response to the 6-inch break is shown in Figure 13. The break and pumping flows are shown in Figure 14.

The time at which the sprays would be turned-off depends upon the flow conditions of the break, i.e., a break flow with higher energy would tend to keep the containment pressure higher thereby delaying this time relative to a break flow with lower energy. However, a break flow with higher energy would melt the ice faster than a flow with lower energy. These two effects tend to counter each other. A high-energy break flow might keep the sprays running longer but it would promote the ice melt thereby providing adequate water for sustained operation of the sprays. A low-energy break flow might not melt all of the ice but with the relatively lower containment pressure, the sprays would likely be turned-off so that all of the ice water would not be needed. The break flow conditions between relatively high break energy and relatively low break energy are less certain. The examination of possible break flow conditions would require the modeling of the RCS and ECCS and therefore was beyond the scope of this study. However, it should be noted that if the sprays were operated continuously in Case 6base, with its conservative ice melt assumptions, the sump water level would have dropped well below the minimum safe level.

6.3 Two-inch LOCA Scenarios

The worst case containment response to a 2-inch cold leg LOCA is illustrated by the containment water levels run with the conservative ice melt parameters (Case 2base) shown in Figure 15. In this scenario, the accumulators did not dump, both containment spray trains were activated upon high containment pressure of 2.9 psig, and the recirculation fans ran continuously. Figure 15 shows the active sump water level in the lower compartment, the water level in the reactor cavity, and the water level in the annular compartment. The annulus steadily accumulated water until it overflowed into the lower compartment at about 4 hours. The sump level initially increased rapidly due to the accumulation of melted ice, containment sprays, and condensate until recirculation pumping started. The reactor cavity slowly filled with the accumulation of lower compartment sprays falling into its entrance. In this calculation, the containment sprays operated continuously without being turned off on low containment pressure. The ice did not completely melt; about 10% of the initial ice remained at 40 hours. The sump level, using the conservative

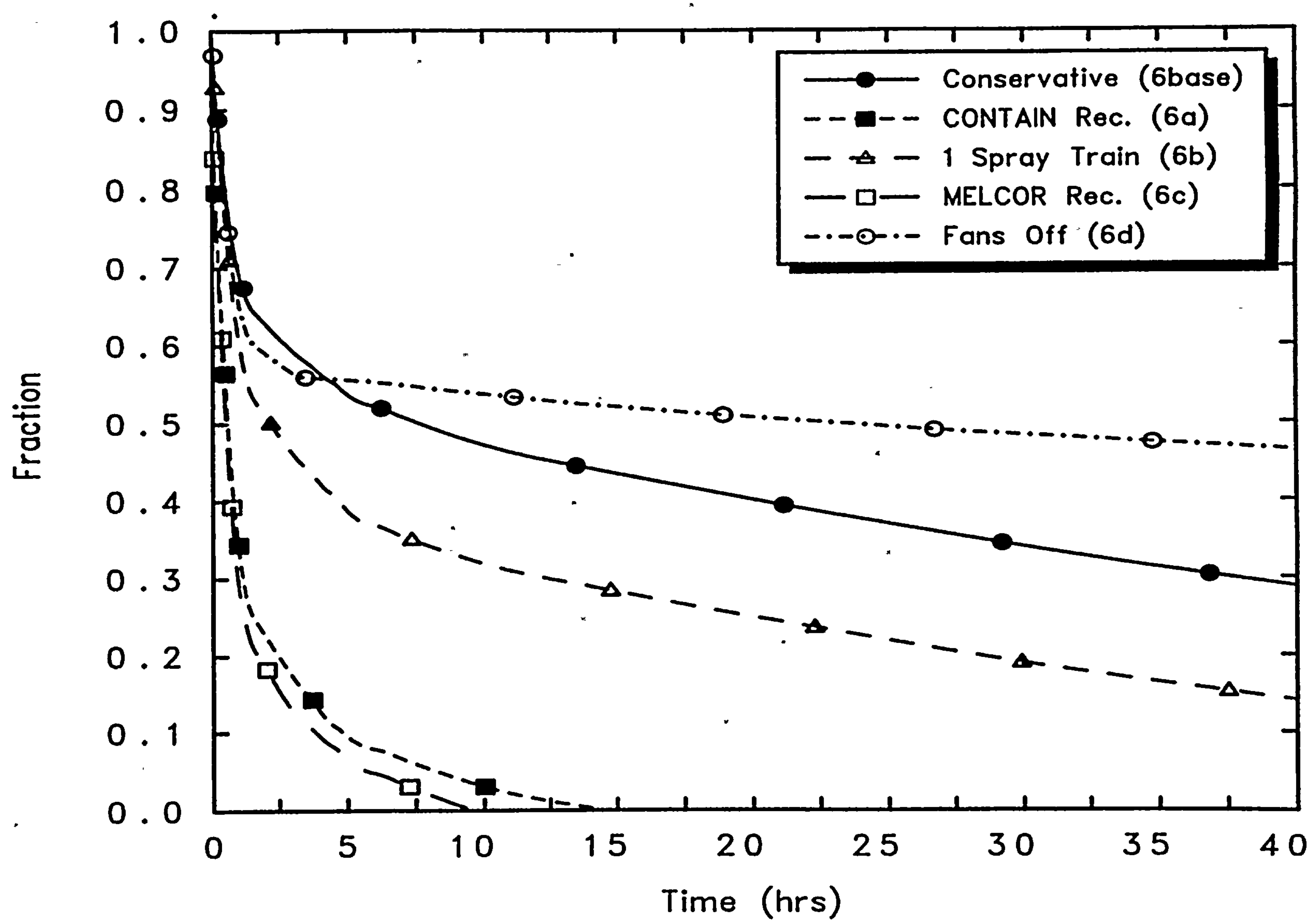

Figure 11: Fractions of Ice Remaining (6–inch)

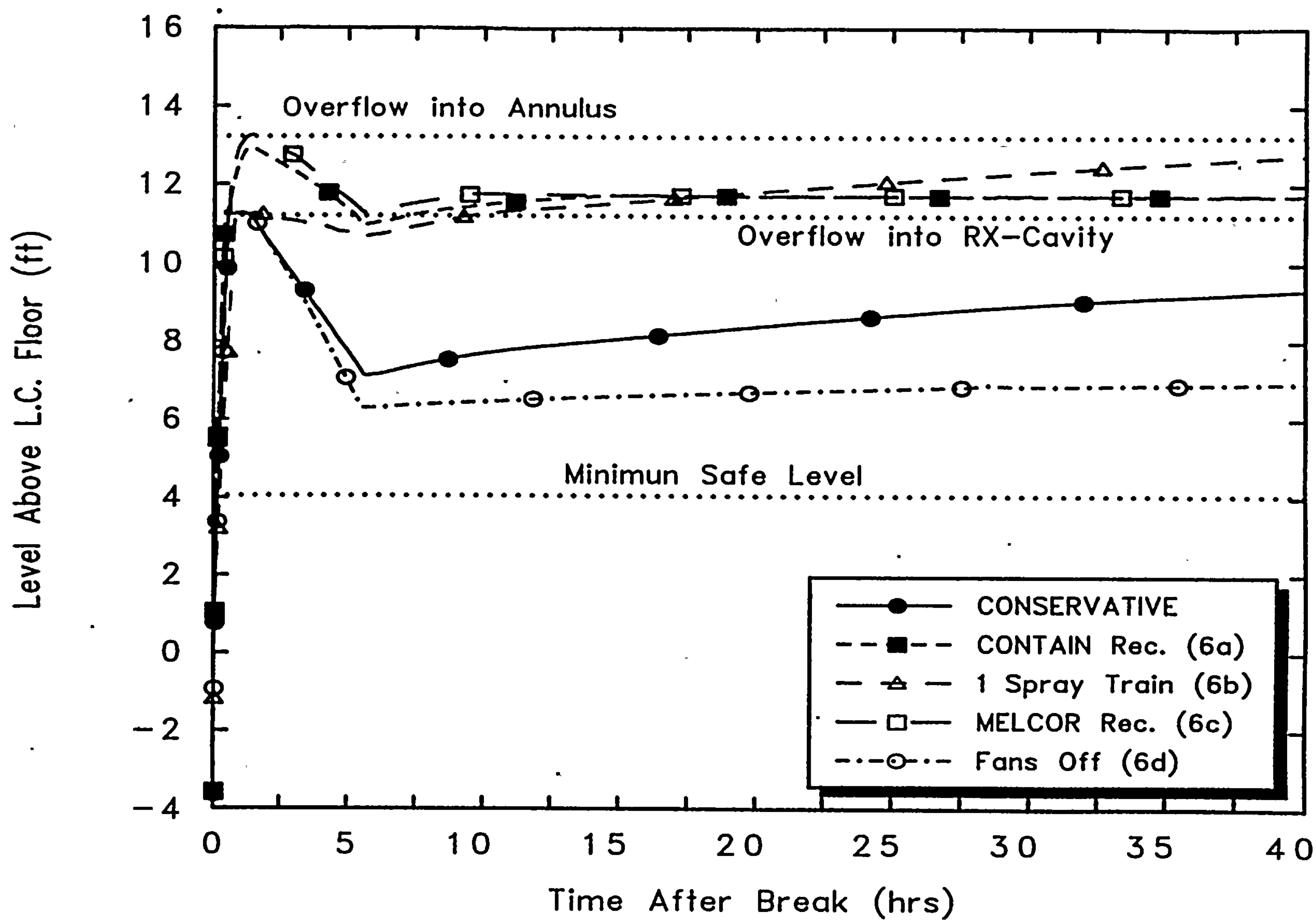

Figure 12: 6-inch LOCA Water Levels (Comparison)

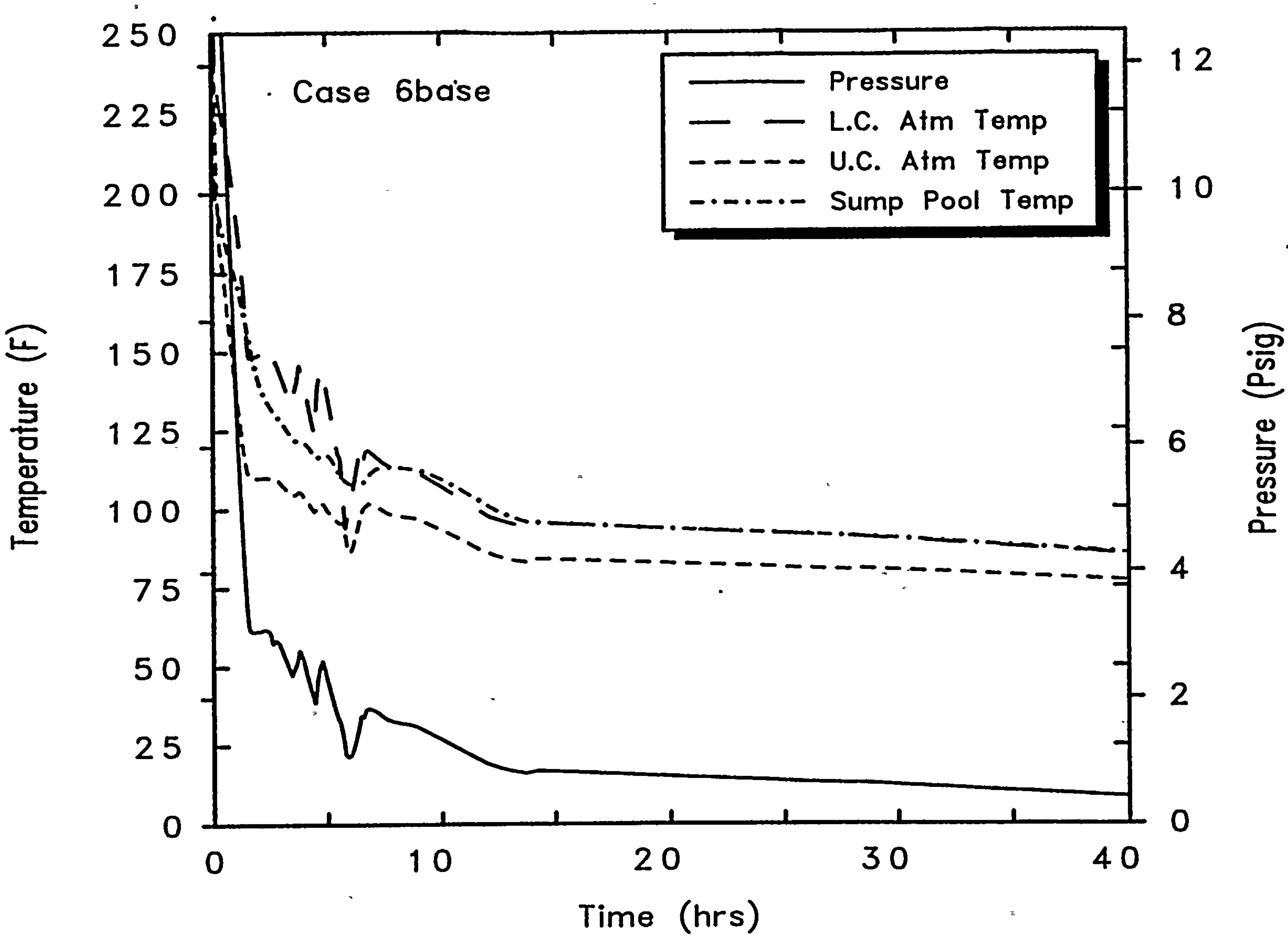

Figure 13: Compartment Responce to 6-inch LOCA

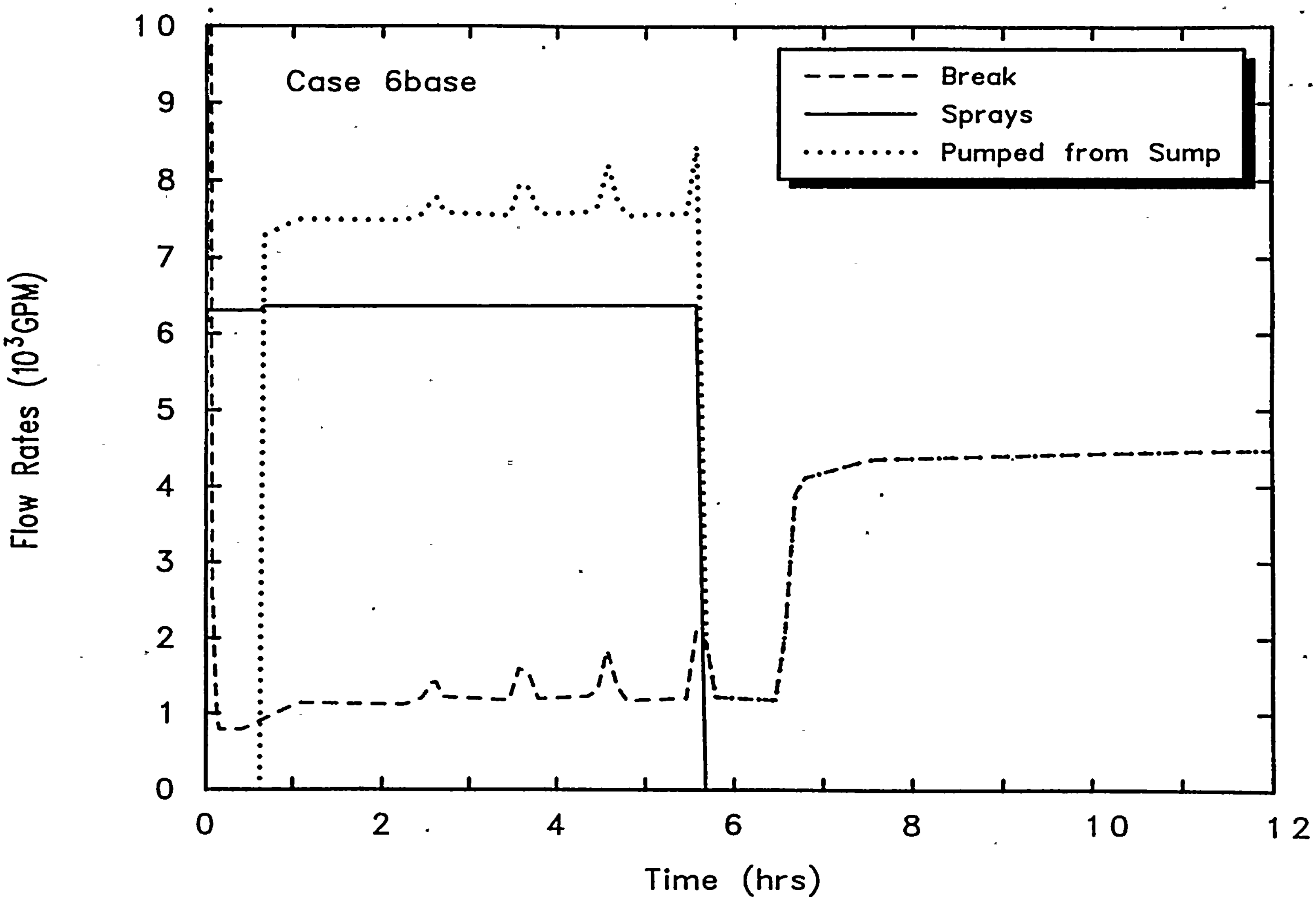

Figure 14: Break and Pump Flows (6-inch)

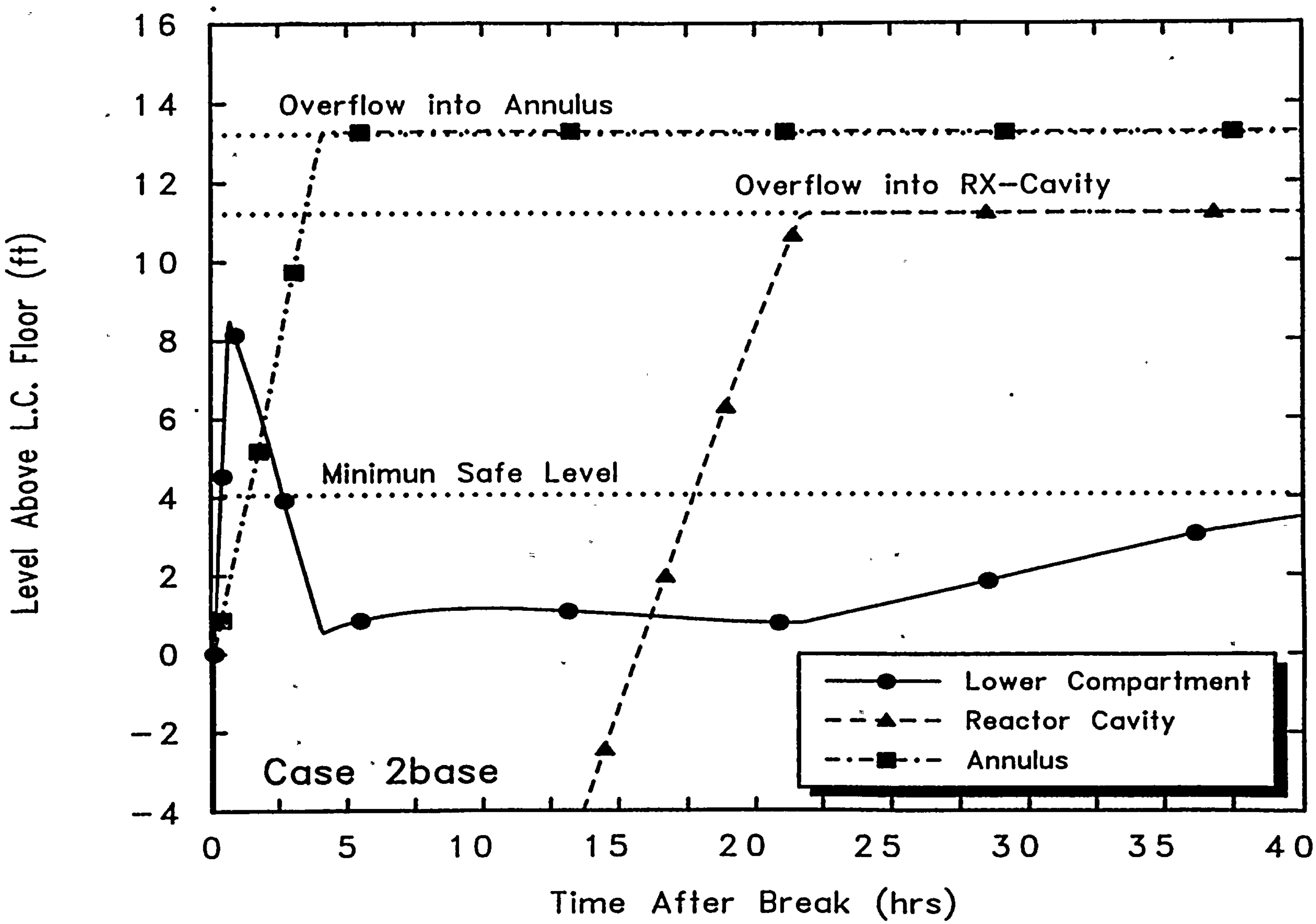

Figure 15: 2-inch LOCA Water Levels (Conservative)

ice melt parameters, dropped well below the minimum safe level for an extended period of time. In fact, its lowest level was 3.5 ft below the safe level.

Other scenarios (Cases 2c, 2b, and 2d) using less conservative ice melt parameters showed the water level remaining above the minimum safe level. This is illustrated by the comparison of their ice melt rates shown in Figure 16 and their corresponding sump water levels shown in Figure 17. Calculations using both the MELCOR and CONTAIN recommended ice melt parameters, indicated that the sump level would remain above the safe level, except for a brief and shallow dip below. A calculation (Case 2b) that was run with the conservative ice melt parameters but with only one spray train also generally remained above the safe level.

The fifth calculation (Case 2j) shown in Figures 16 and 17, was run using the MELCOR code recommended parameters but with the recirculation fans turned off throughout the calculation to determine the importance of these fans. In reality, these fans would be operating but if for some reason, the fans were not available, the ice would melt very slowly because there would be little flow through the ice condenser. In this calculation, the sump was predicted to pump dry at 3.1 hours. Therefore, the importance of operating of the recirculation fans until the ice has completely melted has been illustrated.

The containment pressure and temperature response to this 2-inch break (Case 2base) is shown in Figure 18. The pressure dropped to nearly the 1.5 psig setpoint, but never actually dropped below it, thus the containment sprays were not switched off during the calculation. This behavior was likely an artifact of the control logic controlling the sprays. In reality, the operators would probably have turned off the sprays at about 19 hours. However, turning off the sprays at this time would not have helped keep the sump water levels above the safe level for a substantial period of time. Thus, the conclusions drawn from these analyses were not affected by whether or not the sprays would be turned off at this relatively late time.

The effect of increasing the total ice mass from 2.11 to 2.43 million pounds (after crediting for sublimation) was examined by comparing Cases 2d (2.43E6 lbm) and 2i (2.11E6 lbm). The sump water levels for these two cases, shown in Figure 19, were not significantly affected during the early portion of the calculation where the levels approached the safe level at about 4.5 hours. However, during the late portion of the calculation, the increase in ice mass was needed to keep the water level in the safe zone.

The 2-inch breaks were generally assumed located in the annular compartment because this location was deemed the worst case. The alternative of locating the break in the lower compartment was examined in Case 2k. The sump water levels for Cases 2base and 2k are compared in Figure 20. As shown, the sump level dropped considerably lower when the break was assumed to occur in the annular compartment.

Although it was generally assumed that the break would occur above the water pool surface, it is possible for a break to be submerged, at least during a portion of the scenario. Therefore, Case 2l was run with the break effluence introduced into the pool forming in the annular compartment. In effect, break steam would condense in the pool until the pool saturated, thereby reducing steam to the containment and steam flow through the ice condenser. In Case 2l, the ice was not completely melted until 24.7 hours compared to 15.7 hours for the corresponding Case 2d. The water levels for these two cases are compared in Figure 21. The sump level in Case 2l dipped to a low 0.63 ft below the safe level compared to 0.07 ft above for Case 2d. Thus, if the break were underwater, the sump level would dip slightly lower (~8 inches). One other difference in these two calculations was that the sprays were turned off at about 9.6 hours when the break was submerged due to a lower containment pressure which in turn increased the late term sump water level because the reactor cavity did not fill completely.

The sensitivity of the ice melt parameters was examined by varying the Nusselt multiplier for both the radial and the linear ice melt models. These results (drawn from Table 11) are shown in

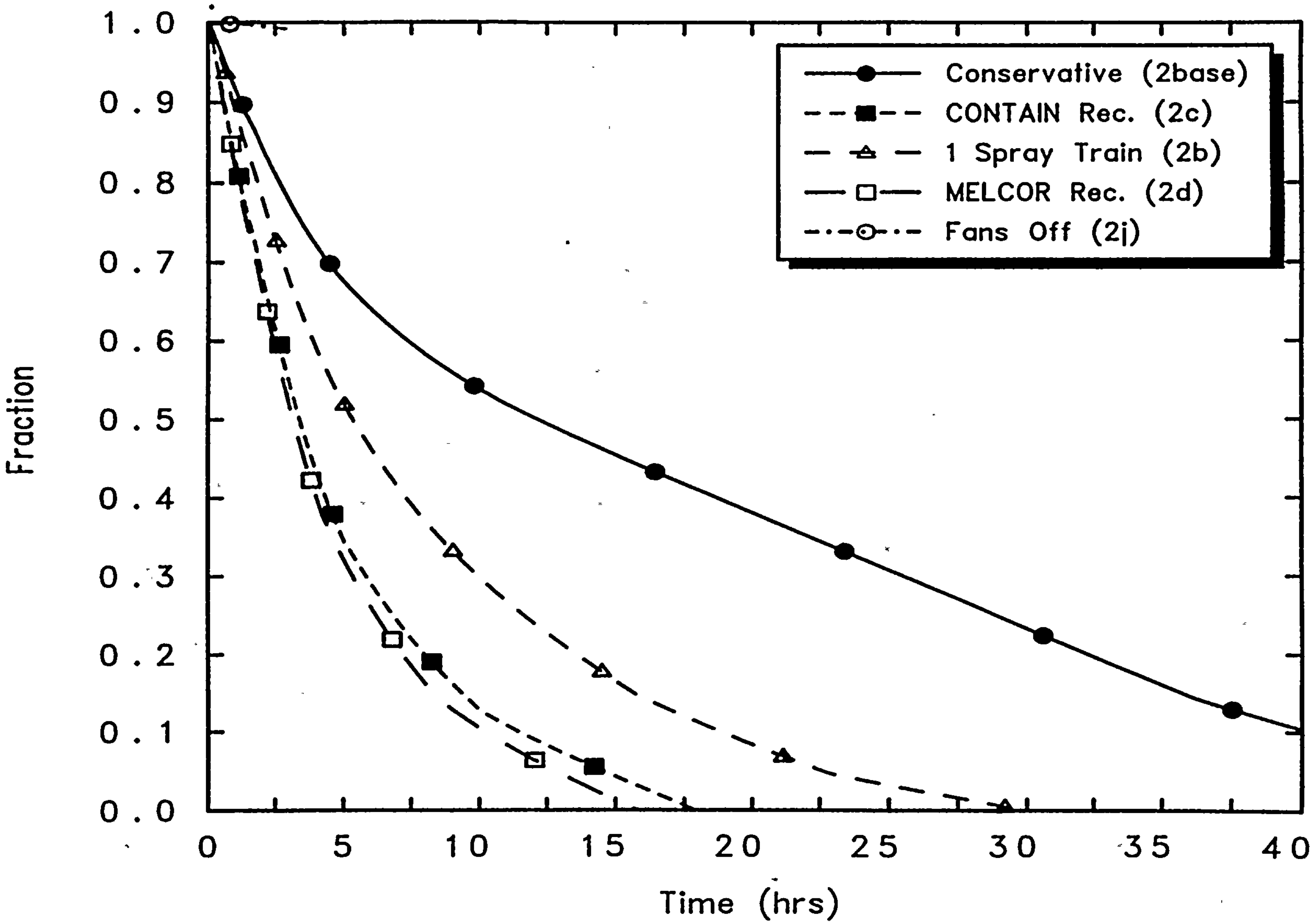

Figure 16: Fractions of Ice Remaining (2-inch)

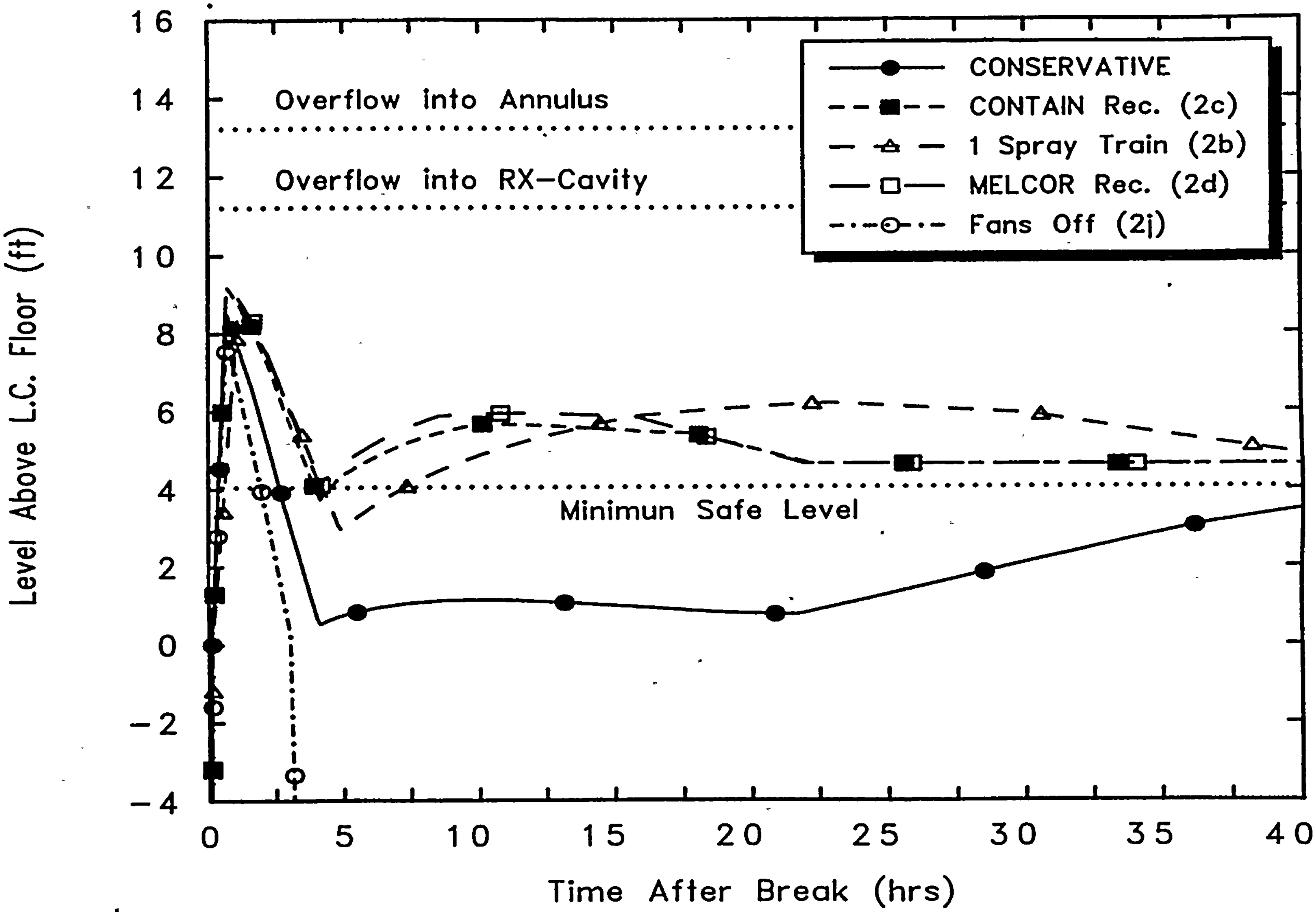

Figure 17: 2-inch LOCA Water Levels (Comparison)

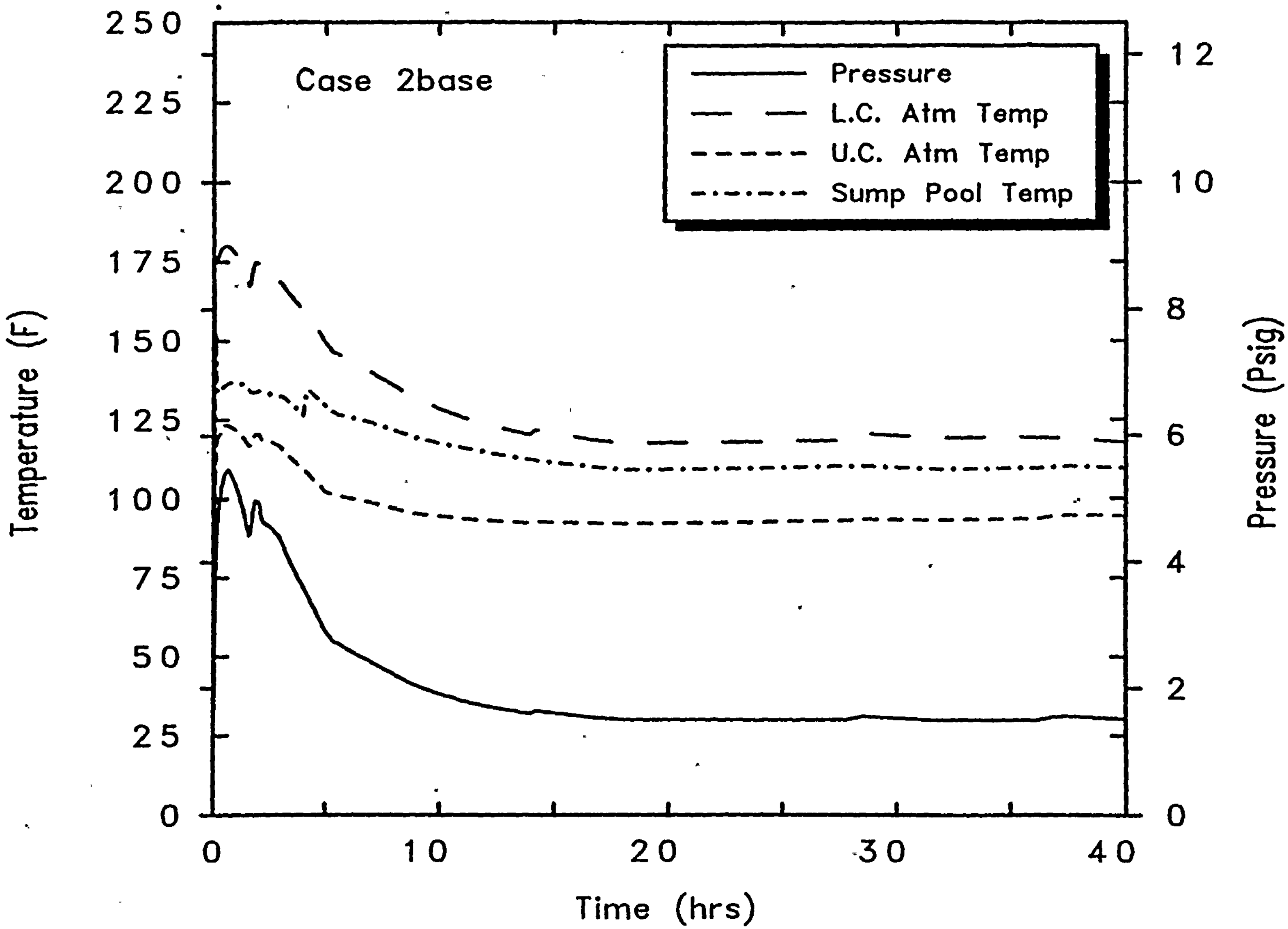

Figure 18: Compartment Responce to 2-inch LOCA

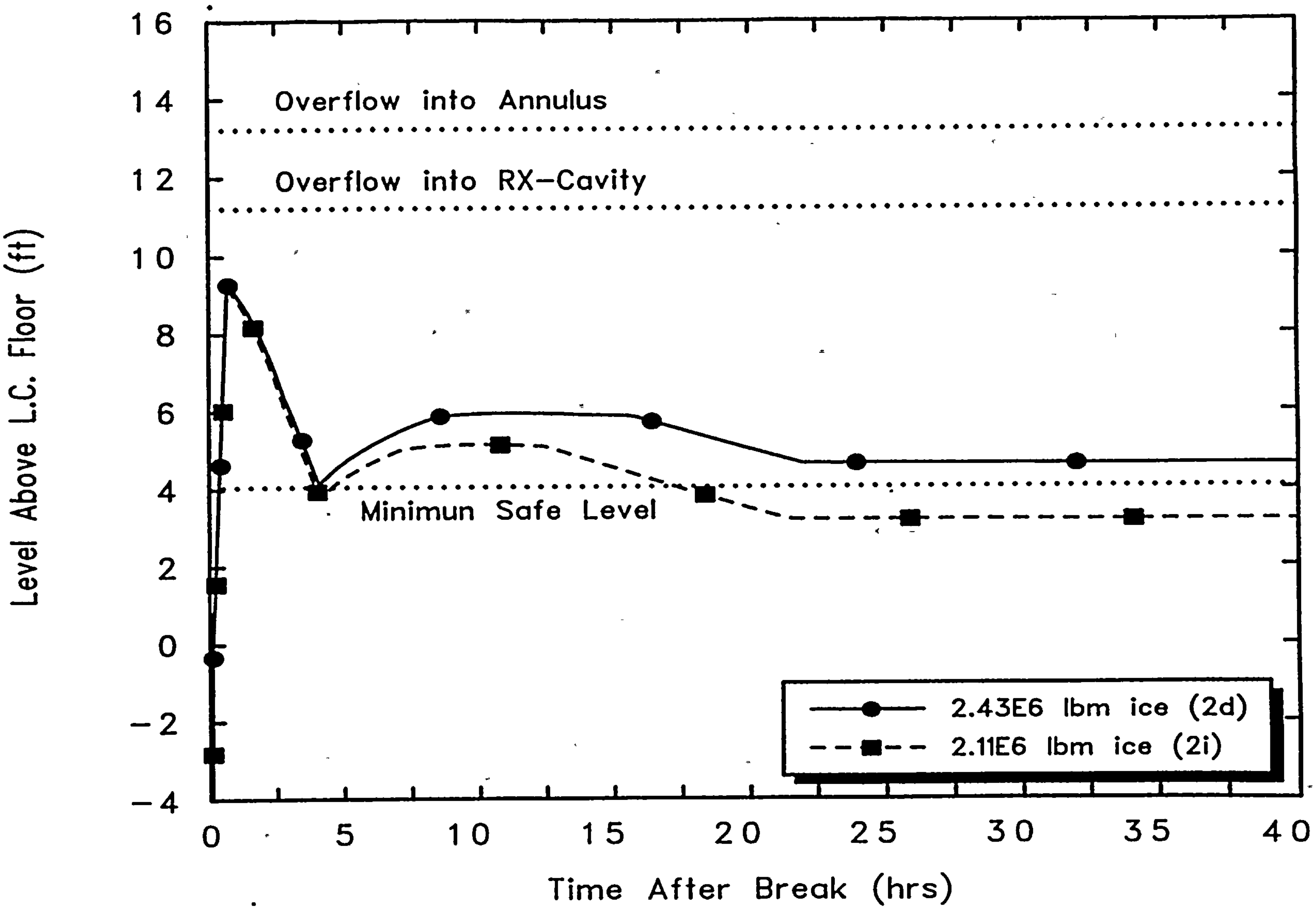

Figure 19: Compare Varition in Ice Mass (2-inch)

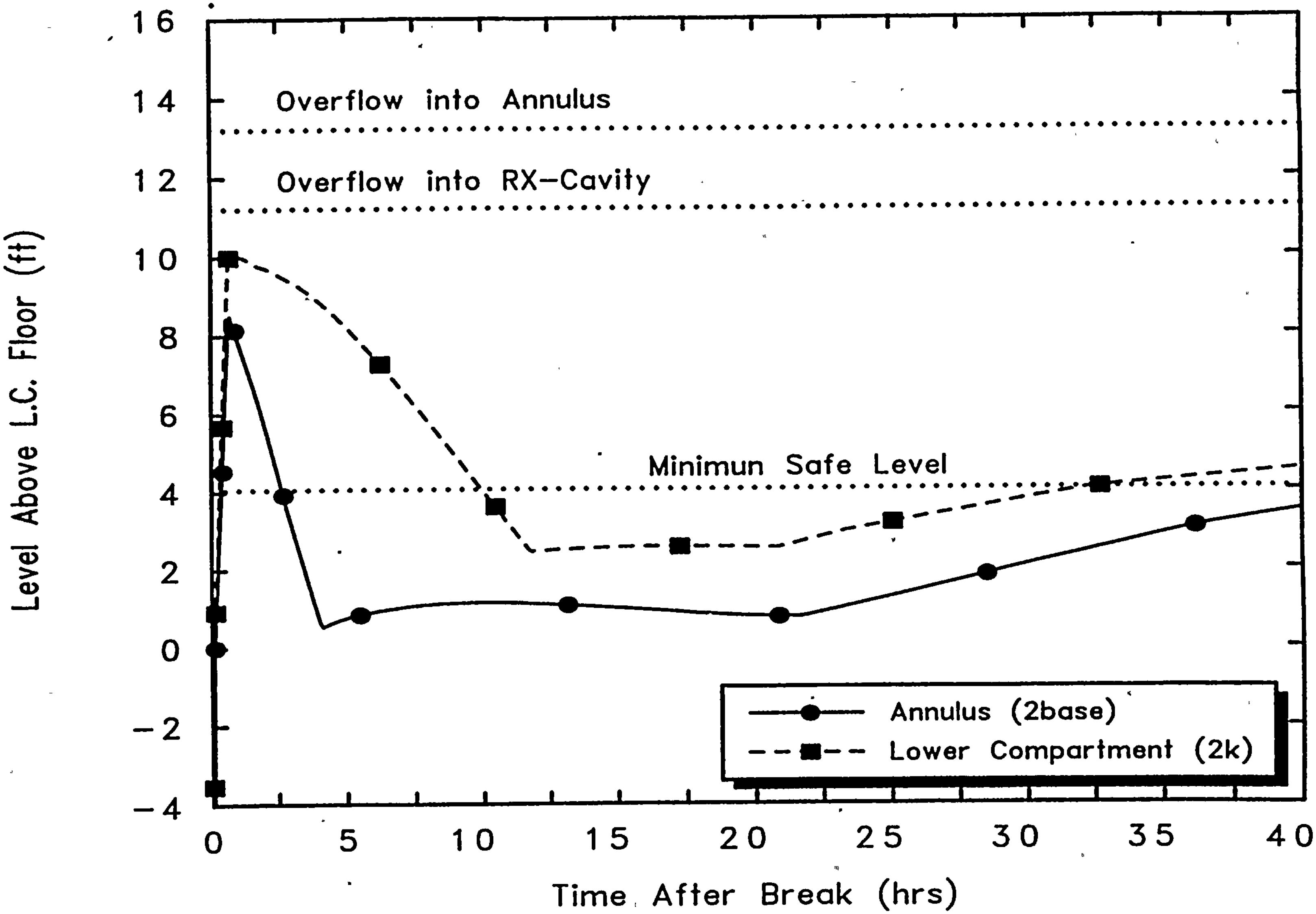

Figure 20: Compare Varition in Break Location

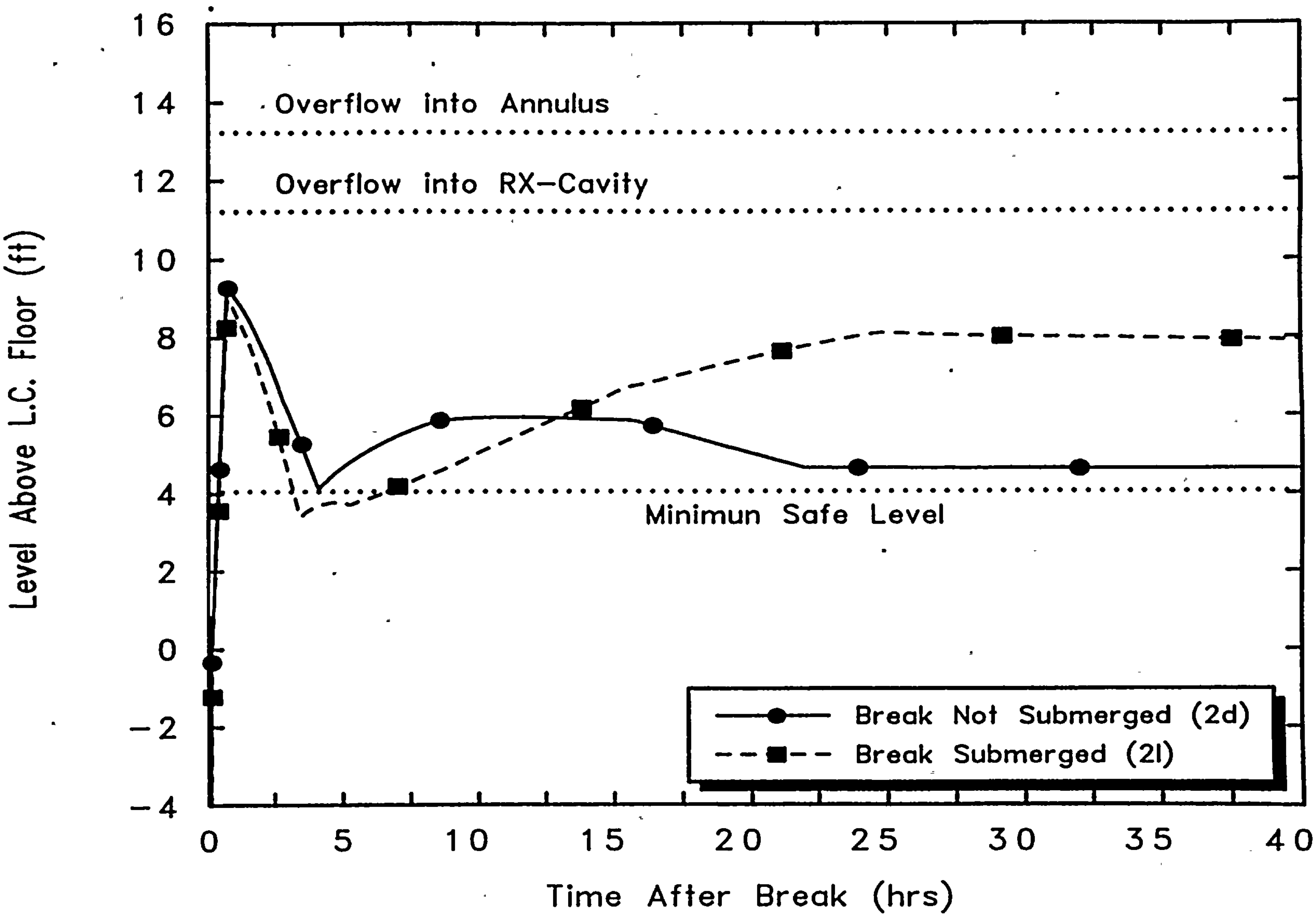

Figure 21: Effect of Break Submergence

Tables 12 and 13 for the radial and linear models, respectively. The two models behaved quite differently given the same Nusselt multiplier. Note again that Case 2d was run with the MELCOR recommended ice melt parameters and that Case 2c was run with the CONTAIN recommended parameters. For the radial model, a multiplier of 1.2 was adequate to keep the water level above the minimum safe level and therefore increasing the multiplier simply improved the situation. In fact, the lowest sump levels in Cases 2e and 2f were the long-term levels after all the dead-ended spaces were filled. Given the linear ice slump model, any multiplier less than the recommended 5.0 number would result in the sump level dropping below the safe level.

Table 12: Impact of Nusselt Multiplier Using Radial Melt Model

Case	Nusselt Multiplier	Minimum 40 Hr Level (ft)	Ice Melt Time (hr)
2d	1.2	0.07	15.7
2e	2.4	0.58	10.7
2f	3.6	0.58	9.0

Table 13: Impact of Nusselt Multiplier Using Linear Melt Model

Case	Nusselt Multiplier	Minimum 40 Hr Level (ft)	Ice Melt Time (hr)
2base	1.2	-3.51	> 40
2g	2.4	-2.00	31.3
2h	3.6	-1.04	22.8
2c	5.0	0.30	17.9

7.0 FINDINGS

The findings of these analyses are:

- The request to increase Technical Specification total ice to 2.43 million pounds is needed to ensure adequate sump water even if all the ice melts should all of the dead-ended spaces fill with water.

- The 6-inch break scenarios all showed a containment water level well above the minimum safe level, even in the calculation that assumed the most conservative ice melt parameters.

- When the 2-inch calculations were run using the conservative ice melt parameters, the water level dipped well below the minimum safe level. The lowest level was 3 feet below the safe level but when the calculations were run using either the MELCOR or the CONTAIN recommended ice melt parameters (i.e., realistic parameters), the containment water level remained above the safe level. Thus, the results of the 2-inch break calculations are not as conservative as the results for the 6-inch break. However, this may not pose a serious threat to ECCS operability because:

    1. The minimum safe level (approximately 7-foot above the suction elevation) was established to eliminate concerns regarding vortexing and air-ingestion corresponding to ECCS design flow rate of 15,600 GPM. Following a 2-inch break, the total ECCS flow rate is less than 8000 GPM. As a result of this reduced flow rate, potential for air ingestion due to lower water level is found to be very low.

    2. The calculations are based on very conservative set of assumptions regarding ice melt models and operator response. The more realistic assumptions minimize the likelihood of water level being lower than the safe level.

These findings were dependent upon information provided to SEA that SEA was not able to independently verify. First, these analyses used geometrical data supplied by the utility. Secondly, and probably more importantly, these analyses used break source terms and containment spray temperatures calculated by the MAAP4 code which could not be verified because the RCS and ECCS were not modeled with MELCOR. The concern here is that only two types of breaks were modeled and only one RCS response for each of these breaks was modeled. Analyses show that given certain break conditions, the ice likely will not melt completely until late in the scenario. If the containment sprays continue to operate, thereby filling all the dead-ended space with water without the ice completely melting, then there would be insufficient water in the sump for pumping. SEA has confirmed sufficient water given the two break source terms provided to SEA but was unable to confirm whether or not an alternative break or RCS response to that break might keep the containment pressure high while not melting the ice.

The systems responses used in these analyses were consistent with FSAR data and the EOPs, i.e., that the sprays would start on a high pressure of 2.9 psig and be turned off on a low pressure of 1.5 psig and that the recirculation fans would operate continuously. The importance of turning off the sprays as soon as possible and keeping the recirculation fans operating until all ice has melted has been shown.

A question that was not addressed further related to differences between the MELCOR and the MAAP4 ice melt models. Note that SEA did not have access to MAAP4 code manuals describing the MAAP4 models. Further note that the MAAP4 models were validated using data from a Westinghouse ice condenser experiment that was also not available to SEA while the MELCOR models were validated using data from the PNL experiments. Thus, two separate independent codes validated against two separate experiments, but showing somewhat different results, i.e.,

the MAAP4 6-inch break ice melt (Case Bench) was on the order of the MELCOR conservative parameter ice melt rates rather than with the MELCOR recommended ice melt parameters. Was this because the MAAP4 analyses assumed conservative ice model parameters or was it due to differences in the experimental data?

In conclusion, the worst case scenario was determined to be a small break in the annular compartment, where break effluence would tend to fill this dead-ended volume, with both containment spray trains operating continuously. Using ice melt modeling parameters that successfully simulated the PNL ice condenser experiments, and were subsequently recommended by the MELCOR and CONTAIN code development staffs, the sump water level was found to remain above the minimum safe water level.