2.6 Argonne 1/40 Liner Scale DCH Experiments for a Zion-Like Containment

Table 2-6 (Reference 19) lists the initial conditions for the various experiments performed as part of the Argonne test program. As indicated by this table, the tests varied the materials used to represent the molten core debris, the reactor coolant system pressure at the time of vessel failure, the initial containment pressure, the initial containment temperature, and most importantly the conditions within the containment atmosphere. Specifically, tests were performed where the atmosphere was inerted with nitrogen, inerted with steam, and experiments were also run with an atmosphere supporting combustion.

Figure 2-7 illustrates the technique used to represent the Zion reactor vessel lower head, reactor cavity, the instrument tunnel and the exit into the steam generator compartment. As illustrated by this figure, also taken from reference 19, the length of the instrument tunnel is somewhat distorted as a result of this experimental configuration. This is not viewed as a substantial shortcoming of the experiment, and if anything, enables more entrainment to take place in the instrument tunnel; therefore it is a potential conservatism in the experimental configuration. It is to be noted that this particular aspect was also part of the Sandia 1/10 linear scale test as will be discussed later. Figure 2-8 illustrates the compartmentalization used for the Zion subcompartment model. Particularly, note the location of the "cavity exit", which is the exit of the instrument tunnel into steam generator compartment. With the substantial compartmentalization provided by the seal table room and the concrete walls defining the steam generator compartment, including the cylindrical wall supporting the crane, there is large amount of structure obstructing the flow path of core debris as it would exit the instrument tunnel and flow towards the major open volumes of the containment. Consequently, this structure, as noted by the numerous experiments discussed above, could separate the core debris from the flowing gaseous medium, deposit this material to a large extent within the steam generator compartment and result in localized high temperatures within the containment (in the steam generator compartment), but with minimal pressurization of the containment atmosphere. As will be discussed, this is the focus of the MAAP model and the Sandia two cell equilibrium model (TCE), which has been used to correlate the numerous experiments as well as to extrapolate to nuclear power plant conditions.

Figure 2-9 and Figure 2-10 illustrate the major result of these experiments, i.e. the containment pressure increase resulting from the HPME is typically between 1.5 to 2.5 bars depending upon the specific conditions. Also, as illustrated in Figure 2-10, the pressure increases resulting from using uranium thermite (Tests U1A, U1B and U2) are less than or equal to those resulting from iron thermite. Table 2-7 summarizes the test results from the ANL experiments and clearly illustrates that while substantial fractions of the molten material were swept out of the cavity (sweepout fraction), the maximum pressure increases in the containment for all the experiments lie well within the capabilities of a large dry containment such as Zion.

The 1/40 scale experimental program paid substantial attention to the details of linearly scaling the containment geometry for a Zion-like system. They showed that the subcompartment structures effectively trapped the molten debris and that there was only limited energy transfer with the containment atmosphere. Furthermore, experiments with uranium dioxide thermite showed that there was very little influence of real materials on the results.

Table 2-6 Experimental Initial Conditions

	IET-1RR	IET-3	IET-6	IET-7	IET-8	U1A	U1B	U2
Melt	Fe/Al_2O_3	Fe/Al_2O_3	Fe/Al_2O_3	Fe/Al_2O_3	Fe/Al_2O_3	Corium	Corium	Corium
Mass, kg	0.82	0.82	0.71	0.71	0.71	1.13	1.13	1.13
D_H	1.3	1.1	1.1	1.1	1.1	1.1	1.1	1.1
$P_{RCS,0}$, MPa	6.7	5.7	6.6	6.1	6.5	3.0	6.0	4.3
N_B, g-moles	9.84	8.43	9.65	8.88	9.36	4.18	8.87	5.89
$P_{c,0}$, MPa	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2
$T_{c,0}$, K	318	315	310	310	473	300	300	301
Atm., mol%								
H_2	0.0	0.0	2.0	0.0	3.9	0.0	0.0	2.6
O_2	0.1	10.8	9.9	10.1	7.7	0.6	0.5	11.6
Steam	0.0	0.0	0.0	0.0	49.0	0.0	0.0	0.0
N_2	99.9	88.8	87.5	89.4	37.4	99.0	99.0	84.6

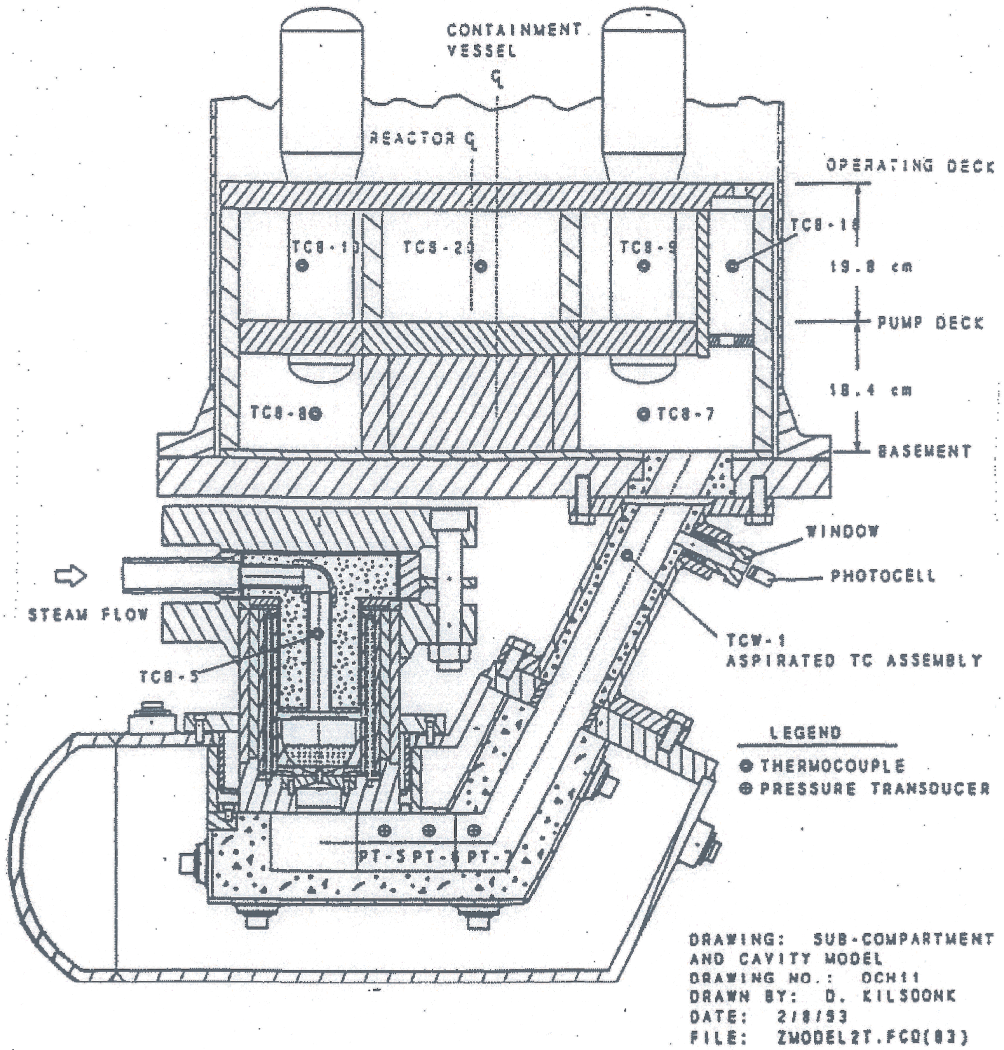

Figure 2-7 Cross-sectional view of Zion subcompartment and cavity model

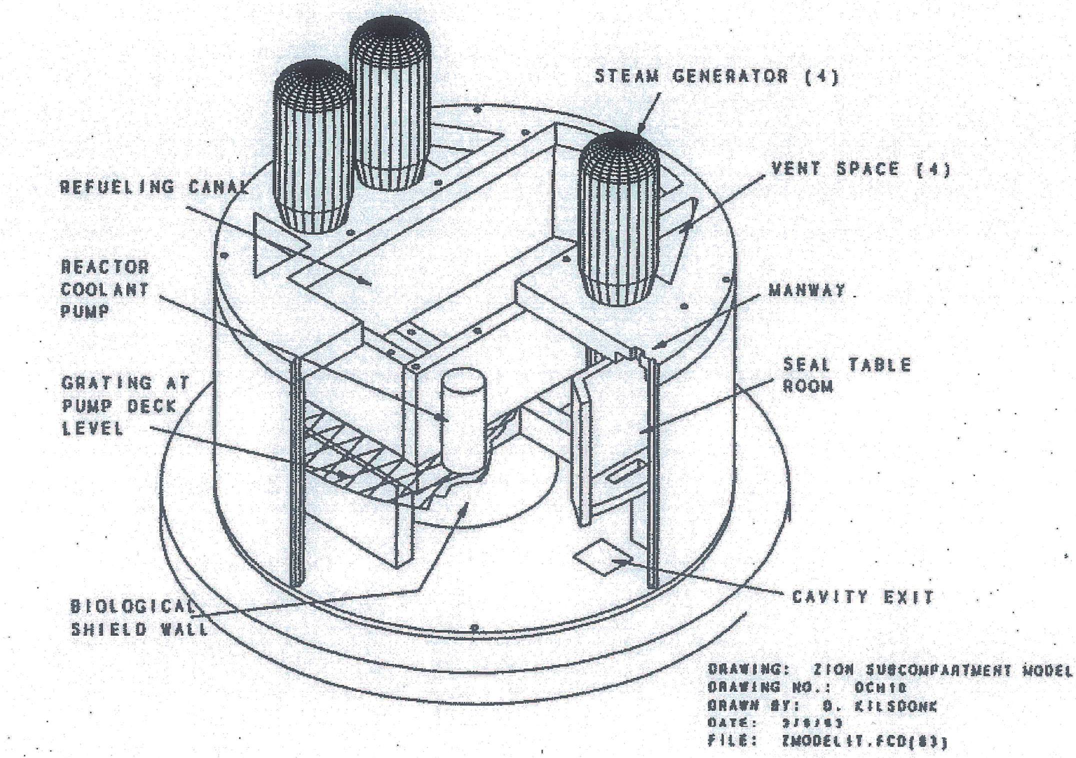

Figure 2-8 Three-dimensional view of the Zion subcompartment model

Table 2-7 Summary of Test Results

	IET-1RR	IET-3	IET-6	IET-7	IET-8	U1A	U1B	U2
Driving Pressure, $P_{RCS,0}$, MPa	6.7	5.7	6.6	6.1	6.5	3.0	6.0	4.3
Blowdown Steam, g-moles	9.84	8.43	9.65	8.88	9.36	4.18	8.87	5.89
Melt Mass, kg	0.79	0.75	0.71	0.69	0.70	1.130	1.130	1.130
Initial Cont. Pressure, $P_{CONT,0}$, MPa	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
Blowdown Time Constant, τ_s, secs	0.23	0.41	0.28	0.32	0.33	0.38	0.54	0.49
Initial Containment Atmosphere Composition, mole%								
H_2	0.0	0.0	2.0	0.0	3.9	0.0	0.0	2.6
O_2	0.1	10.8	9.9	10.1	7.7	0.6	0.5	11.6
Steam	0.0	0.0	0.0	0.0	49.0	0.0	0.0	0.0
N_2	99.9	88.8	87.5	89.4	37.4	99.0	99.0	84.6
$\Delta P_{MAX,CAVITY}$, kPa	550	200	480	430	290	90	400	185
$\Delta P_{MAX,Cont}$, kPa	150	190	250	166	133	45	111	185
Sweepout Fraction	0.705	0.735	0.691	0.793	0.766	0.190	0.795	0.295
H_2 Pre-existing, g-moles	0	0	2.3	0	3.0	0	0	3.1
H_2 Produced, g-moles	4.1	4.7	4.9	5.2	5.2	5.0	6.0	6.0
O_2 Depleted, g-moles	~0	1.8	2.1	1.8	0.4	~0	~0	3.0

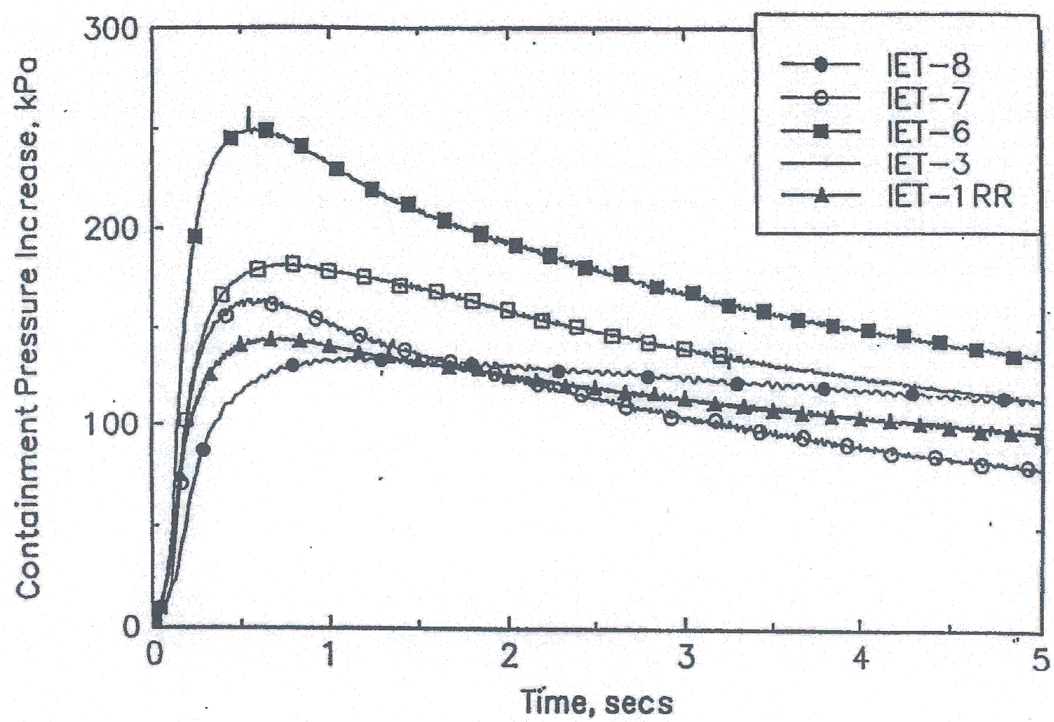

Figure 2-9 Containment loads obtained in the IET tests

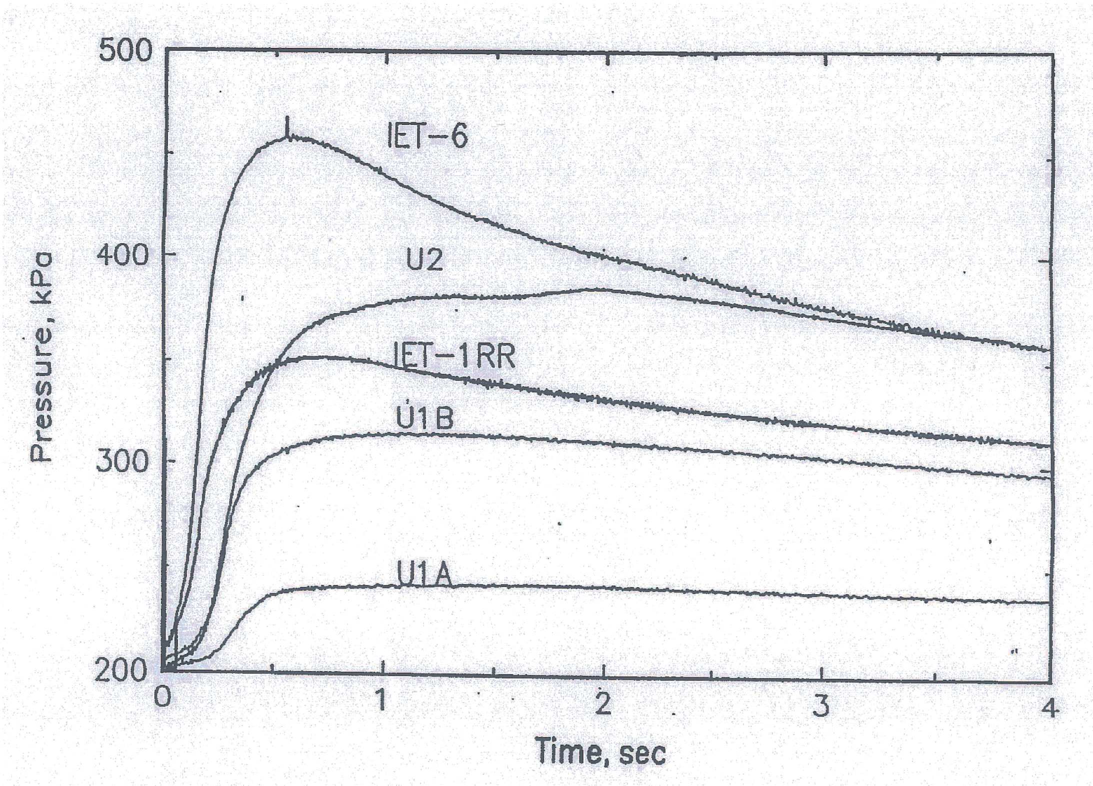

Figure 2-10 Containment loads obtained in the corium experiments

2.7 Sandia 1/10 Scale DCH Experiments for a Zion-Like Containment

To experimentally address the scaling issues, the 1/40 scale Argonne test had counterpart tests performed at 1/10 scale in the Sandia Surtsey facility. These experiments are documented in reference 15, 20, 21, 22, 23, 24, 25, 26 and summarized in reference 27. The Surtsey facility is a large vessel that can simulate a large dry containment at a 1/10 linear scale.

Figure 2-11 shows the Surtsey facility configuration with a Zion-like reactor cavity configuration added outside of the Surtsey vessel. Also, this figure shows the steam driven accumulator used to pressurize the simulated RPV lower head to cause the melt dispersion. This figure was taken from reference 27 and presents a general characterization of the significant scale used in this counterpart test series. Figure 2-12 and Figure 2-13 are taken from the same reference and show the details of the simulation for the Zion-like reactor cavity and instrument tunnel, as well as the containment structures in the steam generator compartment room illustrated in Figure 2-13. As was noted for the 1/40 scale ANL test, the reader should take note of the exit of the instrument tunnel noted by No.7 in Figure 2-13, and the large amount of structure that could separate melt from the blowdown gases, thereby limiting the melt dispersion to this compartment. If this is the case, only the gases within this compartment are substantially heated to temperatures approaching the melt temperature, meaning only a limited extent of pressurization as a result of HPME. Furthermore, note in Figure 2-12 that the ex-Surtsey location of the reactor cavity results in a somewhat longer instrument tunnel than is typical of the reactor system. This does not provide any substantial shortcoming of the experiment, and if anything represents a conservatism in the experimental configuration since more entrainment would likely occur as the melt moves upward through this tunnel in the presence of high velocity gases.

The initial conditions for the SNL counterpart tests at 1/10 scale are given in Table 2-8, also taken from reference 27. As is illustrated by this table, the conditions of RCS pressure, containment temperature and containment gas compositions follow similar variations to those for the Argonne tests. In particular, the containment conditions included atmospheres inerted by nitrogen (IET-I), steam, carbon dioxide as a simulant for steam (IET-5) and atmospheres where combustion of hydrogen generated during the blowdown, as well as pre-existing hydrogen, could occur. With these various atmospheric conditions, the experiments investigated a broad range of accident conditions, including a range of clad oxidation fractions with subsequent release to the containment atmosphere. It should also be noted, in this regard, that the thermite used in these experiments had a significant amount of chromium added to represent molten zirconium that could be ejected with the melt and which had not been oxidized as part of the core degradation. This very active metal (chromium) tended to be oxidized by the steam blowdown and provide hydrogen at very high temperatures that could burn (recombine) as it enters the atmosphere where oxygen was present. It is to be noted that later experiments deleted this chromium component since integral code calculations for the core melt progression and slumping to the RPV lower head have shown little, if any, unreacted metals in the molten core debris if the reactor vessel were to fail under pressure. Therefore, the inclusion of chromium in these experiments was an additional conservatism (tending to provide higher pressures in Surtsey than would be the case in the actual containment) along with the minor conservatism represented by the longer instrument tunnel.

Table 2-8 Initial Conditions for the IET Experiments

		IET-1	IET-1R	IET-3	IET-4	IET-5	IET-6	IET-7	IET-8A	IET-8B
Date performed		9/13/91	2/7/92	12/13/91	3/20/92	5/13/92	6/18/92	7/9/92	7/30/92	8/26/92
Steam pressure (MPa)		7.1	6.3	6.1	6.7	6.0	6.3	5.9	1.06	6.2
Steam temperature (K)		600	585	585	555	586	571	599	421	554
Steam driving gas (g•moles)		468	507	485	582	453	505	416	4.1 (N_2)	545
Cavity water (kg)		3.48	3.48	3.48	3.48	3.48	3.48	3.48	62.0	62.0
Basement water (kg)		0	0	0	71.1	71.1	0	71.1	71.1	71.1
Surtsey pressure (MPa)		0.200	0.197	0.189	0.200	0.205	0.199	0.200	0.200	0.203
Surtsey temperature (K)		295	275	280	295.0	302	308	303	304	298
Surtsey gas moles (g•moles)		7323	7737	7291	7323	7318	6961	7129	7105	7360
Initial gas composition in Surtsey (mol.%)	N_2	99.90	99.78	90.60	90.00	16.90	87.10	85.95	85.32	85.80
	O_2	0.03	0.19	9.00	9.59	4.35	9.79	9.57	9.85	9.79
	H_2	0.00	0.02	0.00	0.00	2.76	2.59	3.97	4.33	3.91
	CO_2	0.01	0.00	0.02	0.02	75.80	0.00	0.03	0.03	0.03
	Other	0.06	0.01	0.38	0.39	0.19	0.52	0.48	0.47	0.47
Initial hole diameter (cm)		3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Final hole diameter (cm)		4.04	4.02	4.53	4.22	4.31	3.91	4.08	3.50	4.10
Plug in STR ceiling		Yes*	No	Yes	No	No	No	No	No	No
Thermite composition										
iron oxide (kg)		29.26								
chromium (kg)		4.65								
aluminum (kg)		9.09								
Thermite charge (kg)		43.00								
Freeboard volume inside subcompartment structures		4.65 m^3								
Freeboard volume in Surtsey dome		85.25 m^3								
Total freeboard volume		89.8 m^3								

* The concrete plug in the ceiling of the seal table room was forcibly ejected by the thermite/water interaction in the cavity.

The results for the Zion-like experiments are plotted in Figure 2-14 and Figure 2-15, illustrating the containment pressurization in inerted and non-inerted atmospheres, respectively. In an inerted atmosphere, the pressure increase is approximately 1 bar, and in a non-inerted atmosphere, including the potential for burning of combustible gases as they are produced, as well as pre-existing hydrogen, the pressure increase is 2.8 bars. Both of these illustrate that the pressure increase resulting from a high pressure melt ejection in a geometry representing the internal structure of a containment is limited to values far below those which would challenge the containment integrity. Furthermore, these results are quite close to the pressure increase observed in the Argonne 1/40 scale experiments, hence, the counterpart experiments performed at Argonne and Sandia at two different scales have illustrated that linear scaling is the appropriate approach for performing these experiments. Furthermore, this is also the appropriate approach for extrapolating to the reactor system. Specifically, the pressure increases observed in the Argonne and Sandia experiments would be expected to be the same in the reactor case given this type of accident sequence. As indicated above, the accident sequences envisioned and the experimental configurations, if anything, provide a worst case scenario for reactor systems.

Figure 2-16 shows a comparison of the predicted pressurization efficiencies versus the predicted pressurization efficiencies for a wide range of experiments and many different scales using the two cell equilibrium model (TCE). This approach is summarized later on, but is used here to illustrate the fact that these results, at many different scales, show quite good agreement in terms of the potential containment pressurization. Also, when a linear scale is used, the predicted pressure increases are, for all practical purposes, identical. This provided a substantial point for resolving this issue with respect to nuclear power plants, both experimentally and analytically.

The major conclusions for this counterpart set of experiments were that:

1. Approximately 77% of the melt released from the RPV was dispersed into the Surtsey vessel.

2. Of the material dispersed into the Surtsey vessel, typically 10% was found outside of the steam generator compartment. The remainder of the material was separated from the gas flow stream and deposited within the steam generator compartment.

3. The hydrogen produced by oxidation of the chromium during the blowdown process was burned during the HPME and contributes significantly to the measured pressurization. In particular, this caused an additional 1.5 bar increase over the inerted experiments. However, pre-existing hydrogen did not appear to burn on a timescale that had a significant influence on the peak vessel pressure.

4. All of the counterpart tests resulted in containment pressure increases far below those providing a challenge to containment integrity.

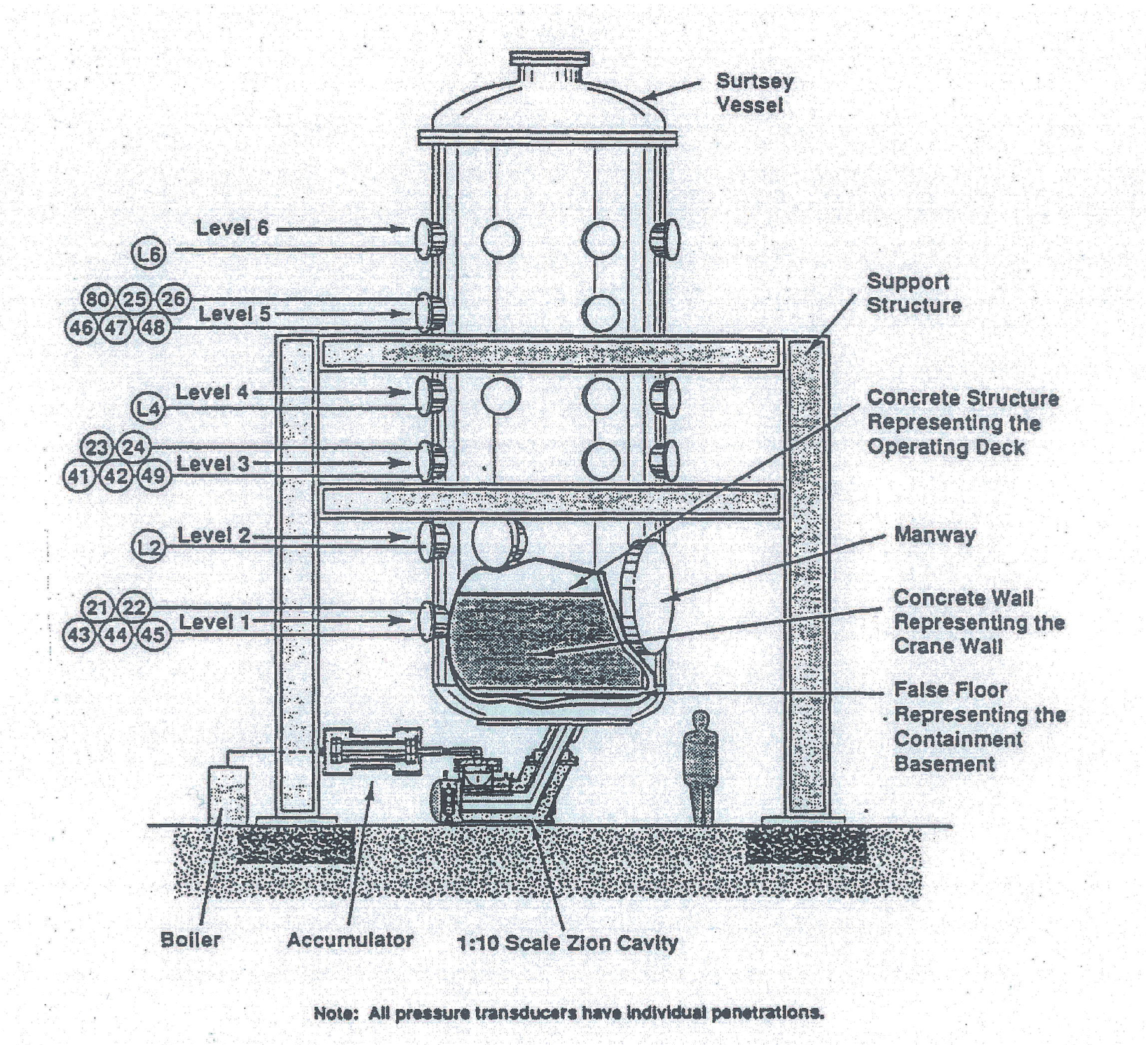

Figure 2-11 Surtsey vessel, high-pressure melt ejection system, and subcompartment structures used in the 1/10 scale IET experiments

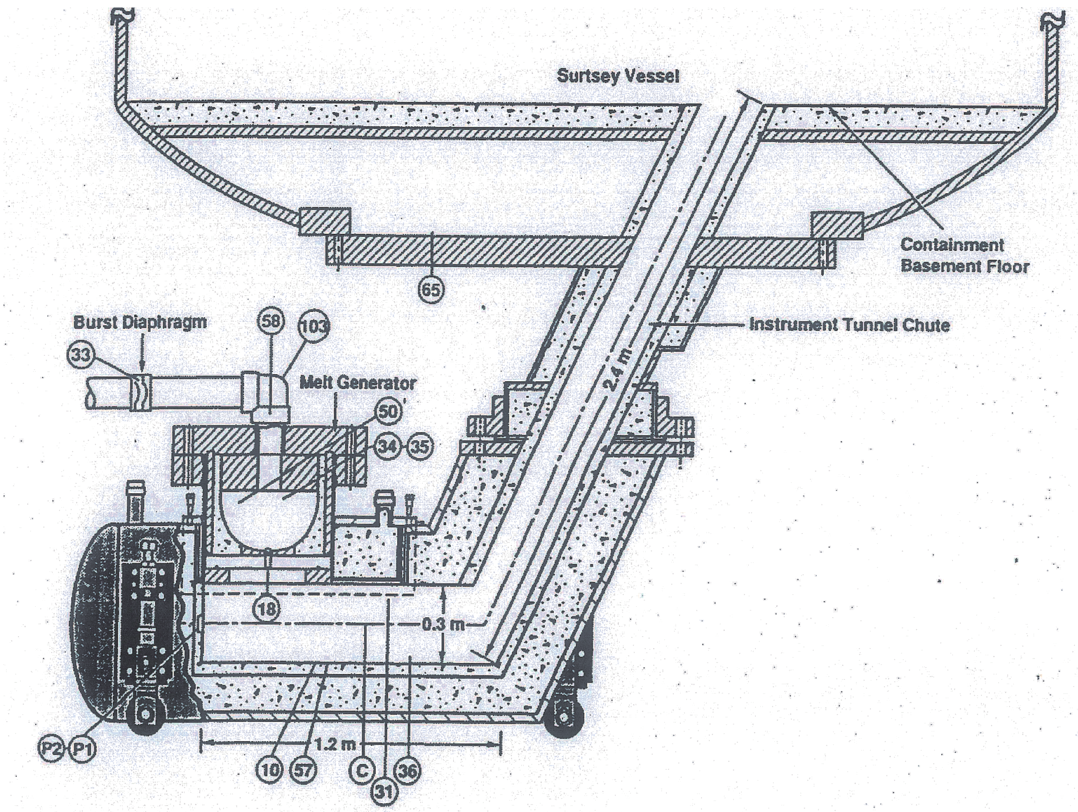

Figure 2-12 Schematic of the 1:10 linear scale model of the Zion reactor Cavity