ANALYSES OF CONDITIONS IN A LARGE, DRY PWR CONTAINMENT DURING A TMLB' ACCIDENT SEQUENCE

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ABSTRACT

The aim of the paper is to give an assessment of the conditions which would develop in the large, dry containment of a modern Westinghouse-type PWR during a severe accident where all safety systems are unavailable. The analysis is based principally on the results of calculations using the CONTAIN code, with a 4 cell model of the containment, for a station blackout (TMLB') scenario in which the vessel is assumed to fail at high pressure.

The first challenge to the containment results from the direct containment heating (DCH) event following vessel failure. This was studied using a special version of CONTAIN 1.11, which includes the CORDE module, developed by AEA Technology to model high pressure melt ejection from the cavity. These calculations predict pressures significantly below the peak assumed containment failure pressure (0.99 MPa), even if DCH is accompanied by a rapid burn of most of the hydrogen present in the containment. The calculated DCH pressure was very insensitive to the presence of modest quantities of water (up to ~ 100 te) in the cavity, although larger quantities led to a significant reduction in the peak pressure.

The analysis has been continued to investigate the containment conditions over the following two days of the accident. Although the calculations are based on a station blackout with vessel failure at high pressure, a range of sensitivity studies has allowed quite general conclusions to be drawn about the long term behaviour in the containment. In particular, the following are noted.

(i) If much of the debris is in contact with water, so that decay heat can boil water directly, then the pressure rises steadily to reach the assumed containment failure point after 1½ to 2 days. If most of the debris becomes isolated from water, for example, because of water is held up on the containment floors and in sumps and drains, the pressure rises too slowly to threaten the containment on this timescale.

(ii) If a core-concrete interaction occurs, most of the associated fission product release takes place soon after relocation of molten fuel to the containment. The aerosols which transport these (and other non-gaseous fission products released earlier in the accident) in the containment agglomerate and settle. As a result, 0.1% or less of the aerosols remain airborne a day after the start of the accident.

(iii) Hydrogen and carbon monoxide, which would accumulate in the containment are not expected to burn because the atmosphere would be inerted by steam. If, however, enough of the steam is condensed, for example, by recovering the containment sprays, a burn could occur but the resulting pressure spike is unlikely to threaten the containment unless a transition to detonation occurs.

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1. INTRODUCTION

This paper summarises the results of calculations of the conditions in the containment of a large, Westinghouse-type PWR during a TMLB' accident sequence. The objective of the work, which has been carried out by AEA Technology, was to provide support, using mechanistic methods, to the development of the safety case and accident management guidance for a reference UK PWR design. These calculations complement the primary circuit accident analysis described in Reference [1].

The nature of the threat to the containment in the TMLB' accident depends on whether:

(a) the primary circuit remains intact and at high pressure up to lower head failure,

or (b) the primary circuit fails due to creep failure of a vulnerable primary circuit component (eg surge line or hot leg), resulting in a primary circuit depressurisation.

The present study is primarily concerned with the first scenario, where vessel failure at high pressure may lead to high pressure melt ejection (HPME), direct containment heating (DCH) and a potential early threat to the containment integrity. Calculations of the DCH pressures are described in Section 3. Section 4 goes on to describe calculations of the long-term (up to about 2 days) pressure rise in the containment; Section 5 discusses the potential threat to the containment from a hydrogen burn, if the containment atmosphere was de-inerted by recovery of the sprays; and in Section 6, an assessment of the long-term airborne fission product inventory described. Finally, the main conclusions are presented in Section 7; some of the conclusions are relevant to both high pressure and low pressure TMLB' scenarios.

2. CODE VERSION, MODELS AND ASSUMPTIONS

The calculations have employed the CONTAIN code (Version 1.11(UK)). This version is based on the official release version of CONTAIN 1.11 [2] but includes some modifications: in particular, the CORDE code [3] has been included as a module to calculate the source of dispersed debris to the containment during DCH. The containment was represented using a 4-cell model which is illustrated in Figure 1. The 4 cells represent the cavity, the lower inner containment, the lower annular compartments and the upper containment. The large upper containment which makes up over 75% of the free volume in the containment, has a volume of 67000 m^3. The numerous structures and walls in the containment building are modelled using a set of generic structures with appropriate surface areas, thicknesses, masses, composition and orientation.

The accident conditions are based on a SCDAP/RELAP5 calculation for a TMLB' scenario where it was assumed conservatively that the vessel remained at high pressure until lower head failure occurred. In practice, it is considered more likely that natural circulation of hot gases within the primary circuit when the core overheats would lead to early depressurisation of the primary circuit, probably as a result of hot-leg or surge line failure.

The SCDAP/RELAP5 calculations, both with and without early vessel failure, have been described in Reference [1]. The timings of major events during the accident scenario are listed in Table 1. The SCDAP/RELAP5 calculation indicates that the pilot operated safety relief valves (POSRVs) will open for the first time at around 4000 s after reactor trip. The prediction of the flows from the POSRVs then provide sources of steam, water and hydrogen to the CONTAIN model until the SCDAP/RELAP5 calculation ends, when a blockage forms in the core.

The late-phase in-vessel melt progression were extrapolated from the SCDAP end-state using engineering judgement and calculations, which provided sources of steam and hydrogen to the containment. Based on the extrapolated conditions at vessel failure, it was assumed that about 60% of the core debris took part in the HPME and DCH, after 12300 s. The remaining core material was assumed to slump into the cavity after 13000 s. The CORCON module in CONTAIN was then used to calculate the behaviour of the debris in the containment until the end of the calculations, after 200000 s.

3. DIRECT CONTAINMENT HEATING CALCULATIONS

3.1 "Dry Cavity" Results

An assessment of the containment conditions indicated that very little water would be present in the cavity when the vessel failed. The first calculations therefore assumed a nominal amount (100 kg) of water in the cavity. The presence of water in the cavity cannot be ruled out however, and the effect it would have is discussed in Section 3.

The containment pressure response for the base case calculations is illustrated in Figure 2 while the peak calculated pressure is listed in Table 2, together with the results of a number of sensitivity cases.

The sources of steam and hydrogen prior to DCH increase the containment pressure to 0.19 MPa. Figure 2 shows that the pressure in the cavity reaches a peak of 1.4 MPa about 2 s after vessel failure. This is shortly after gas blow-through at 1.4 s. As the cavity vents, the pressure in the rest of the containment rises and eventually reaches a peak value of 0.763 MPa after 9 s, at the end of a 5 s hydrogen burn, which DCH is assumed to trigger.

Figure 3 shows the cell gas temperatures. Cell 2, immediately downstream from the cavity, gets very hot but this has a modest impact on the overall containment pressure because of the relatively small volume of the cell. This is an important mitigating effect because 56% of the debris remains in cell 2 and the other small cells (1 and 3) and this debris only interacts with a small fraction of the containment atmosphere as a whole.

Over 95% of the free metal (Fe and Zr) which remains in the melt is oxidised during DCH. Over 70% of the oxidation results from steam reactions because the lower compartments soon become relatively starved of oxygen. This effect is mitigative because the reaction with steam is less exotermic than that with oxygen. However, the hydrogen produced may burn later.

The sensitivity results in Table 1 show the importance of simultaneous hydrogen burning during DCH. Without a hydrogen burn, a modest peak pressure of about 0.6 MPa is predicted. The cases with hydrogen burns yield significantly higher pressures, of the order of 0.8MPa but even these are well below the assumed containment failure pressure of 0.99MPa. The highest pressure is calculated when only one cell is used to represent the containment because the mitigating effects of compartmentalisation noted above are not modelled.

3.2 The Effect of Cavity Water on DCH

Table 2 summarises the peak containment pressure for DCH calculations with quantities of water ranging up to 200 te present in the cavity. The peak pressure in the containment is very slightly reduced from the dry cavity prediction of 0.76 MPa when modest quantities of water are present but falls significantly if more than 100 to 150 te of water are added. With the cavity half full of water (~ 240 te), the DCH pressure is 0.66 MPa.

The results illustrate that cavity water has a limited effect on DCH pressures because competing phenomena tend to cancel. Adding water tends to reduce the DCH pressure in the containment because thermal energy from the melt is used to boil water which thus tends to quench the melt. Furthermore, the steam which is generated oxidises some of the metal in the melt, at the expense of the more exothermic reaction with oxygen. However, the extra hydrogen which is produced may later burn and add to the pressure rise, while the steam which is generated when the debris is quenched increases the gas inventory of the containment atmosphere.

Furthermore, this extra, cold stream enables more heat to be removed from the debris while it is in the lower containment, before it is trapped or transported to the upper containment. This adds energy, which would otherwise be retained by the debris, to the containment atmosphere.

CONTAIN-DCH calculations for the Surry [4] and Ringhals reactors predict that modest amounts of cavity water actually lead to small increases in DCH pressure. Recent tests in the 1/10 seal Surtsey facility [5], which have used molten thermite to simulate DCH in a compartmentalised PWR geometry, are also of interest. In separate tests, with and without small quantities of water present in the cavity, but identical in other respects, no significant difference was detected in the peak containment pressure.

In contrast with the Surry and Ringhals results, none of the present base case calculations show any increase in containment pressure, compared with the dry cavity case, when water is added to the cavity. In the Ringhals and Surry containment models, the volume of the receiving cells were about 30% and 20% of the total containment respectively, compared with only 7% in the present model. The effect of cavity water is believed to depend on the containment compartmentalisation, so it is not surprising that different calculated trends are observed with different geometries.

To investigate this point, sensitivity calculations were run in which the volume of the receiving cell in the present model was increased from 7% to about 30% of the containment volume. The total containment volume was unchanged. The results (Table 2 "b" cases) now show a small increase in pressure when a modest amount of water (40 te) is added, indicating that there is no inconsistency with the earlier work.

4. LONG-TERM CONTAINMENT PRESSURE

4.1 Reference Calculation

The CONTAIN calculation described in the previous section was continued to study the long-term response of the containment after vessel failure and direct containment heating.

After the DCH calculation was completed at 12320 s, it was assumed that all the core debris in the containment formed layers on the floor of the lower compartments, beneath pools of water (the lower cells in the CONTAIN model). All the liquid water in the containment (except condensate on structures) is located in these pools in the present model. There was no provision in the reference case for water to be retained in sumps isolated from the core debris.

The debris which remained in cell 2 after DCH was added to the lower cell in cell 2. Cell 4, the upper containment, does not include a lower cell and the debris in cells 3 and 4 was added to the lower cell in cell 3, where a water pool can collect; all condensation from cell 4 overflows to the pool in cell 3. Debris which had remained in the core during DCH (but which was almost molten) was allowed to relocate into the cavity at 13000 s.

The debris added to the lower cells was assumed to comprise oxide alone. This is a good approximation for cells 2 and 3, since almost all the free metal was oxidised during DCH. The impact which residual metal in the melt and steel from ablated concrete could have on the hydrogen inventory in the containment is discussed in Section 5. The CORCON code, which is included as an integrated module in CONTAIN, was used to model the debris in the lower cells.

The total decay heat source in the debris was taken as about 25 MW at 13000 s, which is about 80% of the best estimate total decay heat. No other decay heat source was included in the calculation. Caesium and iodine released from the core melt in-vessel were assumed to remain trapped on structures there throughout. The sensitivity of the results to the decay heat is discussed in the next section.

No concrete was ablated by the debris introduced to cell 3, where the initial debris temperature (1190 K) was below the assumed concrete ablation temperature (1466 K). In cell 2, the initial debris temperature was 2168 K and 2100 kg of concrete were ablated as the debris cooled. The debris in cells 2 and 3 soon reached a steady temperature between 400 and 500 K and remained at this level for most of the calculation while the decay heat from the UO_2 was transferred to the overlying water pools.

The debris in the cavity did not quench and concrete ablation continued there throughout the calculation, as the decay heat was shared between the concrete and the cavity pool. 169 te of concrete were ablated in the cavity by the end of the calculation, yielding 4500 kg of CO_2 and 13900 kg of H_2O.

Heat from the debris which is passed to the water pools boils water and the pressure in the containment gradually rises as shown in Figure 4a. The water pools initially contain 300 te of water; the steam added to the containment atmosphere as the pools boil is the major cause of the pressure rise in the containment; the gases generated from core-concrete interaction make only a minor contribution. The assumed containment failure pressure (0.99 MPa) is reached after 180000s (50 hrs). Since containment failure is not modelled in this calculation, the pressure continues to rise.

The pool water inventories for the reference calculation are shown as a function of time in Figure 4b. Condensation runoff from containment structures returns to the pools, mainly in cells 2 and 3. When these are full, they overflow to the pool in the cavity until this boils dry just after 100000 s. The water levels in cells 2 and 3 then fall until the entire water inventory in the containment has evaporated just before the end of the calculation, when the pressure has risen to 1.07 MPa.

4.2 Sensitivity Studies

In this section, calculations which explore the sensitivity of the long-term pressure transient in the containment to the distribution of the core debris and water are described. As with the reference calculation, containment failure was not modelled and so, in cases where the assumed containment failure pressure (0.99 MPa) was reached, the pressure continued to rise until the calculations were stopped after 200000 s (55½ hrs).

The results of the calculations are presented in Table 4 and in Figures 4 to 8. Table 4 includes the containment pressure at 200000 s, in each case. Figures 4a - 8a show the calculated pressure transients and Figures 4 - 8 the histories of the water pool inventories.

The pressure transients are characterised by two distinct phases as follows:

Phase (i) While water remains in pools containing debris, water is boiled and the pressure rises relatively quickly as water vapour is added to the atmosphere. The temperature of the atmosphere remains close to saturation.

Phase (ii) When all pools containing debris have boiled dry, the debris heats the containment directly. Some of this heat is absorbed by the atmosphere, raising its temperature and some by remaining water pools (via the atmosphere) which may evaporate and eventually boil, adding water vapour to the atmosphere. However most of the heat is transferred (via the atmosphere) to containment structures which have a much greater heat capacity than the atmosphere. As a result, the containment pressure rises much more slowly than in Phase (i).

The assumed containment failure pressure is reached after 1½ to 2 days in cases where Phase (i) is important, ie where a high proportion of the water pools are in contact with debris. In cases where debris is largely isolated from water pools, the pressure remains below the assumed containment failure pressure throughout the calculations.

The individual sensitivity calculations are discussed in the following paragraphs.

(i) Debris Absent from the Cavity (Case 2)

This case corresponds to all core debris being released from the vessel and being ejected from the cavity during DCH. A long-term core-concrete interaction was avoided, since, as in the reference case, the thin debris layers in the lower containment quickly quenched. As a result, there was no long-term heat loss to the concrete and all the decay heat was used to boil the water pools in cells 2 and 3. The pressure in the containment therefore rose more quickly than in the reference calculation, until these pools boiled dry after about 67000 s (Phase (i)) but thereafter rose only very slowly (Phase (ii)) since over 160 te of water remained trapped in the cavity pool, in contact with no direct heat source. The containment pressure is still well below the assumed failure pressure at the end of the calculation.

(ii) Decay Power (Case 3)

In the reference calculation, 80% of the total best estimate decay heat has been included in the CONTAIN model while the remaining 20% is assumed to be associated with fission products which have remained within the vessel. In the long term, while some of the power in the vessel would be absorbed by structures in the vessel, some would be transferred to the containment, either by resuspended fission products or as the gas within the vessel became heated. In Case 3 the decay power allocated to the core debris in the CONTAIN model was increased to 100% of the best estimate power. As a result, the time when the assumed containment failure pressure of 0.99 MPa was reached was brought forward to about 33 hours, compared with about 50 hours for the reference calculation. This follows because the gradient of the pressure rise in Phase (i) of the transient is increased. Once all the water has boiled, however, the rate of pressure rise is much reduced (Phase (ii)) so that the pressure rise at the end of the calculation (1.19 MPa) is only about 10% greater than for the reference case (1.07 MPa)).

The increased power was retained for the remaining two cases described below.

(iii) Debris in the Lower Containment Isolated from Water Pools (Case 4)

In the reference case, all the debris in the containment interacted with water pools. Case 4 explores the importance of this assumption by placing all the debris in the lower containment in cell 2, with a small water pool having a nominal capacity of $9m^3$. The water in the cell 3 pool is now effectively "held up" in the containment and isolated from the debris. As a result, Phase (i) of the transient is curtailed and the final pressure is reduced to 0.93 MPa, below the assumed failure pressure of 0.99MPa.

(iv) Debris Completely Isolated from Water (Case 5)

For Case 5, the debris was all concentrated in cell 2 while most of the water was allowed to accumulate in the unheated pools in cell 3 in the containment and in cell 1 (the cavity). This equivalent to a DCH scenario where all the debris is ejected from the cavity and comes to rest in the containment away from the main water reservoirs. Without the ability to add mass to the atmosphere by boiling water, the debris decay heat can only increase the containment pressure by raising the temperature, that is, there is no Phase (i) to the transient. The atmosphere only contributes a small part of the containment's heat capacity, most of which is accounted for by the structures and so the pressure only rises to 0.45 MPa after 200000 s.

5. HYDROGEN BURNS FOLLOWING RECOVERY OF SPRAYS

In this section, the containment loads and temperatures are considered which could result from a hydrogen burn about 1 day after the start of the TMLB' accident scenario with high pressure vessel failure.

For the reference DCH calculations described in Section 3.1, it was assumed that a hydrogen burn occurred immediately following vessel failure, during DCH. The hydrogen concentration was then too low for a further burn during the long-term calculation. Furthermore, even if significant amounts of hydrogen were present, high concentrations of steam from boiling water pools meant that a burn could only occur if the spray system was recovered so that the de-inerting steam would condense.

In the calculations described in this section, conditions where a burn could occur have been created by assuming that:

(i) no burn occurred during DCH, so that the early hydrogen inventory was retained during the long-term transient; and

(ii) the containment sprays were recovered after 24 hours and, for some calculations:

(iii) metals present in the core-concrete melt in the cavity were oxidised by steam to provide a further source of hydrogen.

Table 5 summarises the results of the hydrogen burn calculations.

The results of Cases 1 and 2 show that insufficient hydrogen was generated during the in-vessel and DCH phases of the accident for a burn to threaten the containment if sprays de-inert the atmosphere during the long-term transient. However, further hydrogen and carbon monoxide could be generated during the core-concrete interactions in the cavity. If all the available metal (including the concrete reinforcing bars) reacted with steam or carbon dioxide, the containment inventory of combustible gas would be almost doubled. The results of Cases 3, 4 and 5, where this additional hydrogen has been added as a source, show that such an increase would lead to much higher temperatures and pressures during a burn. However, the results indicate that a burn would still not threaten the containment, even if the inhibiting effect of steam on the hydrogen flame speed was rendered ineffective, for example by the turbulence which would be generated by the sprays. A transition to detonation could pose a threat but this possibility has not been assessed as part of the present work.

No hydrogen burn calculations have been provided for the TMLB' scenario with early primary circuit failure. However similar conclusions may be appropriate for that case. Although the early hydrogen inventory would be smaller because DCH would be avoided, the long-term hydrogen source would be greater since a larger fraction of the debris would contribute to the core-concrete interaction in the cavity.

6. LONG-TERM AIRBORNE FISSION PRODUCT AEROSOLS

Four long-term CONTAIN sensitivity calculations have been completed to investigate the behaviour of fission products released during the molten core-concrete interaction. Each is a repeat of the reference long-term calculation for the high pressure TMLB' scenario, with an additional aerosol source derived from one of three calculations using the CORSOL code. CORSOL couples CORCON with the equilibrium chemistry code SOLGASMIX [6] to calculate the releases of chemical species during a molten core-concrete interaction. The aerosols released include fission products but the bulk of the mass is inert material (mainly SiO_2) from the concrete. In all the calculations, the scrubbing effect of the overlying water pool on the fission product release has been neglected.

The first CORSOL case (the "high pressure" case) corresponds to the TMLB' scenario with DCH described in Sections 3 and 4, in which there are 43 te of molten core debris in the cavity. The initial melt temperature is 2900 K. The second "low pressure" CORSOL case refers to the TMLB' scenario with vessel failure at low pressure, where most (129 te) of the core melt is in the cavity, again with an initial temperature of 2900 K. In the third "low pressure" sensitivity CORSOL calculation, the sensitivity of the fission product release to the initial melt temperature was investigated by reducing the initial melt temperature to just under 2000 K. In this third calculation, CORSOL predicted that the melt temperature rose to a peak value of 2600 K before falling. In the first two cases, the melt temperature fell continuously.

The CORSOL reference calculations with the high melt temperatures (2900 K) indicated that the majority of the fission product release takes place over a relatively short period (~ 15 mins), following the start of the core-concrete interaction at 13000 s. The timespan for fission product release was found to be sensitive to the initial melt temperature but even for the case with the very low initial melt temperature of 2000 K, fission product release was essentially complete within 3 hours. The release of concrete aerosols persisted, as concrete ablation continued throughout the CORSOL calculations.

The high pressure scenario CONTAIN case has been used as the basis for all the calculations, even though CORSOL data for both the high pressure and low pressure TMLB' scenarios are considered. This is not an important approximation because differences between the long-term containment response in the two scenarios are likely to be small compared with other uncertainties and approximations, such as those associated with the molten core-concrete interaction.

One CONTAIN calculation was run using data from each of the three CORSOL cases. A further CONTAIN sensitivity case was run to investigate uncertainties in the source from the CORSOL "low pressure" sensitivity case. For these CONTAIN calculations, the CORSOL sources have been divided into two components: an "early" source, which is assumed to contain most of the fission products, and a "late" source, which is mainly inert. The "early" aerosol is only used to track the fission products in the calculations. The transfer of a small part of the fission product decay heat from the core debris to the aerosol has not been modelled as it is not expected to influence the containment conditions significantly.

The masses and timescale of the aerosol sources are given in Table 6. The four CONTAIN sensitivity calculations were continued for 86400 s (24 hrs) to allow the airborne fission product inventory in the containment 1 day after shutdown to be estimated. The results are presented in Figures 9-12 and in Table 7.

The calculations described in Section 4 indicate that the pressure in the containment would rise slowly as the core-concrete interaction proceeds, as decay heat from the core debris boils water in overlying pools. However, it was found that the pressure was unlikely to rise sufficiently to threaten the containment integrity until at least a day or so after shutdown.

Thus only fission products which remain airborne in the containment after a day or more would contribute to the source term, providing there is no resuspension of deposited material.

Figures 9-12 illustrate how the airborne mass of the early fission product bearing aerosol diminishes after the source ends. In each case, less than 0.1% of this aerosol remain airborne after 24 hours. The depletion occurs because of agglomeration and gravitational settling. In practice, the CORSOL results show that traces of some fission products may continue to be released with the late aerosol. Even when this is allowed for, however, the fission product concentrations after 24 hours are 0.1% or less in every case.

7. CONCLUSIONS

(1) Direct containment heating (DCH) calculations using CONTAIN coupled with the CORDE high pressure melt ejection code predict containment pressures significantly below the assumed containment failure pressure, even if DCH triggers a rapid hydrogen burn.

(2) The addition of modest quantities of water (up to 100 te) have no significant effect on the predicted DCH pressure in the containment but the calculated pressure is reduced if larger quantities of water are added.

(3) After vessel failure, as long as sufficient debris remains in contact with water in pools, the decay heat can raise the containment pressure efficiently by boiling the water and adding mass (steam) to the atmosphere. CONTAIN calculations indicate that this mechanism could increase the pressure sufficiently to threaten the containment after 1½ to 2 days.

(4) If the bulk of the debris becomes isolated from water pools, the decay heat must raise the temperature in the containment to raise the pressure. This is much less efficient because the massive containment structures must be heated as well as the atmosphere and the calculations indicate that it would take many days for the pressure to increase enough to threaten the containment.

(5) Recovery of containment sprays a day or so into a severe accident could condense sufficient steam to de-inert the containment atmosphere. However CONTAIN calculations for the present scenario predict that a burn would not threaten the containment. This conclusion holds even if the inhibiting effect of steam is eliminated, for example by turbulence associated with the sprays and even if the hydrogen generated during a core-concrete interaction is taken into account.

(6) The calculations predict that 0.1% or less of the fission products released during the core-concrete interaction remain airborne in the containment 24 hours after shutdown. This follows because the aerosols which transport the fission products in the

containment deposit on surfaces, mainly as a result of agglomeration and gravitational settling.

8. ACKNOWLEDGEMENT

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Table 1

TMLB' Accident Scenario : Main Event Summary

Event	Time (s)
Reactor Trip	400
Secondary SG Dryout	4300
POSRV Open	4450
Start of Core Uncovery	7000
Start of Fuel Rod Relocation	8550
End of SCDAP/RELAP5 Calculation	9470
Debris Relocation to Lower Head	11500
Lower Head Failure and High Pressure Melt Ejection	12300
Remaining Core Material Slumps into Cavity	13000
End of CONTAIN Calculation	200000

Table 2

"Dry Cavity" DCH Results

% of Core Debris in DCH	Hydrogen Burn		Change from Base Case	Peak Upper Containment Pressure During DCH (MPa)
	Delay (s) from Start of DCH	Duration (s) (Upper Containment)		
58	4	5	Base Case	0.763
58	4	10	10s Burn	0.727
58	-	-	No Burn	0.599
88	4	5	More Debris	0.845
58	14	5	Burn Delayed	0.744
58	4	5	2-cell CONTAIN Model	0.866
58	4	5	5-cell CONTAIN Model	0.762
58	4	5	Very Low Debris Trapping Rate	0.779
58	4	5	Very High Debris Trapping Rate	0.676
58	4	5	Debris Particle Diameter Doubled from 0.3 mm to 0.6 mm	0.761

Table 3

DCH : The Effect of Cavity Water

Mass of Water in Cavity (te)	Peak Upper Containment Pressure (MPa)	
	(a)Cases with Unconditional 5s Hydrogen Burn	(b)Volume of Receiving Cell Increased from 7% to 30% of Containment
0.1 ("Dry Cavity" Case)	0.763	0.782
2.0	0.741	0.790
80	0.744	0.780
160	0.708	-
240	0.658	-

Table 4

Summary of Long Term Sensitivity Calculations

Case No	Description	Fuel				Water Pools		Containment Pressure (MPa) at End of Calculation (200000 s, or 55.6 hrs)
		Fraction (%) in Cell No.			Power in Fuel as % of Best Estimate Total	Cell 2 Full Volume (m^3)	Cell 3 Full Volume (m^3)	
		1	2	3				
1	Reference Case	39	18	43	80	101	58	1.07
2	No Fuel in Cavity	0	35	65	80	101	58	0.67
3	Increased Power	39	18	43	100	101	58	1.19
4	Fuel in Lower Containment Isolated from Pools	39	61	0	100	9	150	0.93
5	All Fuel Isolated from Water	0	100	0	100	9	150	0.45

Table 5

CONTAIN Calculations of Hydrogen Burns Following De-inerting of the Containment Atmosphere by Sprays

Hydrogen Burn Case Number	Burn Trigger Conditions Specified in CONTAIN Data	Conditions at Start of Burn					Details of Burn		Peak Conditions in Upper Containment	
		Time (s)	Total Hydrogen Inventory (kg)	Initial Conditions in Upper Containment			Duration (s) in Upper Containment	Mass H_2 Burnt (kg)	Pressure (MPa)	Temperature (K)
				Volume Fractions		Pressure (MPa)				
				H_2O	H_2					
1	Default	91240	762	.336	.071	.188	78	536	.290	490
2	Default but start of burn delayed	95000	762	.082	.097	.120	8	751	.400	1138
3	Default (Increased H_2 inventory)	89080	1454	.544	.084	.322	132	1066	.539	629
4	Default but start of burn delayed (Increased H_2 inventory)	95000	1454	.081	.170	.132	3	1436	.613	1629
5	Inhibiting effect of steam on flame speed removed (Increased H_2 inventory)	89080	1454	.544	.084	.322	6	1407	.850	1096

Table 6

Summary of Core-Concrete Aerosol Sources for CONTAIN Derived from CORSOL Calculations

Description of Source	Case and Total Aerosol Masses:			
	(1) "High Pressure" Reference Case (43te melt 2900K initial temperature)	(2) "Low Pressure" Reference Case (129te melt 2900K initial temperature)	(3) "Low Pressure" Sensitivity Case (i) (129te melt ~2000K initial temperature)	(4) "Low Pressure" Sensitivity Case (ii)
Early Source Aerosol including fission products	3400 kg (13000 - 13800s)	9400 kg (13000 - 14400s)	176 kg (13000 - 25000s)	3840 kg (13000 - 25000s)
Late Source Mainly inert aerosol	23 kg (13800 - 86400s)	750 kg (14400 - 86400s)	7300 kg (25000 - 86400s)	3670 kg (25000 - 86400s)

Notes (i) The CORSOL calculations gave no data for the size for the aerosol particles. Values of 0.9e-6m mass mean diameter, 0.83 geometric standard deviation were assumed for the CONTAIN calculations.

(ii) The mass split between the early and late source for the low pressure sensitivity case was uncertain because the CORSOL data were insufficiently detailed. Cases 3 and 4 bound the possible range.

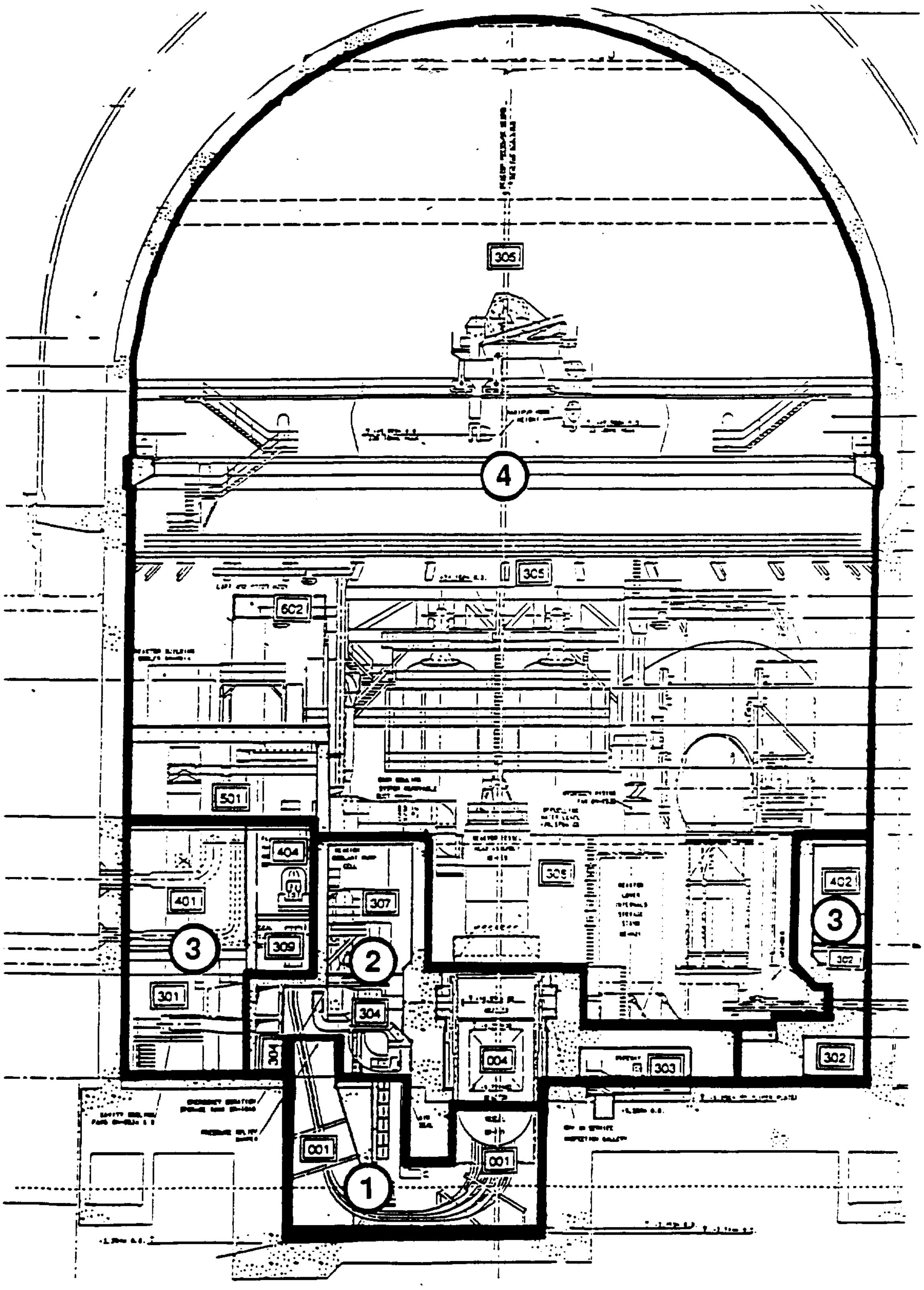

Figure 1. Cell arrangement for 4-cell CONTAIN model.

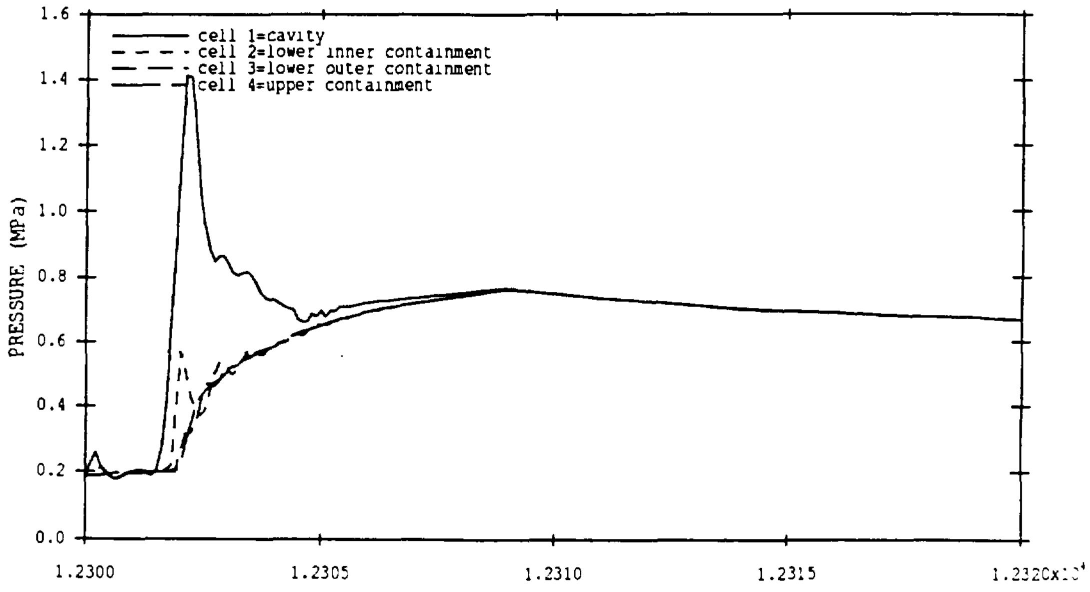

Figure 2 Cell Pressures during DCH : Dry Cavity

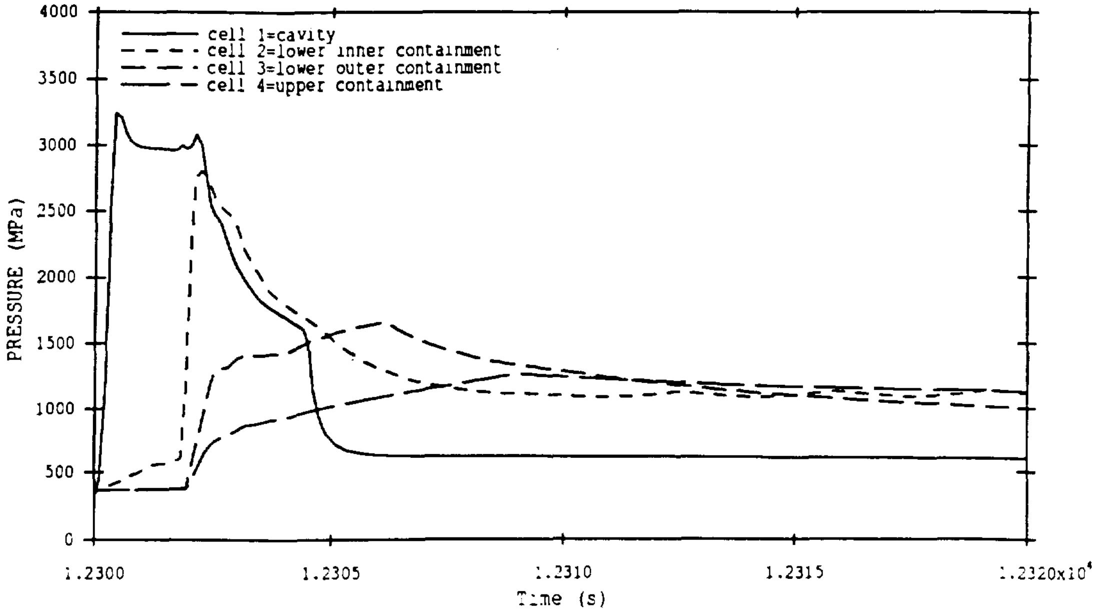

Figure 3 Cell Temperatures during DCH : Dry Cavity

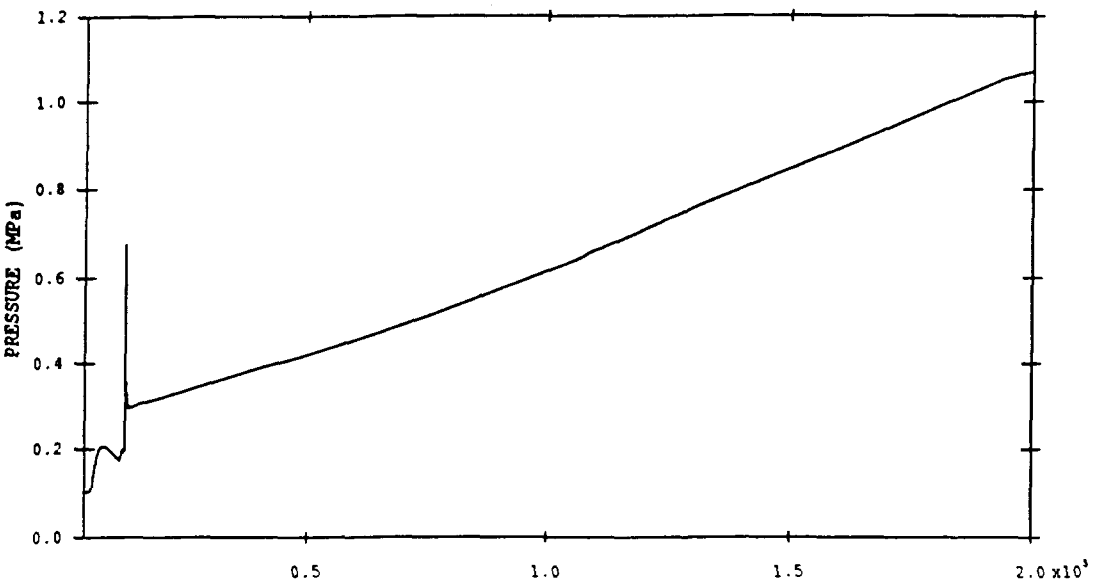

Figure 4a Case 1, Reference Case, Containment Pressure

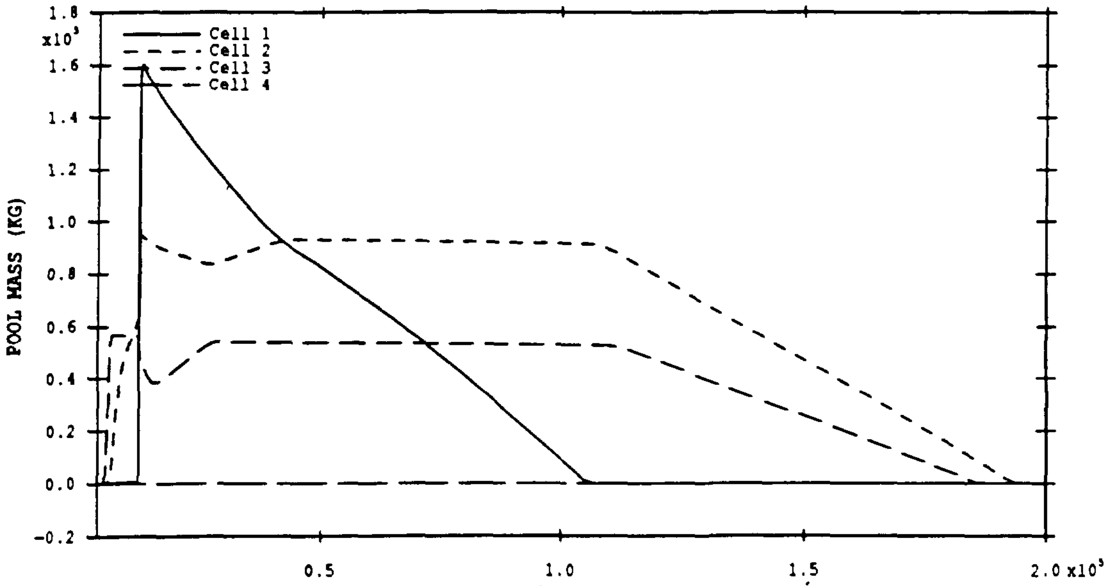

Figure 4b Case 1, Reference Case, Pool Water Inventories

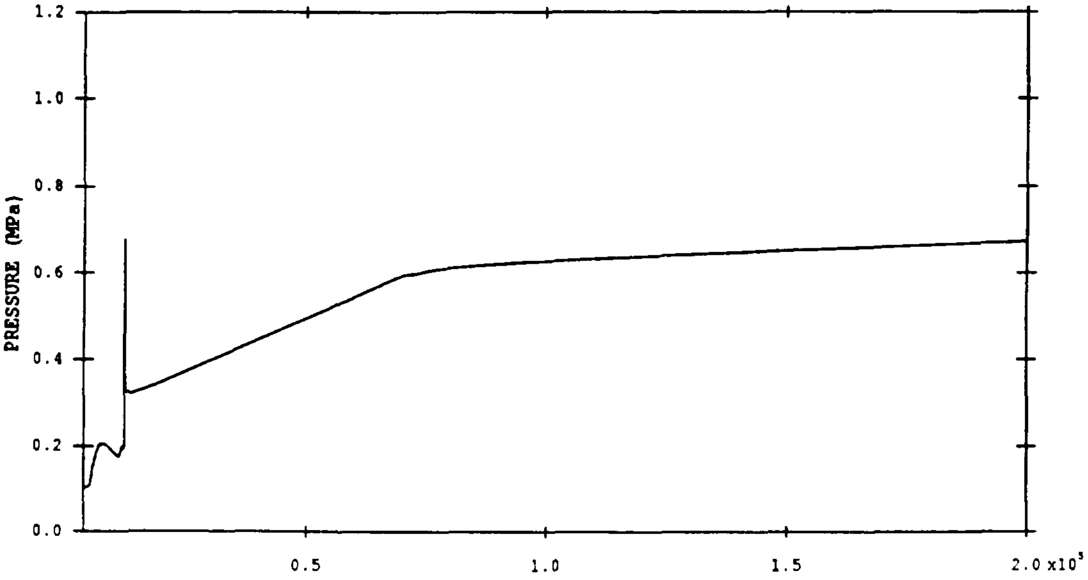

Figure 5a **Case 3, No Fuel in Cavity, Containment Pressure**

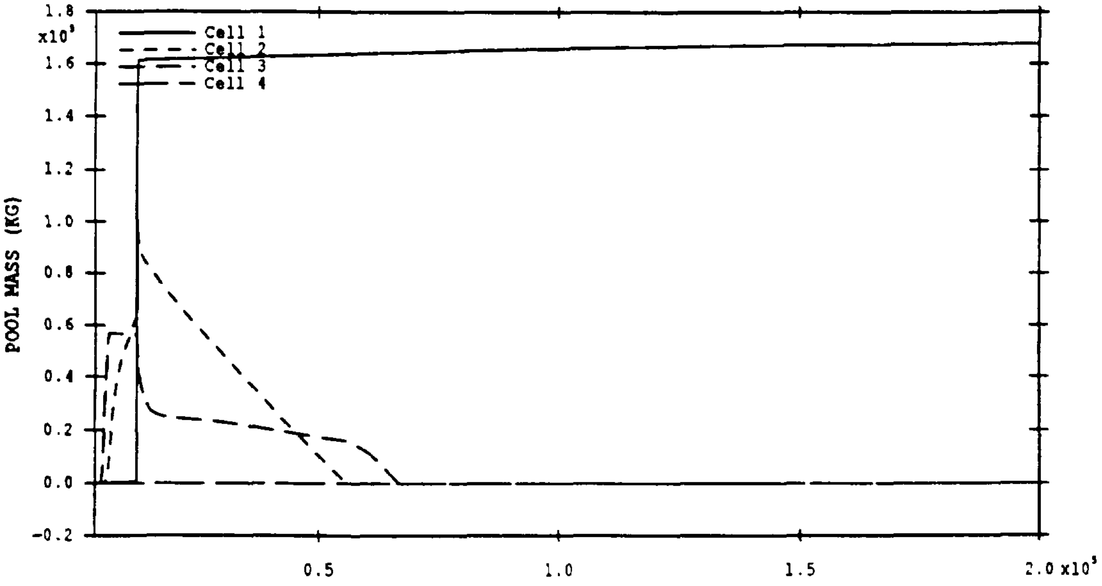

Figure 5b **Case 3, No Fuel in Cavity, Pool Water Inventories**

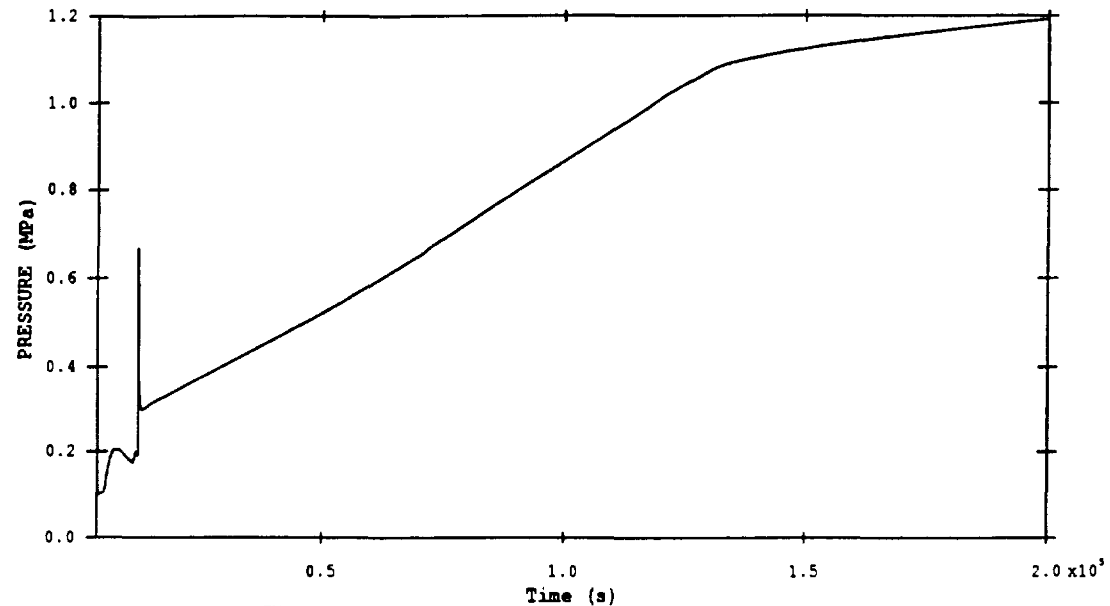

Figure 6a **Case 2, Increased Power, Containment Pressure**

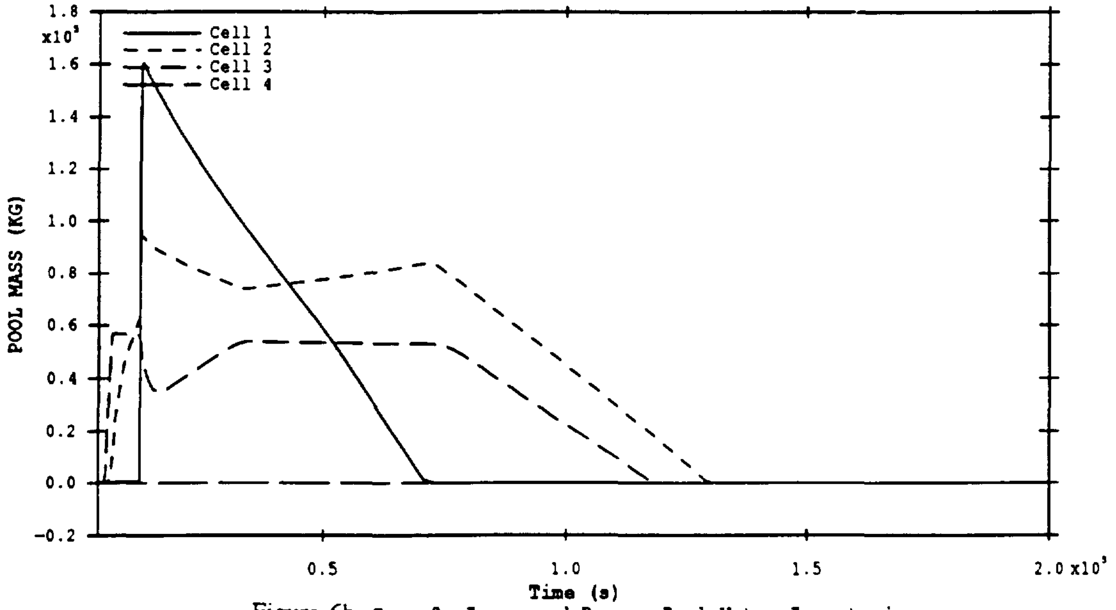

Figure 6b **Case 2, Increased Power, Pool Water Inventories**

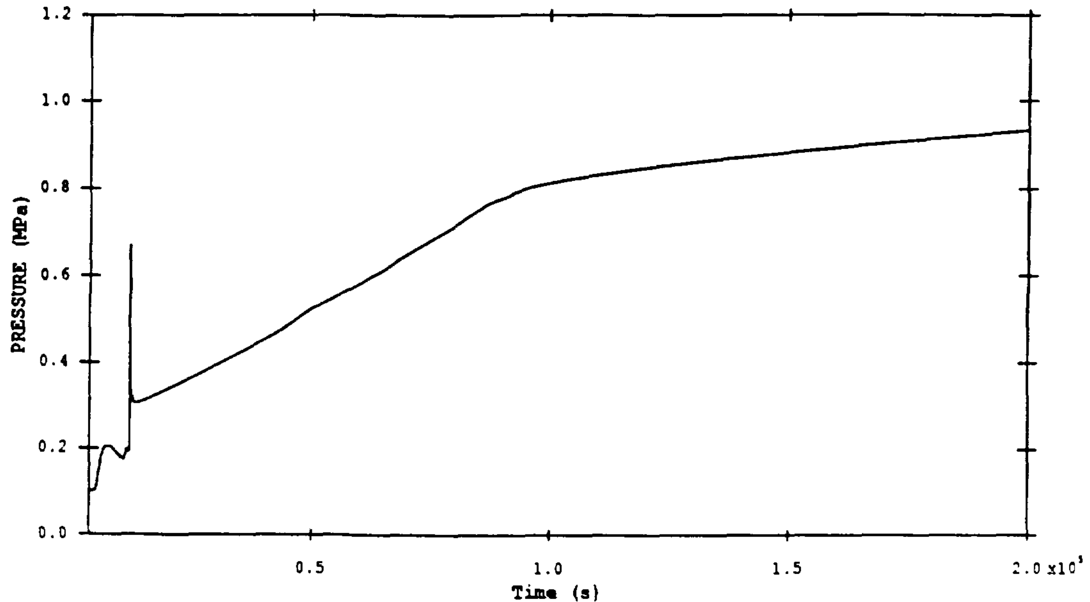

Figure 7a **Case 9, Increased Power, Containment Pressure**

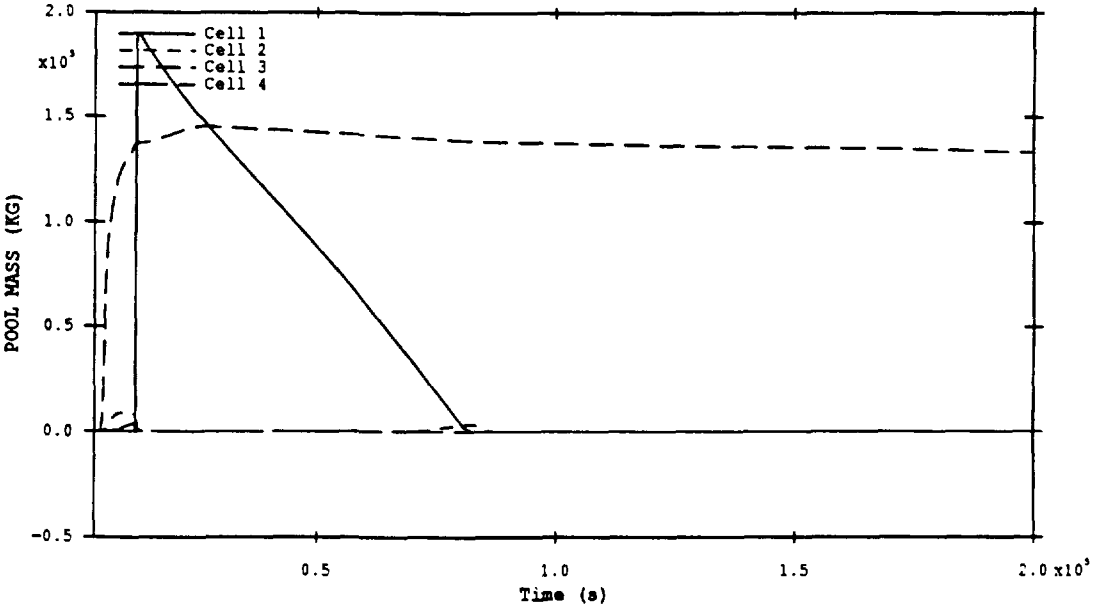

Figure 7b **Case 9, Increased Power, Pool Water Inventories**

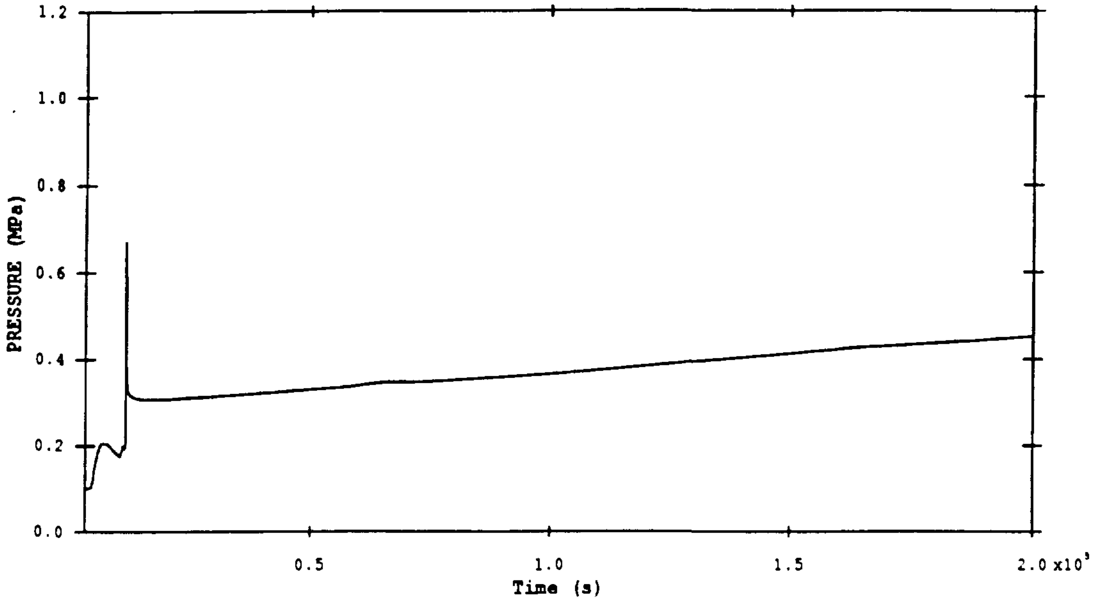

Figure 8a Case 11, Increased Power, Containment Pressure

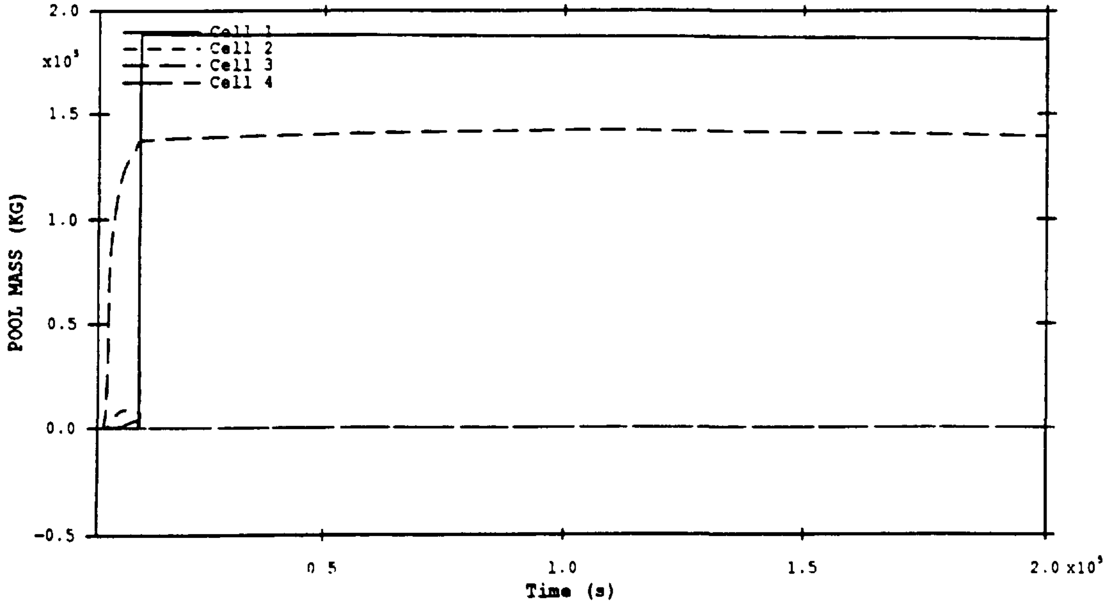

Figure 8b Case 11, Increased Power, Pool Water Inventories

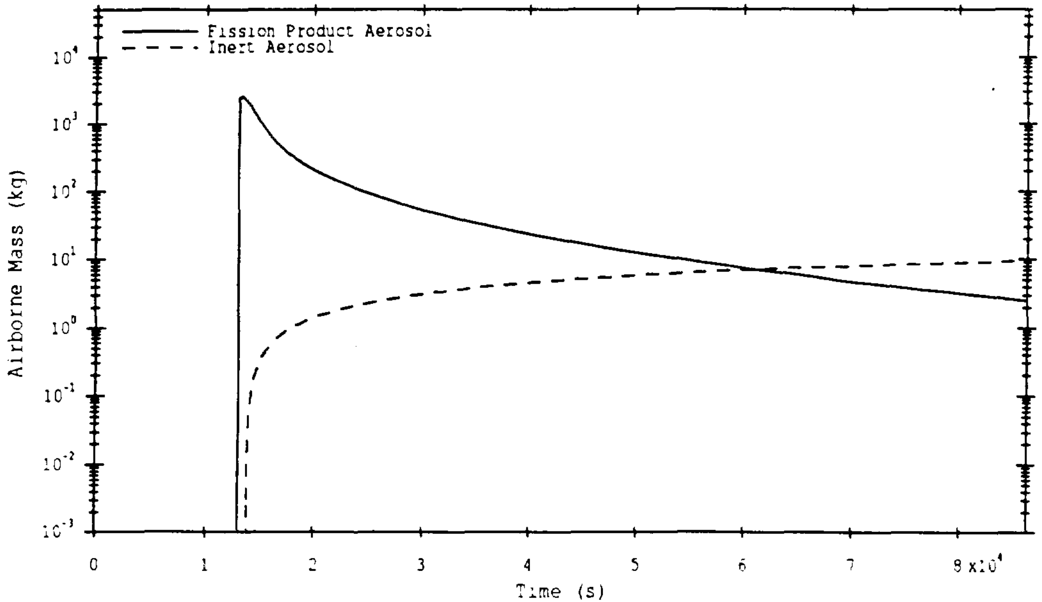

Figure 9 Airborne Long-Term Core Concrete Aerosol : (1) High Pressure Reference Case

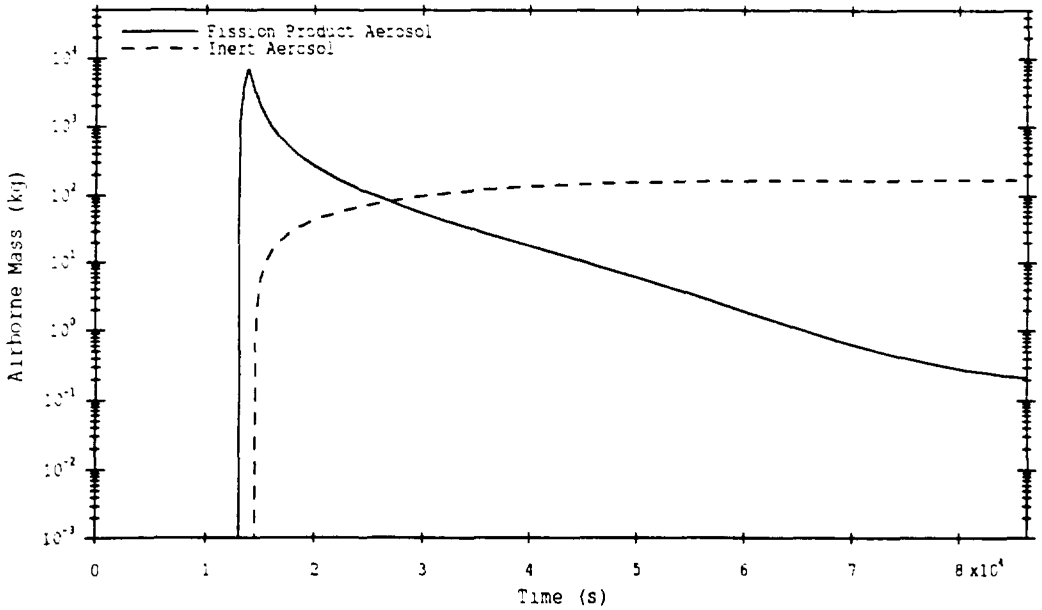

Figure 10 Airborne Long-Term Core Concrete Aerosol : (2) Low Pressure Reference Case

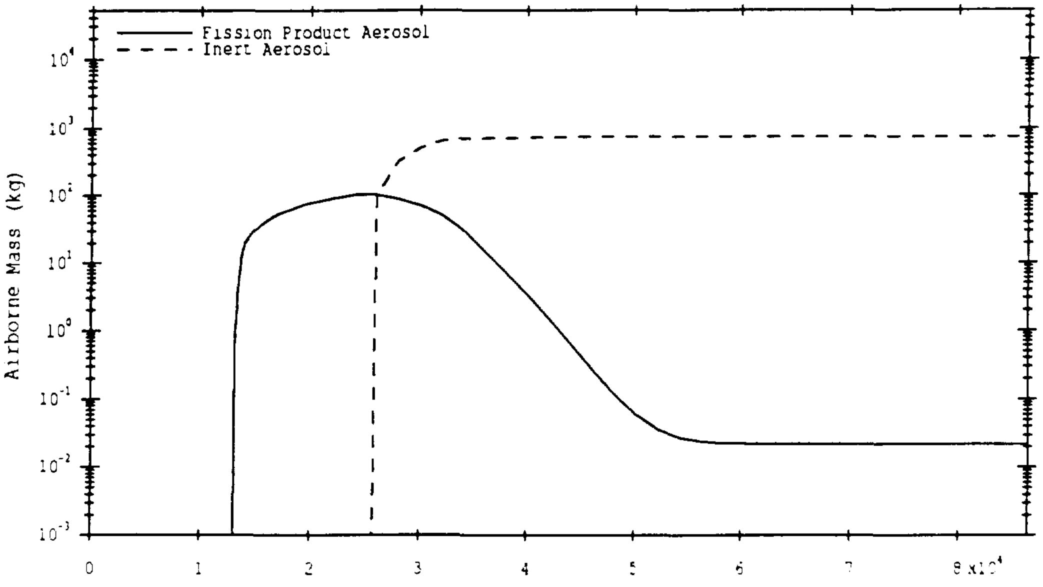

Figure 11 Airborne Long-Term Core Concrete Aerosol : (3) First Low Pressure Sensitivity

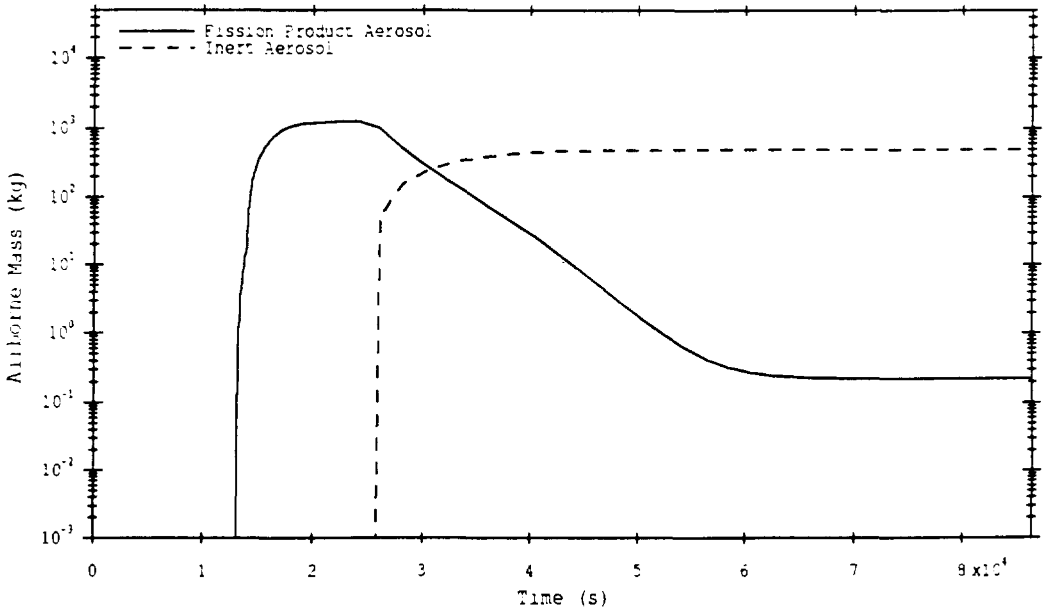

Figure 12 Airborne Long-Term Core Concrete Aerosol : (4) Second Low Pressure Sensitivity