RESULTS OF DIRECT CONTAINMENT HEATING INTEGRAL EXPERIMENTS AT 1/40TH SCALE AT ARGONNE NATIONAL LABORATORY

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ABSTRACT

A series of integral tests have been completed that investigate the effect of scale and containment atmosphere initial composition on Direct Containment Heating (DCH) phenomena at 1/40 linear scale. A portion of these experiments were performed as counterparts to integral experiments conducted at 1/10th linear scale at Sandia National Laboratories. The tests investigated DCH phenomena in a 1/40th scale mockup of Zion Nuclear Power Plant geometry. The test apparatus was a scaled down version of the SNL apparatus and included models of the reactor vessel lower head, containment cavity, instrument tunnel, lower subcompartment structures and the upper dome. A High Pressure Melt Ejection (HPME) was produced using steam as a blowdown gas and iron-alumina thermite with chromium as a core melt simulant. The results of the counterpart experiments indicated no effect of scale on debris/gas heat transfer and debris metal oxidation with steam. However, the tests indicated a slight effect of scale on hydrogen combustion, the results indicating slightly more efficient combustion with increasing scale. The experiments demonstrated the effectiveness of the subcompartment structures in trapping debris exiting the cavity and preventing it from reaching the upper dome. The test results also indicated that a 50% air - 50% steam atmosphere prevented hydrogen combustion. However, a 50% air - 50% nitrogen did not prevent hydrogen combustion in a HPME with all other conditions being nominally the same.

INTRODUCTION

Risk studies of U. S. nuclear power plants have focused attention on low probability, beyond design basis, severe accidents. These accidents involve a core melt, relocation to the vessel lower head, failure of the lower head, and release to the containment. The release of the molten core material (corium) to the containment can produce thermal or pressure loadings that pose a threat to the integrity of the containment. Of interest here is a corium release in a PWR while the vessel is at elevated pressure. In such a case the corium will be forcibly ejected into the containment cavity. An event of this type is termed a High Pressure Melt Ejection (HPME). The fundamental question is: Will the HPME cause an energy transfer to the containment atmosphere large enough to produce a pressure load that threatens the containment integrity? The transfer of energy

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to the containment atmosphere is termed Direct Containment Heating (DCH).

The sources and mechanisms for direct containment heating will be described below. There are four sources of energy to the containment atmosphere. The first is the addition of the blowdown gasses (steam and hydrogen) from the reactor coolant system (RCS) to the containment. The mass of gas in the RCS is typically an order of magnitude less than the mass of gas in the containment. Therefore, the blowdown source of energy to the containment is negligible. The transfer of the corium thermal energy to the containment, debris/gas heat transfer, is a second source of energy. The blowdown of the primary system gasses into the cavity will fragment and disperse the corium out of the cavity into the containment. In general this source of energy will be large for HPME's. However, it is expected that the efficiency of this debris/gas heat transfer will increase with debris flight path. The presence of many lower compartment structures in the containment building can trap debris, reducing the flight path and consequently lead to significant mitigation of the debris/gas heat transfer. A second mitigation of the debris/gas heat transfer can occur due to quenching of the debris by water in the containment or cavity. It should be noted that debris quenching by water will lead to vaporization and the addition of gas moles to the containment atmosphere. Water vaporization is, therefore, a source of energy to the containment. However, the net effect of debris quenching is an energy sink. The third source of energy to the containment is the release of chemical energy in the corium via metal oxidation reactions with steam or oxygen. This energy source may be significant if the corium released from the vessel contains a significant fraction of "reactive" metal. In the prototype case this reactive metal is zirconium which readily has exothermic reactions with steam or oxygen at high temperatures. The corium may also contain significant amounts of metal iron; however, the oxidation reactions with iron are only slightly exothermic. Therefore, iron oxidation does not present a significant energy source. The oxidation of the metal is expected to occur mainly in the cavity where highly fragmented melt is intimately mixed with high velocity steam exiting the primary system. The fourth source of energy to the containment is the combustion of hydrogen. There may be three sources of hydrogen in the containment. Hydrogen may be in the containment pre-existing to the HPME due to in-vessel zirconium oxidation and then subsequent release from the primary system to the containment. In vessel oxidation also leads to hydrogen in the blowdown gasses which is a second source of hydrogen to the containment. The third source of hydrogen is the metal steam reactions during the debris dispersal phase of the HPME and blowdown. Hydrogen combustion may be a significant source of energy, possibly the dominant one, to the containment.

The NRC has been sponsoring a research program to resolve the DCH issue. An important part of this effort is an integral effects testing program. In general the objective of this program is assess the effects of scale on DCH phenomena. This is being accomplished by performing integral and counterpart experiments in two different facilities. Experiments at 1/40th linear scale are being conducted at Argonne National Laboratory and at 1/10th linear scale at Sandia National Laboratories. The more specific objective of the counterpart testing is to simulate the fundamental interrelated processes and effects of a HPME. The experiments incorporate melt ejection from the vessel, high pressure blowdown of primary system, entrainment and sweepout of debris from the cavity, transport and trapping in the lower containment subcompartments, oxidation of metallic constituents in the melt, combustion of hydrogen, and vaporization of water in

the containment. The experiments employed the geometry of the Zion Nuclear Power Plant (NPP). These tests provide important data in order to validate system level codes. In addition the experiments will be used to evaluate scaling methodologies proposed by the SASM group and SNL.

This paper reports on the ANL experiments. The specific objective of the experiments was to conduct integral DCH tests applying the SNL scaling methodology using a 1/40th scale mockup of the SNL 1/10th scale facility. Useful counterparts to the SNL tests have been insured by employing linear geometric scaling to the greatest extent feasible. The facility includes models of the vessel lower head, cavity, subcompartments and containment dome. In addition operating conditions were matched to the greatest extent possible to minimize sources of difference in the results, other than the scale distortions. Measurements in the tests are made of the primary system pressure history, the cavity and containment pressure responses, gas temperatures, debris disposition, hydrogen production and oxygen depletion.

The integral tests at ANL have addressed several questions. The first and most important relates to the effect of scale on DCH phenomena. Comparison of test results between ANL and SNL have indicated little effect of scale on debris gas/heat transfer and metal-steam oxidation/hydrogen production. The scale effects on hydrogen combustion are somewhat more unclear. However, the results indicate a small marginal increase in hydrogen combustion, with an increase in scale from 1/40th to 1/10th. The ANL tests have also addressed the question of whether steam in the containment atmosphere will inert hydrogen combustion. Tests were run comparing 50% inerting of air by nitrogen or steam in the containment. The results indicated that steam was effective in inerting the hydrogen combustion while the nitrogen was not. The ANL tests have also addressed questions regarding the debris sweepout from the cavity. Gas temperature measurements indicate that the blowdown gasses and the melt nearly thermally equilibrate during the cavity sweepout. This process alone significantly contributes to the measured pressure response of the containment. The ANL tests have also addressed the question of over what time scale is hydrogen produced during HPME. Gas sample analyses have indicated that significant hydrogen is produced in the cavity during the sweepout process. This occurs on the time scale of the blowdown. The hydrogen results from steam oxidation reaction with the "reactive" metal in the melt. However, data indicates that hydrogen is produced on time scale well after the blowdown. This hydrogen may be produced from slow reactions with "non-reactive" iron. The effectiveness of the subcompartment structures in trapping debris was also addressed in these experiments. The results here indicate that only 5-10% of the debris ejected from the vessel is transported to the upperdome.

DESCRIPTION OF THE EXPERIMENTS

The first step in specifying the experiments was the selection of the NPP and the accident sequence. The selected NPP is the Zion Nuclear Power Plant. The accident is precipitated by a station blackout, followed by a pump seal LOCA. The core melts and relocates to the vessel lower head. The HPME is begun by a failure of an instrument tube penetration.

Table 1 provides a summary of the specified reference initial and boundary conditions for the NPP, SNL and ANL scales. For convenient comparison of the ANL

and SNL dimensions to the NPP, columns are given with the equivalent full scale value. The hole diameter in the experiments were scaled to the final hole calculated hole diameter in the NPP because ablation of the hole during the melt ejection could not be scaled properly. The composition of the containment atmosphere was the main parameter varied in the tests.

The driving pressure specification in the test was dictated by a pump seal LOCA as 6.2 MPa. The only significant area of geometric distortion in the experiments was the scaled volume of primary system. Due to facility limitations the SNL volume is approximately 18.2% underscaled with respect to the ANL RCS volume.

The core melt simulant used was produced by an iron/alumina thermite with the addition of chromium. The chromium does not participate in the thermite reaction, however, it adds a "reactive" metal to the simulant. The chromium will oxidize with steam similar to zirconium. Therefore, it is considered a good substitute. The same thermite and chromium powders were used in both the ANL and SNL tests. Due to non-uniformities in the iron oxide powder used in the thermite the reaction was non-stoichiometric and resulted in 1.4 mass% of the simulant containing aluminum. Further details on this can be obtained in Allen et al (1991). The excess aluminum adds additional "reactive" metal. The temperature of the simulant at ejection has been measured in the SNL facility by two-color pyrometers as 2550 K. This is 230 degrees of superheat with respect to the melting point of the alumina. The specific enthalpy of the simulant at 2550 K is 2.8 MJ/kg compared to 1.15 MJ/kg for the prototype melt at 2600 K. The specific metal-steam oxidation energy is 1.20 MJ/kg for the simulant and 1.22 MJ/kg for the prototype melt. The mass of hydrogen produced per mass of melt oxidized by steam is 0.0318 and 0.0156 for the simulant and prototype respectively. This data includes the iron oxidation. The density of the simulant melt is 4000 kg/m³, approximately one-half of the oxidation prototype melt.

The scaling rationale for selecting the initial simulant melt mass was based on preserving the ratio of total melt energy input, including oxidation and hydrogen combustion energy, to the containment volume between the prototype and experiment. In effect this matches the maximum expected pressure increase from a single cell adiabatic calculation. Details on this calculation is given in the results. Applying this approach resulted in the specification of 0.71 kg of melt ejected in the ANL experiments.

The ANL experiments were conducted in the Corium EX-Vessel Interaction (COREXIT) facility.

A schematic of the experiment apparatus is shown in Figure 1. Major components of the facility include an explosion resistant containment cell, a 1.51 m³ expansion vessel (EV) and a high pressure steam boiler. The expansion vessel stands approximately 3.4 meters high and is 0.76 meters in diameter. The vessel is trace heated and insulated. It can accommodate a steam atmosphere.

The steam delivery system consists of an accumulator volume representing the primary system volume, and a pneumatically actuated ball valve designed for high pressure steam. The accumulator, valve, and all piping in the steam delivery system are heated and insulated.

The Zion cavity model was designed and built from drawings supplied by the SNL DCH team. A schematic of the cavity is shown in Figure 2. Bolted on top of the pipe body is a saddle piece, referred to as the top cap, which contains the melt generator and injector (MGI). The cavity keyway is elongated by a transition chute which connects the cavity to the bottom of the expansion vessel. The elongation is required in order to allow room for the melt generator to fit underneath the expansion vessel. Thus, the keyway, is elongated by 1.7 times its correctly scaled length. The melt generator is shown in Figure 3. The melt generator also includes a baffle plate in order to diffuse the steam jet entering from the accumulator.

The model of the Zion subcompartment structures is shown schematically in Figure 4. The model is a scaled down version of the model used in the SNL test. Prominent features which are modeled include the seal table room, refueling canal, biological shield wall, reactor coolant pumps, steam generators, floor grating and operating deck floor. The walls and floors are constructed from concrete and mortar. The structure has been painted with epoxy paint. The model was built up from the lower flange of the expansion vessel. The perimeter of the model is defined by a circular concrete wall which simulates the crane wall in the plant. The walls and floors are held together by 1/4" threaded rods. Seals are made at various joints with high temperature RTV silicon rubber.

Table 2 details the type and location of instrumentation that was recorded during the test. All pressure measurements were taken with strain gauge type transducers. Temperature measurements were made with type K thermocouples at various locations. The thermocouples in the subcompartment model were bare junction. The thermocouples located in the expansion vessel were also bare junction. Cavity gas temperatures were measured by an aspirated thermocouple assembly. The assembly consists of a bare-junction tungsten rhenium thermocouple, shielded by 1/4" stainless steel tube. The tube has a slot cut in the end to draw gas through and over the junction. The flow area through the slot equals the cross sectional flow area of the tube. The TC junction is set back away from the slot. The tube is inserted into the cavity through a hole in the wall near the cavity exit. The end of the tube is connected to a solenoid valve which vents the assembly to a gas bottle. The solenoid valve is opened from 0 to 0.5 seconds after the start of the HPME. The start of the high pressure melt ejection is signalled by a twisted pair of varnished copper wires located just below the brass melt plug. When melt is ejected it contacts the wires, vaporizing the varnish and making an electrical connection between the two wires. This signal actuates the automatic gas sampling system. Gas composition measurements were made by use of gas grab sample bottles. All sample bottles are evacuated prior to the test. The disposition of the thermite melt was measured after the test. The recovery was typically made by vacuuming the debris from each specific location of interest. The debris is maintained in sealed plastic bags. Particle sizing, when possible, was carried out with a sonic sifter.

Test operations are begun by preheating the apparatus to the correct initial temperatures. If called for by the test, water is added to the cavity. The EV is then pressurized to the initial condition. The steam generator is brought to the test specified pressure. The accumulator is pressurized with steam from the boiler to the test specification.

The test is begun by starting the data acquisition and then depressing a start

button which activates a timer. This applies power to the ignitor assembly which starts the thermite reaction. The reaction proceeds downward until it encounters a burn wire located above the melt plug. This actuates the opening of the steam valve. The valve opening time is typically 100 milliseconds. At some time after the steam introduction the thermite reaction reaches the brass plug in the melt generator and fails the plug. This starts the high pressure melt ejection and is signalled by the burn wire under the plug. The burn wire signal starts a timer which actuates the automatic gas sample bottles. At specified times after the melt ejection gas samples are also taken manually.

EXPERIMENTAL RESULTS

Table 3 summarizes the initial conditions for the six Integral Effects Tests (IET) completed. A brief description of each test and the rationale for selecting the conditions of each of the test is summarized below.

IET-1R and 1RR were counterpart to the SNL IET-1 and 1R tests. These tests contained nitrogen inerted containment atmospheres to allow a separate measurement of the hydrogen produced in the metal oxidation by the blowdown steam. IET-1R was repeated in IET-1RR for two reasons. First the application of the steam to melt generator was mistimed with the failure of the brass plug and the melt was partially ejected under low pressure conditions. Secondly, the blowdown time of the accumulator (primary system) was elongated due to vaporization of significant amounts of condensate in the system.

The IET-3 test was counterpart to SNL IET-3. The initial conditions for IET-3 were nominally the same as IET-1RR with the exception of the containment atmosphere. The initial atmosphere composition was 50 mole percent air and 50 mole percent nitrogen. Hydrogen produced in the metal steam reactions can combust with the oxygen in the atmosphere.

IET-6 was counterpart to SNL IET-6. This test further changed the atmosphere composition by adding pre-existing hydrogen. The amount of hydrogen added was consistent with the levels produced by approximately 50 % in-vessel zirconium oxidation during the core degradation process.

IET-7 was not run counterpart to any specific SNL test. This initial conditions in this test were nominally the same as IET-3 with the exception of the initial containment pressure which was reduced by one half. This test was motivated to test the effect of the ratio of the initial driving pressure to the initial containment pressure. This has been identified as an important scaling group in the CLCH model of Theofanous (1992).

The IET-8 test was not run counterpart to any specific SNL test. This test nominally repeated the same initial conditions of IET-6 with the exception of the containment atmosphere. This test used steam instead of nitrogen. This represents a more realistic state of the containment during a pump seal LOCA.

Table 4 summarizes the results of all the tests. The driving pressure in these tests vary from 5.7 to 6.7 MPa. Figure 5 shows a typical pressure history in the vessel obtained in the experiments. Figure 6 shows the mass flow rate of steam exiting the vessel. This result indicates that the HPME in the experiments is

characterized initially by the ejection of melt and steam simultaneously. This is followed by a period of single phase steam ejection starting at approximately 0.22 seconds. Similar results were obtained in all of the experiments.

Figure 7 plots the containment pressure response obtained in all of the experiments. It is noted that the largest increase was obtained in the test containing pre-existing hydrogen, IET-6. The second and third largest increases were obtained in IET-3 and 7 were the containment atmospheres were partially inerted with nitrogen. The lowest increases were obtained in the fully inerted IET-1RR and the partially steam inerted IET-8.

Figure 8 shows a typical pressure response of the cavity in the tests. Also plotted is the containment pressure and the output of a photodiode positioned at the cavity exit. The photodiode outputs a signal when the luminescent melt is present at the cavity exit. This indicates that the pressure difference between the cavity and containment is associated with the sweepout of the melt from the cavity. Figure 9 plots the temperature of the gasses exiting the cavity in IET-3 as measured by the aspirated thermocouple assembly located near the cavity exit. This measurement indicates the high heat transfer rates that occurs between the melt and blowdown gasses during the cavity sweepout period. The cavity sweepout is also characterized by the significant conversion of the blowdown steam to hydrogen. This is indicated the analysis of gas grab samples taken in the cavity during the sweepout period. The results of cavity gas grab sample analysis for all tests showed 30 to 60 mole % hydrogen. These samples were taken from 0 to 0.5 seconds after the start of the HPME.

In addition to the gas samples taken in the cavity, many gas samples were taken in the upperdome. All of these samples were taken nominally at the same elevation and at different radial locations near the vessel walls. In tests IET-1 through 3 samples were taken at one and 7.5 minutes after the HPME. Three samples were taken at each time. The samples were found to be very consistent and the results were averaged to obtain the vessel atmosphere composition post test. In IET-6 through 8 gas samples were also take at 30 seconds after the HPME. These samples indicated lower hydrogen and greater oxygen concentrations that those samples taken at later times. Table 5 summarizes the results of gas sample measurements. These data have a significant impact on the interpretation of hydrogen production and combustion in the experiments. This will be expanded on in detail in the following section of the paper.

Table 6 summarizes the debris disposition for the ANL IET tests. The distribution of the debris was consistent in all the tests. It is noted that there was nearly complete ejection of the melt (over 90 %) from the melt generator in all tests. The sweepout fraction from the cavity varied from 69 to 79 percent in all of the tests. The data indicates that of the debris swept out of the cavity, nearly 90 percent of it is trapped within the subcompartment. Of the debris retained in the subcompartment 20 to 30 percent of it is trapped in the seal table room. All of the debris retained in the cavity is present as an evenly dispersed crust on the walls and the floor.

The size of the debris particles is an important piece of information. However, it is difficult to characterize the size after the test. The debris retained in the subcompartment is typically present as re-agglomerated particles. Therefore, it is difficult to characterize their size. Only the debris that is transported

to the upper dome appears to solidify at the size that is produced by the HPME. Table 7 summarizes that results of a sonic sifting analysis of the debris found outside the subcompartment.

A meaningful way to compare tests at different scales or with different initial conditions is on the basis of the measured pressurization efficiency, η . This is defined as

$$\eta = \frac{\Delta P_{\text{exp}}}{\Delta P_{\text{max}}}, \quad (1)$$

where ΔP_{EXP} is the peak pressure increase measured in the upperdome and ΔP_{MAX} is the maximum expected pressure increase based on a single cell adiabatic equilibrium calculation. Pilch and Allen (1991) have developed in detail a single cell equilibrium model for calculating the bounding pressure increases due to a HPME. This was the basis for the scaling rationale used to select the initial melt mass. The maximum pressure increase results from the contributions of the four energy sources to the containment. It gives a bounding estimate because it makes the following assumptions. All of the debris that is ejected from the vessel into the cavity is assumed to participate and fully equilibrate with the containment atmosphere. It assumes all of the metal in the melt to oxidize in steam to the extent that steam is available. All of the hydrogen produced in these reactions is burned to the extent that oxygen is available. Finally it does not account for the mitigating effects of water in the cavity in the containment. The efficiency calculation was carried out for the ANL integral tests and the results are shown in Table 8.

In the next section the experiment results are discussed and interpreted in the context of what insight has been gained into understanding and resolving the DCH issue.

DISCUSSION OF RESULTS

The principal question that motivated this integral effects testing program is; What are the effects of scale on DCH phenomena? Considerable insight has been gained into answering this question. Table 9 compares the results obtained in the three ANL-SNL counterpart tests. The table give columns on the actual measured quantities and also columns on the values scaled up to full size for convenient comparison. Several important points can be noted from this table. The only significant distortion in the initial conditions was the total g-moles of steam in the blowdown gas. The measured maximum pressure increase in the containment was smaller in the larger scale for the inerted 1R tests. However, the maximum pressure increase for the non-inerted 3 and 6 tests was greater in the larger scale. The total amount of hydrogen produced in the test was comparable with no test varying by more than 20%. The percentage of hydrogen burned in IET 6 and 7 also appear comparable. It should be noted that these calculations are based on the long time gas sample data, that is samples taken well after the HPME. However, data taken on a shorter time scale in IET-6, 7 and 8, show less hydrogen production and oxygen depletion than the later data. The calculation of the hydrogen production assumed that all of the change in oxygen is due to hydrogen combustion. This may be in error because the oxygen may also directly react with metal in the melt. This point will be elaborated on in

further detail below. The data on the distribution of the debris after the test are also quite similar. No significant distortion in the sweepout fraction or the transport to the upperdome is indicated with scale. Experiments in both scales demonstrate the effectiveness of the subcompartment structures in trapping debris. The calculated pressurization efficiency for the counterpart tests indicated a larger efficiency for the inerted tests and smaller efficiencies for the non-inerted test when the small scale is compared to the large scale.

From this data, two observations can be made on the effect of 1/40th versus 1/10th linear scale on DCH phenomena. Tests with inerted containment atmospheres, where debris/gas heat transfer and exothermic metal/steam reactions are the only significant energy sources, did not produce any significant difference in containment load with scale. In fact the 1/40th scale ANL test produced a higher pressure load, 150 kPa compared to 110 KPa in the 1/10th SNL scale, and higher efficiency, 31.3% compared to 25.8%. This leads to the first observation that the processes controlling debris/gas heat transfer and debris oxidation is not scale dependent. In contrast with the inerted test, the non-inerted tests yielded higher containment loads in the larger scale. This results lead to a second observation that the efficiency of hydrogen combustion increases with scale. This is tentative. It is strongly dependent on the interpretation of the gas sample data.

The observation that the debris/gas heat transfer and oxidation processes are scale independent arises from data indicating that the cavity sweepout is the controlling mechanism for these processes. The sweepout of the melt by the high velocity blowdown gasses leads to a high degree of mixing in the cavity. This efficient mixing process leads to nearly complete oxidation of the "reactive" metals in the melt and nearly complete thermal equilibration of the melt and blowdown steam. This is supported by measurements of the gas temperature exiting the cavity, Figure 9, and the large hydrogen concentrations found in the cavity gas samples. When the melt is ejected from the cavity into the lower subcompartments the majority, 90 to 95 percent, is trapped by structure where it can no longer efficiently transfer energy to the containment atmosphere. Thus, the cavity interaction becomes the dominant process by which the melt energy is transferred to the containment. This situation is only expected to hold for geometries where the lower compartment structures are effective in trapping the majority of the debris and significantly reducing the effective flight path of debris exiting the cavity. In the limiting case where the containment pressure rise is obtained only by the heat up of the blowdown gasses, the time rate of change of the containment pressure is given by

$$\frac{dP}{dt} = \dot{m} \frac{C_v (\gamma - 1)}{V_{cont}} T \quad (2)$$

where the $\dot{m}$ is the blowdown rate of the accumulator and T is temperature of the gas exiting the cavity. Figure 10 gives the results of the calculation for the blowdown rate obtained in IET-8 with various assumed temperatures exiting the cavity. This is a good comparison because hydrogen combustion was inerted in this test. Similar results are found for IET-1R and 1RR which were inerted by nitrogen. Here gas temperatures from 1500 to 2000 K gives order of magnitude agreement with containment pressure increase. Cavity gas temperatures from 1400 to 1900 K have been measured in the ANL tests. This gives an indication to the role that the cavity sweepout process plays in controlling the energy transfer

to the containment in the ANL tests.

The effects of scale on the cavity sweepout process is somewhat unclear. However, due to the similarity of the sweepout fraction and hydrogen production data between the ANL and SNL tests, it can be inferred that the efficiency of the cavity energy transfer process is roughly scale independent. Therefore, the measured containment loads in the inerted tests were similar.

The observations on the effects of scale on the debris/gas heat transfer process can be summarized as follows. The cavity sweepout process is characterized by large heat transfer rates between the blowdown steam and melt. This leads to a large increase in temperature of the blowdown gas. This process is roughly scale independent. When the subcompartment structures are effective in reducing the flight path and trapping debris ejected from the cavity, the cavity interaction becomes the controlling process for debris/gas heat transfer and metal oxidation. Since this process is scale independent the measured containment loads are independent of scale for inerted tests.

The effects of scale have been minimal on the debris/gas heat transfer and metal oxidation in the counterpart tests. However, there appears to be some scale effects on hydrogen combustion. The data in Table 9 indicate a larger containment pressure loads and higher efficiencies in the larger scale experiments. However gas sample analyses show similar hydrogen production and combustion amounts as indicated in Table 9. In addition the increases in pressure rise in the non-inerted tests relative to the inerted test does not fully account for the amount of hydrogen the gas sample analyses indicates being burned. This is true for tests in both scales.

In IET-6, 7 and 8, gas sample measurements were made also at 30 seconds after the start of the HPME. These measurements indicated that the concentration of hydrogen and oxygen was changing well after the HPME. Figures 11 and 12 show the number of gram-moles of hydrogen and oxygen in the containment atmosphere as a function of time elapsed from the start of the HPME for IET-6 and 8. The physical significance of the plots is open to interpretation, however, the following explanation is plausible.

In the case of IET-6, there was visual evidence of a hydrogen burn that occurred on the timescale of the blowdown. This evidence was obtained by video cameras in the upper dome looking down on the subcompartment structures. The burn occurred as hydrogen produced in cavity exited, passed through the subcompartment and up into the upper dome. The duration of the burn was on the order of 0.2 seconds and commenced just after the start of the HPME. Thus, the visual evidence indicated a burn of hydrogen as a plume exiting the cavity that scaled with the blowdown time. However, the data in Figure 11 show the continued depletion of oxygen and increase of hydrogen well after the blowdown. Extrapolating the oxygen data back to time zero yields a depletion of approximately 1.8 gram-moles of oxygen on the time scale of the blowdown or sweepout. This would correspond to the combustion of 3.6 gram-moles of hydrogen on the time scale of the sweepout. This is consistent with 4.0 gram-moles of hydrogen produced in the inerted IET-1RR test. The data in Figure 11 shows a continued slight increase in H_2 and decrease in O_2 well after the HPME. This can be attributed to the long time oxidation of iron in the melt by both steam and oxygen. There is no indication that any of the pre-existing H_2 burned in IET-6.

The results obtained in IET-6 is contrasted with results obtained in IET-8. The conditions for these two tests were comparable with the exception of steam in the containment atmosphere in IET-8 as opposed to nitrogen in IET-6. In IET-8 there was no visual evidence indicating a hydrogen burn in IET-8 as was obtained in IET-6. The data in Figure 12 indicates very little depletion of O_2 on the sweepout time scale. However, there is a large increase in the hydrogen moles due to oxidation of metal in the melt by steam. This predominately occurred in the cavity, during sweepout, as in all other tests. The data shows the total depletion of one gram-mole of oxygen over a long time scale. This can be attributed to the further oxidation of iron in the melt.

These results show that the apparent discontinuity of the measured pressure increases in the tests and the amount of hydrogen burned, as indicated by long time gas samples can be explained. However, tests with more samples in time should be performed in order to clarify this issue. The findings here may also explain the apparent affects of scale that have been obtained in the non-inerted tests. It is possible that the hydrogen combustion is more efficient at larger scale. Tests run at both scales with gas samples at increased times will help to clarify this issue.

CONCLUSIONS

A series six of integral experiments have been completed that investigate DCH phenomena in Zion Nuclear Power Plant geometry at 1/40th scale. Three experiments, IET-1RR, 3 and 6, were counterpart to 1/10th scale integral experiments at SNL. These tests directly addressed issue of scale effects on DCH phenomena. In addition tests were conducted that investigated the effect containment atmosphere initial condition by decreasing the initial pressure in IET-7 and partially inerting with steam in IET-8. The following major conclusions are drawn from these tests:

- 1) There is little effect of scale on debris/gas heat transfer and debris oxidation. In these tests the majority of debris swept out of the cavity was trapped in the lower subcompartments. In these cases the transfer of thermal energy from the debris is confined to the cavity region during sweepout.
- 2) The lower subcompartment structures were effective in trapping 90 to 95 percent of the debris that exited the cavity.
- 3) The efficiency of hydrogen combustion increased with increasing scale in the counterpart experiments. However, when measured by the actual containment pressure load, this effect is small. Complete quantification of scale effect on hydrogen combustion cannot be made at this time due to some open questions which require resolution. There remains a question with regards to the time scale of hydrogen production and combustion. Tentative data from the ANL tests indicate significant amounts of hydrogen being produced and oxygen being depleted well after the HPME. In addition the fraction of the pre-existing hydrogen which burns remains unanswered. More experiments are required in order to resolve the hydrogen burn question.

- 4) A decrease in the initial containment pressure from 0.2 to 0.1 MPa did not produce a significant change in the containment loading. The pressurization efficiency was approximately the same while the pressure increase was less due to the lower atmosphere heat capacity in the lower pressure test.
- 5) The effect of a more prototypic atmosphere composition was investigated in the IET-8 test. In this test the initial containment atmosphere contained 50 percent steam and 50 percent air. The steam was effective in preventing the combustion of the hydrogen compared to the IET-3, 6 and 7 tests which contained initially 50 percent air and 50 percent nitrogen.

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Table 1. Summary of Specified Reference Initial and Boundary Conditions

	Zion NPP	SNL (1/10)	ANL (1/40)	SNL (FS)	ANL (FS)
Melt Mass, kg	54,000	43	0.71	45,000	45,400
Composition, Mass Fraction	61% UO ₂ , 15% Zr, 24% SSr	52% Fe, 11% Cr, 3% Al, 34% Al ₂ O ₃		-----	-----
Temperature, K	2600 K	2500 K		-----	-----
RPV Gas Composition	Steam	Steam	Steam	-----	-----
Pressure, MPa	17.0 (6.2*)	6.2	6.2	-----	-----
Volume, m ³	360.0	0.345	6.1x10 ⁻³	345	368
Hole Dia, cm	Initial 2.54 Final 35.0	3.5	0.89	35.0	35.0
Containment Free Vol, m ³	77,000	89.8	1.51	89,800	91,100
Pressure, MPa	0.20	0.20	0.20	-----	-----
Composition, Mol%	50% air, 46.0% Steam, 4.0 H ₂	Varied	Varied	-----	-----
Temperature, K	373	300	300	-----	-----
Cavity Water, kg	2600	3.48	0.057	3480	3480
Depth, cm	6.7	0.9	0.23	9.0	9.0
Containment Water, kg		71	1.18	71,000	71,000
Depth, cm		1.5	0.38	15.0	15.0

* Pump seal LOCA initiated by station blackout.

Table 2. Instrumentation

Channel No.	Type ⁽¹⁾	Range	Location/Purpose
1	Current/Continuity	0-50 mV	Ignition signal and start of HPME
2	Thermocouple	0-485°C	Accumulator Gas Temperature
3	"	"	" " "
4	Pressure Transducer	0-1500 psig	Accumulator Pressure
5	" "	"	" "
6	Continuity	0-1.5 V	Signal to Open Steam Valve
7	Pressure Transducer	0-1500 psig	MGI Pressure
8	" "	"	" "
9	" "	0-100 psig	Cavity Pressure
10	Thermocouple	0-485°C	Cavity Floor Temperature
11	"	"	" " "
12	Photo cell	0-1 V	Cavity Window/Measure Melt Ejection
13	Thermocouple	0-1233°C	Seal Table Room Gas Temperature
14	Microswitch	0 - 6 V	Valve Open Signal
15	Pressure Transducers	0 - 125 psia	EV Pressure
16	" "	"	" "
17	Thermocouple	0 - 1233°C	Subcompartment Gas Temperature
18	"	"	" " "
19	"	"	" " "
20	"	"	" " "
21	Pressure Transducer	0 - 100 psig	EV Pressure
22	" "	"	" "
23	" "	"	" "
24	Thermocouple	0 - 485°C	Refueling Canal Temperature
25	"	"	EV Temperature H = 0.79 m
26	"	"	" " H = 1.22 m
27	"	"	" " H = 1.63 m
28	"	"	" " H = 1.83 m
29	Pressure Transducer	0 - 100 psig	Aspirated TC Assembly Pressure
30	Thermocouple W-Re, Base	0 - 2300°C	Cavity Gas Temperature
31	Thermocouple	0-485°C	EV Temperature H = 2.13 m
32	"	"	" " H = 2.59 m

⁽¹⁾ All thermocouples are bare bead type K unless otherwise noted.

Table 3. Initial Conditions for ANL Fe/Al₂O₃-Cr Tests.

	IET-1R	IET-1RR	IET-3	IET-6	IET-7	IET-8
D _H , cm	0.89	1.3	1.1	1.1	1.1	1.1
P _o , MPa	6.2	6.7	5.7	6.6	6.1	6.5
g-moles Steam	8.55	9.84	8.43	9.65	8.88	9.36
P _{co} , MPa	0.2	0.2	0.2	0.2	0.1	0.2
T _{co} , K	308	318	318	315	318	477
EV Atm, Mole %						
N ₂	99.9	99.9	88.8	87.5	89.9	37.4
O ₂	0.0026	0.12	10.8	9.9	10.1	7.7
H ₂ O	~0	~0	~0	~0	~0	50.0
H ₂	~0	~0	~0	2.0	~0	3.9

Table 4. Summary of Results from ANL 1/40 Scale Tests

	IET-1R	IET-1RR	IET-3	IET-6	IET-7	IET-8
P _o , MPa	6.2	6.7	5.7	6.6	6.1	6.5
ΔT _{p-e} , s ⁽¹⁾	-0.6	0.22	0.28	0.29	0.81	0.42
Ejected Melt Mass, kg	0.81	0.79	0.75	0.69	0.71	0.70
Blowdown Duration, s (P/P _o = 0.1)	3.20	0.61	1.00	0.76	0.82	0.82
Blowdown Steam, g-moles	8.55	9.84	8.43	9.65	8.88	9.36
Initial EV Pressure, MPa	0.2	0.2	0.2	0.2	0.1	0.2
Initial EV Atmosphere Composition, mole%						
H ₂	~0	~0	~0	2.0	~0	3.9
O ₂	0.0026	0.12	10.8	9.9	10.1	7.7
N ₂	99.9	99.9	88.8	87.5	89.9	37.4
Δ P _{max, cavity} , kPa	920	550	200	480	430	290
Δ P _{max, dome} , kPa	170	150	190	250	166	133

⁽¹⁾ Elapsed time from pressurization of melt generator to onset of melt ejection.

⁽²⁾ An unknown amount of debris was lost from this region during the recovery procedures.

Table 5. Summary of Gas Sample Measurements for ANL IET-1, 1R, 1RR, 3 and 6

Gas	IET-1	IET-1R	IET-1RR	IET-3	IET-6		IET-7		IET-8	
Background/Initial Conditions										
N ₂ (mol %)	99.4	99.9	99.9	88.8	87.5		89.4		37.3	
H ₂	<0.01	<0.01	<0.01	<0.01	2.0		±0.01		3.8	
O ₂	0.5	0.0026	0.12	10.8	9.9		10.1		7.7	
CO ₂	0.0048	0.004	0.011	0.011	0.013		0.021		0.5	
CO ₁	<0.01	<0.006	<0.005	<0.02	<0.01		<0.01		0.2	
H ₂ O	0	0	0	0	0	0	0	0	50.0	
Mean Concentrations in Upper Dome					a	b	a	b	a	b
N ₂	97.1	96.0	95.5	88.3	88.0	88.3	88.2	88.0	29.1	30.0
H ₂	1.28	3.14	3.36	0.965	2.6	2.2	2.7	2.0	8.3	4.8
O ₂	0.46	0.094	0.13	9.23	8.1	8.3	6.8	8.0	5.5	6.1
CO ₂	0.33	0.19	0.18	0.677	0.53	0.51	---	---	1.0	0.28
CO	0.64	0.48	0.70	0.18	0.17	0.13	---	---	1.4	1.0
H ₂ O	0	0	0	0	0	0	0	0	54.0	57.5

a) Mean of samples taken at 1 and 7.5 minutes.

b) Means of samples taken at 30 seconds.

Table 6. Summary of Debris Disposition

Location	IET-1R	IET-1RR	IET-3	IET-6	IET-7	IET-8
A. Initial Thermite Mass, g	820.0	820.0	820.0	713.0	713.0	713.0
B. Recovered from MGI, g	4.0	43.3	67.3	30.3	4.0	11.8
C. Recovered from Cavity and Chute, g	197.1	260.8	232.2	262.7	153.7	179.3
D. Seal Table Room, g	*	148.9	163.1	167.9	113.6	158.7
E. Remaining Subcompartment Structures, g	511.1	358.2	428.2	339.6	448.9	405.3
F. Total Retained in Subcompartment = D + E, g	551.1	507.1	591.3	507.5	562.5	564.0
G. Outside Structures, g	87.7	114.6	37.8	81.3	26.2	22.6 ⁽¹⁾
H. Total Recovered = B + C + F + G, g	799.9	925.8	928.6	881.8	746.48	804.5
Percent Increase (H-A)/A × 100%	-2.5	12.9	13.2	23.0	4.7	12.8
Fraction Ejected Into Cavity (A-B)/A	0.995	0.947	0.918	0.966	0.994	0.984
Fraction Sweepout of Cavity (F+G)/(C+F+G)	0.752	0.705	0.734	0.691	0.793	0.766
Fraction Transported out of Subcompartment F/(F+G)	0.147	0.184	0.060	0.138	0.045	0.0385

¹ An unknown amount of debris was lost during the vacuuming procedure.

Table 7. Particle Size

Test	Driving Pressure, MPa	Hole Size, mm	D, mm
1R	6.2	11	700
1RR	6.7	13	458
3	5.7	11	1009
6	6.6	11	1044
7	6.1	11	400

Table 8. DCH Pressurization Results

	IET-1RR	IET-3	IET-6	IET-7	IET-8
a) Experiment peak pressurization in cavity region, kPa	550	200	480	430	290
b) Experiment peak pressurization in done region, kPa	150	190	250	166	133
c) Theoretical maximum pressurization (adiabatic), kPa	479	904	1106	813	1108
d) DCH Efficiency = $\frac{(b)}{c} \times 100$	31	21	23	20	13

Table 9a. Counterpart Test-1R

	ANL	SNL	ANL (FS)	SNL (FS)
P_o , MPa	6.7	6.3	6.7	6.3
M_d , kg	0.79	38.37	45,800	38,400
Blowdown Time, s	0.61	3.42	23.92	34.2
Blowdown Steam, g-moles	9.84	477	593,000	477,000
P_{co} , MPa	0.2	0.2	0.2	0.2
T_{co} , K	318	290	318	290
EV atmosphere, mole %				
N_2	99.9	99.8	99.9	99.8
O_2	0.12	0.19	0.12	0.19
H_2	~0	~0	~0	~0
$\Delta P_{max, cavity}$ kPa	550	265	550	265
$\Delta P_{max, cont}$ kPa	150	110	150	110
% Sweepout	70.5	67.0	70.5	67.0
% Dispersed to Upper Dome	18.4	10.5	18.4	10.5
H_2 Pre-Existing, moles	0	0	0	0
H_2 Produced ¹ , g-moles	4.0	223	241,00	223,000
O_2 Depleted ¹ , g-moles	0	0	0	0
DCH Efficiency, %	31.3	25.8	31.3	25.8
Percentage of H_2 Burned	0	0	0	0

¹ Based on mean of gas sample measurements at 1 and 7.5 minutes.

Table 9b. Counterpart Test 3

	ANL	SNL	ANL (FS)	SNL (FS)
P_o , MPa	5.7	6.1	5.7	6.1
M_d , kg	0.7	38.5	42,200	38,500
Blowdown Time, s	1.00	3.05	39.2	30.5
Blowdown Steam, g-moles	8.43	456	508,000	456,000
P_{co} , MPa	0.2	0.19	0.2	0.19
T_{co} , K	318	290	318	290
EV atmosphere, mole %				
N_2	88.8	90.6	88.8	90.6
O_2	10.8	9.0	10.8	9.0
H_2	~0	~0	~0	~0
$\Delta P_{max, cavity}$ kPa	200	370	200	370
$\Delta P_{max, cont}$ kPa	190	246	190	246
% Sweepout	73.5	61.7	73.5	61.7
% Dispersed to Upper Dome	6.0	8.8	6.0	8.8
H_2 Pre-Existing, moles	0	0	0	0
H_2 Produced ¹ , g-moles	4.65	223	280,00	223,000
O_2 Depleted ¹ , g-moles	1.75	9.3	106,000	93,000
DCH Efficiency, %	21.0	31.2	21.0	31.2

Table 9c. Counterpart Test 6

	ANL	SNL	ANL (FS)	SNL (FS)
P_o , MPa	6.6	6.3	6.6	6.3
M_d , kg	0.69	40.7	41,600	40,700
Blowdown Time, s	0.761	3.2	29.8	32.0
Blowdown Steam, g-moles	9.65	505	582,000	505,000
P_{co} , MPa	0.2	0.2	0.2	0.2
T_{co} , K	318	308	318	308
EV atmosphere, mole %				
N_2	87.5	87.1	87.5	87.1
O_2	9.9	9.8	9.9	9.8
H_2	2.0	2.6	2.0	2.6
$\Delta P_{max, cavity}$ kPa	480	1020	480	1020
$\Delta P_{max, cont}$ kPa	250	279	250	279
% Sweepout	69.1	83.4	69.1	83.4
% Dispersed to Upper Dome	13.8	13.8	13.8	13.8
H_2 Pre-Existing, moles	2.28	1800	138,000	180,000
H_2 Produced, g-moles	4.89	308	295,00	308,000
O_2 Depleted ¹ , g-moles	2.11	168	127,000	168,000
DCH Efficiency, %	22.6	28.1	22.6	28.1

Figure 1. COREXIT Facility.

Figure 2. Zion Cavity Model.

Figure 3. Schematic of Melt Generator and Injector (MGI).

Figure 4. Schematic of the Subcompartment model.

Figure 5. IET-8 Blowdown History.

Figure 6. IET-8 RCS Blowdown Rate.

Figure 7. ANL IET Results.

Figure 8. IET-8 Cavity Pressure and Photocell Output.

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