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RESULTS OF EPRI/ANL DCH INVESTIGATIONS AND MODEL DEVELOPMENT*

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by

B. W. Spencer and J. J. Sienicki

Reactor Analysis and Safety Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

and

B. R. Sehgal and M. Merilo

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

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B. W. SPENCER and J. J. SIENICKI (Argonne National Laboratory, USA)
B. R. SEHGAL and M. MERILO (Electric Power Research Institute, USA)

ABSTRACT

The results of a series of five experiments are described addressing the severity and mitigation of direct containment heating. The tests were performed in a 1:30 linear scale mockup of the Zion PWR containment system using a reactor-material corium melt consisting of 60% UO_2, 16% ZrO_2, 24% SSt at nominally 2800C initial temperature. A "worst-case" type test involving unimpeded corium dispersal through an air atmosphere in a closed vessel produced an atmosphere heatup of 323K, equivalent to a DCH efficiency of 62%. With the addition of structural features which impeded the corium dispersal, representative of dispersal pathway features at Zion, the DCH efficiency was reduced to 1-5%. (This important result is scale dependent and requires larger scale tests such as the SURTSEY program at SNL plus mechanistic modeling for application to the reactor system.) With the addition of water in the cavity region, there was no measurable heatup of the atmosphere. This was attributable to the vigorous codispersal of water with corium which prevented the temperature of the atmosphere from significantly exceeding T_{sat}. In this case the DCH load was replaced by the more benign "steam spike" from corium quench. Significant oxidation of the corium constituents occurred in the tests, adding chemical energy to the system and producing hydrogen. Overall, the results suggest that with consideration of realistic, plant specific, mitigating features, DCH may be no worse and possibly far less severe than the previously examined steam spike. Implications for accident management are addressed.

INTRODUCTION

It has been recognized for several years that a LWR core melt accident occurring at elevated reactor coolant system (RCS) pressure may conceivably lead to vigorous dispersal of core materials into the containment volume. Simply stated, this requires a sequence in which molten core materials collect in the lower head of a reactor pressure vessel and immediately, or over some length of time, degrade the head structure to the extent that it fails, causing an ejection of the accumulated core materials through the breach at the prevailing vessel-to-containment pressure differential. The ejection of core materials (corium) is to some extent accompanied by, and notably followed by, blowdown of the RCS to the containment atmosphere via the breach. The blowdown gas is comprised of steam and hydrogen. If the blowdown gas flow is of such a magnitude that it entrains and disperses corium droplets as it flows from the compartment beneath the reactor to the larger volumes of the containment, then the extent to which the atmosphere becomes a heat sink for the sensible and chemical energy of the corium needs to be addressed.

Corium dispersal actually encompasses a wide spectrum of severity. For example, low follow-on flowrate would be expected after corium flows from a failed lower head during low pressure sequences (large-break LOCA initiator or depressurized system. In this case, the ejected core materials would largely remain in the reactor cavity/pedestal region. In the absence of water, the principal heat sink for the core debris would be the concrete, resulting in familiar molten core/concrete interaction (MCCI). With modest blowdown flowrate, some core materials would be dispersed while the rest would remain beneath the vessel. A "benign" dispersal of corium in this manner could actually be beneficial since the spread out corium would be more readily coolable given the sustained presence of water. At the end of spectrum, however, are cases of high blowdown flowrate involving combined effects of elevated vessel pressure and large head breach size.

It is straightforward to scope the worst possible consequence of such a process, i.e., if all ejected core debris were dispersed into the containment atmosphere and heated that atmosphere adiabatically. For example, a simple calculation for a TMLB' sequence based upon Zion PWR reactor and containment parameters, using conditions specified in Ref. 1, results in calculated atmosphere temperature of 990K and pressure of 1.2 MPa (159 psig). This calculated pressure exceeds the ultimate strength capability of the Zion large, dry containment which is estimated to be 134 psig [2]. (The specific calculation assumes a corium temperature of 2533 K, 50% initial Zr oxidation, 100% oxidation in air, containment volume of 80,000 m^3 with initial temperature and pressure of 407K and 0.4 MPa, respectively, and initial vessel pressure of 17 MPa; however, this calculation uses 67,000 kg corium which is about 50% of the total corium mass of 138,400 kg specified in Ref. 1.) The direct containment heating (DCH) risk issues are: i) to what extent is such a worst-case scenario plausible, and ii) to what extent do real plant features plus realistic physical phenomena lessen the severity of containment loads from that suggested by simple scoping-type calculations.

The Electric Power Research Institute (EPRI) sponsored a number of reactor-material experiments addressing DCH phenomena at Argonne National Laboratory. These experiments were performed as part of the larger Corium-Water Thermal Interaction (CWTI) study from 1984 to 1986 [3,4]. The purpose of this paper is to report on the findings of those experiments and also on the development of the HARDCORE [5] and PARSEC [6] computer codes which contain detailed models of physical phenomena encountered in cavity interactions and DCH, respectively. The experiments are particularly noteworthy for their use of reactor-material corium (60% UO_2, 16% ZrO_2, 24% SSt @ 2800C) as well as wide parameter variations involving i) inert vs. air atmosphere, ii) presence or absence of structural barriers in the dispersal pathway, iii) presence or absence of water in the containment mockup, iv) presence or absence of water in the cavity mockup, and v) blowdown flowrate. The experiment configuration for the tests reported here mocks up the key features of the Zion containment at a 1:30 linear scale.

RELATIONSHIP TO OTHER STUDIES

The CWTI/DCH tests were performed before in-vessel core-melt progression codes such as MELPROG [7] and CORMLT [8] were sufficiently advanced to provide sequence-specific guidance regarding corium conditions at DCH onset (i.e., corium composition, mass, temperature, oxidation state, etc.). Similarly, models pertaining to breaching of the vessel lower head were at a scoping stage only. Hence the relevance of experiment conditions to calculated accident conditions remains to be determined. These in-vessel studies have been identified as key factors to reducing uncertainties in DCH initial conditions [9].

The USNRC has major programs under way involving cavity interaction tests, DCH tests, and model development. The SURTSEY program at SNL consists of thermite tests (55% Fe, 45% Al_2O_3 @ 2700C) performed at a 1:10 linear scale [10]. Results of these programs will provide valuable comparisons with the EPRI information which may foster consensus on this important risk issue. Other experimental and analytical programs are under way elsewhere, notably in the UK and Sweden, which directly address DCH issues.

The DCH phenomena also has important relationships to other containment phenomena. Specifically, the vigorous ejection of corium from the vessel and subsequent blowdown into the containment atmosphere would be expected to cause an "aerosol spike." The aerosol material would be expected to consist of all constituents of the core materials owing to the dominance of mechanical forms of aerosol production. A large aerosol presence was found in some of the SNL tests and was visually observed in the posttest CWTI/DCH atmosphere although the latter tests were not instrumented to quantify the aerosols.

For sequences with water present, DCH may also be expected to cause a "hydrogen spike" as predicted by analyses and observed in CWTI/DCH test results. The consequence of this is scenario dependent. The issue principally involves any effects attributable to the abruptness of the spike, since the hydrogen would eventually be produced during the corium quenching or, alternatively, as one of the combustible, noncondensable gases released by MCCI. The issue is particularly complex, but one should note that scoping-type DCH calculations have typically included 100% chemical energy release, whether it be attributable to oxidation in air or in steam with subsequent hydrogen burn.

Finally, this work has important relationship to accident management studies since the potential for mitigation by interaction of the airborne debris with structural barriers, interaction with water in the cavity, and interaction with water in the bottom of the containment have all been addressed.

BACKGROUND

The DCH test results reported here are the outgrowth of a number of small-scale, simulant-material tests and related analyses under way at ANL since 1980. The earliest tests were sponsored by Nuclear Safety Analysis Center (NSAC), created at EPRI following the TMI accident. These tests addressed ex-vessel hydrodynamic phenomena in the reactor cavity resulting from corium expulsion and vessel blowdown. Owing to immediate application to the NRC's then current Zion and Indian Point risk studies [11], the reference cavity geometry was decided to be a general mockup of the Zion cavity. That choice has continued through the DCH tests reported here, plus current SNL SURTSEY tests, largely because Zion remains the reference PWR with large, dry containment in NRC risk studies [12]. High-speed photography was used in the early tests to characterize the sweepout behavior, particularly the flowrate threshold corresponding to sustained sweepout, using water, Cerrolow (a dense, metallic alloy), and particle beds initially in the cavity and using nitrogen blowdown gas [13]. Results were found to be well correlated using the relationship:

$$U_{L,d} \geq C \left[\frac{(\rho_H - \rho_L) g \sigma_H}{\rho_L^2}\right]^{1/4} \tag{1}$$

where ρ = density, g = gravitational acceleration, σ = surface tension, sub H refers to heavy fluid, and sub L refers to the light fluid (gas). The term in brackets is the familiar Kutateladze grouping. A coefficient 2.46 for C corresponds to levitation of the maximum size stable droplets formed in the blowdown gas stream. Use of the coefficient 3.2 corresponds to the onset of fluid layer flooding (upward flow) on vertical surfaces. This type phenomenon was also observed in the tests. Use of the coefficient 3.7 corresponds to the threshold of liquid entrainment in vertical, separated flow. Disengagement of fluid droplets from liquid layers was also observed to be part of the sweepout process in the tests. Actual data correlated best with the 2.46 coefficient although such precision is not meant to be suggested. In current "pressure cutoff" studies, the Kutateladze (Ku) number used as a convenient indicator of sweepout threshold is equivalent to C^2 in Eq. 1.

Application of the sweepout threshold criterion, Eq. 1, using coefficient 2.46 to a TMLB' sequence with initial containment pressure of 0.4 MPa (4 atm absolute) and steam blowdown gas indicates that any water present in the cavity would be swept out at steam blowdown flowrates in excess of ~10 m/s and similarly for corium at steam blowdown flowrates in excess of 30 m/s. The 30 m/s threshold flowrate for corium dispersal is attained on average in the particular Zion dispersal pathway when the breach size in the vessel lower is about 0.01 m^2, ~110 mm equivalent diameter (choked flow, 17 MPa). For comparison, a single instrumentation guide tube penetration has a bore diameter of 40 mm which would enlarge to 170 mm after passage of 25% of the core inventory under TMLB' conditions [14].

Two other points were noted as regards these dispersal thresholds, both concerning the possible presence of water in a Zion-like cavity. Calculations indicate that even in low pressure sequences, water is likely to be dispersed from the cavity by action of the steam exit flowrate owing to corium quench in the water. Any blowdown from the RPV would add to the total efflux flowrate. Secondly, when there is a significant level of water in the cavity, the gas blowdown is observed to cause a cratering in the liquid level beneath the breach (blowdown jet) and wave growth in the surrounding liquid. This wave was observed to grow to completely occlude the pathway cross section when the initial water level was greater than ~30% of the tunnel (pathway) height. This resulted in buildup of a pressure differential across the water slug which continued until the slug completely cleared the exit of the pathway. This liquid slug formation was found to be a mechanism to build up a high pressure in the cavity for the time duration until the dispersal pathway was cleared. Importantly, the initial slug ejection mode of water dispersal involved less than half the water inventory, the rest remaining in the cavity subject to the continued dispersive action of the RCS blowdown.

In subsequent tests sponsored by IDCOR, molten Wood's Metal was ejected into the cavity mockup followed by simulated vessel blowdown [15]. It was found that the water slug ejection carried with it a sizable amount of the corium simulant, actually increasing the sweepout fraction. These early ejection tests also showed evidence of the "punchthru" phenomenon wherein three stages of ejection from the simulated reactor pressure vessel (RPV) could be discerned, namely: 1) a stage of nominally single-phase ejection of the melt, 2) a subsequent stage of two-phase ejection initiated when the high-pressure gas punches through the melt layer, and 3) a subsequent single-phase gas blowdown stage following full depletion of the melt. This kind of melt ejection behavior is also evident in DCH data and is one of the numerous cavity interaction phenomena modeled in HARDCORE, as is the ablation-induced enlargement of the breach as high-temperature corium is ejected.

The preceding physical picture evolved from tests and modeling addressing sweepout thresholds. The same basic concepts also apply for cases of interest to DCH where the blowdown flowrate may greatly surpass the threshold values. Additional simulant-material tests were performed to address what ultimately becomes of melts vigorously swept from the cavity into other regions of the containment by a vigorous vessel blowdown [16]. Once again, Zion was used as the specific containment modeled for experiments. This work was sponsored by the Industry Degraded Core Rulemaking (IDCOR) Program. The results confirmed previous findings that with water present in the cavity there were two distinct modes of sweepout. The first stage was characterized by ejection of a water slug out the inclined pipeway which typically carried melt debris with it. The second stage involved gradual dispersal owing to effects of the follow-on blowdown gas as described previously. A principal finding of this study was that most of the dispersed melt was intercepted in a recess in the compartment beneath the seal table (Fig. 1). This particular structural feature of Zion intercepted ~90% of the dispersed melt in these tests, causing it to be redirected onto the (basement-level) floor. The remaining small mass of ejected melt continued its upward flow to the ceiling of this lower (basement) compartment. It is not possible to draw specific conclusions from these small-scale dispersal tests without development of detailed multi-dimensional modeling since sweepout trajectory effects are so scale dependent (unlike sweepout threshold per Eq. 1). However, some important observations could be made from these tests:

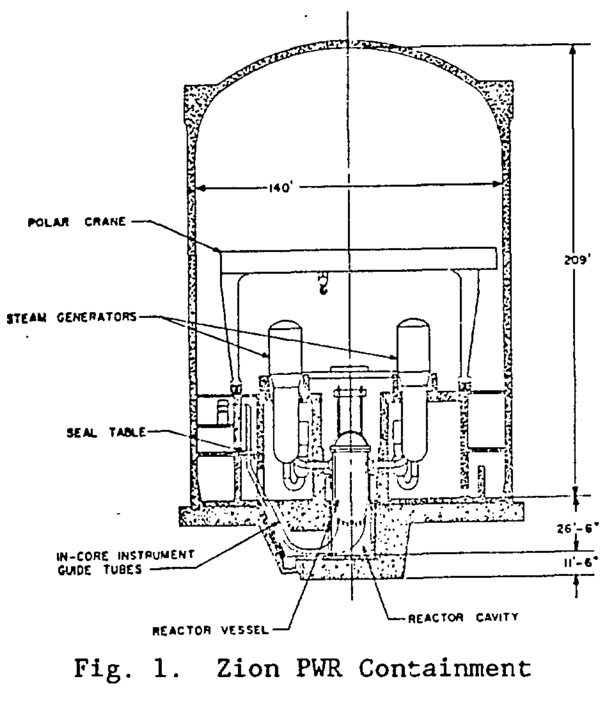

Fig. 1. Zion PWR Containment

1) Structural features of containments, including multiple compartments in the blowdown pathway, may intercept the dispersed droplets thereby shortening their path length in the atmosphere; such features are plant specific.

2) Intercepted droplets may either adhere to structures or may fall back onto the floor. In either event, the energy available for DCH is lessened. In performing the later CWTI/DCH tests, it was regarded as necessary that at least some of the tests be performed with the realistic structural features found in the reference plant, plus the possible presence of water on the basement floor.

II. EXPERIMENT DESCRIPTION

The CWTI/DCH tests were conducted in the Corium Ex-Vessel Interactions (COREXIT) Facility illustrated in Fig. 2. The facility consists of a doubly contained cell, CWTI test apparatus, and ex-

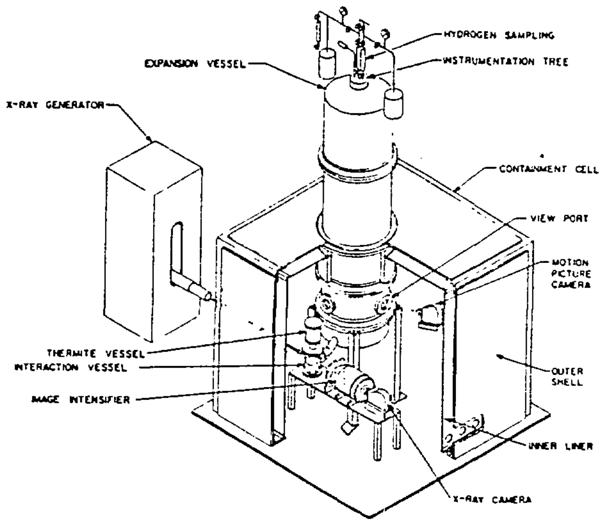

Fig. 2. EPRI/ANL COREXIT Facility

periment control and diagnostics equipment. The experiment apparatus is shown in Fig. 3. The apparatus consists of four basic components: the thermite vessel which is the source of the ejected corium plus follow-on blowdown gas, an interaction vessel which mocks up the reactor cavity, a discharge pipeway which mocks up the shaft configuration connecting the reactor cavity to the steam generator compartment, and an expansion chamber representing the containment volume. The apparatus is about 1:30 linear scale based upon the features of the Zion containment. The overall volume is 1.41 m^3; the expansion chamber measures 762 mm ID by 3.1 m high.

Figure 3 shows the presence of structure within the containment mockup. This structure was used for three of the five DCH tests reported here, and consists of i) a recessed "trap" above the discharge pipeway, ii) a bottom pan assembly, and iii) a horizontal baffle plate. Each of these features represented a containment design feature shown in the simulant-material flow visualization tests to be important to corium dispersal behavior. Specifically, the "trap" intercepted and redirected downward much of the upward directed corium except for fine droplets which flowed upward with the blowdown gas; this had a similar effect as the seal-table mockup as observed in earlier Zion-specific dispersal tests. Secondly, the pan at the bottom of the apparatus was used to hold water, heated to close to saturation temperature (T_{sat}). Hence corium droplets or particles falling downward onto the bottom were quenched and generated steam which contributed to the system pressurization. Thirdly, a horizontal baffle plate separated the containment mockup into upper and lower compartments. The baffle plate had 6% open area, matching the open area in the floor separating the Zion steam generator compartment from the dome region. This type of compartmentalization in containment designs is a realistic impediment to corium dispersal. In two of the tests, the "trap" and baffle plate structures were removed in order to be able to quantify their mitigation effect on DCH.

Test diagnostics consisted of fast-response pressure transducers at numerous locations in the system, numerous 1.6 mm dia type K grounded thermocouples to measure atmosphere temperature, and numerous other TC's to measure structure temperatures. Gas samples were drawn before and following the tests to determine the molar composition of the atmosphere which was used to determine hydrogen generation and/or oxygen depletion. High-speed motion pictures were taken of the corium as it entered the containment mockup from the exit of the discharge pipeway. Flash X-ray cine pictures were taken at 4 ms intervals of corium flow in the cavity mockup. All data was recorded at high speed on an analog type recorder and digitized for data processing and plotting.

The target corium mass used in these tests was 3.2 kg. This corresponds to 50% of the corium inventory for the Zion PWR at the 1:30 linear scale. (Actual injections achieved ranged from 2.3 to 3.9 kg.) The exothermic process used to generate the corium melt for these tests is described by:

$$4.67\ U + 2.83\ Zr + 3\ Fe_2O_3 + 2\ CrO_3 + Ni \rightarrow$$

$$4.67\ UO_2 + 2.83\ ZrO_2 + 6\ Fe + 2\ Cr + Ni + 2.2\ MJ/kg \quad (2)$$

The reaction products have composition 60% UO_2, 16% ZrO_2, 24% SSt (67% Fe, 21% Cr, 12% Ni) by weight. The reaction products have a temperature of 2807C and specific internal energy of 1.82 MJ/kg, referenced to 20C. The melt has a "superheat" of ~160C compared to the liquidus temperature of 2650C for the oxide solution, ~1350C compared to the steel-phase liquidus of 1460C. The thermite reaction takes place at nominally atmospheric pressure to assure good gas separation and pool formation; the melt is subsequently pressurized to burst a bottom diaphragm to initiate the ejection. Details of experiment apparatus and technique can be found in Refs. 3 and 4.

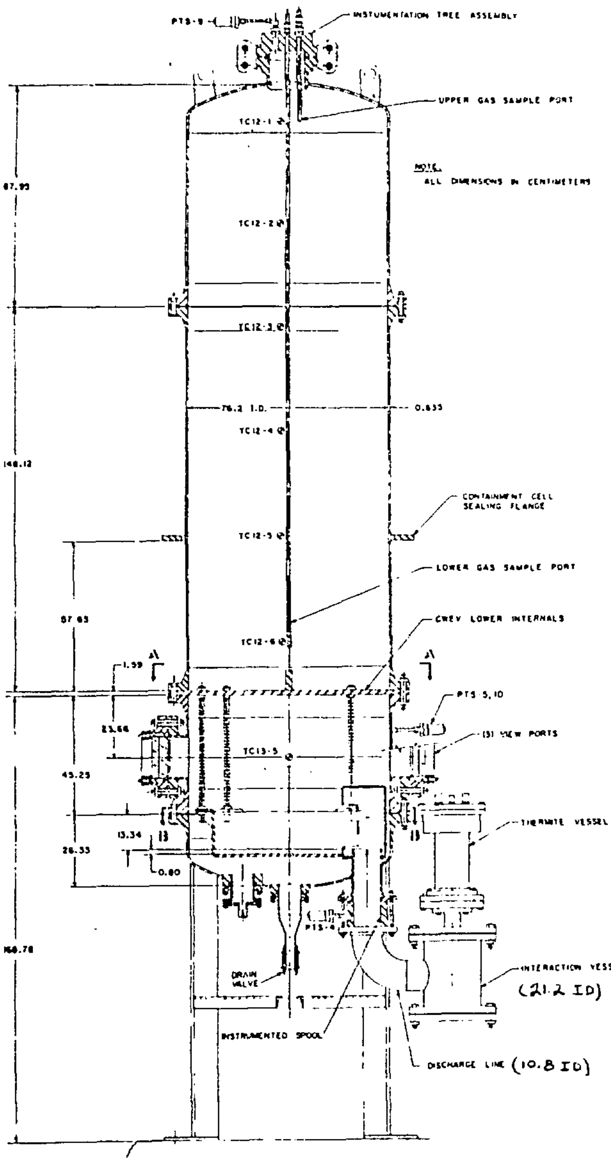

Fig. 3. CWTI Experiment Apparatus with Internal Structures in Place

III. EXPERIMENT RESULTS

Table 1 summarizes the key parameters in the five-test DCH series using the reference Zion configuration. The tests were planned with emphasis on examining real plant features which may mitigate DCH loads. Due to the uncertainty in the magnitude of the loads for these first-of-a-kind tests, the first two tests were performed with an inert atmosphere to limit the potential oxidation energy release. The first three tests all had the Zion-like structures as previously described which impede the upward corium dispersal. Tests CWTI-5 and 6 examined the effects of water initially present in the cavity mockup and containment mockup regions, respectively. Test CWTI-11 was the first to have an air atmosphere; otherwise it was a repeat of CWTI-6. For tests CWTI-12 and 13, the internal structures were removed so that the corium dispersal would occur unimpeded throughout the 3.1 m height of the containment mockup. The air atmosphere was retained. These two tests eliminated the Zion-scaled internal structures and were intended to provide benchmark data, particularly to support model development. Test CWTI-12 was a particularly interesting one for singling out the heat sink effect of water codispersed from the cavity. Test CWTI-13 was a "worst-case" type test, of interest primarily for quantifying DCH mitigation achieved in the other tests as well as for model development.

Sweepout Results

Conditions and results pertaining to the ejection of the corium melt into the cavity mockup, the follow-on gas blowdown, and the sweepout of corium from the cavity to the containment mockup region are summarized in Table 2. The injection pressure was nominally about 5 MPa (~710 psig). The nozzle size was 12.7 or 25.4 mm diameter. Sweepout was achieved in all tests, ranging from 9 to 61% of the corium mass ejected into the cavity mockup. Those factors having greatest effect on sweepout were the mass of corium ejected, the presence or absence

Table 1. Summary of EPRI/ANL CWTI-DCH Tests

CWTI	Dispersal Impediments	Atmosphere	Water in Cavity Mockup	Water in Containment Mockup
5	shroud/baffle	inert	5.6 kg	6.2 kg
6	shroud/baffle	inert	none	6.2 kg
11	shroud/baffle	air	none	6.2 kg
12	none	air	4.6 kg	none
13	none	air	none	none

Table 2. Initial Conditions/Sweepout Results

CWTI Test No.	5	6	11	12	13
Cavity Water Depth, mm	100	0.0	0.0	85	0.0
Pan Water Depth, mm	25	25	25	0.0	0.0
Pressure at Onset of Injection MPa	5.0	4.7	5.1	2.8	4.0
Injection Nozzle Dia, mm	12.7	12.7	25.4	25.4	12.7
Mass of Corium Injected, kg	3.94	3.75	2.93	2.69	2.27
1-ϕ Injection Duration, s	0.25	0.15	0.04	0.05	0.10
Injector Blowdown Duration, s[1]	0.07	0.07	0.04	0.35	1.6[2]
Avg Sweepout Flowrate, m/s	63	61	170	202	58
Sweepout Threshold Flowrate, m/s	26	36.6	36.6	28.4	36.6
Kutateladze No.	82	38	295	695	34
Percent Corium Sweepout	61	30	30	46	9

[1]Time starts at completion of 1-ϕ injection;
[2]delayed closing of HP reservoir

of water in the cavity, and the magnitude and duration of the follow-on blowdown gas. A steel cavity mockup was used in these experiments. The corium tends to freeze upon contacting the steel walls, forming a crust layer, and the crust formation lessens the corium mass available for sweepout. (The corium charge was reduced from 4 to 3 kg for CWTI-13 to intentionally limit the sweepout and thus avoid endangering the facility. This accounts for the low 9% achieved.) Tests with water in the cavity had the greatest sweepout (61% and 46%), consistent with observations from the flow-visualization tests previously described. The average gas blowdown velocity through the system surpassed the sweepout threshold by a factor of ~2 to 3 for tests with 12.7 mm nozzle dia and ~5 to 7 for tests with 25.4 mm nozzle dia. By design, the duration of the gas blowdown was sufficiently long to assure sweepout of all available melt (excluding crust). Comparison of tests 6 and 11 indicates that the corium mass swept out is not necessarily greater for significantly higher blowdown flowrate, so long as the sweepout threshold is surpassed and the blowdown duration sufficiently long.

Characteristic particle sizes for the swept out debris ranged from 64 to 700 microns for tests CWTI-11 and 13, respectively. Most particles were in the range 100-300 microns.

Oxidation

Data was obtained on the hydrogen generation and/or oxygen depletion that occurred during these tests. The results are summarized in Table 3. No hydrogen was measured in the atmosphere following CWTI-13 wherein no water was present, indicating no spurious sources of hydrogen in these tests. The depletion of oxygen in the posttest atmosphere measured between 4 and 14% of the total oxygen mass present in tests CWTI-11 through 13.

In the CWTI-5 and 6 tests with the inert argon atmosphere, the oxidation processes are assumed to be described by:

$$3\ Fe + 4\ H_2O \rightarrow 4\ H_2 + Fe_3O_4 + 165\ kJ/mole\ Fe_3O_4 \qquad (3)$$

and

$$2\ Cr + 3\ H_2O \rightarrow 3\ H_2O + Cr_2O_3 + 437\ kJ/mole\ Cr_2O_3 \qquad (4)$$

Table 3. Summary of Corium Oxidation Results

CWTI Test No.	5	6	11	12	13
Corium Mass Injected, kg	3.94	3.75	2.93	2.69	2.27
Corium Mass Swept Out, kg	2.44	1.21	0.88	1.31	0.20
Hydrogen Mass Generated, g (Percent of maximum in steam)	32(77%)	20(50%)	2.1(7%)	22(79%)	0
Oxygen Mass Depleted, g (Percent of maximum in air)	-	-	29(31%)[1]	7(5%)[1]	14(67%)[1]
Oxidation Energy Source, MJ	1.1	0.68	0.61	0.92	0.26

[1]Based upon mass of corium swept out

where the iron oxidation state Fe_3O_4 was found from X-ray diffraction exams. With water present only at the bottom of the containment mockup, the hydrogen generation results were equivalent to about 50% extent of reaction based upon all Fe and Cr injected into the system. With water in the cavity as well as containment mockup regions, the extent of reaction reached about 75%. Some of the hydrogen formed in test CWTI-11 is thought to have reacted with oxygen, accounting for the small 7% mass found at the end of the test. This doesn't appear to have happened in CWTI-12 with water in the cavity since the hydrogen generation was about the same as CWTI-5 with the inert atmosphere.

Corium oxidation in air was assumed for tests CWTI-11, 12, and 13. In these cases the reaction products are considered to be U_3O_8, Fe_3O_4, Cr_2O_3, and NiO. The energy release is 1.98 MJ/kg of dispersed corium oxidized. The measured oxygen depletion suggested that the dispersed corium reacted to 67% completion in test CWTI-13 where there was unimpeded droplet flow through the air. With structure present to limit the plume travel, the oxidation was 31% complete although there may have been some reaction with hydrogen in this test (CWTI-11). With water present in the cavity, the enhanced quenching reduced the extent of reaction to only 7%.

The oxidation energy source in these tests, including both the oxidation by steam and by air, is also summarized in Table 3 and is part of the overall energy source to the system.

DCH Results

Results pertaining to corium sweepout and the resultant heating of the atmosphere are summarized in Table 4. In tests CWTI-5 and 12, both of which contained water in the cavity mockup, the measured peak temperature of the atmosphere actually decreased by 2 and 15K, respectively, as a result of the corium ejection process (Fig. 4). This was because of the dominating effect of the water in the cavity in those tests, which; being initially at near T_{sat}, actually had a cooling effect upon being dispersed into the atmosphere. This water was an important heat sink to the codispersed corium, and the atmosphere was not heated significantly above saturation condition. These two tests had the largest measured pressure increases, 0.42 and 0.27 MPa, respectively (Fig. 5), which primarily is attributable to steam formation rather than atmosphere heating. Note that the presence of structure in CWTI-5 was not an important factor since the quenching effect of the cavity water was the dominating effect in these two tests.

Tests CWTI-6 and 11, both having structure present plus water only in the bottom of the containment mockup, both experienced a modest heatup of the atmosphere of 53 and 24K, respectively. In both tests the pressurization amounted to 0.12 MPa which was attributable to steam formation, the small heatup, and the blowdown gas. By far the greatest heating of the atmosphere occurred for CWTI-13 where all potential mitigating features had been removed from the system. The heatup amounted to 323K, and the pressure rise was 0.22 MPa, attributable to the heating (plus blowdown gas). This result had been anticipated for CWTI-13 and was the reason for the reduction in corium mass. The large heatup was caused by a sweepout mass of only 0.2 kg.

Table 4. Summary of Direct Containment Heating Results

CWTI Test No.	5	6	11	12	13
Corium Mass Swept Out, kg	2.44	1.21	0.88	1.31	0.20
Atmosphere Initial Press, MPa	0.10	0.10	0.10	0.10	0.10
Atmosphere Initial Temp, K	419	408	411	422	298
Atmosphere Peak Press, MPa	0.52	0.22	0.22	0.37	0.32
Atmosphere Peak Temp, K	417	461	435	407	621
Measured Peak Heatup, K	-2	53	24	-15	323
Calculated Maximum Equilibration Heatup, K	1261	1139	2039	1768	522
DCH Efficiency, %	0	5	1	0	62

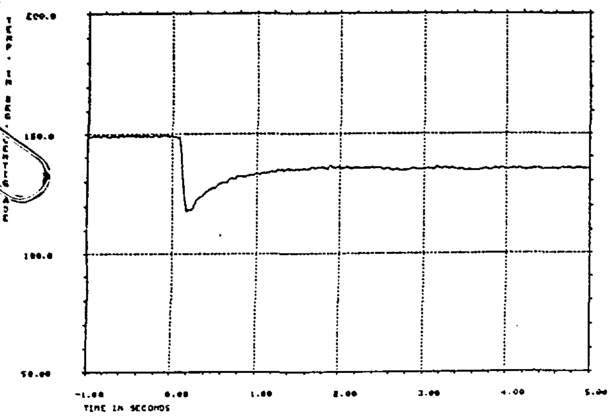

Fig. 4. Temperature of Containment Mockup Atmosphere During CWTI-12

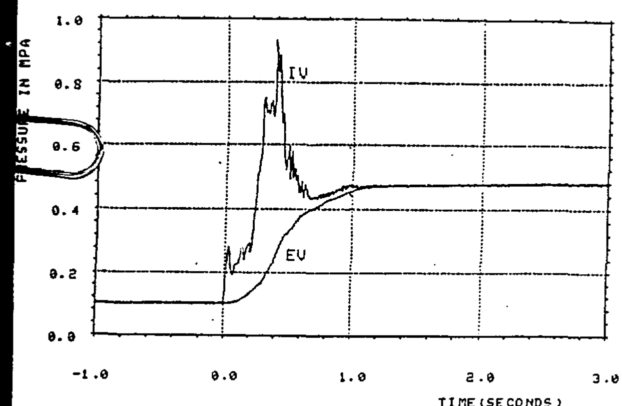

Fig. 5. Pressure in Cavity Mockup (IV) and Containment Mockup (EV) for CWTI-5

It is convenient to characterize the DCH by an efficiency term in order to compare results among tests independent of the unavoidable variations in dispersed corium mass. The efficiency is defined here as:

$$\text{DCH Eff.} = \frac{\text{Measured Atm. Heatup}}{\text{Max. Equilibration Atm. Heatup}} \times 100 \qquad (5)$$

The numerator is the peak heatup actually achieved in the tests. The denominator is the maximum attainable temperature increase assuming adiabatic conditions and based upon temperature equilibration between the swept out corium and the atmosphere, including blowdown gas and including 100% corium oxidation. These maximum calculated heatups are given in Table 4 for the conditions of the five CWTI/DCH tests.

There is a dramatic difference between the DCH efficiencies calculated for these tests. The efficiency was a very high 62% for CWTI-13 where all potential mitigating features had been removed. With structural features present which impeded the corium dispersion through the atmosphere, the efficiencies were reduced dramatically to 5 and 1% for tests CWTI-6 and 11, respectively. When water from the cavity was codispersed with the corium, there was no heatup regardless of whether structure was present.

IV. DCH MODELING

The results of the CWTI/DCH tests, simulant material flow visualization tests described earlier, and SNL SURTSEY tests have been used in the development and validation of our DCH models HARDCORE [5] and PARSEC [6]. Since these models and their applications to the tests as well as reactor system have been described elsewhere [5,6,17], only a few key findings will be reiterated here.

HARDCORE calculates the two-phase flow of corium, water, and a steam-noncondensable gas mixture from the cavity through the instrument tunnel following the onset of gas blowdown through the vessel breach. Modeling is included for the calculation of local blowdown jet velocities along the basemat and walls inside the cavity, entrainment of liquid droplets from layers and films using mechanistic entrainment rate correlations, oxidation of metallic constitutents, and freezing of corium as crusts upon structure inside the cavity and tunnel. HARDCORE calculates that the relatively small corium sweepout attained in the CWTI/DCH tests (9-61%) is principally the result of the high surface-to-volume ratio of the 1:30 scale experiments which favors solidification of stable crusts upon the steel surfaces of the cavity mockup. Sweepout in the reactor system is predicted to exceed 90% of the corium mass entering the cavity during the vessel blowdown stage [17].

HARDCORE analysis of the CWTI/DCH tests indicates that the observed droplet sizes of the dispersed corium are better predicted using droplet entrainment stability modeling from accumulated liquid layers rather than hydrodynamic breakup in the gas stream. This may be attributable to rapid crusting of the corium oxide phase following droplet formation. Using this criterion, the median droplet size indicated in reactor-scale calculations is 2.5 mm [5].

PARSEC calculates details of the heat transfer and oxidation processes for a corium droplet "cloud" dispersed into a closed volume. The modeling includes a dense cloud effect which reduces radiation heat transfer to the walls. It also includes models of the corium plume behavior when the top of the vessel is contacted. However, it does not yet include droplet trajectory and trapping effects in the presence of structures. Figure 6 shows the calculated vessel pressure for the CWTI-13 test in relation to the test data. Also shown is the calculated pressurization attributable to the (prolonged) blowdown during this test. Figure 7 shows a calculation of the predicted oxygen depletion behavior for this test. The oxidation time scale is about the same as the DCH time scale, ~2 s. The predicted oxygen mass consumed was 10.3 g compared to 14 g based on gas sample results. Figure 8 also shows calculated aerosol production, primarily attributable to vaporization of the metal phase of the corium. A total mass of 10.3 g of aerosol is predicted, ~5% of the dispersed corium mass.

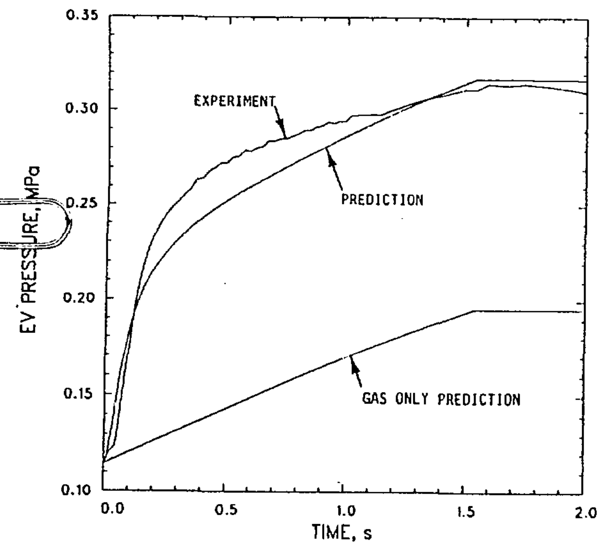

Fig. 6. PARSEC Analysis of CWTI-13 Test

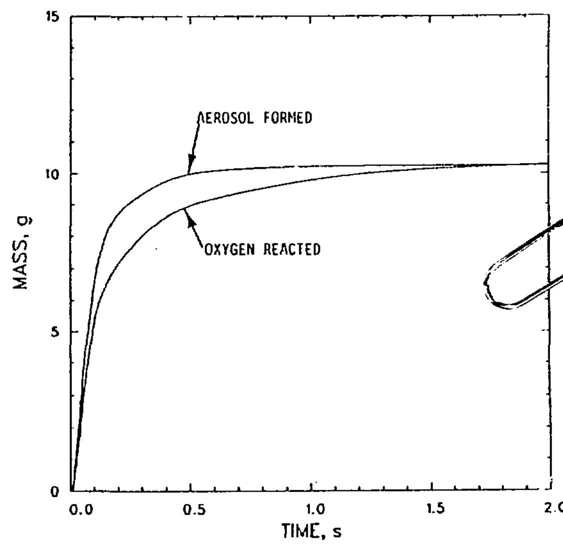

Fig. 7. PARSEC Code Results for CWTI-13 DCH Test

V. DISCUSSION

The CWTI-13 test demonstrated the large thermal and pressure loads that can result when corium droplets are vigorously dispersed through the air atmosphere of a closed volume. The test produced a high 62% atmosphere heating efficiency despite the relatively small scale of the test apparatus. Contrastingly, the other four tests in the series all indicated atmosphere heating efficiencies of five percent or less; indeed, three tests had heating efficiencies of 0 or 1%. The reason for this dramatic difference is that these four tests contained water as a competing available heat sink and three of the tests additionally contained structural features which lessened the principal corium path length through the atmosphere. The path length effect on DCH is particularly dependent upon scale, and it is not possible to quantify the mitigating effects of structures without the broader picture afforded by large-scale tests such as SURTSEY plus mechanistic plume-tracking and droplet tracking models. Nonetheless, the principal that structural dispersal impediments can lessen DCH severity appreciably compared with worst case-type calculations is certainly consistent with test results.

In conceptualizing these tests, it was also envisioned that water would exist somewhere in the containment, if not in the cavity then certainly on the floor of the lower compartments. This picture is not necessarily based upon operation of engineered safety features (ESF's) but rather on the accumulation of liquid and condensate on the floor when sufficient water is necessarily released from the RCS to precipitate core uncovery and core melt. This water will play a role in the ex-vessel accident sequence, notably to quench particles falling onto the floor. The steam generated adds to the containment load. Hence the presence of this layer of water was mocked up in the first three DCH tests. It is doubtful that this water alone would provide any significant DCH mitigation if corium were dispersed unimpeded through the containment atmosphere; in fact, multi-compartment and structural impediments are always present to some extent to intercept and redirect corium to the floor.

The presence of water in the reactor cavity was shown by test results to be an effective mitigator of DCH. The initial water slug ejection into the atmosphere plus the subsequent codispersal of corium and remaining water by the follow-on blowdown gas created a dispersion of water droplets in the atmosphere together with the dispersed corium droplets. The fact that the peak measured temperatures did not appreciably exceed T_{sat} indicates that the dispersed water was an effective heat sink for the dispersed corium. The addition of steam to the system by this quench process contributed to pressure increase, but to a lesser extent than the same energy going into atmosphere heatup. In effect, the dominating source of loads became steam formation rather than DCH. The steam spike issue was addressed previously and determined not to threaten the integrity of a Zion-like large dry containment [1].

The presence of water in the cavity creates a potential local pressure loading which needs to be evaluated further. The water slug formation in the dispersal pathway causes pressure buildup until the slug exits into the steam-generator compartment. Subsequently the cavity itself experiences a two-phase blowdown. This cavity pressurization behavior is clearly seen in test results such as CWTI-5 where the pressure in the cavity mockup exceeded 0.7 MPa (87 psig) for about 200 ms (Fig. 5). To avoid this slug binding effect requires a relatively shallow water layer in the cavity according to flow visualization test results [13,16].

Accident Management Implications

If the DCH risk is perceived to warrant it, certain measures are suggested by test results to be effective at mitigating DCH. First, any structural barrier which lessens the dispersal pathlength through the containment atmosphere can lessen DCH. It is likely that many containment designs already possess such barriers by way of multiple compartments or other features. Secondly, presence of water on the floor can quench the corium, preventing or lessening its attack on the concrete. Test results indicated that water on the floor at saturation temperature, as might exist from RCS water depletion, produces steam which contributes to containment pressure spike. The presence of subcooled water as an accident management provision would serve the same beneficial quenching function while minimizing steam formation. The presence of water in the blowdown pathway was shown in the tests to be a particularly effective DCH mitigator. Again, the benefits in the reactor system are potentially greater than achieved in the tests by use of subcooled water to minimize steam generation.

A notable finding in the test results was that significant oxidation occurred when water was present, resulting in hydrogen generation. It should be noted that this is likely to occur in the reactor system whether water is used as a quench media or not owing to the fact that the blowdown gas in the reactor system is largely steam. HARDCORE predicts extensive corium oxidation attributable solely to the flow of steam blowdown gas past the dispersed corium droplets.

VI. SUMMARY AND CONCLUSIONS

The results of this study suggest that DCH may not be such a significant risk factor as previously envisioned when realistic plant features are taken into account, albeit large-scale tests such as SURTSEY and validated mechanistic codes are necessary for application to reactor scale. Test results showed that the unimpeded dispersal of corium into air could indeed result in a large energy transfer to the atmosphere (62% efficient). However, tests with realistic structures and water showed benign effect on the atmosphere (0-5% DCH efficiency). The corium energy (including oxidation energy) was largely transferred to alternate available heat sinks such as structure and water or retained in the corium mass over the dispersed droplet heating time frame. In cases with water in the mockup of the reactor cavity, the dispersed water was such an effective heat sink for the dispersed corium that the atmosphere temperature remained at essentially T_{sat}.

In this case the DCH essentially became a steam spike in the sense that rapid steam generation was the principal consequence of the corium dispersal and quench.

Specific conclusions from the series of 1:30 linear scale, reactor-material tests include the following:

1. Test data indicated three stages of corium ejection from the thermite vessel: an initial single-phase liquid expulsion, a two-phase ejection following gas "punchthru," and a follow-on single-phase gas blowdown.

2. Vigorous corium sweepout was observed in all tests, the result of vessel blowdown flowrate which exceeded the ~30 m/s sweepout threshold. The percentage sweepout attained in the tests was consistent with freezing-induced plateout on the steel walls of the cavity mockup modeled in HARDCORE. The same modeling predicts nearly complete sweepout from a concrete reactor cavity.

3. Vigorous dispersal of water was also observed for those tests that had water present in the cavity. Consistent with flow visualization tests and with HARDCORE modeling, the water dispersal occurred in two stages; an initial ejection of a water slug followed by sustained codispersal with the corium by action of the blowdown gas.

4. Oxidation of corium metallic constituents by steam resulted in hydrogen production. There was indication of hydrogen combustion in the air atmosphere of test CWTI-11. In other tests the indicated completeness of reaction ranged form 50 to 79%.

5. Oxidation of corium by free oxygen occurred in those tests that were conducted in an air atmosphere. The data indicated that the extent of reaction reached 67% for the severe heating conditions of CWTI-13, but was only 5% for CWTI-12, presumably due to the quenching effect of water in the cavity mockup.

6. The measured atmosphere heatup was found to depend strongly on the presence or absence of mitigating features in the tests. With no mitigating features the heatup amounted to 323K, equivalent to a DCH efficiency of 62% (i.e., 62% of the maximum possible heatup was attained, including account of maximum chemical energy release). With structures present to impede the corium droplet dispersal, the efficiency was reduced to 1-5%. With water present in the cavity, there was no measurable heatup.

7. The measured atmosphere pressure rise was found to depend upon heating of the atmosphere and formation of steam from the corium quench process, as well as the accumulation of blowdown gas. Tests with water in the cavity resulted in no heatup but appreciable steam generation and were therefore effectively steam spike tests.

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