OECD MCCI Project
Category 3 Tests to Generate 2-D Core-Concrete Interaction Data:
Final Report

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1.0 INTRODUCTION

1.1 Background

Ex-vessel debris coolability is an important light water reactor (LWR) technical challenge. For existing plants, resolution of this challenge will confirm the technical basis for severe accident management guidelines (SAMGs). For new reactors, understanding this challenge will help confirm the effectiveness of the design and implementation of new accident mitigation features and severe accident management design alternatives (SAMDAs). The first OECD-MCCI program conducted reactor material experiments focused on achieving the following technical objectives: i) provide confirmatory evidence and data for various cooling mechanisms through separate effect tests to support model development, and ii) provide long-term 2-D core-concrete interaction data for code assessment and improvement.

Debris cooling mechanisms investigated as part of the first MCCI program included: i) water ingress through cracks/fissures in the core debris, ii) melt eruption caused by gas sparging, and iii) large-scale crust mechanical failure leading to renewed bulk cooling. The results of this testing and associated analysis provided an envelope (principally determined by melt depth) for debris coolability. However, this envelope does not encompass the full range of potential melt depths for all plant accident sequences. Cooling augmentation by additional means may be needed at the late stage to assure coolability for new reactor designs as well as for various accident sequences for existing reactors. In addition, the results of the CCI tests showed that lateral/axial power split is a function of concrete type. However, the first program produced limited data sets for code assessment. In light of significant differences in ablation behavior for different concrete types, additional data would be useful in reducing uncertainties and gaining confidence in code predictions.

Based on these findings, a broad workscope was defined for the follow-on MCCI program. The workscope was divided into the following four categories:

1. Combined effect tests to investigate the interplay of different cooling mechanisms, and to provide data for model development and code assessment purposes.
2. Tests to investigate new design features to enhance coolability, applicable particularly to new reactor designs.
3. Tests to generate two-dimensional core-concrete interaction data.
4. Integral tests to validate severe accident codes.

In addition to the experimental work, an analysis task was defined to develop and validate coolability models that form the basis for extrapolating the experiment findings to plant conditions.

To broaden the database generated as part of the MCCI-1 program [1], the project completed two additional large scale CCI experiments in the third test category defined above. Specifications for all five tests are provided in Table 1-1. This final report documents the results of the CCI-4 [2] and CCI-5 [3] tests that were completed as part of the MCCI-2 program.

1.2 Objectives and Approach

The overall objective of the test series was to provide information in several areas, including: i) lateral vs. axial power split during dry core-concrete interaction, ii) integral debris coolability data following late phase flooding, and iii) data regarding the nature and extent of the cooling transient following breach of the crust formed at the melt-water interface. The experiment approach was to investigate the interaction of prototypic core melts with specially-designed 2-D concrete test sections. The initial phase of the tests was conducted under dry cavity conditions. After a predetermined time interval and/or ablation depth was reached, the cavities were flooded with water to obtain data on the coolability of core melts after core-concrete interaction had progressed for some time.

Tests CCI-1 through CCI-3 principally addressed the effect of concrete type on 2-D cavity erosion behavior and late phase debris coolability. Test CCI-4 expanded the parameter base addressed in the test series by examining the influence of core melt composition on cavity erosion behavior and coolability. The specific objectives of this test [2] were to: i) increase the metal content of the melt to the highest practical level to more accurately mock up a prototypic BWR core melt composition at the time of vessel failure, and ii) modify the apparatus design to increase the duration of the dry core-concrete interaction phase. The approach for satisfying the first objective was to place a metal-bearing concrete insert on top of the concrete basemat that was ablated into the melt prior to onset of basemat ablation, thereby increasing the melt metal content to the target level. This technique was originally developed as part of the Advanced Containment Experiment Molten Core Concrete Interaction (ACE/MCCI) test series [4] that focused on quantifying fission product source term due to core-concrete interaction. The approach for satisfying the second objective was to slightly reduce the initial inside dimension of the concrete crucible (i.e., 50 cm to 40 cm) to provide more concrete for ablation, in addition to allowing the ablation to proceed to a greater depth into the crucible relative to the limits utilized in the original test series [1].

Test CCI-5 focused on examining the influence of melt pool aspect ratio on the radial/axial power split under dry cavity conditions. The specific objective was to increase the test section aspect ratio (i.e., test section width/melt depth) to the greatest extent possible to more accurately mock up prototypic conditions. The approach was to modify the test section design to include a single concrete sidewall that would undergo ablation, whereas the opposing sidewall was made from refractory MgO that essentially created an adiabatic boundary condition. The initial distance between the sidewalls was also increased from 50 cm to 79 cm to maximize the aspect ratio at the start of the experiment. With the choice of siliceous concrete and melt composition (see Table 1-1), CCI-5 was thus a repeat of CCI-3, but with the aspect ratio increased to the greatest extent possible given the facility hardware constraints.

Table 1-1. Specifications for CCI Tests.

Parameter	Specifications for Test:				
	CCI-1	CCI-2	CCI-3	CCI-4	CCI-5
Corium	100 % oxidized PWR + 8 wt% SIL	100 % oxidized PWR + 8 wt% LCS	100 % oxidized PWR + 15 wt% SIL	78 % oxidized BWR with 7.7 wt % SS and 10 wt % LCS ^b	100 % oxidized PWR + 15 wt% SIL
Concrete type ^a	SIL (U.S.-type)	LCS	SIL (EU-type)	LCS	SIL (EU-type)
Basemat cross-section	50 cm x 50 cm	50 cm x 50 cm	50 cm x 50 cm	50 cm x 40 cm	50 cm x 79 cm
Initial melt mass (depth)	400 kg (25 cm)	400 kg (25 cm)	375 kg (25 cm)	300 kg (25 cm)	590 kg (25 cm)
Test section sidewall construction	Electrode walls: Inert Nonelectrode walls: concrete	Electrode walls: Inert Nonelectrode walls: concrete	Electrode walls: Inert Nonelectrode walls: concrete	Electrode walls: Inert Nonelectrode walls: concrete	Electrode walls: Inert Nonelectrode wall No. 1: concrete Nonelectrode wall No. 2: Inert
Lateral/Axial ablation limit	35/35 cm	35/35 cm	35/35 cm	45/42.5 cm	40/42.5 cm
Initial melt temperature	1950 °C	1880 °C	1950 °C	1850 °C	1950 °C
System pressure	Atmospheric				
Melt formation tech.	Chem. reaction (~30 s)				
Melt heating technique	DEH				
Power supply operation prior to water addition	Constant @ 150 kW	Constant @ 120 kW	Constant @ 120 kW	Constant @ 95 kW	Constant @ 145 kW
Criteria for water addition	1) 5.5 hours of operation 2) ablation → 5 cm of limit	1) 5.5 hours of operation 2) ablation → 5 cm of limit	1) 5.5 hours of operation 2) ablation → 5 cm of limit	1) 7.0 hours of operation 2) ablation → 5 cm of limit	1) 6.0 hours of operation 2) ablation → 5 cm of limit
Inlet water flowrate/temp.	2 lps/20 °C				
Water depth over melt	50 ± 5 cm				
Power supply operation after water addition	Constant voltage				
Test termination criteria	1) $T_{\text{melt}} < T_{\text{con, sol}}$, 2) ablation arrested, or 3) ablation → limit				
Operational Summary	Successful: pronounced lateral erosion in one sidewall	Successful: symmetrical cavity erosion	Successful: pronounced lateral erosion	Successful: symmetrical cavity erosion	Successful: pronounced lateral erosion; cavity not flooded due to offgas system plugging

^aSIL denotes siliceous concrete, LCS denotes Limestone/Common Sand concrete.^bAfter erosion of concrete/metal inserts and at start of basemat ablation

Note that in these tests a significant iron-bearing metal phase was not involved, but may be present during an accident at levels approaching or exceeding 30 wt %. Based on the initial melt density of $\sim 6500 \text{ kg/m}^3$, the steel may be layered below the oxide phase. Thus, data from this test series may not be directly applicable to reactor accident sequences, but the results are nonetheless useful for code validation purposes. The input power levels used in the tests were selected so that the fluxes from the melt to concrete surfaces and the upper atmosphere were initially in the range of that expected early in the accident sequence (i.e., $150\text{-}200 \text{ kW/m}^2$).

This final report provides a summary of the results from the CCI-4 and CCI-5 tests. Following a description of related studies in the next section, an overview description of the test facility is then provided, followed by a summary of the thermal-hydraulic and posttest examination results for both tests. The report then concludes with a discussion focused on comparing and contrasting the results from all five tests that were carried out as part of the MCCI-1 and MCCI-2 programs. Additional information regarding the apparatus, procedures, and results are provided in detailed data reports that were prepared for each test [2,3].

1.3 Related Studies

The purpose of this section is to identify and briefly discuss findings from related studies regarding core-concrete interaction under both dry and wet cavity conditions. The review is organized under these two headings to facilitate presentation of the material.

1.3.1 Dry Cavity Experiments

Early transient high temperature steel simulant experiments were conducted under dry cavity conditions by Powers et al. [5,6] at Sandia National Laboratories to identify basic phenomenology associated with core-concrete interaction. These early transient tests were followed by additional sustained heating experiments using metallic melts at different power levels by Copus et al. [7,8] and Tarbell et al. [9] at Sandia, as well as Alsmeyer et al. [10,11] at Karlsruhe Institute of Technology (KIT; formerly Forschungszentrum Karlsruhe) in Germany. Recently, Sevón et al. at VTT in Finland [12] conducted transient metal tests focused on quantifying the ablation characteristics for hematite concrete, which is the type used as sacrificial material in the EPR reactor pit. In terms of reactor material testing, a series of 1-D experiments addressing thermal-hydraulic behavior and fission product release were conducted by Thompson et al. [4,13] and Fink et al. [14] at Argonne National Laboratory. In addition to these tests, several large scale 1-D core melt tests were carried out at Sandia under both transient [15] and sustained heating [16-18] conditions. Finally, 2-D core-concrete interaction experiments under dry cavity conditions have been carried out at the VULCANO test facility at CEA in France [19,20]. Results from both the simulant and reactor material testing programs are summarized below.

Powers et al. [5,6] conducted early exploratory tests at Sandia that investigated the transient interaction of superheated steel melts (up to 200 kg) with basaltic and limestone/common sand concretes. These tests revealed that concrete erosion is primarily a melting process as opposed to a mechanical spallation process, and that water vapor and CO_2

released by concrete decomposition are reduced to hydrogen and CO. The results also showed that the heat transfer rate to the concrete was influenced by the gas generation rate and the crucible geometry.

These tests were followed by additional SURC-series experiments by Copus et al. [7,8] that featured enhanced instrumentation to monitor the melt and concrete temperatures during the interaction and to quantify aerosol release, as well as induction heating of the metal melt in order to mock up decay heat within the melt. A key element of these experiments was the addition of zirconium to the melt after the interaction was underway. The experiments exhibited large increases in melt temperature, erosion rate, concurrent gas release, and aerosol production following zirconium addition. Another phenomenon that was identified was the extensive production of low density oxide foam.

In addition to the high temperature sustained heating tests, Tarbell et al. [9] conducted the FRAG test series to investigate the long-term interaction of solidified core debris with various concrete types. During cooldown of the metallic phase during long-term core-concrete interaction, partial or complete solidification of the metal phase may occur, leading to sustained concrete attack by an overlying solid mass. The results showed that low-temperature debris is capable of eroding both basalt and limestone/common sand concrete types; typical erosion rates were of the order of 3-4 cm/hour for the input power levels applied during the tests.

Aside from the metal tests conducted within the U.S., the BETA test series [10] at KIT provided early valuable data on multi-dimensional core-concrete interaction using metallic melt. A total of 19 experiments were conducted in the series; most tests (i.e., 16) utilized siliceous concrete, although three experiments utilized limestone/common sand concrete. The metal melts were also inductively heated using a cylindrical, annular induction coil to simulate decay heat, and different input power levels were used to mock up different stages of the accident sequence. Early, rapid cooling of the metal phase was observed in these tests. For siliceous concrete, axial erosion was found to be more significant than radial. The limestone/common sand tests exhibited a more uniform radial/axial power split.

Motivated by the findings of the SURC metal test series [7,8], additional experiments were carried out in the BETA test facility [11] to further investigate the influence of cladding oxidation on ablation behavior. The results confirmed the strong influence of the Zr oxidation process during the early cavity ablation phase with siliceous concrete, which was attributed to the exothermic reduction of SiO_2 by the Zr to form Si metal that was later oxidized by CO_2 and H_2O concrete decomposition gases.

More recently, the transient interaction between metallic melt and concrete was investigated by Sevón et al. in the HECLA program [12] by pouring melt streams into concrete crucibles and observing the cavity ablation behavior as the melt cooled. Five experiments were conducted in this test series; the first two used ordinary siliceous concrete, while the last three used hematite concrete typical of that used in the reactor pit of the Olkiluoto 3 EPR plant in Finland. The main objectives of these tests were to: i) investigate the ablation characteristics of this special concrete type in comparison to ordinary siliceous concrete, and ii) obtain

thermophysical property data for the concrete as little information was available in the open literature at the time. Based on the experiment results, it was estimated that ~ 83 mm of sacrificial concrete would be ablated during the initial interaction in the Olkiluoto 3 reactor pit, which is much less than the 500 mm of material provided in the plant design.

In terms of reactor material experiments, six large scale reactor material experiments addressing thermal-hydraulic behavior and fission product release during core-concrete interaction were conducted by Thompson et al. [4,13] and Fink et al. [14] at Argonne National Laboratory. These tests were carried out in a one dimensional test section that examined axial erosion behavior. Direct Electrical Heating (DEH) of the melt was used to simulate fission product decay heat. The melt was doped with non-radioactive isotopes of key fission product species to mock up fission products in the melt. The results showed that the concrete erosion process is closely linked to concrete type, and that fission product release during core-concrete interaction is actually quite low [14].

In addition to the 1-D core melt experiments conducted at ANL, several large scale 1-D tests were carried out at Sandia under both transient [15] and sustained heating [16-18] conditions. The initial TURC experiment series [15] consisted of pouring suboxidized $[(U,Zr)O_{2-x}]$ core melts into limestone/common sand crucibles and observing the extent of concrete ablation and aerosol release as the melts cooled. The results indicated very rapid crust formation on the concrete surfaces upon initial contact, which resulted in no detectable concrete ablation over the course of either test. The subsequent SURC test series [16-18] investigated the longer term interaction of suboxidized core melts interacting with limestone/common sand and basaltic concrete crucibles by inductively heating tungsten susceptors that were positioned in the crucible. Consistent with findings from the other programs, the results of these tests showed an initial rapid period of erosion and melt temperature escalation during the Zr oxidation phase, followed by a reduced erosion rate and declining melt temperature after the cladding was fully oxidized.

Aside from U.S. programs, studies of multi-dimensional core-concrete interaction under dry cavity conditions have also been carried out at the VULCANO test facility at CEA [19,20]. The main experimental objectives of this program are to investigate long-term 2-D core concrete interaction using either purely oxidic core melt, or stratified configurations consisting of metal and oxide layers, which is the expected condition at plant scale. The major finding from these tests is the ablation is non-isotropic for siliceous concrete [21], which is consistent with the findings from the OECD/MCCI-1 core-concrete interaction test series [1].

1.3.2 Wet Cavity Experiments

In terms of wet cavity conditions, low temperature simulant experiments have been conducted by Theofanous et al. [22] to identify phenomena associated with melt coolability, while high temperature simulant experiments have been conducted at Sandia by Blose et al. [23,24], as well as Sdouz et al. [25] and Alsmeyer et al. [26] at KIT, to investigate coolability with concurrent concrete erosion. In terms of reactor material testing, the COTELS [27,28] and MACE [29,30] experiment programs have been carried out to investigate coolability mechanisms

under prototypic MCCI conditions. Results from both the simulant and reactor material testing programs are summarized below; more thorough discussions of the findings in this area are provided by Farmer [30] and Sehgal [31].

To investigate fundamental phenomena associated with melt coolability, simulant material experiments were conducted by Theofanous, Liu, and Yuen [22]. In these tests, glycerin and liquid nitrogen were used to simulate the melt and overlying coolant, respectively. Gas sparging from MCCI was simulated by purging air through a porous plate located at the bottom of the apparatus. Fission product decay heat was simulated by the sensible heat deposited in the glycerin due to cooling of the purged gas from the inlet temperature to the melt pool temperature. Experiments were conducted in two different geometries; namely, cylindrical and square test sections. In the cylindrical tests, the diameters of the two test sections were 15 and 45 cm. For the rectilinear test sections, three different scales were investigated: 70 cm x 70 cm, 100 cm x 100 cm, and 120 cm x 120 cm. For the small scale tests conducted in the circular geometry, quench was not achieved due to the formation of wall-anchored crusts which inhibited the melt-coolant interaction. However, for the larger scale tests, quench was generally achieved. In particular, the data indicates that the time to quench increases with initial melt depth and decreases with increasing sparging rate. The principal mechanism leading to coolability in these experiments was volcanic eruptions. These eruptions lead to enhanced debris surface area available for contact with the overlying coolant. The same phenomenon was first identified through reactor material experiments under MCCI conditions [29].

Three melt coolability experiments were conducted at Sandia using high temperature simulants with sustained heating and concurrent concrete erosion. These experiments include the SWISS tests [23], conducted with stainless steel melts interacting with limestone/common sand concrete, and the WETCOR test [24] that utilized an oxide simulant interacting with Basaltic concrete. These tests also provided valuable data on debris coolability, but complete quench was not obtained in any of these experiments due in part to the formation of crusts that anchored to the test section sidewalls, eventually leading to decoupling of the melt pool from the crust as the core-concrete interaction proceeded downwards. However, these tests were quite valuable as they provided information on the effect of an overlying water pool on aerosol scrubbing during core-concrete interaction, since this data is sparse in the literature.

Other simulant material debris coolability data under top flooding conditions was obtained at KIT by Sdouz et al. [25] and Alsmeyer et al. [26] as part of the COMET test program. These were large scale multi-component (metal - oxide) mixture tests that focused on examining two-dimensional cavity erosion behavior using siliceous concrete in a stratified configuration under top flooding conditions. Consistent with the dry cavity metal test results, these experiments exhibited ablation behavior that was biased downwards. In these experiments, the simulant oxide phase was on top the metal phase that was heated and therefore driving the axial erosion. This oxide material showed little evidence of coolability following top flooding.

In terms of prototypic experiments, a total of 10 reactor material tests that investigated Fuel Coolant Interaction (FCI) and debris coolability were carried out within the framework of a joint study between NUPEC and the National Nuclear Center (NNC) in Kazakhstan [27,28].

Each experiment was conducted in two phases; i.e., test series “B” investigated FCI aspects of the initial water injection onto molten corium, while the follow-on series “C” tests investigated the long-term aspects of MCCI under the conditions of continual water injection.

For these tests, based on the rate of steam transport to the condensation system, the steady-state melt/water heat flux was reported to range from 0.2 to 0.7 MW/m². In all cases, both the concrete sidewalls and base of the crucible were found to be eroded. In addition, an interstitial pebble bed formed at the interface of the core material and the concrete; the bed was composed of concrete decomposition products (presumably the aggregate). The depth of this pebble bed was found to increase with increasing ablation depth. The depth of the discolored concrete region surrounding the decomposed pebble bed was also found to increase with ablation depth. Posttest examinations revealed the important finding that crust anchoring to the concrete sidewalls with subsequent melt/crust separation did not occur for any of these tests. The absence of anchoring was presumably attributable to the sidewall decomposition that occurred.

The tests were classified in terms of the debris mass that was rendered in the form of a particle bed above the remaining corium layer. In particular, Case (1) corresponded to formation of a particle bed containing 20-40 wt % of the total debris mass, Case (2) corresponded to 70-80 wt % of the debris mass in the particle bed, while Case (3) corresponded to no particle bed formation. For experiments in which particle bed formation occurred (i.e., Cases (1)-(2)), the depth of the bed was found to increase with increasing basemat erosion depth, and with increasing melt specific power density. Particle bed depths ranged from 7 to 12 cm. In the Case (3) tests, no particle bed formation occurred; these experiments were characterized by comparatively lower power density. The mechanism by which these beds formed (e.g., entrainment by concrete decomposition gases) was not identified as part of this work. The coherent solidified corium layer remaining over the basemat was always found to contain cracks and crevices which axially spanned the depth of the layer. The test results indicate that water was able to penetrate into these cracks and crevices during the test, in addition to penetrating into the intervening gap formed at the sidewall corium-concrete interface due to sidewall erosion. In fact, for these tests the cooling mechanisms of water ingress through interstitial porosity and particle bed formation over the solidifying core material were of sufficient magnitude to effectively quench the core material and terminate the MCCI, as evidenced by thermocouple measurements in the basemat.

A series of large scale melt coolability experiments were conducted at Argonne National Laboratory as part of the Melt Attack and Coolability Experiment (MACE) [29,30]. The specific objectives of the program were to explore the possible benefits of massive addition of water to an MCCI already in progress insofar as: i) quenching and stabilizing the heat generating core melt, and ii) arresting or even terminating basemat ablation. Early tests M0 and M1b were conducted with 70 % oxidized PWR melt compositions, while the later tests M3b and M4 were conducted with fully oxidized core melts. Three tests in the matrix were conducted with limestone/common sand (LCS) concrete, while the fourth test was conducted with siliceous concrete. A principal parameter in the test matrix was test section lateral span, which was varied from 30 cm x 30 cm up to 120 cm x 120 cm. Core melt masses in these various scale tests have ranged from 100 to 1800 kg.

The M0 experiment was conducted with a purely concrete test section, thereby allowing both axial and radial cavity ablation data to be obtained. This test provided early data on the effectiveness of the melt eruption cooling mechanism, with a substantial fraction of the initial core melt mass rendered in the form of a coolable bed by eruptions. Unfortunately, the crust anchored to the test section electrodes located along two opposing walls of the test section, and this eventually led to a configuration in which the melt had separated from the crust by the end of the experiment. Researchers thought that this experiment distortion may have precluded complete quench of the core debris. On this basis, the facility was redesigned to incorporate inert MgO sidewalls, thereby making it one dimensional, and the electrodes were recessed into the MgO sidewalls to reduce the surface area available for the crust to bond to. The balance of the integral experiments in the program (i.e., M1b, M3b, and M4) was conducted with this test configuration. Unfortunately, crust anchoring with subsequent melt-crust separation occurred in all these tests, and so a definitive demonstration of debris coolability was not obtained as a part of this program.

2.0 FACILITY DESCRIPTION

Principal elements of the test facility for both CCI-4 and CCI-5 consisted of a test apparatus, a power supply for Direct Electrical Heating (DEH) of the corium, a water supply system, two steam condensation (quench) tanks, an off gas system to filter and vent the off-gases, and a Data Acquisition System (DAS). A schematic illustration of the facility is provided in Figure 2-1, while an overview photograph showing key elements of the facility is provided in Figure 2-2. The specifications for the individual tests conducted as part of the CCI test series were previously summarized in Table 1-1. With the exception of the DAS, the entire system was housed in an explosion-rated containment cell. All operational features of the tests, including DEH input power, water supply, and gas flows, were remotely controlled from the experimenter's console located outside the containment. The various elements of the facility are described in sequence below.

The overall facility design was effectively the same for both tests. However, the apparatus for each experiment was modified in order to achieve the specific test objectives (see Section 1.2). Thus, to avoid duplication, a single description is provided for common facility elements, while design variations are explicitly addressed for each test.

2.1 Test Apparatus

2.1.1 CCI-4 Test Apparatus

The principal components of the apparatus, shown in Figure 2-3, consisted of a bottom support plate, three sidewall sections, and an upper enclosure lid. The overall structure was 3.4 m tall. The two upper sidewall sections had a square internal cross sectional area of 50 cm x 50 cm. The concrete test section for containment of the core melt was located at the bottom of the apparatus. A top view of this component is shown in Figure 2-4, while cross-sectional views of the electrode and non-electrode sidewalls are provided in Figures 2-5 and 2-6, respectively. The cross-sectional area of the cavity was 50 cm x 40 cm. The distance between the tungsten electrodes was the same as that of previous tests [1] (50 cm), while the distance between the concrete sidewalls was reduced by 10 cm to a width of 40 cm. This increase in sidewall thickness, combined with a 5 cm extension in allowable ablation, provided a total of ten extra centimeters of concrete for lateral ablation per sidewall. The basemat thickness was increased by 2.5 cm to 57.5 cm to accommodate up to 42.5 cm of axial ablation. This design maintained a minimum concrete thickness of 15 cm in both the sidewalls and basemat for melt containment.

As shown in Figure 2-4, the electrode sidewalls of the lower section were fabricated from castable MgO¹ refractory, while the non-electrode sidewalls were fabricated from Limestone/Common Sand (LCS) concrete. A photograph showing typical components after fabrication is provided in Figure 2-7. The middle sidewall section was fabricated from a high temperature refractory concrete², while the upper section and lid were made from locally obtained LCS concrete. The chemical composition of the cast MgO is shown in Table 2-1,

¹Periclase Permanente 98-AF; from National Refractories and Minerals, Columbiana, OH.

²Tufffloor 2500, Matrix Refractories, Columbus, OH.

Figure 2-1. Key Elements of the CCI Test Apparatus.

Figure 2-2. Overview Photograph of CCI Test Facility.

Figure 2-3. Details of the CCI-4 Test Section.

Figure 2-4. Top View of CCI-4 Lower Test Section.

Figure 2-5. Side View of CCI-4 Lower Test Section Showing Inert MgO Sidewall Sections.

Figure 2-6. Side View of CCI-4 Lower Test Section Showing Concrete Sidewall Sections.

Figure 2-7. Typical Sidewall Components After Fabrication.

Table 2-1. Chemical Composition of Castable MgO.

Element (Oxide Form)	Mass %	
	Element	Oxide
Al (Al_2O_3)	0.24	0.45
B (B_2O_3)	0.12	0.39
Ca (CaO)	0.58	0.81
Fe (Fe_2O_3)	0.14	0.20
Mg (MgO)	58.4	96.8
Mn (MnO)	0.038	0.049
Si (SiO_2)	0.24	0.51
Ti (TiO_2)	0.002	0.003
Zr (ZrO_2)	0.038	0.023
Total		99.24

while the detailed composition of the concrete basemat and sidewalls is provided later in this section. The concrete and MgO were contained within flanged 11 gauge steel forms that secured the lower section to the balance of the existing test section components with an aluminum transition plate. The lower section was fabricated with vertical, flanged casting seams between the MgO and concrete so that the sidewalls could be disassembled to reveal the solidified corium following the test. The MgO sections were intended to be reusable, while the concrete sidewall remnants were disposed of as radioactive waste.

A layer of crushed UO_2 pellets was used to protect the interior surface of the MgO sidewalls against thermo-chemical attack by the corium. In the event that the UO_2 layer did not provide adequate protection, 3.2 mm thick tungsten and molybdenum back-up plates were embedded in these sidewalls as a final barrier to terminate sidewall attack. The plates were instrumented to provide an indication of corium contact with either of these two surfaces during the test. As illustrated in Figure 2-5, multi-junction Type C thermocouple assemblies were also cast within the MgO sidewalls. These thermocouples allowed the time-dependent heat loss from the melt to be estimated from the local temperature gradient and the thermal conductivity of the MgO through standard inverse heat conduction techniques.

Melt pool generation was achieved through an exothermic “thermite” chemical reaction that produced the target initial melt mass over a timescale of ~ 30 seconds. A depiction of the powder loading scheme is provided in Figure 2-8. As is evident from the figure, two iron/alumina sparklers, wrapped with nichrome starter wire, were positioned a few centimeters below the top of the corium charge near the centerline of the test section. One of these sparklers was used to initiate the thermite reaction by heating the neighboring powder to the ignition point. (The thermite composition is described in detail later in this section). The second sparkler was provided as a backup in case the first failed to ignite the material.

After the chemical reaction, DEH was supplied to the melt to simulate decay heat through two banks of tungsten electrodes that lined the interior surfaces of the opposing MgO sidewalls. As illustrated in Figures 2-5 and 2-6, the copper electrode clamps were attached to the 2.5 cm thick aluminum bottom support plate that formed the foundation for the apparatus. A total of sixty three 91 cm long, 0.95 cm diameter tungsten electrodes were attached to each electrode clamp at a pitch of 1.9 cm. A photograph showing the electrodes after a typical installation in the clamps but prior to placement of the lower section sidewalls is provided in Figure 2-9. The clamps were attached with water-cooled buss bars to a 560 kW AC power supply. As shown in Figure 2-4, each electrode bank was vertically restrained by a horizontally mounted, 0.95 cm diameter tungsten rod which was recessed into the concrete sidewalls near the tops of the electrodes. These restraints were provided to prevent slumping of the electrodes away from the sidewalls, as occurred in the Scoping Test [32].

As illustrated in Figure 2-4, the electrodes spanned a total width of 120 cm on each sidewall of the lower section. At the start of the experiment, the electrical current was drawn through the center 40 cm lateral span of electrodes that were in direct contact with the melt. As the test progressed and the concrete sidewalls eroded, additional electrodes were exposed to the corium. Electrical current was drawn through these newly exposed heating elements, thereby maintaining a uniform heating pattern in the melt over the course of the experiment. Given the overall electrode span of 120 cm, up to 45 cm of radial sidewall ablation could be accommodated in this design while maintaining uniform heat input. As shown in Figure 2-4, the concrete sidewalls were 61 cm thick, which provided ~ 15 cm of remaining sidewall thickness once the 45 cm radial ablation limit had been reached.

Water was introduced into the test section through weirs located in the upper sidewall section just beneath the lid of the apparatus. The layout for the weirs is shown in Figure 2-10. A total of nine penetrations were cast into the upper lid of the test section. Of these penetrations,

Figure 2-8. Illustration of the CCI-4 Thermite Powder Loading Scheme.

Figure 2-9. Photograph Showing Electrodes Installed in Clamps.

Figure 2-10. Details of the Top Test Section Showing Water Weirs.

six were utilized for Test CCI-4: one stationary lid video camera view port, a port for an insertable water level probe, a 15 cm steam line to the quench system, two light ports, and a port for an insertable crust lance. An illustration of the lid camera installed in the test section is shown in Figure 2-3. For test CCI-5, a seventh port was used for a lid-mounted optical pyrometer that provided data on the surface temperature of the core debris.

The insertable crust lance was designed to fail the crust formed at the melt/water interface in order to obtain data on the transient crust breach cooling mechanism. An illustration of the lance installed in the test section is shown in Figure 2-11, while details of the lance loading device are provided in Figure 2-12. The lance was made from 2.54 cm diameter, 304 stainless steel rod with a pointed tip. The lance contained an electrical isolation hub so that there was no need to terminate DEH power input during the crust loading procedure. As shown in Figure 2-12, the driving force for the lance was simply a 450 kg dead weight that was remotely lowered with the crane during the test. The lance assembly was equipped with a load cell and displacement transducer to record load vs. position data as force was applied to the crust.

Figure 2-11. Illustration of Crust Lance Assembly Installed in Test Section.

The test section components were bolted together on the stationary half of the existing ZPR-9 reactor bed. Zirconia felt and silicon gasket material were used to seal the flanges. An illustration is provided in Figure 2-13. Installation and torquing of test section flange bolts was performed according to an approved procedure to ensure uniform preload on the flange surfaces. Additional reinforcement of each test section component was provided by clamping bars installed in both the North-South and East-West directions. A diagram illustrating the complete flange bolt and clamping bar layout is provided in Figure 2-14.

Figure 2-12. Details of Crust Lance Loading Device.

Figure 2-13. Illustration of Test Section Mounted on ZPR-9 Reactor Bed.

Figure 2-14. Illustration of Test Section Clamping Bars.

2.1.2 CCI-5 Test Apparatus

Test CCI-5 focused on examining the influence of melt pool aspect ratio on the radial/axial power split under dry cavity conditions. Specifically, the test section aspect ratio (i.e., test section width/melt depth) was increased to the greatest extent possible by modifying the test section design to include a single concrete sidewall that would undergo ablation, while the opposing sidewall was made from refractory MgO that essentially created an adiabatic boundary condition. A top view of the modified lower test section design is provided in Figure 2-15, while cross-sectional views of the electrode and non-electrode sidewalls are provided in Figures 2-16 and 2-17, respectively. The thickness of the new non-electrode sidewall was the same as the existing MgO electrode walls (i.e., 25 cm), and it was also protected with a crushed UO_2 pellet liner. This approach had been found to provide an inert (i.e., non-ablative) and highly insulated wall surface. As shown in Figure 2-17, the underside of the test section transition plate was exposed due to the addition of the thin MgO sidewall. To provide thermal protection, the plate was lined with Al_2O_3 insulation and a tungsten heat shield. A similar heat shield design was also used to protect the inner surface of the ACE/MCCI test apparatus lid [4]. The thickness of the concrete sidewall was the same as that used in the CCI-3 test [1].

Figure 2-15. Top View of CCI-5 Lower Test Section.

Figure 2-16. Side View of CCI-5 Lower Section Showing Inert MgO Sidewall Sections.

Figure 2-17. Side View of CCI-5 Lower Test Section Showing Concrete Sidewall.

The selected sidewall dimensions increased the basemat width from the nominal value of 50 cm in Tests CCI-1 through CCI-3 to 79 cm for CCI-5. Taking credit for the symmetry boundary condition, then the aspect (width/melt depth) ratio was increased from (25 cm/25 cm =) 1.0 in tests CCI-1 through CCI-3 to (79 cm/25 cm =) 3.2 for CCI-5, given the initial melt depth of 25 cm for CCI-5 (see Table 1-1). As for Test CCI-4, the safety plan for the tests assumed that a minimum thickness of 15 cm was maintained for all concrete components to ensure final containment of the melt. On this basis, up to 40 cm of lateral ablation could be accommodated in the concrete sidewall. Conversely, up to 42.5 cm of axial ablation could be accommodated given the initial basemat thickness of 57.5 cm.

The balance of the test section design above the lower section was identical to that used in test CCI-4; see Section 2.1.1 for details.

2.2 Water Supply System

The water supply system consisted of a 1900 l capacity tank connected to the flooding weirs in the north and south sidewalls of the top test section through a valve-controlled supply line that provided water to the test section at a specified flow rate. A schematic illustration of the supply

system is provided in Figure 2-18; details of the flooding weirs were shown previously in Figure 2-10. The supply system flowmeter, pressure transducer, level sensor, and thermocouple instrumentation locations are also shown in Figure 2-18.

Figure 2-18. Test Section Water Supply System.

Water flow through the system was driven by an 80 kPa differential pressure in the supply tank at a nominal flow rate of 120 lpm (2 l/s). This inlet flow rate corresponded to a melt/water heat flux of approximately 20 MW/m^2 based on a specific enthalpy of 2.6 MJ/kg for saturated steam at atmospheric pressure, assuming heat transfer occurs through boiling of the overlying coolant. The water flow rate was monitored with a paddlewheel flowmeter. Both the initial water inventory (125 l) and makeup were provided through pneumatic ball valve RV-1, which was opened as needed at the control console to maintain the water volume inside the test section constant at a target level of $125 \pm 13 \text{ l}$ ($50 \pm 5 \text{ cm}$). A redundant supply line, activated by pneumatic ball valve RV-2, was provided in case RV-1 failed to open during the test. A third pneumatic valve, RV-3, was provided in case RV-1 or RV-2 failed in the open position.

Note from Figure 2-18 that the supply line to the test section contained a manual bypass valve downstream of water injection valves RV-1 and RV-2. This valve was vented to a catch pan equipped with an alarmed water detector. During pretest procedures, this valve was left in the open position to divert any water leakage away from the test section. The alarm was intended to notify personnel that a leak was present so that corrective action could be taken. This valve was closed as one of the final steps of pretest operations just prior to evacuation of the cell.

2.3 Quench System

The quench system, shown in Figures 2-19 and 2-20, consisted of a primary quench tank, a secondary spray tank, and a condensate overflow tank. The quench system flowmeter, pressure transducer, level sensor, and thermocouple instrumentation locations are also shown in these two figures.

Figure 2-19. Quench and Overflow Tanks.

Figure 2-20. Spray Tank.

Steam and concrete decomposition gases passed from the test section through a 16.1 cm ID stainless steel pipe into the 680 l capacity, 60 cm ID primary quench tank. This tank contained an initial water inventory of 250 l. With this amount of water, a pool void fraction of ~ 60% could initially be accommodated before the voided water height reached the top of the tank. The quench tank was equipped with a 1.9 cm diameter cooling coil to remove heat from steam condensation, thereby maintaining a subcooled state. The coil water flow was drawn from the building supply system. The flow rate was throttled to nominally 38 lpm, which corresponded to a heat sink of 210 kW assuming a water heat capacity of 4200 J/kg•K and a temperature rise of 80 °C across the coil. If the condensate level in the tank rose to a level of 560 l, spillover into the adjacent 930 l overflow tank occurred through a 2.5 cm ID pipe. The quench tank, and the interconnecting piping between the test section and quench tank, were insulated to minimize heat losses.

The secondary 1230 l capacity spray tank was connected to the quench tank by a 16.1 cm ID stainless steel pipe. In situations where the steam generation rate overwhelmed the primary quench tank, the secondary spray tank served to condense the remaining steam. This tank contained an initial water inventory of nominally 380 l. With this amount of water, a pool void fraction in excess of 60% could be accommodated before the voided water height reached the top of the tank. The spray tank and interconnecting piping between the spray and quench tank were also insulated to minimize heat losses.

2.4 Test Section Pressure Relief System

A pressure relief system was provided to prevent over-pressurization and possible failure of the test section. A schematic illustration of the system is shown in Figure 2-21. The system consisted of a 16.1 cm vent line from the test section to an auxiliary tank containing a nominal initial water inventory of 400 l. The auxiliary tank had an inside diameter of 1.22 m and a capacity of 4100 l. The tank was open to the atmosphere. The pressure relief line to the tank was equipped with a passive, counter-weighted check valve set to open at a differential pressure of nominally 68 kPa. A rupture diaphragm (68 ± 13.4 kPa failure pressure) upstream from the check valve prevented any flow through the line unless the pressure in the test section exceeded the design value of 68 kPa. As shown in Figure 2-21, the relief line was also equipped with a 7.5 cm vacuum breaker valve. This valve was provided to prevent water hammer from occurring due to steam condensation should the pressure relief valve open and then reseal after water had been introduced into the test section.

The initial water inventory in the auxiliary tank was provided to cool gases from the test section and to remove aerosols before noncondensables present in the gas stream passed into the cell atmosphere. The tank was instrumented with a Type K thermocouple to measure water temperature, as well as a differential pressure transducer to measure water depth. The instrumentation locations are shown in Figure 2-21. The instruments were provided so that the steam condensation rate could be determined should the pressure relief valve open during the test. In this manner, there would be no loss of data should the pressure relief system activate.

Figure 2-21. Test Section Pressure Relief System.

2.5 Off Gas System

An illustration of the off gas system is provided in Figure 2-22. Thermocouple and flowmeter instrumentation locations are also shown in this figure. This system filtered and exhausted the noncondensable concrete decomposition gases, as well as the test section covergas, to the cell exhaust. The decomposition gases (H_2 , CO , CO_2) and cover gas exited the spray tank and passed through a flow separator. The cleanup efficiency of this separator was 99% of all entrained solid and liquid when the particle size exceeded 10 microns. After passing through the separator, the flow was vented through a 10 cm diameter line to a filter bank to remove any remaining particulate. The flow then passed through the final off gas flowmeter to the cell atmosphere. The filters were equipped with a passive counter-weighted check valve set to open at a nominal differential pressure of 7 kPa. The bypass valve was provided to ensure that a vent path for the test section was always available in the event that the filters become plugged during the experiment.

Figure 2-22. Off Gas System.

2.6 Cover Gas System

During the test a uniform flow rate of helium was fed into the test section to suppress burning of combustible concrete decomposition gases (H_2 and CO) and to protect test section internals. An illustration of the cover gas system is shown in Figure 2-23. Cover gas flow was modulated by a total of three Hastings Flow Controllers (FC's). One 0-200 slpm FC provided cover gas to the lid camera and light port penetrations, while a second 0-350 slpm FC provided dedicated cover gas flow to the lid camera to prevent aerosol deposition on the camera quartz window through which the melt upper surface was viewed. A third 0-100 slpm FC was used to inert the apparatus on the evening prior to the test.

2.7 Power Supply

The power for Direct Electrical Heating (DEH) of the corium was provided by a 560 kVA single phase AC power supply manufactured by NWL Transformers. Output of the power supply was voltage or current controlled. The supply had four voltage/current ranges: 56.4 V/10 kA, 113 V/5 kA, 169 V/3.3 kA, and 226 V/2.5 kA. The power supply was connected to the two arrays of tungsten electrodes in the test section through water cooled copper pipes. The total voltage drop through the pipes and tungsten electrodes at operational temperature and maximum current was calculated to be less than 0.5 V. The leakage current through the overlying water pool after the cavity was flooded was estimated to be less than 1% of the total current.

Figure 2-23. Cover Gas System.

2.8 Concrete Compositions

As shown in Table 1-1, concrete type was one of the the key parametric variations among the tests conducted as part of the experimental series. Test CCI-4 was conducted with Limestone-Common Sand (LCS) concrete, while CCI-5 was conducted with siliceous concrete. The chemical compositions of these two concretes are shown in Table 2-2. These compositions were determined³ based on chemical analysis of archive samples from the CCI-4 and CCI-5 tests that were produced when the components from these two tests were poured. The reader is referred to the individual data reports [2,3] for additional information regarding the engineering compositions (i.e., mix ratios) and aggregate size distributions for each concrete type.

To prevent downward migration and possible escape of concrete decomposition gases during the course of the experiments, the electrode penetrations through the bottom support plate were sealed using O-rings. As a part of normal pretest operations, the test sections were leak checked at a differential pressure of 83 kPa and found to have very low leak rates. On this basis, essentially all concrete decomposition gases migrated upwards through the melt pool during the experiments, as opposed to partial loss through the bottom support plate of the apparatus.

For CCI-4, the concrete surfaces were protected by a thin (i.e., 3 mm) layer of low density ($\sim 480 \text{ kg/m}^3$) ZrO_2 felt to prevent thermal shock of the concrete basemat and sidewalls during the initial chemical reaction. After the reaction was complete, the felt dissolved into the melt.

³Chemical analysis carried out by the Construction Technologies Laboratories (CTL Group) in Skokie, Illinois.

For CCI-5, this insulation layer was omitted in order to minimize the time to onset of concrete ablation after the thermite burn was completed.

The densities of the concretes used in the tests are shown in Table 2-3. These densities were calculated on the basis of the measured mass and volumes of the concrete archive samples for each test. Instrumentation locations within the sidewalls and basemat are described later in this section.

Table 2-2. Chemical Composition of Concretes.

Oxide	CCI-4 Wt%	CCI-5 Wt%
SiO ₂	25.99	58.27
Al ₂ O ₃	2.78	3.51
Fe ₂ O ₃	1.40	1.33
CaO	27.81	20.20
MgO	9.21	0.92
SO ₃	0.91	0.45
Na ₂ O	0.39	0.49
K ₂ O	0.54	0.80
TiO ₂	0.17	0.15
P ₂ O ₅	0.09	0.07
Mn ₂ O ₃	0.04	0.05
SrO	0.02	0.03
CO ₂	23.80	9.50
H ₂ O, Free	3.58	1.90
H ₂ O, Bound	3.42	2.88
Total	100.15	100.54

Table 2-3. Concrete Densities.

Test	Concrete Density (kg/m³)
CCI-4	2404
CCI-5	2382

2.9 Corium Compositions

As shown in Table 1-1, the initial corium compositions for the two tests were quite different, with CCI-4 conducted with a partially oxidized BWR core melt, while CCI-5 was conducted with a fully oxidized PWR core melt. The compositions for the two tests contained various proportions of calcined concrete as initial constituents. The compositions of the concrete additives were consistent with the type of concrete used for the sidewalls and basemat for each test. Aside from lowering the melting point of the mixtures [33], the additives were incorporated to account for concrete erosion that is expected to occur during the corium spreading phase following breach of the Reactor Pressure Vessel (RPV) [34].

For test CCI-4, one of the key objectives was to increase the metal content of the melt to the highest practical level to more accurately mock up a prototypic BWR core melt at the time of vessel failure. The target value for the initial metal content was 15 wt %⁴. The overall approach for satisfying this requirement was to place a metal-bearing concrete insert that overlaid the basemat for dissolution into the melt prior to onset of basemat ablation, thereby increasing the melt metal content to the target level. This technique was originally developed as part of the ACE/MCCI test series [4] that focused on quantifying fission product source term during core-concrete interaction. The metal content of the inserts, shown in cross-sectional view in Figure 2-24 and in tabular form in Table 2-4, included Zr that represented unoxidized cladding plus iron that, when combined with the Cr metal reaction byproduct from the thermite reaction, produced a mixture that mocked up stainless steel from ablated vessel structures. A photograph showing the inserts in place over the CCI-4 basemat is provided in Figure 2-25.

The initial bulk melt compositions at the start of the interaction with the concrete basemats for the two tests are shown in Table 2-5, while the detailed breakdowns are provided in Table 2-6. In addition, the compositions of the thermites that were used to produce the initial melt volumes are provided in Table 2-7. For Test CCI-4, the bulk compositions shown in Tables 2-5 and 2-6 includes both the initial melt volume produced by the thermite, as well as the materials in the inserts that were ablated into the melt volume prior to contacting the basemat. The estimate includes the expected oxidation of Zr with H₂O and CO₂ gases that were liberated upon decomposition of the concrete in the inserts. For CCI-5, the melt content simply corresponds to the posttest thermite reaction composition as no inserts were used in that experiment.

Figure 2-24. Illustration of CCI-4 Concrete-Metal Inserts over the Concrete Basemat.

⁴See the summary record of the first meeting of the Management Board of the OECD MCCI-2 Project, NEA Headquarters, Paris France 4-5 April 2006.

Figure 2-25. CCI-4 Basemat with Insert Prior to Placement on Test Stand.

Table 2-4. Composition of CCI-4 Concrete/Metal Inserts.

Constituent	Wt%	Mass (kg)
Zr rod	48.88	17.88
Fe rod	24.52	8.97
Limestone/common sand concrete	26.60	9.73
Total	100.00	36.58

Table 2-5. Initial Melt Compositions.

Constituent	CCI-4 (Wt%)	CCI-5 (Wt%)
UO ₂	56.52	56.32
ZrO ₂	21.53	23.13
Calcined Concrete	9.65 ^a	14.14 ^b
Metal components ^c	7.69 ^c	6.41 ^d
Unoxidized cladding	4.61	0.00

^aCalcined LCS concrete: 42.0/14.1/38.8/5.1 wt% SiO₂/MgO/CaO/Al₂O₃

^bCalcined siliceous concrete: 79.0/0.9/15.6/4.5 wt% SiO₂/MgO/CaO/Al₂O₃

^c61.1/38.9 wt % Cr/Fe

^d100 % Cr

Table 2-6. Detailed Melt Composition at the Start of Basemat Ablation.

Constituent	CCI-4		CCI-5	
	Wt %	Mass (kg)	Wt %	Mass (kg)
UO ₂	56.52	169.36	56.32	332.29
ZrO ₂	21.53	64.51	23.13	136.47
SiO ₂	4.05	12.15	11.17	65.90
Al ₂ O ₃	0.49	1.47	0.64	3.78
MgO	1.36	4.08	0.12	0.70
CaO	3.75	11.23	2.21	13.04
Zr	4.61	13.82	0.00	0.00
Cr	4.70	14.08	6.41	37.82
Fe	2.99	8.97	0.00	0.00
Total	100.00	299.67	100.00	590.00

Table 2-7. Thermite Compositions.

Chemical	CCI-4		CCI-5	
	Wt %	Mass (kg)	Wt %	Mass (kg)
U ₃ O ₈	66.44	176.07	58.70	346.33
Zr	16.48	43.67	17.16	101.24
Si	0.84	2.23	1.57	9.26
SiO ₂	1.79	4.74	7.84	46.26
Mg	0.72	1.91	0.07	0.41
Al	0.23	0.61	0.09	0.53
CaO	3.30	8.74	2.21	13.04
CrO ₃	10.20	27.03	12.36	72.93
Total	100.00	265.00	100.00	590.00

Note that the compositions shown in Tables 2-5 and 2-6 do not include an additional mass of crushed UO₂ pellets (typically ~ 300 kg) that was used as a protective layer for the cast MgO (see Figures 2-4, 2-5, 2-15, and 2-16). This material did not participate in the initial exothermic chemical reaction. The pellets were recovered and weighed following each test. This information, as well as chemical analysis of the final melt compositions, indicated that the pellet layer remained essentially intact as an inert protective layer during test operations, with little if any of the material dissolving into the melt.

As depicted in Figure 2-8, the thermite powders were packed into the test sections in large aluminized bags that were pre-installed over the basemats. The weight of bagging material typically amounted to an average contaminant level of ~ 0.04 wt% in the charge. The bagging was utilized to minimize moisture uptake by hygroscopic chemicals in the thermite (CrO₃, CaO, and SiO₂). Excessive moisture uptake was an operational concern since the moisture reacted with metallic constituents to form hydrogen during the thermite reaction. As an additional measure to minimize moisture uptake, exposed concrete surfaces were covered with bagging material before the thermite was loaded. See Figure 2-9 for a photograph showing the film installed over a basemat.

2.10 Instrumentation and Data Acquisition

The CCI facility was instrumented to monitor and guide experiment operation and to log data for subsequent evaluation. Principal parameters that were monitored during the course of the test included the power supply voltage, current, and gross input power to the melt; melt temperature and temperatures within the concrete basemat and sidewalls; crust lance position and applied load; supply water flow rate; water volume and temperature within the test apparatus, and water volume and temperature within the quench system tanks. Other key data recorded by the DAS included temperatures within test section structural sidewalls, off gas temperature and flow rate, and pressures at various locations within the system. An overview of the instrumentation for the CCI test series is provided in this section; complete instrument lists are provided in the individual data reports for each test [2,3]. Measurement uncertainties for the various instruments that were used in the tests are summarized in Table 2-8.

Table 2-8. Summary of Data Measurement Uncertainties for CCI Tests.

Measurement	Instrument	Accuracy
Temperature (other than melt)	Type K thermocouple	$\pm 2.2\text{ }^{\circ}\text{C}$ or $\pm 0.75\text{ }%$
Temperature (melt)	Type C thermocouple	$\pm 4.5\text{ }^{\circ}\text{C}$ or $\pm 1.0\text{ }%$
Temperature (corium upper surface)	Two-color optical pyrometer	$\pm 4.0\text{ }^{\circ}\text{C}$
Pressure	Pressure transducer	Differential: $\pm 0.4\text{ kPa}$ Absolute: $\pm 2.0\text{ kPa}$
Water flowrate	Test section supply and quench tank coil: paddlewheel flowmeters	$\pm 4\text{ }%$
DEH input power	Hall effect meter	$\pm 0.2\text{ }%$
Power supply voltage	Digital voltmeter	$\pm 0.008\text{ }%$
Tank water volume	Magnetic float	$\pm 2\text{ l}$ for quench tank; $\pm 5\text{ l}$ for all other tanks
Debris-water heat flux	Calculated based on steaming rate as measured by quench tank level float.	$\pm 10\text{ }%^a$

^aPrimary contributor is corium surface area (9%)

All data acquisition and process control tasks were managed by a DAS PC executing LabVIEW under Windows XP. Sensor output terminals were connected inside the test cell to model HP E1345A 16-channel multiplexers, which were integrated into a mainframe chassis in groups of eight. An illustration of the DAS setup is provided in Figure 2-26. The multiplexers directed signals to an HP E1326B 5 ½ digit multimeter incorporated into each chassis. Three independent 128 channel systems were used for a total capacity of 384 channels.

Signal noise was reduced by the digitizer through integration over a single power line cycle (16.7 ms). The digitized sensor readings were routed from the test cell to the PC in the control room via two HP-IB extenders. The extenders allowed the ASCII data from the HP to be sent through the cell wall over a BNC cable. The extender within the control room then communicated with a GPIB card within the PC. This configuration also permitted remote control of the multimeter through LabVIEW.

Figure 2-26. DAS Setup for CCI Tests.

Integration of the signal over the period of a power line cycle limited the speed with which the multiplexer could scan the channel list. The theoretical minimum scan time was ~ 1.7 s (i.e., $16.7 \text{ ms} \cdot 100 \text{ channels per chassis}$). Though the three systems operated independently, implying the ability to update all 300 channels in ~ 2 seconds, the actual time required for the update was about 5.5 seconds.

Instrumentation for both tests was selected to provide the necessary measurements to determine the time-dependent 2-D concrete ablation profile and the melt temperature distributions. The instrument layouts for the two tests were slightly different due to the differences in cavity geometry and initial size. Plan and elevation views of the basemat thermocouple layout for CCI-4 are provided in Figures 2-27 and 2-28, respectively, while instrument locations in the concrete sidewalls are shown in Figure 2-6. The analogous illustrations for CCI-5 are provided in Figures 2-29, 2-30, and 2-17. Since CCI-5 only utilized on concrete sidewall, extra thermocouples were mounted off the sidewall centerline to provide better resolution of the ablation progression in the sidewall. The locations of these instruments are shown in Figure 2-31. The thermocouple elevations shown in these figures are all taken with respect to the original height of the basemat surface ($Z=0$).

Figure 2-27. Plan View of CCI-4 Basemat Instrumentation Layout.

Figure 2-28. Elevation View of CCI-4 Basemat Type C Thermocouple Locations.

Figure 2-31. Exterior View of CCI-5 Sidewall Form Showing Instrument Locations.

Both the concrete sidewalls and basemat were instrumented with multi-junction Type K thermocouple assemblies to determine the 2-D ablation profile as a function of time. In addition, Type C thermocouple assemblies in long-body tungsten thermowells protruded upwards from the basemat and laterally inwards from the concrete sidewalls in several locations. The purpose of these instruments was to provide data on the axial and lateral melt temperature distributions as a function of time. For both tests, a total of five four-junction Type C thermocouple arrays in tungsten thermowells (20 junctions total) were cast into the concrete basemat, while each concrete sidewall was instrumented with an eight-junction Type C array in a tungsten thermowell. Photographs showing typical thermocouple assemblies installed in the basemat and sidewall forms prior to placement of the concrete are provided in Figure 2-32 and 2-33, respectively. For test CCI-5, a two-color optical pyrometer was also installed on the test section lid to provide data on the melt upper surface temperature as a function of time.

Aside from the concrete basemat and sidewalls, the MgO sidewalls of the lower test section, as well as the upper sidewall sections, were instrumented with Type K and Type C thermocouples to measure the sidewall heat up prior to water addition, and also to measure the sidewall cooling rate above the melt surface after water was added. Illustrations of these thermocouple locations are provided in Figure 2-3 and 2-34(a).

Several methods were provided for monitoring water level in the test section. One method consisted of a differential level probe which was inserted through a sealed penetration in the lid. The probe was maintained in a retracted position during dry cavity operations. After water was added, the probe was inserted to a distance of ~ 50 cm from the initial basemat surface

(viz. ~ 25 cm from the initial collapsed melt surface). The probe tip was also instrumented with two Type K thermocouples that monitored the plenum gas temperature prior to water addition; thereafter, these thermocouples measured the water temperature over the melt surface. The probe tip location above the melt after insertion is shown in Figure 2-34(b).

Aside from the insertable water level probe, two additional methods were provided to monitor the water volume in the test section. The first was a static water level port located in the North sidewall 55 cm from the initial basemat surface (30 cm from the initial collapsed melt surface). The port location is shown in Figure 2-34(b). The second redundant method was provided by an on-line calculation of the water volume in the test section based on conservation of mass for the water volume in the system, which was fixed at the start of the test.

Figure 2-32. Typical Thermocouple Installation in Basemat Form.

Figure 2-33. Typical Thermocouple Installation in Sidewall Form.

Figure 2-34. CCI-4 (a) Sidewall Thermocouple and (b) Pressure Transducer Locations.

Water levels in the water supply and quench system tanks were monitored with magnetic floats. As a redundant level measurement technique, all tanks were equipped with differential pressure transducers to monitor water heads. Water flow rate to the test section from the supply tank, in addition to the water flow rate through the primary quench tank cooling coil, were monitored with paddlewheel flow meters. Transient water temperatures in all tanks, as well as the temperature differential across the quench tank cooling coil, were monitored using Type K thermocouples. The main steamline between the test section and quench tank was also instrumented with Type K thermocouples to measure the local gas and structure temperatures. The locations of these instruments are shown in Figures 2-13 and 2-18 through 2-21.

Key system pressures were monitored with strain-gauge type pressure transducers. As shown in Figures 2-18 through 2-20 and 2-34(b), the pressure in all system tanks was monitored, and also the test section plenum pressure. An additional transducer was located in the lower test section to monitor the pressure beneath the melt upper surface. This transducer was mounted on the east sidewall of the test section at an elevation of 50 cm beneath the initial concrete surface. As described earlier, the gap between the MgO sidewalls and the electrodes was packed with crushed UO_2 pellets during corium loading. Thus, this transducer recorded the pressure beneath the melt surface as long as the gap remained unplugged during the test.

In terms of the power supply operating parameters, voltage drop across the tungsten electrode bank was monitored with the DAS voltmeter, while current input was monitored with two parallel 5000:1 current transformers. Power input to the melt was monitored with two Hall Effect meters.

In addition to the above instrumentation, visual information regarding the core-concrete interaction and melt quenching behavior was provided by a video camera mounted on the upper lid of the apparatus. The camera location and field of view are shown in Figure 2-3. Five area video monitors were also used to monitor for leaks, and to record any disruptive events should one occur. Finally, the crust lance was equipped with load and displacement transducers to provide data on the crust load vs. time during the crust failure sequence.

2.11 Test Procedures

2.11.1 Pretest Operations

Assembly of the apparatus began by installing the tungsten electrodes (126 total; 63 per side) into machined copper electrode clamps. The electrode clamps were then attached to the bottom of the 2.54 cm thick aluminum support plate which served as the foundation for the entire apparatus. With the electrode clamps installed, the support plate was moved into position on the steel platform that supported the apparatus. The concrete basemat was then placed atop the support plate. The basemat was then completely covered with a continuous sheet of 1.7 mil aluminized Saran film to prevent moisture contamination of the thermite powders from the basemat once the powders were loaded into the test section. The lower test section sidewalls were then set in place. The concrete wall(s) were also covered with aluminized Saran before placement to prevent moisture contamination of the thermite from these components. The lower section flange bolts and clamping bars were then installed and torqued according to an approved procedure.

In parallel with test section assembly, the thermite powders were mixed in preparation for corium loading. As a precursor for initiating mixing, a gas sample test^a was conducted to verify that the initial level of volatile impurities in a sample prepared from the thermite constituents to

^aThe gas sample test procedure consisted of igniting a representative sample of the thermite in a closed vessel. The amount of noncondensable gas produced was then determined from the ideal gas law.

be used for a given test was sufficiently low to preclude excessive gas release during the burn. Upon successful completion of this test, mixing was initiated.

Once the lower section was assembled, preparations for loading of the corium charge began. A single, large 1.7 mil aluminized Saran bag was preinstalled over the basemat. During loading, the thermite charge was placed within this bag in order to reduce the amount of bagging material present in the thermite. As the powders were placed in the test section, the basemat melt temperature thermocouples were monitored to detect any localized heating in the corium powders. If heating was observed, the cell was to be immediately evacuated. As the thermite was placed, the gap between the tungsten electrodes and MgO sidewalls was filled with crushed UO_2 pellets. The crushed pellets served as a protective layer against excessive chemical/thermal attack by the corium during the test. Once loading was completed, two sparkler igniters were placed a few centimeters below the top of the powders near the center of the test section, and then the bag was folded and sealed. An illustration of the loading scheme is provided in Figure 2-8. As described in Section 2.9, the use of the single large bag for containment of the thermite resulted in a low bagging material contaminant level of nominally 0.04 wt % present in the charge at the time of ignition.

Once loading was completed, a removable train containing a 1.0 kg bagged sample of thermite was installed over the powder bed; an illustration is provided in Figure 2-35. The sample train was removed weekly and the sample weighed to monitor the moisture pickup by the thermite during the period between loading and test initiation. Note from Figure 2-35 that the top portion of the train also contained a 4.5 kg canister of desiccant. The desiccant was provided to maintain the plenum gas as dry as possible during pretest operations. As an additional measure to prevent moisture accumulation in the powder bed, the lower test section was continuously purged with argon (2 slpm) from the time loading was completed until the test was initiated.

After installation of the sample train, the remainder of the test apparatus was assembled. This included installation of the transition plate, two upper sidewall sections, and finally the enclosure lid. Peripheral instrumentation was then installed on the lid and sidewalls of the test section. The main steamline run from the test section to the primary quench tank was completed, as well as the pressure relief line from the test section to the auxiliary tank. (The main steamline was closed off from the test section using an insertable blank-off plate throughout pretest operations to preclude moisture migration from the quench tank into the test section).

After assembly was completed, extensive system checkout procedures were performed to ensure that the facility was in proper working order. This included a proof test of the test section at 83 kPad, which is 20 % in excess of the pressure relief system activation pressure of 69 kPad. The pressurization gas for this test was argon. An insertable blind flange was installed upstream of the rupture disk in the pressure relief line to isolate this system. During the test, the apparatus was gradually pressurized to the proof pressure of 83 kPad. After a 1 minute hold at this pressure, the system was isolated to determine the leak rate. The leak rate of all the assembled CCI test sections was found to be ≤ 5 kPa/min (20 slpm) at a nominal pressure of 55 kPad, which

was significantly below the acceptance criterion (i.e., $< 2\%$ of the expected peak gas/vapor generation rate during the tests).

Pretest preparations culminated with a final full system checkout that involved remotely running all equipment with the power supply in operation across a water cooled dummy load. Once the full system check was completed, final system preparations were carried out. These efforts included: (i) hookup of the power supply to the tungsten electrodes through water cooled buss bars, (ii) installation of the final piping connection between the water supply tank and the test section, and (iii) removal of the sample train from the test section. Following connection of the power supply to the electrode clamps, the key for the power supply lockout located in the cell, as well as the key for the interlock located on the control room console, were assigned to a custodian who kept the keys in their possession until the test was initiated. This step was taken to preclude inadvertent activation of the power supply.

Over the several weeks spanning pretest operations, the thermites within the test sections gradually absorbed moisture. Peak moisture pick up for the test series was limited to 0.2 wt%, which was well below the maximum permissible level of 0.3 wt %. This was the last criterion that needed to be satisfied before final approval was granted to proceed with test operations.

2.11.2 Test Operations

The planned operating procedure was essentially the same for both tests. This procedure is described below. The actual test event sequences are summarized in the next Section as part of the presentation of the test results.

On the evening prior to the experiment, the apparatus was inerted with a slow bleed of helium into the test section. On the day of the experiment, the apparatus was brought up to operating conditions, a final walk through inspection was performed by operating personnel, the thermite igniter was hooked up, and finally the power supply was energized before the containment was evacuated and sealed. Data acquisition was initiated, and the video camera

Figure 2-35. Thermite Sample Train.

recorders were started. Coolant and cover gas flows were brought up to design conditions, and the cell ventilation system was closed and sealed. After verifying that operating personnel were at their assigned positions, power was applied to the nichrome wire/sparkler located at the top of the powder charge. Thermite ignition was clearly evident on the lid video camera that viewed the top of the powder bed (see Figure 2-3); based on this information, ignition was announced and logged in the control room. Based on readings from thermocouples located near the bottom of the charge, completion of the burn was also announced and logged. (Thermite burn times were less than one minute for the two tests).

At completion of the burn, the power supply operator initiated a current ramp at a rate of ~ 3000 Amps/minute up to target power (see Table 1-1). After target power was reached, the input power would be held constant at target level power for a specified period of dry core-concrete interaction, or until an ablation trigger limit was reached in either the lateral or axial direction. After one of these two criteria was met, the cavity would then be flooded. However, if a crust was present at the melt upper surface, the crust lance would be used to fail the crust prior to flooding so that the water would be able to contact the underlying melt. Following water addition, the power supply operation would be switched from constant power at the target level to a constant voltage operating mode. This approach would keep the specific power density in the remaining melt zone approximately constant should a solidification (quench) front develop during the interaction (recall that the DEH technique does not appreciably heat solidified corium). Forty five minutes after water addition, or after the debris cooling rate had been reduced to a relatively low level, the crust would be failed with the lance to obtain data on the transient crust breach cooling mechanism. After breach, power supply operations would continue for an additional 45 minutes, yielding a total operating period of 90 minutes with water present in the cavity, or until the maximum ablation limit was reached in either the lateral or axial directions. At this point, the input power would be turned off and the test was terminated. The primary datasets from the experiment were then backed up, and the DAS was restarted in a slow recording mode (1 scan per minute) to record additional information during the long term cooldown. The system was then left unattended overnight.

2.11.3 Posttest Operations

On the day after the experiment, a Health Physics Technician made the initial reentry into the containment cell and performed a survey to determine if any radioactive material had escaped from the apparatus during the test. In all cases, this survey turned up negative. On this basis, personnel reentered the cell and began the normal disassembly process.

Instrument cabling on the apparatus was disconnected and rolled back to terminal boxes in the cell. Peripheral instruments and equipment (i.e., video cameras, pressure transducers, lance load assembly, water level insertion probe drive) were then removed, cleaned, and stored. The test section reinforcing bars and flange bolts were then removed, cleaned, and stored.

At this point, physical disassembly of the test section was initiated. This phase of the work was carried out in anti-contamination suites and full face respirators according to an approved Radiation Work Permit (RWP). The test section main steamline and pressure relief

line were removed from the lid, cleaned, and stored. The test section lid and top sidewall section were then removed, cleaned, and stored. Photographs would then be taken to document the debris state in the as-found condition. Following this step, the middle sidewall section was removed, and splattered corium that had solidified on the inner surfaces of this component was collected and weighed. The middle section was then cleaned and stored.

Removal of the middle section fully revealed the lower test section that contained the solidified core material. At this point, the top surface of the solidified corium could be examined and characterized. Photographs were taken, and measurements of the upper surface elevation profile were made. Sidewall crust material above the upper crust was then removed, collected, and weighed. Any suspended crust material that was present over the bulk of the solidified corium was then collected, characterized, and weighed. A second set of photographs and surface elevation profile measurements were then obtained. During this stage of disassembly, samples were collected for subsequent chemical analysis to determine elemental composition to better characterize the debris distributions.

After the debris upper surface was characterized, the inert MgO sidewalls that backed up the tungsten electrodes were then removed, cleaned, and stored. During this step, the remnants of the crushed UO_2 pellet liner that served as a protective layer behind the tungsten electrodes was collected and weighed. After additional photographs were taken, the North and South sidewalls were removed with the cell crane and set on the platform for examination. During this step, the corium fractured vertically along a plane that roughly followed the original inner surface of the concrete walls. After the concrete walls were set out of the way, the solidified corium over the basemat was lifted from between the two banks of tungsten electrodes and placed on the platform for examination. The basemat and concrete wall remnants were then photographed, and additional measurements were taken to better characterize the overall debris distribution. Additional samples were collected for chemical analysis to provide data on the corium lateral composition variation.

Following these steps, the basemat and sidewall remnants were placed in heavy gauge sheet metal storage containers. The containers were then moved to an adjacent cell for archival storage. With the test specimens out of the way, the electrodes were removed from the clamps on the test section bottom plate. The plate and clamps were then cleaned and stored. Following these steps, the cell was decontaminated back to a shoe cover area, which completed the posttest operations phase of the experiment.

3.0 RESULTS AND DISCUSSION

This section presents the major thermalhydraulic and posttest examination results for the two CCI experiments conducted as part of the test series. A discussion that compares and contrasts key results of these tests, along with the results of tests conducted as part of the MCCI-1 program, is provided at the end of this section. Specifications for the tests are provided in Table 1-1.

3.1 CCI-4 Test Results

As shown in Table 1-1, Test CCI-4 investigated the interaction of a 78 % oxidized Boiling Water Reactor (BWR) core melt, initially containing 10 wt % Limestone/Common Sand (LCS) concrete, with a two-dimensional LCS concrete test section (see Section 2.1 for a design description). For reference, the initial melt composition is provided in Table 2-6. Target input power during dry cavity operation was specified as 95 kW. The planned test operating procedure was detailed in Section 2.11. The actual operating sequence is described below.

3.1.1 Thermalhydraulic Results

CCI-4 was performed on 26 May 2007. An event sequence is provided in Table 3-1. Test operations began by applying electrical current to the nichrome wire located near the top of the charge; the burn time was ~30 seconds. Following the reaction, DEH input to the melt was ramped up to the target power of 95 kW. The power trace for the test is shown in Figure 3-1. In the discussion that follows, time $t = 0$ corresponds to the onset of basemat ablation beneath the concrete-metal inserts that were placed over the basemat (see Section 2.1). As indicated in Table 3-1, target power level was reached at -36.6 minutes, where it was essentially maintained for the balance of the test involving dry cavity operations.

Following the thermite burn, there was a quiescent period during which concrete surfaces were protected by insulating crusts. However, at -10.3 minutes, plenum gas temperatures suddenly increased by several hundred degrees, and the power supply operating current dropped at constant power, indicating onset of concrete ablation within the test section. The data further indicates that ablation of the concrete-metal inserts and concrete sidewalls began at this time. The insert was rapidly eroded, and onset of basemat ablation was detected at the centerline and in the four outer quadrants over the time interval from -6.54 to + 4.41 minutes. The average time for all five arrays was 0.0 minutes, which defines time $t = 0$ for the experiment. The thermal response at the basemat axial centerline is shown in Figure 3-2, while the north and south concrete wall thermal responses at the +0.0 cm elevation are shown in Figures 3-3 and 3-4, respectively (see Figures 2-3 and 2-27 for schematics showing the thermocouple array locations). Note that only data preceding the first off-scale reading by the thermocouples are shown. The dimensions shown in the legends for these figures indicate the distance of the thermocouple junctions from the concrete inner surfaces. As noted earlier, the sequential rise in the temperatures is indicative of the progression of the ablation front into the concrete. In general, onset of ablation at a given location corresponds to the local temperature reaching the LCS concrete liquidus temperature of 1295 °C [4].

Table 3-1. CCI-4 Event Sequence (times relative to onset of ablation of the basemat).

Shifted Time (Minutes)	Event
-38.2	Thermite burn initiated; view of melt surface occluded by aerosol within 5 seconds.
-37.7	Thermite burn completed (burn time ~ 30 seconds); melt temperature ~1900 °C
-36.6	Target DEH input power of 95 kW reached and maintained until power off.
-10.3	Sharp increase in aerosol production and gas plenum temperature, indicating onset of insert ablation.
-6.54 to 4.41	Onset of basemat ablation detected at all five basemat locations; average time for all arrays is 0.0 minutes, which defines time $t = 0$ for the experiment.
0.0	Onset of basemat ablation based on average time at all five basemat locations. Initial melt temperature ~1850 °C.
23.1	DAS communications failure halts data transmission between the PC and the analog to digital converters in the cell. Recovery efforts initiated.
41.0	DAS recovery operations completed and data acquisition restarted.
30.6 to 135.2	Aerosols clear to reveal interaction. The surface is either devoid of crust, or covered in areas with skin crusts that are not stable. Bubbling pool observed.
135.2 to 172.2	Solid crust platelets form on melt surface, attempting to bond together, as well as the test section sidewalls. Convection within the melt is sufficient to periodically break up these formations.
172.2 to 314.6	Crust becomes fixed and bonded to sidewalls. Two-phase eruption and melt extrusion events occur almost continuously through various vent holes that form, migrate, and close (freeze shut) over the extent of the crust surface.
259.2 to 267.4	Crust lance inserted twice in an attempt to breach the bridge crust. Peak load of 3.33 kN applied, but the crust was not breached. Surface elevation measurements were in the range of 66.5 - 69.8 cm at the point of lance contact.
314.6	Last eruption through crust occurs, and vent hole freezes shut. Thereafter, pressurization of lower test section occurs due to continued gas production from CCI with partial gas venting through leaks around the electrode clamps.
383.7	Sparks seen from beneath the test section bottom plate; DEH input terminated.
384.9	Water addition to test section initiated.
403.3 to 407.8	Crust lance inserted again in an attempt to breach the bridge crust. Some breakage occurred on initial contact at an elevation of 69.1 cm, but the full depth of the material was not penetrated to reveal the underlying melt. Peak load of 4.70 kN was applied; surface elevation reduced to ~ 60 cm after first breakage.
458.3	Data acquisition terminated.

As described in Section 2.10, a total of seven multi-junction Type C thermocouple arrays were used to monitor melt temperatures at various axial and lateral locations. Data from an axially configured array in the northwest quadrant of the basemat is shown in Figure 3-5, while data from the laterally configured arrays located in the north and south sidewalls at the +5.0 cm elevation are shown in Figures 3-6 and 3-7, respectively. Finally, data from all melt temperature thermocouples that contacted corium over the course of the test are shown collectively in Figure 3-8 for comparative purposes. Dimensions in the legends again refer to junction elevations with respect to the concrete surfaces. The initial melt temperature following the thermite reaction was ~ 1900 °C. By the time erosion of the concrete basemat commenced, the melt temperature had declined to ~1850 °C.

Figure 3-1. CCI-4 DEH Input Power.

Figure 3-2. CCI-4 Basemat Heatup near Centerline.

Figure 3-3. CCI-4 North Wall Heatup (0 cm elevation).

Figure 3-4. CCI-4 South Wall Heatup (0 cm elevation).

Figure 3-5. CCI-4 Melt Temperatures in Northwest Quadrant of Basemat.

Figure 3-6. CCI-4 Melt Temperatures near the North Wall (+5 cm Elevation).

Figure 3-7. CCI-4 Melt Temperatures near the South Wall (+5 cm Elevation).

Figure 3-8. Collection of CCI-4 Melt Temperatures.

During the first 10 minutes of concrete erosion, several melt temperature thermocouples detected a steady increase in melt temperature from ~1850 °C up to ~2000 °C, which was likely due to exothermic chemical reactions between metallic melt constituents (Zr, Cr, Fe) and concrete decomposition gases. After this initial phase, the data in Figure 3-8 indicates that: i) the average melt temperature declined steadily from ~1800 °C at 50 minutes to ~1550 °C at the time during dry cavity operations ended at 383 minutes, and ii) no large lateral or axial temperature gradients developed in the melt pool during the interaction. Note that the latter observation is not applicable at the pool upper surface late in the experiment sequence (i.e. past 172 minutes), where the sustained presence of the crust is indicative of a large temperature gradient at that boundary.

As shown in Table 3-1, at ~ 23 minutes in the operating sequence, an unidentified DAS communications failure halted transmission between the PC and the Hewlett Packard (HP) analog to digital converters in the cell. The cause was thought to be a transmission error between one of the HP units and one of the two repeaters between each HP and the PC. The error froze traffic along the General Purpose Interface Bus (GPIB) that linked all repeaters with the PC. Diagnostic and recovery operations were initiated, and communications were reestablished at 41 minutes, leaving a 16.9 minute gap in the recorded data. During this time, input power to the melt was maintained at 95 kW based on panel readouts in the control room that were independent of the data acquisition system.

In terms of melt surface behavior, over the time interval from 30.6 to 135.2 minutes, aerosols in the plenum cleared to reveal the upper surface of the core-concrete interaction. The surface was either completely devoid of crust, or covered in areas with skin crusts that were not stable. Bubbling pool behavior was observed. As the experiment progressed past this point, crust platelets began to form on the melt surface. These platelets intermittently bonded together, as well as to the test section sidewalls. However, convection within the melt was sufficient to periodically break up these formations, and the process would begin again. At 172.2 minutes, the crust became permanently fixed and bonded to sidewalls. Over the next two hours of the interaction, two-phase eruption and melt extrusion events occurred almost continuously through various vent holes that would form, migrate, and close (freeze shut) over the extent of the crust surface. During this interval (i.e., from 259.2 to 267.4 minutes), the crust lance was inserted twice in an attempt to breach the bridge crust. A peak load of 3.33 kN was applied, but the crust was not breached. Surface elevation measurements were in the range of 66.5 to 69.8 cm at the point of lance contact, which can be compared with the initial collapsed melt pool height of 25 cm. As discussed in the next section, extensive melt foaming and subsequent corium freezing in the upper regions of the test section gradually led to the development of a large mantle of frozen material on the sidewalls in the upper region of the test section.

The progression of the axial ablation front location during the course of the test is shown in Figure 3-9, while the analogous set of data for the north and south concrete sidewalls are provided in Figures 3-10 and 3-11, respectively. Finally, characteristic erosion rates measured on each concrete surface are shown collectively in Figure 3-12. This collection of data indicates that after the first 50 minutes of the interaction, ablation proceeded fairly uniformly in the axial and radial directions, with no large spatial incoherence in the ablation progression observed until ~ 300 minutes. At this point, axial ablation appears to increase. However, at 314 minutes the

Figure 3-9. CCI-4 Axial Ablation.

Figure 3-10. CCI-4 North Sidewall Ablation.

Figure 3-11. CCI-4 South Sidewall Ablation.

Figure 3-12. CCI-4 Characteristic Axial and Lateral Ablation Data.

bridge crust effectively sealed off the upper region of the test section (see Table 3-1), causing concrete decomposition gases to vent downwards through leaks around the electrode clamps as opposed to upwards through the melt pool. This flow reversal undoubtedly affected the pool thermalhydraulics, and so it is not clear that the accelerated axial erosion observed in Figures 3-9 and 3-12 after 300 minutes is prototypic.

As shown in Table 3-1, the lid camera view showed that the last melt eruption ended at 314.6 minutes, at which time the final vent hole through the crust was plugged by solidifying melt entrained through the hole. Moderate pressurization of the lower test section started at this time (i.e., up to ~ 0.4 bar differential) due to continued gas production from the core-concrete interaction, while the normal gas flow path up through the system was at least partially blocked by the crust. Posttest examinations further indicated that part of the gas flow was then vented through small leaks at the bottom of the test section where the electrode clamps bolted to the test section bottom support plate. Formation of this significant blockage was not detected by the operators during the conduct of the test.

During the final stages of test operations, input power was held constant at 95 kW as concrete erosion continued. At 383.7 minutes, sparks were seen emanating from the bottom of the test section, indicating the development of a minor leak. At this time, power input to the melt was terminated. The cavity was subsequently flooded with ~ 125 liters of water at 384.9 minutes to bring the water level over the melt to ~ 50 cm. After this time, liquid lost to evaporation was periodically replaced to maintain the water level over the melt roughly in the range of 50 ± 5 cm per the test procedure. The debris-water heat flux, calculated on the basis of the steam formation rate normalized by the estimated crust planar surface area in contact with the coolant of 0.2 m^2 , is shown in Figure 3-13. The peak debris cooling rate reached $\sim 2.4 \text{ MW/m}^2$ during the initial flooding stage, but then fell rapidly to a level of $\sim 200 \text{ kW/m}^2$ at the time the test was terminated. However, for this test, the large and relatively impervious mantle of crust material that formed in the upper regions of the test section prevented the water from directly contacting the underlying melt. Thus, the heat flux shown in Figure 3-13 is indicative of the cooling rate of the mantle crust, and not of the underlying melt. The crust lance was inserted again over the time interval from 403.3 to 407.8 minutes in an attempt to dislodge this mantle crust. Some breakage occurred on initial contact at an elevation of 69.1 cm, but the full depth of the material was not penetrated to reveal the underlying melt. The peak load of 4.70 kN was applied; the surface elevation was reduced to ~ 60 cm after first breakage. Due to the sustained presence of this mantle crust, Test CCI-4 unfortunately did not provide any prototypic data on debris coolability.

Data logging continued until 458.3 minutes. At this point, the system was shutdown following the normal termination procedures. The DAQ was restarted to record the long-term cool down data. The experiment was left unattended to cool down overnight.

3.1.2 Posttest Examinations

Following the experiment, the apparatus was carefully disassembled to document the posttest debris configuration. Figure 3-14 provides a picture of the top surface of the mantle crust after removal of the top sidewall section, as well as a sketch showing key elevations. These initial views of the debris confirmed the presence of the large mantle crust at very high elevations relative to the initial collapsed melt depth, as initially surmised from the crust lance elevation

measurements made during the test. The axial distributions of this mantle are better illustrated in Figure 3-15, which provides renderings of the posttest debris configuration as viewed from the west (non-electrode) and south (electrode) sides of the test section. The peak height of the mantle was at ~ 1 m elevation relative to the initial concrete surface. Based on the initial collapsed melt depth of 25 cm, then a melt void fraction of ~ 75% would have been needed for the mantle to form at this elevation. Unlike test CCI-2 for which a mantle crust also formed due to extensive melt foaming [1], there were no discernable openings through this crust that would have provided a pathway for water to contact the underlying melt at the time of cavity flooding.

Figure 3-13. CCI-4 Melt-Water Heat Flux.

Figure 3-14. (a) Top View of CCI-4 Bridge Crust, and (b) Schematic Showing Elevations

(a)

(b)

Figure 3-15. (a) Electrode and (b) Nonelectrode Sidewall Views of the CCI-4 Solidified Debris.

After key features of the mantle crust were documented, this material was removed to gain access to the lower test section cavity. As shown in Figures 4-30, these steps revealed that the remaining corium was essentially in the form of a continuous layer that was distributed fairly uniformly over both the concrete and electrode sidewalls, as well as the concrete basemat. Photographs of the cavity after removal of the crust mantle and middle sidewall section are provided in Figure 3-16. The MgO sidewalls were then removed to gain additional information regarding the shape of the cavity erosion profile. Top and (west) side photographs taken after the sidewalls were removed are provided in Figure 3-17. Consistent with thermocouple readings from the lower section, cavity erosion was found to be fairly symmetrical. Erosion in the upper region of the test section above the initial collapsed pool height was extensive. At these elevations, ablation was probably driven by radiation heat transfer from the melt surface during periods in which the melt pool was collapsed, and also by convective heat transfer directly from the melt when the pool was undergoing extensive voiding.

Additional examinations during this stage indicated that melt had been extruded down into the ~ 3 mm wide gap between the concrete basemat and sidewalls on both the north and south sides of the test section from the top of the remaining basemat surface. On the north side of the assembly, the melt had traveled all the way down to the test section bottom plate, eventually leading to plate breach and loss of melt confinement at 383.7 minutes (see Table 3-1). This extrusion behavior had not been observed in prior CCI tests. Concrete decomposition gas venting out of the bottom of the test section due to sealing of the suspended mantle crust is believed to have been a key driver in this process. A photograph that shows the melt penetration in the northeast corner is provided in Figure 3-18.

Following these examinations, the corium remaining over the basemat and sidewalls was removed and the balance of the test section completely disassembled to fully reveal the final cavity erosion profile. A photograph showing the concrete components after these steps is provided in Figure 3-19. The cavity erosion profile shown in Figure 3-15 (a) is based on contour measurements taken at the centerline of these specimens. Both sidewalls showed slightly concave ablation patterns azimuthally. Thus, the erosion pattern shown in Figure 3-15 is bounding with respect to lateral ablation; erosion near the edges was generally within 3 cm of that at the centerline at all axial elevations. In contrast, the basemat was tapered with the minimum erosion occurring in the southwest quadrant, and the maximum ablation occurring in the northeast quadrant. This is in contrast to previous CCI tests where the basemat ablation profile was fairly uniform. This unique erosion pattern may in part be attributed to gas venting out of the bottom of the test section late in the experiment sequence, as opposed to a naturally occurring phenomenological effect.

As the debris was removed, samples were collected for chemical analysis by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP/AES). These analyses were carried out by the Analytical Chemistry Lab (ACL) at Argonne; analysis details are provided in [2]. Sample locations are shown in Figure 3-15. Key results from the analysis of seven of these samples are provided in Table 3-2. The compositions shown in the table have been simplified in the form of core, structural, and concrete (CaO, SiO₂, MgO, Al₂O₃) oxides; raw data are provided in [2]. Also provided in the table is an estimate of the end-of-test average melt composition that was formulated by taking the melt composition at the start of the test, oxidizing all metals, and then

(a)

(b)

Figure 3-16. (a) View Towards North and (b) South Concrete Sidewalls after Removal of Middle Sidewall Section.

(a)

(b)

Figure 3-17. (a) Top and (b) West Side Views of Cavity After Removal of MgO Sidewalls.

Figure 3-18. Close-up Photo of Northeast Basemat Corner Showing Melt Penetration.

Figure 3-19. Concrete Basemat and Sidewalls after Disassembly (view from southwest).

Table 3-2. Bulk Chemical Analysis Results for Samples Collected from CCI-4 Posttest Debris (data are in wt %).

Oxide	1 Upper surface bridge crust	4 Near bottom of bridge crust close to MgO	5 Near bottom of bridge crust close to cavity interior	7 Bulk material over basemat	8 Bulk material from north concrete wall	9 Bulk material from south concrete wall	10 Bulk material from pit in NE corner of basemat	Estimated End-of-Test Composition
UO ₂	16.80	68.91	19.47	12.88	13.00	14.09	36.34	26.31
ZrO ₂	10.79	19.73	12.47	7.73	8.01	8.30	8.24	12.93
Cr ₂ O ₃	0.37	0.36	0.43	0.31	0.34	0.41	0.41	2.01
Fe ₂ O ₃	3.53	0.05	2.82	3.75	3.54	3.32	1.63	3.19
concrete	68.50	10.95	64.81	75.32	75.10	73.89	53.39	55.56
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

incorporating the slag from the decomposition of 472.7 of concrete that was eroded during the test [2]. All samples contained elevated concrete levels except Sample No. 4 that was obtained near the MgO in the upper region of the test section. This sample was probably deposited during, or soon after, the thermite burn and therefore the composition is representative of the initial melt (see Table 2-7). The elevated concrete levels in both samples obtained from the mantle crust (i.e., Nos. 1 and 5) are consistent with deposition of this material late in the experiment sequence, which is also consistent with visual data obtained from the melt camera (see Table 3-1). This confirms that the mantle was not formed by some test artifact; e.g., a remnant of the thermite burn. Finally, the four samples taken from the interior of the corium cavity below the mantle crust reveal that concrete erosion continued after sealing of the mantle (as evidenced by the comparatively high concrete content of Sample Nos. 7-9 compared to 1 and 4), and that the bulk material in the northeast corner of the test section (Sample No. 10) had higher fuel content relative to the balance of the samples. It is not clear whether this situation existed during the experiment, or developed after test termination due to density-driven stratification.

3.2 CCI-5 Test Results

As shown in Table 1-1, Test CCI-5 investigated the interaction of a fully oxidized Pressurized Water Reactor (PWR) core melt, initially containing 15 wt % siliceous concrete, with a two-dimensional siliceous concrete test section (see Section 2.1 for a design description). The siliceous concrete for this test was of European origin (supplied by CEA); the composition is shown in Table 2-2. For reference, the initial melt composition is provided in Table 2-6. Target input power during dry cavity operation was specified as 145 kW. The planned test operating procedure was detailed in Section 2.11. The actual operating sequence is described below.

3.2.1 *Thermalhydraulic Results*

Test CCI-5 was performed on 25 September 2008. The event sequence is shown in Table 3-13. Test operations began by initiating the thermite reaction with the nichrome wire located at the top of the charge; the burn time was ~40 seconds. Following the reaction, DEH input to the melt was ramped up to the target power of 145 kW. The power trace for the test is shown in Figure 3-20. Time $t=0$ in the figures that follow again corresponds to onset of ablation of the concrete basemat. Target power level was reached at 1.9 minutes, where it was essentially maintained for the balance of the test involving dry cavity operations.

Onset of ablation was detected within the first minute of the interaction at all five thermocouple locations in the basemat, as well as at all five thermocouple locations in the north concrete sidewall of the apparatus. Past this point, axial ablation proceeded slowly but steadily throughout the experiment. However, localized ablation in the north wall was not sustained. Rather, the data suggest that an insulating crust formed on the sidewall that terminated ablation until later in the experimental sequence. The thermal response of the basemat at the centerline is shown in Figure 3-21, while the north wall response at the 0.0 cm elevation is shown in Figure 3-22 (see Figures 2-17, 2-29, and 2-31 for schematics showing the thermocouple array locations). The dimensions shown in the legends indicate the thermocouple junction distances from the concrete surfaces. The rise in the temperatures is indicative of the progression of the ablation front into the concrete. In general, onset of ablation at a given location corresponds to the local temperature reaching the siliceous concrete liquidus of 1250 °C [4].

Table 3-3. CCI-5 Event Sequence (times relative to onset of cavity ablation).

Time (Minutes)	Event
-0.9	Thermite burn initiated; view of melt surface occluded by aerosol within 5 seconds.
-0.3	Thermite burn completed (burn time ~ 40 seconds); melt temperature ~1950 °C
0.0	Onset of ablation detected at all five basemat and all five sidewall TC array locations initially contacted by melt; average time for onset is 0.0 minutes, which defined time $t = 0$ for the experiment. Hereafter, there were local spatial variations, but on average axial ablation proceeds slowly but steadily at ~ 3 cm/hour.
1.9	Target DEH input power of 145 kW reached.
3.5-49.0	Melt surface view effectively blocked by aerosols generated by the CCI.
1.4-10.2	Test section pressure steadily increases from 1.14 to 1.62 Bar at which point test section pressure relief system activated.
40.7	Tap change from 56 to 112 Volt range on the power supply.
49.0-54.0	Aerosols in plenum gradually cleared to reveal the interaction. Melt surface was crust free and highly agitated by sparging gases. Melt surface continued to heat up until the view was lost due to excessive light intensity (through a No. 4 filter). View of surface not recovered until ~ 178 minutes.
44.0-76.0	Bulk melt temperature measurements were scattered, but average value rises from ~ 1710 to ~1780 °C over this interval, while melt surface temperature rises from 850 to 1767 °C at the same time.
158.0	Sidewall ablation suddenly increases and remains fairly steady over the balance of the experiment. Average rate is ~ 10 cm/hour.
171.3-199.0	Test section pressure relief system activates, causing test section pressure to drop gradually from 1.7 to 1.28 Bar over this time interval before settling out.
178.0-280.0	Melt surface video showed predominately a molten surface, but crust segments periodically formed on sidewalls, broke, and were mixed in with melt.
259-271.4	Pyrometer measured steady surface temperature decline from 1513 °C to 1250 °C, before rebounding suddenly back to 1515 °C. During this time, crust grew to cover surface except for a small pocket in NW corner. At 269 minutes, melt began to flow over the crust. At 269.2 minutes, large crust segments gradually broke off and were mixed into the bulk, and by 269.5 most of surface was crust-free.
257.7	Lance inserted to break crust; minimal force was required to puncture the material.
275.4	South MgO sidewall surface temperature reached 1230 °C at the + 10 cm elevation. Decision made to terminate the test on the basis of excessive sidewall heatup.
280.8	Input power to melt terminated. Average input power over the time interval from 0 to 280.8 minutes was 143.8 kW. Peak axial ablation depth was 22.5 cm, while peak radial ablation was 30 cm.
927.8	Data acquisition terminated.

As described in Section 2.10, a total of six multi-junction Type C thermocouple arrays were used to monitor melt temperatures at various axial and lateral locations. In addition, a two-color optical pyrometer was used to provide data on the debris upper surface temperature. Data from the axially configured Type C array located near the basemat centerline are shown in Figure 3-23, while data from the laterally configured array located in the North sidewall are shown in Figure 3-24. Finally, data from all melt temperature thermocouples that made contact with melt during the test are shown collectively in Figure 3-25 for comparative purposes. The melt surface optical pyrometer data are also shown in this figure. The dimensions in the legends again refer to junction elevations with respect to the concrete surfaces.

As is evident from Figure 3-23, the initial melt temperature in the bulk of the pool was $\sim 1950^{\circ}\text{C}$. By 10 minutes into the interaction, the melt temperature had gradually declined to $\sim 1800^{\circ}\text{C}$. From ~ 10 minutes to 76 minutes, temperatures in the pool were scattered, with gradients across the extent of the pool of several hundred degrees observed. These types of gradients can develop under low convection conditions within the pool. However, at ~ 76 minutes, the temperatures began to cluster together near a temperature of $\sim 1780^{\circ}\text{C}$. In the same time interval (i.e., from 44 to 76 minutes), the melt surface temperature was observed to rise from 850 to 1767°C . Past 76 minutes, the average melt temperature continued to decline, falling to $\sim 1620^{\circ}\text{C}$ by the time input power was terminated. During the last 200 minutes of operation with DEH present, melt temperatures were fairly uniform across the extent of the interaction, generally clustering within a band of approximately $\pm 50^{\circ}\text{C}$ of the average temperature at any given time.

Figure 3-20. CCI-5 DEH Input Power.

Figure 3-21. CCI-5 Basemat Heatup Near Centerline.

Figure 3-22. CCI-5 North Wall Heatup (0 cm elevation).

Figure 3-23. CCI-5 Melt Temperatures near the Basemat Centerline.

Figure 3-24. CCI-5 Melt Temperatures near the North Wall (+5 cm Elevation).

Figure 3-25. Collection of CCI-5 Melt Temperatures.

The progression of the axial ablation front location during the course of the test is shown in Figure 3-26, while the analogous set of data for the north concrete sidewall is provided in Figure 3-27. Finally, the maximum erosion rates measured on the two concrete surfaces are shown in Figure 3-28. As is evident from Figure 3-26, onset of axial ablation began as soon as melt contacted the surface, and proceeded steadily thereafter at a rate of ~ 3 cm/hour. However, onset of radial ablation was delayed until later in the experiment sequence. In particular, at 158 minutes, the sidewall ablation rate suddenly increased and remained fairly steady over the balance of the experiment. The average rate was ~ 10 cm/hour near the end of the test. The long delay in the onset of ablation in this wall suggests that the surface was protected by an insulating corium crust that formed soon after initial melt contact with the cold concrete surface. However, the data in Figure 3-28 suggest that radial ablation proceeded at a rate of approximately four times that observed in the axial direction.

Over the time interval from 1.4 to 10.2 minutes, the pressure in the test section steadily increased. The test data, as well as posttest examinations, indicated that this occurred due to plugging of the final off-gas flowmeter by aerosols that were entrained through the system during the thermite burn. The pressure in the test section gradually increased from 1.14 to 1.62 Bar over the time interval from 1.4 to 10.2 minutes, at which time the pressure suddenly decreased to 1.36 Bar. This sudden reduction was caused by activation of the rupture disk in the test section pressure relieve system; the rupture disk was rated for 68 ± 13 kPad. The counter-weighted check valve (see Figure 2-21) subsequently reset, causing the pressure in the test section to gradually rise again. The pressure hovered in the range of 1.36 to 1.7 Bar until 171.3 minutes, at

Figure 3-26. CCI-5 Axial Ablation.

Figure 3-27. CCI-5 North Sidewall Ablation.

Figure 3-28. CCI-5 Characteristic Axial and Lateral Ablation Data.

which point the check valve appears to have reopened, and remained that way during the balance of the test. This occurrence was most likely due to a large increase in noncondensable gas flow associated with the onset of sidewall ablation at 158 minutes (Table 3-1). The fact that the pressure relief line remained open after 171 minutes was verified by the sustained heatup of the water inventory in the auxiliary tank past this time. This data also indicated that there was little flow bypass through the pressure relief system in the time interval following initial rupture disk failure (at 10.2 minutes) up to the time that the relief line reopened (at 171 minutes).

During the course of the interaction, the lid video camera provided some information on melt pool phenomenology. Over the first 49 minutes, the view of the melt surface was effectively blocked by aerosols generated from the core-concrete interaction. At ~ 49 minutes, aerosols in the plenum gradually cleared to reveal the interaction. The surface was observed to be crust free, and was highly agitated by sparging gases. The melt continued to heat up to the point where the view was lost due to high light intensity (through a No. 4 filter) at ~ 54 minutes. The view was effectively lost until ~ 178 minutes. At this time, the melt had cooled to the point where surface features could again be distinguished. This view revealed a predominately molten surface, with crust segments periodically forming on sidewalls, breaking off, and mixing back into the melt. From 259 to 271 minutes, the melt pyrometer measured a steady surface temperature decline from 1513 °C to 1250 °C, before rebounding suddenly back to 1515 °C. During this time interval crust material grew steadily out from the sidewalls to the point where the entire surface was covered, except for a small pocket in the northwest corner. At 269 minutes, melt began to flow over the crust. At 269.2 minutes, large crust segments gradually

broke off and were mixed into the bulk, and by 269.5 minutes most of surface was crust-free. This re-sorption of crust material occurred simultaneously with the sudden increase in surface temperature from 1250 °C to 1515 °C that was recorded by the pyrometer.

As the experiment progressed, the lower test section MgO sidewalls continued to heat up due to convection from the melt. The most intense thermal loading occurred on the south MgO sidewall opposite from the concrete sidewall undergoing ablation. The temperature near the surface in this wall reached 1230 °C at 275.4 minutes. The decision was then made to terminate the test on the basis of excessive sidewall heatup. Input power to the melt was subsequently terminated at 280.8 minutes. Peak axial ablation depth was 22.5 cm at this time, while the peak radial ablation was 30.0 cm. The cavity was not flooded due to the concern that, with the plugged offgas system, the resultant steam spike could lead to gross failure of the test section.

3.2.2 Posttest Examinations

Following the test, the apparatus was carefully disassembled to document the posttest debris configuration. A picture showing the debris upper surface after removal of the middle section transition plate is provided in Figure 3-29. A side view of the lower section after removal of the MgO sidewalls is provided in Figure 3-30, while Figures 3-31 and 3-32 provide two different views of the solidified corium over the basemat after removal from the test section bottom plate. Figure 3-33 provides the analogous photographs of the corium remaining on the North concrete sidewall. Finally, renderings of the posttest debris configuration based on the posttest examination activities are provided in Figure 3-34.

In general, the examinations revealed that, in contrast to tests with limestone/common sand concrete (viz. Test CCI-4 that is described in this report as well as CCI-2 that is documented in [1]), melt foaming was not a major issue and as a result the vast majority of the corium was left as a uniform layer atop the basemat.

Figure 3-29. Top View of the Lower Section after Removal of Upper Components.

Figure 3-30. View from the West of the Solidified Corium over the Basemat. (The sintered UO_2 pellets that protected the south MgO sidewall are visible on the far right of the photograph).

Figure 3-31. View from the North of the Solidified Corium over the Basemat.

(a)

(b)

Figure 3-32. (a) Perspective and (b) Close-up Photographs of Corium on the North Concrete Sidewall.

(a)

(b)

Figure 3-33. CCI-5 Posttest Debris Renderings as Viewed from the (a) West and (b) South.

The morphology of the solidified corium for CCI-5 was somewhat different in comparison to the other CCI tests where the cavity was flooded late in the experiment sequence. In particular, for CCI-5, the solidified corium was dominated by a dense, monolithic, homogenous oxide layer over the basemat with very little porosity and few cracks, covered by a fairly thin (i.e., ~ 5 cm) porous oxide layer. This morphology can be contrasted with the other tests in which there was generally a more substantial layer of porous material (5-10 cm thick) overlying monolithic oxide that had more cracks in comparison to the CCI-5 corium mass. Consistent with the thermocouple data, the posttest examinations indicate that the overall cavity erosion was skewed radially by the end of the experiment.

As the debris was removed, samples were collected for chemical analysis by ICP/AES. Sample locations are shown in Figure 3-33. Key results from the analysis of five of these samples are provided in Table 3-2. The compositions shown in the table have been simplified in the terms of core, structural, and concrete (CaO , SiO_2 , MgO , Al_2O_3) oxides; raw data are provided in [3]. Also provided in the table is an estimate of the end-of-test average melt composition that was formulated by taking the melt composition at the start of the test minus material splatter in the upper regions of the test section (50.44 kg; see Figure 3-33(a)), oxidizing all the remaining metals, and then incorporating the slag from the decomposition of 321.1 kg of concrete that is estimated to have been eroded during the test. Samples from the dense oxide layer (i.e., Nos. 5, 7, 8, and 9) do not indicate a significant dependency of the composition on axial or radial position within the layer. This observation is consistent with the melt temperature thermocouple measurements in the latter phase of the experiment that indicated that the melt pool was well mixed. The composition of the porous oxide layer on top the dense oxide was highly enriched in concrete oxides relative to the dense oxide. Overall, the samples contain slightly more concrete content than would be expected based on the estimated end of test composition. The discrepancy could arise thorough an underestimate of the mass of splatter material removed from the melt zone at the start of the experiment, which is possible since a substantial amount of material was deposited on the MgO sidewalls in the lower section (see Figure 3-33). However, segregating the initially deposited material from that subsequently deposited by melt voiding as the test progressed was not practical.

Table 3-4. Bulk Chemical Analysis Results for Samples Collected from CCI-5 Posttest Debris (data are in wt %).

Oxide	5 Dense Oxide @ Axial Centerline and by North Wall	7 Dense Oxide Near Core- Concrete Interface @ Center of Test Section	8 Dense Oxide Near Axial Centerline @ Center of Test Section	9 Dense Oxide Near Top @ Center of Test Section	10 Porous Oxide @ Center of Test Section	Estimated End-of-Test Composition
UO_2	34.04	33.71	33.39	31.16	25.67	36.47
ZrO_2	12.27	10.14	12.32	12.53	12.70	14.98
Cr_2O_3	0.23	0.15	0.23	0.31	0.37	6.06
concrete	53.46	56.00	54.07	55.99	61.25	42.49
Total	100.00	100.00	100.00	100.00	100.00	100.00

3.3 Discussion

As a whole, The CCI test series investigated the effects of concrete type and input power on two-dimensional core-concrete interaction under both wet and dry cavity conditions. The purpose of this section is to compare the results from the two experiments conducted as part of the current test series with the data from the test series as a whole [1] to identify key parametric effects. Principal variables measured during the experiments included melt temperature, local concrete ablation rates, and debris/water heat flux after cavity flooding. However, tests CCI-4 and CCI-5 did not provide any prototypic debris coolability data for direct comparison to the data obtained under late cavity flooding conditions as part of the MCCI-1 program [1]. As previously discussed, for test CCI-4 direct melt-water contact was precluded by the presence of the large mantle crust that formed in the upper regions of the test section due to extensive melt foaming that occurred over the course of the experiment. For CCI-5, the cavity was not flooded due to plugging of the main gas line for the apparatus. Thus, the following discussion focuses on core-concrete interaction behavior as opposed to debris coolability. The reader is referred elsewhere [1] for a discussion of the results regarding debris coolability under late flooding conditions obtained as part of MCCI-1. Conversely, additional data and discussions regarding coolability under early flooding conditions developed as part of the MCCI-2 project are provided in [35].

A comparison of key results from the CCI test series is provided in Figures 3-34 through 3-36, which provide the estimated average melt temperature and characteristic lateral and axial

Figure 3-34. Average Melt Temperatures for CCI Tests.

Figure 3-35. Axial Ablation for CCI Tests.

Figure 3-36. Lateral Ablation for CCI Tests.

concrete ablation rates for each of the tests. As shown in Figure 3-34, the initial melt temperature for all tests was in the range of 1880-1950 °C. The differences were due to uncertainty/variability in the thermite reaction temperatures for the different chemical mixtures used to generate the initial melt compositions. During dry cavity operations, all tests showed the overall trend of decreasing melt temperature as ablation progressed, which was due to a heat sink effect as relatively cool concrete slag was introduced into the melt, as well as the increasing heat transfer surface area as the melts expanded into the concrete crucibles. The decline in melt temperature may further reflect the evolution of the pool boundary freezing temperature that decreased as additional concrete was eroded into the melt over the course of the tests.

One of the key objectives of the current test series was to investigate the effect of unoxidized Zr cladding on the thermalhydraulics of the core-concrete interaction. To examine this effect, CCI-4 was conducted with a 78 % oxidized BWR melt composition (see Table 3-1). As is evident from Figure 3-34, the effect of the oxidation reaction between Zr and sparging concrete decomposition gases (CO_2 , H_2O) was to cause an exothermic transient in which the melt temperature increased by ~ 100 °C during the first 20 minutes of the test. This same type of transient was observed in metal tests conducted at Sandia [8,9] and KIT [11]. In addition, the effect of Zr oxidation was also investigated as part of the ACE/MCCI test series with core oxide material [13]. Unfortunately, tests conducted in this series with partially oxidized melt and LCS concrete were of very short duration (i.e., several minutes), and so the long term effects of the oxidation reactions on thermalhydraulic behavior were not clear. However, CCI-4 ran for several hours past the point at which all the cladding had oxidized. Moreover, CCI-2 can be considered a counterpart experiment insofar as cladding oxidation state is concerned. Comparison of the results indicates that cladding oxidation reactions cause an early exothermic temperature transient in the melt, and after the reaction is complete, the temperature drops to that consistent with fully oxidized melt conditions.

Additional examination of Figure 3-34 indicates that CCI-1 exhibited slightly different melt temperature behavior compared to the other fully oxidized tests. In this test, the melt temperature was relatively constant over the first ~ 40 minutes of the interaction. One possible contributor to this trend was the fact that this test was run at a 25 % higher power level in comparison to the other CCI tests. In particular, CCI-1 was run at a power level that was consistent with a heat flux of 200 kW/m^2 spread over all surfaces initially in contact with the melt (i.e., axial and lateral concrete surfaces, as well as the overlying atmosphere), whereas the other tests were initiated at a power level consistent with a flux of 150 kW/m^2 (see Table 3-1 for initial gross power levels). However, the lack of a temperature decline may have also been caused by crust formation at the core-concrete interfaces that acted to insulate the melt. Relatively low heat transfer rates to the concrete boundaries were evidenced by the low ablation rates exhibited over the first 40 minutes. Note that this type of behavior is consistent with other transient core oxide tests carried out at Sandia [15], wherein fairly large-mass (200 kg) substoichiometric melts consisting of $(\text{U,Zr})\text{O}_{2-x}$ were dropped into concrete test sections and allowed to cool with no further heating. In these tests, no concrete ablation occurred and the conclusion was drawn that crusts acted to thermally protect the concrete. However, in the current tests the melts were continuously heated. Thus, once the surface crusts failed in CCI-1, ablation

proceeded vigorously and the melt temperature fell rapidly in comparison to the other tests. This initial stable crust behavior may have been linked to the exceptionally low gas content for this concrete type in comparison to others used in the test series (see Table 3-18 in [1]). In particular, gas sparging at the core-concrete interface may provide the mechanical force required to dislodge the crust material from the interface, thereby allowing ablation to proceed. If this interpretation is correct, then the reduced gas sparging allowed the insulating crusts to remain stable over an extended period of time in Test CCI-1, which in turn caused the melt temperature to increase.

Aside from Test CCI-1, examination of Figures 3-35 and 3-36 indicates that the other CCI tests also showed evidence of early crust formation phases that influenced the overall ablation behavior. For CCI-2, both axial and lateral ablation rates were quite low and the melt temperature relatively constant until ~ 30 minutes, after which time a period of rapid erosion occurred. However, unlike CCI-1, these erosion bursts were not sustained. Rather, after ~ 5 cm of ablation, both the axial and lateral ablation rates slowed significantly and approached quasi-steady states. The reduced period of crust stability for CCI-2 is consistent with the idea that gas sparging can disrupt surface crusts, since the gas content of the CCI-2 concrete was significantly greater compared to CCI-1.

Unlike tests CCI-1 and CCI-2, sidewall erosion in test CCI-3 commenced immediately upon contact with melt, and progressed steadily throughout the balance of the test. Conversely, the data suggests that the concrete basemat was protected by an insulating crust until ~ 50 minutes, at which point the crust failed and erosion commenced, albeit at a reduced rate relative to lateral ablation. In contrast, the results of CCI-5 suggest that the sidewall was protected by crust material for nearly 2.5 hours before ablation was initiated. However, once erosion began, the lateral ablation rate approached that observed in CCI-3.

Aside from initial crusting effects, examination of Figures 3-35 and 3-36 indicates that the long-term ablation process is influenced by concrete type. Estimates of average lateral and axial ablation rates for the five tests are provided in Table 3-5. To the extent possible, data points for these estimates were selected near the end of the dry cavity erosion phase for each test so that the erosion rate estimates are indicative of the long-term behavior. Assuming a quasi-steady erosion process, then the heat flux at the core-concrete interface is related to the ablation rate through the expression:

$$q_c'' = \rho_c h_{dc} \dot{\delta}_c, \quad (3-1)$$

where ρ_c is the concrete density, h_{dc} is the concrete decomposition enthalpy, and $\dot{\delta}_c$ is the ablation rate. The assumed property data required to evaluate the above expression is provided in Table 3-6; the corresponding heat flux estimates are provided in Table 3-5. As shown in the table, long-term lateral and axial ablation rates for Tests CCI-2 and CC-4, both of which were conducted with LCS concrete, were about the same. For CCI-2, the concrete erosion rate averaged 4 cm/hr over several hours of interaction before gradually decreasing; the corresponding surface heat flux was ~ 60 kW/m². For CCI-4, the fluxes were slightly lower (i.e., ~ 40 kW/m²), but this is due to a surface scaling effect as the initial cavity size and therefore input power level were reduced to expand the test duration. Thus, the lateral/axial heat flux ratios for these LCS tests are approximately unity.

Table 3-5. Lateral/Axial Ablation Rate and Power Split Estimates for CCI Tests.

Test	Concr. Type	Lateral Ablation		Axial Ablation		Lateral-Axial Heat Flux Ratio	Data Points Utilized for Ablation Rate Estimates
		Ablation Rate (cm/hr)	Heat Flux (kW/m ²)	Ablation Rate (cm/hr)	Heat Flux (kW/m ²)		
CCI-1	SIL (US)	N: 39.1	395	26.1 ^b	265	— ^a	N Lateral: (19.1 cm, 51 min) (29.2 cm, 66 min) S Lateral: (7.6 cm, 54 min) (5.1 cm, 35 min) Axial: (7.6 cm, 53 min) (1.3 cm, 39 min)
		S: 8.4	86				
CCI-3	SIL (EU)	10.0	97	2.5	25	4.0	Lateral: (19.1 cm, 47 min) (29.2 cm, 107 min) Axial: (2.5 cm, 117 min) (5.1 cm, 178 min)
CCI-5	SIL (EU)	9.8	95	2.1	21	4.7	Lateral: (25.0 cm, 250 min) (30.0 cm, 280 min) Axial: (17.5 cm, 134 min) (22.5 cm, 280 min)
CCI-2	LCS	4.0	58	4.0	59	1.0	Lateral: (19.1 cm, 148 min) (29.2 cm, 302 min) Axial: (15.2 cm, 107 min) (24.1 cm, 240 min)
CCI-4	LCS	2.7	39	2.8	41	1.0	Lateral: (10.0 cm, 145 min) (15.0 cm, 255 min) Axial: (12.5 cm, 165 min) (17.5 cm, 271 min)

^aHeat flux ratio not evaluated for this test due to large asymmetry in lateral cavity erosion.^bAblation burst; rate appeared to slow significantly after this time interval; see Figure 3-35.**Table 3-6. Properties of Concretes Used in CCI Test Series.**

Concrete Property	Property for Test:		
	CCI-1	CCI-2 and CCI-4	CCI-3 and CCI-5
Type	SIL (US)	LCS	SIL (EU)
Liquidus Temperature ²³ (°C)	1250	1295	1250
Gas Content (wt %)	4.6	34.1	13.5
Decomposition Enthalpy (MJ/kg) ^a	1.60	2.27	1.72
Density (kg/m ³)	2300	2330	2270

^aEvaluated at concrete liquidus temperature

The relatively uniform power splits for CCI-2 and CCI-4 can be contrasted with the results of the three tests conducted with siliceous concrete. For test CCI-1, the ablation was highly non-uniform, with most of the ablation concentrated in the North sidewall of the test apparatus. As described above, this test was conducted at a higher power density in comparison to CCI-2 and CCI-3. Moreover, the concrete for this test had exceptionally low gas content (see Table 3-18 in [1]). Based on the discussion provided above, it thus appears that crust stability played a major role in determining the ablation progression for this experiment. In particular, the data suggests that after the insulating crust failed on the North concrete sidewall, the input power was dissipated predominately through ablation of this sidewall, while crusts continued to protect the basemat and south sidewall surfaces. As shown in Table 3-5, the ablation rate averaged 39 cm/hr in the North wall over the last 30 minutes of dry cavity operations; the average concrete surface heat flux was $\sim 395 \text{ kW/m}^2$. Conversely, brief ablation bursts that reached 8.4 cm/hr in the South wall and 26 cm/hr axially occurred early in the experimental sequence, but the data suggests that crusts subsequently reformed on these surfaces, resulting in very little ablation over the balance of test operations. Based on these transient effects, a power split estimate was not formulated for this test, since the estimate would be highly speculative.

In contrast to Test CCI-1, the other two tests conducted with siliceous concrete (CCI-3 and CCI-5) seemed to exhibit repeatable, albeit non-isotropic, ablation behavior. For CCI-3, fairly symmetrical ablation occurred insofar as the progression of the ablation fronts into the two opposing sidewalls of the apparatus is concerned. However, unlike Test CCI-2, the lateral ablation was highly pronounced in comparison to axial for this particular test. A similar trend was noted for CCI-5 that was conducted with a single siliceous concrete sidewall. As shown in Table 3-5, lateral ablation averaged 10 cm/hr during the late phases of the CCI-3 and CCI-5 experiments, while the axial ablation rate was limited to 2.1 to 2.5 cm/hr over the same timeframe for the two tests. The corresponding heat fluxes in the lateral and axial directions were roughly 100 and 25 kW/m^2 , respectively. On this basis, the lateral/axial surface heat flux ratios for tests CCI-3 and CCI-5 were estimated as ~ 4 and ~ 4.7 , respectively. These values are significantly higher than the near-unity ratios deduced for tests CCI-2 and CCI-4 with LCS concrete. Thus, the data suggests that there is an effect of concrete type on the spatial heat flux distribution at the core-concrete interface during dry core-concrete interaction. Between these two concrete types, possible explanations for differences in the erosion behavior are chemical composition (LCS concrete has a high CaO/SiO_2 ratio in comparison to siliceous), and concrete gas content (LCS has ~ 2.5 times as much gas as siliceous). A third possible explanation was revealed during posttest examinations. In particular, the nature of the core-concrete interface was noticeably different for Test CCI-2 in comparison to Tests CCI-1, CCI-3, and CCI-5, as shown in Figure 3-37. (Note that a cross-sectional view of the CCI-4 debris is not included in this figure since there was so little core debris remaining on the concrete basemat). As shown the ablation front for the three tests conducted with siliceous concrete consisted of a region where the core oxide had locally displaced the cement that bonded the aggregate. Conversely, the ablation front for Test CCI-2 consisted of a powdery interface in which the core and concrete oxides were clearly separated. The interface characteristics may have influenced the heat transfer rate across the boundaries, thereby resulting in different ablation behavior for the two concrete types.

(a)

(b)

(c)

(d)

Figure 3-37. Axial Debris Morphology for Siliceous Concrete Tests (a) CCI-1, (b) CCI-3, and (c) CCI-5, and LCS Test (d) CCI-2. (All tests were flooded except CCI-5 (c)).

Finally, one of the key test objectives for CCI-5 was to examine the influence of melt pool aspect ratio on the radial/axial power split under dry cavity conditions. The specific objective was to increase the test section aspect ratio (i.e., test section width/melt depth) to the greatest extent possible to more accurately mock up prototypic conditions. The approach was to modify the test section design to include a single concrete sidewall that would undergo ablation, whereas the opposing sidewall was made from refractory MgO that essentially created an adiabatic boundary condition. As discussed in Section 2, with this approach the aspect ratio was increased from a value of ~ 1 for CCI-3 to ~ 3.2 for CCI-5. The relatively close agreement in long-term ablation behavior for tests CCI-3 and CCI-5 indicate that aspect ratio has little influence on ablation characteristics. This observation lends credibility to the measured power split for siliceous concrete insofar as extrapolating the results to plant conditions.

Aside from the overall cavity erosion behavior, video footage from the tests indicated that a crust was present over the melt upper surface during a large fraction of dry cavity ablation phase for all three tests. The crusts contained vent openings which allowed melt eruptions to occur as the tests progressed. The frequency and intensity of the eruptions were directly correlated to the gas content of the concrete for any given test.

In terms of the chemical analyses conducted as part of the test series, samples were collected to: i) characterize the lateral and axial composition variations of the solidified debris, and ii) characterize the composition of corium regions that played key roles in the coolability aspects of the tests (e.g., porous crust zones formed at the melt/water interface, and the material erupted after cavity flooding in CCI-2). See [1] for a discussion of the implications of these results for debris coolability in Tests CCI-1, -2, and -3.

Analysis of samples taken to characterize the lateral composition variation indicate that for most tests, the corium in the central region of the test section had a higher concentration of core oxides in comparison to samples collected near the two ablating concrete sidewalls. Conversely, samples taken to characterize the axial composition variation over the vertical extent of the solidified corium remaining over the basemat indicate that general trend of slightly increasing core oxide concentration as the concrete surface is approached. For all three tests conducted with siliceous concrete, two zones appeared to be present: a heavy monolithic oxide phase immediately over the basemat that was enriched in core oxides, with a second overlying porous, light oxide phase that was enriched in concrete oxides. This axial phase distribution is clearly evident in Figure 3-37.

4.0 SUMMARY AND CONCLUSIONS

Tests CCI-1 through CCI-3 conducted as part of the MCCI program principally addressed the effect of concrete type on 2-D cavity erosion behavior and late phase debris coolability. Test CCI-4 focused on expanding this parameter space by examining the influence of core melt composition on cavity erosion behavior and coolability. The specific objectives were to: i) increase the metal content of the melt to the highest practical level to more accurately mock up a prototypic BWR core melt composition at the time of vessel failure, and ii) modify the apparatus design to increase the duration of the dry core-concrete interaction phase. Conversely, Test CCI-5 focused on examining the influence of melt pool aspect ratio on the radial/axial power split under dry cavity conditions. The specific objective was to increase the test section aspect ratio (i.e., test section width/melt depth) to the greatest extent possible to more accurately mock up prototypic conditions.

In terms of meeting program objectives, both tests CCI-4 and CCI-5 provided valuable data on 2-D cavity erosion behavior. However, neither test unfortunately provided debris coolability data that would have augmented the information gathered as part of the MCCI-1 program. For test CCI-4, the cavity was flooded but direct melt-water contact was precluded by the presence of the large mantle crust that formed in the upper regions of the test section due to extensive melt foaming that occurred over the course of the experiment. For CCI-5, the cavity was not flooded due to plugging of the main gas line for the apparatus. Thus, the following conclusions focus on core-concrete interaction behavior as opposed to debris coolability. The reader is referred to [1] for conclusions that were drawn regarding debris coolability under late flooding conditions based on MCCI-1 test results. In addition, valuable information regarding coolability under early flooding conditions were obtained as part of the CCI-6 test experiment that was conducted as part of MCCI-2 and is documented in [35].

Principal findings from both the CCI tests related to two-dimensional cavity erosion behavior are summarized as follows:

1. All tests showed the overall trend of decreasing melt temperature as ablation progressed, which was due to a heat sink effect as relatively cool concrete slag was introduced into the melt, as well as the increasing heat transfer surface area as the melts expanded into the concrete crucibles. The reduction in melt temperature may have further reflected the evolution of the pool boundary freezing temperature that decreased as additional concrete was eroded into the melt over the course of the tests.
2. All tests showed evidence of initial crust formation on the concrete basemat and sidewalls that resulted in an incubation period in which the ablation rates were very low and the melt temperature was relatively stable. These results are consistent with the TURC tests conducted at Sandia with in-vessel [i.e., (U,Zr)O_{2-x}] melts that were poured into concrete crucibles and allowed to cool with no further heating. The duration of the incubation period appeared to be inversely proportional to concrete gas content, which suggests that crust failure may be driven in part by the mechanical forces that arise from the production of decomposition gases at the core-concrete interface. Crust formation was stochastic, with some surfaces exhibiting initial crust formation while other surfaces did not.

3. Early initial exothermic oxidation of cladding for a partially oxidized melt caused a rapid transient increase in melt temperature of $\sim 100^{\circ}\text{C}$, but once the cladding was oxidized, both the melt temperature and overall cavity ablation behavior approached that observed under fully oxidized conditions.
4. Long-term ablation behavior was found to be closely linked to concrete type. Lateral and axial ablation rates for the LCS concrete test were virtually indistinguishable. Thus, the lateral/axial heat flux ratio for this concrete type was ~ 1 .
5. The relatively uniform power split for the LCS concrete tests can be contrasted with the results of the two tests conducted with siliceous concrete. For test CCI-1, the ablation was highly non-uniform, with most of the ablation concentrated in the North sidewall of the test apparatus. Crust stability may have played a major role in determining the ablation progression for this experiment; i.e., the data suggests that after the crust failed on the North concrete sidewall, the input power was predominately dissipated through ablation of this sidewall, while crusts continued to protect the basemat and south sidewall surfaces during the balance of the interaction.
6. In contrast to Test CCI-1, Test CCI-3 exhibited fairly symmetrical behavior insofar as the progression of lateral ablation is concerned. However, unlike Test CCI-2, the lateral ablation was highly pronounced in comparison to axial ablation. The same conclusion was drawn based on the CCI-5 test results; this experiment was conducted in an increased span test section with one ablating concrete wall. Long term lateral ablation in both CCI-3 and CCI-5 averaged ~ 10 cm/hr, while axial rates were in the range of 2 - 2.5 cm/hr. On this basis, the lateral/axial surface heat flux ratio for the siliceous tests was ~ 4 , which is significantly higher than the near-unity ratio deduced for test CCI-2 with LCS concrete. The relatively close agreement in long-term ablation behavior for tests CCI-3 and CCI-5 indicate that aspect ratio has little influence on ablation characteristics. This observation lends credibility to the measured power split for siliceous concrete insofar as extrapolating the results to plant conditions.
7. Between the two concrete types, possible explanations for differences in the erosion behavior are chemical composition and concrete gas content. A third possible explanation was revealed during posttest examinations. In particular, the core-concrete interface for the siliceous concrete tests consisted of a region where the core oxide had locally displaced the cement that bonded the aggregate. Conversely, the ablation front for the LCS test consisted of a powdery interface in which the core and concrete oxides were clearly separated. Variations in the interface characteristics may have influenced the ablation behavior for the two concrete types.
8. In terms of the chemical analysis results obtained as part of the test series, the corium in the central region of the test section was generally found to have a slightly higher concentration of core oxides in comparison to that adjacent to the ablating concrete sidewalls. Conversely, core oxides were found to be slightly concentrated near the

concrete basemat in comparison to that found in the bulk of the corium for some tests. For all siliceous concrete tests, two zones appeared to be present: a heavy monolithic oxide phase immediately over the basemat that was enriched in core oxides, with a second overlying porous, light oxide phase that was enriched in concrete oxides.

In terms of the applicability to plant conditions, these tests have provided information that will contribute to the database for reducing modeling uncertainties related to two-dimensional molten core-concrete interaction under both wet and dry cavity conditions. However, note that in real plant accident sequences, a significant melt metal fraction may be present that may result in a stratified pool configuration. This type of pool structure was not evaluated in this program. Thus, additional analysis and testing may be required with melts containing a significant metal fraction to further reduce phenomenological uncertainties related to core-concrete interaction, and to evaluate the effects of melt metal content on debris coolability.

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