OECD MCCI Project
2-D Core Concrete Interaction (CCI) Tests:
CCI-5 Test Plan

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by:

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Table of Contents

1. INTRODUCTION.....	1
2. FACILITY DESCRIPTION	3
2.1 Test Apparatus	3
2.2 Instrumentation and Data Acquisition	9
2.3 Corium Composition and Concrete-Metal Inserts	12
2.4 Concrete Composition	12
3. TEST PROCEDURES.....	14
3.1 Pretest Preparations.....	14
3.2 Test Operations	15
3.3 Posttest Procedures	15
4. REFERENCES.....	16

List of Figures

Figure	Page
2-1 Schematic of CCI Test Facility	4
2-2 Top View of Lower Test Section	4
2-3 Side View of Lower Test Section Showing Inert MgO Sidewall Sections	5
2-4 Side View of Lower Test Section Showing Concrete Sidewall Section	6
2-5 Test Section Water Supply System	7
2-6 Illustration of CCI-5 Crust Lance Assembly Mounted in Test Section	8
2-7 Plan View of Basemat Instrumentation Layout (dimensions are in cm)	9
2-8 Elevation View of Basemat Type C Thermocouple Locations	10
2-9 Exterior View of Concrete Sidewall Form Showing Instrument Locations.....	10
2-10 CCI Data Acquisition and Control Systems	11

List of Tables

Table	Page
1-1 Specifications for CCI-5	2
2-1 Post-Reaction Bulk Composition for CCI-5 Thermite	13
2-2 Detailed Pre- and Post-Reaction Compositions for CCI-5 Thermite	13
2-3 Engineering Composition of CCI-5 Siliceous Concrete Basemat and Sidewall	14
2-4 Chemical Composition of Siliceous Concrete (CCI-3 basis [1]).	14

1.0 INTRODUCTION

Ex-vessel debris coolability is an important light water reactor (LWR) safety issue. For existing plants, resolution of this issue will confirm the technical basis for severe accident management guidelines (SAMGs). For new reactors, understanding this issue 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 for various cooling mechanisms through separate effect tests and data for severe accident code model development, and ii) provide longer-term two-dimensional 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 (volcanic-type event), 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 melt depths that are calculated 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 will be useful in reducing uncertainties and gaining confidence in code predictions.

Based on these findings, a workscope was defined for the follow-on MCCI program that can be 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.

Aside from these various testing categories, an analysis workscope was also defined to develop and validate debris coolability models to form the technical basis for extrapolating the experiment findings to plant conditions.

As one of the steps in satisfying these program objectives, the Management Board (MB) approved the conduct of a fifth longer-term 2-D Core-Concrete Interaction (CCI) experiment designed 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 first three tests [1] in this experiment series investigated the interaction of fully oxidized PWR core melt compositions with specially designed concrete test sections that were initially 50 cm x 50 cm in cross-sectional area. Both siliceous and limestone/common sand concrete types were addressed. The fourth test [2] examined the interaction of a partially oxidized BWR melt composition with limestone/common sand concrete.

At the 3rd PRG Meeting of the MCCI-2 Program, the MB approved activities required to conduct the CCI-5 test with the overall objective of increasing the test section aspect ratio (i.e., test section width/melt depth) to the greatest extent possible to more accurately mock up prototypic conditions. To this end, the project prepared two design documents [3,4] that were submitted to the PRG for review. On this basis, the design was finalized and efforts are now focused on assembling parts for conducting the test.

The objective of this test plan is to document the final CCI-5 test design in sufficient detail so that pretest analyses may be conducted by member organizations. Specifications for CCI-5 are provided in Table 1-1. The initial corium composition and concrete types are the same as those of CCI-3, but the dimensions of the test section differs. CCI-3 was conducted with a test section that featured two-ablating sidewalls with an initial basemat cross-section of 50 cm x 50 cm. The input power for CCI-5 during the dry ablation phase is specified to be 145 kW,

Table 1-1. Specifications for CCI-5.

Parameter	Specification
Corium	100 % oxidized PWR with 15 wt % siliceous concrete
Concrete type	Siliceous concrete (CEA-type)
Initial basemat dimension	50 cm x 79 cm
Initial melt mass (depth ^a)	590 kg (25 cm)
Test section sidewall construction	Nonelectrode wall No. 1: concrete Nonelectrode wall No. 2: MgO protected by UO ₂ pellet layer. Electrode walls: MgO protected by UO ₂ pellet layers.
Lateral and axial ablation limits	40 and 42.5 cm, respectively
System operating pressure	Atmospheric
Melt formation technique (timescale)	Chemical reaction (~30 seconds)
Initial melt temperature	1950 °C
Melt heating technique	Direct Electrical (Joule) Heating
Power input prior to water addition	Constant power at 145 kW
Criteria for water addition	1) 6.0 hours of operation with DEH input, 2) lateral ablation reaches 35 cm, or 3) axial ablation reaches 37.5 cm
Inlet water temperature	20 °C
Inlet water flow rate	2 liters/second
Sustained water depth over melt	50 ± 5 cm
Power input after water addition	Constant voltage
Test termination criteria	1) $T_{\text{melt}} < \text{concrete solidus}$, 2) concrete ablation is arrested, or 3) maximum lateral/axial ablation limit is reached.

which is based on the requirement of providing an initial ‘prototypic’ heat flux of $\sim 150 \text{ kW/m}^2$ across all melt surfaces that are not in contact with insulating sidewall material. This is the same surface heat flux requirement used to specify the total input power for tests CCI-2 through CCI-4. The initial melt depth for CCI-5 is set at 25 cm, which is the same as that used in previous tests. Since the surface area of the CCI-5 basemat is larger than that of previous tests, the initial melt mass to achieve this depth is increased considerably to 590 kg. With these specifications, CCI-5 can be considered a repeat of CCI-3, but with the aspect ratio increased to the greatest extent possible using: i) available hardware and ii) an inert wall that provides a symmetry boundary condition on one side of the test section.

2.0 FACILITY DESCRIPTION

The overall facility design and test operating procedures for CCI-5 are similar to those used in the previous four tests [1-2]. However, at the 3rd PRG meeting for MCCI-2, the MB mandated that the project increase the test section aspect ratio to the greatest extent possible. Given the test section overall planar dimensions, the approach for reaching this objective is to increase the aspect ratio to the highest value possible to more accurately mock up conditions at plant scale by incorporating one inert MgO sidewall into the overall design. This step creates a symmetry (i.e., $\sim$ adiabatic) boundary condition on one side of the test section which, in theory, doubles the aspect ratio for a given basemat width. With the symmetry boundary condition, the test simulates erosion in a 50 cm x 158 cm test section. Additional details regarding this modification are provided in the balance of this section, along with a general description of the overall test plan for CCI-5. Specifications for the experiment were provided previously in Table 1-1.

2.1 Test Apparatus

The CCI test facility consists of a test apparatus, a power supply for Direct Electrical Heating (DEH) of the corium, a water supply system, two steam condensation (quench) tanks, a ventilation system to complete filtration and exhaust the off-gases, and a data acquisition system. A schematic illustration of the facility for CCI-5 is provided in Figure 2-1. The apparatus consists of three rectilinear sidewall sections and a lid. The overall structure is 3.4 m tall. The two upper sidewall sections have a square internal cross sectional area of 50 cm x 50 cm.

The test section for containment of the core melt is located at the bottom of the apparatus. A top view of this component is shown in Figure 2-2, while cross-sectional views of the electrode and non-electrode sidewalls are provided in Figures 2-3 and 2-4, respectively. The thickness of the new non-electrode sidewall is the same as the existing MgO electrode walls (i.e., 25 cm), and it is also protected with a crushed UO_2 pellet liner. This approach has been shown to provide an inert (i.e., non-ablative) and highly insulated wall surface. As shown in Figure 2-4, the underside of the test section transition plate is exposed due to the addition of the thin MgO sidewall. To provide thermal protection, the plate is lined with Al_2O_3 insulation and a tungsten heat shield. Note that a similar heat shield design was used to protect the inner surface of the ACE/MCCI test apparatus lid. [5] The thickness of the concrete sidewall is the same as that used in the CCI-3. [1]

Figure 2-1. Schematic of CCI Test Facility.

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

Figure 2-3. Side View of Lower Test Section Showing Inert MgO Sidewall Sections.

The selected sidewall dimensions increase the basemat width from 50 cm in CCI-3 to 79 cm for the current design. Accounting for the symmetry boundary condition, the aspect (width/melt depth) ratio is increased from $(25 \text{ cm}/25 \text{ cm}) = 1.0$ in test CCI-3 to $(79 \text{ cm}/25 \text{ cm}) = 3.2$ for CCI-5, given the initial melt depth of 25 cm for CCI-5 (see Table 1-1). Note that the safety plan for the CCI tests assumes that a minimum thickness of 15 cm is maintained for all concrete components to ensure final containment of the melt. On this basis, up to 40 cm of lateral ablation can be accommodated in the concrete sidewall. Conversely, up to 42.5 cm of axial ablation can be accommodated given the initial basemat thickness of 57.5 cm.

As shown in Figures 2-2 and 2-3, the concrete and MgO sidewalls are contained within a flanged steel form that is used to secure the lower section to the balance of the existing test section components with the aluminum transition plate. The flanges allow the lower sidewalls to be disassembled to reveal the solidified corium following the test. As previously noted, a layer of crushed UO_2 pellets is used to protect the interior surface of the MgO sidewalls against thermo-chemical attack by the corium. Molybdenum and tungsten plates are embedded in the

sidewalls to stop erosion in case the UO_2 protection layer fails. Multi-junction Type C thermocouple assemblies are cast within the sidewalls so that the time-dependent heat loss from the melt can be calculated from the local temperature gradient and the thermal conductivity of the MgO .

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

The melt is produced through an exothermic chemical reaction yielding the target mass over a timescale of ~ 30 seconds. After the chemical reaction, DEH simulating decay heat is applied through two banks of tungsten electrodes. As shown in Figures 2-2 and 2-3, the electrodes line the interior surfaces of the two opposing MgO sidewalls. The electrodes are 9.5 cm in diameter and aligned in a row with a pitch of 1.9 cm. They are attached by copper clamps and water-cooled buss bars to a 560 kW AC power supply. As shown in Figure 2-2, the electrodes span a total width of 120 cm on each sidewall of the lower section. At the start of the experiment, the electrical current is drawn through the center, 79 cm-wide section of electrodes that are in direct contact with the melt. As the test progresses and the concrete sidewall is eroded, additional electrodes are exposed to the corium. Current is drawn through these newly exposed heating elements, thereby maintaining a uniform internal heat pattern in the melt over the course of the experiment. With the overall electrode span of 120 cm, the entire 40 cm of

lateral sidewall erosion can be accommodated while ensuring that the entire melt cross-sectional area is in contact with the electrodes.

A few minutes after the melt is formed, ablation of the concrete basemat and sidewall will commence. As shown in Figure 2-1, a large (15 cm diameter) gas line is used to vent the helium cover gas and the various gas species arising from the core-concrete interaction (i.e., CO, CO₂, H₂O, and H₂) into two adjacent tanks that are partially filled with water. In the initial phase of the experiment when the cavity remains dry, the tanks serve to cool the off-gases and filter aerosols generated from the core-concrete interaction. In the late phase after the cavity is flooded, the tanks serve to condense the steam and, based on the measured condensation rate, provide data on the corium cooling rate. In either case, the helium covergas and non-condensables (CO, CO₂, and H₂) pass through the tanks and are vented through an off gas system that includes a demister, filters, and a gas flow meter. The gases are eventually exhausted through the containment ventilation system and a series of high efficiency filters before finally being released from the building stack.

After a specified period of core-concrete interaction, the cavity will be flooded using an instrumented water supply system. The water enters the test section through two weirs located in the opposing (non-electrode) sidewalls of the top test section. The water supply system is shown in Figure 2-5. After a specified time with water present in the cavity, the crust formed at the melt-water interface will be broken with an insertable crust lance to obtain data on the crust breach cooling mechanism. An illustration of the lance installed in the test section is shown in Figure 2-6. The lance is made from 2.54 cm diameter, 304 stainless steel rod with a pointed tip. The lance contains an electrical isolation hub so that there is no need to terminate power input to the melt during the crust loading procedure. As shown in Figure 2-6, the driving force for the lance is simply a 450 kg dead weight that is remotely lowered with the crane during the test.

Figure 2-5. Test Section Water Supply System.

Figure 2-6. Illustration of CCI-5 Crust Lance Assembly Mounted in Test Section.

2.2 Instrumentation and Data Acquisition

The CCI facility is instrumented to monitor and guide experiment operation and to log data for evaluation of the lateral and axial erosion rates. Principal parameters that are monitored during the course of the test include 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 includes temperatures within test section structural sidewalls, off gas temperature and flow rate, and pressures at various locations within the system.

Detailed plan and elevation views of the basemat thermocouple layout are provided in Figures 2-7 and 2-8, respectively, while the concrete sidewall instrumentation locations are shown in Figures 2-4 and 2-9. Both the basemat and sidewall are 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 tungsten thermowells protrude upwards from the basemat and laterally inwards from the concrete sidewall in several locations. The purpose of these instruments is to provide data on the axial and lateral melt temperature distribution as a function of time. Note that the thermocouple junction locations have been repositioned to provide melt temperature and ablation front location data over the increased range

Figure 2-7. Plan View of Basemat Instrumentation Layout (dimensions are in cm).

Figure 2-8. Elevation View of Basemat Type C Thermocouple Locations.

Figure 2-9. Exterior View of Concrete Sidewall Form Showing Instrument Locations.

of lateral and axial concrete ablation that have been designed into this experiment. The concrete instrumentation layout is similar to CCI-3, with the exception additional thermocouples have been added on both sides of the sidewall centerline at several axial elevations to provide additional data on the radial ablation progression; locations are detailed in Figure 2-9.

Other significant test instrumentation includes a stationary (lid mounted) video camera for observing physical characteristics of the core-concrete interaction. In addition, a pyrometer will be added in order to measure the debris upper surface temperature during periods in which aerosol production does not optically occlude the view of the surface

All data acquisition and process control tasks are managed by a PC executing LabVIEW 6.i under Windows XP. Sensor output terminals are connected inside the test cell to model HP E1345A 16-channel multiplexers, which are integrated into a mainframe chassis in groups of eight. An illustration of the DAS setup is provided in Figure 2-10. The multiplexers direct signals to an HP E1326B 5 1/2 digit multimeter incorporated into each chassis. Three independent 128 channel systems are used for a total capacity of 384 channels.

Figure 2-10. CCI Data Acquisition and Control Systems.

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

Integration of the signal over the period of a power line cycle limits the speed with which the multiplexer can scan the channel list. The minimum time for the digitizer to scan the channel list is ~ 1.7 s (16.7 ms • 100 channels/chassis for this test). Though the three systems operate independently, implying the ability to update all 300 channels in roughly two seconds, the actual time required for the update is about 5.5 s.

2.3 Corium Composition

As shown in Table 1-1, the corium oxide phase composition for CCI-5 is specified to contain 15 wt % calcined siliceous concrete as an initial constituent. As part of the developmental work for the SSWICS-6 and CCI-3 experiments, a specific thermite was developed to produce this particular melt composition. The thermite reaction is of the form:

$$Q = -228.17 \text{ kJ/mole (1.721 MJ/kg);}$$

$$T_{\text{adiabatic}} = 2504 \text{ }^\circ\text{C}; T_{\text{actual}} \sim 2000 \text{ }^\circ\text{C}$$

The composition of the melt produced from this reaction is summarized in Table 2-1, while the detailed pre- and post-reaction compositions are provided in Table 2-2. Note that the pre- and post-reaction compositions shown in these tables do not include the additional mass of crushed UO_2 pellets that are used to line the test section MgO sidewalls. Experience has shown that this material does not participate in the initial exothermic chemical reaction, and remains essentially intact as a protective layer during the ensuing core-concrete interaction. The actual mass of UO_2 that dissolves into the melt over the course of the experiment is determined as part of the posttest examination activities and documented in the test data report.

The thermite powders are packed into the test section in a large, 1.7 mil aluminized Saran bag that is pre-installed over the basemat to prevent water absorption by CrO_3 and concrete oxides (principally CaO and SiO_2), since these constituents are hygroscopic. As an additional measure to prevent moisture infiltration into the thermite from the concrete, the basemat and sidewalls are completely covered with continuous sheets of Saran film before thermite loading.

2.4 Concrete Composition

As shown in Table 1-1, the composition of the CCI-3 concrete basemat and sidewalls is specified to be of the siliceous type. The engineering composition for this particular concrete is shown in Table 2-3. The sand and aggregate for the mix are supplied by CEA as an in-kind

contribution to the program. The estimated chemical composition for this concrete is provided in Table 2-4. This composition is based on analysis of a specimen taken from the CCI-3 concrete archive sample [1]. The actual composition of the concrete for Test CCI-3 will be determined through chemical analysis of a specimen that will be collected during fabrication of the sidewall and basemat components.

Table 2-1. Post-Reaction Bulk Composition for CCI-5 Thermite.

Constituent	Wt%
UO ₂	56.32
ZrO ₂	23.13
Calcined Concrete	14.14 ^a
Cr	6.41

^aCalcined siliceous concrete, consisting of 79.0/0.9/15.6/4.5 wt% SiO₂/MgO/CaO/Al₂O₃

Table 2-2. Detailed Pre- and Post-Reaction Compositions for CCI-5 Thermite.

Constituent	Reactant		Product	
	Wt %	Mass, kg	Wt %	Mass, kg
U ₃ O ₈	58.70	346.33	-	-
UO ₂	-	-	56.32	332.29
Zr	17.16	101.24	-	-
ZrO ₂	-	-	23.13	136.47
Si	1.57	9.26	-	-
SiO ₂	7.84	46.26	11.17	65.90
Mg	0.07	0.41	-	-
MgO	-	-	0.12	0.70
Al	0.09	0.53	-	-
Al ₂ O ₃	-	-	0.64	3.78
CaO	2.21	13.04	2.21	13.04
CrO ₃	12.36	72.93	-	-
Cr	-	-	6.41	37.82
Total	100.00	590.00	100.00	590.00

To prevent downward migration and possible escape of concrete decomposition gases during the course of the experiment, the electrode penetrations through the bottom support plate are sealed using O-rings. As described in the next section, the test section is leak checked at 83 kPa differential pressure as part of pretest operations to verify a low leak rate. On this basis, essentially all concrete decomposition gases migrated upwards through the melt pool during the experiment, as opposed to partial loss through the bottom support plate of the apparatus. Reinforcing rod is eliminated so that it does not mask or delay the attainment of a fully oxidized melt. In previous tests, the concrete surfaces were protected by a layer 3 mm thick layer of ZrO₂ felt insulation (density ~480 kg/m³; thermal conductivity ~0.14 W/m•K at 1170 °C) to prevent thermal shock of the concrete basemat and sidewalls during the initial exothermic chemical reaction. However, for CCI-5 this insulation will be omitted in order to minimize the time to onset of concrete ablation after the thermite burn in is completed.

The density of the siliceous concrete is ~ 2270 kg/m³, which was the calculated value for the CCI-3 concrete based on the measured mass and volume of the CCI-3 concrete archive

sample. The actual density of the CCI-5 concrete will be determined once the concrete components are poured.

Table 2-3. Engineering Composition of CCI-5 Siliceous Concrete Basemat and Sidewall.

Constituent	wt %	Size Distribution
Aggregate	47.4	5-8 mm: 16.6 wt % 8-11 mm: 20.4 wt% 11-16 mm: 10.4 wt%
Sand	30.6	0-2 mm: 12.2 wt % 2-4 mm: 18.4 wt %
Type 1 Cement	15.3	N/A
Tap Water	6.7	N/A

Table 2-4. Chemical Composition of Siliceous Concrete (CCI-3 basis [1]).

Constituent	Wt %
SiO ₂	60.99
CaO	17.09
Al ₂ O ₃	3.61
Fe ₂ O ₃	1.52
MgO	0.87
MnO	0.04
SrO	0.04
TiO ₂	0.16
SO ₃	0.44
Na ₂ O	0.67
K ₂ O	0.83
CO ₂	9.98
H ₂ O	3.76 ^a

^aFree water content is 2.33 wt % while bound water content is 1.43 wt %.

3.0 TEST PROCEDURES

3.1 Pretest Preparations

Assembly of the apparatus begins through the installation of tungsten electrodes into machined copper electrode clamps. The electrode clamps are then attached to the bottom of the 1.9 cm thick aluminum support plate, which serves as the foundation for the entire apparatus. With the electrode clamps installed, the support plate is moved into position on the test stand. The instrumented basemat and four sidewalls are then set in place on the support plate. The lower section flange bolts and clamping bars are then installed and tightened. Following this step, the basemat instruments are connected to terminal boxes that are prewired to the data acquisition system.

Once the lower section is assembled, preparations for loading of the corium charge are initiated. A single large 1.7 mil aluminized Saran bag is preinstalled over the basemat. During loading, the thermite is repackaged into this bag to reduce the amount of bagging material

present in the thermite charge. Once the large bag is filled with thermite, the sparklers used to initiate the chemical reaction are placed in the top of the powders, and the bag is folded and sealed.

Once loading is completed, the remainder of the test apparatus is assembled. This includes installation of the two upper sections and the enclosure lid. Peripheral instruments, including the sidewall and basemat thermocouples used to monitor melt temperature and ablation front progression, are then installed and connected to terminal boxes. The main gas line from the test section to the quench tank is installed, as well as the pressure relief line from the test section to the auxiliary tank. After assembly is completed, system checkout is performed to ensure that the facility is in proper working order. This includes 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.

3.2 Test Operations

Prior to initiating the thermite reaction, a helium gas flow rate is established through the lid of the test section. The thermite is ignited using the sparklers located at the top of the powder charge. Once the reaction is complete (~ 30 seconds), the power supply is ramped at a rate of ~ 3000 Amps/minute up to the initial target power level. As shown in Table 1-1, target power for the dry core-concrete interaction phase of the test is 145 kW. After melt formation, the input power would be held constant at the 145 kW for the balance of dry cavity operations.

After ablation is initiated, the interaction will be allowed to proceed for 6.0 hours, or until the ablation depth reaches 35 cm laterally, or 37.5 cm axially. After one of these criteria is met, the cavity would then be flooded. However, if a crust is 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 145 kW to a constant voltage operating mode. (With constant voltage, the input power density would remain relatively constant if a significant quench front developed). Thirty 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 30 minutes, yielding a total operating period of 60 minutes with water present in the cavity, or until the ablation limit of 40 cm is reached laterally or 42.5 cm axially. At this point, the input power would be turned off and the test terminated.

3.3 Posttest Operations

Following the experiment, the apparatus is carefully disassembled to document the posttest debris configuration. The test section main gas line, lid, and the top and middle sidewall sections are removed to reveal the lower test section, which contains the solidified core debris. The upper surface of the debris is then photographed, and specimens are collected for subsequent chemical analysis. At this point, a vertical core sample will be drilled through the extent of the corium. The core will be removed, photographed, and samples will be collected at several different axial elevations for characterization by Inductively Coupled Plasma Atomic Emission

Spectroscopy (ICP/AES). This analysis will provide raw data on the axial composition variation within the material.

After these measurements are collected, the three MgO and single concrete sidewalls of the lower test section will be removed, thereby fully revealing the solidified corium over the remaining basemat. Once the corium is revealed, a detailed map of the cavity erosion profile will be developed. Additional samples will be collected at this point in order to further characterize the debris through chemical analysis. When these measurements are completed, the basemat and concrete sidewall will be placed in storage containers and archived as part of the test records. The MgO sidewall sections will be cleaned for reuse in subsequent tests.

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