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OECD MCCI Project

2-D Core Concrete Interaction (CCI) Tests:

CCI-2 Test Plan

Rev. 0

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by:

M. T. Farmer, D. J. Kilsdonk, S. Lomperski, and R. W. Aeschlimann
Nuclear Engineering Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439 USA

S. Basu
Project Manager
U.S. Nuclear Regulatory Commission

Table of Contents

List of Figures

Figure **Page**

List of Tables

Table **Page**

1.0 INTRODUCTION

The Melt Attack and Coolability Experiments (MACE) program addressed the issue of the ability of water to cool and thermally stabilize a molten core-concrete interaction when the reactants are flooded from above. These tests provided data regarding the nature of corium interactions with concrete, the heat transfer rates from the melt to the overlying water pool, and the role of noncondensable gases in the mixing processes that contribute to melt quenching. As a follow-on program to MACE, The Melt Coolability and Concrete Interaction Experiments (MCCI) project is conducting reactor material experiments and associated analysis to achieve the following objectives:

i. resolve the ex-vessel debris coolability issue through a program that focuses on providing both confirmatory evidence and test data for the coolability mechanisms identified in MACE integral effects tests, and

ii. address remaining uncertainties related to long-term two-dimensional molten core-concrete interactions under both wet and dry cavity conditions.

Achievement of these two program objectives will demonstrate the efficacy of severe accident management guidelines for existing plants, and provide the technical basis for better containment designs for future plants.

In terms of satisfying these objectives, the Management Board (MB) approved the conduct of two long-term 2-D Core-Concrete Interaction (CCI) experiments 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 of these two tests, CCI-1, was conducted on December 19, 2003.[1] This test investigated the interaction of a fully oxidized 400 kg PWR core melt, initially containing 8 wt % calcined siliceous concrete, with a specially designed two-dimensional siliceous concrete test section with an initial cross-sectional area of 50 cm x 50 cm.

The second of these two planned tests, CCI-2, will be conducted with a nearly identical test facility and experiment boundary conditions, but with a Limestone/Common Sand (LCS) concrete test section to investigate the effect of concrete type on the two-dimensional core-concrete interaction and debris cooling behavior. The objective of this report is to provide the overall test plan for CCI-2 to enable pretest calculations to be carried out. The report begins by providing a summary description of the CCI-2 test apparatus, followed by a description of the planned test operating procedure. Overall specifications for CCI-2 are provided in Table 1-1.

Table 1-1. Specifications for CCI-2.

Parameter	Specification
Corium	100 % oxidized PWR with 8 wt % LCS concrete
Concrete type	Limestone/common sand (LCS)
Initial basemat dimension	50 cm x 50 cm
Initial melt mass (depth[a])	400 kg (25 cm)
Test section sidewall construction	Nonelectrode walls: concrete Electrode walls: MgO protected by UO_2 pellet layer.
Radial ablation limit	35 cm
Axial ablation limit	35 cm
System operating pressure	Atmospheric
Melt formation technique (timescale)	Chemical reaction (~30 seconds)
Initial melt temperature	2100 C
Melt heating technique	Direct Electrical (Joule) Heating
Power supply operation prior to water addition	Constant power at 150 kW
Criteria for water addition	1) 5.5 hours of operation with DEH input, or 2) radial or axial ablation reaches 30 cm
Inlet water temperature	20 C
Inlet water flow rate (2 MW/m^2 equivalent quench rate)	2 liters/second
Sustained water depth over melt	50 ± 5 cm
Power supply operation after water addition	Constant voltage
Test termination criteria	1) Melt temperature falls below concrete solidus, 2) basemat ablation is arrested, or 3) maximum radial/axial ablation limit of 35 cm is reached.

[a]Based on an assumed melt density of 6500 kg/m^3

2.0 FACILITY DESCRIPTION

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-2 is provided in Figure 2-1, while test specifications are provided in Table 1-1. The apparatus for containment of the core material consists of a test section that is ~ 3.4 m tall with a square internal cross-section which measures 50 cm x 50 cm. The concrete crucible is located at the bottom of the test section. 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. As is evident from these figures, the concrete basemat has a cross-sectional area of 50 cm x 50 cm, and is 55 cm deep. Thus, up to 35 cm of axial ablation can be accommodated in the current design.

As shown in Figure 2-2, the electrode sidewalls are fabricated from castable MgO refractory, while the non-electrode sidewalls are fabricated from concrete. The concrete and MgO 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 an aluminum transition plate. The lower section is fabricated with vertical, flanged casting seams between the MgO and concrete so that the lower sidewalls can be disassembled to reveal the solidified corium following the test. The MgO sections are intended to be reusable, while the concrete sidewall remnants will be disposed of as radioactive waste. 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. In the event that the UO_2 layer does not provide adequate protection, then tungsten back-up plates are embedded in these sidewalls as a final barrier to terminate sidewall attack. 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.

Melt generation is achieved through an exothermic chemical reaction yielding the target initial melt mass over a timescale of ~ 30 seconds. After the chemical reaction, DEH is supplied to the melt to simulate decay heat 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 are pitched at 1.9 cm intervals. They are attached by copper clamps and water-cooled buss bars to 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 50 cm lateral span of electrodes that are in direct contact with the melt. As the test progresses and the concrete sidewalls are 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. Given the overall electrode span of 120 cm, then up to 35 cm of radial sidewall ablation can be accommodated in this design while maintaining uniform heat input. As shown in Figure 2-4, the concrete sidewalls have been designed to be 56 cm thick, which provides ~ 20 cm of remaining sidewall thickness once the 35 cm radial ablation limit has been reached.

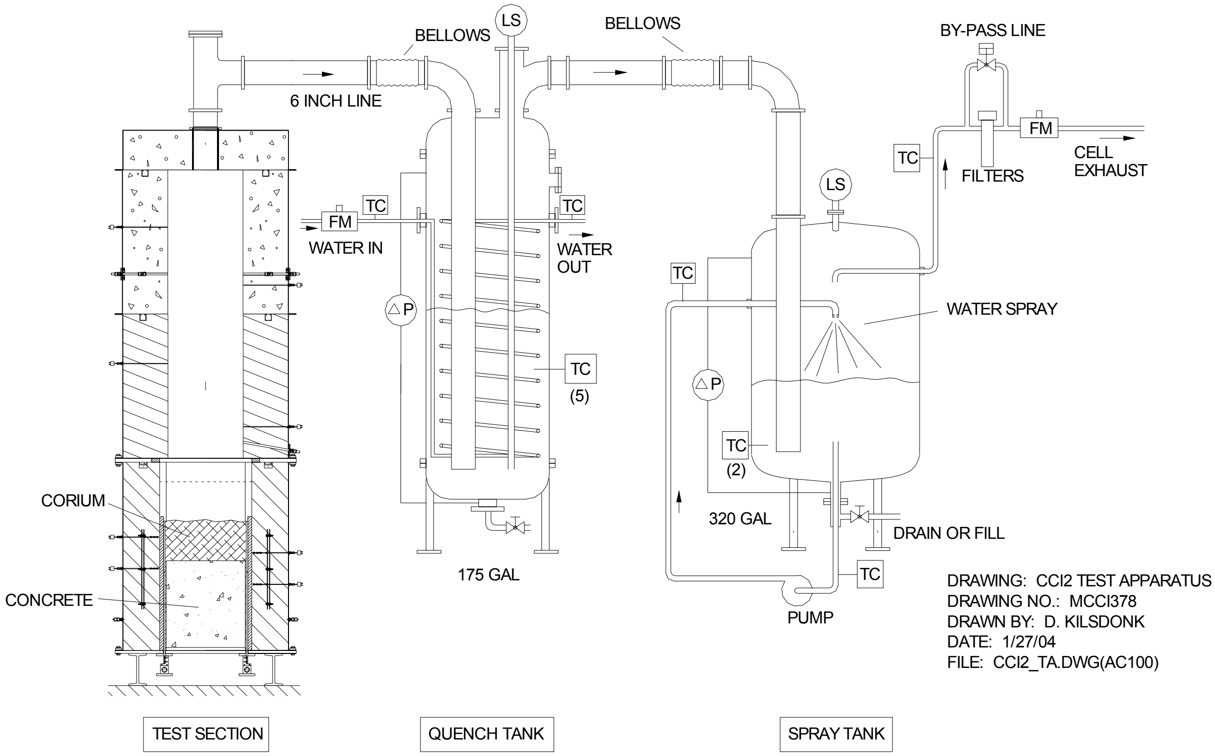


Figure 2-1. Schematic of CCI Test Facility.

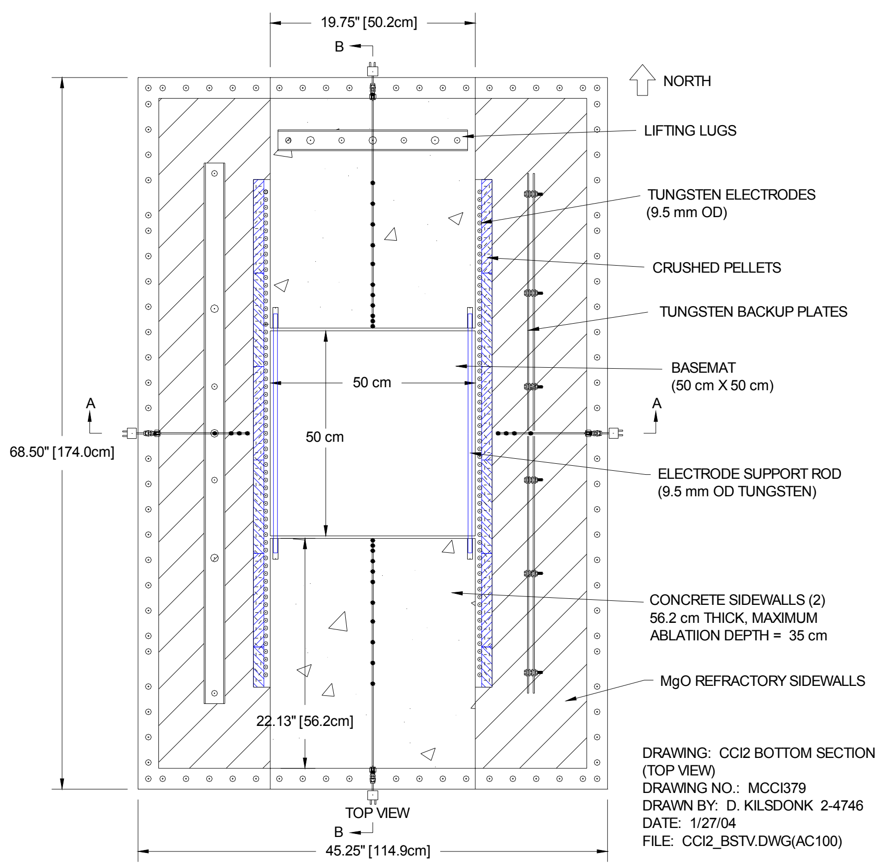


Figure 2-2. Top View of Lower Test Section.

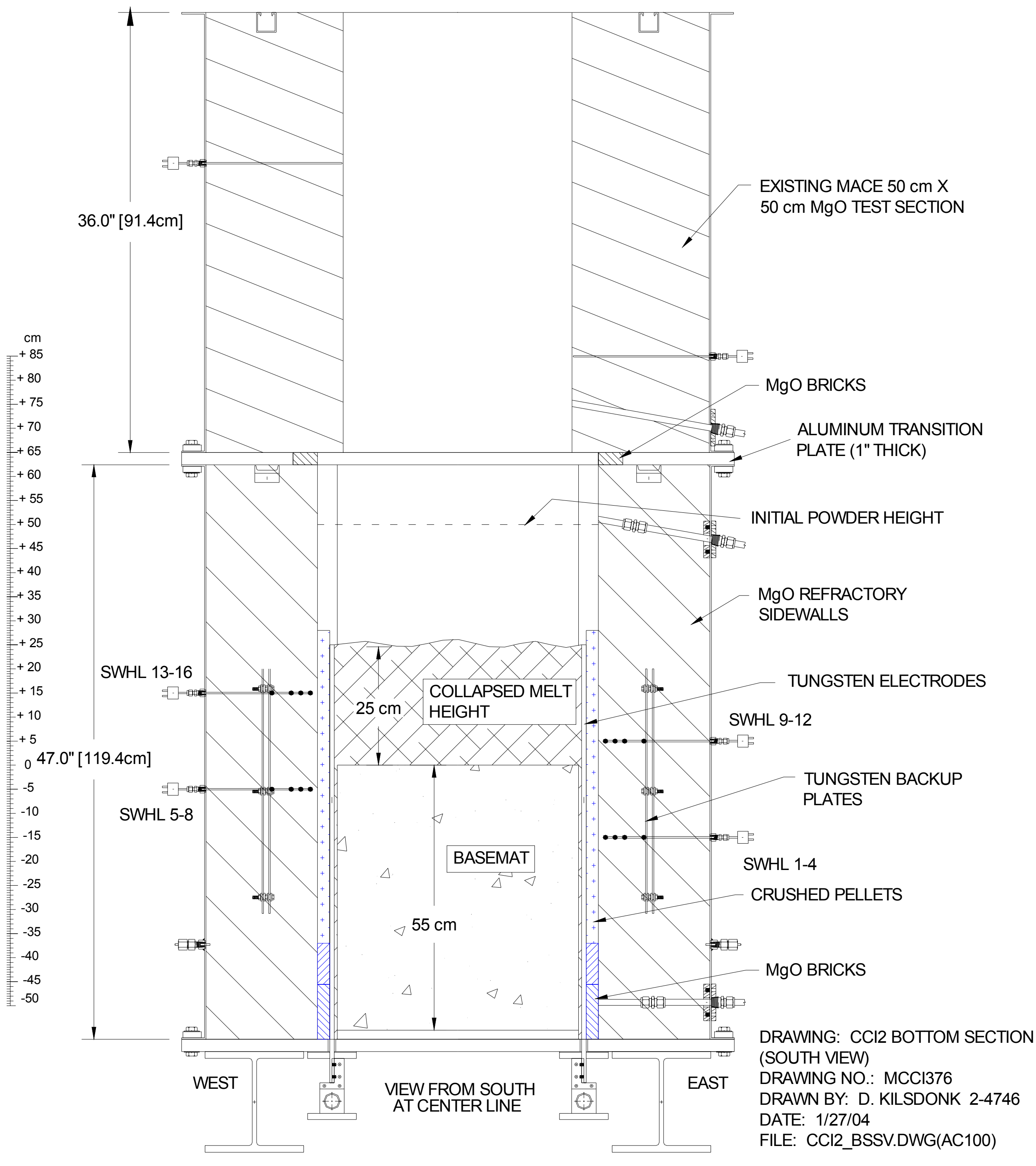


Figure 2-3. Side View of Lower Test Section Showing Inert MgO Sidewall Sections.

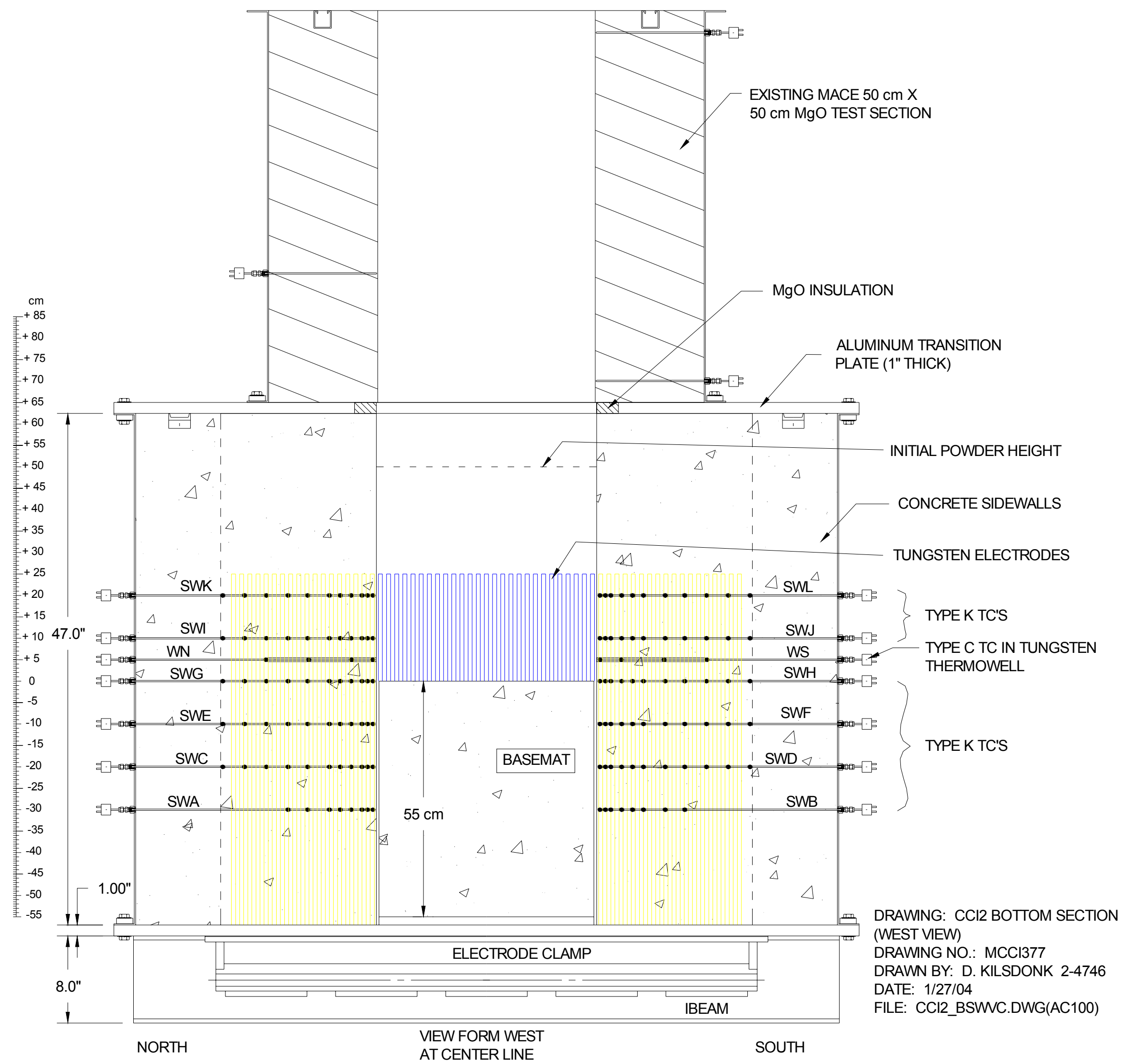


Figure 2-4. Side View of Lower Test Section Showing Concrete Sidewall Sections.

A few minutes after the melt is formed, core-concrete interaction with the concrete basemat and sidewalls will begin. 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, CO_2, H_2O, and H_2) 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, provided data on the corium cooling rate. In either case, the helium covergas and non-condensables (CO, CO_2, and H_2) 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 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.

2.2 Instrumentation and Data Acquisition

The CCI facility is instrumented to monitor and guide experiment operation and to log data for subsequent evaluation. 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.

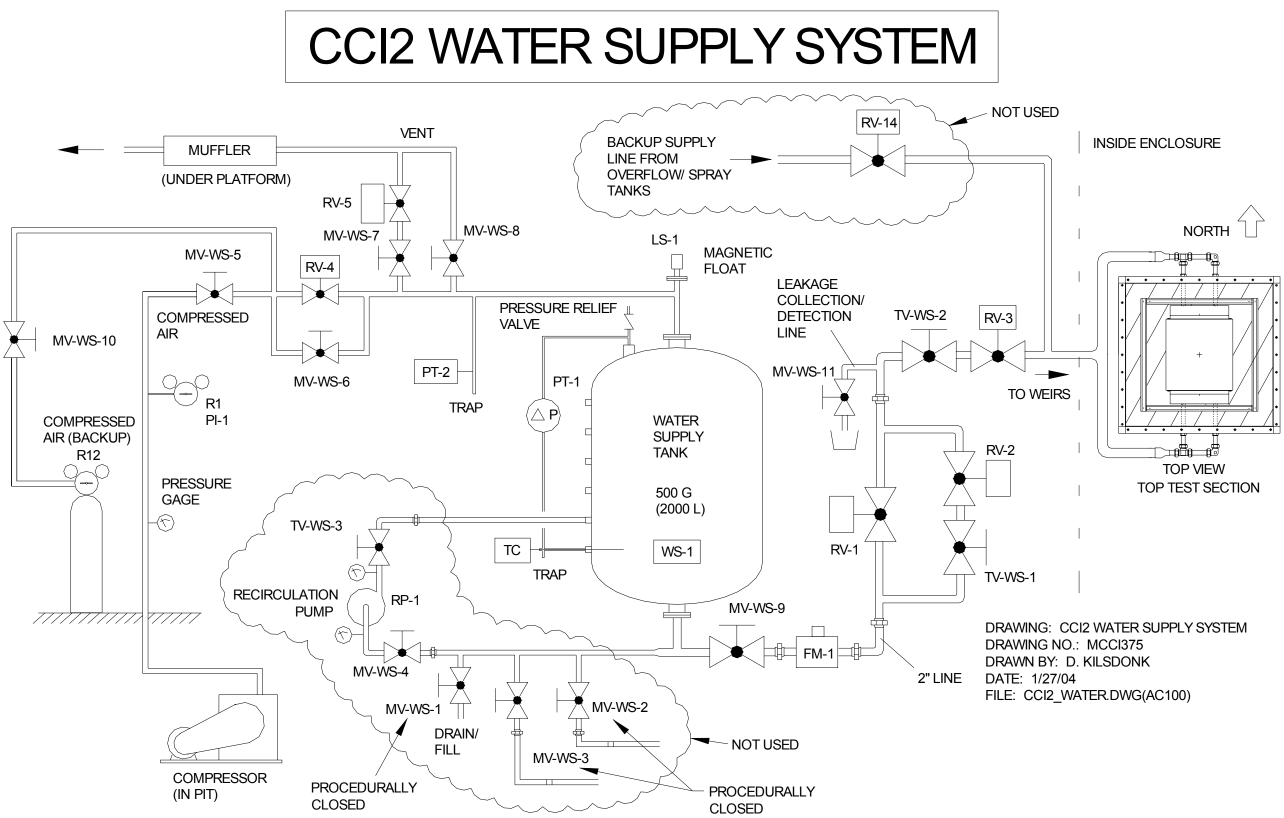


Figure 2-5. Test Section Water Supply System.

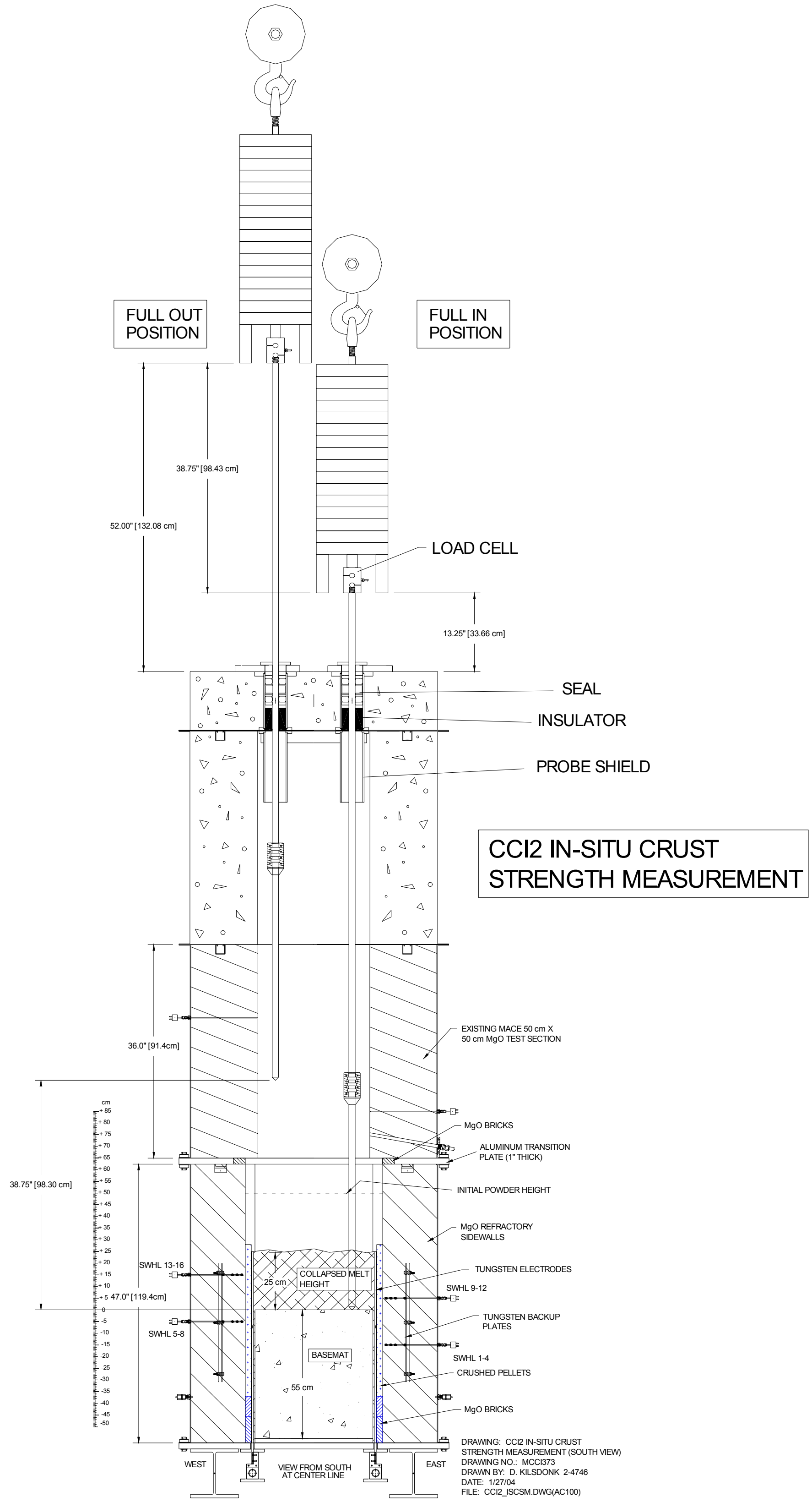
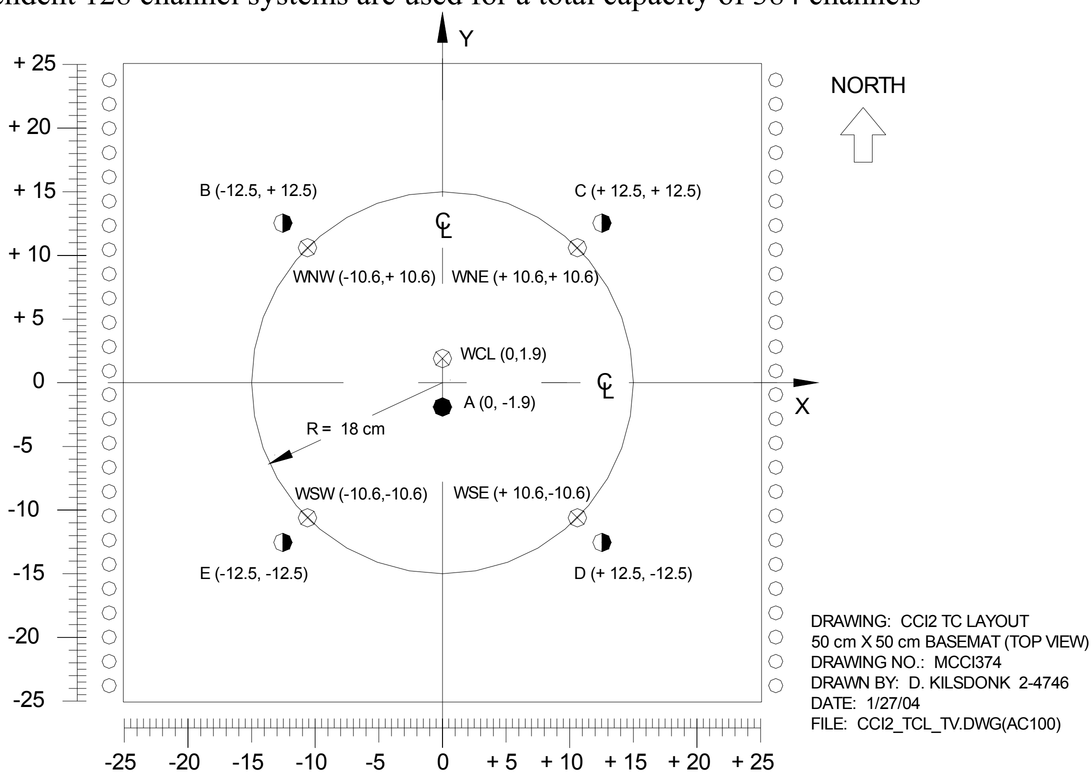


Figure 2-6. Illustration of CCI-2 Crust Lance Assembly Mounted in Test Section.

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 Figure 2-4. Both the basemat and sidewalls of the test section 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 radially inwards from the concrete sidewalls in several locations. The purpose of these instruments is to provide data on the axial and radial melt temperature distribution as a function of time.

Other significant test instrumentation includes a stationary (lid mounted) video camera for observing physical characteristics of the core-concrete interaction.

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 2-9. The multiplexers direct signals to an HP E1326B 5 ½ digit multimeter incorporated into each chassis. Three independent 128 channel systems are used for a total capacity of 384 channels



● MULTI-JUNCTION Cr/Al, INCONEL 600 SHEATH, TIP OF TC FLUSH WITH BASEMAT SURFACE (1 UNIT, 11 JUNCTIONS).
LOCATIONS: 0.0, -1.3, -2.5, -5.1, -7.6, -11.4, -15.2, -19.1, -24.1, -29.2, -34.3 cm.

⊗ MULTI-JUNCTION W5Re/W26Re, TANTALUM SHEATH, TUNGSTEN THERMOWELL (5 UNITS, 4 JUNCTIONS EA.).

◑ MULTI-JUNCTION Cr/Al, INCONEL 600 SHEATH, TIP OF TC FLUSH WITH BASEMAT SURFACE (4 UNITS, 9 JUNCTIONS EA.).
LOCATIONS: 0.0, -2.5, -5.1, -8.9, -14.0, -19.1, -24.1, -29.2, -34.3 cm.

NOTE: ALL TC DIMENSIONS ARE CENTIMETERS

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

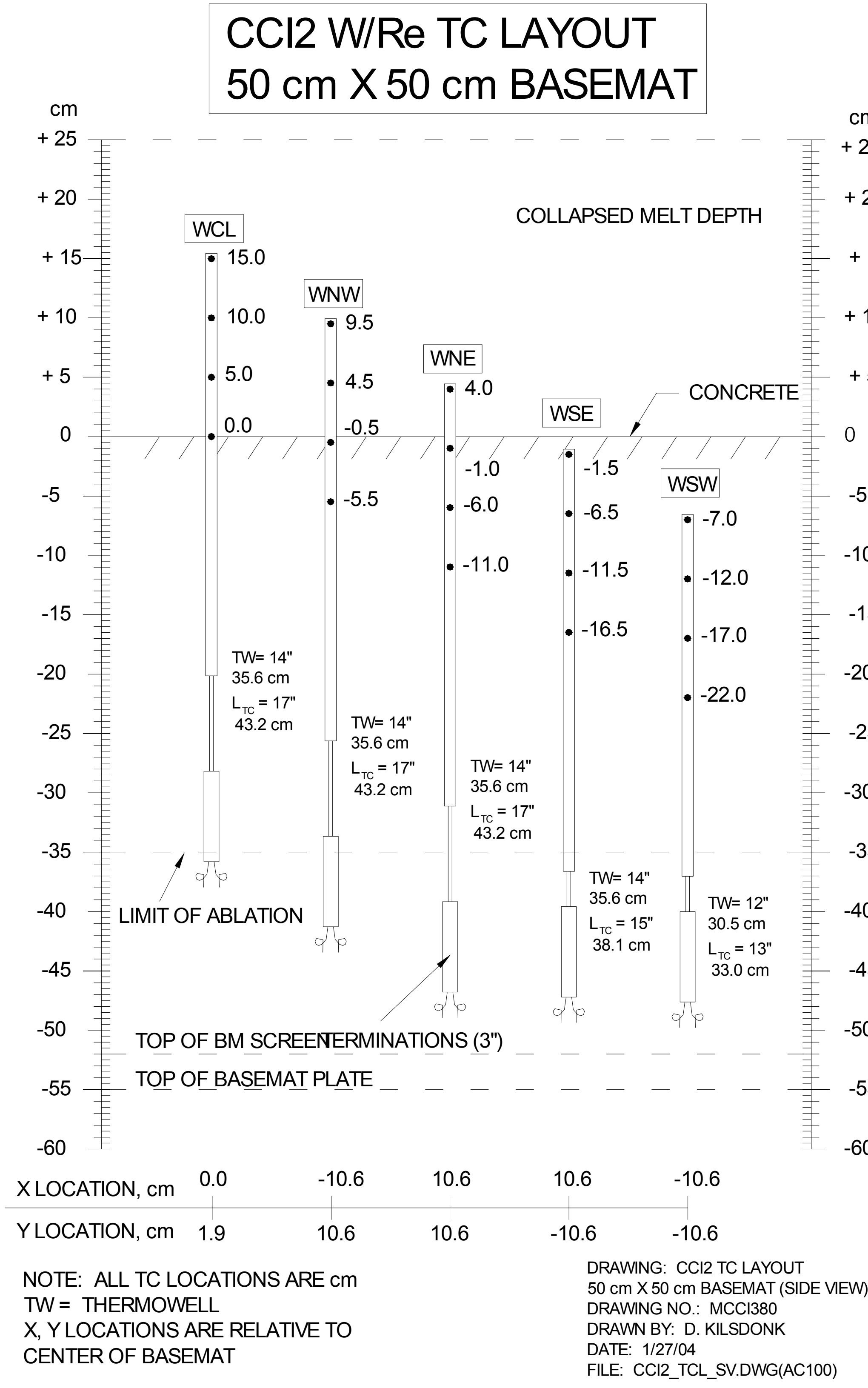


Figure 2-8. Elevation View of Basemat Type C Thermocouple Locations.

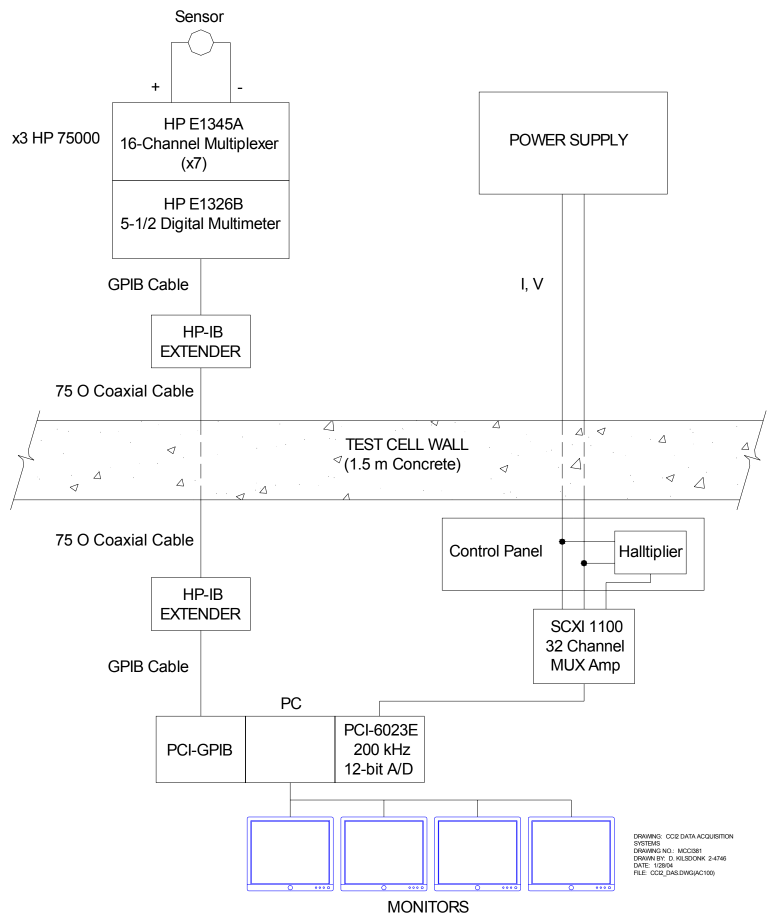


Figure 2-9. CCI Data Acquisition and Control Systems.

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 composition for CCI-2 is specified to contain 8 wt % calcined LCS concrete as an initial constituent. As part of the developmental work for the SSWICS-1 experiment,[3] a specific thermite was developed to produce this particular melt composition. The thermite reaction is of the form:

$$1.22U_3O_8 + 3.3Zr + 0.6Si + 0.32SiO_2 + 0.46Mg + 0.91\ CaO + 0.13Al + 2.01CrO_3 \rightarrow$$

$$3.66UO_2 + 3.3ZrO_2 + 0.92SiO_2 + 0.46MgO + 0.91CaO + 0.065Al_2O_3 + 2.01Cr;$$

$$Q = -262.2\ kJ/mole\ (1.816\ MJ/kg);$$

$$T_{adiabatic} = 2567\ ^{\circ}C$$

$$T_{actual} \sim 2100\ ^{\circ}C$$

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.

Table 2-1. Post-Reaction Bulk Composition for CCI-2 Thermite (Fully Oxidized PWR Corium Containing 8 wt % Limestone/Common Sand Concrete at ~2100 ˚C).

Constituent	Wt%	Total Mass (kg)
UO_2	60.62	242.48
ZrO_2	24.90	99.60
Calcined Concrete	8.07[a]	32.28
Cr	6.41	25.64
Total	100.00	400.00

[a]Calcined limestone/common sand concrete, consisting of 42.0/14.1/38.8/5.1 wt% $SiO_2/MgO/CaO/Al_2O_3$

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

Constituent	Wt %	
	Reactant	Product
U_3O_8	63.01	-
UO_2	-	60.62
Zr	18.42	-
ZrO_2	-	24.90
Si	1.03	-
SiO_2	1.18	3.39
Mg	0.69	-
MgO	-	1.14
Al	0.22	-
Al_2O_3	-	0.41
CaO	3.13	3.13
CrO_3	12.32	-
Cr	-	6.41

2.4 Concrete Composition

As shown in Table 1-1, limestone/common sand concrete is specified for CCI-2. The nominal composition for this concrete is provided in Table 2-3. This concrete is identical to that used in the ACE/MCCI and MACE experiment programs.

Table 2-3. Chemical Composition of Limestone/Common Sand Concrete.

Constituent	Wt%
SiO_2	28.3
MgO	9.6
CaO	26.0
Al_2O_3	3.5
K_2O	0.6
Fe_2O_3	1.6
TiO_2	0.14
Na_2O	1.1
H_2O	6.1
CO_2	21.4

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 lower section sidewall components (four total) 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, most of the thermite is repackaged into this single bag in order to reduce the amount of bagging material present in the thermite charge. Once the large Saran 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. Tungsten starter coils (4 total) for initiating the thermite reaction are then connected near the tops of the electrodes and laid on top of the large Saran bag.

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 instrumentation, including the lower section sidewall Type K TC's used to monitor the radial ablation progression, is 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 150 kW. After melt formation, the input power would be held constant at the 150 kW target for 5.5 hours of dry core-concrete interaction, or until a 30 cm ablation depth was reached in either the radial or axial directions. 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 150 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 35 cm was reached in either the radial or axial directions. 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, two vertical core samples will be drilled through the extent of the corium. The cores 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 four concrete sidewalls of the lower section will be removed, thereby fully revealing the solidified corium over the remaining basemat. Since the corium is revealed, a detailed map of the cavity erosion profile can be developed. Additional chemical samples will be collected at this point in order to further characterize the debris through chemical analysis. When these measurements are completed, the corium ingot will be placed in a storage container and archived as part of the test records. The two MgO sidewall sections will be cleaned for reuse in subsequent tests, while remnants of the two concrete sidewalls will be disposed of as radioactive waste.

4.0 REFERENCES

1. M. T. Farmer, S. Lomperski, D. J. Kilsdonk, and R. W. Aeschlimann, "Core Concrete Interaction (CCI) Tests: CCI-1 Test Data Report-Thermalhydraulic Results," Rev. 0, OECD/MCCI-2004-TR01, January 31, 2004.

2. S. Lomperski, M. T. Farmer, D. J. Kilsdonk, and R. W. Aeschlimann, "SSWICS-1 Test Data Report – Thermalhydraulic Results," OECD/MCCI-2002-TR04, Rev. 0, September 20, 2002.

3. S. Lomperski, M. T. Farmer, D. J. Kilsdonk, and R. W. Aeschlimann, "SSWICS-2 Test Data Report – Thermalhydraulic Results," OECD/MCCI-2002-TR06, Rev. 0, September 20, 2002.