OECD MCCI Project
Category 2 Coolability Engineering Enhancement Tests:
Water-Cooled Basemat Test 1 (WCB-1) Data Report

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FINAL

by:

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1.0 INTRODUCTION

1.1 Background

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 (SAMDA). 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 for severe accident 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 will 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 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.

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

As one of the steps required to satisfy these objectives, the Management Board (MB) approved the conduct of the first Category 2 Test. The MB convened a subcommittee at the 2nd PRG meeting to recommend testing options to investigate generic approaches for augmenting ex-vessel corium coolability in new reactors. Based on the committee deliberations, two general approaches for stabilizing ex-vessel core melts were defined:

- 1) terminating ablation by stabilizing the melt with external water-cooled surfaces
- 2) increasing water ingress into the melt volume by fragmentation

On the basis of these deliberations, the MB approved the conduct of the first large-scale test, which would address the first approach for stabilizing an ex-vessel core melt; i.e., the externally-cooled surface concept.

1.2 Objectives and Approach

Based on the MB directive, the project developed a test plan for a Water-Cooled Basemat test (WCB-1) for PRG consideration [1]. This report was reviewed by the PRG, and after several revisions, the plan was eventually adopted as the basis for conducting the experiment. Test specifications are provided in Table 1-1. The experiment approach was to incorporate a water-cooled basemat into the core-concrete interaction test apparatus. The basemat was composed of five parallel water channels that were instrumented to provide both local and global data on the heat transfer performance. The basemat was covered with a layer of sacrificial concrete that would be ablated by the overlying melt at the start of the experiment. Eventually, the melt would approach and then be thermally stabilized at the interface of the water-cooled basemat. The test was thus designed to provide prototypic data on the transient evolution and stabilization of a core melt in a generic water-cooled core catcher design for advanced plant applications.

WCB-1 was conducted on July 29, 2009. The objective of this data report is to document the thermal-hydraulic as well as posttest examination results from this experiment. To this end, a description of the test apparatus is provided first, followed by descriptions of the test operating procedure and key experiment results.

Table 1-1. Specifications for WCB-1.

Parameter	Specification
Corium	100 % oxidized PWR with 8 wt % siliceous concrete
Test section cross-sectional area	50 cm x 50 cm
Initial melt mass (depth)	400 kg (25 cm)
Test section sidewall construction	MgO protected by UO ₂ pellet layer.
Basemat construction	0-15 cm depth: siliceous concrete
	15-19.4 cm: water-cooled basemat, 5 parallel channels.
System operating pressure	Atmospheric
Melt formation technique (timescale)	Chemical reaction (~30 seconds)
Initial melt temperature	1950 °C
Melt heating technique	Direct Electrical (Joule) Heating
Initial power input level	Constant power at 80 kW ^a
Inlet water temperature	15 °C
Inlet water flow rate	2 liters/second
Sustained water depth over melt	50 ± 5 cm

^aBased on 150 kW/m² design heat flux to bottom and top surfaces of melt (0.5 m² area), plus an additional 5 kW to compensate for a long-term heat losses of 10 kW/m² to MgO sidewalls (0.5 m² area).

2.0 FACILITY DESCRIPTION

The high-level experiment objective of WCB-1 was to provide reactor material test data on the transient evolution and stabilization of a core melt within a generic water-cooled core catcher design for advanced plant applications. The experiment approach was to incorporate a test section featuring a water-cooled basemat into the Core Concrete Interaction (CCI) test facility to study thermal performance under long-term conditions in which melt resistance heating was provided to simulate decay heat. Additional details regarding the test design are provided in the balance of this section.

2.1 Test Apparatus

The WCB-1 test facility consisted of a test apparatus, a power supply for Direct Electrical Heating (DEH) of the corium, a basemat water supply system, a corium top flooding 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 is provided in Figure 2-1. The apparatus consisted of three rectilinear sidewall sections and a lid. The overall structure was 3.4 m tall. The sidewall sections had a square internal cross sectional area of nominally 50 cm x 50 cm.

Figure 2-1. Schematic of WCB-1 Test Facility.

The test section for containment of the core melt was located at the bottom of the apparatus. Cross-sectional views showing the water-cooled basemat installation are provided in Figures 2-2 and

2-3. The design utilized four refractory MgO sidewalls that were each lined with a layer of crushed UO_2 pellets. The pellets served as an inert (i.e., non-ablative) and highly insulating wall surface. As shown in the figures, the refractory walls were equipped with tungsten backup plates to preclude sidewall melt-through if the pellet layer were to fail and sidewall erosion occurred. The plates were instrumented with contact circuits to alert operating personnel in the control room if melt contacted the plates. This detection/mitigation system formed part of the safety planning for the experiments, and on this basis it would have been difficult to modify these components to provide feed throughs for the basemat water lines and instruments. Thus, the connections were brought in through the test section bottom plate. This approach had both design and operational implications, as outlined below.

The refractory sidewalls were contained within a flanged steel form that was used to secure the lower section to the bottom test section support plate and the middle sidewall section. The flanges allowed the lower sidewalls to be disassembled to reveal the solidified corium and water-cooled basemat following the test. Aside from the instrumented basemat, multi-junction Type C thermocouple assemblies were cast within the sidewalls so that the time-dependent heat loss from the melt could be calculated from the local temperature gradient and the thermal conductivity of the MgO.

Figure 2-2. Electrode Sidewall View of Test Section.

Figure 2-3. Non-Electrode Sidewall View of Test Section.

Design details of the water-cooled basemat are shown in Figures 2-4 and 2-5, while a photograph showing the actual test article after fabrication is provided in Figure 2-6. The overall layout consisted of a 15 cm deep layer of sacrificial concrete that sat on top of the water-cooled basemat plate. The plate consisted of five parallel cooling channels that were machined out of a monolithic piece of 4.4 cm thick Type 304 stainless steel. A photograph of the plate after machining is shown in Figure 2-7. Although carbon steel would be a more attractive construction material due to the higher thermal conductivity, melting point, and lower material cost, a non-magnetic material had to be used to preclude induction heating of the plate by the power supply used to resistively heat the melt. The basemat was the critical feature in this experiment, and it was essential to preclude spurious system failures that could develop as a result of fabrication techniques that could have been adopted to reduce costs. Although the monolithic design approach required a great deal of machining and welding, it was nonetheless adopted to minimize the chance of spurious water leaks that could form if the plate were manufactured using a cheaper method in which parts were sealed with gaskets, since these interfaces could provide leakage pathways if thermal stresses warped the plate during the test. A photograph showing the plate as it was being welded is provided in Figure 2-8.

Figure 2-4. Fabrication Details of Water-Cooled Basemat.

Figure 2-5. Details of Basemat Waterline and Instrumentation Feed Throughs.

Figure 2-6. Basemat Test Article Following Fabrication.

Figure 2-7. Photograph of Basemat Plate after Machining (view of bottom surface).

Figure 2-8. Photograph Showing Basemat Plate During Welding Stage.

In one of the original design concepts for this test, the basemat was segmented with non-conductive electrical material (i.e., mica) so that a shorting path could not develop if melt were to come into direct contact with the plate in two different locations. However, there was a concern that the insulation material could cause local hot spot(s) to form that could impede plate thermal performance, and on this basis the segmentation was omitted in the final design used for the test. Thermal analysis (see Appendix A) indicated that the plate should, under normal operating conditions, be protected by an insulating corium crust, and therefore the technical risk associated with omitting the segmentation was deemed to be small.

As described in Section 2.11, the test assembly was instrumented to measure overlying melt pool temperature, ablation profile of the sacrificial concrete, and the plate/coolant thermal response. The plate instrumentation layout was also designed to minimize penetration of the water channel that could lead to the development of leaks over the course of the test. For the multi-junction thermocouple assemblies devoted to measuring melt temperature and basemat erosion, this was accomplished by mounting the assembly feed throughs in the unmachined regions between the individual coolant channels (see Figure 2-22 in Section 2.11). This somewhat limited potential locations for the assemblies, but nonetheless ensured that the feed throughs could not provide a leak path for water. Another design requirement was to electrically isolate these thermocouple assemblies from the basemat to prevent ground loops that would provide alternative current paths for the electrical current used to heat the melt. This was accomplished by using ceramic-sleeve gland seals (Conax) to mount the thermocouples to the basemat plate. In addition, the tungsten thermowells that protected the melt temperature thermocouple assemblies were electrically isolated with ceramic

(fired lavite) sleeves that were used to seat the base of the wells in the plate. Photographs showing the instrument penetrations through the plate as viewed from above and below are provided in Figure 2-9.

Figure 2-9. Photograph Showing Instrument Penetrations in the Cooling Plate (a) From Above, and (b) From Below.

Aside from the thermocouple assemblies, the water channels were also instrumented with *in-situ* high temperature heat flux meters to provide local heat flux measurements. For these units to be effective, they had to be installed directly in the cooling channel so there was no choice but to provide feed throughs that passed directly through the channel cover plates. To ensure a leak-tight fit, specialty units were utilized that were fitted with a 6.4 mm diameter pipe nipple that passed signal wiring through the channel bottom plate; see Figures 2-10 and 2-11. In this manner, the feed throughs could be sealed using high-grade compression fittings that provided reasonable assurance that the fittings would not develop leaks during the test. As noted earlier, once the heat flux meters were installed, the channels were sealed with 3.2 mm thick 304 stainless steel cover plates that were welded in place to ensure a leak-tight fit (see Figure 2-8).

Melt pool generation in this test was achieved through an exothermic “thermite” chemical reaction that produced the target initial melt mass over a timescale of ~ 30 seconds. 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 later in this section). The second sparkler was provided as a backup in case the first failed to ignite the material.

A few minutes after the melt was formed, ablation of the sacrificial concrete basemat began. As shown in Figure 2-1, a large (15 cm diameter) gas line was 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 were partially filled with water. In the initial phase of the experiment as the concrete was eroded, the tanks served to cool the off-gases and filter aerosols

generated from the core-concrete interaction. In the late phase after the cavity was flooded, the tanks served to condense the steam and, based on the measured condensation rate, provided data on the corium cooling rate. In both phases, the helium covergas and non-condensables (CO , CO_2 , and H_2) passed through the tanks and were vented through an off gas system that included a demister and filters. The gases were eventually exhausted through the containment ventilation system and a series of high efficiency (HEPA) filters before finally being released from the building stack.

Figure 2-10. Design Details of Basemat Heat Flux Meter Installation.

(a)

(b)

Figure 2-11. Photographs of (a) Actual Heat Flux Meter After Installation in Channel and (b) Array of Heat Flux Meters Installed with Channel Cover Plates in Position for Welding.

After a specified period of dry core-concrete interaction, 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 2-12. A total of nine penetrations were cast into the upper lid of the test section. Of these penetrations, six were utilized for WCB-1: one 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 optical pyrometer to view the melt upper surface.

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.

Figure 2-12. Details of the Top Test Section Showing Water Weirs.

Figure 2-13. Illustration of WCB-1 Test Section Mounted on ZPR-9 Reactor Bed.

2.2 Basemat Water Supply System

A schematic illustration of the basemat water supply system is shown in Figure 2-14. The instrumentation locations are also shown in this figure. As previously noted, the water supply and return lines to the basemat were brought in through the test section base support plate. Each channel was equipped with an independent water measurement and control system that included both manual and remote isolation valves and a flowmeter. Temperature rise across each channel was measured using Type K thermocouples. The channel piping was constructed from 1.3 cm ID tubing. The individual channel flowrate and water temperature rise data allowed the average heat flux to each channel to be calculated. Each channel was also equipped with a secondary supply line with manual and remote isolation valves that could provide additional water flow to selected channels during the test if excessive heatup was observed. Both the primary and makeup supply lines were fed from 3.9 cm diameter header manifolds, and vented through a common manifold of the same diameter. The bulk temperature rise across the supply and return manifolds and total mass flowrate allowed the average heat flux to the plate to be calculated for comparison to the local channel measurements determined by the heat flux meters and the individual channel mass flux/temperature rise measurements.

Figure 2-14. Basemat Water Channel Cooling Circuits.

Since the basemat water inlet and exits were from the bottom of the plate, this test could not investigate situations in which the bulk water outlet temperature approached saturation, otherwise the channels could potentially vapor-lock and cause premature test termination. Finally, given this design, it was important to vent the air out of the lines before the test section was fully assembled. As shown in Figures 2-4 and 2-7, each channel was equipped with a small (6.4 mm diameter) pipe plug that was mounted at the top of the channel on the inlet side. Prior to installing the test section sidewalls, the water lines were pressurized and the plugs loosened until all the air was vented and the plugs resealed. After this point, test procedures did not allow the water line return side isolation valves to be opened unless the inlet valves were opened and the lines pressurized. This prevented air from reentering the system.

2.3 Test Section 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 2-15; details of the flooding weirs are shown in Figure 2-12. The supply system flowmeter, pressure transducer, level sensor, and thermocouple instrumentation locations are also shown in Figure 2-15. Water flow through the system was driven by a ~ 1 Bar differential pressure in the supply tank at a nominal flow rate of 120 lpm (2 l/s). The inlet water flow rate of 120 lpm corresponds to a melt/water heat flux in excess of 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 inlet water flow rate to the test section 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 $125 \pm 13 \text{ l}$ ($50 \pm 5 \text{ cm}$). 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. The test was initiated with valve RV-3 in the open position.

Note from Figure 2-15 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 prior to evacuation of the cell.

Figure 2-15. Test Section Water Supply System.

2.4 Quench System

The quench system, shown in Figures 2-16 and 2-17, 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. Steam and concrete decomposition gases passed from the test section through a 15 cm 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.

Figure 2-16. WCB-1 Quench and Overflow Tanks.

The secondary 1230 l capacity spray tank was connected to the quench tank by a 15 cm stainless steel pipe. In the event that 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 375 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 tanks was also insulated to minimize heat losses.

Figure 2-17. WCB-1 Spray Tank System.

2.5 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 2-18. The system consisted of a 15 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 differential 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 differential. As shown in Figure 2-18, 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 stream condensation should the pressure relief valve open and then reseal after water had been introduced into the test section.

The initial 400 l water inventory in the auxiliary tank was provided to cool gases from the test section and to remove aerosols before any noncondensables present in the gas stream passed into the cell atmosphere. The tank was instrumented with a Type K thermocouple to measure water temperature and a differential pressure transducer to measure water depth. The instrumentation locations are shown in Figure 2-18. Water depth and temperature 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 2-18. WCB-1 Test Section Pressure Relief System.

2.6 Off Gas System

An illustration of the off gas system is provided in Figure 2-19. This system filtered and vented the noncondensable concrete decomposition gases to the cell exhaust. The decomposition gases (H_2 , CO, CO_2 and the cover gas) exited the spray tank and passed through a flow separator. The cleanup efficiency of the separator was 99% of all entrained solid and liquid when the particle size exceeded 10 microns. After passing through the flow separator, the flow could potentially split into two parallel off gas system lines. One line was constructed from 7.5 cm piping, while the second was made from 10.0 cm piping. The system was designed with the capacity to accommodate large-scale (up to 120 cm x 120 cm) tests. Since WCB-1 used a reduced scale 50 cm x 50 cm test section, the 7.5 cm side of the parallel off gas system was taken out of service using a blank-off plate at the branch point in the system (see Figure 2-19). As a result, all gas flow was diverted through the 10 cm side of the off gas system. The final filters in the system (4 individual filters per filter housing, yielding a total of 8 filters for each side of the off gas system) removed any remaining particulate before venting the off gases through the flowmeter to the cell atmosphere. The filters (10 cm) were equipped with a passive counter-weighted check valve set to open at a nominal differential pressure of 7 kPa. The bypass was provided in the event that the filters plugged during the experiment.

Figure 2-19. WCB-1 Off Gas System.

2.7 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 protect test section internals. An illustration of the cover gas system is shown in Figure 2-20. 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 and optical pyrometer to prevent aerosol deposition on the camera and pyrometer quartz windows through which the melt upper surface was viewed. A third 0-100 slpm FC was used to inert the apparatus on the evening before the test.

Figure 2-20. WCB-1 Cover Gas System.

2.8 Power Supply

The power for Direct Electrical Heating (DEH) of the corium was provided by a 0.56 MW single phase AC power supply made 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 that passed through a wall of the former reactor fuel loading compartment. The calculated total voltage drop through the water cooled copper pipes and tungsten electrodes at operational temperature and maximum current was less than 0.5 V. The leakage current through the overlying water pool during test operation has been estimated to be less than 1% of the total current.

2.9 Corium Composition

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

$$Q = -252.2 \text{ kJ/mole (1.71 MJ/kg);}$$

$$T_{\text{adiabatic}} = 2572 \text{ }^\circ\text{C}$$

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

The bulk 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 mass of the UO_2 pellets that were used to line the test section MgO sidewalls; see Figures 2-2 and 2-3. This material did not participate in the initial exothermic chemical reaction, and remained essentially intact as a protective layer during the ensuing test sequence.

The 400 kg thermite charge was packed into the test section in a large, 1.7 mil aluminized Saran bag which was pre-installed over the basemat. The thermite was packed in the bag to prevent water absorption by CrO_3 and concrete oxides (principally CaO and SiO_2), since these constituents are hygroscopic.

Table 2-1. Post-Reaction Bulk Composition for WCB-1 Thermite.

Constituent	Wt%
UO_2	60.97
ZrO_2	25.04
Calcined Concrete	8.08 ^b
Cr	5.91

^bCalcined siliceous concrete: 79.0/0.9/15.4/4.7 wt% $\text{SiO}_2/\text{MgO}/\text{CaO}/\text{Al}_2\text{O}_3$

Table 2-2. Detailed Pre- and Post-Reaction Compositions for WCB-1 Thermite.

Constituent	Reactant		Product	
	Wt%	Mass (kg)	Wt%	Mass (kg)
U ₃ O ₈	63.38	253.52	-	-
UO ₂	-	-	60.97	243.88
Zr	18.53	74.12	-	-
ZrO ₂	-	-	25.04	100.16
Si	1.00	4.00	-	-
SiO ₂	4.23	16.92	6.38	25.52
Mg	0.04	0.16	-	-
MgO	-	-	0.07	0.28
Al	0.20	0.80	-	-
Al ₂ O ₃	-	-	0.38	1.52
CaO	1.25	5.00	1.25	5.00
CrO ₃	11.37	45.48	-	-
Cr	-	-	5.91	23.64
Total	100.00	400.00	100.00	400.00

Table 2-3. Engineering Composition of WCB-1 Siliceous Concrete Basemat.

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

2.10 Concrete Composition

The composition of the WCB-1 concrete was specified to be of the siliceous type. The specific composition was identical to that used in the CCI-3 experiment [3], since materials for fabrication of this concrete type were in stock at ANL. The engineering composition for this particular concrete is shown in Table 2-3. The sand and aggregate for the mix were supplied by CEA as an in-kind contribution to the program. The 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 [4].

2.11 Instrumentation and Data Acquisition

The WCB-1 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 water-cooled basemat plate; supply water flow rate to the basemat and to the test section; 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, melt/crust upper surface temperature, off gas temperature, and pressures at various locations within the system.

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

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 %.

All data acquisition and process control tasks were managed by a PC executing LabVIEW 8.2 under Windows XP. Sensor output terminals were connected inside the test cell to model HP E1345A 16-channel multiplexers that were integrated into a mainframe chassis in groups of eight. An illustration of the DAS setup is provided in Figure 2-21. The multiplexers directed signals to an HP E1326B 5 ½ digit multimeter incorporated into each chassis. Two of the three independent 128 channel systems were used for WCB-1. The detailed channel assignment lists for each of these two systems are provided in Appendix B.

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.

Integration of the signals over the period of a power line cycle limited the speed with which the multiplexer could scan the channel list. The minimum time for the digitizer to scan the list was ~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 was about 5 seconds.

Figure 2-21. Data Acquisition System Setup for WCB-1.

The basemat for WCB-1 was instrumented to monitor melt temperature during both the concrete ablation and plate-cooling phases of the test using multi-junction Type C thermocouples in tungsten thermowells. In addition, a two-color optical pyrometer was used to measure the debris upper surface temperature during periods when aerosol production did not optically occlude the view of the surface. Multi-junction Type K thermocouples cast directly into the basemat were also used to track the location of the concrete ablation front during the concrete erosion phase of the test. Plan and elevation views of the basemat thermocouple layout are provided in Figures 2-22 and 2-23. The water-cooled basemat and basemat water supply system (Figure 2-14) were instrumented to provide local and global heat transfer performance data.

The test section sidewalls and upper lid were also instrumented with a total of 20 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 the TC locations in the test section sidewalls are provided in Figures 2-24 and 2-25.

One method for monitoring water level in the test section was provided by a differential level probe which was inserted through a sealed penetration in the lid. The probe was maintained in a retracted position during the dry ablation phase until water was added to the test section. After water addition, the probe was inserted to a distance of 63 cm from the initial basemat surface (38 cm from the initial collapsed melt surface). The probe tip was instrumented with two 1.6 mm diameter ungrounded junction Type K TC's which monitored plenum gas temperature prior to water addition; thereafter, the TC's monitored the water temperature over the melt surface. The probe tip locations after insertion are shown in Figure 2-26.

Figure 2-22. Plan View of Basemat Instrumentation Layout (dimensions are in cm).

Figure 2-23. Elevation View of Basemat Type C Thermocouple Locations.

Figure 2-24. WCB-1 Test Section Sidewall Instrumentation (View from West).

Figure 2-25. WCB-1 Test Section Sidewall Instrumentation (View From South).

Figure 2-26. WCB-1 Test Section Pressure Transducer Layout.

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 70 cm from the initial basemat surface (45 cm from the initial collapsed melt surface). The port location is shown in Figure 2-26. The second method was provided by an on-line calculation of the water volume in the test section based on conservation of mass; i.e., the water volume in the test section at any time was equal to the initial volume in the supply/quench system tanks minus the volume in the same tanks at the current time.

The water supply tank was equipped with a magnetic float to measure the time-dependent water level. As a redundant level measurement technique, the supply tank was also equipped with a

differential PT. Water flow rate to the test section was monitored by a paddlewheel flowmeter. The location of the supply system instrumentation is shown in Figure 2-15.

The quench, overflow, and spray tanks were instrumented to measure the transient energy deposition due to steam generation from corium quenching in the test section. The quench and overflow tank instruments are shown in Figure 2-16, while the spray tank instrumentation is shown in Figure 2-17. Each tank was equipped with a magnetic float and (redundant) differential PT to measure the accumulating water volume due to steam condensation. Transient water temperatures in all tanks were monitored using Type K TC's (two in the quench and spray tanks and one in the overflow tank). Water flow rate and temperature differential across the quench tank cooling coil were monitored with a paddlewheel (and redundant ultrasonic) flowmeter and Type K TC's, respectively, thus providing a measurement of the time-dependent energy extraction rate from the water mass in the tank. The main steamline between the test section and quench tank was instrumented with Type K TC's to measure the local gas and pipe structure temperatures. The steamline thermocouple locations are shown in Figure 2-13.

Key system pressures were monitored with strain-gauge type pressure transducers manufactured by Sensym, Inc. As shown in Figures 2-15 through 2-17 and 2-26, the pressure in all system tanks were monitored, as well as the test section plenum pressure. An additional PT was located in the lower test section to monitor the pressure beneath the melt upper surface. This transducer was mounted on the north sidewall of the test section at an elevation of 46 cm beneath the initial concrete surface (see Figure 2-26). The gap between the MgO sidewalls and the electrodes was packed with crushed UO_2 pellets during corium loading. Thus, this PT could sense the pressure beneath the melt surface as long as the gap did not plug 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. Five area video monitors were also used in the cell to monitor for leaks, and to record any disruptive events (e.g., steam explosion) should one occur.

3.0 TEST PROCEDURES

3.1 Pretest Preparations

Assembly of the apparatus began through the installation of tungsten electrodes 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 test stand. The water-cooled basemat was then installed, plumbed up to the supply and return water manifolds, vented of air, and then leak checked. Once these steps were completed, the four sidewalls were set in place on the support plate. The lower section flange bolts and clamping bars were then installed

and tightened. Following this step, the basemat instruments were connected to terminal boxes that are prewired to the data acquisition system.

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 WCB-1 thermite constituents was sufficiently low to preclude excessive gas release during the burn. The results of this test indicated that moisture and nitrogen contents were within acceptable limits. On this basis, mixing was initiated.

Once the lower section is assembled, preparations for loading of the corium charge were initiated. A single large 1.7 mil aluminized Saran bag was preinstalled over the basemat. During loading, the 400 kg 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 evacuated immediately. As the thermite was placed, the gap between the tungsten electrodes and MgO sidewalls was filled with crushed UO₂ 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.

Once loading was completed, a removable train containing a 2.0 kg bagged sample of thermite was installed over the powder bed; an illustration is provided in Figure 3-1. 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 3-1 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.

Once loading was completed, the remainder of the test apparatus was assembled. This included installation of the two upper sections and the enclosure lid. Peripheral instruments were then installed and connected to terminal boxes. The main gas line from the test section to the quench tank was installed, 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 back 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

^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 determined from the ideal gas law; the composition of the evolved gases was determined using gas mass spectroscopy.

Figure 3-1. Illustration of Thermite Sample Train Installed in Test Section.

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. After a 1 minute hold at this pressure, the system was isolated to determine the leak rate. The leak rate of the WCB-1 test section was found to be 2.0 kPa/min (8 slpm) at a nominal pressure of 55 kPad, which was significantly below the acceptable leak rate of the fully assembled test section (i.e., < 2 % of the expected peak gas/vapor generation rate during the test).

Pretest preparations for WCB-1 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 within 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 six week time interval spanning pretest operations, the moisture content of the removable sample of bagged thermite increased gradually from 0.20 wt % to 0.24 wt %. The final moisture content was within the maximum permissible level of 0.3 wt %. On this basis, final approval was granted to proceed with the execution of Test WCB-1.

3.2 Test Operations

The planned test operating procedure is described first, followed by a summary of the actual operating procedure.

As shown in Table 1-1, initial target power for the core-concrete interaction phase was 80 kW. After melt formation, the input power would be held constant at the 80 kW level until the concrete was eroded to a depth of 12.5 cm, as evidenced by thermocouple readings near the bottom of the concrete. Once the concrete ablation depth reached 12.5 cm, leaving a concrete layer 2.5 cm thick over the water-cooled basemat, the cavity would be flooded and the input power held constant at the 80 kW level until the system came to thermal equilibrium. The determinants for thermal equilibrium would be that the steaming rate from the test section, as well as the melt and water channel exit temperatures, remained stable for 15 minutes. After the initial operating stage at a constant power level of 80 kW, the power would be gradually reduced in 10 kW intervals and the system allowed to equilibrate at the new power level. After each adjustment, the power supply would be run in a constant voltage mode for a period of ~ 15 minutes to look for the possibility of water ingress, as would be evidenced by reducing input power at constant voltage.^b Operation in this manner would continue until the input power was reduced to zero, either by gradual quench, or by periodic operator reductions in the input power level.

WCB-1 was performed on 29 July 2009. 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 at 4:47 pm. Coolant and cover gas flows were brought up to design conditions, and the cell ventilation system was closed and sealed per test procedures.

^bFollowing erosion of the concrete, melt pool gas sparging would cease. As a result, the test conditions resembled a SSWICS water ingress test, but with a water-cooled basemat and with input power into the melt by DEH. Thus, with the power supply operated in a constant voltage mode, the input power should decrease as the material quenched if water ingress occurred. However, if the power did not fall appreciably, then the conclusion would be that the input power lied above the dryout limit. In this event, the input power would be reduced in 10 kW intervals spaced out at ~ 15 minute intervals until the power began to decrease at constant voltage. This would define the dryout limit for the melt, which would be another important data point to add to the SSWICS water ingress database. However, this measurement would be unique since it would be made with heating present, which more closely simulates prototypic conditions.

An event sequence for WCB-1 is provided in Table 3-1. In the discussion that follows, time $t = 0$ corresponds to melt contact with the concrete basemat. The criterion used to define the onset of concrete ablation at a given location was that the local temperature reached the siliceous concrete liquidus temperature of 1250 °C. [5]

Table 3-1. WCB-1 Event Sequence (times relative to melt contact with basemat).

Shifted Time (Minutes)	Event
-31.3	DAS started.
-1.1	Power applied to thermite igniter wire.
-0.7	Thermite burn initiated; view of melt surface occluded by aerosol within 5 seconds.
0.0	Thermite burn completed (burn time ~ 40 seconds); melt temperature ~1950 °C
2.1	DEH input power stabilized at target level of 80 kW.
5.0	Aerosols in plenum clear to reveal debris surface. Pool was quiescent and covered with an overlying stable crust.
18.6	Aerosol production from core-concrete interaction began to increase and by 20.6 minutes, view of debris surface was completely blocked.
23.8	Aerosols in plenum cleared again, revealing a quiescent pool covered with a stable crust. By 25.5 minutes, the aerosol production increased to block the view of the surface.
30.7-52.6	Onset of basemat ablation detected at basemat centerline and in all four quadrants.
59.3	Aerosols cleared again, revealing a quiescent melt pool covered with a crust. By 64.3 minutes, aerosol production again increased to block the surface view.
86.6-99.5	Basemat ablation depth reached 2.5 cm at basemat centerline and in all four quadrants; sharp increase in ablation rate.
103.3-105.5	Basemat ablation depth reached 12.5 cm at centerline and in southwest quadrant (A and C array locations); preparations for cavity flooding initiated.
106.1	Water addition to test section initiated. Intermittent sparks observed from melt surface until 107.0 minutes; then the surface went dark for the balance of the experiment. Initial debris cooling rate peaked at 3.3 MW/m ² , and steadily declined until falling below 500 kW/m ² at 120 minutes.
108.3, 110.2, 115.1, 132.9, 149.9, 173.3, 209.1, 229.2	Makeup water added to test section
130.0	Melt temperatures scattered, but stabilized in the range of 1700 – 1900 °C. Debris/water heat flux had fallen to 370 kW/m ² (DEH input power equivalent to 320 kW/m ²). Plate upper surface temperatures at 4 out of 5 locations stabilized in the range of 100-250 °C. Heat fluxes to the plate were low; 10-20 kW/m ² . Power split biased heavily upwards.
130.7	Power supply reached operational limit on Tap 1 (56 V range); switch to Tap 2 (112 V range) initiated.
134.8	Basemat ablation depth reached 12.5 cm in northeast quadrant (E array location)
136.2-140.1	Plate surface temperature in northeast quadrant (junction E-7 in E array) recorded a rapid increase in local temperature from 143 °C to 813 °C; local heating rate was ~ 180 °C/minute.

Table 3-1 (Contd.). WCB-1 Event Sequence (times relative to melt contact with basemat).

Shifted Time (Minutes)	Event
137.1	Input power reduced to 70 kW; constant voltage operation initiated (47 volts). Backup water flows in channels C3, C4, and C5 started; channel flowrates increased from ~ 10 to 12 lpm.
145.2	Plate surface temperature in northeast quadrant continued to hover near 800 °C; input power reduced to 40 kW. Constant voltage operation resumed (39 volts).
152.0	Plate surface temperature in northeast quadrant (E array location) fell below 600 °C and continued to decline thereafter.
145.0 – 165.0	Melt temperatures scattered (1600-1950 °C). Debris-water heat flux declined and then stabilized at 150 kW/m ² . Plate temperature in northeast quadrant declined steadily, while temperature near centerline approached 500 °C. All other plate temperatures were < 400 °C. Plate heat fluxes ranged from 10 to 40 kW/m ² , with an average near 20 kW/m ² . Power split remained biased heavily upwards.
169.5	Basemat ablation depth reached 12.5 cm in northwest quadrant (B array location)
168.2-181.5	Plate surface temperature in northwest quadrant (junction B-7 in B array) recorded a steady increase in local temperature from 223 °C to 743 °C over the time interval; heating rate was ~ 40 °C/minute.
178.4	Input power reduced to 20 kW; constant voltage operation resumed (29 volts).
178.4-194.6	Melt temperatures scattered in the range of 1700-1900 °C. Plate surface temperature in northwest quadrant stabilized in the range of 750 – 780 °C before starting gradual decline. Debris-water heat flux declined steadily to ~ 120 kW/m ² and stabilized. Local plate heat fluxes were in the range of 10 – 25 kW/m ² . Power split remained biased heavily upwards.
194.6	Input power reduced to 10 kW; constant voltage operation resumed (25 volts).
194.6 – 227.0	Melt temperatures steadily declined to 1500 – 1600 °C at the end of the period. Debris cooling rate also fell from 120 to 75 kW/m ² . Input power at constant voltage declined to < 2 kW. Local plate heat fluxes remained in the range of 10 – 25 kW/m ² . Power split remained biased heavily upwards.
227.0	DEH input to melt terminated.
230.3	Data acquisition terminated.

As shown in Table 3-1, data acquisition began at -31.3 minutes relative to initial melt contact with the basemat. As shown in Figure 3-2, power was applied to the nichrome wire/sparkler located at the top of the powder charge at -1.1 minutes. Based on video camera data from the test section and plenum gas temperature readings (Figure 3-3), thermite ignition was announced and logged in the control room at -0.7 minutes. Based on readings from the Type K thermocouples cast flush with the concrete basemat surface (Figures 2-22 and 3-4), the burn front reached the bottom of the powder bed and contacted the concrete in ~ 40 seconds (i.e., at 0.0 minutes), which was within the planning basis for the experiment. The readings from selected melt temperature thermocouples are shown in Figure 3-5 over the first few minutes of the interaction. As is evident from this collection of data, peak melt temperatures near the center of the melt over the first minute were in the range of 1900 to 1960 °C, with the average being close to 1950 °C.

Figure 3-2. Voltage Reading Across Thermite Igniter Shunt.

Figure 3-3. Test Section Plenum Gas Temperatures during the Initial Interaction.

Figure 3-4. Concrete Surface Temperatures over the First 10 Minutes of the Interaction.

Figure 3-5. Bulk Melt Temperature Data over the First 10 Minutes of the Interaction.

At 2.1 minutes, DEH input power was stabilized at the initial target level of 80 kW. By 5.0 minutes, aerosols in the test section plenum cleared sufficiently to reveal the debris surface. The melt pool was quiescent, and was covered with an overlying stable crust. At 18.6 minutes, aerosol production increased, and by 20.6 minutes, the view of the surface was again occluded. In general, aerosol production for this test was substantial, with limited views of the debris surface obtained in the time intervals from 23.3 to 25.5 minutes and from 59.3 to 64.3 minutes. Each of these views indicated a fairly quiescent melt pool covered by an overlying crust.

As in previous tests, there was a calm period following melt formation in which the concrete surface was protected by an insulating crust. Over the time interval from 30.7 to 52.6 minutes, onset of ablation was detected at the basemat centerline and in all four quadrants. However, ablation continued to proceed slowly until ~ 90 minutes. Over the time interval from 86.6 to 99.5 minutes, the basemat ablation depth reached 2.5 cm at the basemat centerline and in all four quadrants. Past 90 minutes, the ablation rate picked up dramatically, with the ablation depth reaching 12.5 cm at the centerline and in the southwest quadrant over the time interval from 103.3 to 105.5 minutes. On this basis, preparations for flooding the cavity were initiated, and cavity flooding began at 106.1 minutes. Intermittent sparks were observed emanating from the melt surface until 107 minutes. The surface then went dark and remained that way for the balance of the experiment. The initial debris cooling rate peaked at 3.3 MW/m^2 , and then steadily declined to 500 kW/m^2 by 120 minutes. Makeup water was periodically added throughout the balance of the test to maintain the water level over the melt roughly in the range $50 \pm 5 \text{ cm}$.

By 130 minutes, the melt temperature measurements were scattered, but had stabilized in the range of 1700 to 1900 °C. The temperature of the upper surface of the water-cooled basemat plate had stabilized in the range of 100 to 250 °C at four out of the five measurement locations. The debris/water heat flux had fallen to 370 kW/m^2 , while the DEH input power was equivalent to 320 kW/m^2 (i.e., 80 kW DEH input power divided by the test section planar area of 0.25 m^2). Conversely, heat fluxes to the plate were quite low relative to the design basis value of 150 kW/m^2 (see Appendix A); i.e., 10 to 20 kW/m^2 . Thus, the up-down power split was biased heavily upwards.

At 134.8 minutes, the basemat ablation depth reached 12.5 cm in the northeast (E-array) quadrant. Subsequently, from 136.2 to 140.1 minutes, the plate surface temperature at this location rapidly increased from 143 °C to 813 °C, yielding a local heating rate of ~ 180 °C/minute. On this basis, the DEH input power was reduced to 70 kW at 137.1 minutes, and the power supply operating mode was switched from constant power to constant voltage. Backup water flows to channels C3, C4, and C5 were started; this increased the channel flowrate from ~ 10 to 12 lpm on the east side of the plate where the high local temperature was observed. At 145.2 minutes, the plate surface temperature in the northeast quadrant continued to hover near 800 °C, and on this basis, the input power was reduced to 40 kW. Constant voltage operating mode was then resumed at the lower power level. By 152 minutes, the plate surface temperature in the northeast quadrant had fallen below 600 °C, and continued to decline thereafter.

Over the time interval from 145 to 165 minutes, melt temperatures were still scattered in the range of 1600 to 1950 °C. After the power reduction, the debris-water heat flux declined and then stabilized at 150 kW/m^2 . The plate temperature in the northeast quadrant continued to decline, while

the temperature near the centerline approached 500 °C. All other plate temperature measurements were ≤ 400 °C. Plate heat fluxes ranged from 10 to 40 kW/m², with an average value near 20 kW/m². The power split remained biased heavily upwards.

At 169.5 minutes, the ablation depth reached 12.5 cm in the northwest quadrant (B array location). From 168.2 to 181.5 minutes, the plate surface temperature in this quadrant steadily increased from 223 °C to 743 °C, yielding an average heating rate of ~ 40 °C/minute. At 178.4 minutes, the input power was reduced to 20 kW, and constant voltage operation was again resumed at the reduced power level. From 178.4 to 194.6 minutes, the melt temperatures remained scattered in the range of 1700 to 1900 °C. The plate surface temperature in the northwest quadrant stabilized in the range of 750 to 780 °C before starting to decline. The debris-water heat flux declined steadily to ~ 120 kW/m² and also stabilized. Local plate heat fluxes were in the range of 10 – 25 kW/m² at this time. The power split remained biased heavily upwards.

At 194.6 minutes, the input power was reduced to 10 kW, and constant voltage operation was resumed. From 194.6 to 227.0 minutes, melt temperatures steadily declined to within the range of 1500 – 1600 °C. The debris cooling rate also fell from 120 to 75 kW/m². Input power at constant voltage declined to < 2 kW. Local plate heat fluxes remained in the range of 10 – 25 kW/m². The power split was still biased heavily upwards. At 227 minutes, DEH input to the melt was terminated. Data logging continued until 230.3 minutes. At this point, the system was shutdown following normal termination procedures. The DAS was restarted to record the long-term cool down data. The experiment was left unattended to cool down overnight.

4.0 RESULTS

A summary of the principal thermalhydraulic results from WCB-1 is provided in this section. A complete list of instruments used in the test is provided in Appendix B, while plots of all data logged from these instruments are provided in Appendix C.

4.1 Electric Power

The DEH power supply voltage, current, and total input power for WCB-1 are shown in Figures 4-1 through 4-3, respectively. At completion of the thermite burn, the power supply voltage was steadily increased until the input power reached the target level of 80 kW at 2.1 minutes. Thereafter, input power was held constant in the range of 80 ± 5 kW during dry cavity operations up to 106.1 minutes, and during the first phase of the interaction with water present in the cavity. The input power was reduced to 70 kW at 137 minutes, and constant voltage operation was initiated at that time. Power reductions to 40, 20, and 10 kW were also carried out at 145.2, 178.4, and 194.6 minutes. Constant voltage operation was maintained after each reduction. Following the last reduction, input power gradually decreased at constant voltage to < 2 kW at 227 minutes, and on that basis, DEH was terminated.

4.2 Melt Temperatures

A total of sixteen W5%Re/W26%Re (Type C) thermocouple junctions were used to monitor melt temperatures at various axial and radial locations in WCB-1. In addition, a two-color optical

Figure 4-1. Power Supply Voltage.

Figure 4-2. Power Supply Current.

Figure 4-3. Total DEH Input Power.

pyrometer mounted in the lid of the apparatus provided data on the melt upper surface temperature. The locations of the junctions for the Type C thermocouple units are shown in Figures 2-22 and 2-23. The thermocouples were configured within four four-junction arrays. The units were all located in the concrete basemat; each of these arrays was protected by a 0.95 cm diameter tungsten thermowell. Data from the four arrays are provided in Figures 4-4 through 4-7, while data from the optical pyrometer is shown in Figure 4-8. To provide an indication of the overall melt temperature behavior during the test, a graph showing data from all melt temperature measurement devices is provided in Figure 4-9. To improve readability, two steps were taken: i) the data have been averaged over ~30 second (i.e., 6 point) intervals, and ii) for the Type C thermocouples, only data preceding the first off-scale reading by the units are shown. Past the first off-scale reading, the thermocouple junctions are assumed to have failed, and thus the data are not deemed to be reliable.

Examination of this collection of data indicates that in the time interval from melt formation up to the point at which rapid concrete ablation commenced at ~ 90 minutes, melt temperatures were scattered in the range of 1750 to 2000 °C. During this interval, melt sparging was minimal due to limited ablation, and so there was no convection within the melt to smooth out temperature variations that developed as a result of the input power to this refractory (i.e., low thermal conductivity) material. However, following onset of significant basemat ablation at ~ 90 minutes, the melt temperature measurements banded more closely together. The bulk temperature declined from ~ 2000 °C at 90 minutes to ~ 1800 °C at the time of cavity flooding at 106.1 minutes. In the five minute interval following flooding, the melt temperature declined an additional 100 °C before stabilizing at ~ 1700 °C. At this point, a stable crust probably formed at the melt upper surface, terminating the bulk cooling transient.

Figure 4-4. Melt Temperature Data from Basemat Type C "WN" Array Data.

Figure 4-5. Melt Temperature Data from Basemat Type C "WS" Array Data.

Figure 4-6. Melt Temperature Data from Basemat Type C "WE" Array Data.

Figure 4-7. Melt Temperature Data from Basemat Type C "WW" Array Data.

Figure 4-8. Data from Melt Surface Temperature Optical Pyrometer.

Figure 4-9. Data from all Melt Temperature Measurement Devices.

After the initial cooling transient, effectively all of the concrete had been consumed over the water-cooled basemat plate. Thus, gas sparging of the pool would have ceased at this time. Past this point (~ 110 minutes), melt temperature measurements again diverge due to the lack of convection within the melt. The temperatures banded in the range of 1600 to 2000 °C until the power was reduced to 20 kW at 178.4 minutes. After this time, all remaining functional junctions indicated a steady melt temperature decline until the test was terminated at 230 minutes.

As noted earlier (see Table 3-1), views of the debris surface during the dry cavity phase of the experiment generally indicated the sustained presence of a crust over the melt. The optical pyrometer data shown in Figures 4-8 and 4-9 support this observation. Peaks in the readings from this device generally correspond to time intervals in which aerosols in the test section plenum cleared to provide a view of the crust upper surface (see Table 3-1). The pyrometer measurements during these intervals indicate crust surface temperatures that declined from ~ 1200 °C early in the interaction to ~ 900 °C just before onset of significant ablation at ~ 90 minutes. Past this time and up to the point of cavity flooding at 106.1 minutes, the surface temperature measurements escalated sharply up to ~ 1400 °C. After cavity flooding at 106.1 minutes, the pyrometer data are no longer reliable as the corium surface would have been quenched to the water saturation point of ~ 100 °C.

4.3 Concrete Basemat Ablation

The basemat was instrumented with five multi-junction Type K thermocouple arrays to monitor the axial progression of the ablation front, as well as the thermal response of the water-cooled basemat plate. The location and identification of these thermocouple assemblies are shown in Figure 2-22. The first junction of each array was mounted flush with the concrete surface. The next five junctions were spaced uniformly at 2.5 cm intervals within the concrete. The seventh junction of each assembly was positioned flush with the basemat upper surface, while the eight was mounted flush with the plate bottom surface. When a thermocouple embedded in the concrete reached the siliceous concrete liquidus temperature of 1250 °C [5], the melt was considered to be in contact with the thermocouple at the junction location.

The sequential rise in signals obtained from all five basemat thermocouple arrays are shown in Figures 4-10 through 4-14. In addition, Figure 4-15 provides the axial ablation depth versus time that was deduced from the data provided by these arrays. As noted earlier, only data preceding the first off-scale reading by each thermocouple junction are shown in Figures 4-10 through 4-14. In general, the data from all units indicated a gradual heatup and ablation of the concrete basemat over the first ~ 90 minutes of the test. Thereafter, a rapid transient occurred in which the remaining ~ 10 cm of the concrete was consumed by erosion over a timeframe of ~ 15 minutes. However, it is noteworthy that at all thermocouple locations, the progression of the ablation front was terminated as the water-cooled plate was approached. This observation was confirmed during posttest examinations, which verified that the plate survived the experiment intact.

Aside from the thermocouples in the concrete, the array junctions located flush with the top and bottom surfaces of the basemat plate also provided valuable data on the plate thermal response (see Figures 4-10 through 4-14). The information from these units is discussed in the next section, along with the other plate thermal response data logged during the test.

Figure 4-10. Basemat Thermal Response at the Centerline (“A” Array).

Figure 4-11. Basemat Thermal Response in the Northwest Quadrant (“B” Array).

Figure 4-12. Basemat Thermal Response in the Southwest Quadrant (“C” Array).

Figure 4-13. Basemat Thermal Response in the Southeast Quadrant (“D” Array).

Figure 4-14. Basemat Thermal Response in the Northeast Quadrant (“E” Array)

Figure 4-15. Basemat Axial Ablation Front Location.

4.4 Water-Cooled Plate Thermal Response

Evaluating both the local and global thermal performance of the basemat water-cooled plate was a key design objective for WCB-1. To that end, the plate was instrumented to measure local temperatures as well as heat fluxes (Figure 2-22). Furthermore, each of the five plate coolant channels was instrumented to measure water flowrate as well as coolant inlet and outlet temperatures (Figure 2-14). The design calculations for the basemat water cooling system are provided in Appendix A. The design-basis heat flux to the plate was 150 kW/m^2 , which roughly corresponds to a 50-50 up-down power split at the initial DEH input power level of 80 kW in the 50 cm x 50 cm test section. Based on the design basis calculations, after the system equilibrated at the design heat flux, the water temperature rise across the water-cooled channels was expected to be $\sim 9^\circ\text{C}$, with the boundary condition on the plate inner surface being highly subcooled nucleate boiling. The top surface of the plate was expected to come to equilibrium at $\sim 373^\circ\text{C}$, with the plate protected by a $\sim 1 \text{ cm}$ deep corium (or concrete slag) crust.

In reality, the up-down power split after the concrete basemat was fully eroded was highly biased to the overlying water layer. The heat fluxes to the plate measured by the nine flux meters that were incorporated into the basemat are shown collectively in Figure 4-16. With the exception of one reading from meter C4M, located in the midpoint of the east-central channel, all flux measurements were exceedingly low, in the range of 10 to 25 kW/m^2 , which is almost an order of magnitude below the design flux of 150 kW/m^2 . The one reading by C4M of slightly over 40 kW/m^2 at 146 minutes corresponded to the time at which the plate surface temperature peaked at slightly over 800°C in the northeast quadrant of the basemat; see Table 3-1. Surface temperatures measured on the upper and lower plate surfaces are shown in Figures 4-17 and 4-18, respectively.

Figure 4-16. Data from All Water-Cooled Basemat Heat Flux Meters.

Figure 4-17. Water-Cooled Basemat Upper Surface Temperatures.

Figure 4-18. Water-Cooled Basemat Lower Surface Temperatures.

Measurements on the water-side of the plate also indicated that the plate heat fluxes were quite low. Flowrates to each of the five cooling channels are shown collectively in Figure 4-19, while water inlet and outlet temperatures, as well as temperatures measured 2 cm below the steel upper surface, are shown in Figures 4-20 through 4-24 for each channel. At 137 minutes, backup water flow in channels C3, C4, and C5 was initiated due to the high plate surface temperature observed in the northeast quadrant; see Figure 4-19. This action increased the flowrate to these channels from ~ 10 to ~ 12 slpm.

As previously noted, the expected coolant temperature rise across the channels at design conditions (i.e. 150 kW/m^2) was 9°C . As is evident from Figures 4-20 through 4-25, the actual temperature rises were much lower; i.e., $1\text{-}2^\circ\text{C}$. This degree of temperature rise is consistent with the heat fluxes shown in Figure 4-16. The steel temperatures measured 2 cm below the plate surface inside the cooling channels also remained relatively cool ($< 100^\circ\text{C}$). This can be contrasted with several of the temperatures measured on the plate upper surface (see Figure 4-17). However, it should be noted that these high temperature measurements were taken in the region of the plate that included the steel ribbing that divided each coolant channel (see Figures 2-4 and 2-22). The temperature at these locations should have been higher in comparison to those in the channel itself. However, the extent of this increase has not been estimated as part of this work since this would require a fairly detailed three-dimensional heat transfer analysis in a complicated geometrical configuration.

4.5 Corium Top-Flooding Quench Rate

After the basemat ablation depth reached the pre-defined level of 12.5 cm, the cavity was flooded to obtain data on the nature and extent of the corium cooling when flooding occurs over a water-cooled basemat plate. To first order, the debris cooling rate can be estimated based on the steaming rate from the test section; i.e.

Figure 4-19. Basemat Cooling Channel Water Flowrates.

Figure 4-20. Channel No. 1 (west) Coolant Inlet/Outlet and Steel Temperatures 2 cm from Plate Surface.

Figure 4-21. Channel No. 2 (west-central) Coolant Inlet/Outlet and Steel Temperature 2 cm from Plate Surface.

Figure 4-22. Channel No. 3 (central) Coolant Inlet/Outlet and Steel Temperatures 2 cm from Plate Surface.

Figure 4-23. Channel No. 4 (east-central) Coolant Inlet/Outlet and Steel Temperature 2 cm from Plate Surface.

Figure 4-24. Channel No. 5 (east) Coolant Inlet/Outlet and Steel Temperatures 2 cm from Plate Surface.

$$q'' = \frac{h_{lv} \cdot \dot{m}_s}{A} \quad (4-1)$$

where h_{lv} is the water latent heat of vaporization at atmospheric pressure (2.256 MJ/kg), $\dot{m}_s$ is the steam mass flow rate, and A is the surface area of the debris in contact with the coolant. The steam flow rate was calculated by first performing an 18 point (~ 90 second) running average on the cumulative water level data in the quench and spray system tanks (see Figures 2-16 and 2-17), and then calculating the derivative of the resultant dataset using a central differencing scheme to obtain the steaming rate. The averaged tank water level data obtained from this analysis is shown in Figure 4-25, while the debris-water heat flux calculated from Eq. 4-1 is shown in Figures 4-26 and 4-27. The test section cross-sectional area in Eq. 4-1 was assumed to equal 0.25 m^2 . The figures also include the DEH input power normalized with the test section area for comparison with the debris cooling rate.

The calculated heat flux varied from 3.3 MW/m^2 immediately after cavity flooding, down to $\sim 100 \text{ kW/m}^2$ at the time the test was terminated. For most of the test, the heat flux to overlying water met or exceeded the DEH input power. This is consistent with a power split that is heavily biased upwards. Note that the same conclusion was drawn based on the plate thermal response results described in the previous section.

Figure 4-25. Combined Quench and Spray Tank Water Volume vs. Time.

Figure 4-26. Heat Flux to Overlying Water Pool.

Figure 4-27. Heat Flux to Overlying Water Pool: Expanded Scale.

4.6 Posttest Examinations

Following the experiment, the apparatus was carefully disassembled to document the posttest debris configuration. Figure 4-28 provides a picture of the top surface of the debris after removal of the top sidewall section. Elevation measurements at this point indicated that the upper surface of the debris was near the initial collapsed pool height of + 25 cm relative to the initial concrete surface elevation.

As the debris was removed, physical characteristics and dimensions were recorded so that accurate renderings of the posttest debris configuration could be produced; the results are provided in Figures 4-29 and 4-30. Since the key objective of this experiment was to examine the performance of the water-cooled plate, the corium was completely removed from the test section to reveal the plate so that it could be physically examined and photographed.

During the latter phase of the experiment, gas sparging from concrete decomposition was absent, and so an anchored crust configuration with an intervening void between the melt pool should not have formed in this test. The posttest examinations confirmed that this was indeed the case. The overall debris configuration consisted of an upper, 10-15 cm thick porous layer that probably formed during the initial phase of the quenching process when gas sparging was still present (i.e., as the remaining ~ 2 cm thick layer of concrete was eroded from the plate upper surface). Beneath the porous layer was a 25 to 30 cm thick monolithic layer of solidified corium with minimal porosity. This layer of material was most likely the balance of the melt pool that was not initially quenched, and thus underwent the longer-term interaction with the water-cooled plate.

Figure 4-28. Top View of Debris after Removal of Top Sidewall Section.

Figure 4-29. Rendering of Posttest Debris Configuration as Viewed from the South.

Figure 4-30. Rendering of Posttest Debris Configuration as Viewed from the West.

Finally, beneath the solid corium layer was a thin (~ 1 cm) layer of concrete that completely covered the plate upper surface. This layer of material was not ablated during the test, confirming that the water cooling was successful in halting the progression of the ablation front. Photographs showing the upper surface of the water-cooled plate are provided in Figure 4-31. Examination of the plate provided no evidence that the plate had melted. A few darkened areas are evident in the photographs that would not wash off. These may be locations where the plate was heated up and the surface locally oxidized or was corroded.

(a)

(b)

Figure 4-31. (a) Face-On and (b) Side Views of Water-Cooled Plate (views from south).

5.0 REFERENCES

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Appendix A

Design Analysis of Water-Cooled Plate Thermal Performance

In order to support the experiment design and planning for test operations, a few simple heat transfer calculations were performed to quantify the cooling plate performance characteristics. The specified objective of these calculations was to ensure that the cooling circuits were capable of keeping the plate temperature well below the melting point. To fulfill this objective, the cooling system needed to dissipate enough power to maintain a crust between the cooling plate and melt. Two design specifications were imposed to achieve this goal:

- 1) The heat load for the system was based on previously observed heat fluxes to the concrete sidewalls and basemat. These heat fluxes were typically $\sim 150 \text{ kW/m}^2$.
- 2) The cooling circuits were to be sized so that saturated nucleate boiling would not occur anywhere along the channel. A transition from subcooled to saturated boiling would degrade heat transfer in this particular geometry. Flow rates and coolant temperatures were selected to ensure that the coolant would remain subcooled.

Thermophysical property data used in the analysis are provided in Table A-1, while results are shown in Table A-2. Based on the design heat flux, the thermal loading to each channel is $\sim 7.5 \text{ kW}$ given the channel dimensions (see Figure 2-4). The channel flowrate was selected to maintain a significant bulk subcooling at the design basis heat flux. Thus, the channel volumetric flowrate was chosen as 12 liters/min per channel, which yields a bulk temperature rise of $\sim 9 \text{ }^\circ\text{C}$ per channel. Given the channel dimensions and flowrate, the channel hydraulic radius and Reynolds number were found to be 2.54 cm and 8890, respectively. The heat transfer coefficient was evaluated from the well-known Dittus Boelter correlation; i.e.,

$$h = \begin{cases} 7.6 \frac{k}{D_h}; & \text{Re} < 2300 \\ 0.024 \text{Re}^{0.8} \text{Pr}^{0.4} \left(\frac{k}{D_h} \right); & \text{Re} \geq 2300 \end{cases}.$$

The flow is turbulent (i.e., $\text{Re} > 2300$), and the convective heat transfer coefficient was thus evaluated from the second expression given above as $1405 \text{ W/m}^2\text{-}^\circ\text{C}$.

With this information and the design heat flux, the water film temperature rise between the bulk and channel surface was evaluated as $\sim 107 \text{ }^\circ\text{C}$. Thus, the wall surface temperature required to dissipate the heat under single phase flow conditions is above saturation, and as a result, subcooled nucleate boiling on the bottom of the plate will develop, albeit at a low level given the low overall water temperature rise across the channel. In any event, onset of subcooled boiling will significantly increase the heat transfer coefficient, thereby maintaining the channel inner surface temperature near saturation. Assuming this boundary condition, then the conduction-limited temperature rise across the plate required to dissipate the design basis heat flux is $272 \text{ }^\circ\text{C}$, and the plate exterior surface temperature will be $\sim 373 \text{ }^\circ\text{C}$. Assuming a corium crust forms on the plate, then the temperature rise across the crust will be $\sim 758 \text{ }^\circ\text{C}$ assuming the crust surface is maintained at the corium solidus temperature, which is further assumed to equal the siliceous concrete solidus of $\sim 1130 \text{ }^\circ\text{C}$ [2]. With

this data and an assumed crust thermal conductivity of $\sim 2 \text{ W/m}^\circ\text{C}$, the equilibrium crust depth that will form on the plate is calculated as $\sim 1 \text{ cm}$.

Table A-1. Thermophysical Properties Assumed in the Analysis.

Property	Water	304 Stainless	Corium Crust
Density (kg/m^3)	990	8000	5000
Thermal conductivity ($\text{W/m}^\circ\text{C}$)	0.64	14	2
Specific heat ($\text{J/kg}^\circ\text{C}$)	4178	500	600
Freezing temperature ($^\circ\text{C}$)	N/A	N/A	1130
Viscosity ($(\text{kg/m}\cdot\text{s})$)	$5.6 \cdot 10^{-4}$	N/A	N/A

Table A-2. Channel Thermal Analysis at Design Basis Conditions (150 kW/m^2 heat flux to plate, 12 liters/minute water flowrate per channel).

Parameter	Value
Plate thickness over flow channels (cm)	2.54
Channel cross-sectional flow area ($\text{cm} \times \text{cm}$)	1.59×6.35
Channel planar area exposed to melt pool ($\text{cm} \times \text{cm}$)	10×50
Channel hydraulic diameter (cm)	2.54
Channel design water flowrate (cm^3/s)	200
Channel water flow velocity (cm/s)	19.8
Channel inlet water temperature ($^\circ\text{C}$)	15
Plate design basis heat flux from melt pool (kW/m^2)	150
Channel Reynolds No. (-)	8890
Channel heat transfer coefficient ($\text{W/m}^2\cdot^\circ\text{C}$)	1405
Individual channel thermal loading from melt pool (kW)	7.5
Bulk water temperature rise along channel ($^\circ\text{C}$)	9.0
Channel water outlet temperature ($^\circ\text{C}$)	24.0
Water film temperature rise to plate assuming single-phase convection ($^\circ\text{C}$)	106.7^a
Channel plate inner surface temperature ($^\circ\text{C}$)	~ 100
Temperature rise across plate ($^\circ\text{C}$)	272
Exterior surface temperature of plate beneath crust ($^\circ\text{C}$)	372
Crust temperature gradient ($T_f - T_i$)	758
Corresponding crust thickness to balance thermal load (mm)	10

^aThe channel inner surface temperature is calculated to slightly exceed saturation, while the bulk temperature at the channel outlet remains highly subcooled. Thus, subcooled boiling will occur on the channel inner surface that will maintain the surface temperature near saturation.

To summarize, after the system equilibrates at the design heat flux, the water channels should exhibit an average temperature rise of $\sim 9^\circ\text{C}$, with the boundary condition on the plate inner surface being highly subcooled nucleate boiling. The exterior temperature of the plate should come to equilibrium at $\sim 373^\circ\text{C}$, with the plate surface protected by a $\sim 1 \text{ cm}$ deep corium crust. This of course assumes that the concrete is fully eroded, and the corium immediately forms a crust on the relatively cold steel plate. However, the situation will not differ significantly if a slag crust forms on the surface, since the thermal conductivities of these two media are approximately the same.

APPENDIX B

Data Acquisition System Channel Assignments

This Appendix provides the channel assignments for the two independent DAS systems that were used to guide operations and record test data for WCB-1. For convenience, these two 128 channel systems were referred to the “Basemat” and “Quench” systems by operating personnel. The channel assignment lists for these two systems are provided in Tables B-1 and B-2. The data recorded on each of channel is provided in Appendix C.

Table B-1. "Basemat" DAS Channel Assignments for WCB-1.

Channel	Variable	Sensor	Location	Elevation	Range/Limit	Accuracy
00	T	Diode Sensor	TC compensation Channels B01-B49		130 C	
01	Reserve					
02	T	TC Type C	Concrete Basemat -4.5 cm, +6.5 cm WN-2	+5.0 cm	2320 C	± 1%
03	T	TC Type C	Concrete Basemat -4.5 cm, +6.5 cm WN-3	-5.0 cm	2320 C	± 1%
04	T	TC Type C	Concrete Basemat -4.5 cm, +6.5 cm WN-4	-15.0 cm	2320 C	± 1%
05	T	TC Type C	Concrete Basemat +13.5 cm, 0.0 cm WE-1	+15.0 cm	2320 C	± 1%
06	T	TC Type C	Concrete Basemat +13.5 cm, 0.0 cm WE-2	+5.0 cm	2320 C	± 1%
07	T	TC Type C	Concrete Basemat +13.5 cm, 0.0 cm WE-3	-5.0 cm	2320 C	± 1%
08	T	TC Type C	Concrete Basemat +13.5 cm, 0.0 cm WE-4	-15.0 cm	2320 C	± 1%
09	T	TC Type C	Concrete Basemat +4.5 cm, -6.5 cm WS-1	+10.0 cm	2320 C	± 1%
10	T	TC Type C	Concrete Basemat +4.5 cm, -6.5 cm WS-2	+3.0 cm	2320 C	± 1%
11	T	TC Type C	Concrete Basemat +4.5 cm, -6.5 cm WS-3	-4.0 cm	2320 C	± 1%
12	T	TC Type C	Concrete Basemat +4.5 cm, -6.5 cm WS-4	-11.0 cm	2320 C	± 1%
13	T	TC Type C	Concrete Basemat -13.5 cm, 0.0 cm WW-1	+15.0 cm	2320 C	± 1%
14	T	TC Type C	Concrete Basemat -13.5 cm, 0.0 cm WW-2	+5.0 cm	2320 C	± 1%
15	T	TC Type C	Concrete Basemat -13.5 cm, 0.0 cm WW-3	-5.0 cm	2320 C	± 1%
16	T	TC Type C	Concrete Basemat -13.5 cm, 0.0 cm WW-4	-15.0 cm	2320 C	± 1%
17	Q	thermopile	Basemat channel # 1 heat flux, north side C1N (S/N 009)	-15.0 cm	3 MW/m ²	± 5%
18	T	TC Type K	Basemat channel # 1 TC, north side C1N (S/N 009)	-15.0 cm	1400 C	± 0.75%
19	Q	thermopile	Basemat channel # 1 heat flux, south side C1S (S/N 002)	-15.0 cm	3 MW/m ²	± 5%
20	T	TC Type K	Basemat channel # 1 TC, south side C1S (S/N 002)	-15.0 cm	1400 C	± 0.75%
21	Q	thermopile	Basemat channel # 2 heat flux, midpoint C2M (S/N 011)	-15.0 cm	3 MW/m ²	± 5%
22	T	TC Type K	Basemat channel # 2 TC, midpoint C2M (S/N 011)	-15.0 cm	1400 C	± 0.75%
23	Q	thermopile	Basemat channel # 3 heat flux, north side C3N (S/N 007)	-15.0 cm	3 MW/m ²	± 5%

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24	T	TC Type K	Basemat channel # 3 TC, north side C3N (S/N 007)	-15.0 cm	1400 C	± 0.75%
25	Q	thermopile	Basemat channel # 3 heat flux, midpoint C3M (S/N 012)	-15.0 cm	3 MW/m ²	± 5%
26	T	TC Type K	Basemat channel # 3 TC, midpoint C3M (S/N 012)	-15.0 cm	1400 C	± 0.75%
27	Q	thermopile	Basemat channel # 3 heat flux, south side C3S (S/N 004)	-15.0 cm	3 MW/m ²	± 5%
28	T	TC Type K	Basemat channel # 3 TC, south side C3S (S/N 004)	-15.0 cm	1400 C	± 0.75%
29	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-1	0.0 cm	1400 C	± 0.75%
30	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-2	-2.5 cm	1400 C	± 0.75%
31	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-3	-5.0 cm	1400 C	± 0.75%
32	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-4	-7.5 cm	1400 C	± 0.75%
33	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-5	-10.0 cm	1400 C	± 0.75%
34	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-6	-12.5 cm	1400 C	± 0.75%
35	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-7 (top of plate)	-15.0 cm	1400 C	± 0.75%
36	T	TC Type K	Concrete Basemat-5.0 cm, 0.0 cm A-8 (bottom of plate)	-17.25 cm	1400 C	± 0.75%
37	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm B-1	0.0 cm	1400 C	± 0.75%
38	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm B-2	-2.5 cm	1400 C	± 0.75%
39	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm B-3	-5.0 cm	1400 C	± 0.75%
40	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm B-4	-7.5 cm	1400 C	± 0.75%
41	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm B-5	-10.0 cm	1400 C	± 0.75%
42	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm B-6	-12.5 cm	1400 C	± 0.75%
43	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm C-7 (top of plate)	-15.0 cm	1400 C	± 0.75%
44	T	TC Type K	Concrete Basemat -13.5 cm, +14.5 cm C-8 (bottom of plate)	-17.25 cm	1400 C	± 0.75%
45	Q	thermopile	Basemat channel # 4 heat flux, midpoint C4M (S/N 006)	-15.0 cm	3 MW/m ²	± 5%
46	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-1	0.0 cm	1400 C	± 0.75%
47	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-2	-2.5 cm	1400 C	± 0.75%
48	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-3	-5.0 cm	1400 C	± 0.75%
49	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-4	-7.5 cm	1400 C	± 0.75%

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50	T	Diode Sensor	TC compensation Channels B51-B99		130 C	
51	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-5	-10.0 cm	1400 C	± 0.75%
52	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-6	-12.5 cm	1400 C	± 0.75%
53	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-7 (top of plate)	-15.0 cm	1400 C	± 0.75%
54	T	TC Type K	Concrete Basemat -13.5 cm, -14.5 cm C-8 (bottom of plate)	-17.25 cm	1400 C	± 0.75%
55	T	TC Type K	Basemat channel # 4 TC, midpoint C4M (S/N 006)	-15.0 cm	1400 C	± 0.75%
56	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-1	0.0 cm	1400 C	± 0.75%
57	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-2	-2.5 cm	1400 C	± 0.75%
58	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-3	-5.0 cm	1400 C	± 0.75%
59	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-4	-7.5 cm	1400 C	± 0.75%
60	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-5	-10.0 cm	1400 C	± 0.75%
61	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-6	-12.5 cm	1400 C	± 0.75%
62	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-7 (top of plate)	-15.0 cm	1400 C	± 0.75%
63	T	TC Type K	Concrete Basemat +13.5 cm, -14.5 cm D-8 (bottom of plate)	-17.25 cm	1400 C	± 0.75%
64	Q	thermopile	Basemat channel # 5 heat flux, north side C5N (S/N 008)	-15.0 cm	3 MW/m ²	± 5%
65	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-1	0.0 cm	1400 C	± 0.75%
66	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-2	-2.5 cm	1400 C	± 0.75%
67	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-3	-5.0 cm	1400 C	± 0.75%
68	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-4	-7.5 cm	1400 C	± 0.75%
69	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-5	-10.0 cm	1400 C	± 0.75%
70	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-6	-12.5 cm	1400 C	± 0.75%
71	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-7 (top of plate)	-15.0 cm	1400 C	± 0.75%
72	T	TC Type K	Concrete Basemat +13.5 cm, +14.5 cm E-8 (bottom of plate)	-17.25 cm	1400 C	± 0.75%
73	T	TC Type K	Basemat channel # 5 TC, north side C5N (S/N 008)	-15.0 cm	1400 C	± 0.75%
74	F	Ultrasonic	Basemat Channel No. 1 Flowrate FM-C1	R=49.94 Ω	38 lpm	± 0.8 lpm%
75	F	Ultrasonic	Basemat Channel No. 2 Flowrate FM-C2	R=49.82 Ω	38 lpm	± 0.8 lpm%

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76	F	Ultrasonic	Basemat Channel No. 3 Flowrate FM-C3	R=49.80 Ω	38 lpm	± 0.8 lpm%
77	F	Ultrasonic	Basemat Channel No. 4 Flowrate FM-C4	R=50.06 Ω	38 lpm	± 0.8 lpm%
78	F	Ultrasonic	Basemat Channel No. 5 Flowrate FM-C5	R=49.97 Ω	38 lpm	± 0.8 lpm%
79	Q	thermopile	Basemat channel # 5 heat flux, south side C5S (S/N 014)	-15.0 cm	3 MW/m ²	$\pm 5\%$
80	T	TC Type K	Water Channel No. 1 Inlet, C1-TW-In (S/N 05)		1400 C	$\pm 0.75\%$
81	T	TC Type K	Water Channel No. 1 Outlet # 1, C1-TW-Out(1) (S/N 15)		1400 C	$\pm 0.75\%$
82	T	TC Type K	Water Channel No. 1 Outlet # 2, C1-TW-Out(2) (S/N 16)		1400 C	$\pm 0.75\%$
83	T	TC Type K	Water Channel No. 2 Inlet, C2-TW-In (S/N 04)		1400 C	$\pm 0.75\%$
84	T	TC Type K	Water Channel No. 2 Outlet # 1, C2-TW-Out(1) (S/N 13)		1400 C	$\pm 0.75\%$
85	T	TC Type K	Water Channel No. 2 Outlet # 2, C2-TW-Out(2) (S/N 14)		1400 C	$\pm 0.75\%$
86	T	TC Type K	Water Channel No. 3 Inlet, C3-TW-In (S/N 03)		1400 C	$\pm 0.75\%$
87	T	TC Type K	Water Channel No. 3 Outlet # 1, C3-TW-Out(1) (S/N 11)		1400 C	$\pm 0.75\%$
88	T	TC Type K	Water Channel No. 3 Outlet # 2, C3-TW-Out(2) (S/N 12)		1400 C	$\pm 0.75\%$
89	T	TC Type K	Water Channel No. 4 Inlet, C4-TW-In (S/N 02)		1400 C	$\pm 0.75\%$
90	T	TC Type K	Water Channel No. 4 Outlet # 1, C4-TW-Out(1) (S/N 09)		1400 C	$\pm 0.75\%$
91	T	TC Type K	Water Channel No. 4 Outlet # 2, C4-TW-Out(2) (S/N 10)		1400 C	$\pm 0.75\%$
92	T	TC Type K	Water Channel No. 5 Inlet, C5-TW-In (S/N 01)		1400 C	$\pm 0.75\%$
93	T	TC Type K	Water Channel No. 5 Outlet # 1, C5-TW-Out(1) (S/N 07)		1400 C	$\pm 0.75\%$
94	T	TC Type K	Water Channel No. 5 Outlet # 2, C5-TW-Out(2) (S/N 08)		1400 C	$\pm 0.75\%$
95	T	TC Type K	Main Water Inlet Header, TMAIN-IN (S/N 18)		1400 C	$\pm 0.75\%$
96	T	TC Type K	Contingency Water Inlet Header, TBACK-IN (S/N 17)		1400 C	$\pm 0.75\%$
97	T	TC Type K	Water Outlet Header, TMAIN-OUT (S/N 06)		1400 C	$\pm 0.75\%$
98	F	Ultrasonic	Quench tank coil (2) FM-2b	R=50.10 Ω	114 lpm	± 0.8 lpm%
99	T	TC Type K	Basemat channel # 5 TC, south side C5S (S/N 014)		1400 C	$\pm 0.75\%$

Explanation of Variable Notations

T = temperature, Q = heat flux, F = flowrate

Table B-2. "Quench" DAS Channel Assignments for WCB-1.

Channel	Variable	Sensor	Location	Level	Range/Limit	Accuracy	Notes
00	T	Diode Sensor	TC Compensation Chs. Q00-Q49		130 C		
01	T	TC Type C	W Sidewall, 1.0 cm deep SW-1	-9.0 cm	2320 C	± 1.0%	
02	T	TC Type C	" " 2.0 " " SW-2	"	2320 C	± 1.0%	
03	T	TC Type C	" " 4.0 " " SW-3	"	2320 C	± 1.0%	
04	T	TC Type C	" " 8.0 " " SW-4	"	2320 C	± 1.0%	
05	T	TC Type C	S Sidewall, 1.0 cm deep SW-5	+3.1 cm	2320 C	± 1.0%	
06	T	TC Type C	" " 2.0 " " SW-6	"	2320 C	± 1.0%	
07	T	TC Type C	" " 4.0 " " SW-7	"	2320 C	± 1.0%	
08	T	TC Type C	" " 8.0 " " SW-8	"	2320 C	± 1.0%	
09	Reserve						
10	Reserve						
11	Reserve						
12	Reserve						
13	Reserve						
14	Reserve						
15	Reserve						
16	T	TC Type C	W Sidewall, 8.0 cm deep SW-12	+31.5 cm	2320 C	± 1.0%	
17	T	TC Type C	" " 1.0 " " SW-9	"	2320 C	± 1.0%	
18	T	TC Type C	" " 2.0 " " SW-10	"	2320 C	± 1.0%	
19	T	TC Type C	" " 4.0 " " SW-11	"	2320 C	± 1.0%	
20	Reserve						
21	T	TC Type K	Steamline internal, vertical run from vessel ML-1		1400 C	± 0.75%	
22	T	TC Type K	Steamline external, vertical run from vessel ML-2		1400 C	± 0.75%	
23	T	TC Type K	Steamline external, lateral run from vessel ML-3		1400 C	± 0.75%	

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24	T	TC Type K	Steamline external, vertical run to quench tank ML-4		1400 C	± 0.75%	
25	Reserve						
26	Reserve						
27	Reserve						
28	Reserve						
29	T	TC Type K	Quench tank internal QT-1	21 cm	1400 C	± 0.75%	
30	T	TC Type K	" " " QT-2	55 cm	1400 C	± 0.75%	
31	T	TC Type K	N Top Section Sidewall, 0.0 cm deep SWHL-17	+193.1 cm	1400 C	± 0.75%	
32	T	TC Type K	N Top Section Sidewall, 2.0 cm deep SWHL-18	"	1400 C	± 0.75%	
33	T	TC Type K	W Top Section Sidewall 0.0 cm deep SWHL-19	+211.5 cm	1400 C	± 0.75%	
34	T	TC Type K	W Top Section Sidewall 2.0 cm deep SWHL-20	"	1400 C	± 0.75%	
35	T	TC Type K	Quench tank coil inlet QT-5		1400 C	± 0.75%	
36	T	TC Type K	Quench tank coil outlet QT-6		1400 C	± 0.75%	
37	T	TC Type K	Quench tank coil outlet QT-7		1400 C	± 0.75%	
38	T	TC Type K	Overflow tank internal OT-1	16 cm	1400 C	± 0.75%	
39	T	Voltage	Igniter Current		100 mV		
40	T	TC Type K	Spray tank internal ST-1	10 cm	1400 C	± 0.75%	
41	T	TC Type K	" " " ST-2	38 cm	1400 C	± 0.75%	
42	T	TC Type K	S Middle Section Sidewall, 0.0 cm deep SWHL-13	+70.0 cm	1400 C	± 0.75%	
43	T	TC Type K	S Middle Section Sidewall, 20.0 cm deep SWHL-14	"	1400 C	± 0.75%	
44	Reserve						
45	Reserve						
46	T	TC Type K	S Middle Section Sidewall 0.0 cm deep SWHL-15	+151.3 cm	1400 C	± 0.75%	
47	T	TC Type K	S Middle Section Sidewall 2.0 cm deep SWHL-16	"	1400 C	± 0.75%	
48	Reserve						
49	Reserve						

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50	T	Diode Sensor	TC Compensation CH Q50-Q99		400 K		
51	Reserve						
52	Reserve						
53	Reserve						
54	T	"	Internal, exhaust line OG-1		"	± 0.75%	
55	T	"	Water supply tank internal WS-1	45 cm	"	± 0.75%	
56	T	Optical Pyrometer	Corium Surface Temperature OP-1	242.9 cm	600-1800 C	± 4.0 C	
57	T	"	Water level probe LP-1	181 cm/62.5 cm	"	± 0.75%	
58	T	"	Water level probe LP-2	181 cm/62.5 cm	"	± 0.75%	
59	T	"	Test vessel plenum gas TS-1	225.5 cm	"	± 0.75%	
60	L	Strain	Supply tank head PT-1		0-35 kPad		S/N D6
61	P	Strain	Supply tank pressure PT-2		0-408 kPa		S/N PT2
62	L	Strain	Test vessel head, insertion probe PT-3		95-150 l		S/N D3
63	L	Strain	Test vessel head, static probe PT-4		114-150 l		S/N D1
64	P	Strain	Test vessel plenum pressure PT-5		0-204 kPa		S/N A17
65	P	Strain	Basemat side pressure PT-6		0-204 kPa		S/N A3
66	Reserve						
67	L	Strain	Quench tank head PT-8		0-35 kPad		S/N D2
68	P	Strain	Quench/overflow tank pressure PT-9		0-204 kPa		S/N A1
69	L	Strain	Overflow tank head PT-10		0-35 kPad		S/N D8
70	L	Strain	Spray tank head PT-11		0-35 kPad		S/N D5
71	P	Strain	Spray tank pressure PT-12		0-35 kPad		S/N D4
72	L	Magnetic Float	Supply tank volume LS-1		350-2000 l		
73	L	Magnetic Float	Quench tank volume LS-2		80-590 l		
74	L	Magnetic Float	Overflow tank volume LS-3		200-900 l		
75	L	Magnetic Float	Spray tank volume LS-4		240-1290 l		

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76	F	Paddlewheel	Water supply flowrate FM-1		680 lpm		
77	F	Paddlewheel	Quench tank coil flowrate FM-2		190 lpm		
78	Reserve						
79	Reserve						
80	Reserve		-				
81	Reserve						
82		-	Calculated Water Volume in Test Section		0-150 l		
83	FC	Flowcontroller	Lid lights & camera covergas flowrate FC-2		0-200 lpm		
84	Reserve						
85		-	Calculated Total Current (Q92+Q93)		0 -10,000 A		
86		-	Calculated Total Power (Q94+Q95)		0-500 kW		
87	FC	Flowcontroller	Test vessel covergas flowrate FC-6		0-100 lpm		
88	FC	Flowcontroller	Lid camera covergas flowrate FC-7		0-350 lpm		
89	V		Pressure transducer power supply #1 voltage		0-30 V		
90	V		Pressure transducer power supply #2 voltage		0-30 V		
91	V	Voltmeter	Power supply voltage		0-200 V		
92	A	Transformer	Power supply current #2		5000 A		
93	A	Transformer	Power supply current #1		5000 A		
94	W	Hall Meter	Power supply power #2		1100 kW		
95	W	Hall Meter	Power supply power #1		1100 kW		
96	L	Strain	Auxiliary Tank Head PT-13		0-35 kPad		S/N D10
97	T	TC Type K	Auxiliary Tank Internal AT-1	43 cm	1400 C	± 0.75%	
98	Reserve						
99	Reserve						

Explanation of variable notations

T = temperature P = pressure L = Level V = Voltage F = Flowrate A = Current W = Power FC = Flow Controller

APPENDIX C

Test Data

This Appendix provides plots of all data recorded during Test WCB-1. The complete channel assignment list is provided in Appendix B. Time $t = 0$ in all plots is referenced to the time at which melt made initial contact with the concrete basemat. This corresponds to 31.3 minutes after onset of data acquisition; see Table 3-1. All data was logged at ~ 5.5 second time intervals during the test. Selected channels have been averaged to improve readability.

Figure C-1. Thermocouple Compensator Temperatures.

Figure C-2. Basemat Type C "WN" Array Data.

Figure C-3. Basemat Type C “WS” Array Data.

Figure C-4. Basemat Type C “WE” Array Data.

Figure C-5. Basemat Type C “WW” Array Data.

Figure C-6. Melt Temperature Optical Pyrometer Data.

Figure C-7. Basemat Type K “A” Array Data.

Figure C-8. Basemat Type K “B” Array Data.

Figure C-9. Basemat Type K “C” Array Data.

Figure C-10. Basemat Type K “D” Array Data.

Figure C-11. Basemat Type K “E” Array Data.

Figure C-12. Test Section Sidewall Heat Loss Data at -9.0 cm Elevation.

Figure C-13. Test Section Sidewall Heat Loss Data at +3.1 cm Elevation.

Figure C-14. Test Section Sidewall Heat Loss Data at +31.5 cm Elevation.

Figure C-15. Test Section Sidewall Heat Loss Data at +70.0 cm Elevation.

Figure C-16. Test Section Sidewall Heat Loss Data at the +151.3 cm Elevation.

Figure C-17. Test Section Sidewall Heat Loss Data at the +193.1 cm Elevation.

Figure C-18. Test Section Sidewall Heat Loss Data at the + 211.5 cm Elevation.

Figure C-19. Test Section Mainline Thermocouple Data.

Figure C-20. Test Section Plenum and Insertable Water Level Probe Thermocouple Data.

Figure C-21. Quench Tank Water Volume, Coil Inlet, and Coil Outlet Temperature Data.

Figure C-22. Miscellaneous Temperatures in Water Supply, Quench, and Off Gas Systems.

Figure C-23. Total Power Supply Power.

Figure C-24. Power Supply Voltage Data.

Figure C-25. Total Power Supply Current Data.

Figure C-26. Power Supply Current Transformer Data.

Figure C-27. Hall Effect Meter Data.

Figure C-28. Voltage across Igniter Shunt.

Figure C-29. Pressure Transducer Power Supply Voltages.

Figure C-30. Water Supply Tank Water Volume Data.

Figure C-31. Quench, Overflow, and Spray Tank Water Volume Data.

Figure C-32. Supply and Quench System Tank Head Data (Backup).

Figure C-33. Test Section Water Volume Data.

Figure C-34. Water Supply Tank Pressure.

Figure C-35. Test Section Pressure.

Figure C-36. Quench/Overflow Tank Plenum Absolute Pressure.

Figure C-37. Spray Tank Plenum Differential Pressure.

Figure C-38. Quench Tank Coil Water Flow Rate.

Figure C-39. Test Section Water Supply Flow Rate.

Figure C-40. Test Section Helium Cover Gas Flow Rates.

Figure C-41. Basemat Cooling Channel Flowrates.

Figure C-42. Basemat Coolant Channel Header Inlet and Outlet Temperatures.

Figure C-43. Basemat Coolant Channel C1 Heat Flux Data.

Figure C-44. Basemat Coolant Channel C1 Temperature Data.

Figure C-45. Basemat Coolant Channel C2 Heat Flux Data.

Figure C-46. Basemat Coolant Channel C2 Temperature Data.

Figure C-47. Basemat Coolant Channel C3 Heat Flux Data.

Figure C-48. Basemat Coolant Channel C3 Temperature Data.

Figure C-49. Basemat Coolant Channel C4 Heat Flux Data.

Figure C-50. Basemat Coolant Channel C4 Temperature Data.

Figure C-51. Basemat Coolant Channel C5 Heat Flux Data.

Figure C-52. Basemat Coolant Channel C5 Temperature Data.