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Quick Look Data Report for COMET Test U2

by M. T. Farmer, B. W. Spencer,
D. J. Kilsdonk, and R. W. Aeschlimann

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and R. W. Aeschlimann**

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Section 1

INTRODUCTION AND SUMMARY OF RESULTS

Investigations are underway at Forschungszentrum Karlsruhe (FZK) addressing methods to terminate and stabilize a core melt accident situation ex-vessel. In this approach, the molten core-concrete interaction (MCCI) begins erosion of the concrete, and after erosion proceeds to some modest depth, it exposes and unseals an array of tubes. The tubes are connected to a water reservoir pressurized by static water head. Upon unsealing, the tubes direct a flow of water into the bottom of the corium layer. The water is forced up through the melt, cooling the melt and causing it to solidify in a form that allows continued permeation and heat removal by the water. Thus, the accident progression can be halted, and the debris may be permanently cooled.

The key aspect of the passive ex-vessel core retention approach described above is the ability of water injected at the bottom of a corium melt layer to quench the melt forming a coolable debris bed in the process. This process has been tested using iron-alumina thermite as a corium simulant with promising results¹. As a part of a collaborative research agreement between FZK and the US DOE, two scoping tests are being conducted at Argonne National Laboratory to test the FZK core retention concept using real reactor materials. The second of these two tests, denoted COMET Test U2, was successfully conducted on December 17 1997. The specifications for this experiment are shown in Table 1-1.

The results of COMET Test U2 are summarized as follows. The initial average melt temperature at completion of the thermite burn and at the start of melt interaction with the borosilicate basemat was ~ 2450 K. The first 5 mm of the basemat was eroded in ~ 10 seconds. Water injection into the melt from the nozzles, embedded 15 mm beneath the basemat surface, was initiated 23 seconds after the start of the interaction. The melt temperature at the onset of injection was ~ 2220 K. The peak water flow rate of ~ 13.5 liters/minute was reached ~ 2 minutes after onset of injection. This flow rate corresponds to half the achievable value of 27 liters/minute based on unimpeded flow through all nine

nozzle orifices at the test driving pressure of 0.2 bar. Thermocouples located within the basemat indicate that basemat ablation was arrested (terminated) ~ 2.4 minutes following flooding initiation. Melt temperature measurements indicate that corium stabilization (i.e., reduction in debris temperature to below the concrete solidus of ~ 1400 K) occurred ~ 15 minutes after onset of injection. These same measurements indicate that the corium was completely quenched to water saturation temperature ~ 37 minutes following flooding initiation. Debris cooling rates realized during the quench process ranged from ~ 10 MW/m² at the start of interaction, down to ~ 1 MW/m² at the time the debris temperature was reduced to the corium solidus. These heat flux estimates are based on the test section planar area of 0.07 m² given the crucible inside diameter of 30 cm. The peak basemat erosion depth for the experiment corresponded to ~ 25 mm, which is 10 mm below the elevation of the nozzle openings. Posttest measurements indicate that all nine nozzles were open to water flow.

The objectives of this data report are to: i) summarize the experiment facility and operating procedures for COMET Test U2, and ii) present the test data.

Table 1-1. Summary of Test Specifications for COMET-U2.

Parameter	Value
Melt Composition	100% oxidized PWR containing 23 wt% borosilicate glass.
Test Section Internal Diameter	30 cm
Initial Melt Mass	150.0 kg
Corresponding Initial Melt Depth	40 cm
Initial Melt Temperature	2320 K
Basemat Nozzles	3 x 3 array
Concrete Thickness Above Nozzles	15 mm
Water Supply Pressure	0.2 bars

Section 2

EXPERIMENT DESCRIPTION

Figure 2-1 illustrates the basic elements of the test apparatus. The system consists of a test vessel wherein the test sequence occurs involving corium melting, MCCI, plug meltout, water injection, and melt quenching. Details of the test section design are shown in Figure 2-2. The test section is constructed from 45.7 cm OD standard weight carbon steel pipe. Top and bottom blind flanges are provided. The inside of the test section is protected over most of its height from the corium melt by a 6.4 cm thick cast MgO pipe. A thin liner of ZrO_2 insulation additionally separates the melt from the MgO. At the bottom of the test section is a 9.5 cm thick borosilicate glass concrete basemat; the concrete was supplied by FZK (composition provided later in this section). The nine water injection nozzles are cast into this concrete layer on a 9.5-cm square pitch (see Figure 2-3). The injection nozzles were also furnished by FZK in 80 mm nozzle length. There are additional penetrations at the bottom of the vessel for insertion of thermocouples to measure the corium and concrete temperature (discussed later in this section). The thermite ignitor wires pass through a Conax fitting near the top of the vessel. There is an additional 10.2 cm pipe penetration located near the top of the vessel for overpressure relief (see Figure 2-1). This line is fitted with a rupture disk such that the vessel will blow down to the cell atmosphere if the internal pressure exceeds 1.36 MPa. The top flange also contains penetrations for additional test section instrumentation including a video camera. A baffle plate assembly is suspended from the top head to protect the top plate penetrations and instrumentation from the effects of corium splatter.

Water is delivered to the test section from a supply tank (Figure 2-4) which is pressurized to a specified level to supply the target water head at the injection nozzles (0.2 bar). The water inlet line is instrumented to monitor water flow rate and transient pressure events. The line also has a check valve to prevent flow reversal, a standpipe to accommodate transient pressurization events, a drain line, and a remote isolation valve. The initial quench process is accompanied by steam formation in the test section. Steam and concrete

COMET-U2 TEST APPARATUS

DRAWING: COMET-U2 TEST
APPARATUS
DRAWING: C126
DRAWN BY: D. KILSONK 2-1-96
DATE: 11/24/97 COMET-U2
FILE: C12TAFCD116

Figure 2-1. COMET-U2 Test Apparatus.

Figure 2-2. Details of COMET-U2 Test Section.

Figure 2-3. COMET-U2 Basemat.

COMET-U2 WATER SUPPLY SYSTEM

Figure 2-4. COMET-U2 Water Supply System.

decomposition gases are vented through a 14.6 cm ID off gas line at the top of the test section to a spray tank. The off gas line is constructed from Schedule 80 carbon steel pipe throughout. The spray tank, shown in detail in Figure 2-5, is instrumented to measure the rate of energy transport from the debris bed. The tank is equipped with a water cooling coil to provide long term cooling. Noncondensable gasses pass from through the exhaust gas cleanup system which consists of a centrifugal separator, banks of metal mesh filters, and a gas flowmeter (Figure 2-6). Noncondensable gases exiting the off gas system pass into the containment cell where they are eventually vented through two sets of HEPA final filters to the atmosphere.

The apparatus is inerted by means of a cover gas system for introducing inert bleed gas (Helium) into the test vessel directly and via instrumentation ports. This system is shown in Figure 2-7. The flow rate of the inert gas is controlled by three flow controllers. The bleed gas exits through the steam off gas line.

Corium/Concrete

The pre- and post-reaction compositions for the COMET Test U2 thermite are shown in Table 2-1. The adiabatic reaction temperature for this thermite was estimated as 2950 K, while the actual reaction temperature (including non-idealities) was estimated as 2320 +/- 70 K. Developmental tests were conducted to verify the expected reaction temperature, gas release, and thermal stability of the thermite mixture. The post reaction composition consists of 89 wt % oxides and 11 wt % Cr metal; the Cr is a necessary byproduct of the thermite reaction. The oxide phase consists of 56 wt% UO_2 , 20 wt% ZrO_2 , and 23 wt% glass, which is in reasonable agreement with the FZK specification of 59 wt % UO_2 , 18 wt % ZrO_2 , and 23 wt % glass. The glass phase consists of 64.4 wt % SiO_2 , 21.1 wt % CaO , 3.5 wt % MgO , 4.9 wt % Al_2O_3 , and 6.1 wt % B_2O_3 . This composition is in reasonable agreement with the test specification of: 62.5 wt % SiO_2 , 20.5 wt % CaO (mocking up 14.5 wt % Na_2O and 6 wt % CaO), 3.5 wt % MgO , > 5 wt % Al_2O_3 , and > 6 wt % B_2O_3 .

The density of the U2 corium under molten conditions is calculated to be 5120 kg/m³ given the post-reaction composition shown in Table 2-1. Thus, the initial collapsed melt depth at the start of the melt/concrete interaction is calculated to be 41.4 cm given the melt mass of 150 kg and the test section ID of 30 cm.

Figure 2-5. COMET-U2 Spray Tank System.

Figure 2-6. COMET-U2 Off Gas System.

Figure 2-7. COMET-U2 Covergas System.

Table 2-1. Pre-and Post- Reaction Compositions for COMET-U2 Thermite.

Constituent	Reactant		Product	
	wt %	Mass (kg)	wt %	Mass (kg)
U ₃ O ₈	51.87	77.81	-	-
UO ₂	-	-	49.92	74.88
Zr	13.28	19.92	-	-
ZrO ₂	-	-	17.95	26.93
Si	6.26	9.39	-	-
SiO ₂	-	-	13.37	20.06
CaO	4.44	6.65	4.44	6.65
MgO	0.73	1.10	0.73	1.10
Al	0.59	0.88	-	-
Al ₂ O ₃	-	-	1.11	1.65
B ₂ O ₃	1.27	1.91	1.27	1.91
CrO ₃	21.56	32.34	-	-
Cr	-	-	11.21	16.82
Total	100.0	150.0	100.0	150.0

The composition of the borosilicate glass concrete basemat is shown in Table 2-2. This composition was specified by FZK. The borosilicate glass for the mix was also supplied by FZK.

Instrumentation/Data Acquisition

Instrumentation is provided to monitor key test processes and to facilitate test operations. The Data Acquisition System (DAS) channel assignments for COMET Test U2 are provided in Table 2-3.

Expendable thermocouples are placed in the corium and in the concrete basemat. The locations of these TC's are shown in Figure 2-8. Two 4-junction high temperature W5%Re/W 26%Re (Type C) thermocouple arrays are used to measure corium temperature at various elevations. These TC's are inserted through the vessel bottom flange in 9.5 mm OD tungsten thermowells to prolong measurement lifetime. Two 2-junction chromel-alumel (Type K) TC arrays are also cast in the basemat through bottom flange penetrations to measure the concrete thermal response. Note that junction KB-1 (see Figure 2-8) is cast "15" mm beneath the concrete surface. This elevation is flush with the top of the water injection nozzles in the basemat, and is used to determine the timing of nozzle opening during the test.

Thermocouples are also provided to measure the temperature of water entering the nozzles, the temperature of water exiting the vessel, the gas space temperature at the top of the vessel, water temperature in the spray tank, and gas temperature in the steam and final off gas lines. As shown in Figures 2-1 and 2-2, thermocouples are also provided to monitor heatup of the vessel outer wall.

System pressures are monitored using strain-gauge pressure transducers; the transducer locations are shown in Figures 2-1, 2-4, and 2-5. Fast response, high range, piezo-electric transducers are also provided at the entrance to the nozzles (PT-6) and in the test section upper plenum (PT-5) to detect any fuel-coolant interaction. These transducer locations are shown in Figure 2-1.

Table 2-2. COMET-U2 Basemat Composition.

<u>Constituent</u>	<u>wt %</u>
Glass ^{a, b}	75.8
Type 1 Cement	15.2
Water ^c	9.0

^a Supplied by FZK

^b Size distribution: 45% 0-1 mm, 17.55%
1-2 mm, 17.55% 2-4 mm, and 19.9%
4-8 mm.

^c Contains 3.33 wt % Liquefier

Table 2 - 3. DAS Channel Assignments for COMET Test U2

COMET PC CHANNEL	METRUM CHANNEL (BACKUP)	SENSOR DESCRIPTION	ID S/N	PARAMETER RANGE/LIMIT	mV RANGE/LIMIT	LOCATION
C00	—	DIODE SENSOR	TEMP. REF.	400° K		TC COMPENSATION FOR CHS. 00 - 47
C01	1 (X50 AMP.)	TC - TYPE K	KA-1	1645° K 1372° C	54.8 mV	BASEMAT ELEVATION: -0.5 cm
C02	—	“	KA-2	“	“	BASEMAT ELEVATION: -2.5 cm
C03	2 (X50 AMP.)	“	KB-1	“	“	BASEMAT ELEVATION: -1.5 cm
C04	—	“	KB-2	“	“	BASEMAT ELEVATION: -3.5 cm
C05	—	TC - TYPE C W5Re/W26Re	CA-1	2593° K 2320° C	0 - 37.1 mV	BASEMAT ELEVATION: +18.0 cm
C06	—	“	CA-2	“	“	BASEMAT ELEVATION: +12.0 cm
C07	3 (X50 AMP.)	“	CA-3	“	“	BASEMAT ELEVATION: +6.0 cm
C08	4 (X50 AMP.)	“	CA-4	“	“	BASEMAT ELEVATION: +0.0 cm
C09	5 (X50 AMP.)	“	CB-1	“	“	BASEMAT ELEVATION: +21.0 cm
C10	6 (X50 AMP.)	“	CB-2	“	“	BASEMAT ELEVATION: +15.0 cm
C11	—	“	CB-3	“	“	BASEMAT ELEVATION: +9.0 cm
C12	—	“	CB-4	“	“	BASEMAT ELEVATION: +3.0 cm
C13	—	“	TS-1	“	“	T.S. PLENUM, EL.: +145 cm 6.0" DOWN FROM LID

Table 2 - 3. DAS Channel Assignments for COMET Test U2 (cont'd)

COMET PC CHANNEL	METRUM CHANNEL (BACKUP)	SENSOR DESCRIPTION	ID S/N	PARAMETER RANGE/LIMIT	mV RANGE/LIMIT	LOCATION
C14	7 (X50 AMP.)	TC - TYPE C W5Re/W26Re	TS-2	2593° K 2320° C	0 - 37.1 mV	T.S. PLENUM, EL.: +122 cm 15.0" DOWN FROM LID
C15	-	TC - TYPE K	WM-1	1645° K 1372° C	54.8 mV	WATER INLET MANIFOLD INTERNAL
C16	-	"	ML-1	"	"	MAIN LINE INTERNAL VESSEL EXIT
C17	-	"	ML-2	"	"	MAINLINE EXTERNAL VESSEL EXIT
C18	-	"	SW-1	"	"	SIDEWALL VESSEL EXTERIOR ELEVATION: +15.0 cm
C19	-	"	SW-2	"	"	SIDEWALL VESSEL EXTERIOR ELEVATION: +80.0 cm
C20	-	"	SW-3	"	"	SIDEWALL VESSEL EXTERIOR ELEVATION: +140.0 cm
C21	-	"	BF-1	"	"	BOTTOM FLANGE VESSEL EXTERIOR
C22	-	"	ML-3	"	"	MAIN LINE EXTERNAL @ MIDPOINT
C23	-	"	ML-4	"	"	MAIN LINE EXTERNAL @ SPRAY ELBOW
C24	8	FM PADDLEWHEEL	FM-1 S/N XX	0 - 68 lpm 0 - 18 gpm	0 - 5 V	WATER SUPPLY FLOWRATE 1/2" LINE BEFORE MANIFOLD
C25						
C26	-	IGNITOR	IGN			TEST SECTION
C27	-	ANEMOMETER	FA-1	0 - 5000 sfpm	0 - 5 V	CELL 4 EXHAUST LINE
C28						

2-14

Table 2 - 3. DAS Channel Assignments for COMET Test U2 (cont'd).

QUENCH PC CHANNEL	METRUM CHANNEL (BACKUP)	SENSOR DESCRIPTION	ID S/N	PARAMETER RANGE/LIMIT	mV RANGE/LIMIT	LOCATION
00 (Q50)	—	DIODE SENSOR	TEMP. REF.	400° K		TC COMPENSATION FOR CHS. Q50 - Q99
01 (Q40)	9 (X50 AMP.)	TC TYPE K	ST-1 (M3B Q40)	1645° K 1372° C	54.8 mV	SPRAY TANK WATER TEMP., ELEVATION: 10 cm
02 (Q41)	—	“	ST-2 (M3B Q41)	“	“	SPRAY TANK WATER TEMP., ELEVATION: 38 cm
03 (Q51)	10 (X50 AMP.)	“	ST-3 (M3B Q51)	“	“	SPRAY TANK COIL INLET TEMP., INTERNAL
04 (Q52)	11 (X50 AMP.)	“	ST-4 (M3B Q52)	“	“	SPRAY TANK COIL OUTLET TEMP., INTERNAL
05 (Q54)	—	“	OG-1 (M3B Q54)	“	“	SPRAY TANK OFFGAS LINE INTERNAL
06 (Q55)	—	“	WS-1 (M3B Q55)	“	“	WATER SUPPLY TANK WATER TEMP.
07 (Q60)	—	PT - STRAIN	PT-1 (M3B Q60) S/N - D6	± 5 PSID	0 - 12.5 V	WATER SUPPLY TANK HEAD PRESSURE
08 (Q61)	—	“	PT-2 (M3B Q61) S/N - A2	0 - 30 PSIA	0 - 12.3 V	WATER SUPPLY TANK LINE PRESSURE
09 (Q62)	12 (divide by 2)	“	PT-3 (M3B Q62) S/N - A7	0 - 60 PSIA	0 - 12.3 V	WATER INLET MANIFOLD
10 (Q63)	13 (divide by 2)	“	PT-4 (M3B Q63) S/N - A11	0 - 60 PSIA	0 - 12.5 V	PRESSURE RELIEF LINE UPPER PLENUM PRESSURE
11 (Q70)	—	“	PT-11 (M3B Q70) S/N - D5	± 5 PSID	0 - 12.7 V	SPRAY TANK HEAD
12 (Q71)	—	“	PT-12 (M3B Q71) S/N - A1	0 - 30 PSIA	0 - 12.0 V	SPRAY TANK PRESSURE

Table 2 - 3. DAS Channel Assignments for COMET Test U2 (cont'd).

QUENCH PC CHANNEL	METRUM CHANNEL (BACKUP)	SENSOR DESCRIPTION	ID S/N	PARAMETER RANGE/LIMIT	mV RANGE/LIMIT	LOCATION
13 (Q72)	-	FLOAT	LS-1 (M3B Q72) S/N 2001	TANK RANGE 330 - 1930 l	1 - 5 V	WATER SUPPLY TANK LEVEL
14 (Q75)	-	FLOAT	LS-4 (M3B Q75) S/N 1002	TANK RANGE 110 - 1230 l	1 - 5 V	SPRAY TANK WATER LEVEL
15 (Q79)	-	FM PADDLEWHEEL	FM-4 (M3B Q79) S/N XX	0 - 50 gpm	0 - 5 V	SPRAY TANK FLOWRATE
16 (Q81)	14	FM MASS FLOW	FC1A (M3B Q81) S/N 629	0 - 6,000 lpm	0 - 5 V	FINAL OFFGAS FLOWRATE EXHAUST LINE #2 (3" LINE)
17 (Q83)	-	FM MASS FLOW	FC-2 (M3B Q83) S/N 176	0 - 200 lpm	0 - 5 V	COVER GAS FLOWRATE FLANGE PORTS
18 (Q84)	-	FM MASS FLOW	FC-3 (M3B Q84) S/N 175	0 - 200 lpm	0 - 5 V	COVER GAS FLOWRATE RELIEF LINE
19 (Q88)	-	FM MASS FLOW	FC-7 (M3B Q88) S/N 389	0 - 350 lpm	0 - 5 V	COVER GAS FLOWRATE TOP FLANGE
	15	PT - PIEZO EL. FAST RESPONSE	PT-5	0 - 10,000 psi		PRESSURE RELIEF LINE UPPER PLENUM PRESS.
	16	PT - PIEZO EL. FAST RESPONSE	PT-6	0 - 10,000 psi		WATER INLET MANIFOLD

COMET-U2 BASEMAT TC LAYOUT

Figure 2-8. Elevation View of COMET-U2 Basemat Instrumentation.

Water supply flow rate to the test section is monitored with a paddle wheel flowmeter. Water levels in the supply and spray tanks are monitored with magnetic level floats. Diverse measurement of the water head in these two tanks is also provided by differential pressure transducers. The final noncondensable gas flow rate is measured with a gas mass flowmeter. Installation locations of these devices are shown in Figures 2-4 through 2-6.

Aside from the above devices, there is various instrumentation associated with operation of the thermite ignitor coil (i.e., remote DC power supply and current meter). Four video cameras are employed for viewing the melt surface, test section water inlet manifold, test section overview, and cell overview.

Data from all instruments is recorded on two DAS systems. Each system consists of a Gateway-Pentium computer operating in conjunction with a HP75000 Series B Multiplexor and Digital Voltmeter. Each channel is power line integrated over one entire 60 Hz power line cycle to eliminate noise. The sampling rate for all channels is approximately once per second. Selected channels from these two systems are redundantly logged on a Metrum RSR 512 tape recorder with a 10 kHz bandwidth. The redundantly logged channels are shown in Table 2-3. The two high range piezo-electric transducers described above are also logged on this system to provide the required sampling rate to document a fuel-coolant interaction should one occur.

Section 3

EXPERIMENT RESULTS

This section summarizes principal test results from COMET Test U2. Plots of all test data from the two primary data acquisition systems are provided in Appendix A

The static water head driving pressure for Test U2 was specified as 0.2 bar (~ 20 kPad) at the nozzle head locations. Given the locations (i.e., elevations) of the test section and the supply tank in the cell, in addition to the initial water inventories in the supply and spray tanks (spray tank water inventory is relevant due to downcomer submergence in this tank; see Figure 2-5), the initial driving pressure in the supply tank was specified as 19 kPad. Given the cell atmospheric pressure of 99 kPa the day of the test, the supply tank pressure was thus specified as 118 +/-1 kPa, which was controlled by operator action at the control room console (i.e., by opening RV-4; see Figure 2-4). This resulted in a pressure of 131.5 +/-1 kPa in the water supply manifold. The manifold was located 86 cm below the tops of the water nozzles, which corresponds to a reduction of 8.5 kPa head pressure at the nozzle openings with respect to the manifold pressure. Given the spray tank plenum pressure of 97 kPa and the downcomer submergence depth of 60 cm, the nominal driving pressure of 20 +/-1 kPad was thus obtained at the nozzle openings given the supply tank pressure of 118 +/-1 kPa. Water transferred from the supply tank to the test section reduces the head at the inlet manifold for constant gas driving pressure in the supply tank. After boiloff, the transferred water also increases the back pressure in the spray tank once the steam is condensed. The water level sensitivity of the supply and spray tanks corresponds to 8.9 liters/cm (i.e., tank ID's are 106.7 cm). Roughly 160 liters of water is required to completely quench the 150 kg corium mass from the reaction temperature of ~ 2450 K down to water saturation temperature. The transfer of this amount of water from the supply tank to the spray tank reduces the driving pressure of 20 kPad at the nozzles by ~ 18 %. This reduction due to transfer processes was not compensated for during the experiment.

TEST RESULTS

The event sequence for Test U2 is shown in Table 3-1. Thermite ignition was announced and logged in the control room at 1.55 minutes relative to the start of the DAS. The determination

Table 3-1 COMET-U2 Event Sequence

<u>Time Relative to Start of DAS</u>	<u>Event</u>
1.55	Thermite burn initiated
1.95	Main steamline melt through at test section exit
2.10	Thermite burn completed; initial melt temperature ~ 2450K.
2.27	Basemat ablation depth reaches 5 mm (KA-1 basis)
2.48	Water influx to test section initiated (FM-1 basis); average melt temperature ~ 2220 K
2.62	Thermocouple KB-1 indicates that local concrete temperature 15 mm below concrete surface reaches 670 K (nozzle opening temperature)
2.74	Basemat ablation depth reaches 15 mm (KB-1 basis)
3.15	Basemat ablation depth reaches 25 mm (KA-2 basis)
4.64	Water inlet flowrate reaches 13.5 liters/minute
4.87	Basemat thermocouple KB-2 (35 mm depth) reaches a peak temperature of 494 K before beginning to decline, indicting termination of basemat ablation.

Table 3-1 COMET-U2 Event Sequence Cont'd

<u>Time Relative to Start of DAS</u>	<u>Event</u>
17.5	All melt temperature thermocouples record temperatures below corium solidus of ~1400 K.
18.5	Water level in test section reaches inlet to main steamline; water supply line isolation valve closed.
25.8 - 27.8	Water supply line re-opened, water level in test section increased to main steamline elevation.
35.3 - 36.2	Water supply line re-opened, water level in test section increased to main steamline elevation.
39.8	All melt temperature thermocouples record water saturation temperature.
40.0	Test terminated.

of burn initiation is based on video data from the test section internal video camera, as well as the failure time of the ignitor embedded within the bed of powders. (The ignitor shunt current data is provided in Appendix A). At 1.95 minutes, a small leak developed in the main steamline near the test section exit. (Posttest examination revealed that the opening was ~ 3 cm long by 1 cm wide. The failure point was located on the bottom of the pipe just outside the threaded fitting welded into the side of the test section at the steamline exit; see Figure 2-2. The opening was due to excessive heatup of this pipe section during the burn.) The thermite burn was completed at 2.1 minutes, which is based on data from thermocouple CA-4 located flush with the upper surface of the concrete basemat; see Figure 2-8. Data from this thermocouple is shown in Figure 3-1. The test section plenum pressure is shown in Figure 3-2. As is evident from the figure, test section pressurization was not a contributing factor to steamline failure; the absolute pressure inside the test section did not exceed 160 kPad up to the point at which the line failed. As shown in Figure 3-2, PT-4 failed (i.e., the transducer cabling was destroyed) at 1.97 minutes due to gaseous discharge from the test section.

Ablation of the borosilicate basemat reached a depth of 5 mm at 2.27 minutes. This observation is based on the response of thermocouple KA-1, located 5 mm beneath the initial concrete surface. The data from the two 2-junction Type K thermocouple arrays embedded in the basemat are provided in Figures 3-3 and 3-4, respectively. Data from these thermocouples are only plotted up to the point where the junctions failed to improve readability; the complete datasets are provided in Appendix A. The location of the basemat ablation front was determined on the basis of a 1523 K reading by the thermocouples located in the basemat, which is the reported liquidus temperature for siliceous concrete². The liquidus temperature for the borosilicate concrete used in this test has not been experimentally determined. Water flow to the test section was initiated 22.8 seconds after melt contact with the basemat (i.e., at 2.48 minutes). Data from the test section water flowmeter is shown in Figure 3-5. Thermocouple KB-1, located at the same elevation as the top of the nozzles in the basemat (see Figure 2-8), recorded a local concrete temperature of 670 K (i.e., nozzle thermal failure temperature) at 2.62 minutes (see Figure 3-4). This same thermocouple detected arrival of the ablation front at the top of the nozzles at 2.74 minutes. At 3.15 minutes, basemat ablation had proceeded to a depth of 25 mm (KA-2 basis; see Figure 3-3). At 4.64 minutes, the water inlet flowrate plateaued at ~ 13.5 liters/minute. The occurrence of the plateau most likely indicates completion of the nozzle opening phase of the test. Shortly after the flowrate

Figure 3-1. Response of Melt Temperature Thermocouple CA-4 Over the First 5 Minutes of the Test.

Figure 3-2. Test Section Plenum Pressure (PT-4) Over the First 5 Minutes of the Test.

Figure 3-3. KA-Array Basemat Thermocouple Response Data.

Figure 3-4. KB-Array Basemat Thermocouple Response Data.

Figure 3-5. Water Inlet Flowrate to the Test Section (FM-1).

plateau (i.e., at 4.87 minutes), the basemat thermocouple located at the 35 mm location recorded a peak temperature of 494 K before beginning a continuous decline, signaling termination of basemat ablation (KB-2 basis; see Figure 3-4). Progression of the ablation front in relation to onset of water flow and termination of basemat ablation is shown graphically in Figure 3-6. Based on the data shown in this figure, the following two observations are made: i) the average basemat ablation rate prior to melt stabilization was ~ 22.7 mm/minute, and ii) melt stabilization was achieved within 1-2 cm of the nozzle locations.

Melt temperature data obtained from the two Type C thermocouple arrays cast into the basemat is shown in Figures 3-7 and 3-8. Based on the data from the thermocouples located above the concrete surface (i.e., $\geq +3$ cm elevations), the average thermite reaction temperature is calculated to be 2450 K, which is slightly above the expected reaction temperature of 2320 ± 70 K. The thermocouple flush with the concrete surface (i.e., junction CA-4 in Figure 3-7) registered a reduced initial temperature due to fin cooling along the length of the tungsten thermowell to the underlying cold concrete. Note that three of the eight high temperature junctions (i.e., junctions CA-1, CB-1, and CB-2) recorded high-temperature spikes (i.e., single-point measurements) ranging from 2840-2930 K near completion of the burn before returning to the nominal temperature of ~ 2450 K. These single-point readings are deemed to be spurious since an integrated (and physically implausible) melt cooling rate of ~ 60 MW would be required to justify the ~ 450 K/second cooling rate recorded by these thermocouples as they returned to the baseline reading of ~ 2450 K. Also note that thermocouple junction CB-3 failed at 17.5 minutes into the test sequence (see Figure 3-8). Thus, data from this thermocouple is only plotted up to the time at which the junction failed to improve readability; the complete dataset is provided in Appendix A.

From Figures 3-7 and 3-8, the average melt temperature at initiation of water flow to the test section (2.48 minutes; see Table 3-1) is estimated as 2220 K. By 17.5 minutes, all temperature readings were < 1400 K (assumed corium solidus), indicating that the corium had been stabilized. At 18.5 minutes, water flow to the test section was terminated by closing remote isolation valve RV-C-1 due to the fact that water level in the test section had reached the elevation of the main steamline inlet (see Figures 2-1 and 3-5). Over the time intervals 25.8-27.8 and 35.3-36.2 minutes, the isolation valve was reopened to replenish the water inventory in the test section as boiloff

Figure 3-6. Basemat Ablation Depth vs. Time in Relation to Other Key Test Occurrences.

Figure 3-7. CA-Array Melt Temperature Data.

Figure 3-8. CB-Array Melt Temperature Data

occurred. At 39.8 minutes, all melt thermocouples recorded the water saturation temperature of 373 K. On this basis, the test was terminated at 40.0 minutes. Thus, the total time required to quench the debris from the initial temperature of ~ 2220 K down to water saturation temperature was ~ 37.3 minutes. For the U2 corium composition (see Table 2-1), the estimated change in specific enthalpy upon cooling from the initial temperature to water saturation temperature is 1.53 MJ/kg (basis for specific enthalpy estimate provided later in this section). Thus, the average melt-water heat flux during the quenching transient is estimated to be 1.45 MW/m^2 given the enthalpy estimate, quench time, initial melt mass of 150 kg, and the test section planar area of 707 cm^2 .

A direct estimate of the time-dependent melt/water heat flux could not be made for this test due to melt-through of the main steamline. As a result of this occurrence, not all steam released from the melt/water interaction was condensed in the spray tank. The rate of steam deposition in the spray tank provides the primary data for estimating the melt/water heat flux in this facility. However, since external heating of the melt was not incorporated as a part of the test approach, a first-order estimate of the time-dependent melt/water heat flux can be obtained on the basis of the rate-of-change of the melt temperature during the experiment. This is accomplished by first averaging the melt temperature measurements to obtain an estimate of the average melt temperature as a function of time. Given this data, the gross melt cooling rate is estimated by the rate of change of the melt temperature in conjunction with the known melt mass and an estimate of the melt specific heat. Given the gross melt cooling rate, the net heat flux due to the melt/water interaction is then obtained after making corrections for the heat losses to underlying concrete and to the test section sidewalls. The various steps are described in greater detail below.

The first step in the heat flux evaluation is the estimate of the average melt temperature as a function of time. The estimate was obtained by arithmetically averaging all melt temperature measurements with the exception of junction CA-4 (see Figure 3-7). As discussed above, this junction was located flush with the initial concrete surface. As a result, the temperature measured during the first several minutes of the test was significantly below the actual temperature due to fin cooling along the length of the thermowell to the underlying cold concrete. The average melt temperature obtained through this approach is shown in Figure 3-9. Note that the highest junction (CB-1) was located at an elevation of +21.0 cm above the initial concrete surface, while the initial

Figure 3-9. Calculated Average Debris Temperature vs. Time.

collapsed melt depth was ~ 40 cm. As a result, there are no direct measurements of the melt temperature in the upper region of the melt. The debris in this upper region is assumed to follow the average cooling curve shown in Figure 3-9.

The second step in the cooling rate evaluation is the estimation of the melt specific heat. The specific enthalpy as a function of temperature has been estimated for the U2 corium given the composition shown in Table 2-1, as well as the solid/liquid phase specific heats and heat of fusion for the individual melt constituents. The U2 oxide phase solidus and liquidus temperatures are taken equal to 1400 and 2400 K, respectively. The solidus temperature is based on the results of differential thermal analysis (DTA) measurements by Roche² during the ACE program for corium containing a significant fraction of siliceous concrete. The liquidus temperature was measured for the U2 corium composition using an in-house DTA apparatus set up for melting point temperature measurements in the range 1750 -3000 K. Thus, the assumed solidus temperature could not be confirmed due to the fact that the melt temperature measurement technique (i.e., pyrometry) was not valid in the expected range where initial sample melting would occur. Chromium initially present in the melt (~ 11 wt %) is treated as a separate, homogeneously dispersed, metallic phase within the oxide with a melting point of 2130 K. The resultant specific enthalpy estimate for the U2 corium is shown in Figure 3-10. Given this result, the average melt specific heat upon cooling from 2220 K to the water saturation temperature is estimated as 870 J/kg•K. Note from Figure 3-10 that the effective specific heat actually varies as the different melting points are encountered during the cooling transient. This effect is not accounted for in the current analysis.

Given the melt temperature and specific heat estimates, the gross melt cooling rate is evaluated by differentiating the melt temperature with respect to time (central difference scheme utilized). The melt mass in the calculation is assumed to equal the initial mass of 150 kg. The result is shown in Figure 3-11. To evaluate the net cooling rate due to the melt/water interaction, the gross cooling rate needs to be corrected for heat losses to the test section sidewalls and underlying concrete. Heat loss to the sidewalls is calculated assuming that the dissipation rate is limited by one-dimensional radial heat conduction into the MgO sidewalls of the apparatus from the melt zone. The upper bound estimate of the sidewall loss is obtained assuming that the surface temperature history of the MgO is equal to the average melt temperature estimate shown in Figure

Figure 3-10. Estimated Temperature - Specific Enthalpy Relationship for U2 Corium.

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Figure 3-11. U2 Energy Balance

3-9 (i.e., any insulating effect of a crust present on the MgO surface is neglected). On this basis, the sidewall surface heat flux estimate is considered to be an upper bound. Given the surface temperature history, the heat flux into the MgO is calculated using a 1-D implicit, finite difference, transient heat conduction model which is capable of treating a variety of boundary conditions. Temperature dependent properties are employed for the MgO sidewall; the properties of the outer steel vessel are assumed to be constant (i.e., thermal conductivity = 40 W/m•K, density = 7870 kg/m³, and specific heat = 690 J/kg•K). The resultant sidewall heat flux estimate is shown in Figure 3-12, while calculated temperature profiles within the sidewall at various times are shown in Figure 3-13. The calculation indicates that at ~ 17 minutes into the test, the sidewalls actually become a source of heat in the energy balance as the debris is quenched.

Given the sidewall heat flux estimate the total energy deposition rate in the sidewalls is evaluated assuming a sidewall heat transfer area equivalent to the initial collapsed melt depth of 40 cm within the 30 cm ID test section (i.e., 0.38 m²). The sidewall cooling power which results from this calculation is shown in Figure 3-11. The net melt/water heat transfer rate is then determined by subtracting the sidewall cooling rate from the gross melt cooling rate; this result is also shown in Figure 3-11.

In theory, a complete evaluation of the melt/water heat transfer rate would also include a correction in the energy balance for heat transfer to underlying concrete. As discussed previously, basemat ablation was essentially terminated at 4.87 minutes in the test sequence (see Table 3-1). Thus, after this time, the net melt/water heat transfer rate shown in Figure 3-11 is deemed to be reliable. Prior to this time, ablation was proceeding at a relatively constant rate of ~ 22.7 mm/minute (see Figure 3-6). Assuming a concrete density of 2350 kg/m³ and a decomposition enthalpy³ of 1.65 MJ/kg, the downward erosion power during this time interval is evaluated as 104 kW. Examination of Figure 3-11 thus indicates that the peak and average melt/water heat transfer rates would be reduced by 14% and 20%, respectively, during the first 2.5 minutes of the interaction with heat transfer to underlying concrete included in the calculation.

Given the corrected cooling rate, the net melt/water heat flux evaluated on the basis of the test section planar area is shown in Figure 3-14. The initial peak heat flux corresponds to ~ 10.5

Figure 3-12. Calculated Heat Flux from Melt Into MgO Sidewalls for Test U2.

Figure 3-13. Calculated Test Section Sidewall Temperature Profiles at Various Times for Test U2.

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Figure 3-14. Melt/Water Heat Flux vs. Time for Test U2.

MW/m². The heat flux does not fall below 1 MW/m² until ~ 18 minutes, at which point the average debris temperature was < 600 K.

POSTTEST DISASSEMBLY

The number of water injection nozzles which were opened during the experiment was determined through posttest examinations. This was done by first closing all nine nozzle isolation valves above the water inlet manifold, and then draining the manifold. Each nozzle valve was then individually opened to determine if sustained water flow occurred through each nozzle, using the water inventory remaining inside the test section as the source for the testing. This procedure indicated that all nine nozzles were open to water flow following the experiment. An integrated flow test was also conducted in which all nine nozzle valves were opened and the total flow rate was measured by the stopwatch and weight method. Prior to conducting the test, the water height over the debris was increased until the water level was flush with the bottom of the main steamline exit from the test section (see Figure 3-1). The total flowrate was measured as 13.8 liters/minute using this technique. This flowrate is noted to be nearly identical to that encountered during the initial quench phase of the experiment (see Figure 3-5).

Posttest disassembly revealed a thin coating of corium (2-3 mm thickness) covering virtually all surfaces inside the main steamline through the 90 degree elbow above the spray tank (see Figure 2-1). This material was recovered and weighed; the mass amounted to 19.7 kg. The lid of the apparatus was removed. The inner sidewalls of the test section were also uniformly coated with a thin layer of solidified corium. The thickness of this material in the upper region of the test section was also in the range of 2-3 mm. The sidewall thickness (and mass) in the lower region could not be determined at the time this report was written since disassembly had not been completed. The depth of the solidified corium on top the concrete basemat was determined to be ~ 33 cm based on elevation measurements, which includes the ~ 3 cm concrete erosion which occurred during the test (see Figure 3-6). The posttest debris depth is thus less than the initial projected collapsed melt depth of 40 cm. Although a relatively small amount of material was transported out of the test section (see above), a significant amount of debris was found adhering to the MgO sidewalls immediately above the solidified melt upper surface. The presence of this material is most likely due to intense sparging of the melt from superheated steam during the initial phase(s) of the melt/water interaction. At the time this report was generated, the test section had

not been removed from the steel outer vessel, so a direct measurement of the corium mass adhering to the sidewalls could not be made.

REFERENCES

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2. M. F. Roche, L. Leibowitz, J. K. Fink, and L. Baker, Jr., "Solidus and Liquidus Temperatures of Core-Concrete Mixtures," NUREG/CR-6032, April, 1993.
3. D. H. Thompson, M. T. Farmer, J. J. Fink, D. R. Armstrong, and B. W. Spencer, "ACE Phase C Final Report: Volume I-MCCI Thermalhydraulic Results," ACE-TR-C42, September, 1997.

APPENDIX A

TEST DATA LOGGED ON PC DAS SYSTEMS

This appendix provides plots of all test data logged on the two PC DAS systems during the experiment. The DAS channel assignments are provided in Table 2-3. Each channel was logged at ~1 second intervals. The time coordinate $t = 0$ in these plots corresponds to the onset of data acquisition (see Table 3-1).

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TEMPERATURE COMPENSATION FOR INSTRUMENTS CHANNELS 1 to 47

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE KA-1

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE KA-2

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE KB-1

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE KB-2

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CA-1

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CA-2

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CA-3

BASEMAT THERMOCOUPLE CA-4

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CB-1

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CB-2

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CB-3

ANL COMET-U TEST #2 17-DECEMBER-97

BASEMAT THERMOCOUPLE CB-4

ANL COMET-U TEST #2 17-DECEMBER-97

T.S. PLENUM THERMOCOUPLE TS-1

ANL COMET-U TEST #2 17-DECEMBER-97

T.S. PLENUM THERMOCOUPLE TS-2

ANL COMET-U TEST #2 17-DECEMBER-97

WATER INLET MANIFOLD THERMOCOUPLE WM-1

ANL COMET-U TEST #2 17-DECEMBER-97

MAIN LINE THERMOCOUPLE ML-1

ANL COMET-U TEST #2 17-DECEMBER-97

TC LOCATION
external @ vessel exit

MAIN LINE THERMOCOUPLE ML-2

ANL COMET-U TEST #2 17-DECEMBER-97

SIDEWALL VESSEL THERMOCOUPLE SW-1

ANL COMET-U TEST #2 17-DECEMBER-97

SIDEWALL VESSEL THERMOCOUPLE SW-2

ANL COMET-U TEST #2 17-DECEMBER-97

SIDEWALL VESSEL THERMOCOUPLE SW-3

ANL COMET-U TEST #2 17-DECEMBER-97

BOTTOM FLANGE THERMOCOUPLE BF-1

ANL COMET-U TEST #2 17-DECEMBER-97

MAIN LINE THERMOCOUPLE ML-3

ANL COMET-U TEST #2 17-DECEMBER-97

MAIN LINE THERMOCOUPLE ML-4

ANL COMET-U TEST #2 17-DECEMBER-97

WATER SUPPLY FLOWRATE FM-1

ANL COMET-U TEST #2 17-DECEMBER-97

ANL COMET-U TEST #2 17-DECEMBER-97

CELL AIR FLOW MONITOR, FA-1

ANL COMET-U TEST #2 17-DECEMBER-97

TEMPERATURE COMPENSATION CHANNELS Q51 to Q99

ANL COMET-U TEST #2 17-DECEMBER-97

TC LOCATION
internal, 10cm. from bottom

SPRAY TANK THERMOCOUPLE ST-1

ANL COMET-U TEST #2 17-DECEMBER-97

TC LOCATION
internal, 38cm. from bottom

SPRAY TANK THERMOCOUPLE ST-2

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK THERMOCOUPLE ST-3

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK THERMOCOUPLE ST-4

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK OFFGAS LINE THERMOCOUPLE OG-1

ANL COMET-U TEST #2 17-DECEMBER-97

WATER SUPPLY TANK THERMOCOUPLE WS-1

ANL COMET-U TEST #2 17-DECEMBER-97

WATER SUPPLY TANK HEAD

ANL COMET-U TEST #2 17-DECEMBER-97

WATER SUPPLY TANK PRESSURE

ANL COMET-U TEST #2 17-DECEMBER-97

WATER INLET MANIFOLD PRESSURE

RELIEF LINE PRESSURE

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK HEAD

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK PRESSURE

ANL COMET-U TEST #2 17-DECEMBER-97

SUPPLY TANK WATER LEVEL

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK WATER LEVEL

ANL COMET-U TEST #2 17-DECEMBER-97

SPRAY TANK HEAT EXCHANGER COOLING WATER FLOWRATE

ANL COMET-U TEST #2 17-DECEMBER-97

FINAL OFFGAS FLOW RATE FC-1a

ANL COMET-U TEST #2 17-DECEMBER-97

COVER GAS FLOWRATE, FLANGE PORTS & RELIEF LINE

ANL COMET-U TEST #2 17-DECEMBER-97

COVERGAS FLOWRATE, RELIEF LINE

ANL COMET-U TEST #2 17-DECEMBER-97

COVER GAS FLOWRATE, TOP FLANGE