OECD MCCI Project
Small-Scale Water Ingression and Crust Strength Tests (SSWICS)
SSWICS-11 Test Data Report: Thermal Hydraulic Results
Rev. 3 - FINAL
June, 2010

by:

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1. Introduction

During the course of the first MCCI program (MCCI-1), seven small-scale water ingression tests were performed with 75 kg corium melts made up of UO_2 and varying amounts of either siliceous or limestone common sand concrete. The concrete contents varied from a low of 4 wt% to a high of 23 wt%. These tests demonstrated that melt cooling can be enhanced by water ingression made possible by thermal stress-induced cracking, and that the role of water ingression increases with decreasing concrete content. The dependence of the water ingression cooling rate on concrete content is strongest for melts containing less than 14% concrete. For melts with 14% or more concrete, little evidence of water ingression cooling was discernible. It was also found that melts with siliceous concrete cooled at about the same rate as melts with a similar amount of limestone common sand concrete.

One aim of the current MCCI program (MCCI-2) is to investigate the role of gas sparging on the corium cooling rate. The gases are a byproduct of the decomposition of concrete, which occurs when the material overheats. Gases generated near the corium/concrete interaction zone at the bottom of the melt are propelled up through the corium by buoyancy forces and the resultant gas flow has the potential to create melt porosity. This porosity is expected to supplement the fissures induced by thermal stress cracking. It is thought that these extra pathways could enhance the amount of water ingression cooling and quench the melt more rapidly than the case without sparging gases.

The first test of the MCCI-2 program was SSWICS-8, a melt quench experiment that duplicated the conditions of SSWICS-6 while adding gas sparging to simulate the flow of concrete decomposition gases. The melts for these tests were formulated to simulate a fully oxidized PWR corium melt containing 15 wt% siliceous concrete. They were both quenched at a system pressure of 1 bar. The new data was to be used to make a comparison between the cooling rates and crust morphologies of corium quenched with and without sparging gases. SSWICS-8 was an operational success in every respect except for the fact that the injected gas appeared to bypass the melt by escaping through the basemat/liner joint and/or flowing up around the melt between the melt/liner interface. Post test examinations of the ingot and a review of the data determined that SSWICS-8 was effectively a repeat of SSWICS-6, i.e., a melt quenched in the absence of sparging gases.

SSWICS-11, the subject of this report, is a repeat of SSWICS-8 with a modified sparging system designed with the goal of ensuring that the injected gas does not bypass the melt. The test was conducted on November 5, 2008. This report includes a description of the test apparatus, the instrumentation used, plots of the recorded data, and some rudimentary data reduction to obtain an estimate of the heat flux from the corium to the overlying water pool.

2. System Description

2.1 Test Apparatus

The SSWICS reaction vessel (RV) has been designed to hold up to 100 kg of melt at an initial temperature of 2500°C. The RV lower plenum consists of a 67.3 cm long, 45.7 cm

Fig. 1. Side view of SSWICS reaction vessel for dryout heat flux measurements.

outer diameter carbon steel pipe (Fig. 1). The pipe is insulated from the melt by a 6.4 cm thick layer of cast MgO. The selected pipe and insulation dimensions result in a melt diameter of 30.5 cm and a surface area of 730 cm². The melt depth at the maximum charge of 100 kg is about 20 cm.

The RV lower flange is insulated with a 6.4 cm thick slab of cast MgO that spans the entire inner diameter of the pipe. The MgO slab and sidewalls form the crucible containing the corium. This particular geometry was chosen to facilitate removal of the slab for the crust strength measurement tests. Corium has a tendency to bond with the MgO insulation and this design allows one to pry the slab away from the MgO walls without damaging the crust.

The RV upper plenum consists of a second section of pipe lined with stainless steel. The role of this liner is to protect the walls of the reaction vessel upper plenum from the heat of thermite ignition. Three 10 cm pipes welded near the top of the vessel provide 1) a vent line for the initial surge of hot noncondensable gases generated by the thermite reaction, 2) a pressure relief line with a rupture disk (7.7 bar at 100°C), and 3) an instrument flange for the absolute pressure transmitter that measures the reaction vessel pressure. Four 6 mm tubes serve as water inlets for melt quenching. A baffle is mounted below the upper flange and the water flow is directed towards the baffle to reduce the momentum of the fluid before it drops down onto the melt. The baffle is also intended to prevent water droplets from being carried up towards the condenser, which would adversely affect the heat flux measurement. A fourth 10 cm pipe welded to the top flange provides an outlet to carry steam from the quenching melt to four cooling coils. A control valve on the line allows pressure regulation for tests carried out at elevated pressure. The water-cooled coils are used to condense the steam flowing from the RV, and the condensate is collected within a 200 cm high, 20 cm diameter condensate tank (CT). Figure 2 is a schematic that provides an overview of the entire SSWICS melt-quench facility.

2.2 Instrumentation

Instrumentation was selected to provide the measurements necessary to determine the melt dryout heat flux. The critical measurement for these tests is the steaming rate in the RV, which is found indirectly by measuring the rate of condensate collection in the CT. A differential pressure sensor is used as the primary sensor for measuring the inventory of the condensate tank while a time domain reflectometer provides a supplementary level measurement.

The melt temperature is measured with a multi-junction probe made up of 4 C-type (W-5%Re/W-26%Re) thermocouples (Fig. 3). The probe is mounted on the bottom flange of the RV and protected from the melt by a tungsten thermowell. The thermowell has a 6 mm o.d. and 1 mm wall, and the top end is positioned 100 mm above the bottom of the melt. The thermocouples are located 90, 65, 40, and 15 mm above the bottom of the melt.

Six C-type thermocouples are used to measure temperatures at the corium/lining interface to show whether water seeps around the edges of the melt to provide unwanted lateral cooling. Two thermocouples are positioned 150 mm above the base of the melt, two at 100 mm, and two at 50 mm. Instruments are listed in Tables 2.1-2.3.

Fig. 3. Instrumentation positions in basemat and lower MgO liner.

#	Channel	Name	Type	Description	Serial #	Output	Range	Accuracy
0	HPS-0	T-CJ-HPS	AD592 IC	Cold junction compensation sensor.	-	1 $\bar{A}$ /K	0-70°C	$\pm 0.5^\circ\text{C}$
1	HPS-1	TM-H100- $\Phi 0$	TC type C	Melt temp. 100 mm above bottom of melt (in tungsten thermowell).	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
2	HPS-2	TM-H80- $\Phi 0$	TC type C	Melt temp. 80 mm above bottom of melt (in tungsten thermowell).	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
3	HPS-3	TM-H60- $\Phi 0$	TC type C	Melt temp. 60 mm above bottom of melt (in tungsten thermowell).	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
4	HPS-4	TM-H40- $\Phi 0$	TC type C	Melt temp. 40 mm above bottom of melt (in tungsten thermowell).	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
5	HPS-5	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
6	HPS-6	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
7	HPS-7	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
8	HPS-8	TIW-H50- $\Phi 0$	TC type C	Melt temp. at inner sidewall 50 mm above bottom of melt.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
9	HPS-9	TIW-H50- $\Phi 180$	TC type C	Melt temp. at inner sidewall 50 mm above bottom of melt.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
10	HPS-10	TIW-H100- $\Phi 90$	TC type C	Melt temp. at inner sidewall 100 mm above bottom of melt.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
11	HPS-11	TIW-H100- $\Phi 270$	TC type C	Melt temp. at inner sidewall 100 mm above bottom of melt.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
12	HPS-12	TIW-H150- $\Phi 0$	TC type C	Melt temp. at inner sidewall 150 mm above bottom of melt.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
13	HPS-13	TIW-H150- $\Phi 180$	TC type C	Melt temp. at inner sidewall 150 mm above bottom of melt.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
14	HPS-14	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
15	HPS-15	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
16	HPS-16	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
17	HPS-17	Reserve	TC type C	-	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
18	HPS-18	TG-RV	TC type C	Gas temp. in reaction vessel upper plenum.	-	0-37 mV	0-2320°C	$\pm 4.5^\circ\text{C}$ or 1%
19	HPS-19	Reserve	TC type K	-	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
20	HPS-20	Reserve	TC type K	-	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
21	HPS-21	Reserve	TC type K	-	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
22	HPS-22	TS-RV-tf	TC type K	Temperature of RV top flange.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
23	HPS-23	TS-RV-1000	TC type K	Outer wall temp. of RV 1000 mm above bottom of melt.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
24	HPS-24	TS-RV-mf	TC type K	Temperature of RV middle flange.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
25	HPS-25	TS-RV-100	TC type K	Outer wall temp. of RV 100 mm above bottom of melt.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
26	HPS-26	TS-RV-bf	TC type K	Temperature of RV bottom flange.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
27	HPS-27	TS-vent	TC type E	Outer wall temp. of vent line.	-	0-70 mV	0-900°C	$\pm 1.7^\circ\text{C}$ or 0.5%
28	HPS-28	TF-CT-102	TC type K	Fluid temp. in condensate tank at a water level of 102 mm.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
29	HPS-29	TF-CT-406	TC type K	Fluid temp. in condensate tank at a water level of 406 mm.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
30	HPS-30	TF-CT-711	TC type K	Fluid temp. in condensate tank at a water level of 711 mm.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
31	HPS-31	TF-CT-1016	TC type K	Fluid temp. in condensate tank at a water level of 1016 mm.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
32	HPS-32	TF-CT-1321	TC type K	Fluid temp. in condensate tank at a water level of 1321 mm.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
33	HPS-33	TF-CT-1626	TC type K	Fluid temp. in condensate tank at a water level of 1626 mm.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
34	HPS-34	TF-HX-in	TC type K	Fluid temp. at HX coolant inlet.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%
35	HPS-35	TF-HX-out	TC type K	Fluid temp. at HX coolant outlet.	-	0-50 mV	0-1250°C	$\pm 2.2^\circ\text{C}$ or 0.75%

Table 2.1 Instrumentation list (part 1 of 2).

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#	Channel	Name	Type	Description	Serial #	Output	Range	Accuracy
36	HPS-36	HF-vent	Thermopile	Heat Flux through connecting line to V-ST.	0632	0-5.50 mV	0-5 kW/m ²	±3%
37	HPS-37	I-ign	DC supply	Current supply for thermite ignitor.	-	0-100 mV	0-25 Amps	-
38	HPS-38	TF-quench	TC type K	Temperature of water injected into RV	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
39	HPS-39	Reserve	-	-	-	-	-	-
40	HPS-40	PA-RV	1810AZ	Absolute pressure in reaction vessel.	02351-00P1PM	1-6 V	0-14 bar gage	±0.14 bar
41	HPS-41	PD-CT	1801DZ	P transmitter to measure condensate inventory.	D-9	0-13 V	0-0.35 bar	±0.004 bar
42	HPS-42	L-TDR-CT	BM100A	Time domain reflectometer to measure CT level.	A02331879A	4 - 20 mA	0 - 2 m	±3 mm
43	HPS-43	VDC-P-supply	-	Voltage of the power supply for the pressure transmitters.	-	0 - 15 V	-	-
44	HPS-44	F-sparge	HFC-203	Flow rate of argon into injector for gas sparging	3621300001	0 - 5 V	0-50 sl/m Ar	±0.5 sl/m
45	HPS-45	Reserve	-	-	-	-	-	-
46	HPS-46	Reserve	-	-	-	-	-	-
47	HPS-47	Reserve	-	-	-	-	-	-
48	HPS-48	Reserve	-	-	-	-	-	-
49	HPS-49	Reserve	-	-	-	-	-	-
50	HPS-50	Reserve	-	-	-	-	-	-
51	HPS-51	Reserve	-	-	-	-	-	-
52	HPS-52	Reserve	-	-	-	-	-	-
53	HPS-53	Reserve	-	-	-	-	-	-
54	HPS-54	Reserve	-	-	-	-	-	-
55	HPS-55	Reserve	-	-	-	-	-	-
56	HPS-56	Reserve	-	-	-	-	-	-
57	HPS-57	Reserve	-	-	-	-	-	-
58	HPS-58	Reserve	-	-	-	-	-	-
59	HPS-59	Reserve	-	-	-	-	-	-
60	HPQ-50	T-CJ-HPQ	AD592 IC	Cold junction compensation sensor.	-	1 $\bar{\Delta}$ /K	0-70°C	±0.5°C
61	HPQ-51	TF-ST	TC type K	Fluid temp. in spray tank.	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
62	HPQ-52	TG-CL-out	TC type K	Gas temperature in condensate tank outlet line to spray tank.	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
63	HPQ-53	TG-ST-in	TC type K	Gas temp. in the spray tank line inlet.	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
64	HPQ-54	TG-ST-out	TC type K	Gas temp. in the spray tank line outlet.	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
65	HPQ-55	F-quench	Paddlewheel	Flow rate of water into reaction vessel (for quenching melt).	3144	0-5 V	0-50 gpm	±0.5 gpm
66	HPQ-56	F-HX	Paddlewheel	Flow rate of cold water to heat exchangers.	3143	0-5 V	0-50 gpm	±0.5 gpm

Table 2.2 Instrumentation list (part 2 of 2).

Table 2.3 Remotely operated valves.

LabVIEW Channel #	Valve Name	Type	Description	Actuator
1	V-CT	Ball valve	Valve on steam line between reaction vessel and quench tank.	Pneumatic
2	V-quench	Ball valve	Valve on quench water supply line into reaction vessel.	Solenoid
3	V-quench-i	Ball valve	Isolation valve on quench water supply line into reaction vessel.	Solenoid
4	V-quench-b	Ball valve	Valve on back-up quench water supply.	Solenoid
5	V-ST	Ball valve	Valve on vent line between reaction vessel and spray tank.	Pneumatic

3. Test Parameters and Course of Test

The specifications for this test are listed in Table 3.1 along with those of the previous ten tests for comparison. The measured masses of the constituents of the corium powder charge are listed in Table 3.2. The 68 kg charge was selected to produce an approximate melt depth of 15 cm. The test was conducted on November 5, 2008.

The facility was preheated to bring the structure temperatures up to about 100°C. During this period the water used for melt quenching was preheated to about 95°C. The preheating is used to reduce the amount of energy absorbed by heat sinks in the early stages of the test. This maximizes the amount of steam reaching the heat exchanger and reduces corrections to the measured corium heat flux. It takes roughly 2 hours for the RV structures to reach 100°C.

Argon was used as the sparging gas and the flow rate directed for the test is 11 slpm (standard liters/minute; corresponds to a superficial gas velocity of 2 cm/s at a temperature of 2000°C). The flow controller is located within the cell and cannot be adjusted from the control room. Therefore the gas flow was initiated at the same time as the RV structure preheat since the cell is inaccessible once the preheat phase has begun.

The igniter coil was energized to initiate thermite ignition, which was first detected by a sudden rise in the upper plenum gas temperature TG-RV. Thermocouples within the tungsten thermowell (TM-H15- ϕ 0 through TM-H90- ϕ 0) began rising about sixty seconds later. The melt thermocouples within the thermowell rose rapidly to peak temperatures of about 1850°C and then began to slowly fall. Figure A.1 shows the melt temperatures measured during the transient (all plots are attached as an appendix). All data has been plotted so that the x-axis origin corresponds with the initial rise in TG-RV.

The next phase of the experiment was the initial quench of the melt. Valve V-CT was opened 99 s after ignition so that steam would be able to travel to the heat exchangers. At the same time, valve V-ST was closed to isolate the vent line and spray tank from the system. Water injection was initiated at 150 s and the flow rate quickly rose to a peak of 10 liters/min.

System pressure rose immediately upon water injection and within 30 seconds it reached a peak of 3.2 bar, which is much higher than peaks reached during SSWICS-9 and SSWICS-8. This unusually high pressure slowed water injection flow so that it fell below the lower range limit for the flow meter, which caused the meter to indicate zero flow. The pressure spike also temporarily suppressed gas sparging flow.

System pressure fell back near one bar at about 500 s and remained there for the rest of the test. The test continued until all melt temperatures had reached the saturation temperature of 100°C, which occurred at an elapsed time of ~5500 s.

Table 3.1 Test specifications for completed SSWICS experiments.

Parameter	Test Number										
	1	2	3	4	5	6	7	8	9	10	11
Melt composition (wt% UO ₂ /ZrO ₂ /Cr/Concrete)	61/25/6/8	61/25/6/8	61/25/6/8	48/20/9/23	56/23/7/14	56/23/6/14	64/26/6/4	56/23/6/14	56/23/6/14	61/25/6/8	56/23/6/14
Concrete type	LCS	SIL	LCS	LCS	LCS	SIL	LCS	SIL	SIL	SIL	SIL
Melt mass (kg)	75	75	75	60	68	68	80	68	23	25	68
Melt depth (cm)	15	15	15	15	15	15	15	15	5	5	15
Initial Melt Temperature (°C)	~2300	~2100	~2100	~2100	~2100	~1950	~2100	~1900	-	-	~1850
System pressure (bar)	1	1	4	4	4	1	4	1	1	1	1
Water injection flowrate (lpm)	4	4	12	13	6	14	13	10	9	9	-
Water injected (liters)	33	39	34	40	61	47	40	41	20	29	>30
Test date (day/mo/year)	30/08/02	17/09/02	30/01/03	13/03/03	15/10/03	24/02/04	14/12/04	25/01/07	14/02/08	5/03/08	11/05/08

Tables 3.2 Corium powder charge and reaction product mass fractions.

Constituent	Mass (kg)
U ₃ O ₈	39.92
CrO ₃	8.40
CaO	1.50
Zr	11.68
Mg	0.04
Si	1.08
SiO ₂	5.32
Al	0.06
Total	68.0

Constituent	Wt %	
	Reactant	Product
U ₃ O ₈	58.70	-
UO ₂	-	56.32
Zr	17.16	-
ZrO ₂	-	23.13
Si	1.57	-
SiO ₂	7.84	11.17
Mg	0.07	-
MgO	-	0.12
Al	0.09	-
Al ₂ O ₃	-	0.64
CaO	2.21	2.21
CrO ₃	12.36	-
Cr	-	6.41

4. Sensor Malfunctions and Abnormalities

Post test examination of the test apparatus and a preliminary review of the data indicate the following:

- 1) The pressure spike suppressed the water injection flow rate below the sensor lower range limit and so injection rate was not properly measured. It is therefore not possible to calculate integrated flow to provide an indication of RV liquid inventory. Thus the usual plot of liquid inventory versus time contains only the condensate tank inventory (Fig. A.6). The plot shows that at least 30 liters of water were injected and post test examination confirms that the melt remained covered with water during the entire test (water remained in the RV after the test).
- 2) The pressure spike upset the regulation of gas sparging flow for several minutes. The flow dropped to zero, recovered within about two minutes, overshoot the set point, and then settled back at the set point after another two minutes.
- 3) Boiling occurred on the secondary side of the heat exchanger as the outlet temperature peaked at 124°C. It took more than 3 minutes for the temperature to fall back below 100°C. The flow rate through the heat exchanger was also disturbed during this period.

5. Data Reduction

Some simple calculations have been performed to provide a preliminary assessment of the test data. The first is a calculation of the coolant inventory in the RV as a function of time. The inventory is the difference between the total amount of liquid injected and the amount boiled off and collected in the CT:

$$M_{H_2O-RV} = \sum_{t=0}^{t=t_{end}} \rho \dot{V} \Delta t - \frac{\pi D^2}{4} \frac{\Delta P}{g} \quad (5.1)$$

where data from sensor F-quench is used for the volumetric flow rate $\dot{V}$ and the liquid density ρ is taken to be 998 kg/m³. The condensate inventory is calculated with readings from sensor PD-CT (ΔP) and the tank diameter D of 0.203 m. Figure A.6 shows CT inventory.

The corium heat flux was calculated using two different methods. The first considers the rate of condensate collection, which is a measure of the steam flow rate from the RV. Accurate determination of the heat flux at the corium surface must, however, account for various heat sinks. During the injection phase, energy is absorbed raising the coolant to the saturation temperature. Some of the vapor produced by the quenching melt condenses on the walls of the upper plenum to heat the RV structures to the saturation temperature. Later, heat losses from the upper plenum generate continued condensation. Accounting for these heat sinks, the rate of energy transfer through the corium surface is written as:

$$Q = M_{RV} c_p \frac{\partial T}{\partial t} + \dot{m} h_{fg} + [M_s c_M \frac{\partial T}{\partial t} + Q_{HL}] \Big|_{up} \quad (5.2)$$

where $\dot{m}$ is mass flow rate of condensate into the CT, M_s is the mass of the RV upper plenum structures, c_M is their heat capacity, and Q_{HL} represents total upper plenum heat losses. For this report, liquid subcooling has been neglected (an accurate assumption after the injection phase) along with heat losses and time variations in structure temperatures. The condensation rate is calculated from the time derivative of the differential pressure signal PD-CT. The heat transfer rate from the corium is then:

$$Q = \frac{1}{g} \frac{\pi}{4} D^2 \frac{\partial \Delta P}{\partial t} h_{fg} \quad (5.3)$$

where D is again the inner diameter of the CT and the heat of vaporization h_{fg} is 2256 kJ/kg°C (TG-RV registered 100°C through most of the transient). The heat flux is obtained by scaling Q with the initial surface area of the corium (0.071 m²). The derivative was calculated with pairs of averaged ΔP readings (an average of 5 measurements at 0.5 Hz) centered around a Δt of 60 s. The averaging and length of Δt were necessary to reduce oscillations in the calculated heat flux.

The second method of calculating corium heat flux uses an energy balance on the secondary side of the heat exchanger. The measured parameters are the coolant flow rate on the secondary side of the cooling coils and the inlet and outlet coolant temperatures. The cooling power of the heat exchanger is then:

$$Q_{HX} = \rho \dot{V}_{HX} c_p (T_{out} - T_{in}) \quad (5.4)$$

where readings from sensors TF-HX-in and TF-HX-out were used for temperatures T_{in} , and T_{out} , respectively. Data from the flow meter F-HX was used for $\dot{V}_{HX}$ while the density and heat capacity of water were taken to be 982 kg/m^3 and $4.18 \text{ kJ/kg}^\circ\text{C}$, respectively.

The cooling power of the heat exchanger is related to the steam flow rate out of the RV by the following:

$$Q_{HX} = \dot{m} [h_{fg} + c_p (T_{sat} - T_{con})] \quad (5.5)$$

where $\dot{m}$ is the mass flow rate of steam into the heat exchanger (identical to the flow rate of condensate into the CT, as defined in equation 5.2). From equation 5.5 it can be seen that if condensate leaves the heat exchanger at the saturation temperature, i.e., there is no subcooling, the cooling power of the heat exchanger is equal to the product of $\dot{m}$ and h_{fg} . In this case, according to equation 5.2, the cooling power of the heat exchanger equals the heat transfer rate from the melt. However, the condensate does not, in general, leave the heat exchanger at the saturation temperature. The result of this subcooling is an overestimation of the corium heat flux when using equation 5.5 and the assumption of $T_{sat} = T_{con}$ (as plotted in figure A.10).

The corium heat flux could be calculated more accurately with the heat exchanger energy balance through the addition of a condensate temperature measurement at the heat exchanger outlet. However, the calculation would still require the steam mass flow rate, which would be derived from the CT level measurements. Thus the heat exchanger energy balance, with the assumption of $T_{sat} = T_{con}$, is considered to be a rough check of the heat flux measurements derived directly from the CT level measurements using equation 5.3.

6. Post Test Examination

Post test disassembly revealed that the ingot did not bond to the liner as usual, but instead bonded strongly to the basemat. Since both liner and basemat are made of the same material, the cause of the bonding is likely to be the presence of the tungsten tubes (Fig. B.1).

The basemat/liner/ingot assembly is shown in Figs. B.2 and B3. The liner was lifted away to leave only the ingot and basemat (Fig. B.4). The smooth white-green surface around the outer circumference of the ingot is the remains of the zirconia felt that covers the inside surface of the liner. The felt is normally white. Much of the felt was scraped away to reveal the corium below (Figs. B.5 and B.6). Because the melt cooled so quickly, we had expected to find a rubble bed, but discovered instead a solid mass with very few cracks.

We attempted to separate the ingot from the basemat for sectioning. The top portion of the ingot cracked and separated during this operation. The portion that remained on the ingot is shown in Fig. B.7. The remainder of the corium was then removed for final disposal of the material. An intermediate stage is shown in Fig. B.8. Note the tip of the thermowell slightly off center.

The ingot exhibited an unusually porous structure and there appeared to be fewer cracks than in previous ingots. Ingot mass is $\sim 61.8 \text{ kg}$, which is calculated by subtracting the 6.2 kg of

corium attached to the liner walls above the ingot from the initial thermite mass of 68 kg. The porosity is estimated to be roughly 37%, which is calculated from the ingot mass, density of 6000 kg/m³, and an approximate average height of 23 cm (Figs. B.5-B.6).

Figure A.1 Temperatures in tungsten thermowell.
Figure A.2 Temperatures of selected steel structures.

Figure A.3 Total pressure in reaction vessel and position of valve V-quench.
Figure A.4 Condensate tank inventory as measured by ΔP and level sensors.

Figure A.5 Water injection into RV, HX secondary side flow rate, sparge rate.
Figure A.6 Condensate tank liquid inventory.

Figure A.7 Secondary side fluid temperatures at HX inlet and outlet.
Figure A.8 Miscellaneous gas and fluid temperatures.

Figure A.9 Fluid temperatures in the condensate tank.

Figure A.10 Heat flux at corium surface based on mass and energy balances.

Figure B.1 Basemat pretest.

Figure B.2 Basemat and liner with corium post test.

Figure B.3. Corium top view.

Figure B.4. Corium with liner removed.

Figure B.5. Corium front view.

Figure B.6. Corium back view.

Figure B.7. Corium removal, step 1.

Figure B.8. Corium removal, step 2.