**OECD MCCI Project
Small-Scale Water Ingression and Crust Strength Tests (SSWICS)
SSWICS-9 & 10 Design Report**

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1. Introduction

The Melt Attack and Coolability Experiments (MACE) program at Argonne National Laboratory addressed the issue of the ability of water to cool and thermally stabilize a molten core/concrete interaction (MCCI) when the reactants are flooded from above. These experiments provided unique, and for the most part repeatable, indications of heat transfer mechanisms that could provide long term debris cooling. However, the results did not demonstrate definitively that a melt would always be completely quenched. This was due to the fact that the crust anchored to the test section sidewalls in every test, which led to melt/crust separation, even at the largest test section lateral span of 1.20 m. This decoupling is not expected for a typical reactor cavity where the lateral span is much larger, ~5-6 m. Instead, the crust is expected to fracture under the weight of the coolant and the crust itself so that coolant contact with the melt is maintained. However, because of a lack of knowledge of the strength of the crust, one cannot be certain that it would actually fracture under such circumstances.

As part of the MCCI-1 and MCCI-2 programs, a series of separate-effects experiments has been conducted to measure corium quench rates and crust strength to investigate the various debris cooling mechanisms identified in the MACE program. Each quench test involved cooling a molten mass of UO_2 , ZrO_2 , and concrete constituents, which produced a corium ingot that was later load tested to determine its mechanical strength. The quench tests were designed to optimize measurements of heat flux from the corium surface and consequently the ingots that were formed were not of optimal thickness for the strength measurements.

For the quench tests, a minimum corium depth of 150 mm was deemed necessary to obtain a satisfactory heat flux measurement. However, 150 mm is too much for optimal load testing and so the ingots were sectioned (cut in the radial direction) to increase their aspect ratio (diameter/thickness) to make them more suitable for load testing. Unfortunately, the cutting process is laborious and involves much handling of the ingot and therefore decreases the certainty that the mechanical strength of the sections is close to that of the original ingot. This uncertainty would be eliminated if the ingots produced by the quench tests could be tested without having to cut them.

SSWICS-9 & 10, in contrast to previous tests, are designed to optimize the ingot for load testing. A reduced amount of corium will be used in the quench test to produce a thinner ingot. The ingot will then be load tested without sectioning. This report details the design modifications and test conditions that will be used to carry out the SSWICS-9 & 10 quench tests.

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 (18") outer diameter carbon steel pipe (Fig. 2.1). The pipe is insulated from the melt by a 6.4 cm thick layer of cast MgO , which is called the "liner". The selected pipe and insulation dimensions result in a melt diameter of about 30 cm and a surface area of 707 cm^2 . 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 (the “basemat”) that spans the entire inner diameter of the pipe. The basemat and liner form the crucible containing the corium. A 2-mm thick layer of ZrO₂ felt covers the basemat to absorb the initial thermal shock of thermite ignition. The felt, in turn, is covered with a 0.25 mm thick tungsten plate to ensure that the corium does not adhere to the basemat. This particular geometry was chosen to facilitate removal of the basemat for the crust strength measurement tests. Corium has a tendency to bond with the MgO insulation and this design allows one to detach the basemat from the liner without damaging the crust.

The RV upper plenum consists of a second section of pipe with a stainless steel protective liner. 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 (1/4”) 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. The water-cooled coils condense the steam, which is collected within a 200 cm high, 20 cm diameter condensate tank (CT). Figure 2.2 is a schematic that provides an overview of the entire SSWICS melt-quench facility.

Some differences between this configuration and that of earlier tests:

- Sand will not be added to the 5 mm gap to reduce lateral heat transfer. The melt is so thin and the surface to volume ratio so high that the presence of the sand would have little effect on the melt cooling rate
- The ZrO₂ felt over the basemat replaces the thicker cast ZrO₂ used in all previous tests. The basemat requires less thermal shock protection from the smaller melt
- The lower MgO liner has been reduced in height by a factor of two because of the lower melt inventory
- Some of the consumable instruments will be omitted (detailed in next section)

2.2 Instrumentation

The melt mass is only 1/3 that of previous quench tests since it has been optimized for subsequent measurements of mechanical strength. Because of the greatly reduced melt depth, some of the single-use instruments that have been installed for past tests will be omitted for these two tests. The TCs that would measure the interface temperature between the melt and MgO liner (TIW in previous tests) will be omitted because they would all be above the level of the melt and therefore irrelevant. The heat flux meters that would normally be installed in the liner and basemat will also be omitted. They are intended to estimate lateral heat losses and therefore reduce uncertainty in the measured dryout heat flux. However, the greatly reduced melt depth will make it very difficult to detect dryout heat flux and so the heat flux meters would be of limited utility.

Figure 2.1 Side view of reaction vessel.

Figure 2.2 SSWICS melt quench facility.

This test will employ all the instrumentation used in prior tests to measure the melt cooling rate. The critical measurement in this regard is the steaming rate in the RV, which is found indirectly by measuring the rate of condensate collection in the CT. The condensate inventory is measured with a differential pressure sensor, PD-CT, and a time domain reflectometer, L-TDR-CT.

The remaining instrumentation provides supplementary information to further characterize the test conditions. The nomenclature used to identify thermocouples is as follows: TM (temperature within the corium melt), TF (fluid temperature), TG (gas space temperature), TS (structure temperature), H# (height above the bottom of the melt, in mm, ϕ # (angle relative to direction north, in degrees). For example, TM-H0- ϕ 180 is located at the bottom of the melt and south of the RV axis.

Four single-junction, tantalum-sheathed TCs will be used to measure melt temperature. This was accomplished in previous tests with a multi-junction TC protected by a thermowell, but it will be omitted here to avoid creating a hole in the ingot that could compromise the strength measurement. The TCs will be positioned as shown in Fig. 2.3 with the tips above the surface of the melt and in contact with the bottom of the melt. The melt is considered quenched when all four TCs reach the saturation temperature, and this is the basis for terminating the test. If all four thermocouples fail, which is not improbable because of the lack of thermowell protection, a test will continue to run for an elapsed time of at least 1/3 that of the previous SSWICS test of the same melt composition (see Section 4. Test Parameters). Tables 2.1 and 2.2 list the sensors and major valves, respectively.

Figure 2.3 Reaction vessel thermocouple locations.

#	Channel	Name	Type	Description	Serial #	Output	Range	Accuracy
0	HPS-0	T-CJ-HPS	AD592 IC	Cold junction compensation sensor.	-	1□A/K	0-70°C	±0.5°C
1	HPS-1	TM-H0-Φ0	TC type C	Melt temperature at bottom of melt	-	0-37 mV	0-2320°C	±4.5°C or 1%
2	HPS-2	TM-H90-Φ0	TC type C	Melt temperature at bottom of melt	-	0-37 mV	0-2320°C	±4.5°C or 1%
3	HPS-3	TM-H180-Φ0	TC type C	Melt temperature at bottom of melt	-	0-37 mV	0-2320°C	±4.5°C or 1%
4	HPS-4	TM-H270-Φ0	TC type C	Melt temperature at bottom of melt	-	0-37 mV	0-2320°C	±4.5°C or 1%
5	HPS-5	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
6	HPS-6	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
7	HPS-7	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
8	HPS-8	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
9	HPS-9	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
10	HPS-10	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
11	HPS-11	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
12	HPS-12	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
13	HPS-13	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
14	HPS-14	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
15	HPS-15	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
16	HPS-16	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
17	HPS-17	Reserve	TC type C	-	-	0-37 mV	0-2320°C	±4.5°C or 1%
18	HPS-18	TG-RV	TC type C	Gas temp. in reaction vessel upper plenum.	-	0-37 mV	0-2320°C	±4.5°C or 1%
19	HPS-19	Reserve	TC type K	-	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
20	HPS-20	Reserve	TC type K	-	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
21	HPS-21	Reserve	TC type K	-	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
22	HPS-22	TS-RV-tf	TC type K	Temperature of RV top flange.	-	0-50 mV	0-1250°C	±2.2°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	±2.2°C or 0.75%
24	HPS-24	TS-RV-mf	TC type K	Temperature of RV middle flange.	-	0-50 mV	0-1250°C	±2.2°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	±2.2°C or 0.75%
26	HPS-26	TS-RV-bf	TC type K	Temperature of RV bottom flange.	-	0-50 mV	0-1250°C	±2.2°C or 0.75%
27	HPS-27	TS-vent	TC type E	Outer wall temp. of vent line.	-	0-70 mV	0-900°C	±1.7°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	±2.2°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	±2.2°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	±2.2°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	±2.2°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	±2.2°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	±2.2°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	±2.2°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	±2.2°C or 0.75%
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%

Table 2.1 Instrumentation list (part 1 of 2).

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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	Reserve	-	-	-	-	-	-
45	HPS-45	Reserve	-	-	-	-	-	-
46	HPS-46	Reserve	-	-	-	-	-	-
47	HPS-47	Reserve	-	-	-	-	-	-
48	HPS-48	Reserve	-	-		0-40 mV	0-3 MW/m ²	±5%
49	HPS-49	Reserve	-	-		0-40 mV	0-3 MW/m ²	±5%
50	HPS-50	Reserve	-	-		0-40 mV	0-3 MW/m ²	±5%
51	HPS-51	Reserve	-	-		0-40 mV	0-3 MW/m ²	±5%
52	HPS-52	Reserve	-	-		0-40 mV	0-3 MW/m ²	±5%
53	HPS-53	Reserve	-	-		0-40 mV	0-3 MW/m ²	±5%
54	HPS-54	Reserve	-	-		0-50 mV	0-1250°C	±2.2°C or 0.75%
55	HPS-55	Reserve	-	-		0-50 mV	0-1250°C	±2.2°C or 0.75%
56	HPS-56	Reserve	-	-		0-50 mV	0-1250°C	±2.2°C or 0.75%
57	HPS-57	Reserve	-	-		0-50 mV	0-1250°C	±2.2°C or 0.75%
58	HPS-58	Reserve	-	-		0-50 mV	0-1250°C	±2.2°C or 0.75%
59	HPS-59	Reserve	-	-		0-50 mV	0-1250°C	±2.2°C or 0.75%
60	HPQ-50	T-CJ-HPQ	AD592 IC	Cold junction compensation sensor.	-	1□A/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
Panel	V-HX	Ball valve	Valve on cooling-water line to heat exchangers.	Solenoid
Panel	V-C-CT	Ball valve	Control valve on steam line between reaction vessel and quench tank.	Electric

3. Data acquisition and control systems

All data acquisition and process control tasks are managed by a PC executing LabVIEW 6.i under Windows XP. Sensor output terminals are connected to model HP E1345A 16-channel multiplexers and the signals are digitized by an HP E1326B 5 ½ digit multimeter located within the test cell (Fig. 10). Signal noise is reduced by integration over a single power line cycle (16.7 ms). The digitized sensor readings are routed from the test cell to the PC in the control room via two HP-IB extenders. The extenders allow the ASCII data from the HP to be sent through the cell wall over a BNC cable. The extender within the control room then communicates with a GPIB card within the PC. This configuration also permits remote control of the multimeter through LabVIEW. The power line cycle integration results in a minimum (theoretical) time of 0.75 s to scan the channel list (16.7 ms * 45 channels). In practice, however, the acquisition of a single scan is at a frequency of approximately 0.5 Hz.

Valves are controlled with the PC using a relay card housed within an SCXI chassis (National Instruments). These electromechanical relays are capable of switching up to 8 A at 125 VAC or 5 A at 30 VDC. They are operated via a switch controller in the SCXI chassis, which communicates with the PC through a general-purpose data acquisition card. As shown in Fig. 3.1, the relays in the control room operate devices within the test cell indirectly, through a second relay. This is intended to provide an additional level of electrical isolation between the NI switching hardware and high voltage sources within

Figure 3.1. Data acquisition and control systems.

the cell. As an added safety measure, all wiring is routed through a control panel that can be switched from automatic (PC) control to manual control in the event of computer failure.

4. Test Parameters

The corium composition for SSWICS-9 will be identical to that of SSWICS-6. The composition of SSWICS-10 will duplicate that of SSWICS-2. Both melts will be quenched at atmospheric pressure. Corium compositions for all previously completed tests are shown in Table 4.1. The proposed test procedure, which is similar to that of SSWICS-6, is summarized as follows:

- 1) Preheat RV structures and water inventory to ~100°C.
- 2) Arm thermite ignition system.
- 3) Ignite thermite to begin test.
- 4) Confirm that melt reaches target temperature of ~2000°C (usually within one minute of the first sign of ignition).
- 5) Commence water injection at a rate of ~15 liters/min until 15 liters of water have been injected into the RV.
- 6) No other operator actions until corium is quenched, which is expected to take place in less than two hours.
- 7) The melt is considered quenched, and the test complete, when readings from all four thermocouples at the corium/basemat interface reach the saturation temperature of 100°C.

Table 4.1 Test specifications for completed SSWICS experiments.

Parameter	Test Number							
	1	2	3	4	5	6	7	8
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
Concrete type	LCS	SIL	LCS	LCS	LCS	SIL	LCS	SIL
Melt mass (kg)	75	75	75	60	68	68	80	68
Melt depth (cm)	15	15	15	15	15	15	15	15
Initial Melt Temperature (°C)	~2300	~2100	~2100	~2100	~2100	~1950	~2100	~1900
System pressure (bar)	1	1	4	4	4	1	4	1
Water injection flowrate (lpm)	4	4	12	13	6	14	13	10
Water injected (liters)	33	39	34	40	61	47	40	41
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