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Experiment Operations Plan for the TH-2 Experiment in the NRU Reactor

Prepared by G. E. Russcher, C. L. Wilson, L. J. Parchen, M. D. Freshley

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

A series of thermal-hydraulic and cladding materials deformation experiments were conducted using light-water reactor fuel bundles as part of the Pacific Northwest Laboratory Loss-of-Coolant Accident (LOCA) Simulation Program. This report is the formal operations plan for TH-2--the second experiment in the series of thermal-hydraulic tests conducted in the National Research Universal (NRU) reactor, Chalk River, Ontario, Canada. The major objective of TH-2 was to develop the experiment reflood control parameters and the procedures to be used in subsequent experiments in this program. In this experiment, the data acquisition and control system was used to control the fuel cladding temperature during a simulated LOCA by using variable reflood coolant flow.

SUMMARY

The Loss-of-Coolant Accident (LOCA) Simulation Program was conducted by Pacific Northwest Laboratory (PNL) to evaluate the thermal-hydraulic and mechanical deformation behavior of full-length light-water reactor (LWR) fuel bundles under LOCA conditions. The test conditions were designed to simulate the heatup, reflood, and quench phases of a large-break LOCA; and the experiments were performed in the National Research Universal (NRU) reactor using nuclear fission to simulate the low-level decay power typical of these conditions.

The formal experiment operations plan for the second thermal-hydraulic experiment (TH-2) is presented in this document. The objective of the TH-2 experiment was to characterize reflooding thermal-hydraulic conditions, cooling system parameters, and the operating sequence necessary to produce test rod peak cladding temperatures from 1033 to 1089K (1400 to 1500°F) for at least 150 s. The peak cladding temperatures were much lower than those achieved in the first thermal-hydraulic experiment (TH-1), but the test rods were at the peak temperature for a longer period of time.

The TH-2 experiment evaluated the capability of the data acquisition and control system (DACS) and the loop control system (LCS) to control the variable reflood flow rate, thus producing an elevated peak cladding temperature for an extended time. The TH-2 fuel rods were filled with helium at 0.101 MPa (14.7 psia), which is low enough that many LOCA transients could be simulated without test assembly deformation or fuel rod rupture. The TH-2 test assembly and the experiment operations were both quite similar to those for the previous thermal-hydraulic experiment (TH-1); consequently, only design differences between TH-1 and TH-2 are described in this report.

An approved draft copy of the experiment operations plan for TH-2 was sent to Chalk River Nuclear Laboratories (CRNL), Chalk River, Ontario, in October 1981 just prior to the TH-2 experiment. This report represents the formal documentation of the experiment operations plan for TH-2.

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TABLES

INTRODUCTION

The Loss-of-Coolant Accident (LOCA) Simulation Program was conducted in the National Research Universal (NRU) reactor at Chalk River Nuclear Laboratories (CRNL),[a] Chalk River, Ontario, Canada, by Pacific Northwest Laboratory (PNL).[b] The program was sponsored by the U.S. Nuclear Regulatory Commission (NRC) to evaluate the thermal-hydraulic and mechanical deformation behavior of full-length, 3% enriched light-water reactor (LWR) fuel rod bundles during the heatup, reflood, and quench phases of a simulated LOCA. Low-level nuclear fission heat was used to simulate the decay heat in the fuel that is typical of a LOCA.(1)

Previous experiments in this program have emphasized higher temperature LOCA fuel failure. The first thermal-hydraulic experiment (TH-1) evaluated the resultant peak fuel cladding temperatures due to various reflood delay times and various constant reflood flow rates. Peak temperatures were as high as 1366K (2000°F) but only for brief periods. The second thermal-hydraulic experiment (TH-2) was limited to much lower temperatures for longer periods of time at the peak temperature. It was less hazardous than any of the preceding experiments. The objective of TH-2 was to characterize the reflooding thermal-hydraulic conditions necessary to produce test fuel rod cladding peak temperatures from 1033 to 1089K (1400 to 1500°F) for at least 150 s. A secondary objective was to develop experiment protection controls that would trip the NRU reactor and establish emergency reflood coolant flow if a) the peak fuel cladding temperature exceeded a trip set point or b) the cladding heatup rate was not maintained within a range of set points during the heatup time.

The TH-2 test series was primarily a calibration experiment to develop the reflood control parameters and procedures to be used in the subsequent materials test (MT-3). The TH-2 experiment evaluated the capability of the data acquisition and control system (DACS) and the loop control system (LCS) to control the variable reflood flow rate, thus producing an elevated peak cladding temperature for an extended time. TH-2 fuel rods were filled with helium to 0.101 MPa (14.7 psia), which was low enough that many LOCA transients could be simulated without causing test assembly deformation or fuel rod rupture.

The remainder of this report consists of:

- a summary of the design differences between TH-2 and TH-1

(a) Operated by Atomic Energy of Canada Ltd. (AECL).
(b) Operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

- a safety hazards statement
- the operating procedure for TH-2
- a sample Test Parameter Log (Appendix A) and an Experiment Conditions log (Appendix B).

DESIGN DIFFERENCES

The TH-2 design was quite similar to the first thermal-hydraulic experiment (TH-1), and various components were used in other experiments (MT-1 and MT-2). Consequently, only design differences between TH-1 and TH-2 are described here; detailed descriptions can be extracted from References 2 and 3.

TH-2 TEST ASSEMBLY

The TH-2 shroud and guard rods had been previously used in MT-1 and MT-2; see Reference 3 for details of the shroud and guard rod design and instrumentation. Twelve new test rods were used for the TH-2 experiment. The instrumentation that monitored the hanger tube, the shroud, and the guard rod bundle is summarized in Table 1. None of the instrument leads were routed to high-pressure connectors; all were connected to feed-through junctions at the reactor head closure.

A test rod bundle with new fuel rods and new instrumentation formed the cruciform fuel region of the test assembly. The 12 fuel rods were pressurized to 0.101 MPa (14.7 psia) with helium. These rods were instrumented as before except for pressure switches, pressure transducers, and test fuel rod 4D (which replaced the liquid level detector used in MT-1 and MT-2). Rod 4D had one thermocouple (TC) mounted in the fission gas plenum. The test rod instrumentation is also summarized in Table 1, where the DACS terminal number, its name, and its sensor location in the test train are given. Some instrumentation that was mounted on the shroud or the guard rods had failed during MT-1 and MT-2 (Table 1).

NRU FACILITIES

The NRU facilities and the LCS were basically unchanged from previous LOCA experiments.[2,3] The same reactor fuel loading surrounding the test position was used to provide the desired power distribution.[4]

In the past, control of the reflood flow rate was either programmed into the LCS or manually selected by the LCS operator during transient operation. The low reflood rate was selected from three options. During the TH-2 transient testing, low reflood flow was selected by the DACS from eight preset LCS rates that ranged from 0.013 to 0.152 m/s (0.5 to 6.0 in./s). Ideally, the DACS automatically selected the LCS reflood rate based on a control feedback algorithm to maintain the peak cladding temperature of the 12 test rods between 1033 and 1089K (1400 and 1500°F). The control feedback parameters were developed during the transient tests, which were run using two methods of reflood system control: preprogrammed or preprogrammed and automatic. The DACS

TABLE 1. Instrumentation Summary

No.	DACS Name	Location in.	Location Component	No.	DACS Name	Location in.	Location Component
1	Undefined		[b]	37	TC-9-1F-S-C	48.32	TA
2	TC-1-6A-IN	-0.95	TA[a]	38	Undefined		[b]
3	TC-1-1F-IN	-0.95	TA	39	TC-10-6A-S-C	55.28	TA
4	TC-2-6F-S-C	8.03	Failed	40	TC-10-6F-S-C	55.28	TA
5	TC-2-1A-S-C	8.03	TA	41	TC-10-1F-S-C	55.28	TA
6	Undefined		[b]	42	TC-10-1A-S-C	55.28	Failed
7	TC-3-5B-OR-1	13.28	TA	43	TC-11-6C-OR-4	60.53	TA
8	TC-3-5E-OR-2	13.28	TA	44	TC-11-4F-OR-1	60.53	TA
9	TC-3-2E-OR-3	13.28	TA	45	TC-11-1D-OR-2	60.53	TA
10	TC-3-2B-OR-4	13.28	TA	46	TC-11-3A-OR-3	60.53	TA
11	TC-3-6A-S-C	13.28	TA	47	TC-11-6F-S-C	60.53	TA
12	TC-3-1F-S-C	13.28	TA	48	TC-11-1A-S-C	60.53	TA
13	TC-4-6F-S-C	18.53	TA	49	Undefined		[b]
14	TC-4-1A-S-C	18.53	TA	50	TC-12-5B-SP-3	68.32	TA
15	TC-5-6A-S-C	27.32	TA	51	TC-12-5E-SP-4	68.32	TA
16	TC-5-1F-S-C	27.32	TA	52	TC-12-2E-SP-1	68.32	TA
17	Undefined		[b]	53	TC-12-2B-SP-2	68.32	TA
18	TC-6-6A-S-C	34.28	Failed	54	Undefined		[b]
19	TC-6-6F-S-C	34.28	TA	55	TC-13-3B-IR-2	76.28	TA
20	TC-6-1F-S-C	34.28	TA	56	TC-13-6C-IR-2	76.28	TA[d]
21	TC-6-1A-S-C	34.28	Failed	57	TC-13-4F-IR-4	76.28	TA[d]
22	TC-7-6C-OR-4	39.53	TA	58	TC-13-1D-IR-2	76.28	TA[d]
23	TC-7-4F-OR-1	39.53	Failed	59	TC-13-3A-IR-4	76.28	TA[d]
24	TC-7-1D-OR-2	39.53	TA	60	TC-13-6A-S-C	76.28	TA
25	TC-7-3A-OR-3	39.53	TA	61	TC-13-6F-S-C	76.28	TA
26	TC-8-5B-OR-1	42.24	Failed	62	TC-13-1F-S-C	76.28	Failed
27	TC-8-5E-OR-2	42.24	TA	63	TC-13-1A-S-C	76.28	TA
28	TC-8-2E-OR-3	42.24	TA	64	Undefined		[b]
29	TC-8-2B-OR-4	42.24	TA	65	TC-14-5B-SP-3	89.32	TA
30	TC-8-6F-S-C	42.24	Failed	66	TC-14-5E-SP-4	89.32	TA
31	TC-8-1A-S-C	42.24	TA	67	TC-14-2E-SP-1	89.32	TA
32	TC-9-5B-OR-1	48.32	TA	68	TC-14-2B-SP-2	89.32	TA
33	TC-9-5E-OR-2	48.32	TA	69	Undefined		[b]
34	TC-9-2E-OR-3	48.32	TA	70	TC-15-3B-IR-4	97.28	TA
35	TC-9-2B-OR-4	48.32	TA	71	TC-15-6C-IR-4	97.28	TA[e]
36	TC-9-6A-S-C	48.32	TA	72	TC-15-4F-IR-2	97.28	TA[e]

TABLE 1. (contd)

No.	DACS Name	Location in.	Location Component	No.	DACS Name	Location in.	Location Component
73	TC-15-1D-IR-4	97.28	TA(e)	109	TC-17-2B-IR-4	118.28	TA(f)
74	TC-15-3A-IR-2	97.28	TA(e)	110	TC-17-6A-S-C	118.28	TA
75	TC-15-6A-S-C	97.28	TA	111	TC-17-6F-S-C	118.28	TA
76	TC-15-6F-S-C	97.28	TA	112	TC-17-1F-S-C	118.28	TA
77	TC-15-1F-S-C	97.28	Failed	113	TC-17-1A-S-C	118.28	TA
78	TC-15-1A-S-C	97.28	TA	114	Undefined		(b)
79	Undefined		(b)	115	TC-18-4B-OR-3	139.28	TA
80	TC-16-5B-SP-3	110.32	TA	116	TC-18-5C-OR-3	139.28	TA
81	TC-16-5E-SP-4	110.32	Failed	117	TC-17-5D-OR-3	118.28	TA(c)
82	TC-16-2E-SP-1	110.32	TA	118	TC-18-4E-OR-4	139.28	TA
83	TC-16-2B-SP-2	110.32	TA	119	TC-18-3E-OR-4	139.28	TA
84	TC-16-6A-C-3	110.32	TA	120	TC-17-2D-OR-1	118.28	TA(c)
85	TC-16-6F-C-4	110.32	TA	121	TC-18-2C-OR-1	139.28	TA
86	TC-16-1F-C-1	110.32	TA	122	TC-18-5C-IR-4	139.28	TA
87	TC-16-1A-C-2	110.32	TA	123	TC-17-5D-IR-4	119.29	TA(c)
88	TC-17-4C-IR-3	118.28	TA	124	TC-18-4E-IR-1	139.28	TA
89	Undefined		(b)	125	TC-18-3E-IR-1	139.28	TA
90	TC-17-3D-IR-5	118.28	TA	126	TC-17-2D-IR-2	118.28	TA
91	TC-15-3C-IR-2	97.28	TA	127	TC-18-2C-IR-2	139.28	TA
92	TC-17-4C-IR-C	118.28	TA	128	TC-18-6A-S-C	139.28	TA
93	TC-17-3D-IR-C	118.28	TA	129	TC-18-6F-S-C	139.28	TA
94	TC-15-3C-IR-C	97.28	TA	130	TC-18-1F-S-C	139.28	Failed
95	TC-17-4C-IR-1	118.28	TA	131	TC-18-1A-S-C	139.29	TA
96	TC-17-3D-IR-3	118.28	TA	132	TC-20-OT-1	167.70	TA
97	TC-15-3C-IR-7	97.28	TA	133	TC-20-OT-3	167.70	TA
98	TC-15-5B-IR-3	97.28	TA(e)	134	TC-20-OT-2	167.70	TA
99	TC-17-5E-IR-4	118.28	TA(f)	135	TC-21-HT-1	187.23	TA
100	TC-15-2E-IR-1	97.28	TA(c)(e)	136	TC-19-4D-IR-C	157.0	TA
101	TC-17-2B-IR-2	118.28	TA(f)	137	TC-15-3C-IR-1	97.28	TA(c)
102	TC-15-5B-IR-C	97.28	TA(c)	138	TC-17-3D-IR-4	118.28	TA
103	TC-17-5E-IR-C	118.28	TA	139	Undefined		(b)
104	TC-15-2E-IR-C	97.28	TA(c)	140	Undefined		(b)
105	TC-17-2B-IR-C	118.28	TA	141	Undefined		(b)
106	TC-15-5B-IR-1	97.28	TA(c)(e)	142	SPND-3-6F-S-3	13.28	TA
107	TC-17-5E-IR-2	118.28	TA(f)	143	SPND-3-1A-S-1	13.28	TA
108	TC-15-2E-IR-3	97.28	TA(c)(e)	144	Undefined		(b)

TABLE 1. (contd)

No.	DACS Name	Location in.	Location Component	No.	DACS Name	Location in.	Location Component
145	SPND-6-6A-S-2	34.28	TA	181	Undefined		
146	SPND-6-1F-S-4	34.28	Failed	182	Undefined		
147	Undefined		(b)	183	Undefined		
148	SPND-10-6A-S-2	55.28	TA	184	Undefined		
149	SPND-10-6F-S-3	55.28	TA	185	Undefined		
150	SPND-10-1F-S-4	55.28	TA	186	Undefined		
151	SPND-10-1A-S-1	55.28	TA	187	Undefined		
152	SPND-12-IF-C	68.32	Failed	188	Undefined		
153	Undefined		(b)	189	Undefined		
154	SPND-13-6A-S-2	76.28	Failed	190	Undefined		
155	SPND-13-6F-S-3	76.28	TA	191	TC-90-HO-1	336.0	H/L-24[h]
156	SPND-13-1F-S-4	76.28	TA	192	TC-90-HD-2	336.0	H/L-24
157	SPND-13-1A-S-1	76.28	Failed	193	TC-90-HD-3	336.0	H/L-24
158	Undefined		(b)	194	TC-90-HD-4	336.0	H/L-24
159	SPND-15-6A-S-2	97.28	TA	195	Undefined		
160	SPN0-15-6F-S-3	97.28	TA	196	Undefined		
161	SPND-15-1F-S-4	97.28	TA	197	Undefined		
162	SPND-15-1A-S-1	97.28	Failed	198	Undefined		
163	SPND-16-1F-C	110.32	Failed	199	Undefined		
164	Undefined		(b)	200	Undefined		
165	SPND-17-6A-S-2	118.28	Failed	201	SRCS-FR-LO-W	-337.0	FE-4[i]
166	SPND-17-6F-S-3	118.28	TA	202	SRCS-FR-HI-GH	-333.0	FE-3
167	SPND-17-1F-S-4	118.28	Failed	203	STBY-FL-OW	382.0	FE-9
168	SPND-17-1A-S-1	118.28	TA	204	U2LP-PR-ES-S-1	447.0	PDT-90
169	Undefined		(b)	205	U2LP-TA-OS-DR-1	+447.0	PDT-90
170	SPND-18-6F-S-3	139.28	TA			-1176.0	
171	SPND-18-1A-S-1	139.29	TA	206	SRCS-S-TC-IN-1	-180.0	TE-2
172	Undefined		(b)	207	SRCS-S-TC-OT-1	+363.0	TE-3
				208	SRCS-S-PS-IN-1	-82.0	PT-5
173	Undefined			209	SRCS-S-PS-OT-1	+369.0	PT-6
174	Undefined			210	SRCS-S-FR-1	+950.0	FY-6
175	Undefined			211	SRCS-S-FR-IN-1	-432.0	FV-1
176	Undefined			212	SRCS-S-FR-OT-1		FI-2[j]
177	Undefined			213	SRCS-TC-RF-LP-1	-450.0	TE-17
178	Undefined			214	SRCS-TC-RF-TA-1	-225.0	TE-18
179	Undefined			215	U2LP-FL-OW-1	-1560.0	FT-4D
180	Undefined			216	SRCS-FR-LO-B	-409.0	FE-4B

TABLE 1. (contd)

No.	DACS Name	Location in.	Location Component	No.	DACS Name	Location in.	Location Component
217	SRCS-S-PS-OT-2	+950.0	PT-4	301	PSD-10-S-1		DACS
218	Undefined			302	PSD-11-OR-1		DACS
219	ACUM-WT	-238.0	WIS[k]	303	PSD-11-S-2		DACS
220	Undefined			304	PSD-12-SP-1		DACS
221	U2LP-TC-IN-1	-1176.0	TE-78	3D5	PSD-13-IR-1		
222	U2LP-TC-OT-1	+447.0	TE-79	306	PSD-13-S-2		DACS
223	Undefined			307	PSD-14-SP-1		DACS
224	Undefined			308	PSD-15-IR-1		DACS
225	SRCS-FR-HI-B	-413.0	FE-3B	309	PSD-15-S-2		DACS
257	SRCS-DE-LT-A	(l)	LCS[m]	310	PSD-16-SP-1		DACS
258	SRCS-RF-TR-IP	Low RF	LCS(n)	311	PSD-16-C-2		DACS
				312	PSD-17-IR-1		DACS
289	PSD-1-IN-1		DACS[e][g]	313	PSD-17-IR-2		DACS
290	PSD-2-S-1		DACS	314	PSD-17-IR-3		DACS
291	PSD-3-OR-1		DACS	315	PSD-17-IR-4		DASC
292	PSD-3-S-2		DACS	316	PSD-17-S-5		DASC
293	PSD-4-S-1		DACS	317	PSD-18-OR-1		DACS
294	PSD-5-S-1		DACS	318	PSD-18-IR-2		DACS
295	PSD-6-S-1		DACS	319	PSD-18-S-3		DACS
296	PSD-7-OR-1		DACS	320	PSD-20-OT-1		DACS
297	PSD-8-OR-1		DACS	321	PSD-17-SD-6		DACS
298	PSK-8-S-2		DACS	322	PSD-19-IR-C		DACS
299	PSD-9-OR-1		DACS	323	PSD-19-IR-2		DACS
3C0	PSD-9-S-2		DACS	324	Undefined		
				325	Undefined		

(a) Test assembly (TA), elevation (in.) relative to the bottom of the fuel column.
(b) Sensor removed.
(c) Sensor relocated.
(d) Level 13 safety trip circuit thermocouples.
(e) Level 15 safety trip circuit thermocouples.
(f) Level 17 safety trip circuit thermocouples.
(g) DACS average pseudo sensor (calculated signal).
(h) NRU head mounted at location L-24.
(i) Sensor element is located in the U-2 loop or steam/reflood loop relative to the test fuel column bottom and measured along the hydraulic channel. See AECL Flowsheet, E-4531-F-1, Rev. 9, January 28, 1981.
(j) Bypass steam loop; location irrelevant.
(k) Hydraulic head located below the fuel column bottom.
(l) Transient signal.
(m) Loop control system signal for forced transient operation.
(n) Low reflood water inventory signal; also trips the NRU reactor.

provided a reactor trip and maximum reflooding signal to the LCS for test assembly protection. Protective trip logic limited the test fuel environment in several ways: maximum allowable cladding temperature, maximum and minimum allowable heatup rates, and time limitations for both cladding temperatures and fast-fill reflooding to preselected levels. The protective trip signal always responded the same: 1) the reactor was conditionally tripped and 2) emergency reflood flow was initiated.

Safety trip circuitry and trip set point criteria (as compared with protective trip logic) always remained the same.(3) In addition, the normal procedure to be used in reactor shutdown between powered operations was a conditional reactor trip to minimize the time between powered operations.

EXPERIMENT OPERATIONS

The TH-2 experiment consisted of 14 transient tests. As indicated previously, these tests were designed to develop a calibrated control system that would produce high fuel cladding temperatures for 150 to 200 s. Successive operating conditions chosen for these tests were highly dependent on preceding test results. Consequently, the test description provided in Table 2 presents the ranges of key parameters for the transient tests.

Initial TH-2 transient tests checked out the DACS/LCS control logic and qualified the protective trip set points, overshoot, and trip circuitry. Protective trip set points were set by the experimenters throughout the tests and were always more conservative than the safety trip set points. Protective trip logic included limits on the reflood fast-fill level, reflood delay time, transient heatup rate, and peak fuel cladding temperature. The protective trip logic was based on sensor sampling as frequently as five times per second. Protective trips were designed to insure fuel integrity; safety trips were designed to protect the pressure tube and reflood loop piping and to preclude the release of excessive radioactivity. The safety trip logic and circuitry were the same as designed for previous experiments.(3) Safety trip set points are summarized in Tables 3 and 4. The two trip circuits (protective and safety) and their operation were completely independent.

TABLE 2. Experiment Operating Conditions

Parameter	Preconditioning	Reflood Calibration	Pretransient	Characterizing Transients
Reactor power, MW	130	0	7.5	7.5
Coolant	U-2 water	U-1 steam/ reflood water	U-1 steam	U-1 steam/ reflood water
Coolant flow, kg/s (lbm/h)	0 to 16.3 (0 to 129,400)	0.378 (3000)	0.378 (3000)	0.378 (3000)
Reflood delay, s	NA[a]	0 to 40	NA	0 to 40
Reflood rate, m/s (in./s)	NA	0.007 to 0.254 (0.3 to 10.0)	NA	0.013 to 0.152 (0.5 to 6.0)
Fast fill level, m (in.)	NA	0.610 to 1.524 (24 to 60)	NA	0.914 to 1.219 (36 to 48)
Peak cladding temperature, K (°F)	700 (800)	444 (340)	727 (850)	1033 to 1089 (1400 to 1500)
Reactor trip	Safety	Safety	Protective and safety	Protective and safety

(a) Not applicable.

TABLE 3. Pretransient and Transient Safety Trip Set Points

Parameter	Location	Use	Operating Limits	Trip Set Point
Hanger tube temperature - high	LCS[a]	Pretransient and transient	691K (785°F)	839K (1050°F)
Outlet pipe temperature - high	LCS	Pretransient and transient	672K (750°F)	700K (800°F)
Fuel cladding temperature - high[b]				
Level 13 305 PSD-13-IR-1	DACS[c]	Pretransient and transient	1305K (1890°F)	1361K (1990°F)
Level 15 308 PSO-15-IR-1	DACS		1305K (1890°F)	1361K (1990°F)
Level 17 315 PSD-17-IR-4	DACS		1278K (1840°F)	1333K (1940°F)
Standby reflood flow - low	LCS	Transient	1.27 cm/s (0.5 in./s)	0.76 cm/s (0.3 in./s)[d]
Accumulator inventory - low	LCS	Transient	22.7 kg (50 lbm)	11.3 kg (25 lbm)

(a) LCS = loop control system.
(b) Standard trip set point criterion; see Table 4 for nonfunctional TC criteria.
(c) DACS = data acquisition and control system.
(d) 0.51 cm/s (0.20 in./s) to be used during reflood loop calibration.

TABLE 4. Standard and Defaulted Safety Trip Set Point Criteria for Operating and Nonoperating Fuel Cladding Thermocouples

Summary of TC Operating Conditions	Criteria and Safety Margins (SM)	Sensors at Level 17	Sensors at Level 15	Sensors at Level 13
		DACS Thermocouple Numbers		
		315,PSD-17-IR-4[a] (99,101,107,109)	308,PSD-15-IR-1 (71,72,73,74, 98,100,106,108)	305,PSD-13-IR-1 (56,57,58,59)
		Trip Set Point Temperatures, K (°F)		
$2 \le$ Number of operating TCs on each of Levels 13, 15, 17	Standard SM = 56K (100°F)	1333 (1940)	1361 (1990)	1361 (1900)
$2 \le$ Number of operating TCs on each of Levels 15 and 17	Standard SM = 56K (100°F)	1333 (1940)	1361 (1990)	
$2 \le$ Number of operating TCs on each of Levels 15 and 17 or Levels 13 and 17	Alternate SM = 84K (150°F)	1305 (1890)	1333 (1940)	1333 (1940)
$2 \le$ Number of operating TCs on only Level 15, 17, or 13	Fallback SM = 111K (200°F)	1305 (1890)	1305 (1890)	1305 (1890)

(a) These pseudo sensor data (PSD) are the calculated time-average of the following DACS sensor-numbered data: 99, 101, 107, 109.

SAFETY HAZARDS REVIEW

The TH-2 experiment was as benign as the first thermal-hydraulic experiment and was less hazardous than either of the two previous materials tests (MT-1 and MT-2). In TH-1, test fuel rod cladding temperatures were as high as 1366K (2000°F); no unstable cooling or Zircaloy reactions were experienced. TH-2 operation was to be limited to <1117K (1550°F) under all conditions. Protective trip circuitry, as well as the designed experiment operations, provided that limitation. TH-2 contained 12 test fuel rods (compared with 11 in TH-1) surrounded by 20 guard rods. Consequently, TH-2 could have provided up to 3.2% more fission products than TH-1, but the safety margins used to predict fission product availability and releasability for TH-1 were at least 100%. The possible decrease in the margin was insignificant. Another conservative feature of the TH-2 test assembly was the fact that all fuel rods were pressurized to only 0.101 MPa (14.7 psia). The materials tests each contained 11 fuel rods pressurized to 3.21 MPa (465 psia) that were designed to rupture; however, no significant fission product release was detected from any of them.

Other safety analysis reports[5,6] were also valid for the TH-2 experiment because its operating conditions were well within the envelope of cases analyzed and reported there.

TH-2 OPERATING PROCEDURE

This section describes the operating procedures that were followed for the TH-2 experiment. Reflood calibration and transient operating conditions are summarized in Table 5 and described below. Experiment conditions logs for the initial adiabatic transient, the first characterizing transient using LCS control, and the first characterizing transient using DACS control are presented in Tables 6, 7, and 8, respectively.

TABLE 5. TH-2 Operating Conditions

Parameter	Reflood Calibration	Adiabatic Transients	Characterizing Transients
Reactor power, %	0	6 to 8	6 to 8
Coolant	U-1 steam/reflood water	U-1 steam/ reflood water	U-1 steam/ reflood water
Coolant flow[(a)] initial condition, kg/s (lbm/h)	0.378 (3000)	0.378 (3000)	0.378 (3000)
Reflood delay, s	0 to 40	NA[(b)]	0 to 40
Reflood rates, m/s (in./s)	0.0254 and 0.051 (1.0 and 2.0)	NA	0.008 to 0.038 (0.35 to 1.50)
Fast fill level, m (in.)	NA	NA	0.9 to 1.2 (36 to 48)
Peak cladding temperature, K (°F)	444 (340)	1033 to 1089 (1400 to 1500)	1033 to 1089 (1400 to 1500)
Reactor trip	Safety	Protective and safety	Protective and safety

(a) Transient initiated by termination of steam flow.
(b) Not applicable.

TABLE 6. Experiment Conditions Log for the Adiabatic Transient

A. Protective trip temperatures for Levels 13, 15, and 17 977K (1300°F)

B.

TH Run Number	Delay Time, s	Reflood Rate in./s	Reflood Rate Duration, s
TH-2.01	Not applicable	0.0	~30 s

C. Maximum allowed time (____ s) for reflood water to quench sensor__ at Level ___ Not applicable

D. DACS control No

E. Time-temperature for test control (if needed)
Not applicable

F. Control functions coefficients (if needed) Not applicable

G. Temperature increase across test assembly for pretransient ____________

Test Director ____________

TABLE 7. Experiment Conditions Log for the First Characterizing Transient Using LCS

A. Protective trip temperatures for Levels 13, 15, and 17 1103K (1525°F)

B.

TH Run Number	Delay Time, s	Reflood Rate in./s	Reflood Rate Duration, s
TH-2.02	10	2.0	63
		1.6	23
		1.3	11
		1.1	23
		0.9	19
		0.8	200

C. Maximum allowed time (__ s) for reflood water to quench sensor ____ at Level _____ Not applicable

D. DACS control No

E. Time-temperature for test control (if needed)

Time	Upper Limit, K(°F)
0	769 (925)
10	853 (1075)
20	922 (1200)
30	1011 (1360)
40	1089 (1500)
42	1103 (1525)
∞	1103 (1525)

F. Control functions coefficients (if needed) Not applicable

G. Temperature increase across test assembly for pretransient ____________

Test Director ____________________

TABLE 8. Experiment Conditions Log for the First Characterizing Transient Using DACS

A. Protective trip temperatures for Levels 13, 15, and 17 1103K (1525°F)

B.

TH Run Number	Delay Time, s	Reflood Rate in./s	Reflood Rate Duration, s
TH-2.03	10	2.0	63
		1.6	12

C. Maximum allowed time (22 s) for reflood water to quench sensor__ at Level _____

D. DACS control Yes; DACS control 85 s after start of transient

E. Time-temperature for test control (if needed)

Time	Upper Limit, K (°F)
1	732 (857)
32	983 (1309)
42	1016 (1368)
58	1058 (1445)
87	1078 (1480)
∞	1078 (1480)

DACS took over control 85 s after start of transient at a reflood rate of 1.6 in./s. The minimum time under DACS control at this rate was 10 s.

F. Control functions coefficients (if needed) 1.0 ΔT, 1.0 T', 1.0 T"

G. Temperature increase across test assembly for pretransient __________

Test Director ____________________

TEST CONFIGURATION

1. TH-2 assembly installed in L-24 NRU reactor position.

2. Reflood loop connected to the L-24 NRU reactor position.

3. U-1 steam supply connected to the reflood loop.

4. NRU reactor fuel and absorber assemblies loaded as required.

LOOP SYSTEM PREPARATIONS

1. Start up the U-1 loop.

2. Insure that U-2 makeup tanks (which supply water to the U-1 loop) are full.

3. Preheat the steam/reflood loop to 408K (275°F).

4. Fill reflood accumulators at 311 ±6K (~100 ±10°F). Check water temperature in the three accumulators.

5. Verify that the nitrogen supply for accumulator pressurization is adequate.

6. Calibrate loop instruments as shown in Table 9.

7. Implement the safety trip set points as shown in Tables 10 and 11 for the pretransient and transient phases of the experiment. The trip pseudo sensors used on the DACS to represent the cladding high-temperature trip circuits and sensors are detailed on Table 12.

NRU REACTOR PREPARATIONS (CRNL)

1. Confirm that two linear rate and two log rate neutron flux detectors (ion chambers) are set and being recorded for the experimenter in the NRU reactor control room.

2. Confirm that the REDACE data will be taken on demand or at a 30-s frequency when requested.

3. Adjust the neutron detector scatter plug as required. Establish mean power trip set points as required.

TABLE 9. Steam/Reflood Loop Calibration

Sensor	Loop Parameter	DACS	Instrument Range	Acceptance Accuracy
TE-2	Inlet coolant temperature	206	394 to 700K (250 to 800°F)	±1K (±2°F)
TE-3	Outlet coolant temperature	207	422 to 973K (300 to 1300°F)	±6K (±10°F)
FY-6	Steam flow rate, reflood boiling	210	0 to 0.378 kg/s (0 to 3000 lbm/h)	±0.014 kg/s (±100 lbm/h)
FV-1	Inlet steam system control flow rate	211	0 to 0.378 kg/s (0 to 3000 lbm/h)	±0.014 kg/s (±100 lbm/h)
FI-2	Outlet steam system control flow rate	212	0 to 0.032 kg/s (0 to 250 lbm/h)	0.0013 MPa (±10 lbm/h)
PT-5	Steam inlet pressure	208	0 to 0.69 MPa (0 to 100 psia)	±0.034 MPa (±5 psia)
PT-6	Steam outlet pressure	209	0.069 to 0.345 MPa (0 to 50 psia)	±0.017 MPa (±2.5 psia)
PT-4	Steam pressure control, outlet region	217	0 to 0.69 MPa (0 to 100 psia)	±0.034 MPa (±5 psia)
FI-4	Reflood coolant, low flow rate	201	0.013 to 0.254 m/s (0.5 to 10 in./s)	±5%
FI-3	Reflood coolant, high flow rate	202	0.013 to 0.305 m/s (0.5 to 12 in./s)	±5%
FI4b	Reflood coolant, low flow rate (backup)	224	0.013 to 0.254 m/s (0.5 to 10 in./s)	±5%
FI3b	Reflood coolant, high flow rate (backup)	223	0.013 to 0.305 m/s (0.5 to 12 in./s)	±5%
FE-9	Standby reflood coolant flow	203	0.013 to 0.305 m/s (0.5 to 12 in./s)	±10%
TE-17	Reflood coolant temperature control valve, inlet	213	305 to 322K (90 to 120°F)	±5%
TE-18	Reflood coolant temperature control valve, outlet	214	305 to 322K (90 to 120°F)	±5%

TABLE 10. Pretransient and Transient Trip Set Points

Parameter	Location	Use	Operating Limits	Trip Set Point
Hanger tube temperature - high	LCS[a]	Pretransient and transient	691K (785°F)	839K (1050°F)
Outlet pipe temperature - high	LCS	Pretransient and transient	672K (750°F)	700K (800°F)
Fuel cladding temperature - high[b,c]				
Level 13 305 PSD-13-IR-1	DACS[d]	Transient	1305K (1890°F)	1361K (1990°F)
Level 15 3D8 PSD-15-IR-1	DACS		1305K (1890°F)	1361K (1990°F)
Level 17 315 PSD-17-IR-4	DACS	Transient	1278K (1840°F)	1333K (1940°F)
Low steam flow trip	LCS	Pretransient	0.378 kg/s (3000 lbm/h)	0.277 kg/s (2200 lbm/h)
Standby reflood flow - low	LCS	Transient	1.78 cm/s (0.7 in./s)	1.27 cm/s[e] (0.5 in./s)
Accumulator inventory - low	LCS	Transient	22.7 kg (50 lbm)	11.3 kg (25 lbm)

(a) LCS = loop control system.
(b) Standard trip set point criterion; see Table 11 for nonfunctional TC criteria.
(c) In use during transient operation only.
(d) DACS = data acquisition and control system.
(e) 0.64 cm/s (0.25 in./s) to be used during reflood loop calibration.

TABLE 11. Standard and Defaulted Safety Trip Set Point Criteria for Operating and Nonoperating Fuel Cladding Thermocouples

Summary of TC Operating Conditions	Criteria and Safety Margins (SM)	Sensors at Level 17	Sensors at Level 15	Sensors at Level 13
		DACS Thermocouple Numbers		
		315,PSD-17-IR-4[a] (99,101,107,109)	308,PSD-15-IR-1 (71,72,73,74, 98,100,106,108)	305,PSD-13-IR-1 (56,57,58,59)
		Trip Set Point Temperatures, K (°F)		
2 $\leq$ Number of operating TCs on each of Levels 13, 15, 17	Standard SM = 56K (100°F)	1333 (1940)	1361 (1990)	1361 (1900)
2 $\leq$ Number of operating TCs on each of Levels 15 and 17	Standard SM = 56K (100°F)	1333 (1940)	1361 (1990)	
2 $\leq$ Number of operating TCs on each of Levels 15 and 17 or Levels 13 and 17	Alternate SM = 84K (150°F)	1305 (1890)	1333 (1940)	1333 (1940)
2 $\leq$ Number of operating TCs on only one of Level 15, 17, or 13	Fallback SM = 111K (200°F)	1305 (1890)	1305 (1890)	1305 (1890)

(a) These pseudo sensor data (PSD) are the calculated time-average of the following DACS sensor-numbered data: 99, 101, 107, 109.

TABLE 12. Cladding High-Temperature Trip Sensors

Level	Pseudo Sensor Thermocouples	DACS Sensor Number	DACS Pseudo Sensor	DACS Sensor Number
13	TC-13-6C-IR-2	56	PSD-13-IR-1	305
	TC-13-4F-IR-4	57		
	TC-13-1D-IR-2	58		
	TC-13-3A-IR-4	59		
15	TC-15-6C-IR-4	71	PSD-15-IR-1	308
	TC-15-4F-IR-2	72		
	TC-15-1D-IR-4	73		
	TC-15-3A-IR-2	74		
	TC-15-5B-IR-3	98		
	TC-15-2E-IR-1	100		
	TC-15-5B-IR-1	106		
	TC-15-2E-IR-3	108		
17	TC-17-5E-IR-4	99	PSD-17-IR-4	315
	TC-17-2B-IR-2	101		
	TC-17-5E-IR-2	101		
	TC-17-2B-IR-4	109		

4. Confirm that all trip set points are activated, and report to the experiment director when ready for experiment operation.

DACS COMPUTER PREPARATIONS AFTER PRECONDITIONING

1. Load the DACS with labeled, certified tape and disks.

2. Start a dummy test and set the DACS mode to idle.

3. Set the steady-state scan rate at 1 s.

4. Set the transient scan rate at 40 ms.

5. Set the immediate display scan rate at 4 s.

6. Set the graphic display scan rate at 5 s.

7. Format the steady-state immediate display with the sensors listed in Table 13.

8. Format the transient graphic display.

9. Identify and remove failed sensors from displays, pseudo sensors, and trip circuits.

10. Reset Keithley amplifiers to the 0.1 scale and change self-powered neutron detector (SPND) coefficients; reduce by a factor of 10.

11. Report to the experiment director when ready for pretransient experiment operation.

REFLOOD CALIBRATION TEST OPERATING PROCEDURE (to be followed in sequence)

1. Calibrate the reflood prefill controls to fill the test nozzle annulus to Level 0.

2. Place the DACS in the steady-state mode.

3. Increase test section steam flow to 0.378 kg/s (3000 lbm/h), and control test section backpressure to 0.276 MPa (40 psia).

4. Enter the reflood rates, duration, and delay time in the LCS.

5. Print a sensor status report to insure that the test assembly and all TCs are $\geq$422K (300°F).

6. Reproduce the DACS immediate and graphic displays.

7. Turn on the video tape recorder and zero the counter when loading a new tape.

8. Prefill and drain a total of three times; display on graphic terminal.

9. Switch the DACS to the transient mode 20 s before issuing the verbal command "BEGIN THE TRANSIENT" (directed to the LCS operator), and record the time.

10. LCS operator initiates the transient.

11. Reproduce the DACS immediate and graphic displays as required.

12. Stop the test when reflood water passes the TCs at Level 20.

13. Change the DACS mode to steady state for 5 min and then to idle.

TABLE 13. DACS Immediate Display Test Sensors

Sensor Name	DACS Sensor Number	Sensor Name	DACS Sensor Number
TC-13-3B-IR-2	55	TC-17-3D-IR-5	90
TC-15-3C-IR-2	91	TC-17-3D-IR-C	93
TC-15-3C-IR-C	94	TC-17-3D-IR-4	138
TC-15-3C-IR-7	97	TC-17-2D-OR-1	120
TC-15-3B-IR-4	70	TC-17-2D-IR-2	126
TC-17-4C-IR-3	B8	TC-17-5D-IR-4	123
TC-17-4C-IR-C	92		

14. Make a historical request on the DACS graphic display and reproduce copies of the following data:

    - reflood rate (DACS sensors 201 and 202)
    - steam flow rate (DACS sensor 211)
    - TCs at selected levels (DACS sensors 289, 291, 296, 297, 299, 302, 304, 305, 307, 308, 310, 313, 317, and 320).

15. Print all DACS data throughout the transient at 5-s intervals.

16. Repeat Steps 1 through 15 for calibrating the assembly, using the designated reflood rate and delay time shown in Table 5.

17. Turn off the video recorder, and record the counter reading.

18. Make a tape copy on the OACS, and make a disk image copy on tape as time permits.

19. As necessary, repeat Loop System Preparations and DACS Computer Preparations sections before proceeding to Pretransient Operating Procedure.

PRETRANSIENT OPERATING PROCEDURE (to be followed in sequence)

1. Set the protective reactor trip set points for DACS and LCS control (values must be approved and recorded by the test director).

2. LCS operator will set timers for reflood delay times (values must be approved and recorded by the test director).

3. Check accumulator water levels (weights), and record the values in the Test Parameter Log.

4. Input the following information in the Test Parameter Log (this step does not apply for adiabatic transients):

   - name (DACS number) and level of sensor to be used for reflood water quench measurement

   - maximum allowed time for quench at the level selected

   - list of sensors (maximum 20) for hot spot search (no pseudo sensors)

   - time-temperature pairs (maximum 20 pairs) for low-limit window, high-limit window, and operator-controlled temperatures

   - DACS-controlled reflood rates (yes - to control; no - not to control)

   - if DACS-controlled, specify the reflood rate numbers and their corresponding reflood coolant rates to be preset in the LCS

   - control function coefficients weighting flow rates and delays for the DACS control algorithm.

5. Start a new test on the DACS; change DACS mode to steady-state.

6. Insure that the REDACE scan frequency for NRU data is 30 s.

7. Increase the NRU reactor power to the low neutron level.

8. Set the inlet steam flow rate to 0.378 kg/s (3000 lbm/h) and test section backpressure to 0.28 MPa (40 psia).

9. Before proceeding, the NRU reactor operator must acknowledge that the neutron power will not exceed the neutron power level requested by the test director.

10. Increase the NRU neutron power to 4.0%. With the reactor power at nominally 50% of the pretransient power, scan the DACS immediate display for the hottest TC and reproduce the display.

11. Insure that the test assembly inlet temperature stabilizes at 439 ±3K (330 ±10°F).

12. Adjust the NRU neutron power level to obtain a steady-state 178K (320°F) temperature increase across the test assembly.

13. Check the peak cladding temperature, steam flow, test assembly inlet temperature, and outlet pressure.

14. Make a hard copy of the DACS immediate and graphic displays.

15. Activate the video tape recorder.

TRANSIENT OPERATING PROCEDURE (to be followed in sequence)

1. Prefill the inlet annulus three times and drain it twice. Display test assembly temperatures on the DACS graphic display.

2. Change to the transient operating mode on the DACS; 20 s later, issue the verbal command "BEGIN THE TRANSIENT" (directed to the LCS operator); and record the time in the Test Parameter Log.

3. LCS operator begins the transient.

4. Shut down the reactor when the test assembly is quenched or when the transient time exceeds 200 s at the desired cladding temperature range.

5. Shut off reflood water flow only after upper TCs have quenched (this step does not apply for adiabatic transients).

6. Record reflood water used (accumulator weight difference) in the Test Parameter Log (this step does not apply for adiabatic transients).

7. Insure that tripping the reactor has returned control to the DACS (transient forcing signal #257 = 0).

8. Return the DACS mode to steady state for 5 min and then to idle, ending the data record.

9. End the test on the DACS. Verify that the Test Parameter Log is completed.

10. Turn off the video tape recorder, and record the location.

11. Copy the following historical data on the DACS:

    - reproduce the data from the hottest pseudo sensors at Levels 15 and 17
    - plot data for sensors 289 and 290
    - plot data for DACS sensor 211
    - plot data for DACS sensors 201 and 202
    - plot data for DACS sensors 70, 91, 97, and 137

- plot data for DACS sensor 314
- plot data for DACS sensor 308
- plot data for DACS sensor 315.

12. Make a tape copy of the DACS data.

13. Make a disk image copy of the DACS data.

14. Return to Pretransient Operating Procedure section for successive transients.

15. Terminate the experiment and remove the test train to the bay using established CRNL procedures.

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APPENDIX A

TEST PARAMETER LOG

APPENDIX A

TEST PARAMETER LOG

LOCA Simulation in NRU

Run number: ____________________

Date: ____________________

1.0 PRECONDITIONING ACTIVITIES

Date: __________ Time: __________

Data stored on data tape number: __________ Disk number: ________

1.1 Power calculations (attach to log)

2.0 PRETRANSIENT ACTIVITIES

Tape number: __________

Disk configuration: DP0 __________

DP1 __________

DP1F __________

2.1 Operation summary

PARAMETER/UNITS	SPECIFIED VALUE/ ACCEPTED RANGE	ACTUAL VALUE
Steam flow rate, lbm/h	3000 (±5%)	__________
Steam inlet temperature, °F	325 (±15)	__________
Maximum fuel cladding temperature, °F	800 (NA)	__________
Sensor name ________________		__________
Sensor name ________________		__________
Sensor name ________________		__________
Total test assembly ΔT, °F	320 (±10)	__________
Outlet pressure, psia	40 (±5%)	__________

2.2 Print all sensor data with DACS in steady-state mode; review.

2.3 Protective trip set points (pretransient and transient)

PARAMETER/UNITS	VALUE
Hanger tube temperature--high, °F	______
Outlet pipe temperature--high, °F	______
Steam flow--low, lbm/h	______
Fuel cladding temperature, °F	
Level 17--high	______
Level 15--high	______
Level 13--high	______
Level _ time to quench	______

3.0 SPECIAL COMMENTS ON RUN CONDITIONS:

3.1 Preparations:

3.2 Pretransient:

3.3 Transient:

3.4 Post-transient:

4.0 CONDITIONS CAUSING RUN TERMINATION:

5.0 SPECIAL CONDITIONS TO BE CONSIDERED IN THE ANALYSIS OF THE TEST RUN:

6.0 CONDITIONS THAT MAY CAUSE THE TEST TO BE INVALID:

7.0 INSTRUMENTATION FAILURES BEFORE TEST:

8.0 INSTRUMENTATION FAILURES AFTER TEST TERMINATION:

9.0 GENERAL COMMENTS ON TEST:

APPENDIX B

EXPERIMENT CONDITIONS LOG

APPENDIX B

EXPERIMENT CONDITIONS LOG

A. Protective trip temperatures for Levels 13, 15, and 17 ________________

B.

TH Run Number	Delay Time, s	Reflood Rate in./s	Reflood Rate Duration, s

C. Maximum allowed time (___s) for reflood water to quench sensor ___ at Level ___

D. DACS control ____

E. Time-temperature for test control (if needed)

F. Control functions coefficients (if needed) ________________________

G. Temperature increase across test assembly for pretransient ____________

Test Director ____________________

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A series of thermal-hydraulic and cladding materials deformation experiments were conducted using light-water reactor fuel bundles as part of the Pacific Northwest Laboratory Loss-of-Coolant Accident (LOCA) Simulation Program. This report is the formal operations plan for TH-2--the second experiment in the series of thermal-hydraulic tests conducted in the National Research Universal (NRU) reactor, Chalk River, Ontario, Canada. The major objective of TH-2 was to develop the experiment reflood control parameters and the procedures to be used in subsequent experiments in this program. In this experiment, the data acquisition and control system was used to control the fuel cladding temperature during a simulated LOCA by using variable reflood coolant flow.

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