RD-14M Experiments

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Outline

- Summary of RD-14M test matrix
- RD-14M LOCA experiments
- RD-14/ACR LOCA test matrix and results
- Natural circulation experiments
- Transition from shutdown cooling experiments
- Loss of forced flow experiments
- Single pump trip experiments
- Flow stability tests

CANDU Integral Test Facility Program

Objectives

- To provide integrated experimental data on thermal hydraulic behavior in a multiple-channel test facility
  - Single channel-per-pass: RD-14
  - Multiple channels-per-pass: RD-14M
- To improve the understanding of the underlying physical phenomena governing behavior
- Facilitate validation of codes

RD-14M Test Matrix

Type of Test	Number of Tests
LOCA	
Small Break	9
Critical Break	27
Large Break	18
With Channel Void Measurement	18
ACR Conditions	9
Natural Circulation	
Partial Inventory	49
Transition	34
Commissioning	14
Transition to Shutdown Cooling	9
Loss-of-Flow	8
Single Pump Trip	12
Flow Stability	9

RD-14M LOCA Experiments

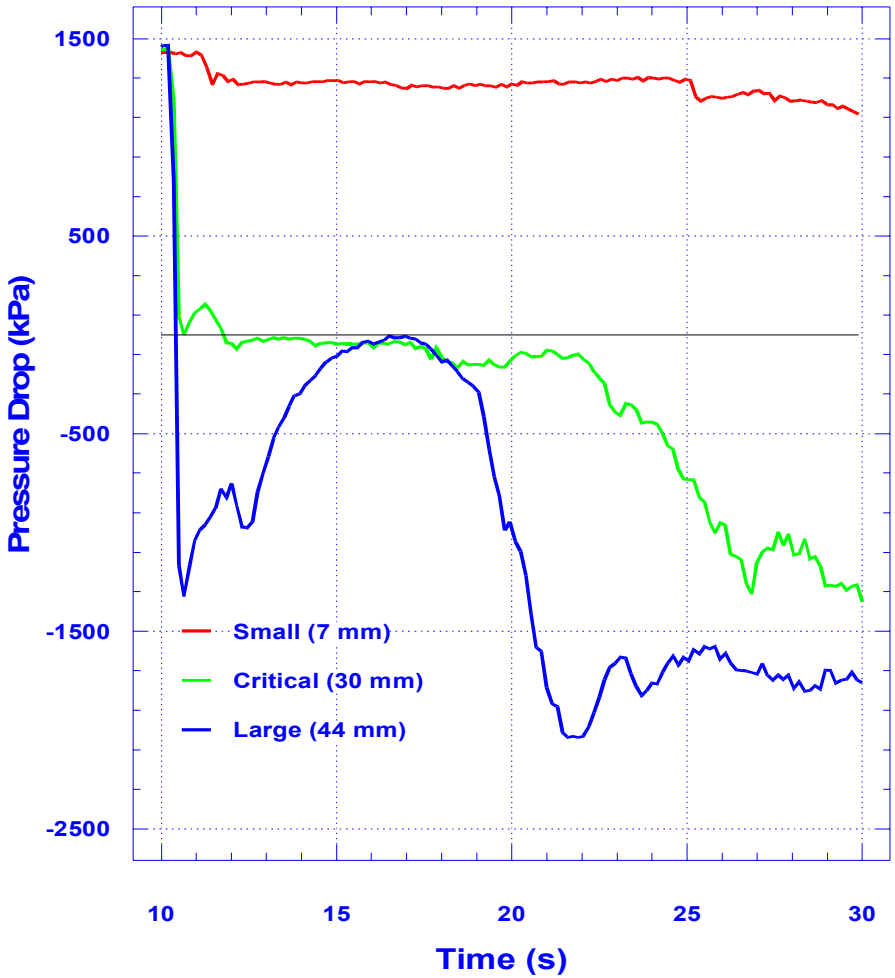
Definition:

- **Small Break LOCA**
  Simulates a feeder-sized break on an inlet or outlet header

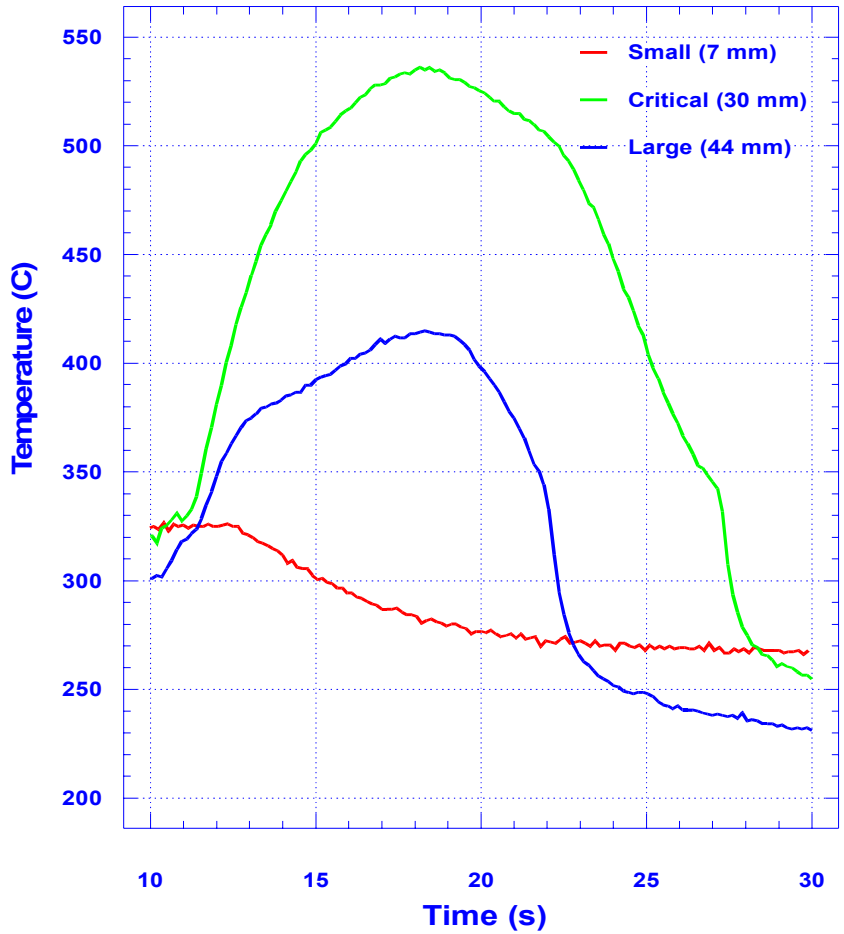
- **Critical Break LOCA**
  Results in the formation of flow split points in the heated portion of the channels for several seconds in the first 10 seconds of the blowdown transient

- **Large Break LOCA**
  Simulates an end cap failure of an inlet or outlet header (100% header break)

Pressure Drop Between Inlet (HD8) and Outlet (HD5) for Small, Critical and Large Breaks



Maximum FES Cladding Temperature for Small, Critical and Large Breaks



Evolution of Critical Break Experiments

- Critical break LOCA experiments have been carried out since 1990
- The tests have evolved over the years as the needs have changed as has the available instrumentation
- 1990-1994
  - First sets of tests to investigate the thermalhydraulic behavior of RD-14M under critical-break conditions
- 1996
  - Incremental change to carry out tests at FES temperatures closer to licensing analysis conditions

Evolution of Critical Break Experiments

- 1999
  - Incremental change using faster scanning rates and fast response pressure transducers to focus on the early stages of a LOCA event
    - Previous tests gave adequate data for the overall LOCA event, not specifically the early stages
- 2001
  - Complete development of a device (neutron scatterometer) capable of measuring void in an RD-14M channel during the early stages of a LOCA event
  - Tests carried out were counterparts to tests conducted in previous years
  - Provided previously unavailable data on channel voiding
- 2002
  - Incremental change to ACR-typical conditions

1990 - 1994 Critical Break LOCA Experiments - 1

Objectives:

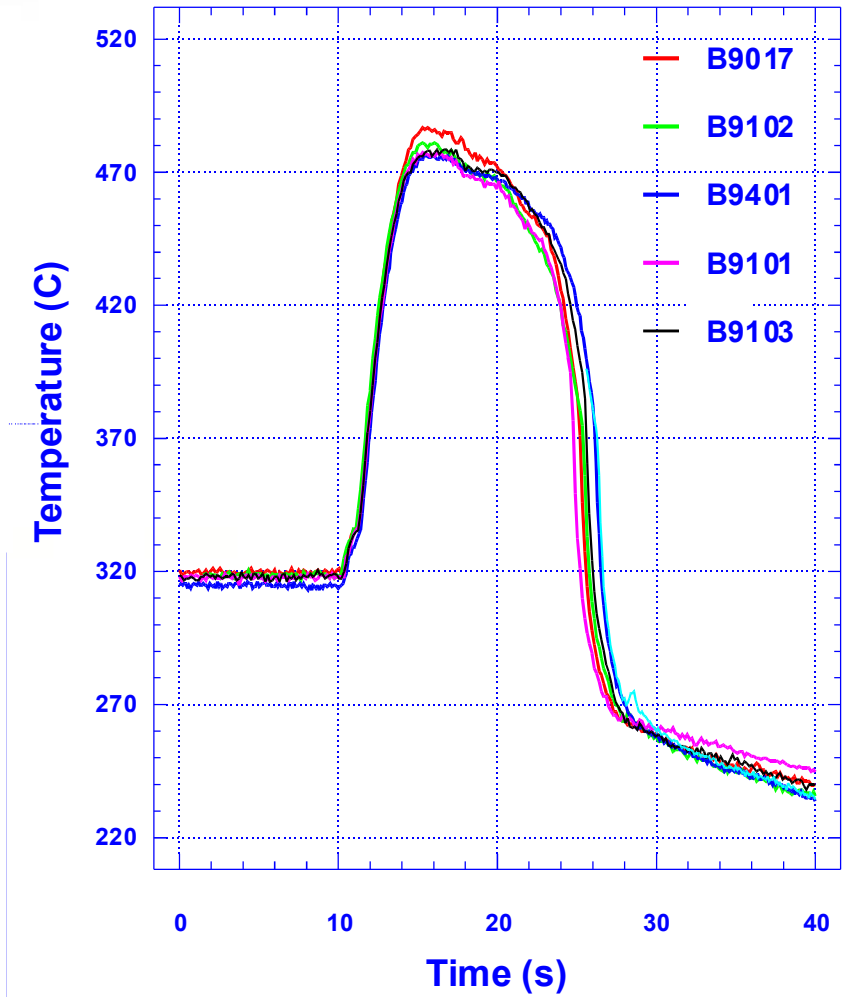
- To investigate the thermalhydraulic behavior of RD-14M under critical-break conditions
- To examine the effect of break size, primary-side flow rate, decay power level, isolation of surge tank and mode of ECC on blowdown and refill behavior

1990 - 1994 Critical Break LOCA Experiments - 2

- Typical Test Procedure:

0 sec.	Start data acquisition
10 sec.	Open break valve (MV8)
12 sec.	FES power to decay level and start main pump ramp (exponential)
P < 5.5 MPa(g)	Open ECC isolation valves to start high-pressure ECC injection
When ECC tank depletes	Terminate high-pressure ECC and start low-pressure ECC
	End of test

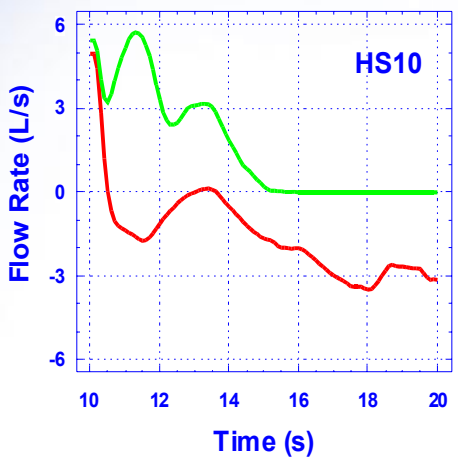
HS13 Top, Center FES Clad Temperature during Blowdown

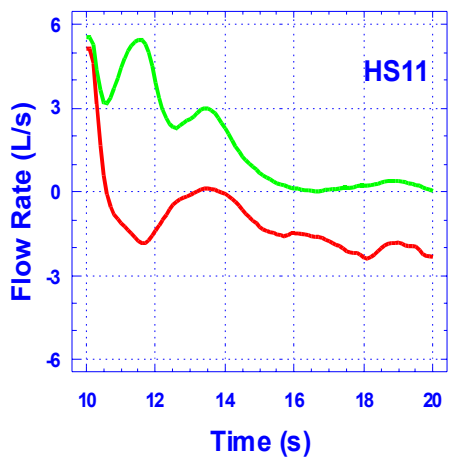


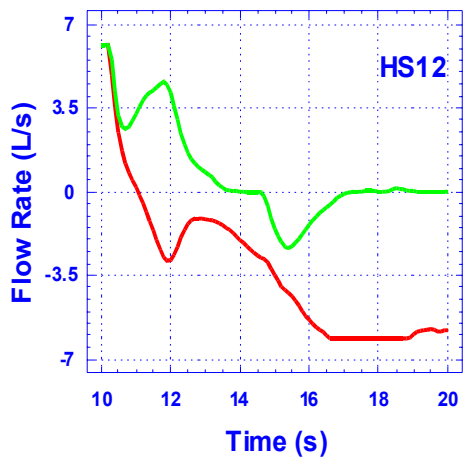
Results of Critical Break Experiments

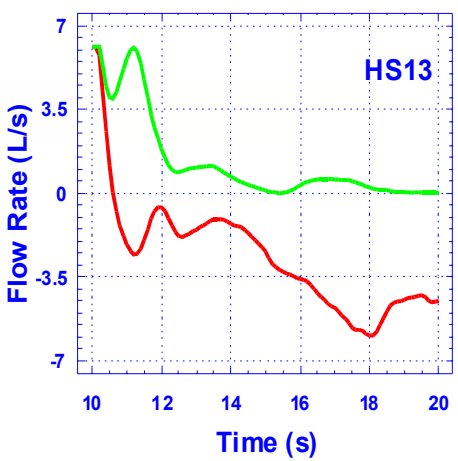
- In all critical break tests, flow split points developed in the majority of the test sections downstream of the break during the first 10 s
- The maximum Fuel Element Simulator temperatures occurred during the initial blowdown period, prior to the introduction of ECC
- In all tests, the high-pressure, pumped ECC was effective in cooling all test sections
- ECC was not essential for channel cooling during the initial blowdown transient

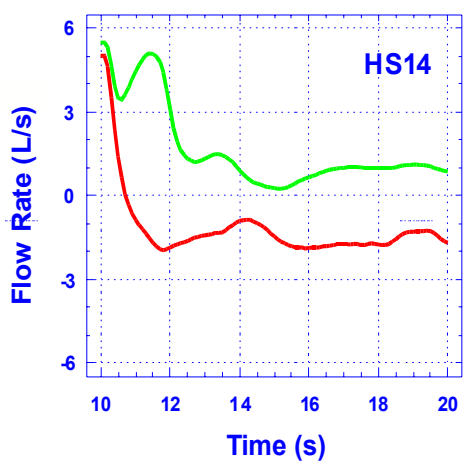
B9401 - Heated Section Flow Rates in Critical Pass







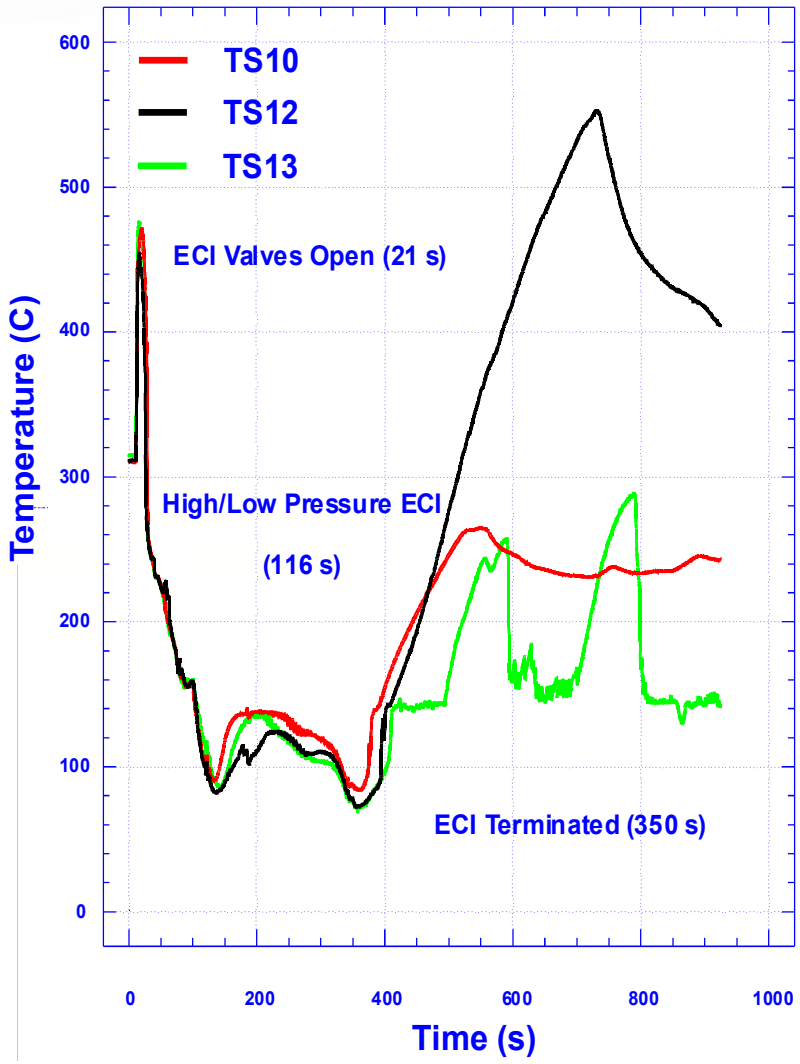




Legend

- Inlet Flow
- Outlet Flow

B9401 - Top FES Clad Temperatures at Mid-Point of Test Section



1996 Critical-Break LOCA Experiments

Objective:

- To provide additional experimental data on the thermalhydraulic behavior of critical inlet header break LOCAs
- Specifically, to provide experimental FES temperature data closer to licensing analysis conditions

B96 LOCA Tests - 1

Facility and Procedure Modifications

Concern: Fuel Element Simulators (FES) expected to operate well beyond historical range (traditional set point = 600°C)

Potential for damage to FES

Impact of FES damage on reproducibility

B96 LOCA Tests - 2

Modifications:

1) Only one active test section per pass, TS8 and TS13. Other test sections isolated at the headers using blanks. This confined any potential damage to one channel.
2) Step-wise change in FES trip set points (700°C, 840°C and 1000°C). Helped establish FES operating limits for future tests, and provided data to assess reproducibility on early blowdown.

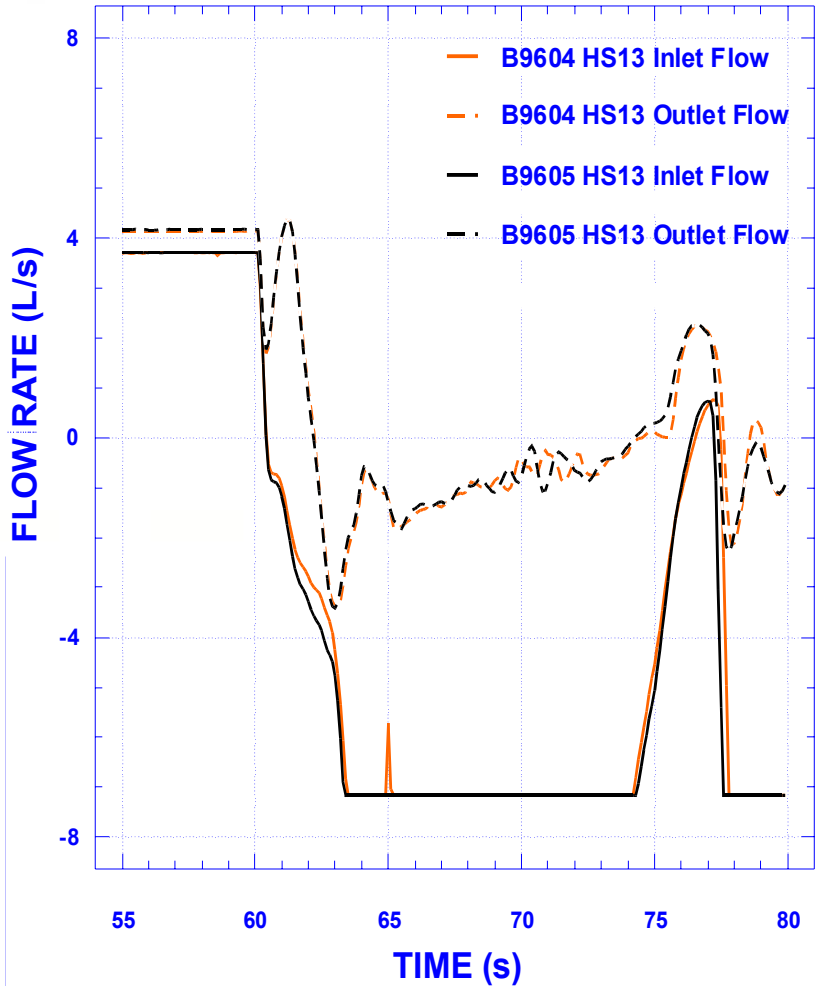
Post-test radiography conducted on Test Section 13 to identify any deformation

B96 LOCA TESTS - Results

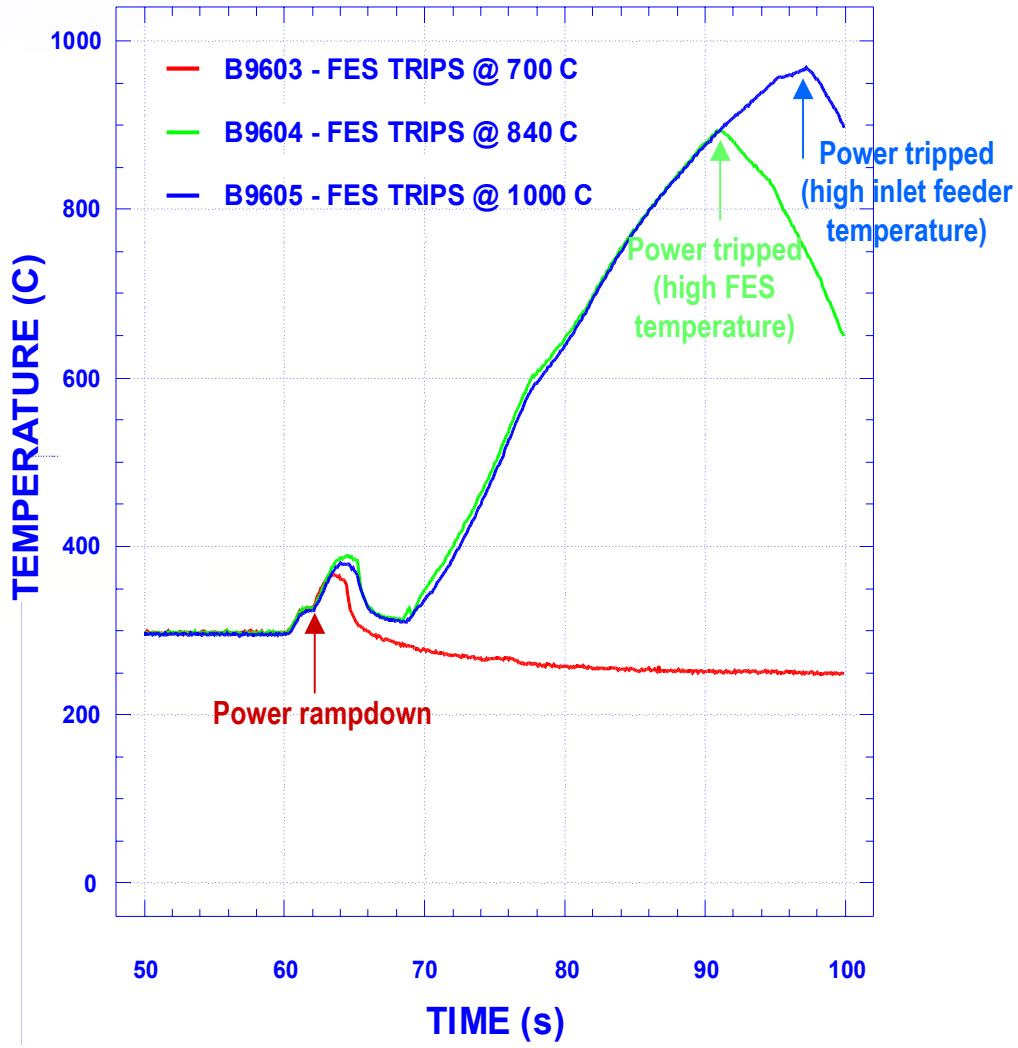
B9604 and B9605

- Similar conditions (18 mm break and 50% pump speed, different FES trip points, no ECC)
- Excellent agreement between tests
- Early flow-split point followed by flow reversal
- Degradation of pumping efficiency increased reverse flow through TS13 reducing the rate of FES temperature rise
- Hottest FES temperatures near inlet end
- Maximum FES temperature was 968°C
- No FES heat-up in other pass (TS8)

Flow Split Point in Broken Pass (18-mm Break, 50% Initial Pump Speed)



FES Clad Temperatures – Element 7, Segment 2 (18 mm Inlet Header Break, 50% Initial Pump Speed)



B96 LOCA Tests

Summary

- Maximum FES temperature of 968°C achieved
- No deformation of FES bundle or pressure tube
- Established FES operating limits for other tests (natural circulation)

RD-14M Channel Voiding During Large LOCA - 1

- **Background**
  - During the initial transient that follows a large break LOCA, initial coolant voiding occurs as a result of flashing and transport of stored energy in the fuel
  - The rate of depressurization and channel voiding are key parameters to be captured during validation exercises
  - Historically, scanning rates and instrumentation used in RD-14M LOCA experiments were chosen to capture behavior over the entire blowdown transient
    - Scanning rate was too slow to adequately capture the initial depressurization resulting in un-quantified uncertainties in code calculations during this phase

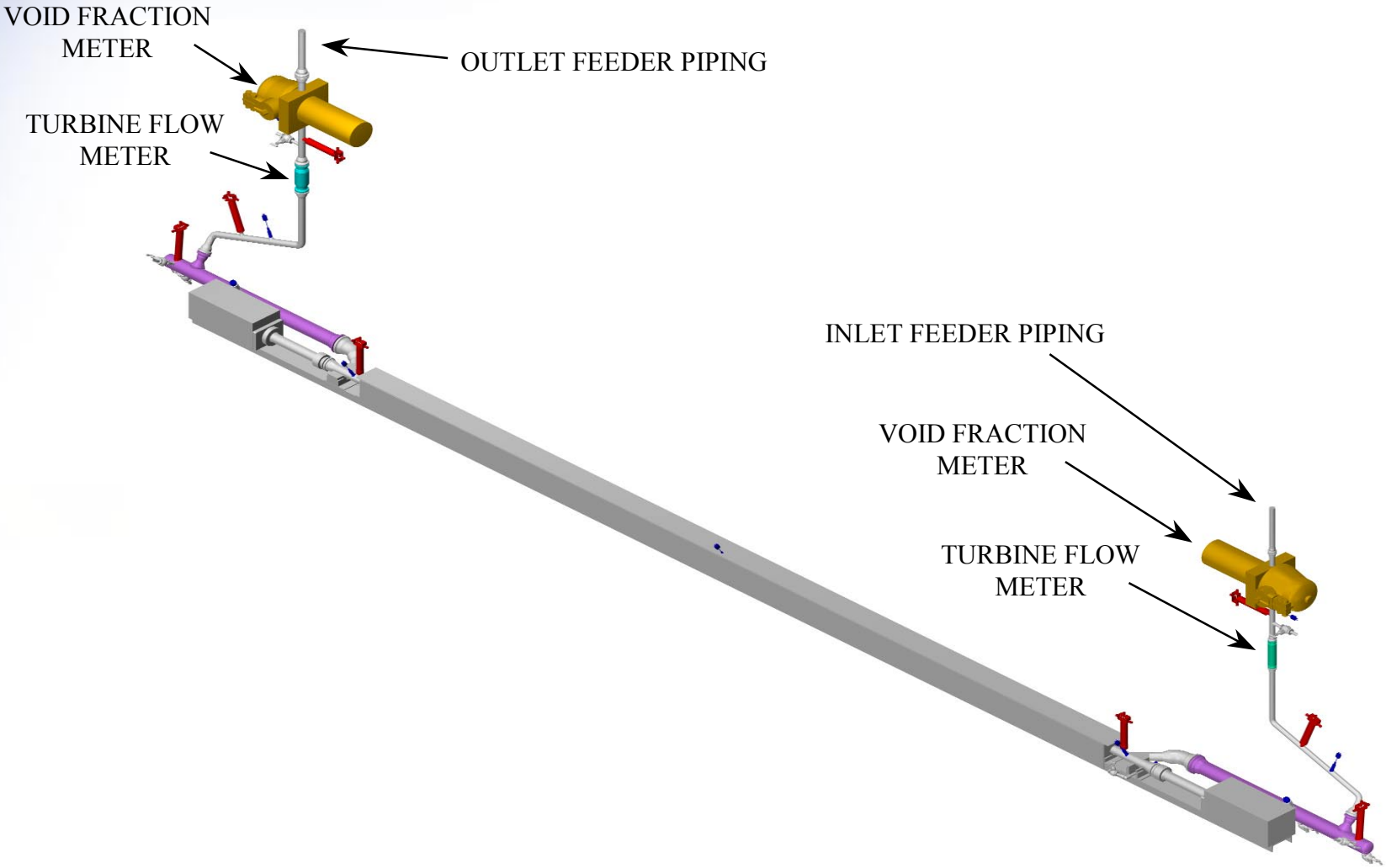
RD-14M Channel Voiding During Large LOCA - 2

- RD-14M Experiments B9901 and B9902
  - To reduce / eliminate these deficiencies, modifications were made to the loop and test procedures:
    - These experiments specifically focused on the early stages of a LOCA event, and did not have ECC addition
    - Substantially faster scanning rates and quick response pressure transducers were used

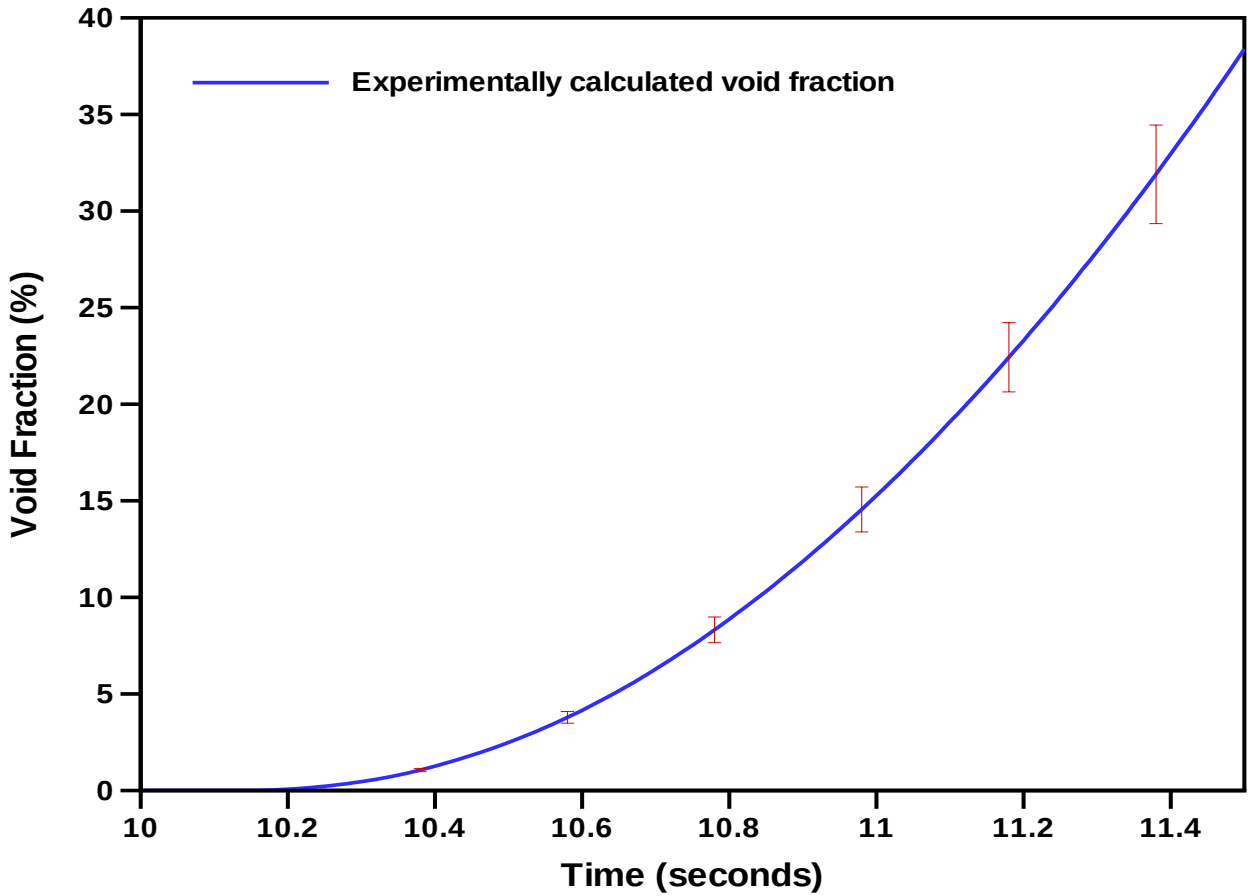
RD-14M Channel Voiding During Large LOCA - 3

- RD-14M Experiments B9901 and B9902
  - These improvements provided previously unavailable information:
    - More accurate and detailed data on the initial depressurization rates
    - Enabled the calculation of average channel voiding rates (by integrating the single-phase flows leaving a channel)

RD-14M Channel Voiding During Large LOCA - 4



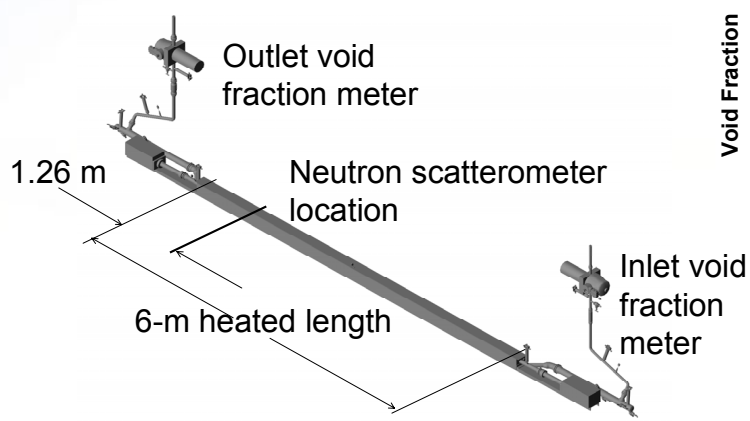
Average Channel Void Fraction from Integrated Flow

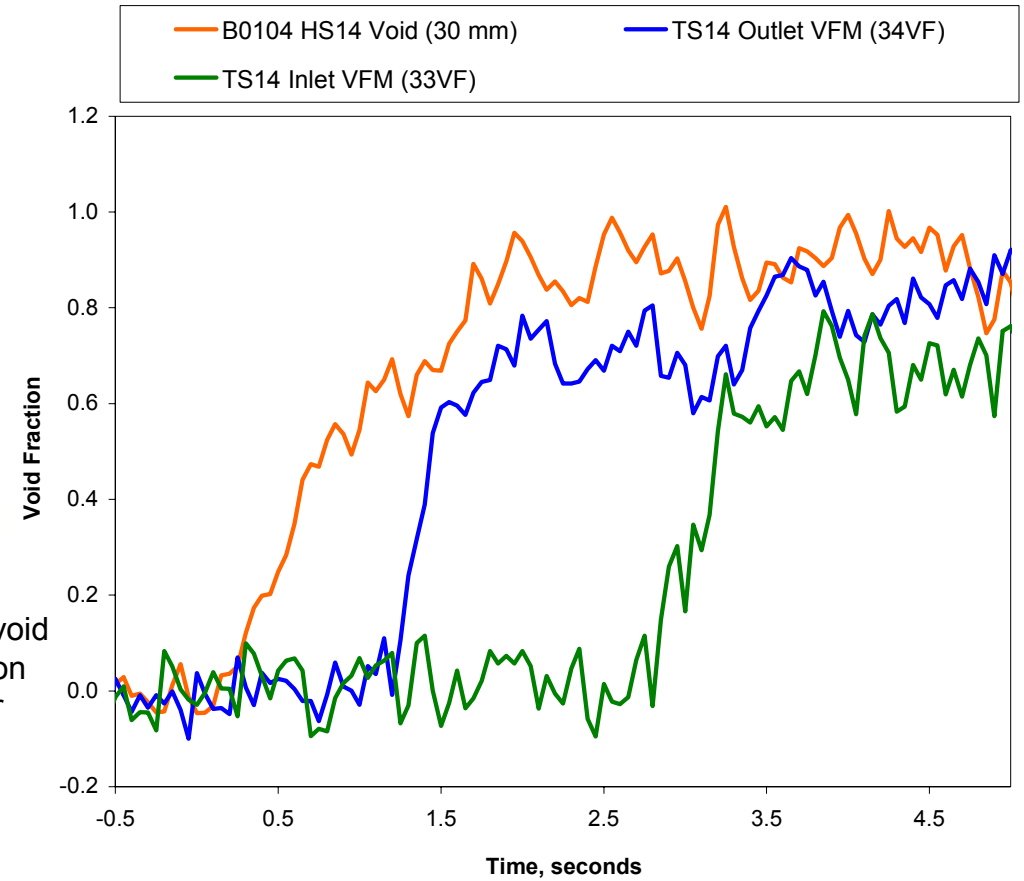


RD-14M Channel Voiding During Large LOCA - 5

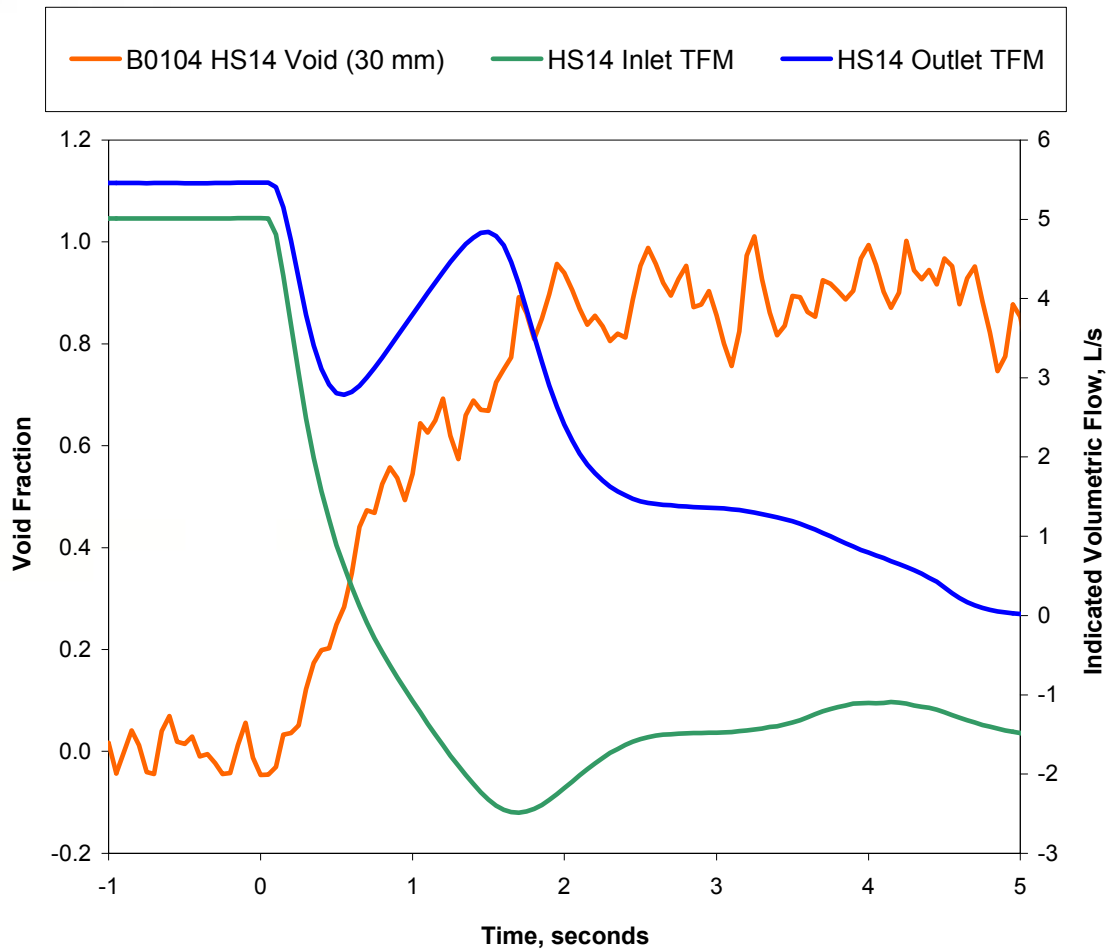
- Direct measurement of channel voiding in RD-14M under LOCA conditions is now possible with the neutron scatterometer
- Critical and large LOCA tests performed in 2001 with the neutron scatterometer on HS14
  - No ECC

TS14 Void Fractions - Test B0104

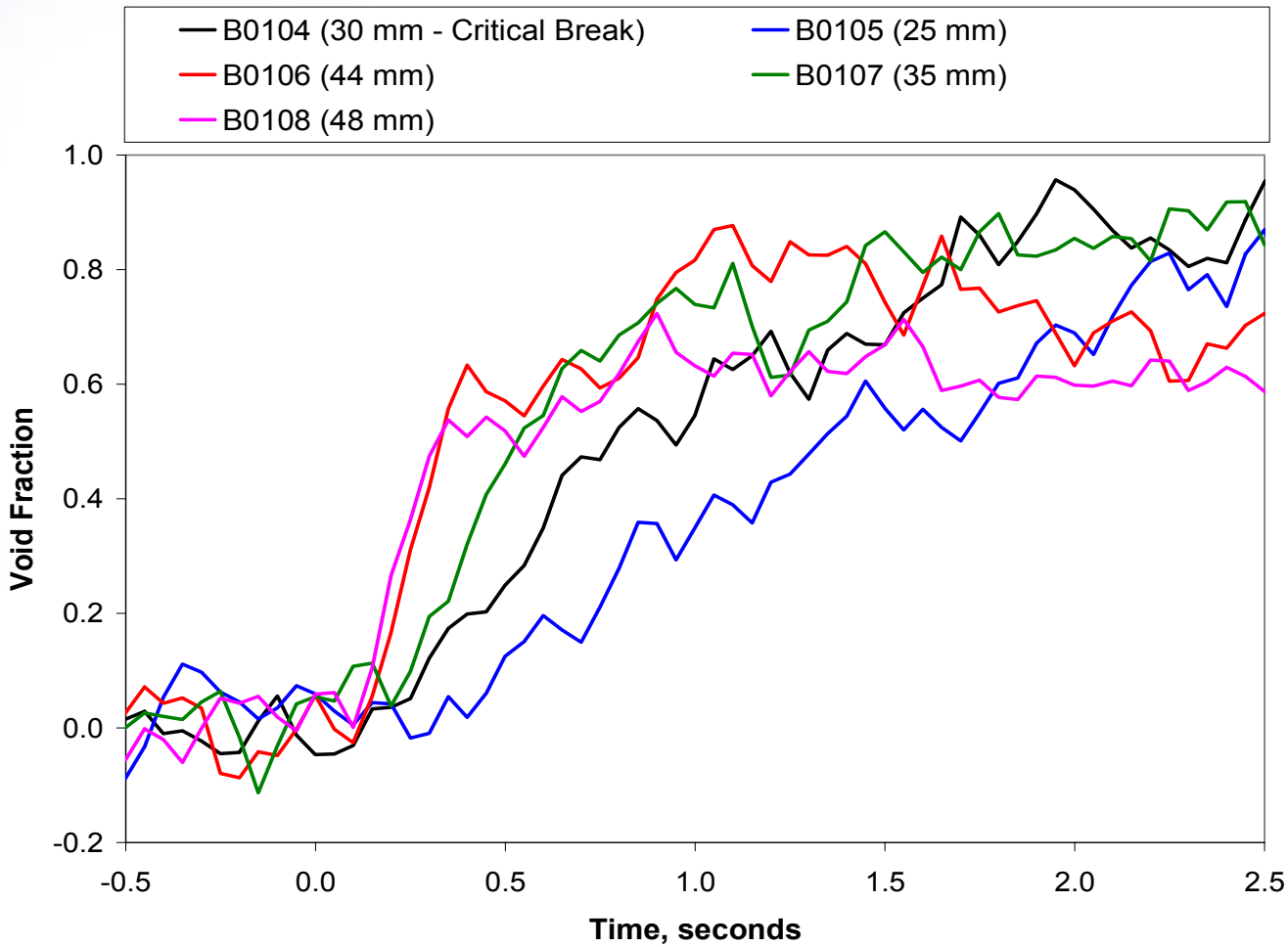




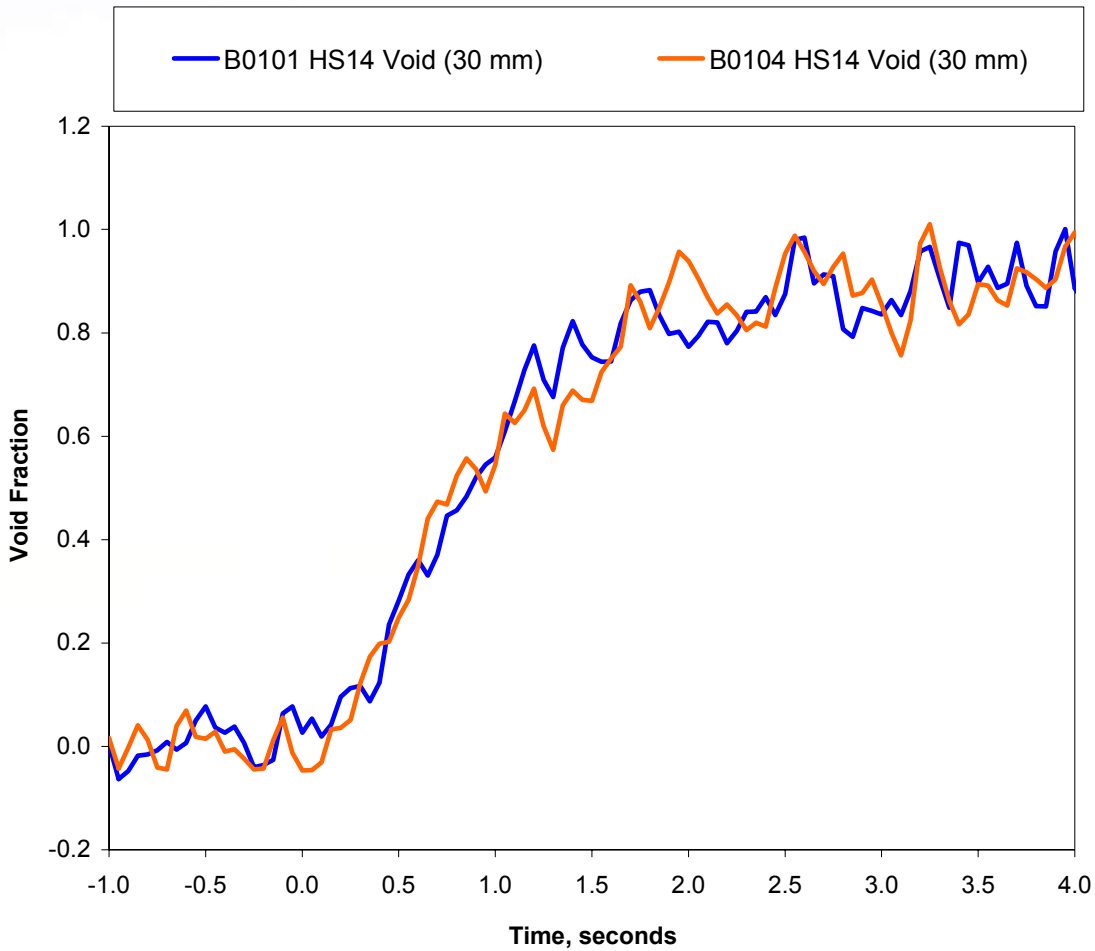
TS14 Inlet and Outlet Flows
Test B0104



Channel Void Fraction for Various Break Sizes



HS14 Void Fraction – 30-mm Counterparts



RD-14/ACR Test Matrix

- RD-14/ACR LOCA
  - Performed without ECC
  - Small, critical, and large break
  - Tests extend the range of the RD-14M database to ACR typical pressures and temperatures
  - (LOCA tests with ECC planned for 2003/04)

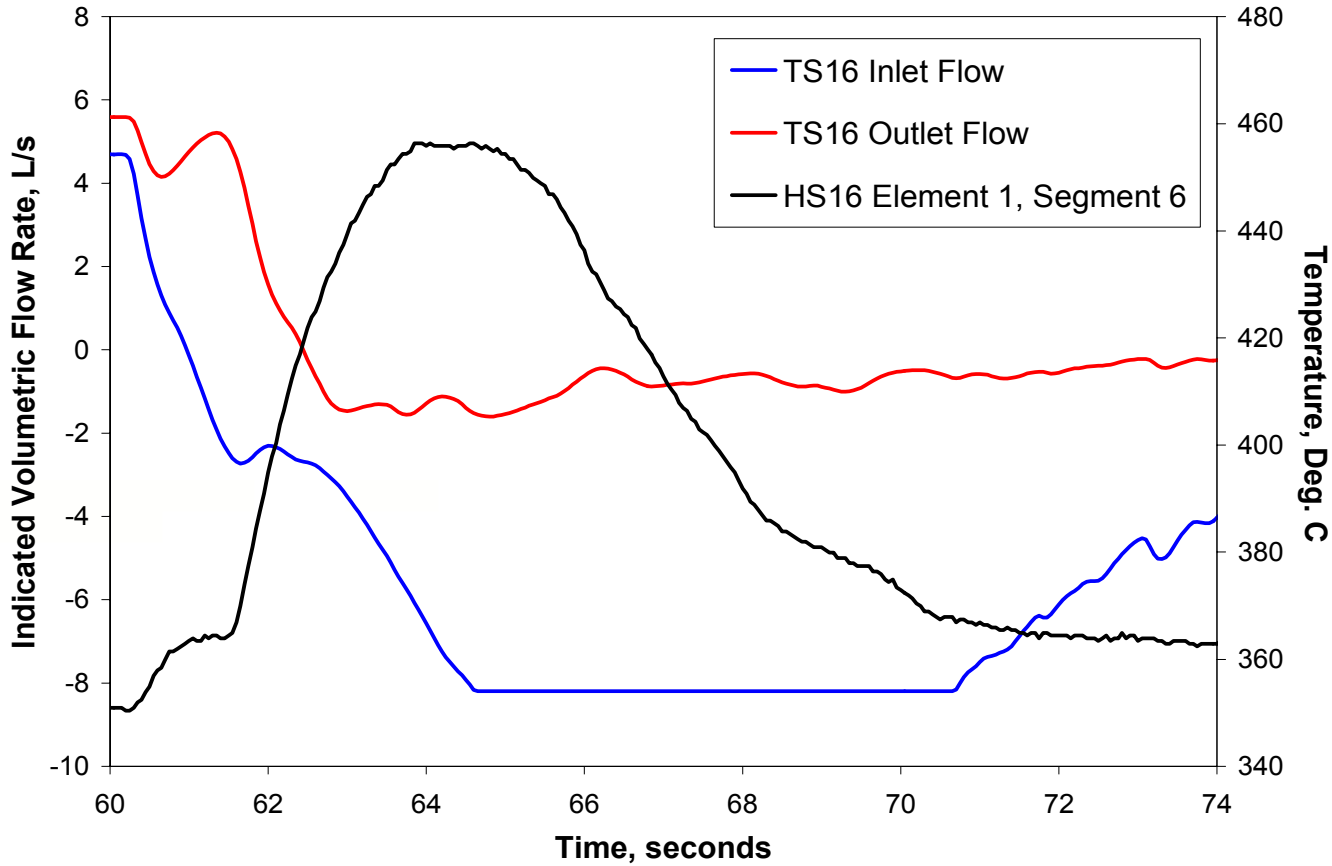
Nominal Initial Conditions for RD-14/ACR LOCA Tests

Reactor Cooling System:	
Nominal Input Power	1 MW/pass
Pressure (Outlet Header)	11.9 MPa(g)
Flow Rate (Primary Pumps)	4.7 L/s
Inlet Header Temperature	~275ºC
Outlet Header Temperature	~322ºC
Secondary System:	
Pressure	6.3 MPa(g)
Feedwater Temperature	~220ºC

RD-14/ACR Test Matrix

Test	Break Size (mm)	Secondary-Side Pressure
B0203	3.0	Constant at 6.3 MPa(g)
B0204		Rampdown starting 2 sec. after break
B0207	6.75	Constant at 6.3 MPa(g)
B0208		Rampdown starting 2 sec. after break
B0206	12.0	Constant at 6.3 MPa(g)
B0202	15.0	Constant at 6.3 MPa(g)
B0209		Constant at 6.3 MPa(g)
B0201	18.4	Constant at 6.3 MPa(g)
B0205	25.0	Constant at 6.3 MPa(g)

RD-14/ACR Test B0209
Critical Break



Natural Circulation in RD-14M - 1

- Identify behavior
- Identify and quantify key phenomena
- Develop and validate models

Natural Circulation in RD-14M - 2

Natural Circulation Tests Conducted

– Partial Inventory	(T-series)	49
– Transition	(R-series)	34
– Commissioning	(C-series)	14

Natural Circulation in RD-14M - 3

T-Series Experiments: Procedure

- Starting from single-phase natural circulation, reduce inventory through a series of discrete drains with usually a brief period between drains
  - T88 to T90 tests used quick, frequent drains - scoping tests
  - T92 / 93 tests used slow drains, better quality data

Natural Circulation in RD-14M - 4

- R-Series: Transition to Natural Circulation Tests:
  - Establish steady-state, forced convective flow at desired operating conditions
  - Drain a fixed quantity of fluid from outlet header (giving an average loop void)
  - Trip main coolant pumps
  - Monitor resulting natural circulation behavior until steady-state is achieved or test terminated due to high Fuel Element Simulator temperature (600°C)

Natural Circulation in RD-14M - 5

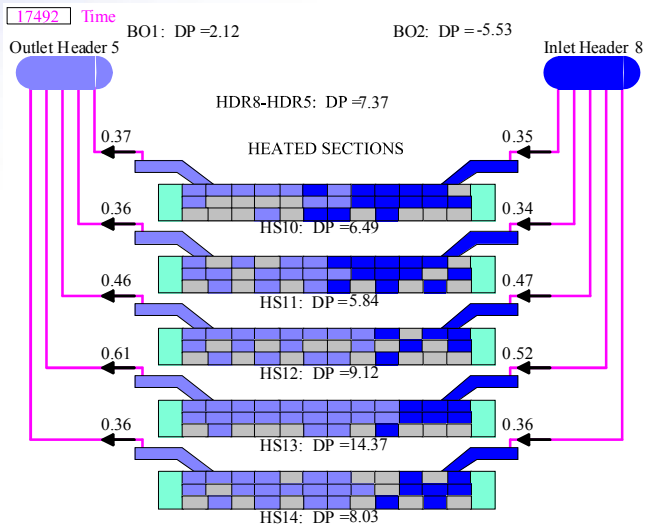
- R-Series: Loop Shrinkage Tests:
  - Alternate procedure for establishing Transition to Natural Circulation conditions
    - Establish steady-state, forced convective flow at desired operating conditions (full pressure)
    - Drain a fixed quantity of fluid from outlet header (giving an average initial loop void)
    - Trip main coolant pumps
    - Ramp down the secondary side pressure (this results in fluid shrinkage in the RCS)
    - Monitor resulting natural circulation behavior until steady-state is achieved

Natural Circulation in RD-14M - 6

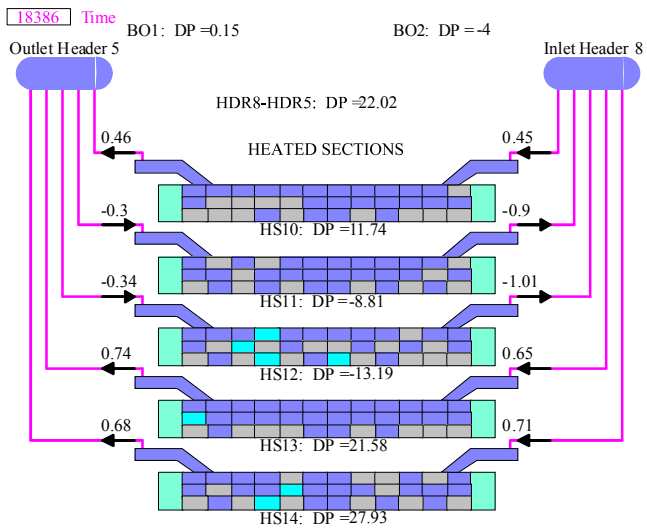
Test Conditions Investigated

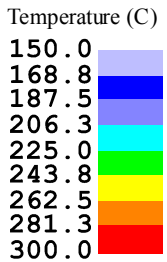
POWER	160,100 and 60 kW/pass
SECONDARY-SIDE PRESSURE	4.5, 4.0, 1.0, 0.1 and 0 MPa
SURGE TANK	on/off
DRAIN RATE	0.03 to 0.2 L/s
SECONDARY-SIDE SYSTEM	High / Low Power
OUTLET HEADER INTERCONNECTS	Dynamic and Geometric Scaled
ECC ADDITION	15-33 L/s
MAKE-UP WATER ADDITION	0.08 kg/s
ECC ISOLATION VALVES	open/closed
TRACE HEATING	on/off

Uni-directional flow



Bi-directional flow





Natural Circulation in RD-14M - 7

General Behavior

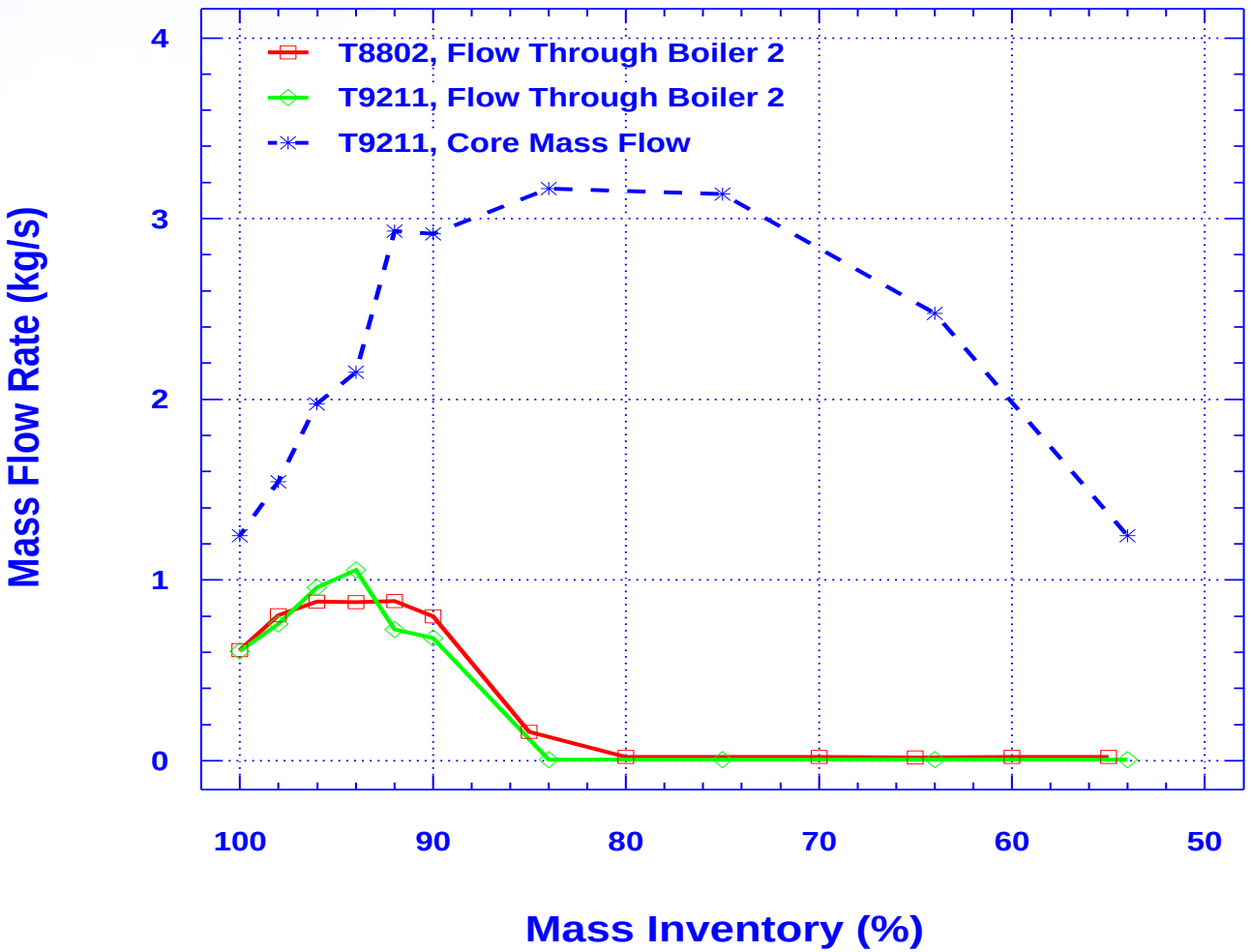
- Similar to PWR: reduction in inventory introduces void in the hot leg increasing loop flow rates
- Further reduction in inventory results in a maximum flow through the Steam Generators (SG)
  - High power / high secondary pressure (160 kW/pass, > 4.0 MPa) unidirectional flow maintained until about 85% inventory after which bi-directional flow established in high elevation channels, good cooling maintained
  - Low secondary-side pressures (≤1.0 MPa), flows highly oscillatory, bi-directional flow at 90-95% primary inventory

Natural Circulation in RD-14M - 8

General Behavior (continued)

- In all tests, continued reduction in primary inventory was accompanied by additional flow reversals
- Bi-directional flow caused a breakdown in net flow, as measured through the SG's, but did not cause a simultaneous breakdown in core or channel cooling

Comparison of Boiler 2 and Total Core Mass Flow Rates
RD-14M Tests T8802 and T9211



Natural Circulation in RD-14M - 9

General Behavior (continued)

- For the majority of tests heat-up did not occur until primary inventories were reduced to <70%
- In a small subset of experiments at 160 kW/pass and secondary-side pressure 1.0 MPa(g), tests were terminated at primary fluid inventories >85% when FES cladding temperatures exceeded the trip setting of 600°C
- Additional experiments at 160 kW/pass and secondary-side pressure 1.0 MPa(g) were performed with an FES trip temperature of 800°C
  - Maximum FES temperatures remained below 700°C

P.J. Ingham, J.C. Luxat, A.J. Melnyk, T.V. Sanderson, "NATURAL CIRCULATION EXPERIMENTS IN AN INTEGRAL CANDU TEST FACILITY," IAEA Technical Committee Meeting on Experimental Tests and Qualification of Analytical Methods to Address Thermohydraulic Phenomena in Advanced Water Cooled Reactors, Paul Scherrer Institute, Villigen, Switzerland, 1998 September 14-17.

Natural Circulation in RD-14M - 10

Summary

- Extensive database of natural circulation experiments in RD-14M
- Natural circulation is effective even at significantly reduced RCS inventory
- Bi-directional flow caused a breakdown in net flow, as measured through the SG's, but did not cause a simultaneous breakdown in core or channel cooling

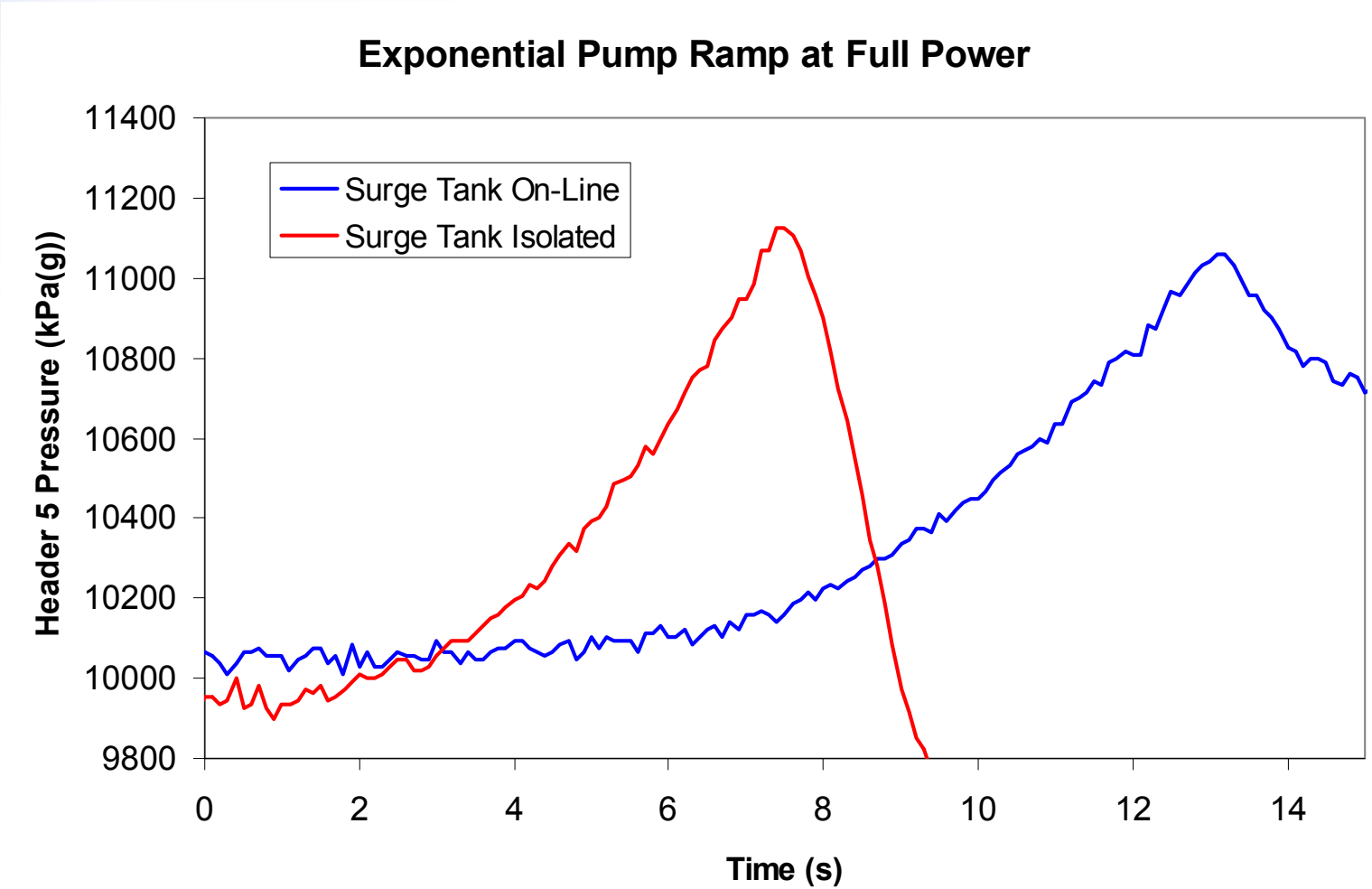
Transition from Shutdown Cooling Tests

- Investigate the thermal hydraulic behavior in a figure-of-eight loop following a simulated loss of shutdown cooling
  - These tests were carried out to address specific station worker safety concerns when reactors are shutdown for routine maintenance
- Procedure
  - Loop drained to just above headers (similar to conditions during routine outage)
  - Power to test sections turned on to simulate a loss of shutdown cooling flow
  - Subsequent addition of make-up water was also simulated in these tests

Loss of Forced Flow Tests

- Provide experimental data and information on the pressurization transient following a loss-of- forced flow event
- Specifically, station data is not recorded frequently enough (every 6 seconds) to adequately assess the simulation uncertainty of system thermal hydraulic codes
- The tests focused on the rate of pressurization following either a linear or exponential reduction in the speed of both primary pumps at full-power conditions. The effect of isolating the surge tank was also examined

Loss of Forced Flow Tests



Single Pump Trip Tests

Background

- In the past, station data was used for trip point assessment
- This data was not adequate to quantify differences between actual measurements and the system thermal hydraulic code calculations for single pump trip events
- A series of experiments was conducted to address the simulation uncertainty associated with system thermal hydraulic codes used for reactor trip assessment and validation

Single Pump Trip Tests

Procedure

- Surge tank online
- Dynamic header interconnect installed
- RD-14M loop brought to desired operating conditions (full-power or ambient)
- Primary pump 1 was ramped down using a pre-programmed exponential pump ramp
- Tests were performed over a wide range of conditions designed to give different levels of subcooling

Flow Stability Tests

- Tests to investigate the effects of quality in the outlet headers on primary flow stability
  - Initial conditions: full power, full flow
  - Induced quality by one of two means: decreased primary pump speed or decreased primary pressure
  - Tests conducted without an interconnect, and with one of two interconnect types: dynamic or geometric

Summary

- Comprehensive database of integral thermal hydraulics experiments exists for CANDU
  - RD-14M scaled using approach of Ishii and Kataoka
  - Wide range of test types including LOCA, natural circulation, flow stability, transition to shutdown cooling, loss-of-flow, and single pump trip
  - Experiments performed over a wide range of conditions
  - Extensively used for code validation
- Existing integral thermal hydraulics database has been extended to ACR pressures and temperatures (RD-14/ACR)

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