RD-14M Facility Description

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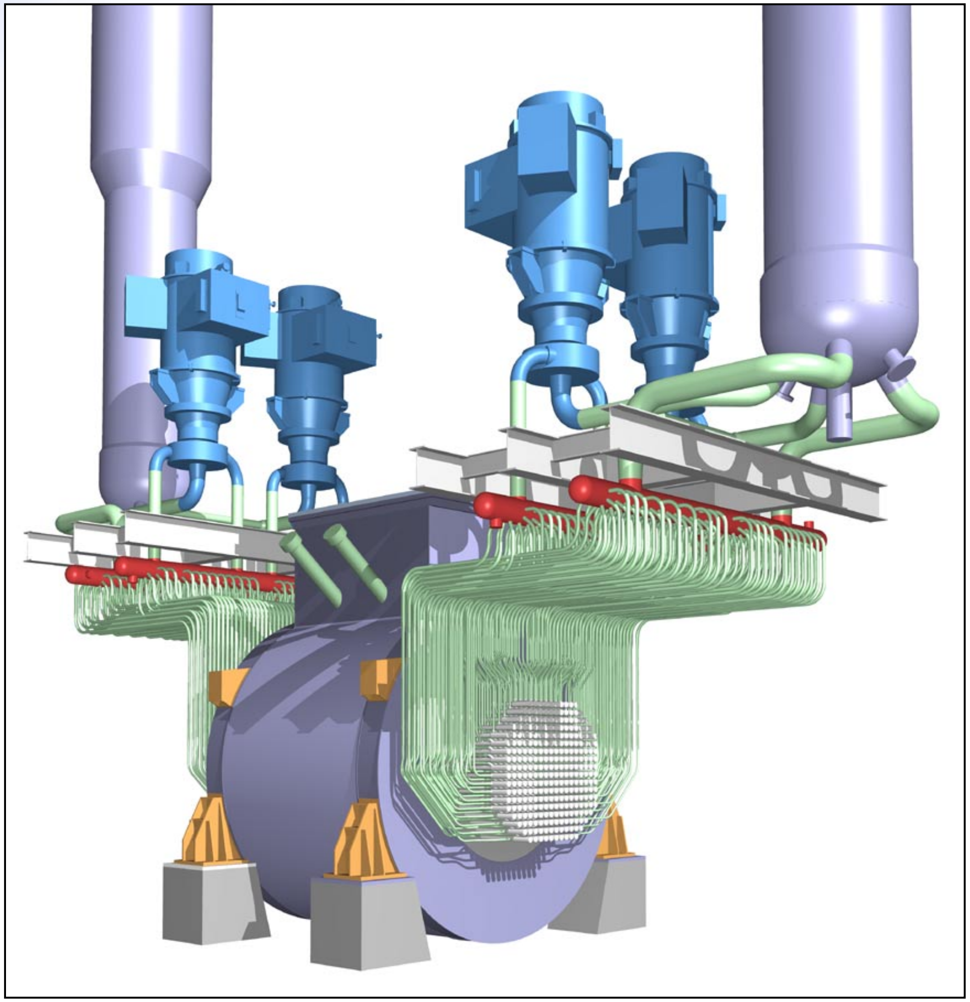
Outline

- History of CANDU integral facilities
- Details of RD-14M
  - Major components (e.g., test sections, fuel element simulators, ECC and blowdown systems)
  - Instrumentation
- Data acquisition
- RD-14/ACR configuration
- Electronic database

CANDU Integral Facilities

ACR Reactor Coolant System Layout



Showing piping above and below headers

All large reactor coolant piping above headers

CANDU Integral Test Facility Program

Objectives

- **To provide integrated experimental data on thermal hydraulic behavior in a multiple-channel test facility**
- **To improve the understanding of the underlying physical phenomena governing behavior**
- **Facilitate validation of codes**

History of CANDU Integral Test Facilities

• RD-4	(1974)	Small scale
• RD-12	(1976 to 83)	Half scale
• RD-14	(1983 to 87)	Full elevation One channel per pass Full-scale channels
• RD-14M	(1987 to present)	Full elevation Five channels per pass Scaled channels
• RD-14/ACR	(2001 to present)	Full elevation One channel per pass ACR pressures and temperatures Scaled channels

History of CANDU Integral Test Facilities - RD-14

The RD-14 facility was a full-elevation model of a typical CANDU reactor cooling system. It was built to provide improved understanding of CANDU thermal hydraulics and to expand databases to validate CANDU analysis codes.

<u>Key Feature</u> - single full-scale channel per pass

History of CANDU Integral Test Facilities - RD-14 (cont.)

- Types of Tests:
  - LOCA
  - Natural Circulation
  - Loss of forced flow
  - Steam-line break
  - Flow stability

History of CANDU Integral Test Facilities - RD-14M

- We wanted to study the interaction among parallel channels in a single pass in natural circulation and blowdown / ECC transients

- RD-14 was modified to a multiple channel geometry

CANDU Integral Test Facility: RD-14M

What is RD-14M?

RD-14M is a figure-of-eight loop possessing many of the physical and geometrical characteristics of a CANDU reactor cooling system (RCS).

RD-14M Program Objectives

To support reactor safety and licensing issues surrounding the CANDU RCS system by providing integrated experimental data on the thermal hydraulic phenomena in a figure-of-eight test facility under postulated accident conditions.

These data are used to:

- **Improve the understanding of underlying physical phenomena governing behavior**
- **Develop and validate models**
- **Enhance the ability to predict thermal hydraulic behavior in reactor specific geometries**

How Has RD-14M Been Used?

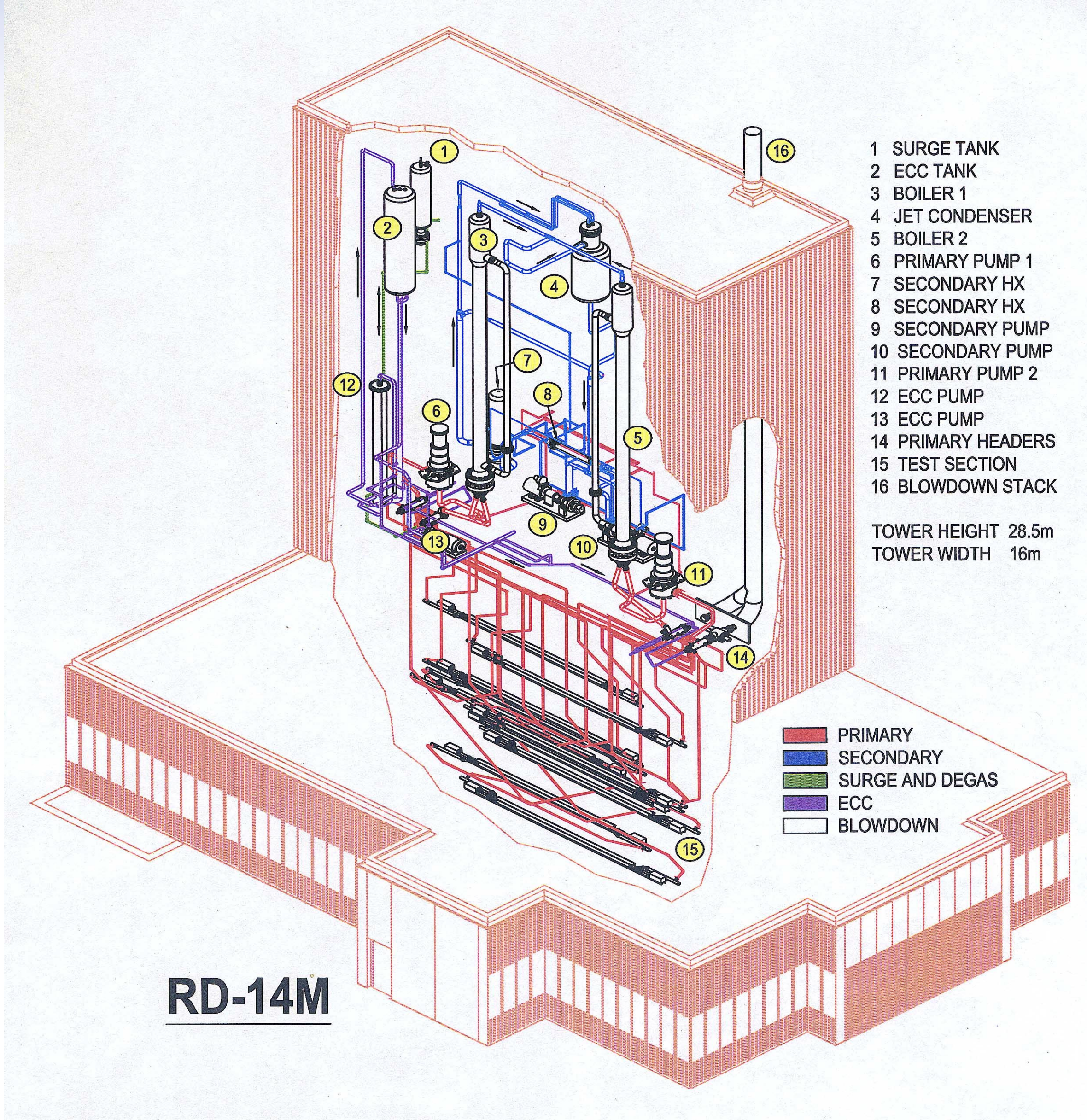
- Data on the initial blowdown, refill behavior and emergency core coolant (ECC) effectiveness for a range of LOCA conditions
- Data and analysis on the effectiveness of core cooling without forced flow
- Data on the effectiveness of header interconnects for mitigating flow oscillations
- Data on shutdown / maintenance cooling scenarios

Design Features of RD-14M

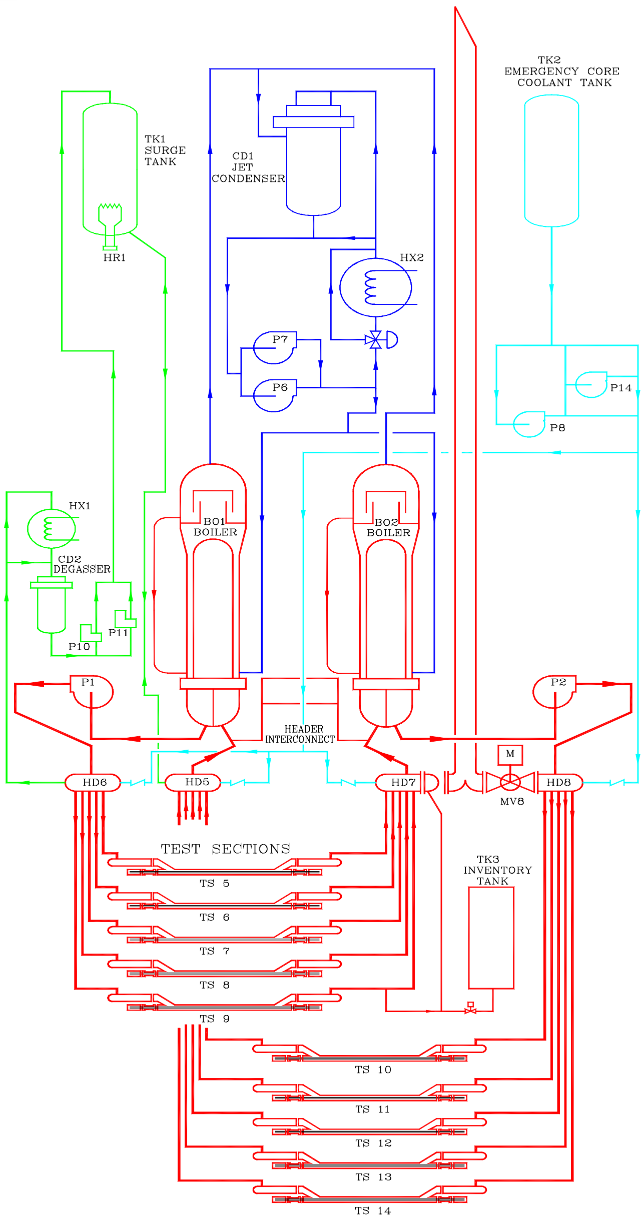
- Full elevation changes between major components and full linear dimensions
- Ten full length electrically heated channels
- Simulation of all RCS components - channels, end-fittings, feeders, headers, and steam generators
- Simulation of all phases of a LOCA scenario including break and ECC
- Natural circulation and shutdown / maintenance cooling simulation
- Full pressure and temperature conditions
- Extensively instrumented
- Dedicated data acquisition system

Major Components of RD-14M

- Reactor cooling system
- Secondary side
- ECC system
- Blowdown system
- Instrumentation and controls
- Power supplies


1 SURGE TANK
2 ECC TANK
3 BOILER 1
4 JET CONDENSER
5 BOILER 2
6 PRIMARY PUMP 1
7 SECONDARY HX
8 SECONDARY HX
9 SECONDARY PUMP
10 SECONDARY PUMP
11 PRIMARY PUMP 2
12 ECC PUMP
13 ECC PUMP
14 PRIMARY HEADERS
15 TEST SECTION
16 BLOWDOWN STACK
TOWER HEIGHT 28.5m
TOWER WIDTH 16m
PRIMARY
SECONDARY
SURGE AND DEGAS
ECC
BLOWDOWN
RD-14M

RD-14M Flow Schematic



Scaling - Philosophy

- Facility designed to preserve DYNAMIC SIMILARITY with CANDU RCS based on a developed set of scaling criteria
  - Similar fluid mass flux, transit times, and pressure and enthalpy distributions in the RCS
- Where scaling criteria could not be applied, past experience and engineering judgement were used

Reactor Cooling System

- Contains all of the major RCS components that are present in a CANDU reactor
- Full-scale elevation between major components
- In general, component dimensions are scaled
- Design conditions:
  - Pressures up to 12.5 MPa(g) at temperatures up to 350ºC
  - Maximum power 11 MW
  - Maximum flow 24 kg/s
  - (RD-14/ACR: 16.5 MPa(g) and 343ºC)

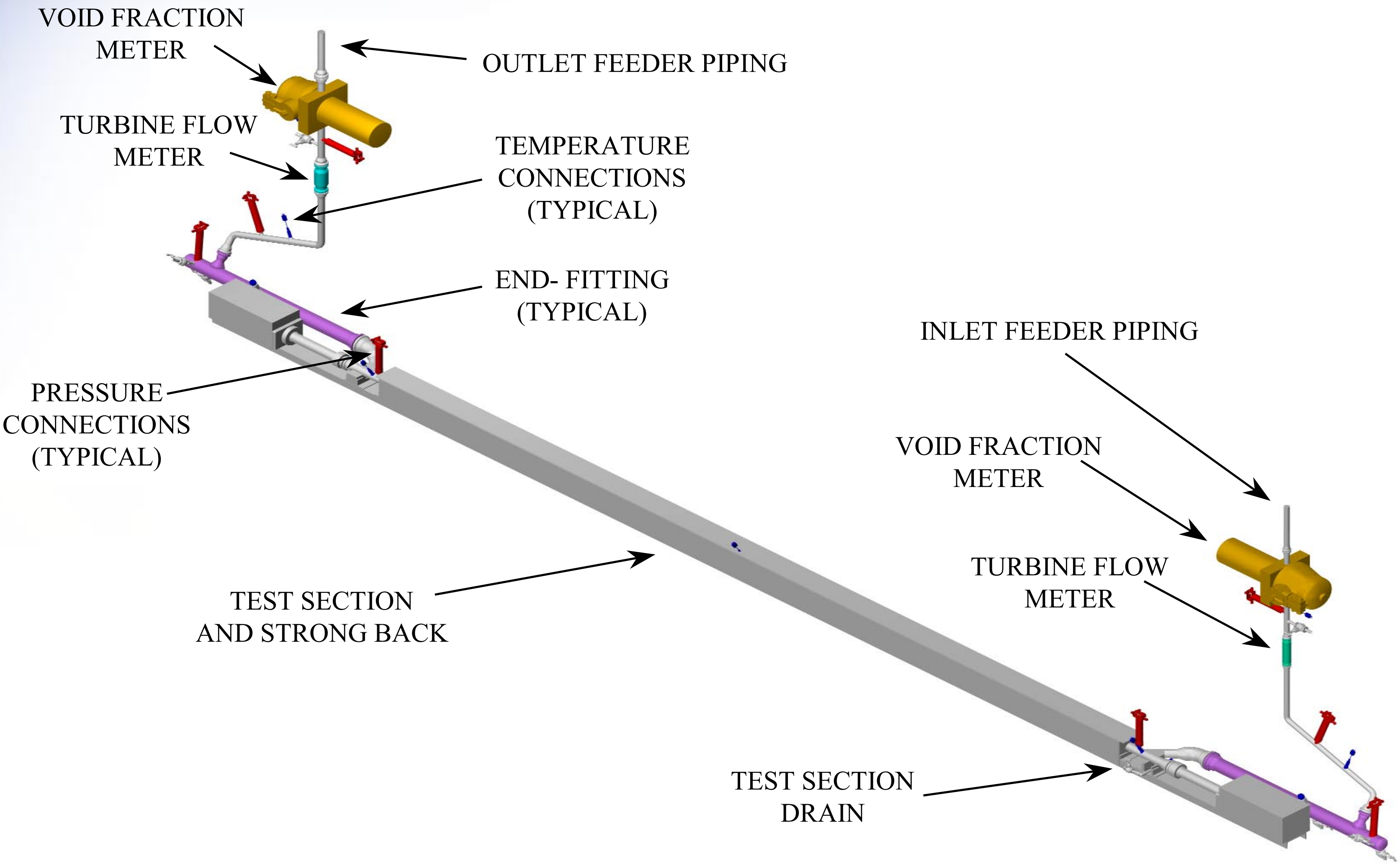
RCS - Major Components

- Heated sections
- Feeders
- Headers
- Steam generators
- Pumps
- Surge system (pressurizer)
- Header interconnect

Test Sections - 1

- Reactor core is represented by ten test sections (five per pass)
- Each test section consists of:
  - A full-length assembly of seven fuel-element simulators
  - Inlet and outlet end-fitting simulators
  - Pressure tube
  - Strongback

Test Sections - 2



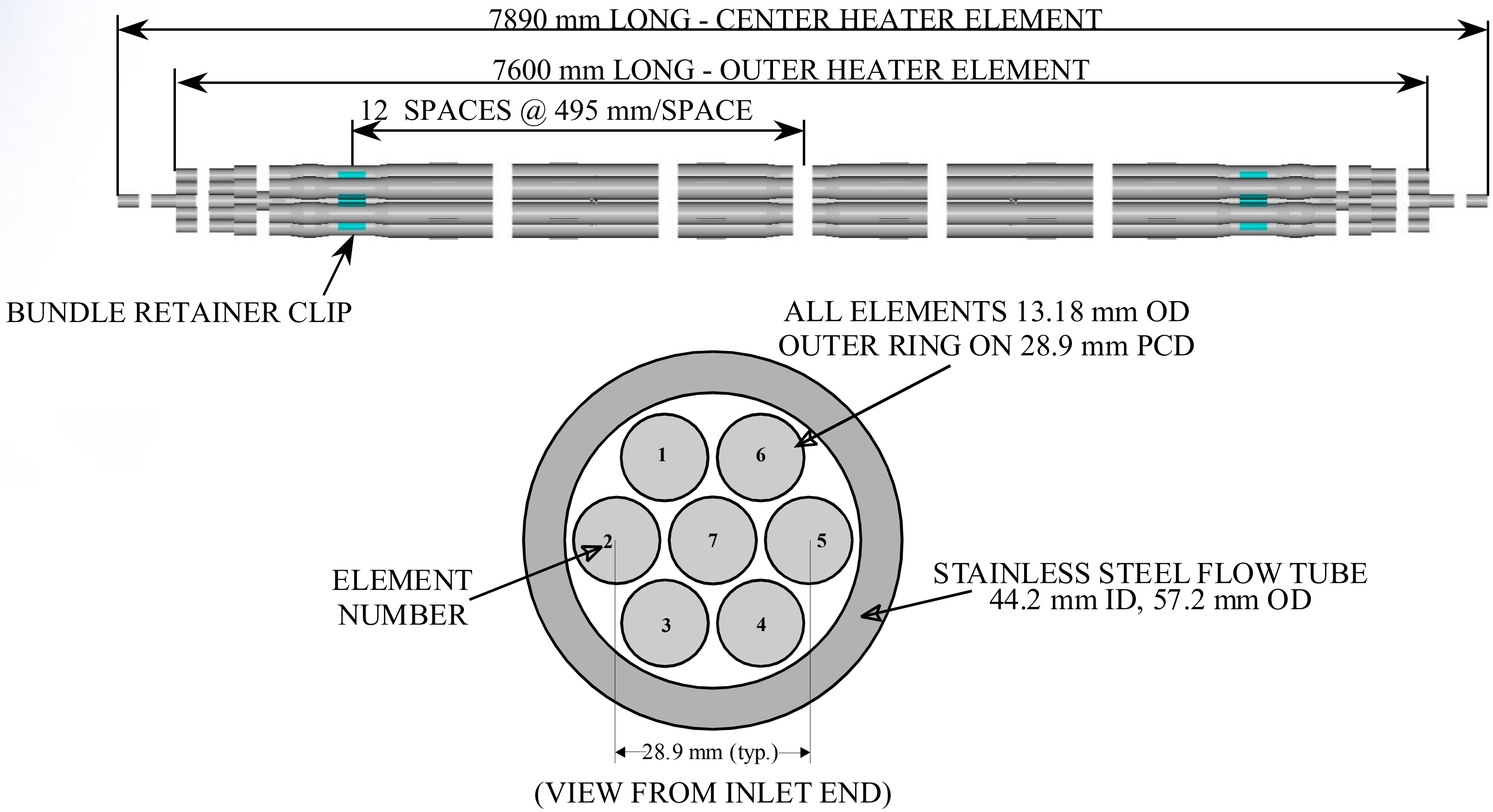
Heated Sections - Fuel Element Simulators (FES)

- **Construction:**
  - Centre core of magnesium oxide
  - Surrounded by a 7.62-mm O.D. electrically heated Inconel-625 tube
  - 13.18-mm O.D. type-304 stainless steel cladding
  - Cladding electrically insulated from the heated tube by a boron nitride annulus

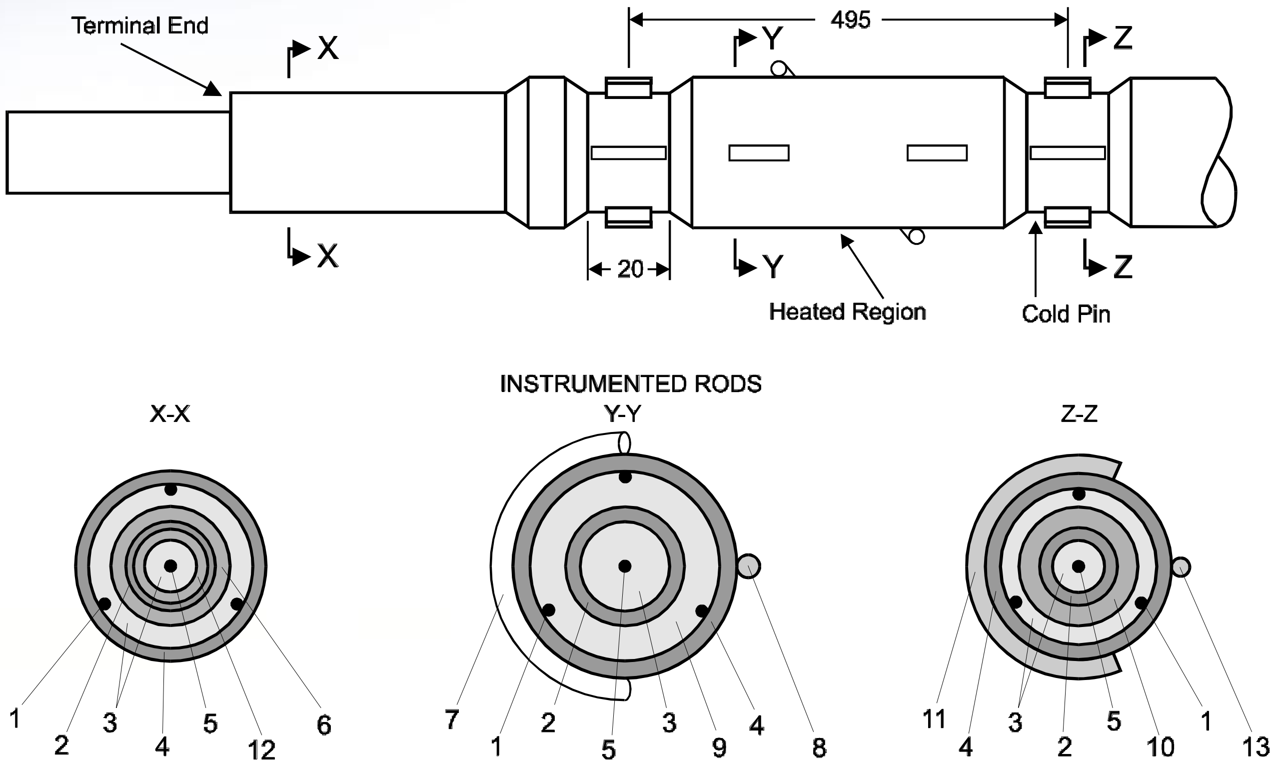
Heated Sections - Fuel Element Simulators (FES) Scaling

- Since a CANDU channel contains 37 fuel elements, the flow in the RD-14M seven-element channels was reduced proportionately
- The total flow of the five channels in a RD-14M pass equals the core average flow of a CANDU channel
- The total power of the five channels in a RD-14M pass equals the core average power of a CANDU channel
- The average power per heated pin in RD-14M is equal to the average power per fuel element in the CANDU reactor

Heated Sections - Fuel Element Simulators (FES)



Fuel Element Simulators

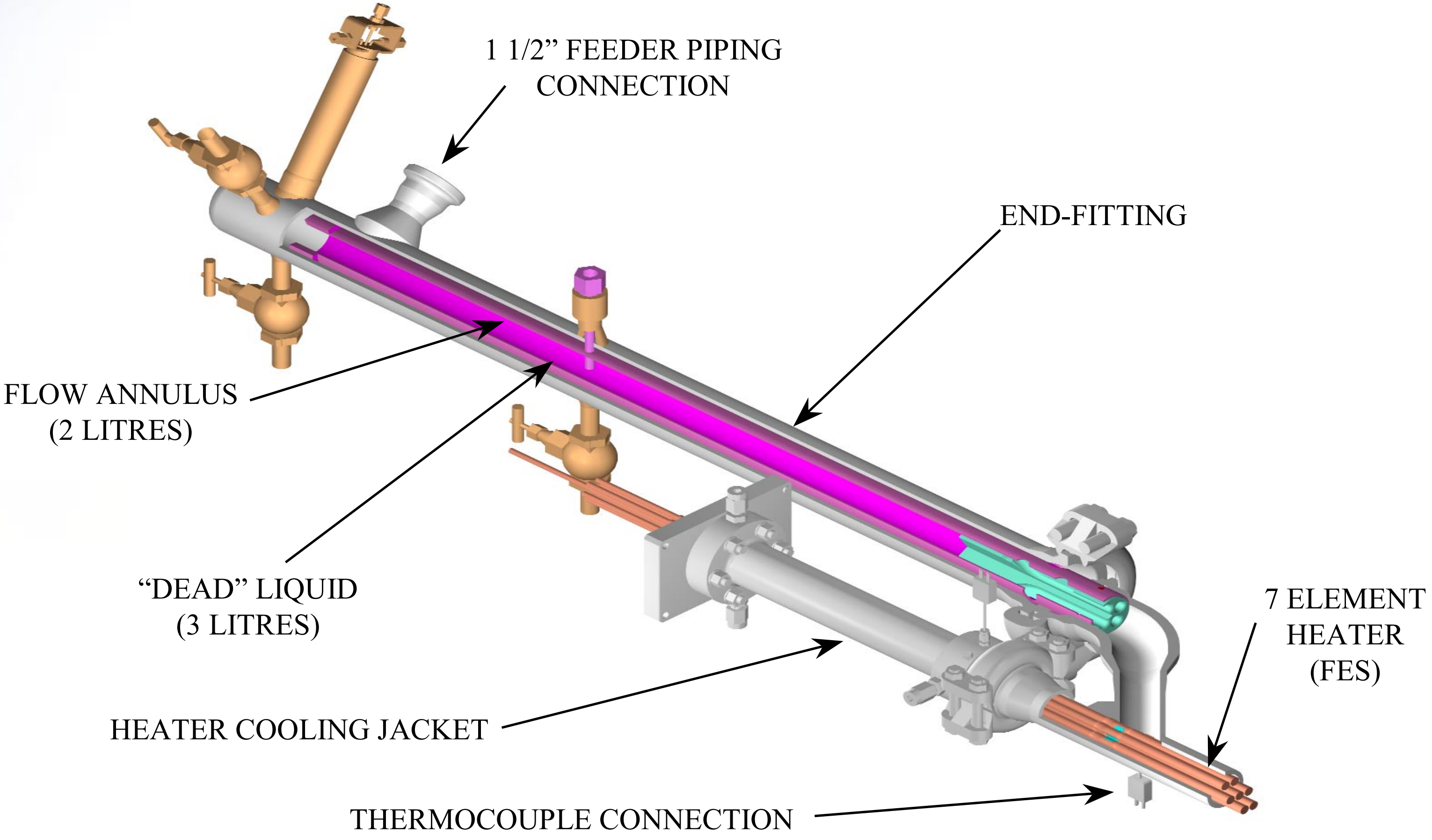


1. Sheath Thermocouple
2. Inconel 625 Heater Tube
3. MgO
4. 304 Stainless Steel Sheath
5. Core Thermocouple
6. Nickel 200 Terminal End Oversleeve
7. Spiral Spacer Wire
8. Bundle Bearing Pad (outer elements only)
9. Boron Nitride
10. Nickel 200 Cold Pin Oversleeve
11. Bundle Retaining Clip
12. Copper Tube Terminal End
13. Cold Pin Spacer Wire

Heated Sections – End-Fittings

- CANDU reactor end-fittings allow access to the fuel for online refueling
- RD-14M end-fittings are designed to simulate the reactor end-fittings with similar pressure drop and scaled thermal mass and fluid volumes
- Major end-fitting components and sections are simulated:
  - Liner tube and flow annulus
  - Shield plug
  - Deadspace

Test Sections – End-Fitting to Channel Connection



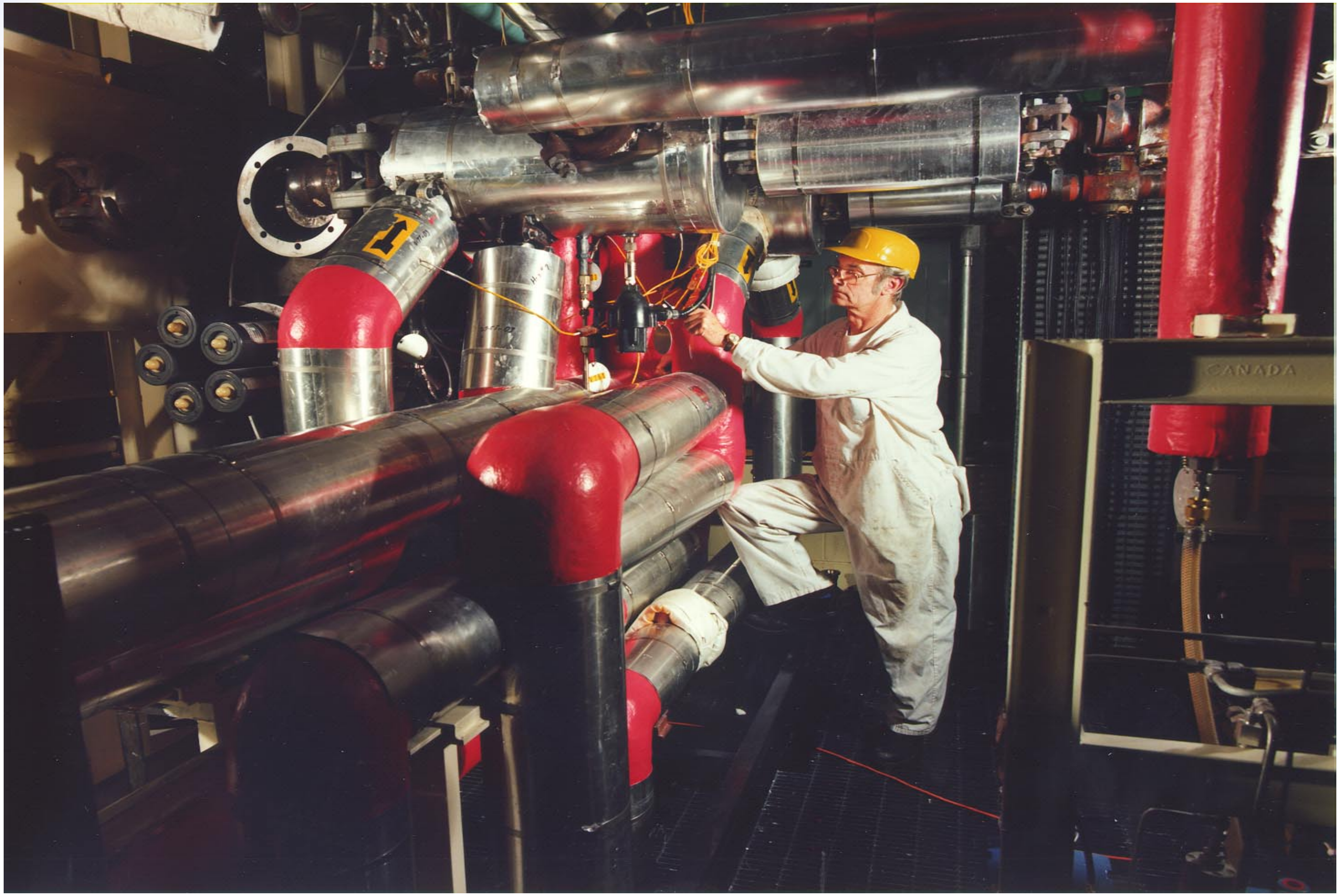
Feeders

- Five feeder / channel geometries representing three middle channels, one top channel and one bottom channel of a reactor
- Flow balancing orifices installed in some inlet feeders of both the reactor and RD-14M
- Flow resistance of RD-14M orifices has been characterized (RC-2491)

Feeders - Scaling

- Full vertical height and linear length
- Feeder connections to the headers attach at various angles
- Feeder geometries cover the range of horizontal lengths and flow restricting orifices present in the CANDU reactor

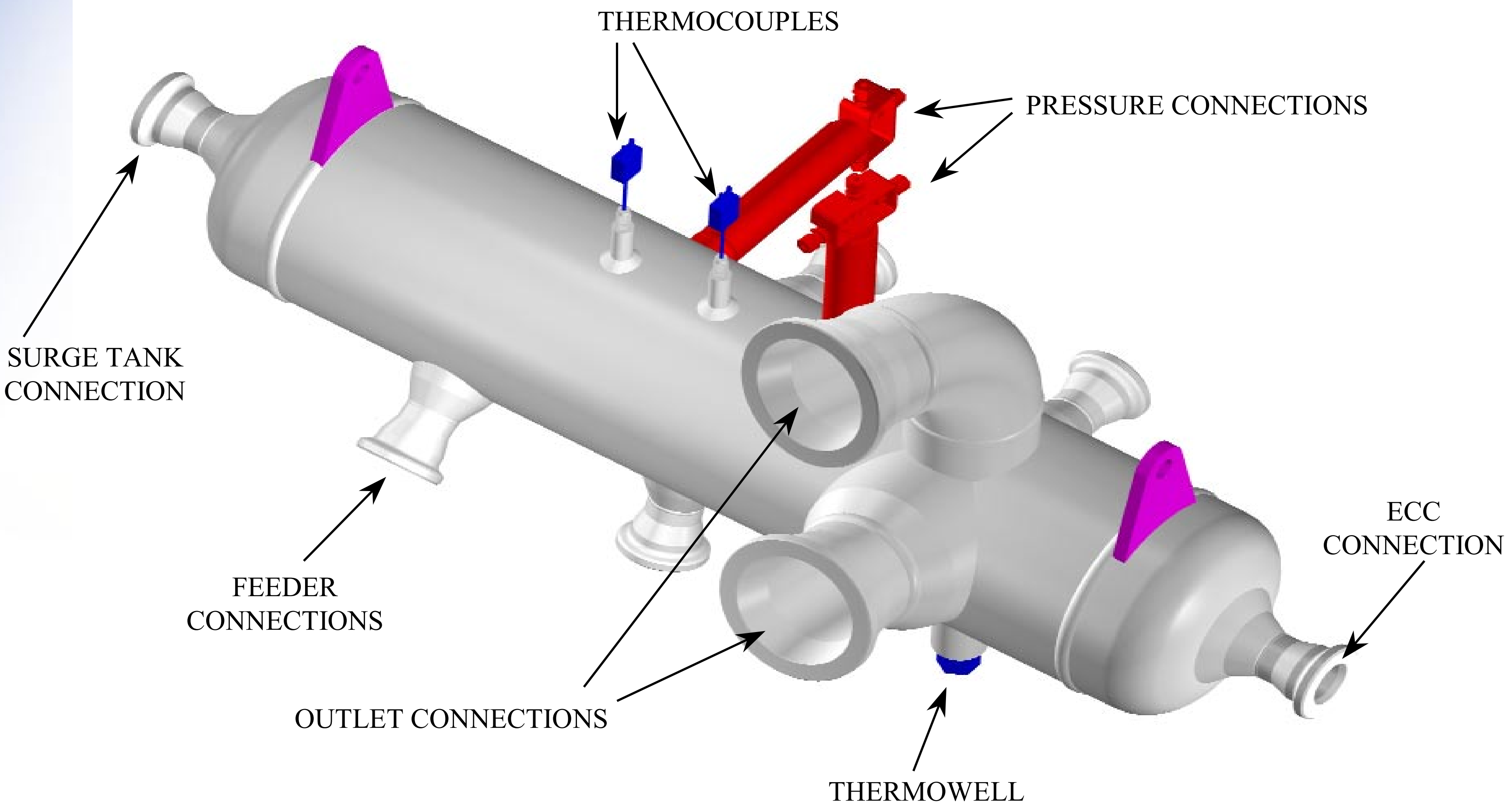
Feeders



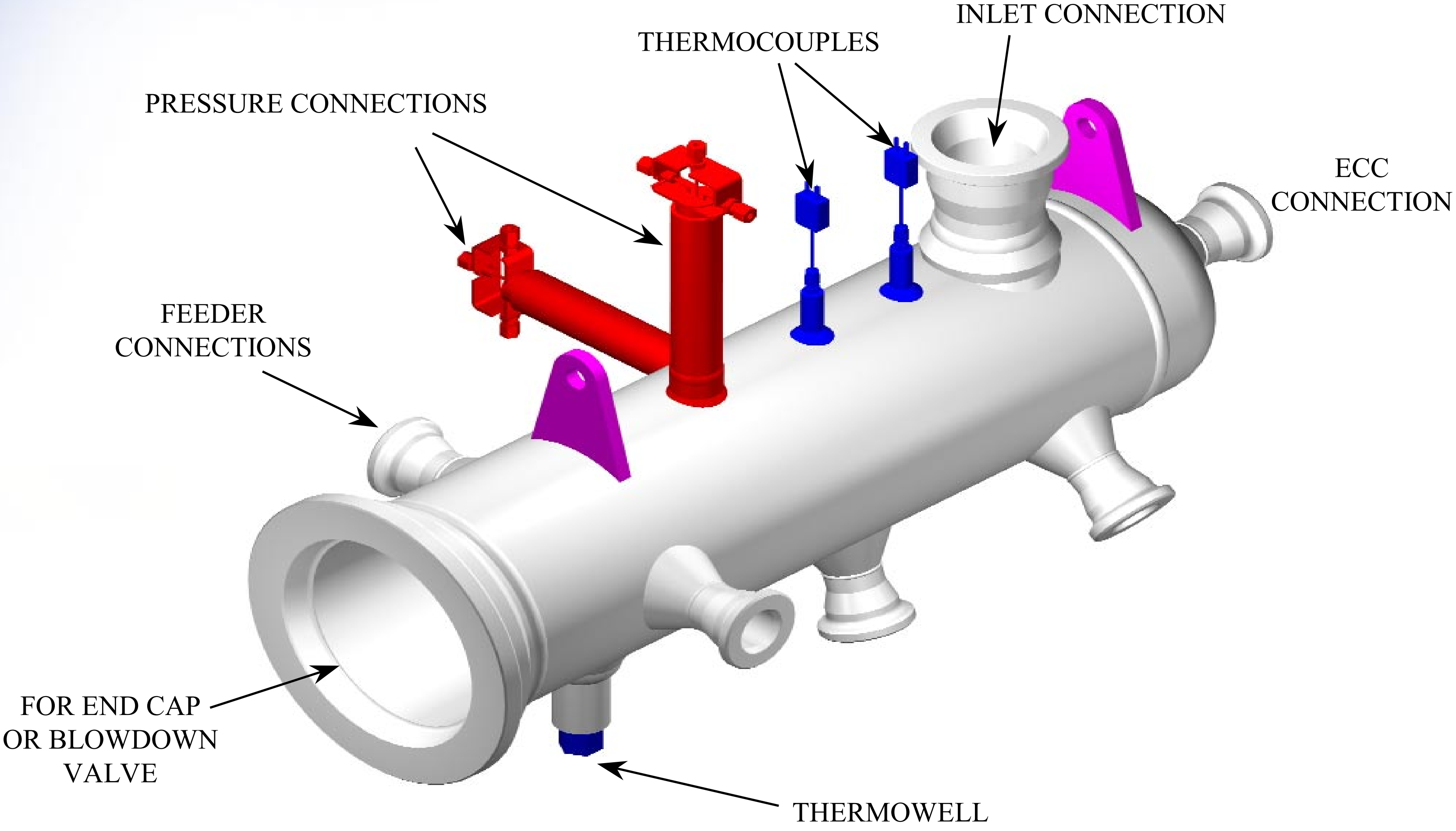
Headers

- Four headers total - an inlet and an outlet header for each pass
- Feeders connect to a header at various angles
- ECC into the ends of each header
- Header 8 (an inlet header) also contains a connection to the blowdown system
- Headers are scaled based on physical considerations such as flow path, volume, feeder-nozzle orientation, and thermal mass

Outlet Header 5



Inlet Header 8



Steam Generators - 1

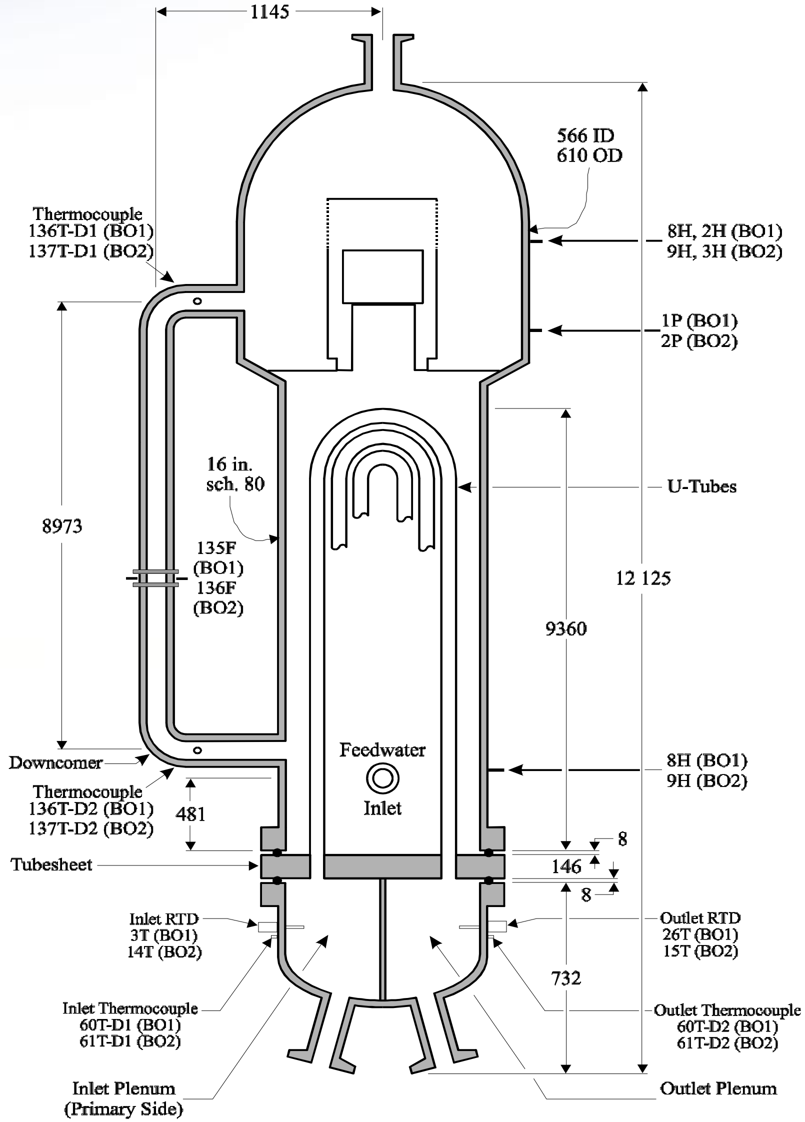
- Recirculating U-tube steam generators
- Spiral arm steam separators located in the upper end of the shell
- RD-14M steam generators scaled approximately 1:1 in terms of vertical height and individual tube diameter, mass flux, and heat flux

Steam Generators - 2

	RD-14M	Typical CANDU Reactor
Number of tubes	44*	3550
Tube I.D. (mm)	13.6	13.8
Tube O.D. (mm)	15.8	16.0
Tube Wall Thickness (mm)	1.1	1.1
Tube Material	Incoloy-800	Incoloy-800
Average Tube Length (m)	18.8	17.5

Note * : Some tubes have been blocked due to leakage. The actual number of operating tubes for an experiment may be less than 44.

Steam Generators - 3



Steam Generators - 4

Main Coolant Pumps - 1

Bingham centrifugal pumps

- Vertical, single stage design with single suction and discharge
- Variable speed AC motor
- Pump head 220 m at 24 kg/s flow

Characterization

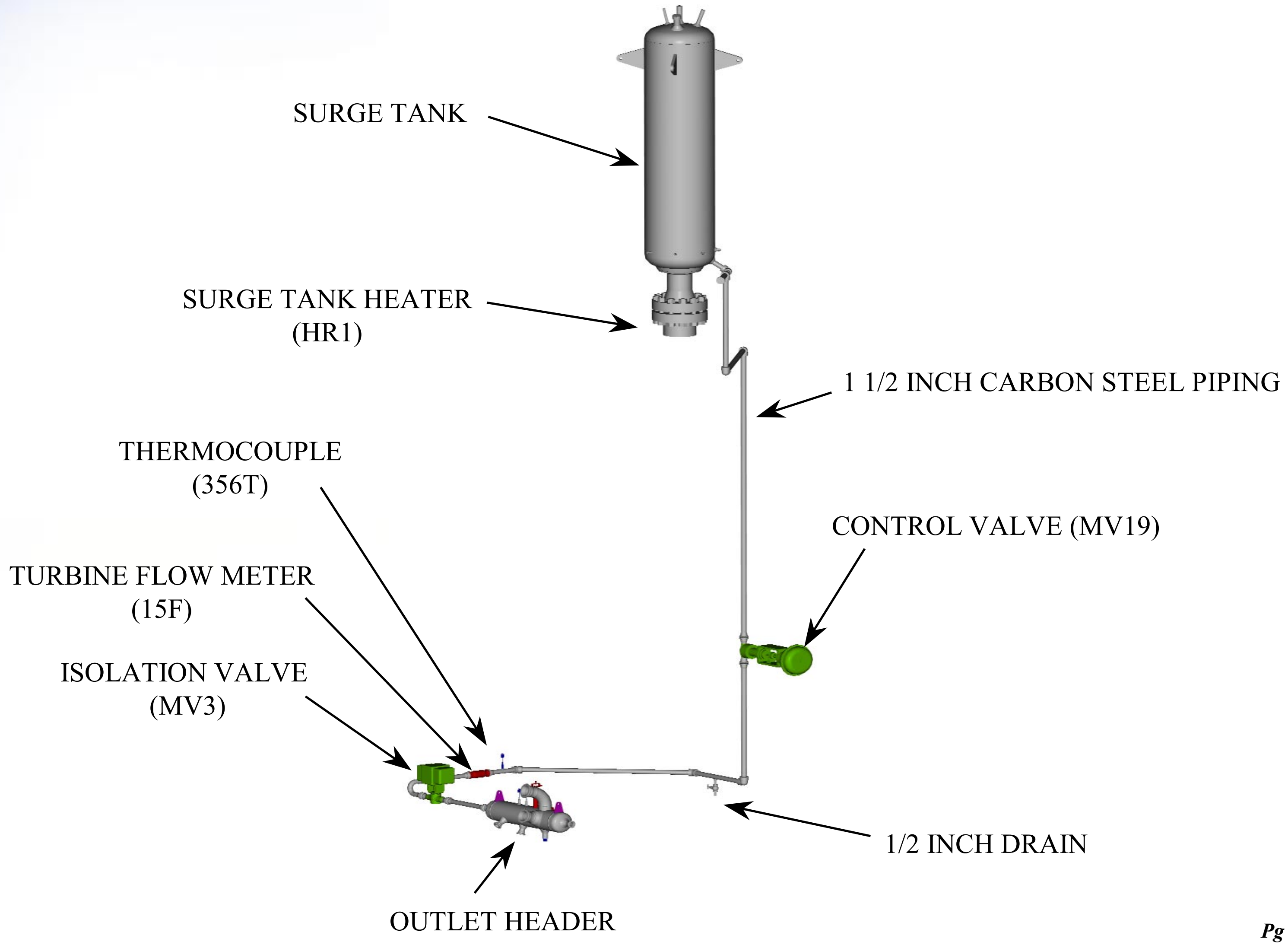
- Performance has been characterized under single-phase liquid conditions

Main Cooling Pumps - 2

Surge System (Pressurizer) - 1

- Two functions:
  - Means of controlling the RCS pressure
  - Accommodates expansion and contraction of the RCS coolant due to density or phase change
- Surge tank contains a 100-kW immersion heater that is used to pressurize the system
- Usually isolated just prior to starting a transient experiment

Surge System (Pressurizer) - 2



Miscellaneous - Insulation and Heat Losses - 1

- RCS components insulated to reduce heat losses:
  - Typically light-weight, low-thermal conductivity (0.091 W / (mK)) hydrous calcium silicate pipe insulation
    - 65-mm thick for nominal pipe sizes from 2 to 3.5 inches
    - 76-mm thick for 1-, 1.25-, and 4-inch pipe
  - Heated sections insulated with granular vermiculite fill

Miscellaneous - Insulation and Heat Losses - 2

- **Reactor feeders are enclosed in a cabinet that provides highly effective insulation**
- **RD-14M RCS heat losses have been characterised (RC-2491). Heat losses are evenly distributed.**
- **As a fraction of channel power, RD-14M heat losses, under natural circulation conditions, are larger than a CANDU reactor**
- **As a consequence, RD-14M feeders and end-fittings are trace heated to balance expected heat losses**
  - **Not used for all tests**

Secondary Side

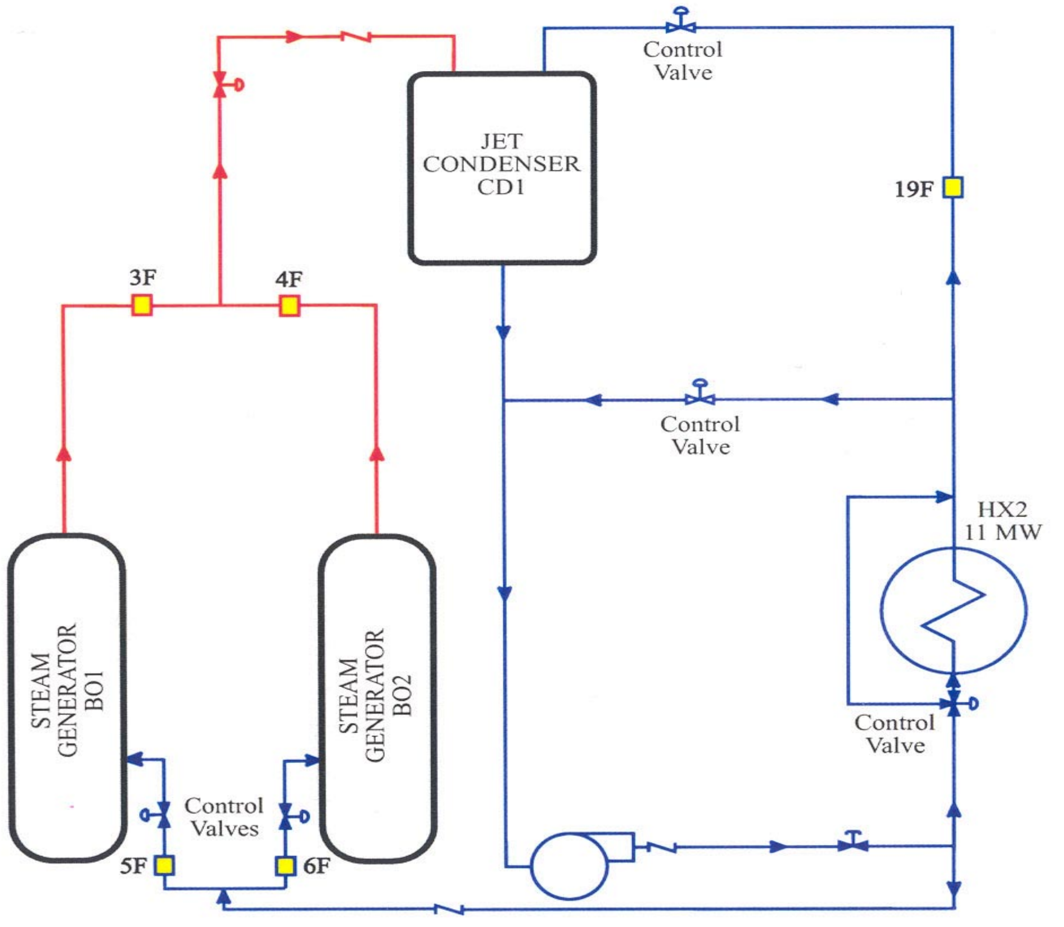
- Steam generators have full vertical height
- Remainder of RD-14M secondary side exists as a heat sink to remove energy from the RCS. It provides similar boundary conditions as a CANDU reactor's secondary side.
- Two configurations:
  - High-power configuration capable of removing 500 kW to 11 MW
  - Low-power configuration capable of removing < 500 kW (used during most natural circulation experiments)

Secondary Side - Controls

- Level controls for each steam generator
- Feedwater temperature control
- Secondary side pressure

Tests are usually run with a fixed level in each of the steam generators, a fixed secondary side pressure, and a fixed feedwater temperature

Secondary Side
(High Power Configuration Shown)



ECC System - 1

RD-14M configuration is for ECC injection into each of the headers

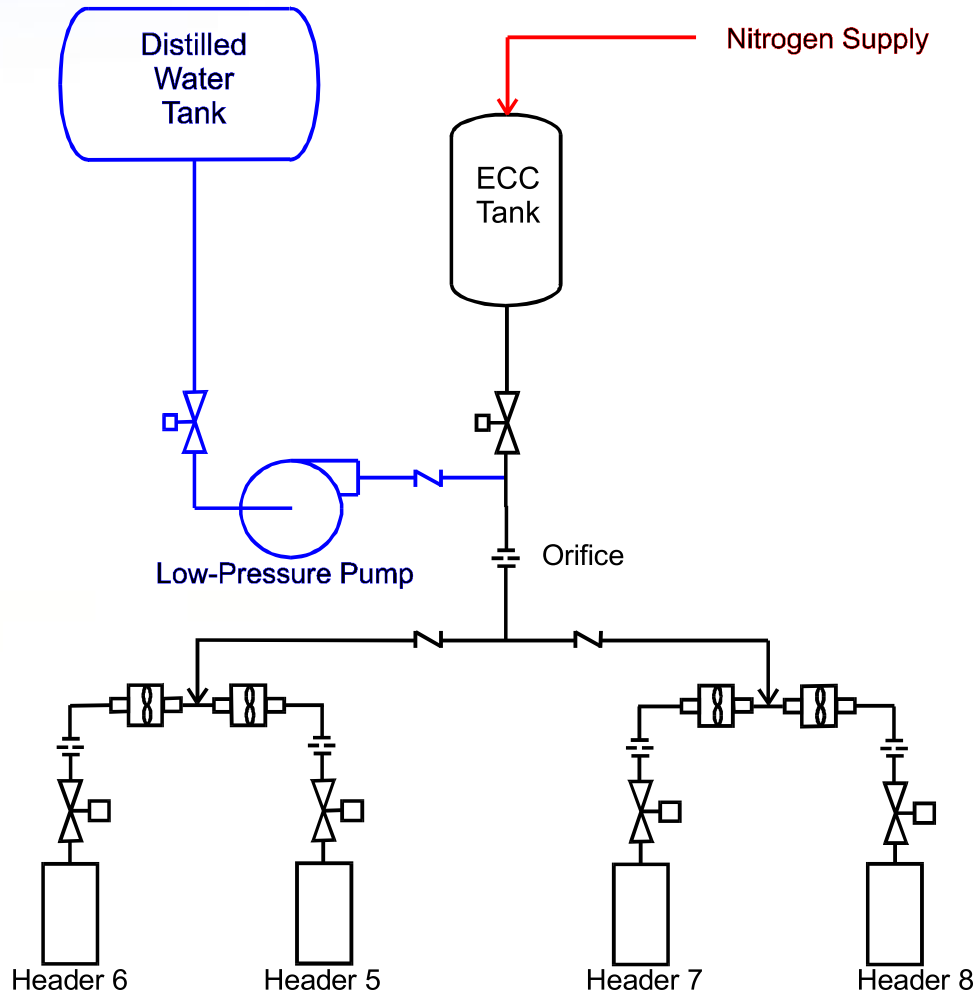
High-Pressure Phase

- **First ECC following a LOCA**
- **In a CANDU reactor the system consists of either high-pressure accumulator tanks, or high-pressure pumps. Both of these system types can be simulated in RD-14M.**

Recovery Phase

- **Liquid that has accumulated at the bottom of the containment building is circulated through a heat exchanger and injected back into the RCS**
- **Simulated in RD-14M using a low pressure (1.5 MPa(g) head) pump**

ECC System - CANDU 6 Configuration



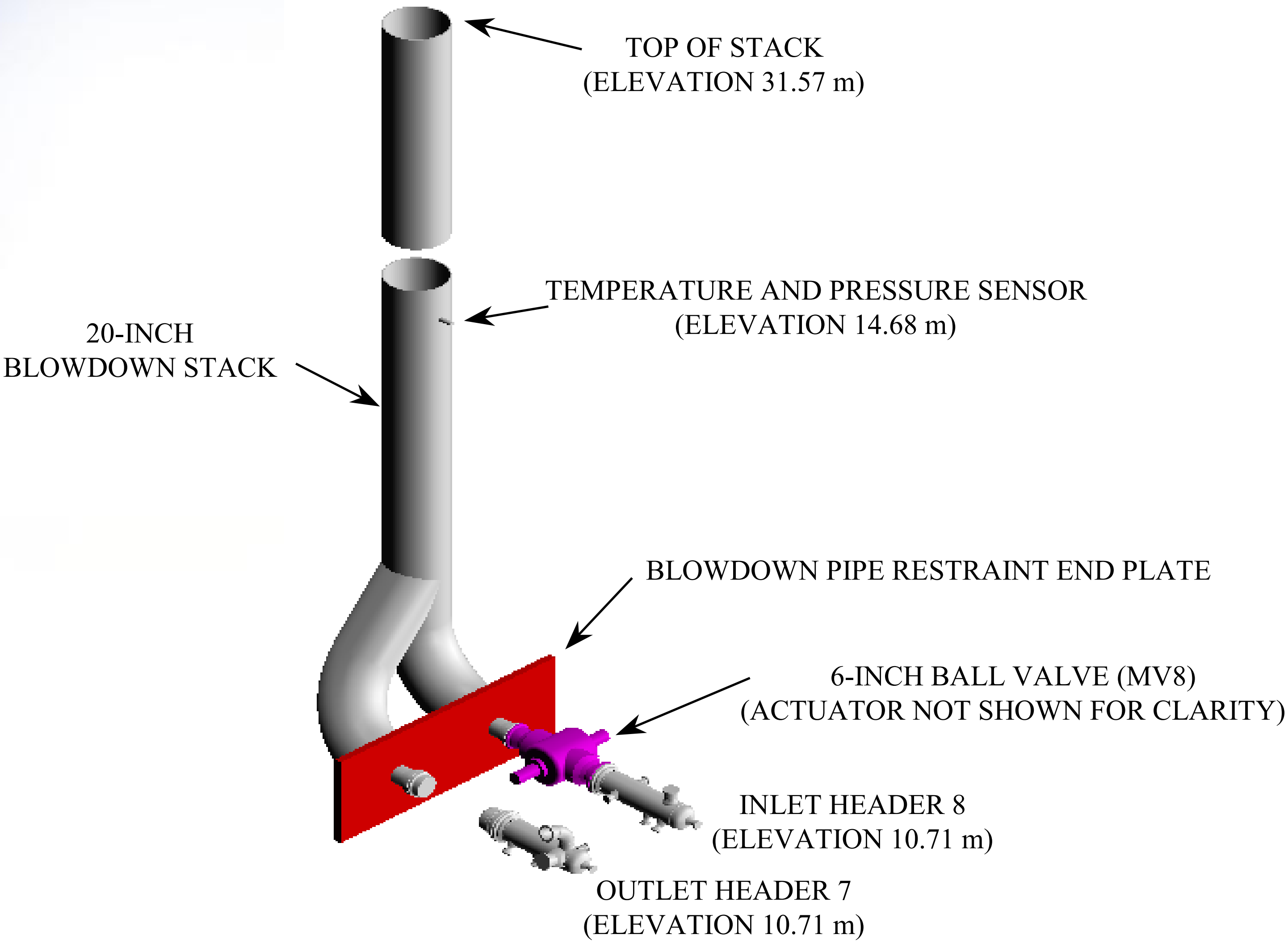
ECC System - 2

- **High pressure and low pressure ECC pumps have been characterized (RC-2491)**
- **In RD-14M, the ECC isolation valves are usually opened when the RCS pressure drops below a setpoint value (typically 5.5 MPa(g))**

Blowdown System - 1

- Used to simulate breaks in the RCS
- Inlet header or outlet header breaks can be simulated
- A blowdown is initiated by opening a fast-acting valve connected to the header
  (both a 2-inch or a 6-inch valve can be used)
- An orifice plate is installed upstream of the fast-acting valve
- A range of orifice sizes can be installed to simulate varying break sizes

Blowdown System - 2



Blowdown System - 6 inch Valve

Instrumentation

- Instruments strategically located to measure key thermal hydraulic parameters
- Both component and geometric arrangement considered
- High and low range instrumentation and duplication to ensure accuracy
- Regular calibration schedule against traceable standards

Instrumentation - Pressure Drop

- Approximately 60 pressure-drop measurements around the RCS circuit and various measurements on the secondary side and the ECC system
- Pressure drop across all potential flow paths measured
- Duplicate multi-range instruments on key components (e.g., heated sections, pumps, etc.) to accurately measure a large range of pressure drop
- Majority of instruments are Rosemount 1151DP cells

Instrumentation – Pressure - 1

- Approximately 24 RCS pressure measurements made at each header and at the inlet and outlet to each channel
- 1 surge tank / pressurizer pressure measurement
- 3 secondary side pressure measurements made in each steam generator and in jet condenser

Instrumentation – Pressure - 2

- Majority of instruments are Rosemount 1151GP cells
- Druck pressure transducers are used in selected key locations to give faster response time
- All pressures recorded and reported as gauge
- Response times have been characterized

Instrumentation - Flow Rate - 1

- 22 RCS flow measurements located at entrance and exit of each channel and at the main coolant pump discharge (turbine flow meter)
- Mass flow rate of steam leaving each steam generator (orifice plate with mass flow computer)
- Feedwater flow rate to each steam generator (turbine flow meter)
- Downcomer flow rate in each steam generator (orifice plate)

Instrumentation - Flow Rate - 2

- Flow to inventory tank in natural circulation tests (turbine flow meter)
- ECC flows to each header (turbine flow meter)
- Mass balance check prior to each experiment
- Turbine flow meters calibrated to traceable standards using gravimetric technique
- Pressure drop across turbine flow meters has been characterized (RC-2491)
- Response times have been characterized

Instrumentation – Temperature - 1

- Over 90 temperature measurements in the RCS including inside select steam generator tubes (K-type thermocouples and RTD's)
- Approximately 280 temperature measurements of Fuel Element Simulators (K-type thermocouple)
- About 30 temperature measurements in the secondary side including shell side measurements at various locations (K-type thermocouple and RTD's)

Instrumentation – Temperature - 2

- Energy balance before tests
- RTD’s calibrated to traceable standards
- Thermocouple transmitters calibrated to traceable standards
- Thermocouples have been verified to be within NBS standards
- Response time of thermocouples has been characterized

Instrumentation - Power

- Individual power measurements to each channel using thermal RMS voltmeters and ampmeter
  - This is the most accurate measurement of channel power
  - Very slow scan rate (data logged separately from the main data acquisition system)
- Voltage and power from each of the four power supplies using Wattmeters
  - Less accurate (measurements require correction) but much faster
  - Scanned by the main data acquisition system

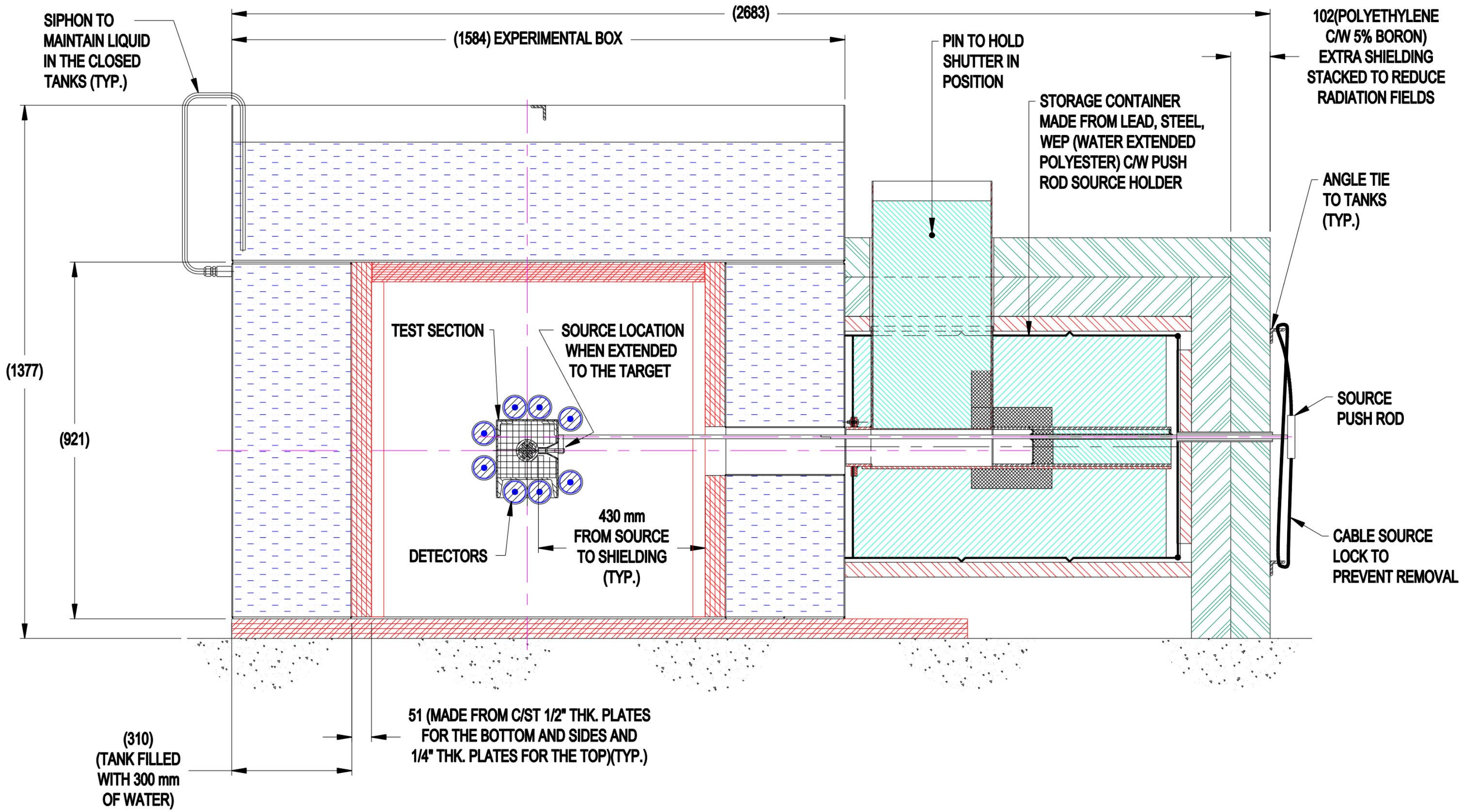
Instrumentation - Void Fraction

- 4 two-beam gamma densitometers measuring steam generator inlet and outlet fluid density
- 2 three-beam gamma densitometers measuring fluid density at main coolant pump discharge
- 20 single-beam densitometers measuring fluid density at inlet and outlet to each channel
- Conductivity probes and fibre optic probe for local (qualitative) measurements

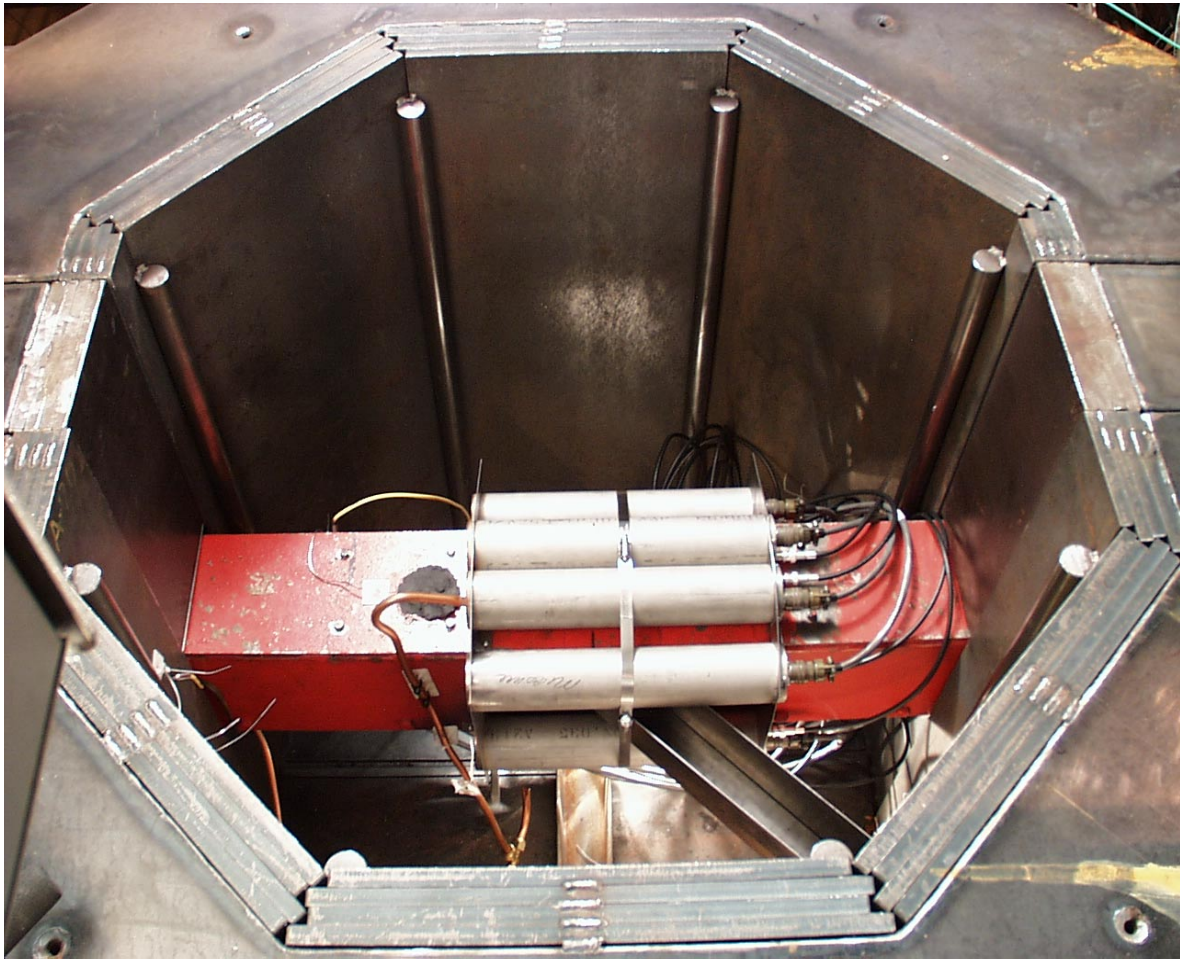
Measurement of RD-14M Channel Void During Large LOCA

- Problem:
  - Ratio of metal to fluid volume in the RD-14M channel (1.5) limits the sensitivity to changes in void fraction
  - Fast response rate required to capture void-fraction changes during the early phase of a large LOCA
  - Reasonable measurement accuracy required (10% void-fraction uncertainty)
- Solution - Neutron scatterometer:
  - Utilizes fast neutrons that are not easily absorbed by channel metal mass
  - Fast neutrons are moderated and scattered by liquid water in the channel
  - High sensitivity to channel void
  - Overall uncertainty of the neutron scatterometer during a LOCA is ±10% void

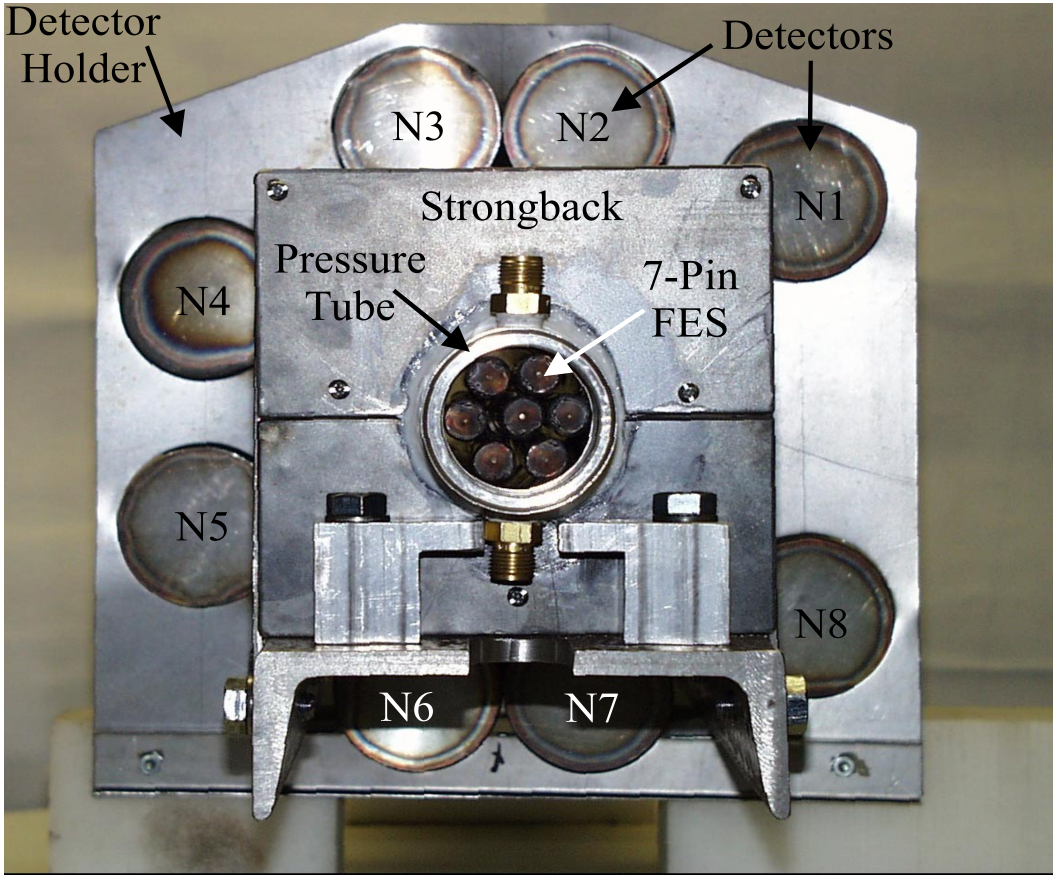
Side View - Source Deployed



Inside of Scatterometer



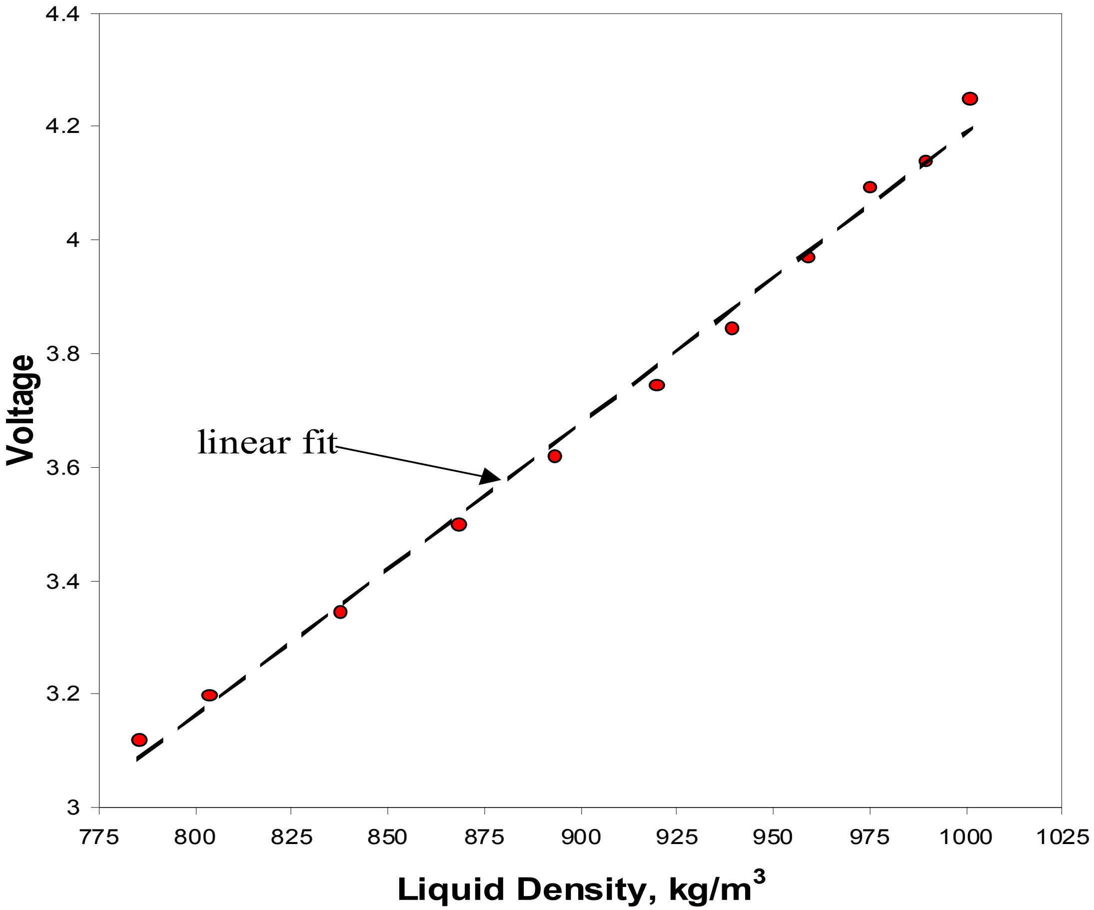
Location of Detectors (Simulated Test Section)



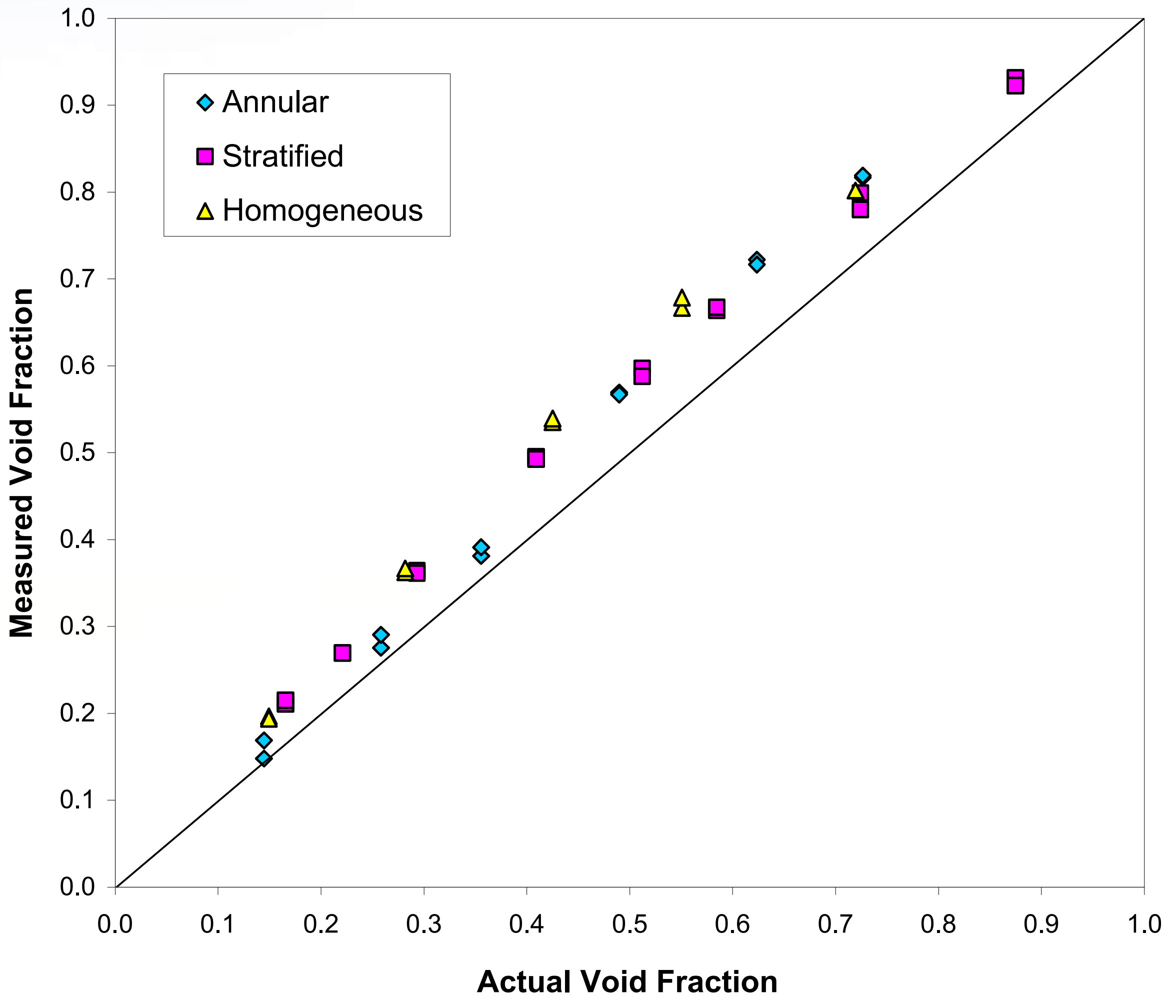
Neutron Scatterometer

- **The neutron scatterometer has been extensively characterized**
  - **Variation with liquid density – correction applied to detector output**
  - **Effect of flow regime/non-linearity – correction applied to detector output**
  - **Time response of overall system (detectors and electronics) – correction applied to detector output**
- **Overall uncertainty of the neutron scatterometer (after all corrections and uncertainty source terms taken into account):**
  - **±10% void**
  - **This uncertainty has been shown to be valid under both steady-state and transient conditions**

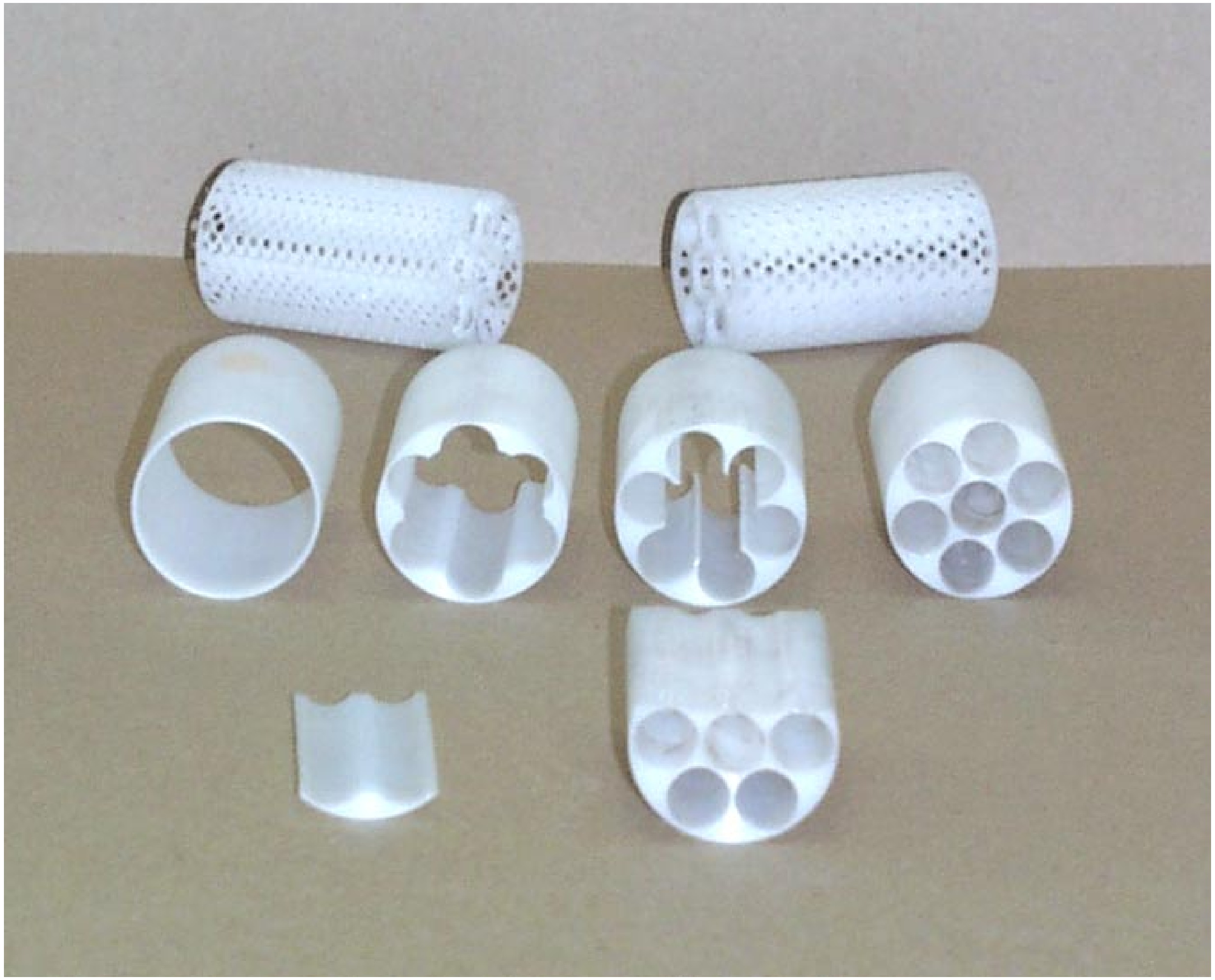
Variation of Detector Output with Liquid Density



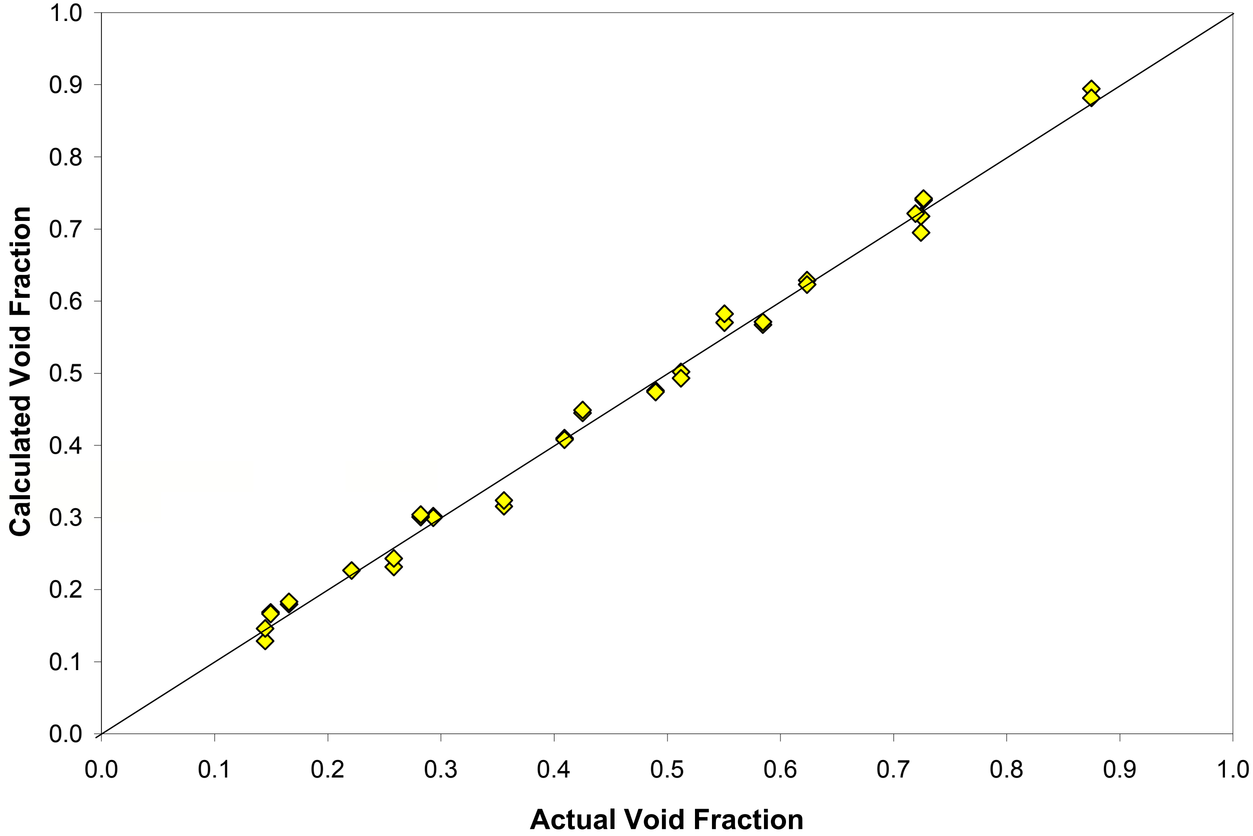
Effect of Flow Regime



Polyethylene Spool Pieces (Flow Regime Tests)



Void Fraction After Correction for Non-Linearity



Instrumentation - Miscellaneous

- Level measurements in pressurizer (surge tank), inventory tank, secondary side jet condenser, and ECC inventory tanks
- Collapsed liquid level measurements in each steam generator and steam generator drum
- Speed and current for each main coolant pump

Instrumentation - Data-Acquisition System

- Computer Products A / D system
- 8 chassis, 12-bit A / D conversion with 120 differential inputs for a total of 960 input channels
- Maximum sampling rate of 20,000 samples/sec. for a single channel
- Typical full-instrument scan rate for an experiment is 10 to 20 scans/sec. (scan rate is the rate that the full complement of instrumentation is sampled)

Instrument Measurement Error

- **Detailed uncertainty analysis procedures have been developed for all instruments**
  - **Based on an ANSI standard for uncertainty analysis, and consistent with a similar ISO specification**
  - **Utilizes the calibration database to give calibration uncertainty, non-linearity, and calibration drift**
  - **Calibration drift based on:**
    - **Pre- and post-test calibration data, or**
    - **Historical data**

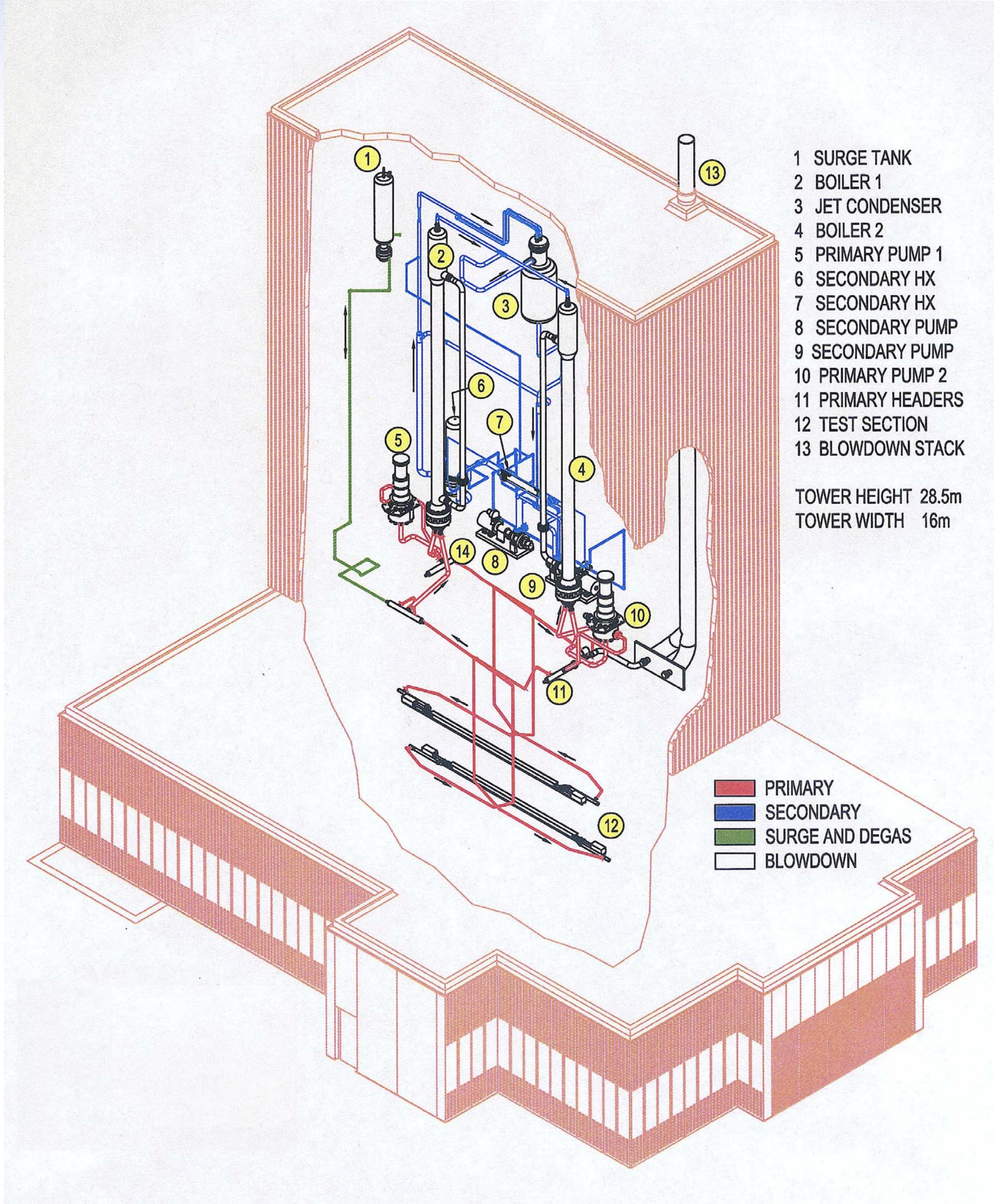
Instrument Measurement Error

- Selected instruments have corrections
  - Rosemount Differential Pressure Cells
    - Zero shift with static line pressure (has been characterized in loop)
    - Span shift with static line pressure
  - Certain thermocouple transmitters require correction for non-linearity
  - Power measurements using Wattmeters
- Time response of most instruments has been characterized
  - First-order response (time constant), or
  - Second-order, critically damped response (time constant), or
  - Second-order, over-damped response (time constant and damping coefficient)

RD-14/ACR

- **The RCS of the RD-14M facility was modified in 2001 to run at ACR pressure and temperature**
  - **This was an incremental change in the facility to obtain data for code validation at higher pressures and temperatures**
- **Above header piping mostly the same as the standard RD-14M configuration**
- **Headers and below header piping built specifically for the RD-14/ACR configuration**
  - **Able to switch between standard RD-14M configuration and the RD-14/ACR configuration**

RD-14/ACR


1 SURGE TANK
2 BOILER 1
3 JET CONDENSER
4 BOILER 2
5 PRIMARY PUMP 1
6 SECONDARY HX
7 SECONDARY HX
8 SECONDARY PUMP
9 SECONDARY PUMP
10 PRIMARY PUMP 2
11 PRIMARY HEADERS
12 TEST SECTION
13 BLOWDOWN STACK
TOWER HEIGHT 28.5m
TOWER WIDTH 16m
PRIMARY
SECONDARY
SURGE AND DEGAS
BLOWDOWN

RD-14M Facility Description

- Facility description extensively documented (RC-2491)
  - Contains information on loop characterization
- Extensive collection of reports and memoranda describing loop characterization and instrumentation behavior
- Facility description specifically for the RD-14/ACR configuration (108-126410-470-001)

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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