Separate Effects Thermal Hydraulics Test Facilities
(Non-Proprietary Presentation)

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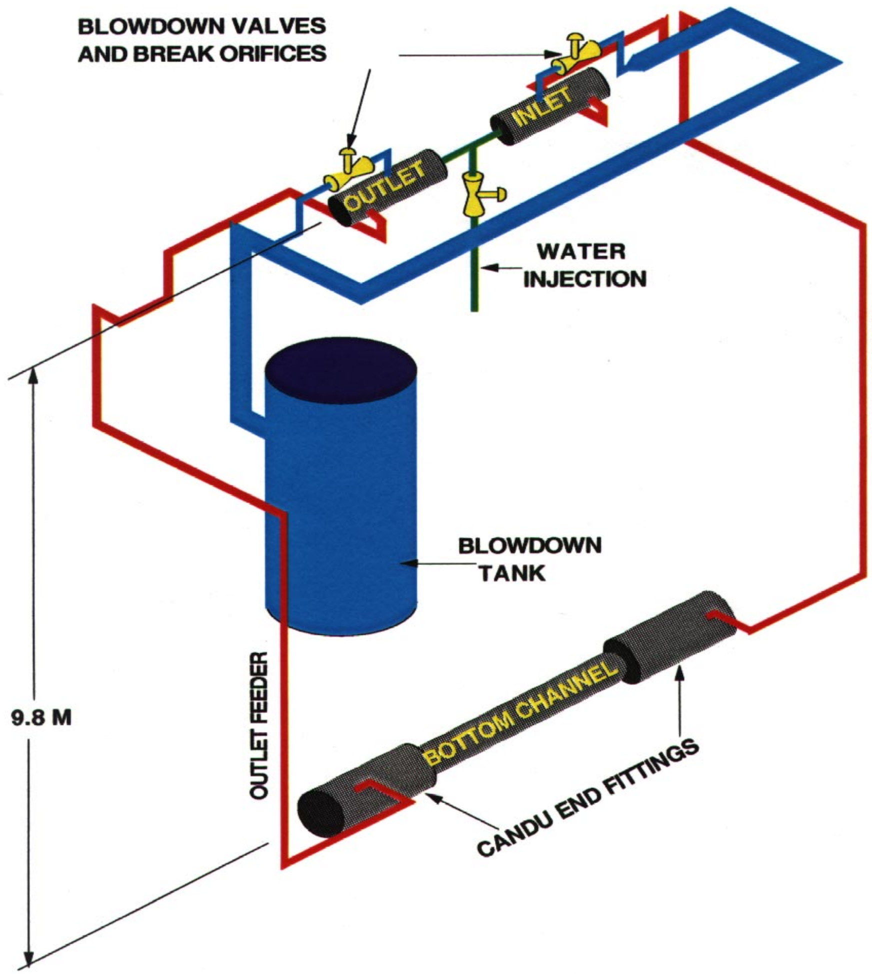
Thermal Hydraulics Facilities

- **Integral Facilities:**
  - RD-14
  - RD-14M
- **Component Facilities:**
  - Cold-Water Injection Test (CWIT) facility
  - Large-Scale Header (LASH) facility
  - Transparent Header facility
  - Component Characterization facility (RD-14M inlet header)

Cold Water Injection Test Facility (CWIT)

- Full-scale heated fuel channel with electrically-heated fuel string
  - Axial uniform and cosine power profiles
  - Full 37 element Fuel Element Simulator (FES) bundles (CANDU 6)
- CANDU representative feeders and end-fittings
- Actual CANDU 6 end-fittings modified for heated fuel string
  - Inlet and outlet feeders connected to scaled headers
- ECC injection system
- Blowdown system
- Program ran from the 1970's until 1998

Cold Water Injection Test Facility



CWIT Test Facility

CWIT Program Objectives

- **Perform thermal hydraulic experiments, under postulated-accident conditions, in a geometry representative of that in a CANDU fuel-channel/feeder system**
- **Provide experimental data necessary to develop and validate thermal hydraulic computer codes and models used in CANDU safety and licensing analysis**

History of CWIT Facility

- Constructed in mid-1970's at Stern Laboratories Inc. (SL) in Hamilton, Ontario
- Different fuel channel/FES designs used over the years: grown in sophistication and complexity
  - Two channel configuration with uniform power distribution along FES (upper/top and lower/bottom channels)
  - Maintenance Cooling Test (MCT) channel
  - Single channel configuration with cosine power distribution
    - Replaced bottom channel (top channel blanked off)
- Different headers and feeder arrangements used over lifetime of the facility

Scaling of CWIT Facility

- Full-size channels and end-fittings
- Feeders
  - Pipe diameter is CANDU-typical
  - Configuration was chosen for practical reasons and does not mirror any specific reactor feeder
- Vertical separation between the headers and upper channel (5 m), and the headers and lower channel (10 m), correspond to CANDU reactor elevations (headers and uppermost/lowermost channels)

37-Element Cosine Power Fuel Channel

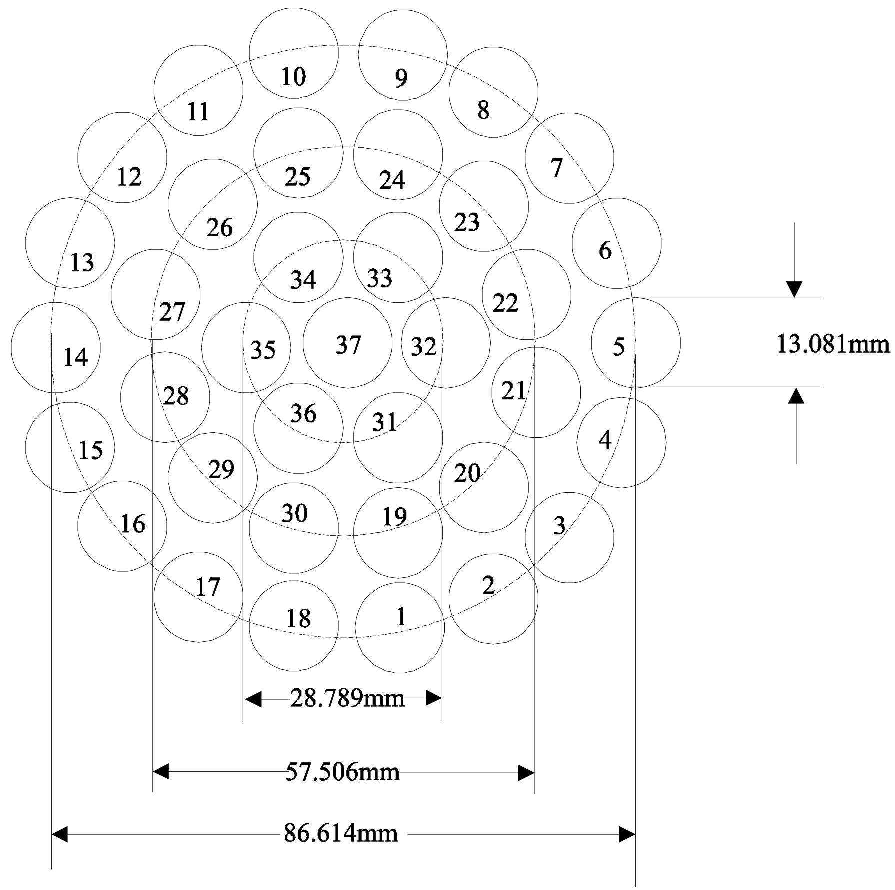
- 37-element FES
  - Maximum power: 300 kW
  - Maximum sheath temperature: 800ºC
  - Maximum pressure: 7 MPa
  - 6-m heated length (total length 11.6 m)
- Zircalloy-niobium pressure tube
- CANDU-6 end-fittings (from Gentilly-2)

Cross-Section of CWIT 37-Element Fuel Bundle

Instrumented Elements

Outer ring	Middle ring
9	24
8	19
7	30
6	25
5	
4	
2	
10	

Inner ring	Center Element
33	37
31	
36	
34	



Injection System

- Injection system has both low and high pressure feed pumps
  - Maximum flow-rate of 6 L/s @ 7 MPa, 100°C
- Sub-cooled water injection to either or both of the inlet and outlet headers
- Installation of orifices in the injection system allow for tests of varying injection flow rates

Instrumentation

- Over 300 instruments
  - Thermocouples: surface, fluid, FES sheath
  - Absolute and differential pressure transducers
  - Orifice and venturi flowmeters
  - Gamma densitometers (on the feeders)
  - FES power measurements

Instrumentation – Fuel Channel (Cosine)

- 100 FES sheath thermocouples on 17 different elements at eight axial planes
- 20 surface and 8 fluid thermocouples per end-fitting (located at four different axial planes)
- 54 surface thermocouples attached to the pressure tube at six axial planes
- Differential pressure across channel
- Pressure transducer in each end-fitting

Instrumentation – Feeders

- Surface thermocouples along feeders
- Pressure transducer and fluid thermocouples near inlet and outlet of channel
- Feeder and test section differential pressures
- Gamma densitometer on each feeder

Instrumentation - Headers

- Fluid and surface thermocouples
- Pressure transducers on each header
- Header-to-header differential pressure

Types of CWIT Tests

- Three main types of tests carried out
  - Refill
  - Flow stratification
  - Standing start
- Other types of tests carried out
  - Channel spray, header/feeder spray
  - Flow stability
  - Inclined feeder refill
  - Non-condensable gas injection
  - Passive heat rejection

CWIT Refill Experiments

- These tests were performed to study the refilling of a CANDU fuel-channel/feeder system by injecting cold water into a steam-filled system (hence Cold Water Injection Test facility!)
- Procedure
  - Preheat loop with superheated steam (260°C to 300°C)
  - Isolate loop at desired pressure (steam filled)
  - Establish FES power
  - Initiate blowdown and inject ECC
    - Blowdown through one or both headers
    - ECC into one or both headers

CWIT Flow Stratification Experiments

- These tests were carried out to determine the occurrence of coolant stratification in fuel channels under certain low flow conditions during reactor shutdown
- Procedure
  - Preheat loop with subcooled water at desired pressure and temperature
  - Establish desired inlet flow rate and apply FES power
  - Increase FES power to form void in the channel

CWIT Standing Start Experiments

- These tests were conducted to study fuel cooling during loss of forced flow. During these tests, referred to as "standing start" tests, the FES power is suddenly applied to a full, stagnant fuel channel
- Procedure
  - Preheat loop with subcooled water at desired temperature
  - Establish loop filled with subcooled water at desired pressure and temperature
  - Apply power to FES
  - Wait for venting of steam (Intermittent Buoyancy Induced Flow, IBIF)

Test procedures and test setups (for all test types) are given in the electronic database

CWIT Data/Database

- Data reports issued for each test series
- Data archived on CD-ROM in a standardized ASCII format
- Electronic database (MS Access), developed for the RD-14M program, also contains information on CWIT
  - Details of test setups, procedures, and conditions
  - Instrumentation for each test
- Facility description report

Large-Scale Header (LASH) Facility

- Facility consists of an inlet and an outlet header connected by six banks of five “U” shaped feeders (30 feeders total)
- Inlet and outlet headers are full-scale diameter, half-length CANDU headers (Pickering NGS headers)
- Facility located at Stern Laboratories Inc. (SL) in Hamilton, Ontario
- Program ran from the early 1980’s until 1997 (1995 in inlet/outlet header arrangement)

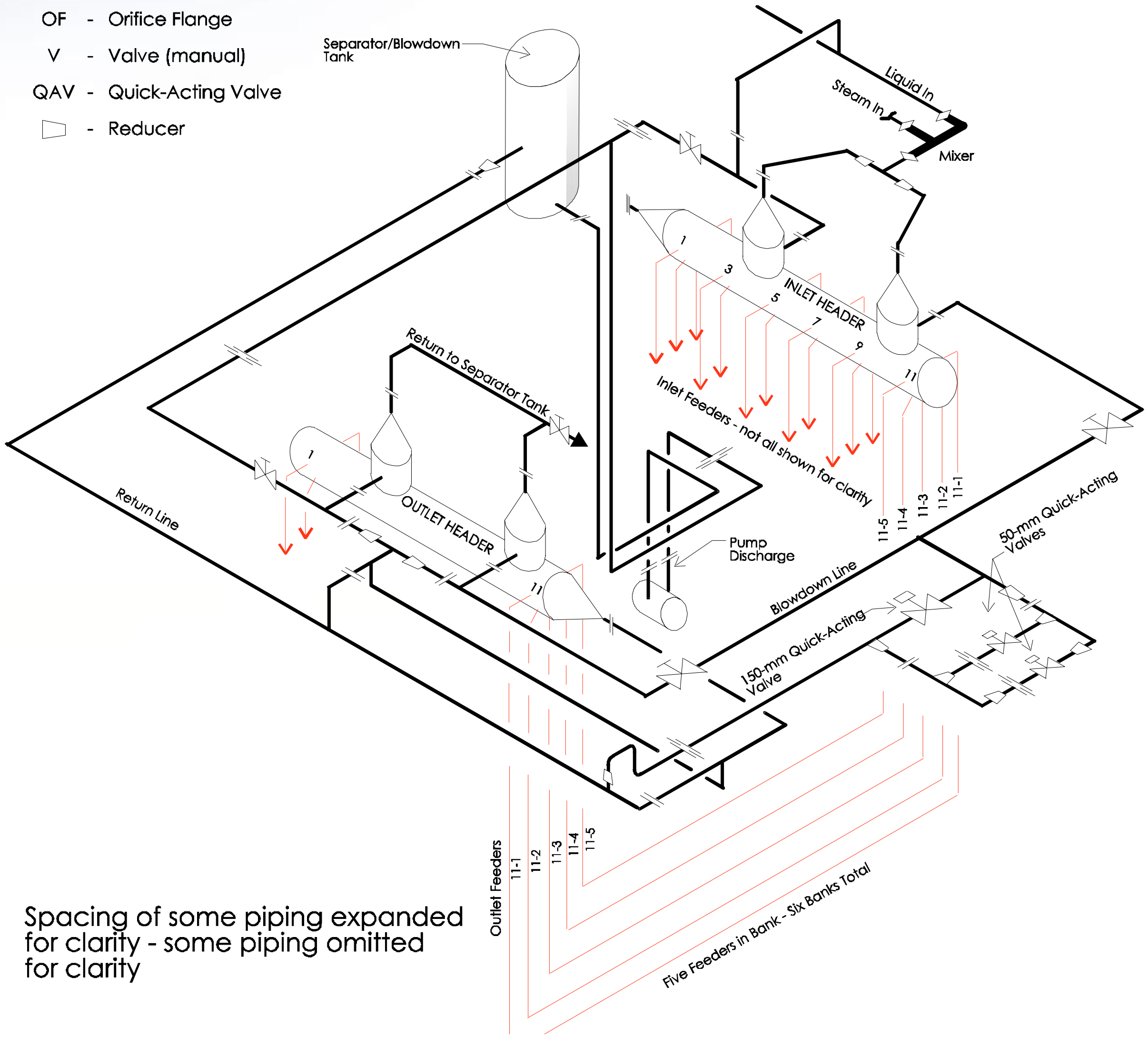
Large-Scale Header (LASH) Facility

OF - Orifice Flange

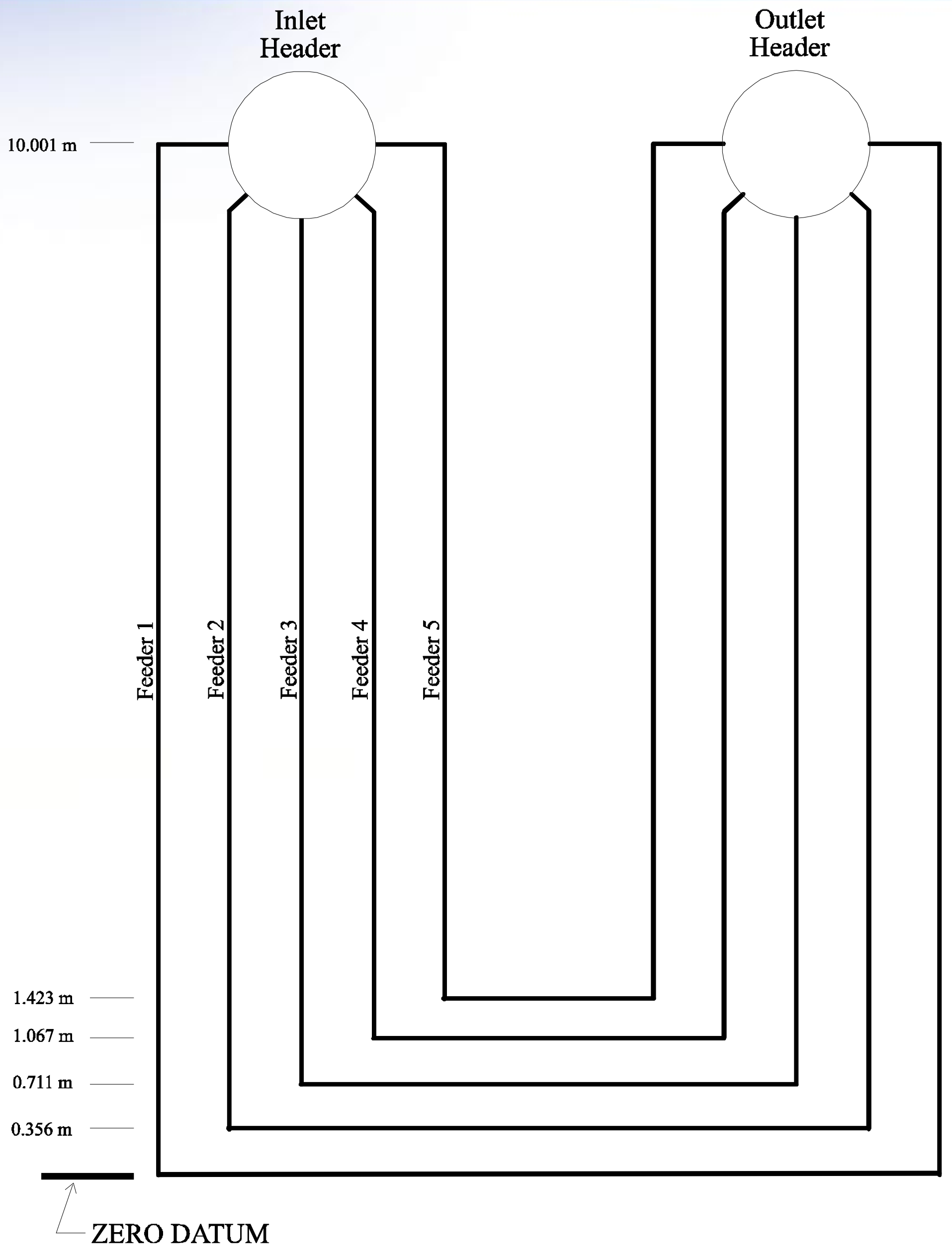
V - Valve (manual)

QAV - Quick-Acting Valve

[reducer symbol] - Reducer



Spacing of some piping expanded for clarity - some piping omitted for clarity


Inlet Header
Outlet Header
10.001 m
Feeder 1
Feeder 2
Feeder 3
Feeder 4
Feeder 5
1.423 m
1.067 m
0.711 m
0.356 m
ZERO DATUM

LASH Program Objectives

- **Perform thermal hydraulic experiments in a header geometry representative of that in a CANDU reactor, under postulated-accident conditions.**
- **Provide experimental data necessary to develop and validate thermal hydraulic computer codes and models used in CANDU safety and licensing analysis**

Scaling of LASH Facility

- **Full-scale diameter (0.325 m) and half-length (4.2 m) headers**
- **Feeders are similar diameter (50-mm I.D.) to CANDU feeders**
- **Full-scale vertical height between headers and the horizontal feeder sections**
  - **Vertical separation between the headers and lowest feeders is 10 m, which approximately corresponds to the maximum full-scale height in a CANDU reactor**

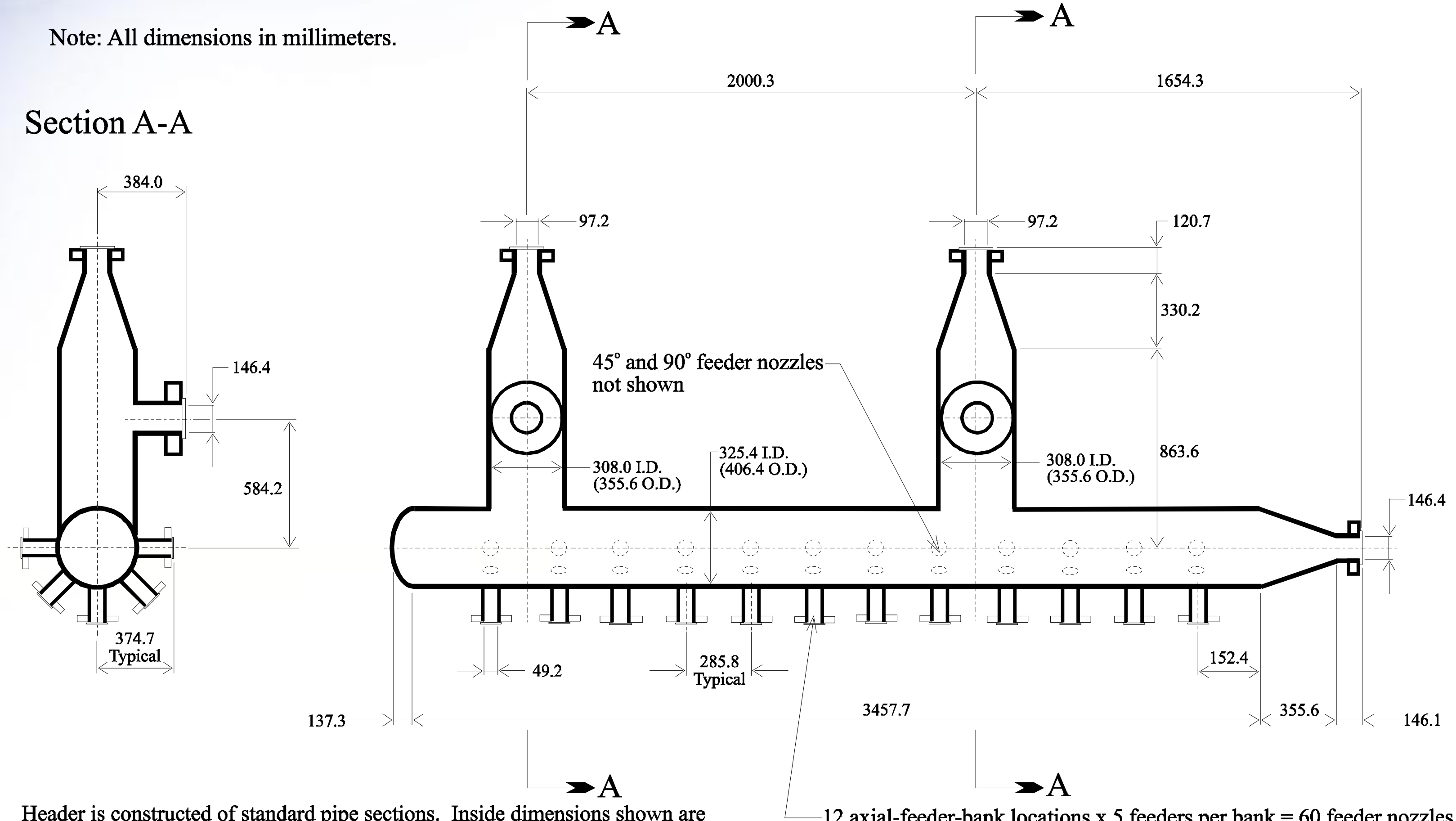
LASH Facility Description

- Inlet and outlet headers each have two turrets
- Each header has 60 feeder nozzles
  - 12 axial banks of five nozzles
  - Every other bank is used for feeders
  - The nozzles at the other banks are blanked off or used for instrumentation
- Feeders are "U" shaped
  - Each feeder consists of a vertical inlet section and a vertical outlet section connected by a horizontal section
  - Horizontal sections (sometimes referred to as test sections) are unheated
  - Orifices installed in feeders to provide single-phase flow resistance similar to CANDU fuel channel

Two-Phase Injection System

- Superheated steam and liquid water injected into mixer
- Maximum superheated steam flow rate
  - ~4 kg/s at 7 MPa, 350°C
- Liquid water pumps
  - Main pump rated at 54 L/s with a 380-m head, and a maximum pressure of 14.6 MPa at 315 °C
  - Two other pumps connected in series are used to give additional liquid flow when required
    - Each pump is rated at 28 L/s with 188-m head

LASH Inlet Header



Header is constructed of standard pipe sections. Inside dimensions shown are based on dimensions provided in [2-1] and Figure A-1.

Instrumentation

- **Over 300 instruments**
  - Flowmeters
  - Liquid-level probes
  - Thermocouples: surface and fluid
  - Absolute and differential pressure transducers
  - Gamma densitometers

Instrumentation – Headers

- Liquid levels in each header are inferred using conductivity/differential pressure/thermocouple level probes (rakes)
  - Instrument rakes are located at non-feeder banks
  - Each instrumented bank contains one, two, or all three types of probes
  - Number and types of probes changed over the history of the facility
- Fluid and surface thermocouples
- Pressure transducers on each header
- Header-to-header differential pressure

SLI Conductivity/DP Probe

Protected-Proprietary

SLI Conductivity/DP Probe

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Instrumentation – Feeders

- There are instrumented and non-instrumented feeders
- Surface and fluid thermocouples at several places along feeders
- Absolute pressure transducers at test sections
- Test section differential pressures
- Gamma densitometers
- Turbine flowmeters at test sections

Types of LASH Tests

- Inlet Header Injection
- Blowdown and Blowdown / Refill
- MFVE (Multi-Feeder Venting Experiments)

LASH Two-Phase Injection Experiments

- **These tests were performed to study phase distributions in the headers and feeders**
  - Tests were performed with steady-state or near steady-state two-phase injection into the inlet header
- **Procedure 1 (increasing inlet-header injection quality)**
  - Preheat loop with subcooled water (desired pressure, temperature, and flow rate)
  - Inject superheated steam into mixer to achieve desired injection quality
  - Record data
  - Increase injection quality in steps of 0.2 to 0.5% until turbine flowmeter reaches maximum flow rate

LASH Two-Phase Injection Experiments

- **Procedure 2 (decreasing inlet-header injection quality)**
  - Preheat loop as before
  - Start from high steam injection flow rate
  - Decrease inlet-header injection quality

- **Procedure 3 (time-dependent two-phase injection)**
  - Preheat loop as before
  - Record data continuously
  - Slowly increase steam injection flow rate

- **One series of tests was carried out with steam injection into the horizontal feeders**

LASH Blowdown/Refill Tests

- These tests were parametric studies conducted to examine the rewet and refill characteristics of CANDU-type headers and feeders during cold-water injection
  - These tests are the most relevant to LBLOCA
- Tests were conducted at Stern Laboratories (AECL representative: J. Kowalski (now with CNSC))
- Two series of blowdown/refill tests are discussed here:

- Purpose: database for header model development and to get information on header behavior that could be applied to CANDU reactors

LASH Blowdown/Refill Tests

- **Procedure**
  - Preheat loop to desired temperature and pressure using superheated steam
    - Superheated steam throughout all feeders was not achieved - water holdup in the feeders was an issue and the associated volume could be estimated for each test
  - Initiate blowdown by opening quick-acting valve(s)
  - Inject cold water into one or both headers

LASH Blowdown/Refill Tests

- **Parametric study**
  - Injection to inlet header only or both headers (through the north turret(s))
  - Various break orifice sizes (50, 100, 150 mm) and locations (inlet, outlet, or both headers through the south turret(s))
  - Various initial preheat temperatures: 170-293°C
  - Various ECI flow rates: 26-60 kg/s

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Calculation of Refill Times

- **Headers**
  - Inferred based on conductivity probe rakes located at the north, mid, and south locations of the headers
    , the outlet header only had a rake at the mid location)
  - Average refill time taken based on the three refill times (north, mid, south)
- **Feeders**
  - Inferred based on surface temperature measurements on instrumented feeders (compared to saturation temperature)

Example - - ECI Mass Flow

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Example -   - Header-Header DP

Example -

Predicted and Inferred Header and Loop Refill Times

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Results – Effects on Refill

- **Effect of break orifice size: negligible (orifice located at vertical midpoint on the south turret(s) - above water level so only steam discharged)**
- **Effect of break location (ECI into both headers)**
  - **When break located on only one header, that header refilled first (due to increased ECI flow into that header)**
  - **e.g., Test (outlet header break):**
    - **Average refill times:**
  - **e.g., Test (inlet header break):**
    - **Average refill times:**

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Example - - ECI Mass Flow

Results – Effects on Refill

- **Effect of ECI flow rate: faster refill for increased flow rate**
  - e.g., Test versus Test
    - Test average refill times:
    - Test average refill times:
- **Effect of initial temperature: small effect**
- **Effect of ECI location (inlet only or both headers): feeder refill times were shorter for injection into the inlet header than injection into both headers**
  - Test series versus

LASH Multi-Feeder Venting Experiments

- Following a loss-of-maintenance shutdown cooling in a drained shutdown CANDU reactor, a large number of feeder channels may experience flow stagnation. Local boiling will occur in these channels followed by the eventual venting of steam from the channels to the feeders and then the header(s). The purpose of the MFVE program was to provide experimental data on whether this steam will completely condense upon contact with the header liquid, or result in the escape of steam and/or liquid from the header riser pipe.

LASH Multi-Feeder Venting Experiments

- **Two series of tests were carried out**
  - For phase one tests, the LASH outlet header was initially filled with subcooled water, and steam was injected into the header through the ten feeders of feeder banks 4 and 5
  - A similar procedure was used for phase two tests, however, a saturated liquid-buffer region, in each of the ten feeders, initially separated the injected steam from the subcooled liquid in the header.

- **The facility set-up was significantly different for these tests than traditional LASH tests.**

Phase-One Configuration

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Phase-Two Configuration

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LASH Data/Database

- Data reports issued for each test series
- Data archived on CD-ROM in a standardized ASCII format
- Electronic database (MS Access), developed for the RD-14M program, also contains information on LASH
  - Details of test setups, procedures, and conditions
  - Instrumentation for each test
- Facility description report

Transparent Header/Feeder Facility

- Similar to the LASH facility in terms of header and feeder dimensions
- Headers and feeders constructed of clear acrylic to allow for flow visualization (better understanding of LASH data)
- Air/water injection
- Facility consists of an inlet and an outlet header connected by six banks of five “U” shaped feeders (30 feeders total)
- Inlet and outlet headers are full-scale diameter, half-length CANDU headers (Pickering NGS headers)
- Facility located at WL

Transparent Header/Feeder Facility

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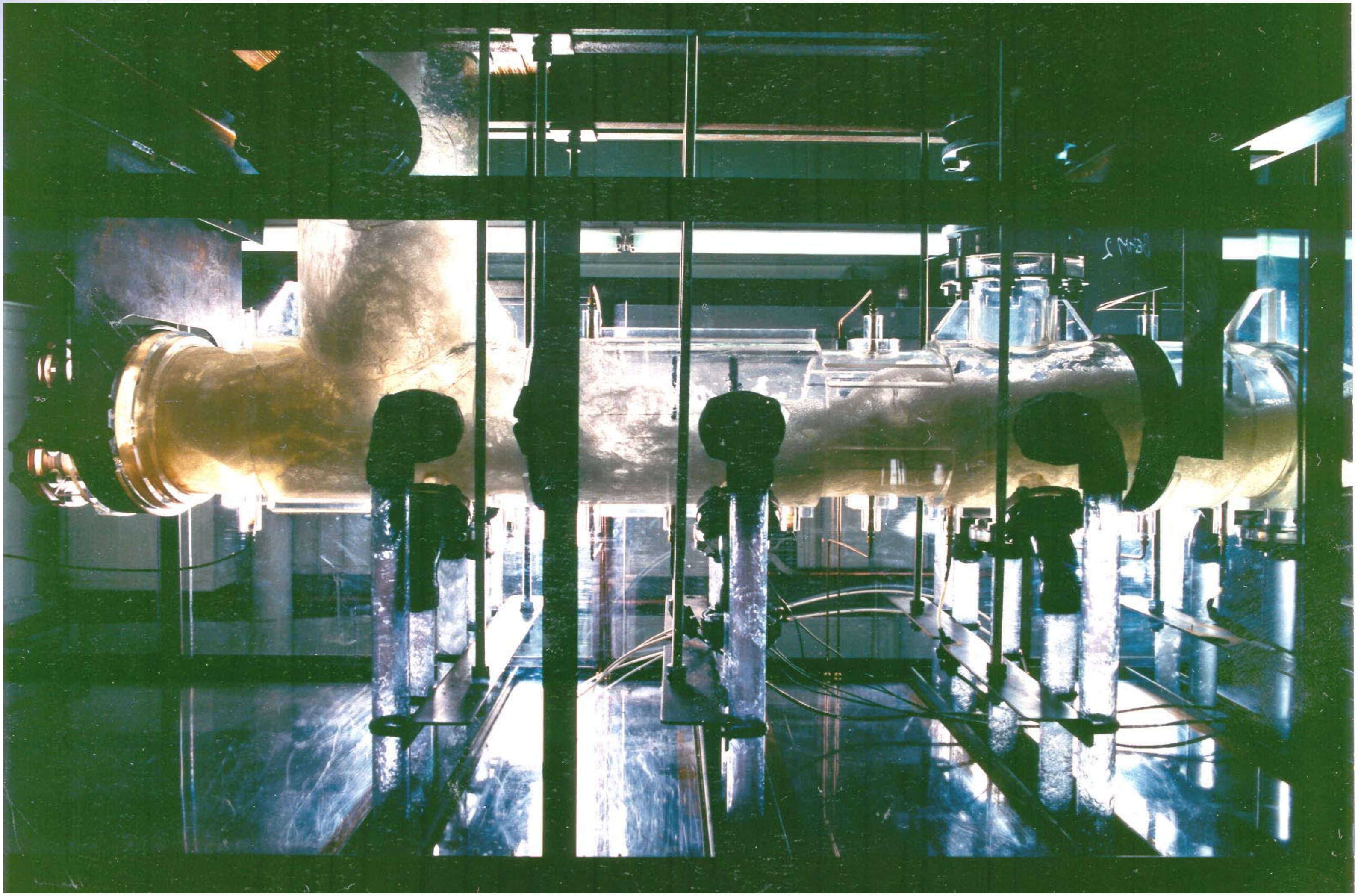
Transparent Header/Feeder Facility

Transparent Header/Feeder Facility



Scaling of Transparent Header/Feeder Facility

- Full-scale diameter (0.325 m) and half-length (4.2 m) headers
- Feeders are similar diameter (50-mm I.D.) to CANDU feeders

Instrumentation

- Video
- Header-Header differential pressure
- Air flow
- Water flow

- Evaluated instrumentation
  - DP level
  - Conductivity rake
  - LASH-type combination DP level / conductivity rake

Operational Capabilities

- Pressure: 275 kPa(g)
- Temperature: 30°C
- Air injection flow: 60 L/s
- Water injection flow: 100 L/s

Video

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SLI Conductivity/DP Probe

Protected-Proprietary

SLI Conductivity/<u>DP</u> Probe

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RD-14M Component Characterization Facility (CCF)

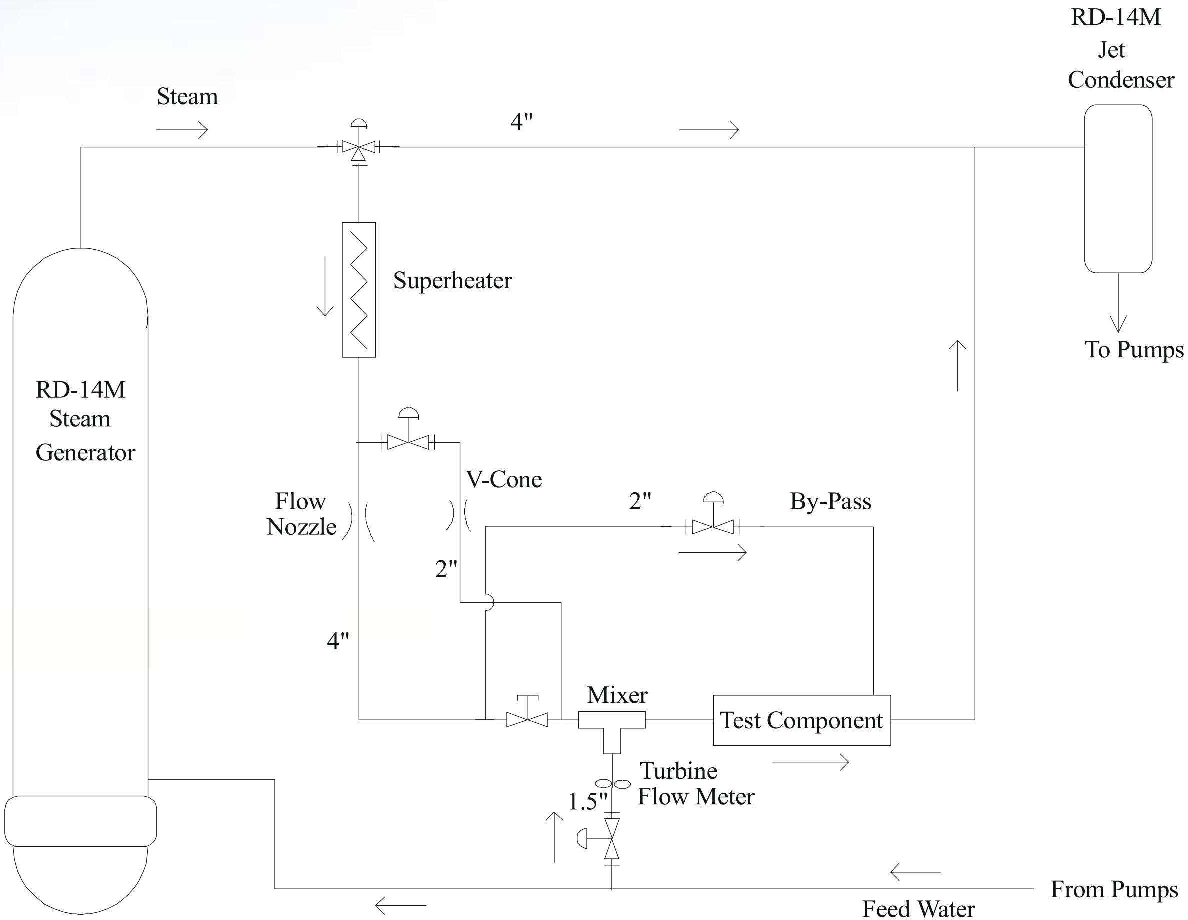
- **An RD-14M sub-facility exists that allows the thermal hydraulics testing of various RD-14M components**

  - **i.e., a test component can receive a wide range of single and two-phase steam-water mixtures**

  - **The CCF is connected to the RD-14M secondary side**

  - **An RD-14M inlet header has been characterized under two-phase injection conditions**

Schematic of CCF



CCF Instrumentation (Generic)

- Steam mass flow rates: 4-inch flow nozzle or a 2-inch V-cone flowmeter (differential pressure type metering device)
- Liquid water mass flow rates: turbine flowmeter
- Temperatures (e.g., superheater outlet)

CCF Loop Parameters

- Design pressure: 7.4 MPa(g)
- Design temperature: 343°C

- Operating pressure: 5.5 MPa(g)
- Operating temperature: 260°C

- Maximum flow rates
  - Steam: 5.5 kg/s
  - Water: 5.4 kg/s

CCF Features

- Water supply: 0.06 to 5.4 kg/s
- Steam supply: 0.008 to 5.5 kg/s @ 5.5 MPa(g)
  0.002 to 0.25 kg/s @ 0.1 MPa(g)
- Steam superheater: 125 kW
- Steam-water mixer: desuperheater-type
- Automatic or manual control of flow rates
- Steam by-pass line
- Blowdown line

Schematic of RD-14M Inlet Header in the CCF

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RD-14M CCF: Inlet Header

- A series of tests was conducted to investigate flow and phase distribution in the feeders and phase distribution in the header
- The effect of mass flow rate, pressure and void fraction was examined

Inlet Header Instrumentation

- Void fraction, gauge pressure and fluid temperature were measured upstream of the inlet header
- Each of the five feeders, located downstream from the inlet header, were instrumented with a conductivity probe, turbine flow meter, single-beam gamma densitometer, thermocouple and gauge pressure cell
- An orifice plate was installed in each feeder line
  - Provided a flow split to the feeders similar to that of the RD-14M facility under single-phase conditions
  - Orifice was instrumented with three differently ranged differential pressure cells to provide additional flow measurement data
- The inlet header was instrumented with thermocouples (fluid and metal temperatures), differential pressure cells (collapsed fluid levels), a gauge pressure cell, and single-ended conductivity probes (phase location)

Flow & Phase Distribution to the Feeders

- **Two-phase flow injection to the RD-14M inlet header through the inlet turret**
  - **Void was distributed to all five feeders for two-phase inlet mass flows greater than 3.75 kg/s**
  - **Void was distributed to only some of the feeders for two-phase inlet mass flows less than 3.75 kg/s**
  - **System pressure had no effect on the void distribution in the feeders**
  - **As the header inlet void fraction increased, the feeder void fractions also increased in all feeders containing void**

Phase Distribution in the Inlet Header

- Flow and void through feeders at the same cross-section and elevation significantly differed under certain conditions
  - Suggests asymmetric phase distribution in the header in both the axial and latitudinal directions
- Both these phenomena will uncover feeder nozzles, void the feeders, and cause undesirable thermal hydraulic conditions in the primary heat transport system
- Under other boundary conditions, void symmetry in the inlet header was well established

Summary

- Separate effects experiments performed for major CANDU components:
  - Full-scale channel and end-fittings (CWIT)
  - Headers (LASH, Transparent Header and CCF)
- Separate effects experimental programs have been unfunded since 1997/98

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