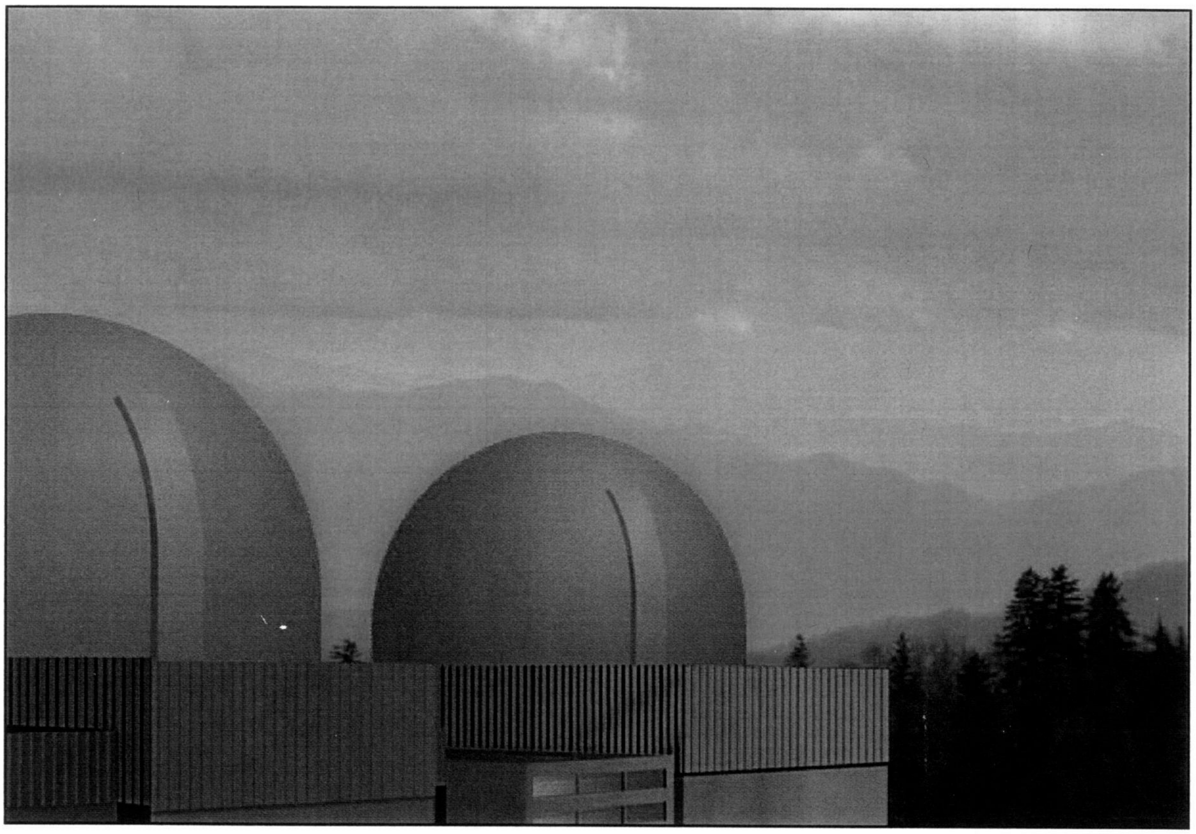
Meeting on ACR Thermal Hydraulics



Meeting with the NRC in Washington DC
February 5-6, 2003

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ACR-700 Thermal Hydraulics Meeting Agenda

February 5, 2003:

8:30 a.m. - 8:45 a.m.	Introductory Comments - NRC
8:45 a.m. - 9:00 a.m.	Introductory Remarks - AECL
9:00 a.m. - 9:45 a.m.	CANDU Thermal Hydraulics - Overview
9:45 a.m. - 10:00 a.m.	Break
10:00 a.m. - 12:00 Noon	CATHENA Thermal Hydraulics Code
12:00 Noon - 12:15 p.m.	Opportunity for public comment
12:15 p.m. - 1:15 p.m.	Lunch
1:15 p.m. - 3:15 p.m.	Separate Effects and Integral Experiments
3:15 p.m. - 3:30 p.m.	Break
3:30 p.m. - 4:45 p.m.	CATHENA Validation
4:45 p.m. - 5:00 p.m.	Opportunity for public comment
5:00 p.m.	Adjourn

February 6, 2003:

8:30 a.m. - 8:45 a.m.	Introductory Comments (NRC)
8:45 a.m. - 10:30 a.m.	Fuel Channel Thermal Hydraulics
10:30 a.m. - 10:45 a.m.	Break
10:45 a.m. - 12:00 Noon	Fuel Channel Thermal Hydraulics (Cont.)
12:00 Noon - 12:15 p.m.	Opportunity for public comment
12:15 p.m. - 1:15 p.m.	Lunch
1:15 p.m. - 3:00 p.m.	Moderator Thermal Hydraulics
3:00 p.m. - 3:15 p.m.	Break
3:15 p.m. - 4:00 p.m.	Moderator Thermal Hydraulics (Cont.)
4:00 p.m. - 4:30 p.m.	General Discussion
4:30 p.m. - 4:45 p.m.	Opportunity for Public Comment
4:45 p.m. - 5:00 p.m.	Conclusion (NRC)
5:00 p.m.	Adjourn

ACR Thermal Hydraulics
- An Overview -

By Andrew White, Director
Reactor Safety Division
Presented to US Nuclear Regulatory Commission
Washington DC
February 5-6, 2003

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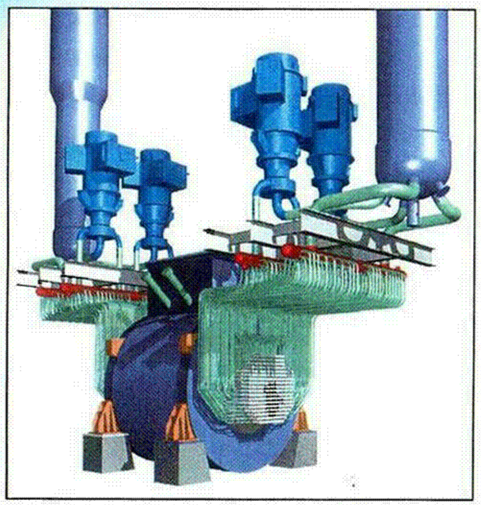
Outline

- ACR specific features
- CATHENA Thermal Hydraulics Code
- Separate Effects and Integral Experiments
- CATHENA Validation
- Fuel Channel Thermal Hydraulics
- Moderator Thermal Hydraulics

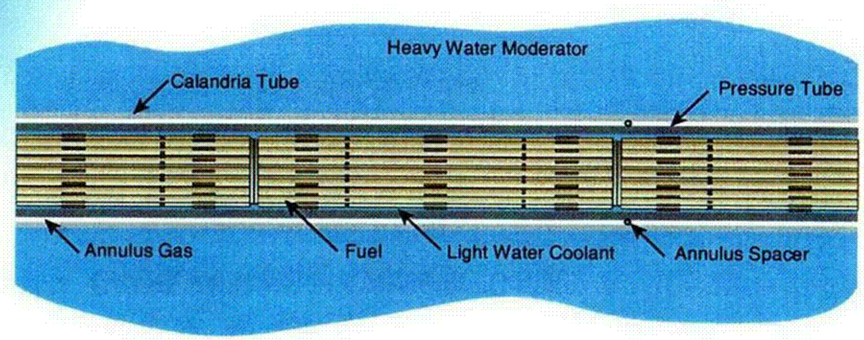
ACR Reactor Coolant System Layout



Showing piping above and below headers

-All large reactor coolant piping above headers

Fuel Channel Details



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ACR System

- Below "Header", Unique Features:
  - Horizontal Fuel Channels, Pressure Tube, Calandria Tube
  - 43-Element Fuel Bundle
  - Individual Fuel Channels supplied by Feeder Pipes from a Header
  - End Fittings allow on-power refueling
  - Moderator Heat Sink
- Above "Header", Common Features (with other reactors):
  - Vertical U-Tube Steam Generators
  - Centrifugal Pumps

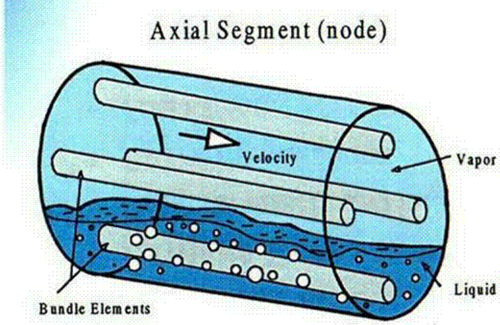
Outline

- ACR specific features
- **CATHENA Thermal Hydraulics Code**
- Separate Effects and Integral Experiments
- CATHENA Validation
- Fuel Channel Thermal Hydraulics
- Moderator Thermal Hydraulics

CATHENA

- Canadian Algorithm for THErmalhydraulic Network Analysis
- One-dimensional, two-fluid system thermal hydraulics code
- Developed by AECL for thermal hydraulics analysis of CANDU reactor coolant systems

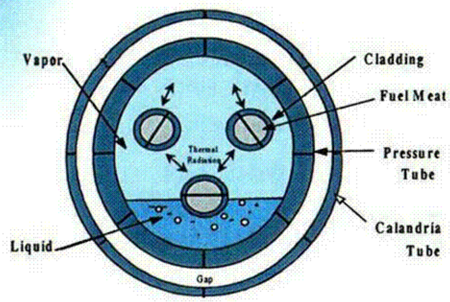
CATHENA THERMAL HYDRAULICS MODEL



- Non-equilibrium model
  - 2-velocities,
  - 2-temperatures
  - 2-pressures
  - plus noncondensables
- Flow regime dependent constitutive relations couple two-phase model
- CATHENA "interfaces" to other codes:
  - Fuel Behavior: CATHENA / ELOCA
  - Plant Control: CATHENA / LEPCON
  - Physics: CATHENA / RFSP

C02

CATHENA's Heat Transfer Model



- Multiple surfaces per thermal hydraulic node
- Radial and circumferential conduction modeled
- Models heat transfer within bundles subjected to stratified flow
- Radiation heat transfer calculated
- Built-in temperature dependent material property tables
- Models deformed geometry and pressure/ calandria tube contact

Outline

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Experimental Data Base

- CANDU System Makes Use of International Data Sets:
  - Edwards Pipe Blowdown (Break Discharge)
  - Marviken Blowdown Tests (Break Discharge)
  - Dartmouth Air/Water Flooding in Straight Pipe (Counter Current Flow)
  - GE Large Vessel Blowdown Tests (Level Swell)
  - Christensen Power Void Tests (Coolant Voiding)
  - *..... and others*

Experimental Data Base – CANDU Specific

- Can by subdivided into:
  - Small Scale Experiments
  - Component Experiments
  - Integral Experiments
  - CANDU Plant Transients
- Small Scale Experiments, Examples:
  - Flooding – downstream of an elbow (relevant to feeder)
  - Pressure Tube / Calandria Tube Heat Transfer Experiments
  - Horizontal Tube Rewetting / Refilling Experiments
  - Pressure Tube Circumferential Temperature Distribution

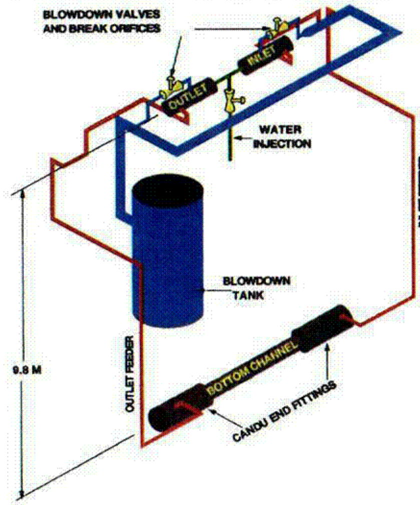
C03

Experimental Data Base – CANDU Specific

- **Full-Scale Component Experiments:**
  - Feeder Refilling, Cold Water Injection Test Facility
  - Channel Stratification Studies, Cold Water Injection Test Facility
  - Header Studies, Large Scale Header Facility
  - Header Studies, Header Visualization Facility
  - Pump Characterization, CANDU Pump Facility
  - End Fitting Studies, End Fitting Characterization Facility

Cold Water Injection Facility (CWIT)

- Full-scale heated fuel channel with simulated fuel string
- CANDU representative feeders and end fittings
- Designed to investigate feeder/channel refill performance, as well as flow stratification within CANDU bundle



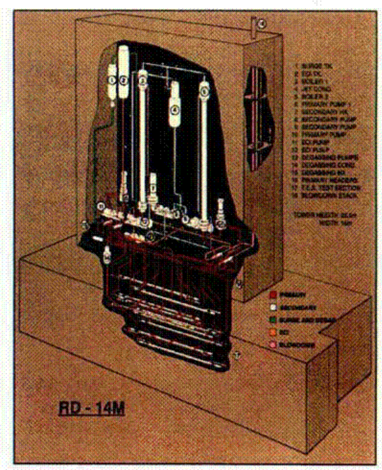
CWIT Test Facility

Experimental Data Base – CANDU Specific

- History of AECL 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
  - RD-14M - (1987 to present) - full elevation, five channels per pass
  - RD-14M – (2001 to present) – re-configured to ACR conditions (higher temperature / pressure)
- Integral Experiments:
  - LOCA,
    - Small, Large, Critical
    - With and Without Emergency Core Cooling (ECC)
  - Natural Circulation
    - Single- and Two-Phase
  - Loop Stability
  - Shutdown Cooling Experiments

RD-14M Thermal Hydraulics Facility

- Full elevation changes between major components and full linear dimensions.
- Reactor typical heat- and mass-transfer rates
- Ten full length electrically heated channels.
- Simulation of all primary-side components - channels, end-fittings, feeders, headers, and steam generators.
- Full pressure and temperature conditions (current CANDUs and ACR).
- Extensively instrumented.
- Dedicated data-acquisition system.



C04

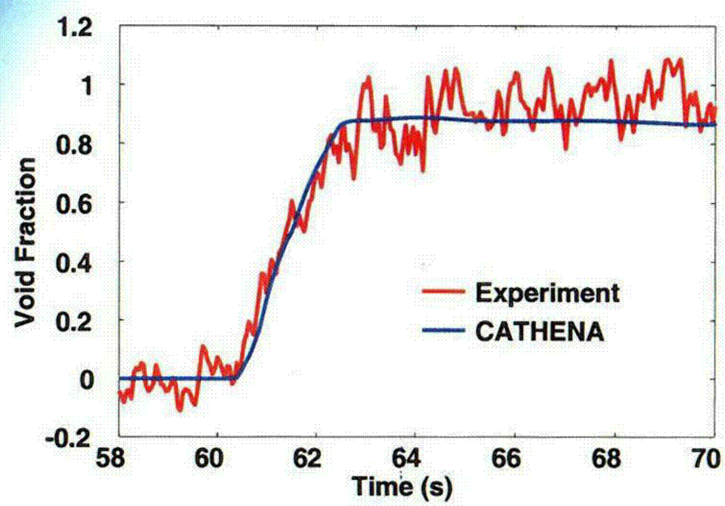
Outline

- ACR specific features
- CATHENA Thermal Hydraulics Code
- Separate Effects and Integral Experiments
- **CATHENA Validation**
- Fuel Channel Thermal Hydraulics
- Moderator Thermal Hydraulics

CATHENA VALIDATION

- Summary of validation process:
  - Validation has proceeded on a phenomenon-by-phenomenon basis
  - Standardized and documented models of facilities used where they exist
  - Default code settings used throughout unless otherwise specified and justified
  - Data selected in validation process includes numerical tests, separate effects, component and integral tests, as well as transients in CANDU plants
  - Sensitivity analysis conducted to identify impact on simulations of experimental errors used as boundary conditions (e.g., power) and nodalization
  - Uncertainty analysis conducted to identify impact on code results (e.g., uncertainty in heat transfer correlations)

CATHENA Validation, Example of Calculation of Channel Void During LOCA

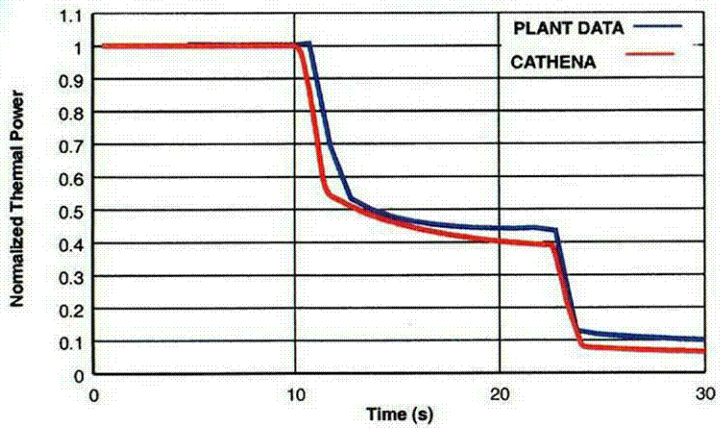


CATHENA Validation, CANDU 6 Plant Transient, Single-Pump Trip

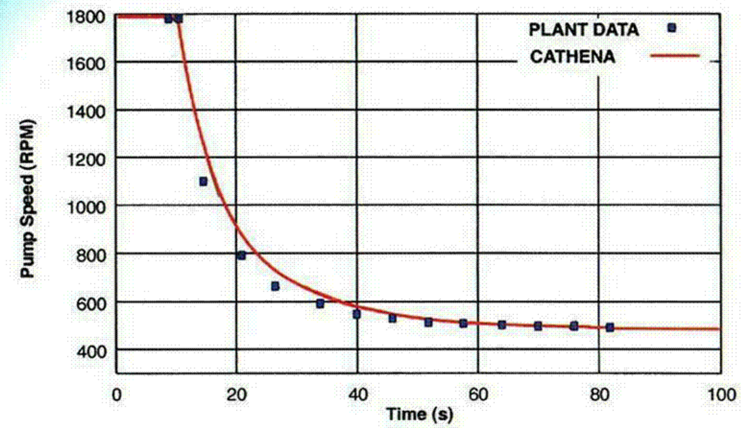
- CATHENA CANDU-6 integrated model includes 28 channels in 4 passes, 4 steam generators, emergency coolant injection system, inventory control system, and reactor regulation system (3775 nodes)
- Sequence of events
  - Main coolant pump 4 switched off at t=0 s
  - pump trip initiates a reactor step back to 60% of full power (step back endpoint)
  - reactor trips at approx 13 s on Shutdown System 1 (SDS1) low pressure signal from Reactor Outlet Header 5

C05

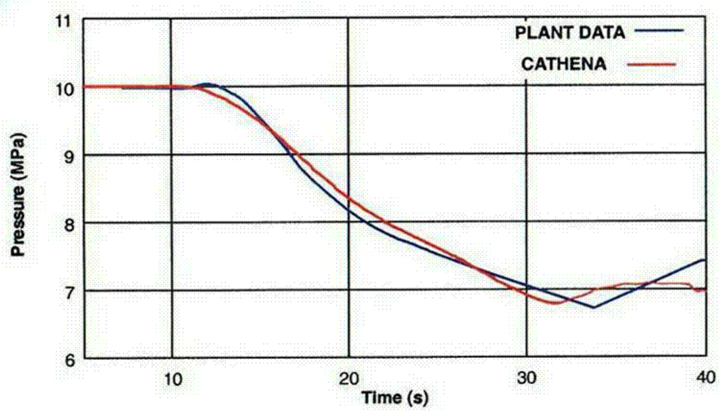
Thermal Power Transients



Pump Run-down Speed



Outlet Header 5 Pressure



Outline

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C06

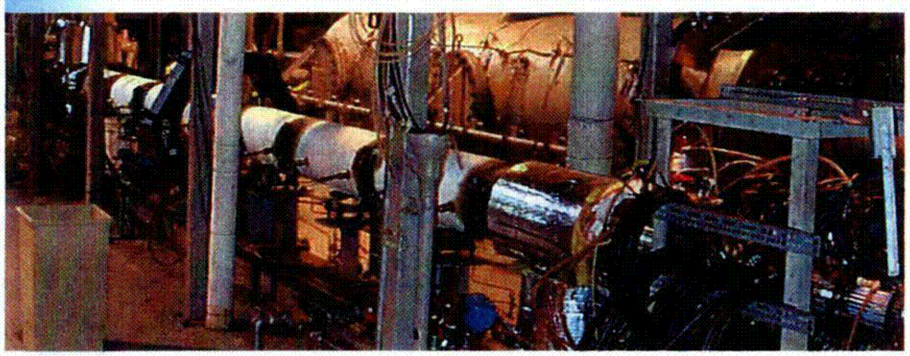
Fuel Channel Thermal Hydraulics Parameters

- Fuel string pressure drop
  - establishes channel flow based on pump characteristics
- Critical heat flux (CHF)
  - determines trip set-points
  - a determinant in setting reactor power, operating margins
- Post-dryout (PDO) behavior
  - establishes behavior in operation beyond dryout
    - heat transfer, and drypatch stability and spreading

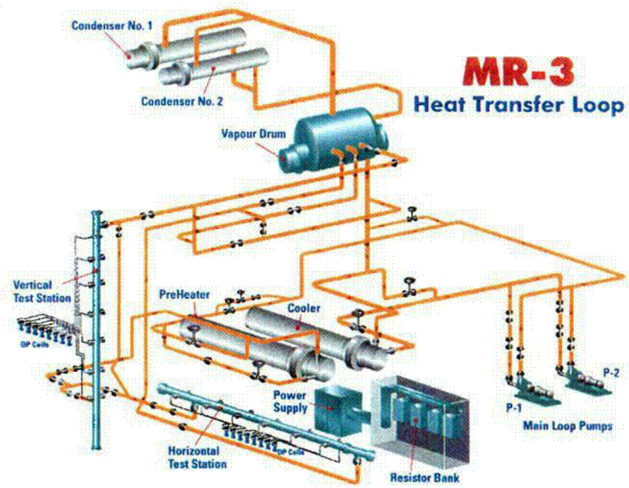
Experimental Facilities

- Full-scale high pressure steam-water loop
  - models CANDU conditions of pressure & temperature
- Full-scale low pressure Freon-134 loop
  - simulates high pressure steam-water conditions
  - fluid-to-fluid modeling well established for converting to water-equivalent conditions
- Small-scale steam-water and Freon-134 loops
  - simple test sections or bundle sub-assemblies
  - fundamental and separate-effect studies

Water Test Facility



Freon Test Facility



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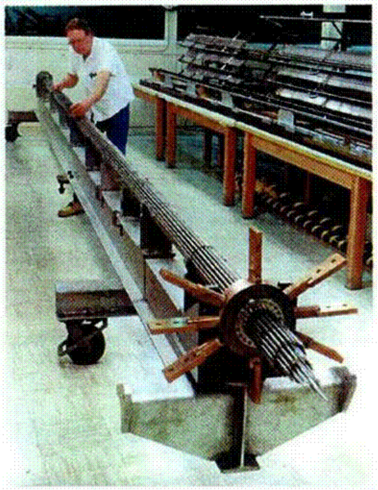
Fuel Bundle Simulator

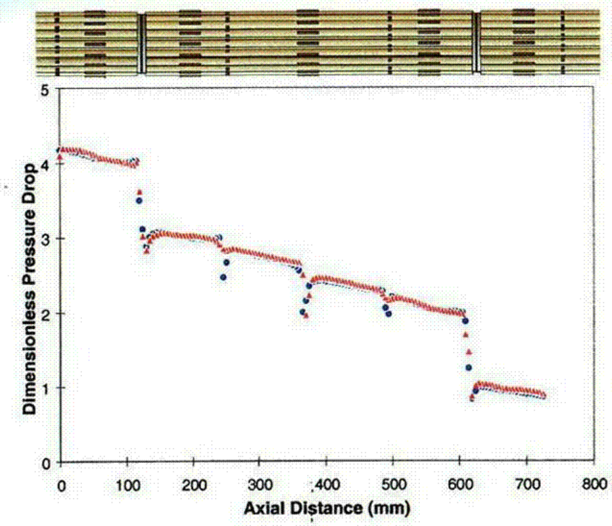
- A 6-m (20 ft) long full-scale bundle string with junction and appendages
- Non-uniform axial and radial power distributions



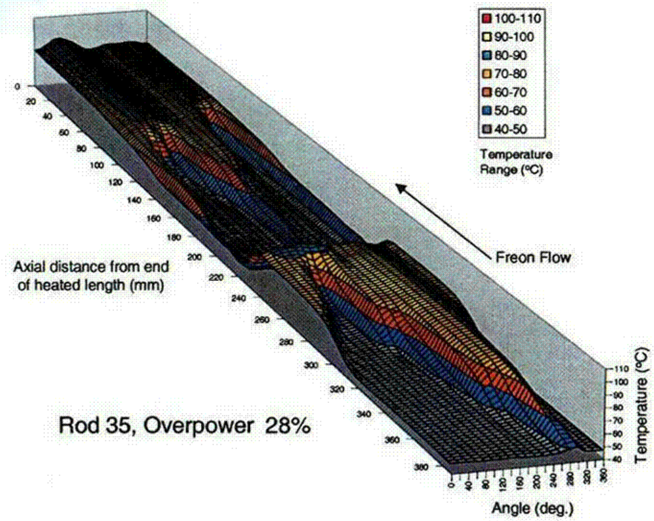
Advanced Instrumentation

- Sliding probes for pressure drop measurements
  - detailed hydraulic characterization
- Sliding thermocouple assemblies for dryout detection and fuel clad temperature measurements
  - cover almost the entire fuel clad area
  - detects initial & subsequent dryout locations
  - allows 3-D representation of clad temperature

Freon Pressure Drop Test Results



PDO Clad Temperature Profile



C08

ACR Thermal Hydraulic Qualification

- Existing database, correlations and models will be extended to ACR conditions
- ACR qualification will include CHF, pressure drop, post-dryout measurements in water and Freon

	Existing database	ACR conditions
Channel outlet pressure	6 to 11 MPa (870 to 1600 psi)	12.5 MPa (1800 psi)
Mass flow rate	7 to 23 $kg.s^{-1}$ (15 to 51 $lb.s^{-1}$)	26 $kg.s^{-1}$ (57 $lb.s^{-1}$)
Inlet subcooling	10 to 75 °C (18 to 135 °F)	49 °C (88 °F)

Outline

- ACR specific features
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- Separate Effects and Integral Experiments
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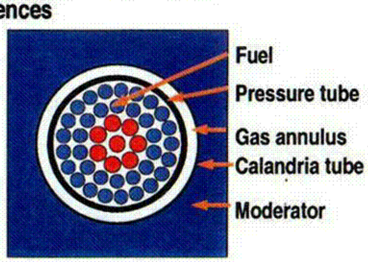
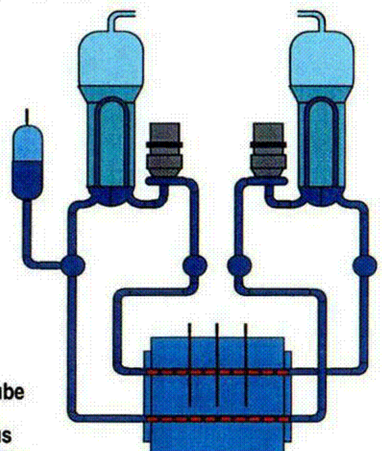
- Fuel Channel Thermal Hydraulics
- **Moderator Thermal Hydraulics**

ACR Moderator

- The moderator is a low-pressure, low temperature system (separate from the reactor coolant).
- Heat is continuously removed from the moderator during normal operation.
- The moderator acts as a heat sink in the event of certain accident sequences





Moderator Thermal Hydraulics

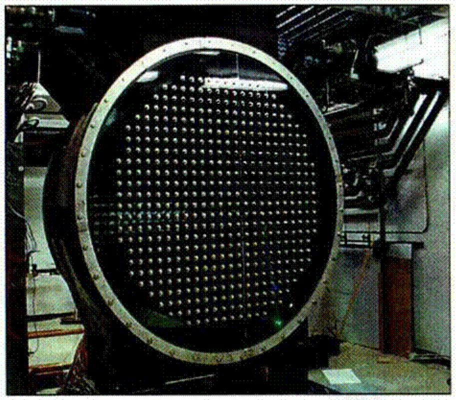
- Need to predict moderator circulation patterns and temperature distribution to ensure adequate cooling margin for all channels.
- Need to predict moderator circulation for postulated accident scenarios to ensure availability of moderator heat sink.
- A 3-D single phase computational fluid dynamics computer code (MODTURC_CLAS) is used to predict moderator flow and temperature distribution.

C09

Moderator Test Facility

- Large-scale facility to measure three-dimensional velocity and temperature distributions in moderator geometry

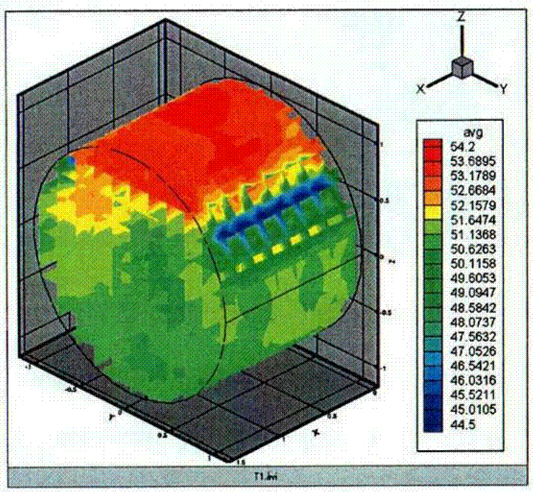
- Calandria vessel with fuel channel simulator heaters and coolant flow system
- 1/4 scale calandria used to validate CANDU 9 design
- 1/3 scale calandria is being built to validate ACR design



Moderator Test Facility Capabilities

- Typical measurements in MTF (steady-state tests)
  - Flow visualization (using dye injection at the inlet nozzles).
  - 3-component velocity measurements using 3-D Laser Doppler Velocimetry (LDV).
  - Temperature distribution measurements using arrays of fixed and movable thermocouples.
  - A typical steady-state test lasts for 4 weeks.
- Transient tests can also be performed (temperature measurements only) and last for about a day.
- Separate effects tests can also be performed to provide additional measurements to validate models used in MODTURC_CLAS (pressure drop, jet development, buoyancy, etc).

CANDU 9 Thermal Measurements



ACR Moderator Circulation Design

- Key ACR design aspects that affect moderator circulation:
  - Smaller lattice pitch (higher hydraulic resistance).
  - Reactivity devices (could affect local temperatures).
- Assessment of ACR preliminary design using MODTURC_CLAS showed similar thermal hydraulic behavior to the CANDU 9, despite the smaller lattice pitch and the reactivity devices.
- Tests in a modified MTF will be conducted to verify the design.

C10

Summary

- There is a large body of experimental and theoretical work supporting the understanding of key phenomena, and the development and validation of computer codes for CANDU thermal hydraulics, covering:
  - Reactor coolant system
  - Fuel channels
  - Moderator

- The experimental database and computer codes are being extended to ACR conditions

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CATHENA Thermal Hydraulics Code

By Dave Richards, Manager
Prepared by Bruce Hanna, CATHENA Code Holder
Containment and Thermalhydraulics Analysis Branch
Presented to US Nuclear Regulatory Commission
Washington, DC
February 5-6, 2003

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Outline

- Introduction
- CATHENA Thermal Hydraulic Model
- GENHTP Wall Heat Transfer Model
- CATHENA Numerical Methods
- Heat Transfer Numerical Methods
- Uncertainty Analysis
- Conclusion

CATHENA

- Canadian Algorithm for THErmal Hydraulic Network Analysis
- One-dimensional, two-fluid system thermal hydraulics code
- Developed by AECL for thermal hydraulic analysis of CANDU reactor coolant systems during postulated events and is applicable to ACR analysis

Applications

Power Reactor Design & Analysis
- CANDU 6
  - Gentilly-2,
  - Wolsong 1 through 4
  - Pt. Lepreau
  - Embalse
  - Cernavoda 1 and 2
  - Qinshan 1 and 2
- CANDU 3
- CANDU 9
- RBMK
- ACR

Applications

Other Reactors Design & Analysis

- SlowPoke designs (SDR, SES-10)
- MAPLE designs (MX10, MMIR and external to AECL)
- NRU
- (CNF) *Canadian Neutron Facility*
- DIDO designs (FRJ-2)
- Small PWR and BWR (e.g., submarines)

Applications

- **Experimental Facilities**
  - Facility and experimental design assist
  - Analysis of test results

e.g., RD-14M
BTF (In-reactor Blowdown Test Facility)

Code Evolution

- RAMA - EVET (~1977)
  - Reactor Analysis IMplicit Algorithm
  - Equal phase Velocities & Equal phase Temperatures
  - Characteristic-finite difference numerical method
- RAMA - EVUT (~1983)
  - Equal phase Velocities & Unequal phase Temperatures
  - Account for vapor-to-liquid temperature difference during flow stratification
- RAMA - UVUT (~1984)
  - Unequal phase Velocities & Unequal phase Temperatures
  - Account for vapor-to-liquid temperature and velocity difference during flow stratification and refilling events

Code Evolution

- ATHENA (~1985)
  - Algorithm for Thermal Hydraulic Network Analysis
  - Renamed because of significant differences (numerics and models) from prior RAMA codes
- CATHENA (~1985)
  - Canadian Algorithm for Thermal Hydraulic Network Analysis
  - *Renamed to distinguish code from "ATHENA" derived from* RELAP-5

Code Evolution

- Development Highlights to MOD-3.5d/Rev 0 Version
  - MOD-3.2e Sept 1988 - 2D conduction heat transfer model
  - MOD-3.3a Nov 1989 - adopted for CANDU 3 design assist
  - MOD-3.5 Aug 1993 - adopted for Wolsong CANDU 6 analysis
    - Adoption of a formal Software Quality Assurance program
  - MOD-3.5a Sept 1995 - NRU (finned fuel) heat transfer coefficients
  - MOD-3.5b/Rev 0 January 1996 - adopted for CANDU 9 design assist
  - MOD-3.5b/Rev 1 Feb 1998- first for PC's (Windows 95/NT)

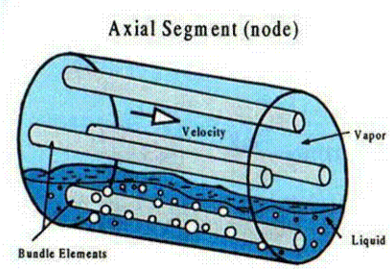
Code Evolution

- MOD-3.5c/Rev 0 March 1999
  - Addition of PVM (Parallel Virtual Machine) interface
    - external control codes
    - 3D reactor kinetics codes
  - Access to uncertainties in correlations and models
- MOD-3.5d/Rev 0
  - Currently in pre-release testing
  - ACR design assist and analysis code
  - ACR specific addition examples
    - CANFLEX MkV fuel bundle CHF
    - best-estimate PDO heat transfer correlations

CATHENA Thermal Hydraulic Model

- Two-fluid non-equilibrium thermal hydraulic model
- Gas phase can include up to 4 noncondensable components
- H_2O and D_2O properties included
- Component models such as point-reactor kinetics, valves, tanks, volumes, T-junctions and pumps
- Flexible set of control system models specified through the input file or connected to external codes through PVM

CATHENA Thermal Hydraulic Model



- Non-equilibrium model (2-velocities, 2-temperatures 2-pressures) plus noncondensables
- Flow regime dependent constitutive relations couple two-phase model

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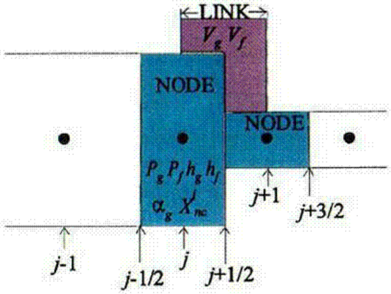
CATHENA Thermal Hydraulic Model



- Semi-implicit finite difference solution method (time step limited only by accuracy considerations)

Thermal Hydraulic Conservation Equations

- Mass conservation - phase k

$$\frac{\partial}{\partial t}\langle\alpha_k\rho_k\rangle + \frac{1}{A}\frac{\partial}{\partial z}\left(A\langle\alpha_k\rho_k v_k\rangle\right) = m_{ki} - \Gamma_{zk}$$

- Momentum conservation - phase k

$$A\frac{\partial}{\partial t}\langle\alpha_k\rho_k v_k\rangle + \frac{\partial}{\partial z}\left(A\langle\alpha_k\rho_k v_k v_k\rangle\right) + \frac{\partial}{\partial z}\left(A\langle\alpha_k P_k\rangle\right) =$$

$$\left\langle P_i\frac{\partial}{\partial z}(\alpha_k A)\right\rangle + A\left[\tau_{ki} - m_{ki}v_{ki} + \tau_{kw} - P'_{ki}\right] + A\langle\alpha_k\rho_k\rangle g_z$$

CATHENA: A thermalhydraulic code for CANDU analysis, Nuclear Engineering and Design 180 (1998) 113-131

Thermal Hydraulic Conservation Equations

- Energy conservation - phase k

$$A\frac{\partial}{\partial t}\langle\alpha_k\rho_k i_k\rangle + \frac{\partial}{\partial z}\left(A\langle\alpha_k\rho_k v_k i_k\rangle\right) - A\frac{\partial}{\partial t}\left(\langle\alpha_k P_k\rangle\right) =$$

$$A\left\langle P_i\frac{\partial}{\partial t}(\alpha_k)\right\rangle + A\left[\tau'_{ki}v_{ki} - P''_{ki} - q_{ki} - q_{kw} + m_{ki}i_{ki}\right] + A\langle\alpha_k\rho_k v_k\rangle g_z$$

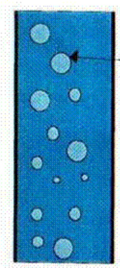
- Where the total enthalpy i_k is defined by

$$i_k = h_k + \frac{v_k^2}{2}$$

Constitutive Equations

- Thermodynamic (e.g., state) properties

$$\rho_k = f(P_k, h_k)$$



- Interface transfers
  - Interface shear

$$\tau_{ki} = \pm\frac{1}{8}A_i f_i \rho_i\left(v_g - v_f\right)^2$$

- Where
  - f_i is a friction factor,
  - A_i is the interface area per unit volume, and
  - ρ_i is a characteristic interface density

C12

Constitutive Equations

- **Interface transfers**
  - Heat transfer

$$q_{ki} = A_i\left[\lambda_{ki}\left(h_{ki} - h_k\right) + m_{ki}\left(h_{ki} - h_k\right)\right]$$

- Where
  - λ_{ki} is a generalized heat transfer coefficient,
  - h_{ki} is the interface enthalpy (e.g., h_g^{sat} & h_f^{sat}), and
  - m_{ki} is the mass transfer of phase k
    - M_{gi} is positive for boiling
- Vapor generation

$$m_{gi} = -m_{fi} = \frac{q_{wi} - \sum_k \lambda_{ki}\,(h_{ki} - h_k)}{h_g - h_f}$$

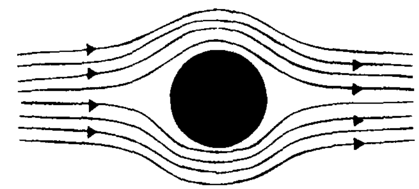
- q_{wi} is the subcooled boiling heat transfer

Constitutive Equations

- **Interface transfers**
  - Apparent or virtual mass

$$P'_{ki} = \pm\rho_{AP}\left[\frac{\partial}{\partial t}\left(v_g - v_f\right) + v^*\frac{\partial}{\partial z}\left(v_g - v_f\right)\right]$$

- Where
  - ρ_{AP} is an apparent density (1/2 ρ_f for a sphere in a liquid), and
  - V^* is an effective interface velocity



- Term also ensures hyperbolicity of hydraulic equation set

Constitutive Equations

- **Interface transfers**
  - Work performed by the apparent mass

$$P''_{ki} = v_{ki}P'_{ki}$$

- Where
  - v_{ki} is the interface velocity for phase k

Constitutive Equations

- **Wall**
  - Heat transfer

$$q_{kw} = A_{kw}\lambda_{kw}\left(T_w - T_k\right)$$

- Where
  - A_{kw} is the wall contact area for phase k, and
  - λ_{kw} is the heat transfer coefficient for phase k
- Shear

$$\tau_{kw} = \frac{1}{2}A_{kw}f_{kw}\rho_k v_k^2$$

- Where
  - f_{kw} is the wall friction factor for phase k

Constitutive Equations

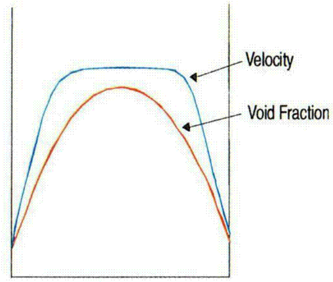
- "Profiles"
  - Necessary to distinguish between averages of products and products of averages, eg.
  - Mass flux

$$\langle \alpha_k \rho_k v_k \rangle \equiv C_{0k} \langle \alpha_k \rangle \langle \rho_k \rangle \langle v_k \rangle$$

  - Momentum flux

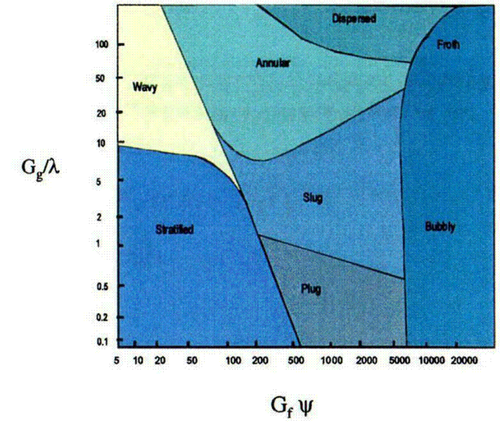
$$\langle \alpha_k \rho_k v_k^2 \rangle \equiv C_{1k} \langle \alpha_k \rangle \langle \rho_k \rangle \langle v_k \rangle^2$$

  - The C_{nk} profile coefficients can be defined through flow regime and average parameters



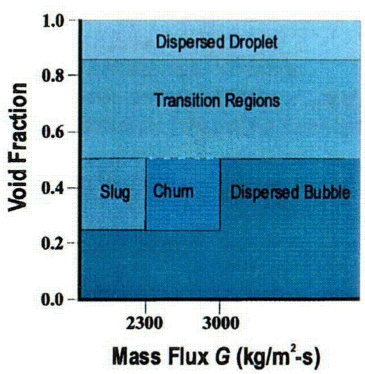
Flow Regime Maps

Typical flow regime map for flow in horizontal pipes



Flow Regime Maps

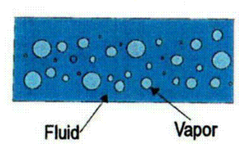
- Mixed Flow

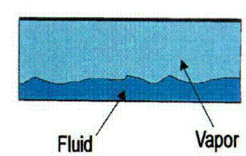


Flow Regime Maps

- Horizontal pipes and fuel channels

n	$W_n = 1.0$ (stratified)	$1.0 > W_n > 0.0$ (transition)	$W_n = 0.0$ (mixed)	Prime Influence
1c	$j^* < 1.0$	$1.0 \le j^* < 10.0$	$j^* \ge 10.0$	Channel Flux
1p	$j_f < j_{f,min}$	$j_{f,min} \le j_f < j_{f,max}$	$j_f \ge j_{f,max}$	Pipe Flux
2	$U_r^* < 0.75$	$0.75 \le U_r^* < 1.0$	$U_r^* \ge 1.0$	Flow Instability
3	$\alpha_g > 0.1$	$0.1 \ge \alpha_g > 1 \times 10^{-5}$	$\alpha_g \le 1 \times 10^{-5}$	Void Fraction
4	$C_s^* < 1.0$	$1.0 \le C_s^* < 5.0$	$C_s^* \ge 5.0$	Flooding Limit
5	$U_e^* < 1.0$	$1.0 \le U_e^* < 11.0$	$U_e^* \ge 11.0$	Entrainment
6	$\lvert v_f \rvert \le v_1$	$v_1 < \lvert v_f \rvert < v_2$	$\lvert v_f \rvert \ge v_2$	Turbulence





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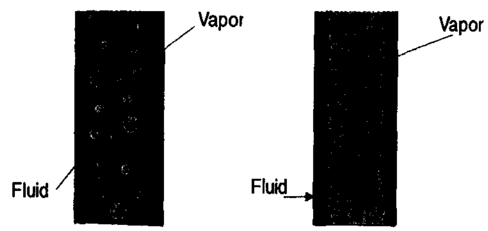
Flow Regime Maps

- **Vertical pipes**

n	$W_n = 1.0$ (annular)	$1.0 > W_n > 0.0$ (transition)	$W_n = 0.0$ (mixed)	Prime Influence
1	$j_f < 3.0$	$3.0 \leq j_f < 5.0$	$j_f \geq 5.0$	Liquid Flux
2	$\alpha_g > 0.8$	$0.8 \geq \alpha_g > 0.4$	$\alpha_g \leq 0.4$	Void Fraction
3	$U_e^* < 1.0$	$1.0 \leq U_e^* < 11.0$	$U_e^* \geq 11.0$	Entrainment
4	$\lvert v_f \rvert \leq v_1$	$v_1 < \lvert v_f \rvert < v_2$	$\lvert v_f \rvert \geq v_2$	Turbulence



Flow Regime Map Use

- **Constitutive Equation Calculation**
  - Calculate mixed flow regime relations
  - Calculate separated flow regime relations
  - Combine constitutive equations using the product of the flow regime transitions

$$F_A = W_s F_S + (1 - W_s) F_M$$

$$W_s = \prod_n W_n$$

Modeling Assumptions

- **All variables are time & area averages**
  - Unrealistic to expect results to apply to either very short time or very short spatial increments
    - Δt must be large enough that a "time" average is meaningful. For example, larger than the time required for a bubble to pass a given location
    - Δz must be larger than a typical bubble diameter

Modeling Assumptions

- **Viscous dissipation terms are neglected in comparison with thermal energy transfers**
  - Implies less accuracy for high velocity gas flows – e.g., near a break or gas shock tube simulations
- **Bulk shear neglected**
  - Less damping of small pressure waves
- **Axial conduction and local free convection included as a source term in energy equation**

Modeling Assumptions

- Flow regime map is calculated based on local variables with transition criteria developed from steady-state, well-developed flow conditions
  - Time & distance required for transition to occur is neglected
    - Bubbles coalesce instantaneously
    - Flow stratifies instantaneously
  - Transitions will be calculated to occur more quickly than observed
  - Hydraulic calculations can be expected to be less "stable" than observed

Constitutive Assumptions

- Correlations are based on steady-state, well developed conditions
  - *Time required to develop boundary layers assumed in* shear and heat transfer correlations is neglected
    - Reduced stability

CATHENA Thermal Hydraulic Model

- Fluids Available
  - H_2O and D_2O
- Noncondensables (carried with vapor)
  - Air
  - N_2
  - H_2
  - He
  - Ar
  - CO_2

CATHENA Thermal Hydraulic Model

- Full Network, User Defined by Input File
- Mass Conservative
- Special Considerations for Horizontal Stratified Flow
- Automated Timestep Control Algorithm

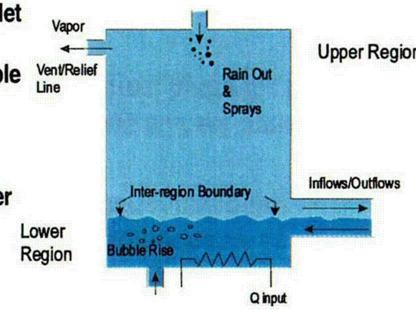
CATHENA Component Models

- Generalized Tank
- Volumes
- T-Junctions
- Reactor Kinetics*
- Valves/Orifices
- Delay Line
- Discharge/Break
- ECI Accumulator
- Heat Balance
- Heat Exchanger
- Junction Resistance
- Pump
- Separator
- Crept Pressure Tube

*3D kinetics included through a system control model

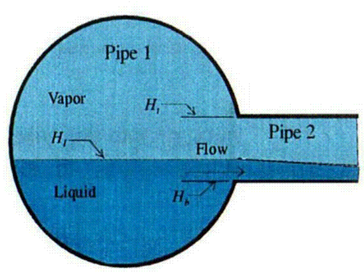
CATHENA Component Models

- Generalized Tank
  - Two region two-fluid model
    - Upper region includes droplet "rain-out" model
    - Lower region includes bubble "rise" model
    - Inter-region heat transfer and surface condensation
    - Wall heat transfer and heater model included



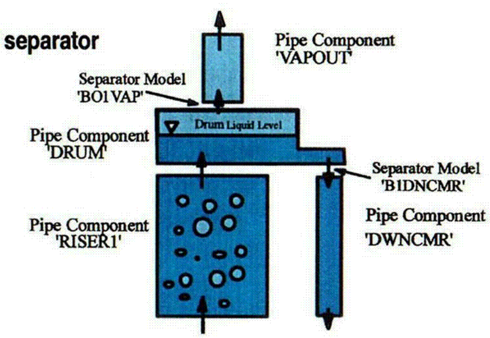
CATHENA Component Models

- Separator
  - Horizontal pipe connection modeling
    - Entrances specified by the user through the pipe geometry input
    - Includes vapor and liquid pull through models



CATHENA Component Models

- Separator
  - Secondary-side separator modeling
    - User specified separator efficiency



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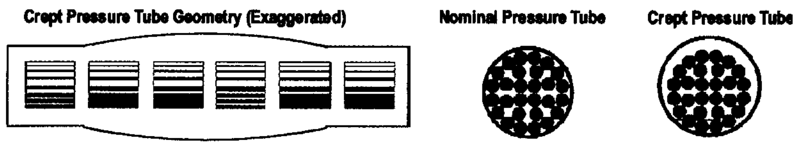
CATHENA Component Models

- Crept Pressure Tube
  - Allow user specification of "creep-profile" as a function of axial position
  - Include integrated effect of pressure-tube aging on channel pressure drop and critical heat flux calculations



Thermal Hydraulic Components

COMPONENTS

PIPE - length, volume, pressure-losses
RESERVOIR - location for a boundary condition
VOLUME - connection between multiple pipes
TANK - a two (2) region volume where level is tracked
T-JUNCTION - volume component with special entrance & exit loss functions

CONNECTIONS

- how components are connected to form a hydraulic network

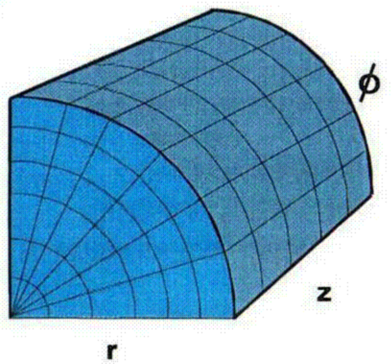
System Control Models

- Control models are a part of the input file
- Integrated point kinetic modeling routines
- Interface to external routines supplied by the user and integrated with the code when the executable code is generated
- A PVM interface to external control or other programs
  - ELOCA (fuel thermal-mechanical deformation)
  - C6CON (plant controllers for a CANDU 6)
  - 3D kinetics models

CATHENA Solid Heat Transfer Model (GENHTP)

- Model for heat transfer within all solid components as cylindrical elements with user defined inner and outer boundaries
- Conduction within solid components and all heat transfer between solid components and the thermal hydraulic fluids (liquid, vapor & two phase mixtures)
- Examples: - radial conduction within multi-region fuel
  - radial conduction within pipe walls
  - fuel pin-to-fluid heat transfer
  - pipe wall-to-fluid heat transfer

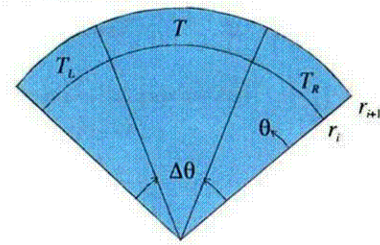
CATHENA Solid Heat Transfer Model (GENHTP)



- Comprehensive solid heat transfer model
  - Radial conduction
  - 2-D radial and circumferential conduction
  - Axial conduction has not been included since refilling is predominately across the fuel channel (not along)

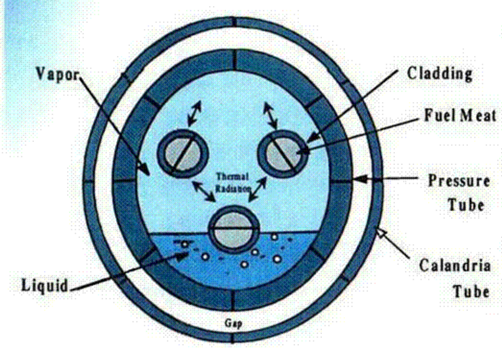
CATHENA Solid Heat Transfer Model (GENHTP)

- General 2D conduction



$$\frac{\partial}{\partial r}\left(Kr\frac{\partial T}{\partial r}\right) = -r\left(q''' - \rho C_p \frac{\partial T}{\partial t}\right)$$

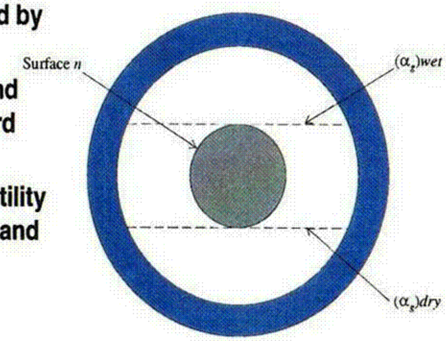
CATHENA Solid Heat Transfer Model (GENHTP)



- User specified number of heat transfer surfaces
- Thermal radiation
- Contact solid-solid
- Zr/Steam reaction
- Pressure-tube deformation
- Thermal stratification

CATHENA Solid Heat Transfer Model (GENHTP)

- Surface "elevation" in stratified flow determined by α_{wet} and α_{dry} values
- Built in values for α_{wet} and α_{dry} available for standard bundle geometries
- BUNDLE preprocessor utility created to calculate α_{wet} and α_{dry} for nonstandard geometries



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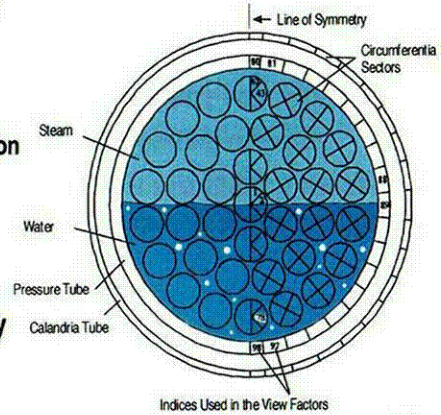
CATHENA Solid Heat Transfer Model (GENHTP)

- Radiation model
  - 2D heat transfer in bundle
  - Diffuse grey surfaces
  - Inter-region volume transparent to radiation
  - Temperature for each region uniform
- Radiation heat transfer defined by view factor matrix
- MATRIX preprocessor utility created to calculate view factor matrix

$$\overline{q}'' = \sigma \tilde{E}\left[\tilde{I} - \tilde{F}\left[\tilde{I} - \tilde{E}\right]\right]^{-1}\left[\tilde{I} - \tilde{F}\right]\overline{T}^{4}$$



CATHENA Solid Heat Transfer Model (GENHTP)

- Zr/steam reaction
  - Parabolic rate law

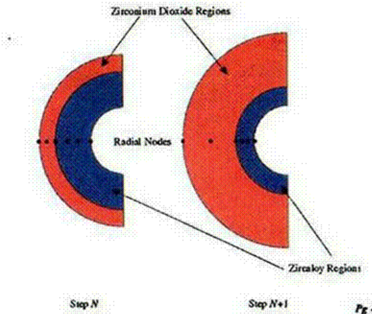
$$\frac{d\delta}{dt} = \frac{k}{\delta} e^{-\Delta E/RT}$$

δ=Zr thickness consumed
k Arrhenius rate constant
ΔE activation energy
R gas constant
T temperature

  - Heat generation

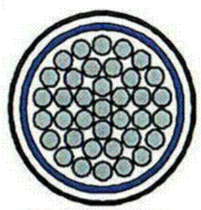
$$Q = C A_s \frac{d\delta}{dt}$$

C heat generation per unit volume of Zr
A_s surface area

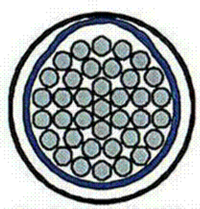


CATHENA Solid Heat Transfer Model (GENHTP)

- Pressure-tube deformation
  - 1D Circular "GRAD" Model
    - Simple circumferential strain calculation
    - Non-uniform deformation as a function of PT temperature but circular assumption used for contact calculation
  - 2D "PTRING" Model
    - Thin shell calculation
    - Contact defined only for deformed PT sectors allowing PT sag calculations



PT Ballooned (5%)



Non-Circular Deformation

CATHENA Numerical Methods

- Semi-implicit finite difference method
  - First-order upwind donor-cell
  - Dependent variables are:
    - Void fraction
    - Gas pressure
    - Phase enthalpies
    - Noncondensable mass fractions

    } Node Values

    - Phase velocities } Link Values
  - All finite-difference equations solved simultaneously in a sparse matrix solver
  - Mass truncation error correction algorithm

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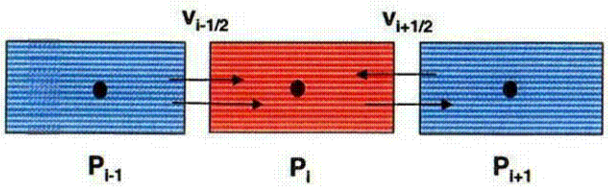
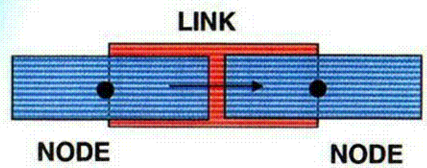
CATHENA Numerical Methods

- **Conservation equation discretization**



CATHENA Numerical Methods



- NODE-LINK structure
  - A NODE represents the control volume for mass and energy conservation
    - 4 equations (gas and liquid mass and energy)
    - 1 additional equation for each noncondensable component
  - A LINK represents the control volume for momentum conservation
    - 2 equations (gas and liquid momentum)

CATHENA Numerical Methods

- Gas Mass Conservation Equation (node n)

$\frac{\partial}{\partial t}\left(\alpha_g \rho_g\right)$ Approximated as

$$\chi_1 = (\rho_g)_j^n \left(\alpha_g^{n+1} - \alpha_g^n\right)_j + \left(\left(\frac{\partial \rho_g}{\partial P}\right)^n \left(P_g^{n+1} - P_g^n\right) + \left(\frac{\partial \rho_g}{\partial h_g}\right)^n \left(h_g^{n+1} - h_g^n\right) + \sum_{i=1}^{n} \left(\frac{\partial \rho_g}{\partial X_{nc}^i}\right)^n \left(X_{nc}^{i,n+1} - X_{nc}^{i,n}\right)\right)_j (\alpha_g)_j^n$$

$\frac{1}{A}\frac{\partial}{\partial z}\left(C_{og}\alpha_g \rho_g v_g\right)$ Approximated as

$$\chi_2 = \frac{\Delta t}{V_j} \sum_L (AC_{0g})_L \, \mathrm{SGN}_L \left[-(\alpha_g \rho_g)_J^n v_{gL}^n + \alpha_{gJ}^n v_{gL}^n \left\{ \left(\frac{\partial \rho_g}{\partial P_g}\right)_J^n (P_{gJ}^{n+1} - P_{gJ}^n) + \left(\frac{\partial \rho_g}{\partial h_g}\right)_J^n (h_{gJ}^{n+1} - h_{gJ}^n) \right\} + (\alpha_g \rho_g)_J^n v_{gL}^{n+1} + \rho_{gJ}^n v_{gL}^n \alpha_{gJ}^{n+1} \right]$$

CATHENA Numerical Methods

- Gas Mass Equations

m_{gi} Approximated as

$$\chi_3 = \Delta t \left(m_{gi}^n + \frac{\partial m_{gi}^n}{\partial P}\left(P_g^{n+1} - P_g^n\right) + \frac{\partial m_{gi}^n}{\partial h_g}\left(h_g^{n+1} - h_g^n\right) + \frac{\partial m_{gi}^n}{\partial h_f}\left(h_f^{n+1} - h_f^n\right) + \sum_{i=1}^{n} \frac{\partial m_{gi}^n}{\partial X_{nc}^i}\left(X_{nc}^{i,n+1} - X_{nc}^{i,n}\right) \right)_j + \varepsilon_g$$

See "CATHENA: A thermalhydraulic code for CANDU analysis", Nuclear Engineering and Design 180 (1998) 113-131

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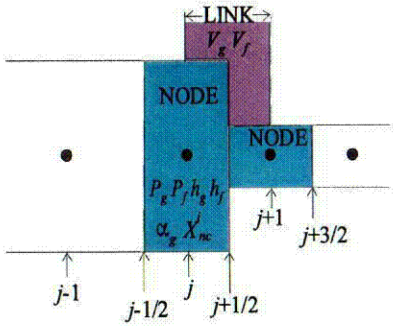
CATHENA Numerical Methods

- Semi-implicit terms included for major influences
- Momentum
  - Wall shear
    - Taylor series expansion in phase velocity
- System models
    - Semi-implicit in densities, void fraction and velocity
  - Pumps models
  - Valve models
  - Discharge models

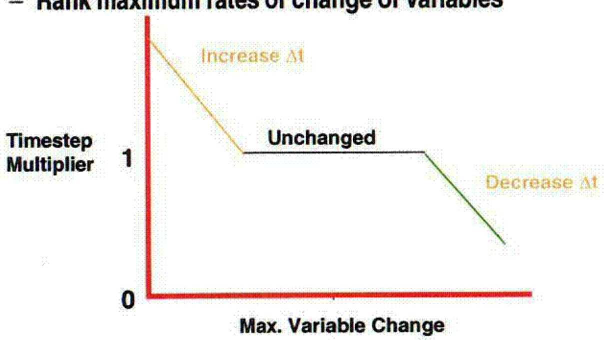


CATHENA Numerical Methods

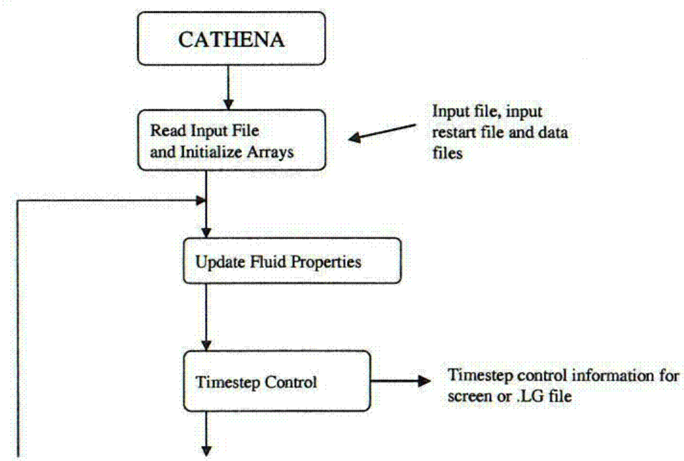
- Matrix Solution Methodology
- Solution of the coupled linear finite-difference equations
  - Directly solve the linear equations
    - Use a sparse matrix solution package to simultaneously solve for all of the dependent variables (SMPAK or MA28)
    - More efficient sparse matrix solution algorithms have been examined
      - SMPAK was adopted for MOD-3.5d/Rev 0
      - Parallel solution methods and matrix partitioning are being examined for future applications

CATHENA Numerical Methods

- Time step Control Algorithm
  - An adaptive timestep control algorithm
    - Ensure accuracy of solution with nonlinear source terms
    - Maintain reasonable computation efficiency
  - Rank maximum rates of change of variables



CATHENA Numerical Methods



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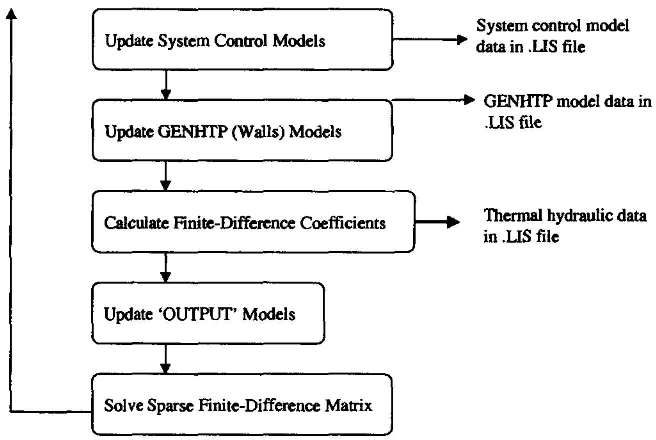
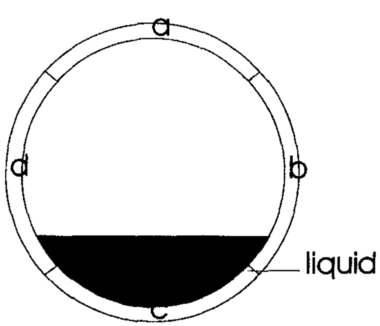
CATHENA Numerical Methods



CATHENA Solid Heat Transfer Model (GENHTP)

- Numerical Methods for Conduction
  - Rayleigh-Ritz for radial conduction
  - Finite-difference for circumferential conduction
- Semi-implicit method for heat transfer to thermal hydraulics and radiation heat transfer between wall surfaces
  - Based on 1st order Taylor series expansion with error correction

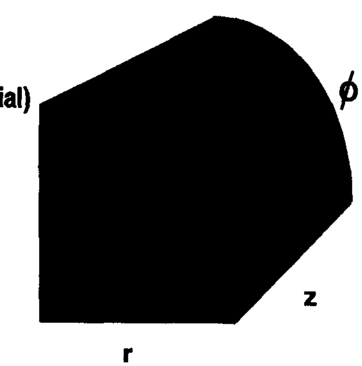
CATHENA Numerical Methods



- Pipes or fuel can be divided into circumferential sectors
  - Each sector has potentially a different temperature history

Heat Transfer Numerical Methods

- Solid conduction 1D and 2D algorithms
- Two well established numerical methods used in CATHENA
  - finite-element (radial)
  - finite-difference (circumferential)



Heat Transfer Numerical Methods

- **Conduction numerics:**
  - 1D

$$\delta F(T) = 2\int_{r1}^{rm} \delta T\left(-\frac{\partial}{\partial r}\left(K_r \frac{\partial T}{\partial r}\right) - r\left(q''' - \rho C_p \frac{\partial T}{\partial t}\right)\right)dr$$
$$+2r_1\delta T\left(-K\frac{\partial T}{\partial r} + h_{c1}\left(T - T_{f1}\right)\right)\Big|_{r1}$$
$$+2r_m\delta T\left(-K\frac{\partial T}{\partial r} + h_{cm}\left(T - T_{fm}\right)\right)\Big|_{rm}$$

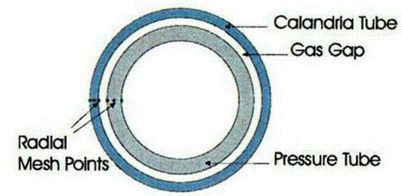
$$T(r) = \sum_{i=1}^{N} c_i \beta_i(r)$$ trial function assumed

linear function of radius

  - 2D

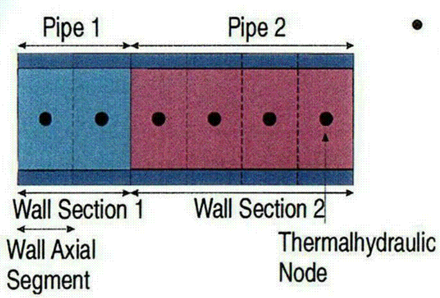
q''' Replaced by function containing finite-difference calculation for circumferential heat transfer

Heat Transfer Numerical Methods



- Radial heat transfer
- Number of radial nodes each model contains is specified in the input model
- For ease of modeling, several nodes can be combined into a radial region
  - A region has a common thermal property and heat generation specifications

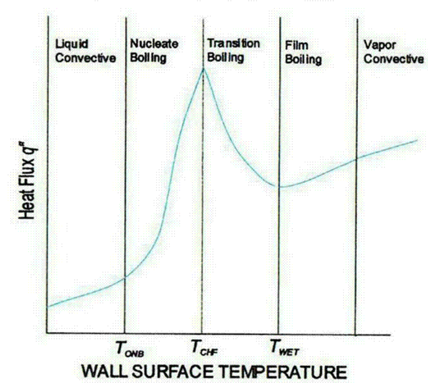
Heat Transfer Numerical Methods



- Typical wall model axial nodalization (shown)
- Alternative wall model axial nodalization may be specified
  - Must be consistent with the wall-to-fluid heat transfer integration method specified

Heat Transfer Numerical Methods

- Independent heat transfer calculation for each GENHTP surface (i.e., axial node, model sector & cylinder)
  - Heat transfer defined by transitions on boiling curve



- Onset of Nucleate Boiling (ONB): $T_{wall} = T_{sat}$
- Onset of Significant Void (OSV): Saha-Zuber
- Critical Heat Flux (CHF): Groeneveld-Leung tables
- Rewet Temperature: Groeneveld

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Heat Transfer Numerical Methods

- Heat transfer correlations
  - Default set of correlations covering entire boiling curve
    - Single-phase liquid convective to gas convective and condensation
      - Liquid and nucleate boiling [modified Chen]
      - Transition [Bjornard & Griffith]
      - Film boiling [Leung PDO tables]
      - Vapor [Heinemann]
  - Additional heat transfer correlations are available for special conditions, e.g.,
    - Cross-flow conditions in steam generators (e.g., Short)
    - CHF for specific fuel bundles (CANFLEX)

Heat Transfer Numerical Methods

- Due to the changes in fuel channel geometry due to pressure tube deformation, the following feedback effects are included in CATHENA:
  - The changes in conduction heat transfer area due to changes in the surface area and radial thickness
  - The change in radiation matrices
  - The change in Zr emissivity due to oxidation at high temperatures

Heat Transfer Numerical Methods

- Semi-implicit wall-to-fluid heat transfer numerics
  - 1st order Taylor series expansion in fluid enthalpies and pressure (saturation temperature)
  - Two passes in heat transfer models
    - Heat transfer coefficients
    - Update wall temperatures and obtain heat fluxes
  - Correction for non-linear fluid properties performed to ensure energy conservation across the wall-to-fluid interface

Heat Transfer Numerical Methods

- Links to ELOCA to model:
  - ELOCA is a single-element fuel thermal mechanical code
    - Conduction within the fuel
    - Metallographic changes in fuel and sheath
    - Expansion of fuel pins
    - Release of fission products into the gap with the consequential change in gap conductivity

Uncertainty Analysis

- CSAU requires uncertainty range of specific parameters such as correlations be assessed.
  - The impact of the uncertainty in the correlations coefficients in CATHENA on a simulation can be assessed by "modifying" their value through a defined uncertainty.
  - The new value of the correlation coefficient can be defined through an internally defined standard deviation, σ, and offset (bias), ê.
  - The new value of the correlation coefficient can alternatively be defined by a user defined multiplier or bias.

Uncertainty Analysis

- Example uncertainty assessment application.
  - The values defined for Groeneveld CHF tables for tubes were defined as

    σ = 7.82% with a bias ê = 0.69%
  - Run simulation without uncertainty inclusion
  - Run simulation(s) with uncertainty additions
    - Separate ".aux" file specifies the location (i.e., where in the simulation) and magnitude of uncertainty application
    - CATHENA automatically renames all output to indicate an uncertainty calculation was being performed

Conclusion

- CATHENA thermal hydraulic and wall heat transfer models
  - Current release provides extensive analysis capabilities for CANDU analysis
  - MOD-3.5d/Rev 0 builds on this base for ACR analysis
- Extensive code validation program performed for current release and planned for future releases

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TECHNOLOGIES INC.

Separate Effects and Integral Thermal Hydraulics Test Facilities

By Paul J. Ingham, Manager
Experimental Thermalhydraulics and Combustion Branch
Presented to US Nuclear Regulatory Commission
Washington DC
February 5-6, 2003

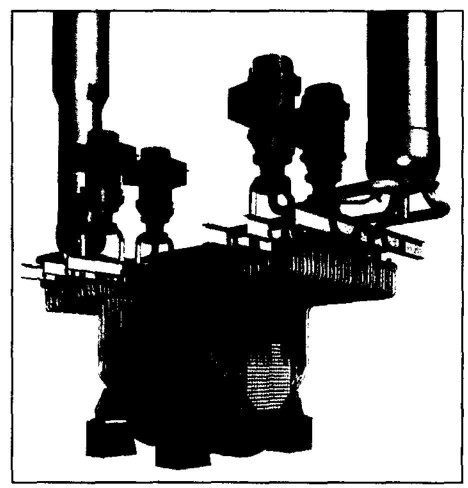
AECL
TECHNOLOGIES INC.

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
  - End-fitting Characterization Test facility

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

<u>Objectives</u>

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

History of 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 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 Integral Test Facilities - RD-14M

We wanted to study the interaction among parallel channels in a single pass in themosiphoning 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 thermalhydraulic 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 behaviour
- develop and validate models
- enhance the ability to predict thermalhydraulic behaviour in reactor specific geometries

How Has RD-14M Been Used?

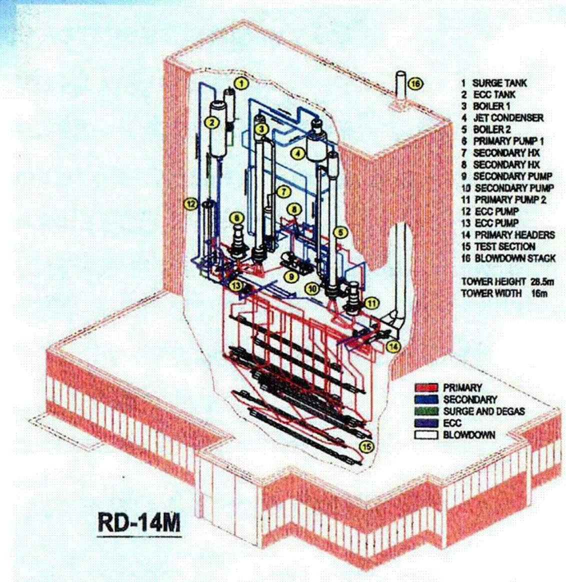
- Data on the initial blowdown, refill behaviour and emergency core coolant (ECC) effectiveness for a range of LOCA conditions
- Data and analysis on the effectiveness of core cooling without forced flow
- Data on the effectiveness of header interconnects for mitigating flow oscillations
- Data on shutdown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

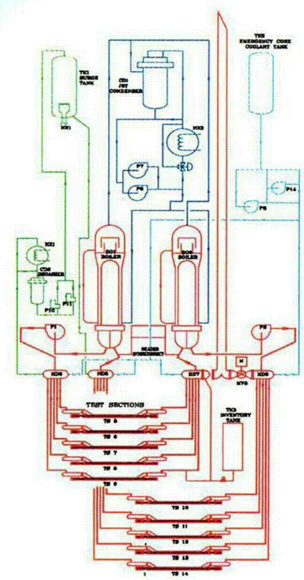
Design Features of RD-14M

- 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
- Blowdown / 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





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 to provide a conservative <u>component</u> design.

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Scaling - Development of Criteria

- Approach of Ishii and Kataoka used to develop scaling criteria to obtain dynamic similarity.
- Write the governing thermalhydraulic equations in dimensionless form (mass, energy, and momentum balances) using drift flux model or homogeneous models as required.
- Achieve dynamic similarity by adjusting facility design variables (pipe length, diameter, etc.) to match value of dimensionless groups for facility and reactor.

Scaling - Key Dimensionless Groups

Phase change number	Drift flux number
Density ratio	Froude number
Friction number	Orifice number
Subcooling number	Critical heat flux number
Time ratio group	Heat source number

Scaling - Results

- Full linear dimensions and elevation changes present in a typical CANDU reactor were maintained. If this requirement was not met, simulation of the reactor void distribution, caused by elevation induced flashing, would not be possible (this is particularly important under natural circulation conditions.)
- Some compromises in the scaling of some components had to be tolerated (headers).
- The fact RD-14M was a modification to RD-14 influenced much of the scaling for the below header piping.

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)

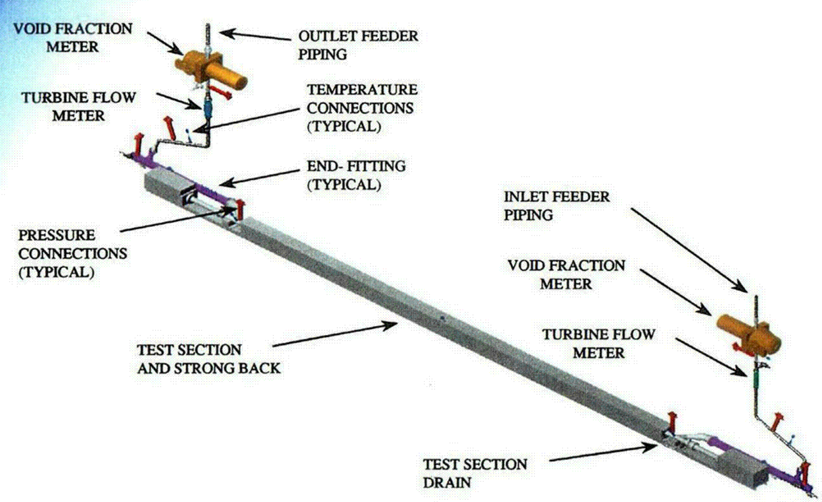
RCS - Major Components

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

Test Sections

- 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



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 sheath
  - sheath electrically insulated from the heated tube by a boron nitride annulus

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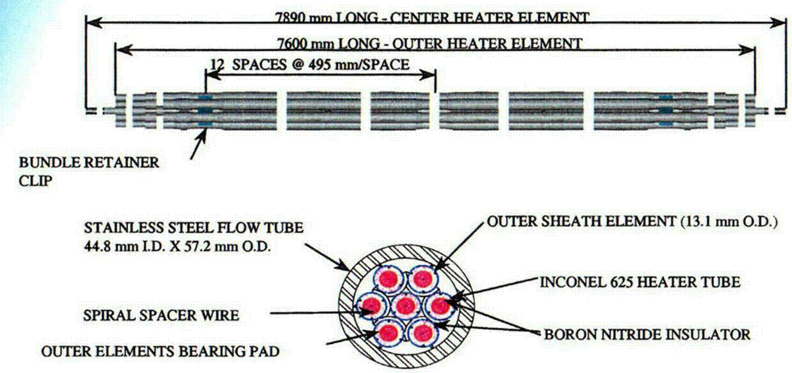
Heated Sections - Fuel Element Simulators (FES) Scaling

- 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.

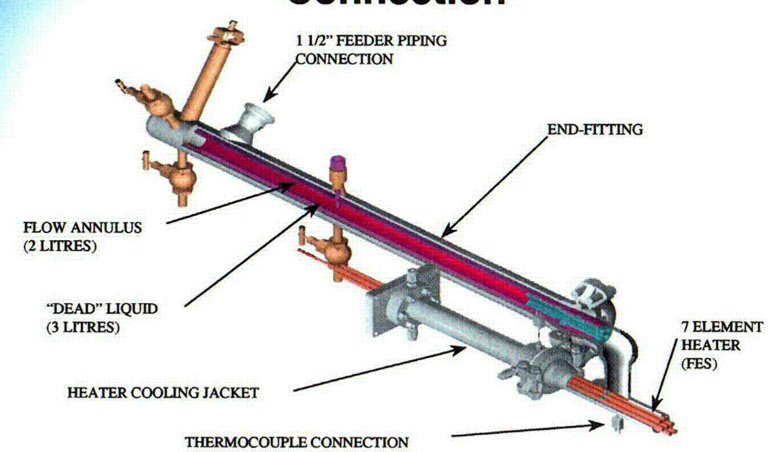
Heated Sections - Fuel Element Simulators (FES)



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



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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

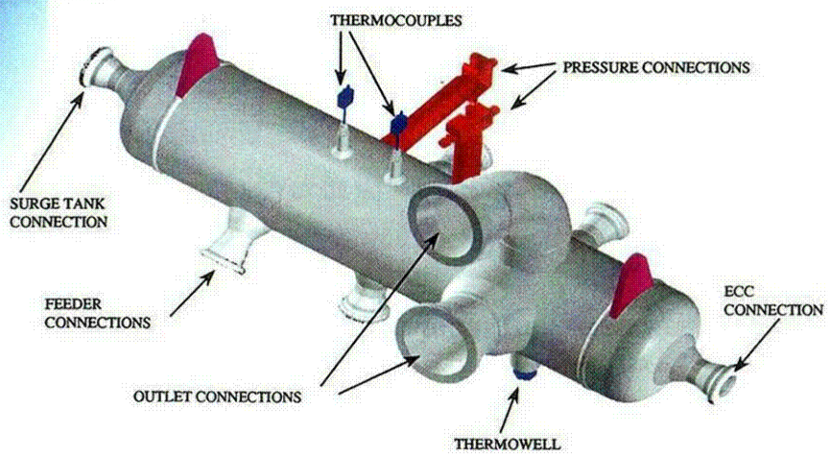
- Full vertical height and linear length
- Scaled diameters, but the range of feeder diameters in RD-14M cover the range found in the ACR.
- Feeder connections to the headers attach at various angles.
- Feeder geometries cover the range of horizontal lengths and flow restricting orifices present in the CANDU reactor.

Feeders

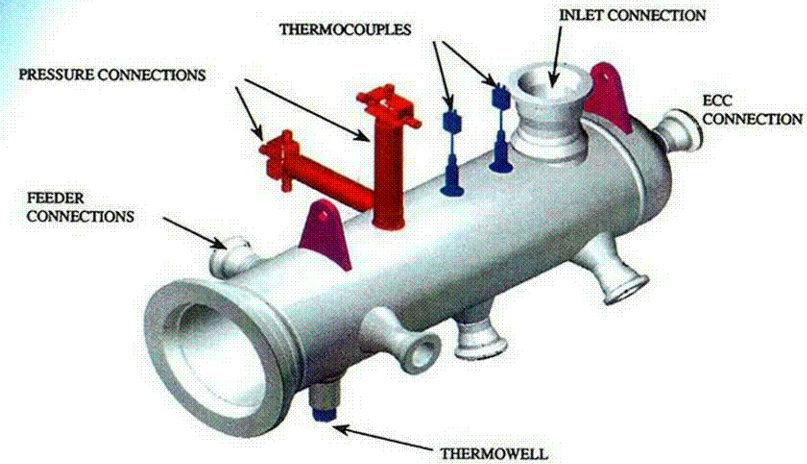
Headers

- 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

- **Recirculating U-tube boilers**
- **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

	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.

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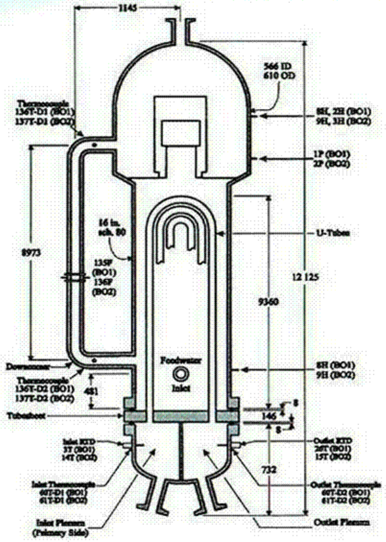
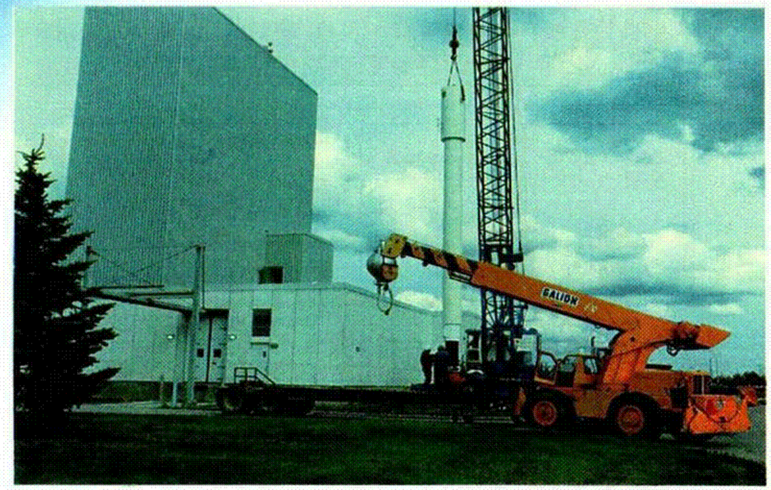
Steam Generators



Steam Generators



Main Coolant Pumps

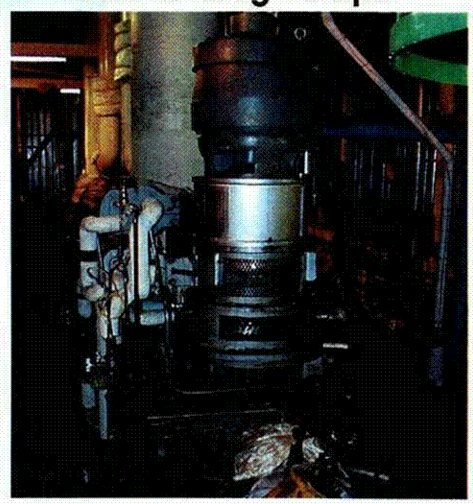
Bingham centrifugal pumps

- 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

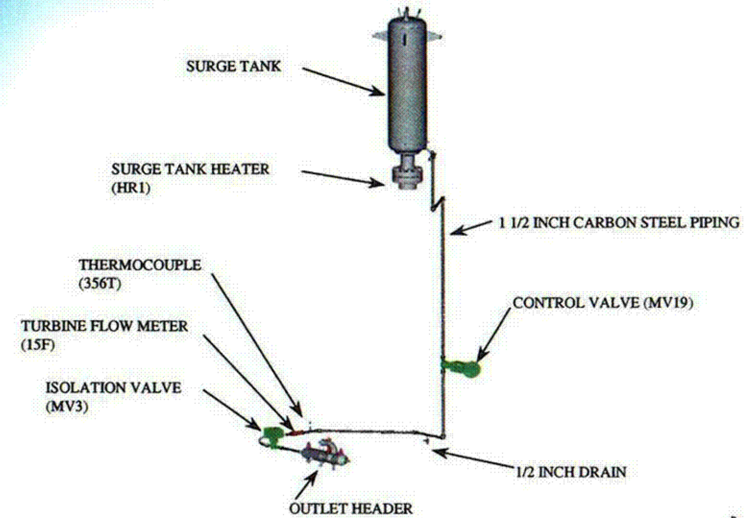


C24

Surge System (Pressurizer)

- 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
- No scaling - typically isolated just prior to starting a transient experiment

Surge System (Pressurizer)



Miscellaneous - Insulation and Heat Losses

- 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

- 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 large relative to 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

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Secondary Side

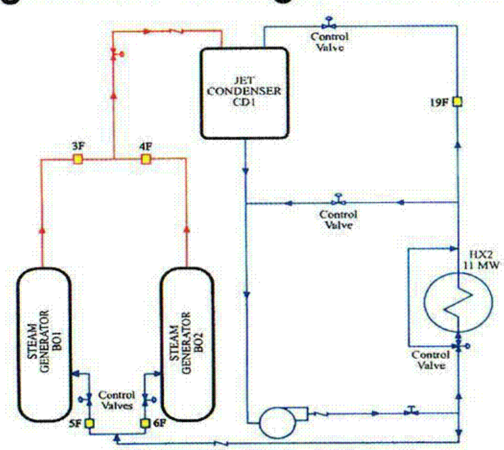
- Steam generators have full vertical height.
- Remainder of secondary side does not model any reactor components. RD-14M secondary side exists as a heat sink to remove energy from the RCS.
- Two configurations:
  - high-power configuration capable of removing 500 kW to 11 MW
  - low-power configuration capable of removing < 500 kW (used during most natural circulation experiments)

Secondary Side - Controls

- Level controls for each boiler.
- Boiler feedwater temperature control.
- Secondary side pressure.

Tests are typically run with a fixed level in each of the boilers, a fixed secondary side pressure, and a fixed feedwater temperature.

Secondary Side (High Power Configuration Shown)



ECC System

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.

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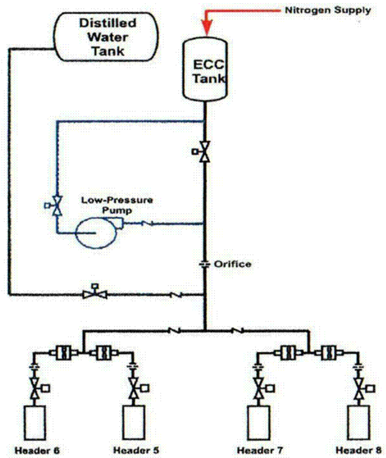
ECC System - CANDU 6 Configuration



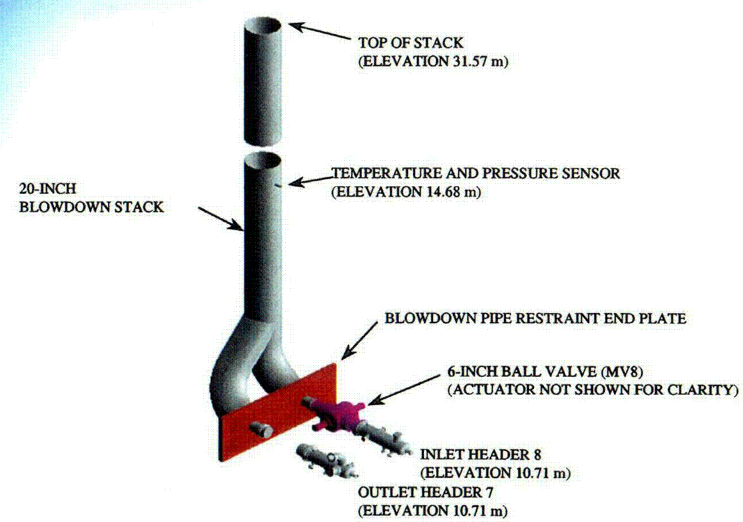
ECC System

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

Blowdown System

- 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



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Blowdown System - 6 inch Valve

Instrumentation

- Instruments strategically located to measure key thermalhydraulic 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 (i.e. heated sections, pumps, etc.) to accurately measure a large range of pressure drop.
- Majority of instruments are Rosemount 1151DP cells.

Instrumentation - Pressure

- 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 boiler and in jet condenser.

Instrumentation - Pressure

- 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

- 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 boiler (orifice plate with mass flow computer)
- Boiler feedwater flow rate to each boiler (turbine flow meter)
- Boiler downcomer flow rate in each boiler (orifice plate)

Instrumentation - Flow Rate

- 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

- Over 90 temperature measurements in the RCS including inside select boiler 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

- 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)
  - scanned by the main data acquisition system

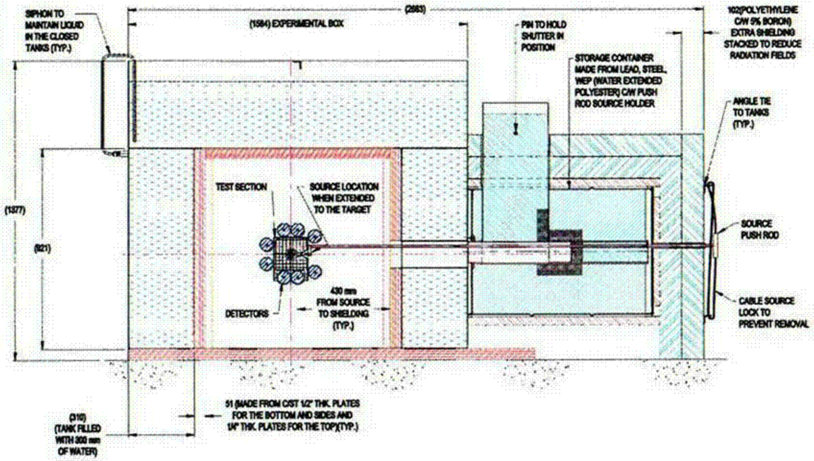
Instrumentation - Void Fraction

- 4 two-beam gamma densitometers measuring boiler 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

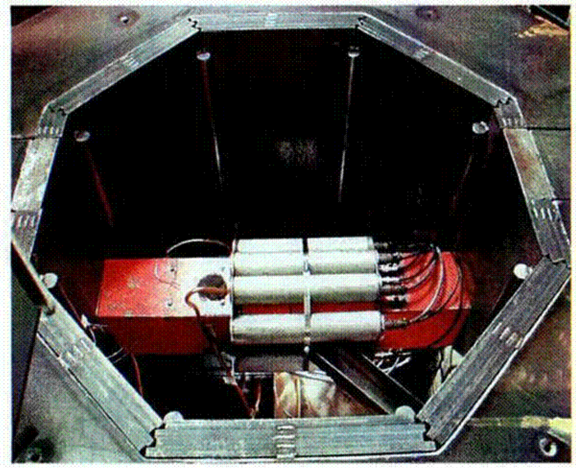
Measurement of RD-14M Channel Void During Large LOCA

- 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



Instrumentation - Miscellaneous

- Level measurements in pressurizer (surge tank), inventory tank, secondary side jet condenser, and ECC inventory tanks
- Collapsed liquid level measurements in each boiler and boiler 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)

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RD-14M TEST MATRIX

Type of Test	Number of Tests
Natural Circulation	
Partial Inventory	49
Transition	27
LOCA	
Small Break	9
Critical Break	27
Large Break	18
With Channel Void Measurement	18
ACR Conditions	9
Flow Stability	9
Transition to Shutdown Cooling	9
Loss-of-Flow	20

RD-14M LOCA EXPERIMENTS

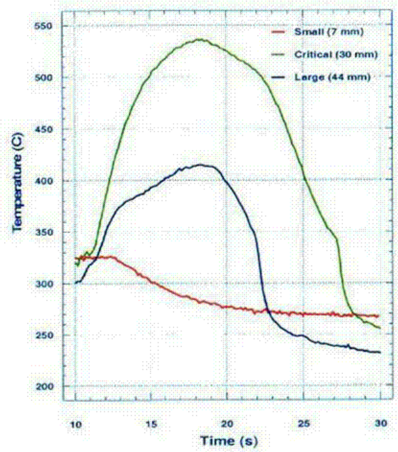
Definition:

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

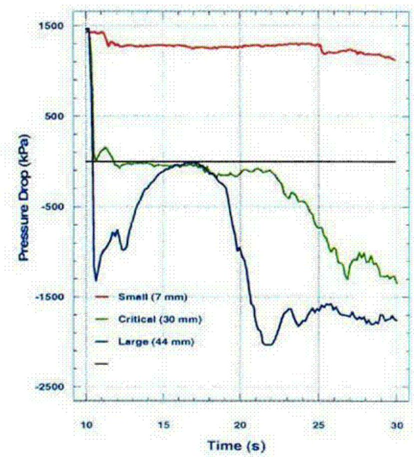
Critical Break LOCA -
Results in the formation of flow split points in the heated portion of the channels for several seconds in the first 10 seconds of the blowdown transient

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

MAXIMUM FES SHEATH TEMPERATURE FOR SMALL, CRITICAL AND LARGE BREAKS



PRESSURE DROP BETWEEN HD8-HD5 FOR SMALL, CRITICAL AND LARGE BREAKS



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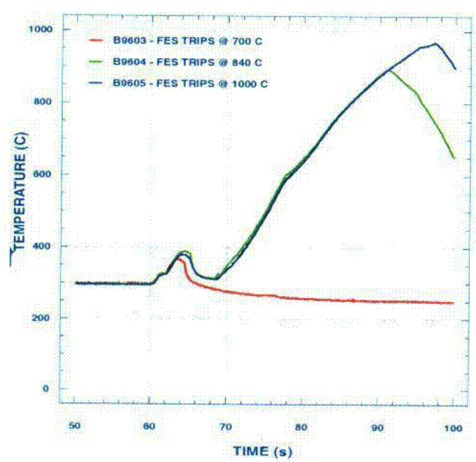
RD-14M LOCA Experiments

- Critical break LOCA tests (1990/91 and 1994):
  - Examined the effect of break size, RCS flow rate, decay power level, isolation of surge tank and mode of ECC on blowdown and refill behaviour
  - In all 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

RD-14M LOCA Experiments

- Critical break LOCA tests (1996):
  - Provided experimental fuel element simulator temperature data between 700°C and 1000°C
    - Maximum temperature of 968°C was achieved
    - Representative of an overpower transient (CANDU 6)
  - Performed with a single channel-per-pass configuration to minimize potential damage to fuel element simulators

FES SHEATH TEMPERATURES - ELEMENT 7, SEGMENT 2 (CRITICAL INLET HEADER BREAK, 50% PUMP SPEED)



RD-14M Channel Voiding During Large LOCA

- 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 behaviour over the entire blowdown transient.
    - insufficient information to adequately quantify the uncertainties associated with code calculations during the early blowdown phase of a LOCA.

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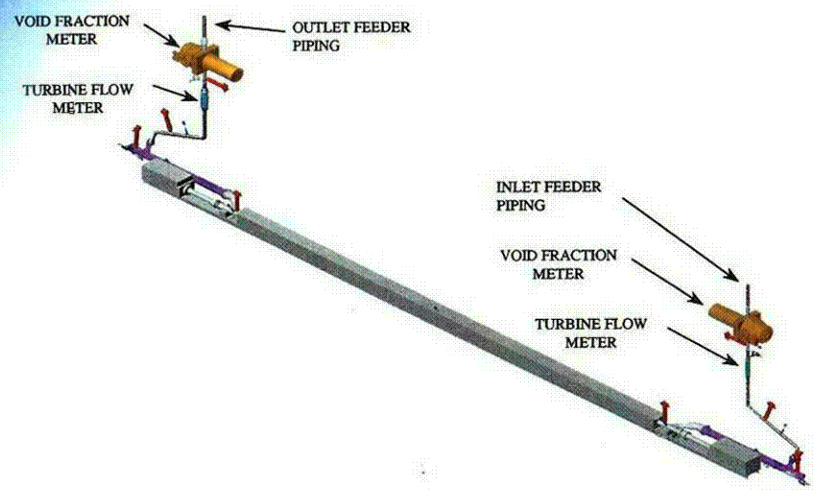
RD-14M Channel Voiding During Large LOCA

- **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 instrumentation and transducers were used.

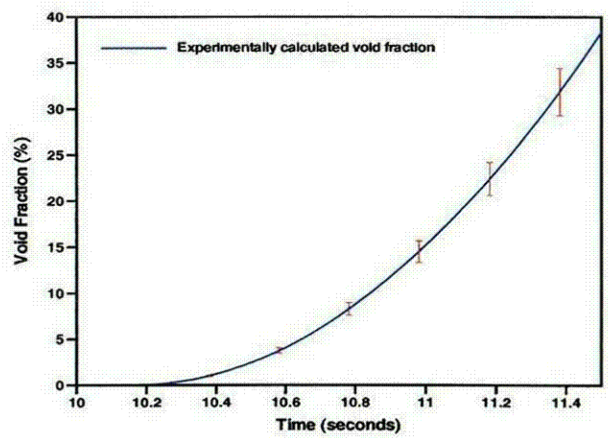
RD-14M Channel Voiding During Large LOCA

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

RD-14M Channel Voiding During Large LOCA



Average Channel Void Fraction from Integrated Flow



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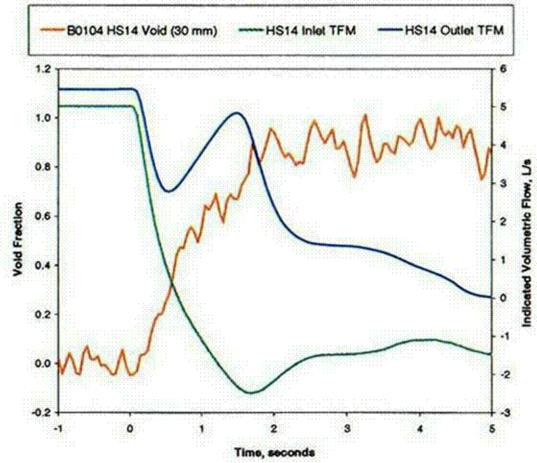
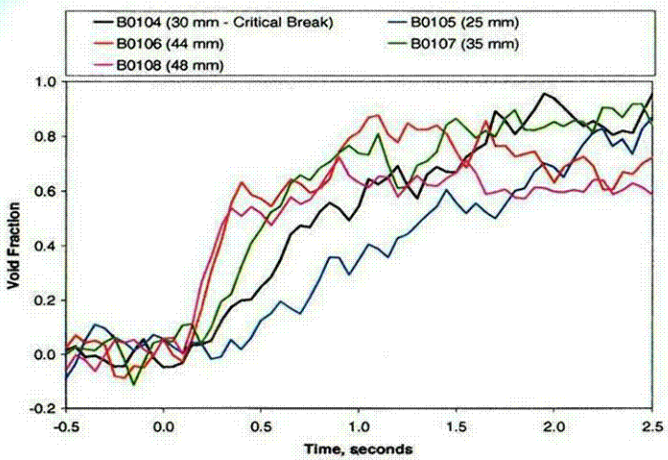
RD-14M Channel Voiding During Large LOCA

- **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 Inlet and Outlet Flows Test B0104



Channel Void Fraction for Various Break Sizes



Natural Circulation in RD-14M

Natural Circulation Tests Conducted

– Partial Inventory	(T-series)	49
– Transition	(R-series)	27

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NATURAL CIRCULATION TESTS PROCEDURE

- **PARTIAL INVENTORY TESTS:**
  - Establish steady-state, single phase natural circulation flow at desired operating conditions
  - Drain a fixed quantity of fluid intermittently from outlet header and monitor resulting thermalhydraulic behaviour
  - Repeat intermittent draining until test terminated due to high Fuel Element Simulator temperature (600°C)

NATURAL CIRCULATION TESTS PROCEDURE

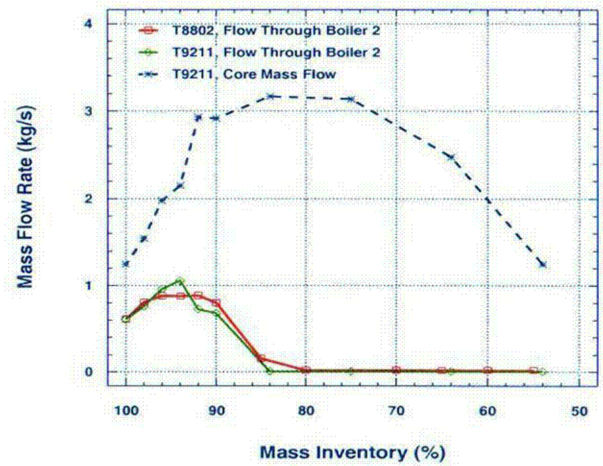
- **TRANSITION TO NATURAL CIRCULATION TESTS:**
  - Establish steady-state, forced convective flow at desired operating conditions
  - Drain a fixed quantity of fluid from outlet header
  - Trip main coolant pumps
  - Monitor resulting natural circulation behaviour until steady-state is achieved or test terminated due to high Fuel Element Simulator temperature (600°C)

Natural Circulation in RD-14M

General Behaviour

- 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 (≤1.0MPa), flows highly oscillatory, bi-directional flow at 90-95% RCS inventory

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



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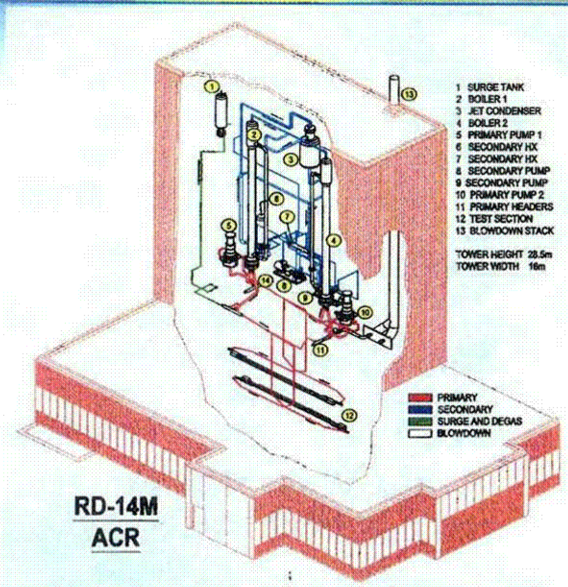
Natural Circulation in RD-14M

General Behaviour (continued)

- In all tests, continued reduction in RCS 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
- For the majority of tests, heatup did not occur until RCS inventories were reduced to <70%

RD-14/ACR

- The RCS of the RD-14M facility was modified in 2001 to run at ACR pressure and temperature
- 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 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)

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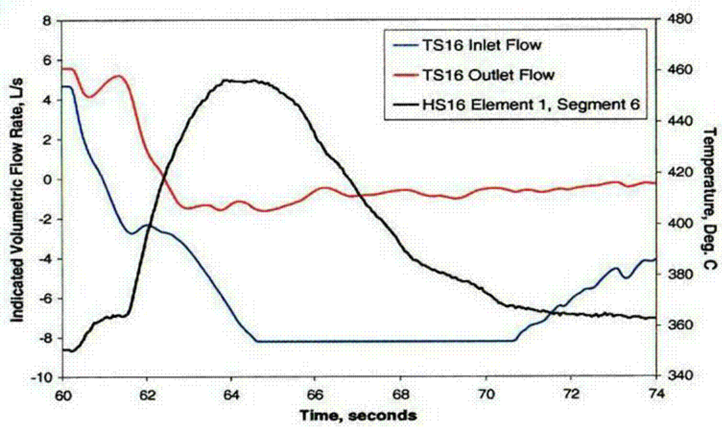
NOMINAL INITIAL CONDITIONS FOR RD-14/ACR LOCA TESTS

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)
Boiler Level	55%
Feedwater Temperature	~220°C

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



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 behaviour
- Facility description specifically for the RD-14/ACR configuration
  - Will be completed by 2003 April

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RD-14M Data

- Data reports issued for each RD-14M test
- Data for each test archived on CD-ROM in a standardized ASCII format
- Data CD-ROM's contain:
  - actual experimental data
  - initial average conditions
  - instrumentation scan list including description of instruments, ranges, calibration types, and engineering units
  - pre-test pressure-drop, mass-flow, and energy balances
  - full and empty readings for all gamma densitometers

Electronic Database

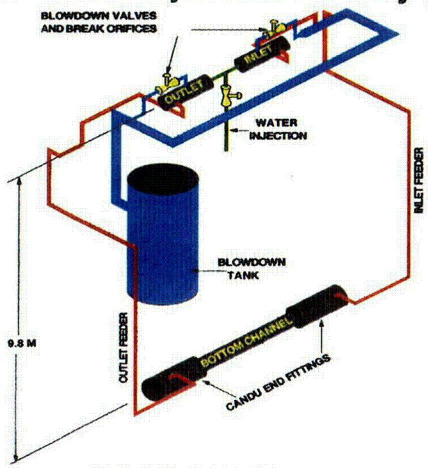
- An electronic database (MS Access) was developed and is continually maintained for the RD-14M program
- Provides a means of accessing, searching, and viewing:
  - details of test conditions and procedures
  - instrumentation setup for each experiment
  - entire history of instrument calibrations
  - summary of documentation relevant to specific experiments, facility description and characterization, and instrumentation
- Aids in the analysis of experiments, and provides a means of electronically archiving relevant information

Component Test Facilities

Cold Water Injection Facility (CWIT)

- Full-scale heated fuel channel with electrically-heated fuel string
  - Axial uniform and cosine profiles
  - Full 37 element 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 has been completed

Cold Water Injection Facility (CWIT)



CWIT Test Facility

Cold Water Injection Facility (CWIT) Test Procedures

- Refill experiments
  - 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
- Flow stratification experiments
  - 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

Cold Water Injection Facility (CWIT) Test Procedures

- Standing start experiments
  - 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)

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
- Feeders are similar diameter (50-mm I.D.) to CANDU feeders
- Full-scale vertical height between headers and the horizontal feeder sections
- Experiments performed:
  - two-phase injection experiments to study phase distributions in the headers and feeders
  - a high pressure ECC system exists to perform refill experiments following a simulated LOCA
- Program has been completed

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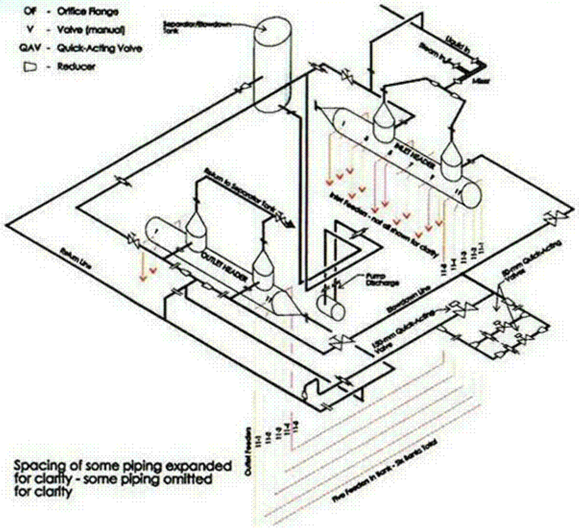
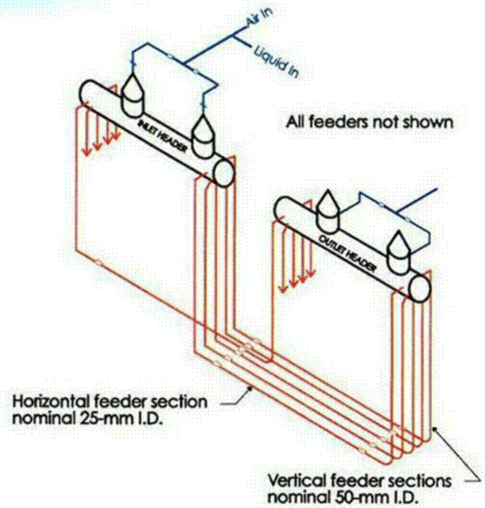
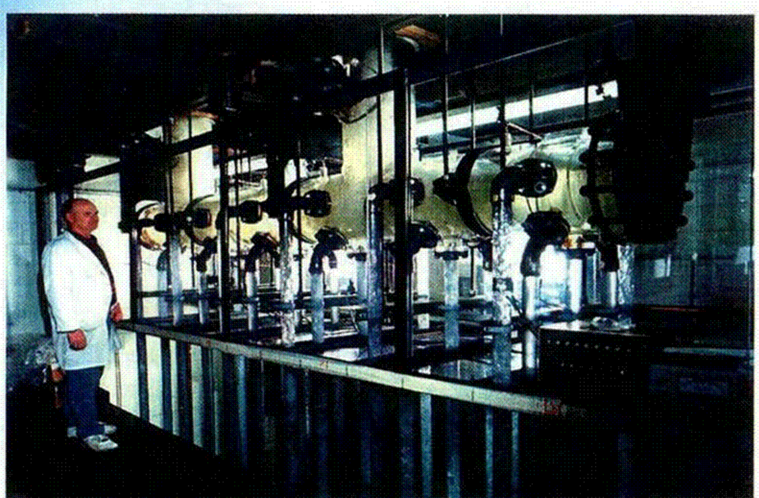
Large-Scale Header (LASH) Facility



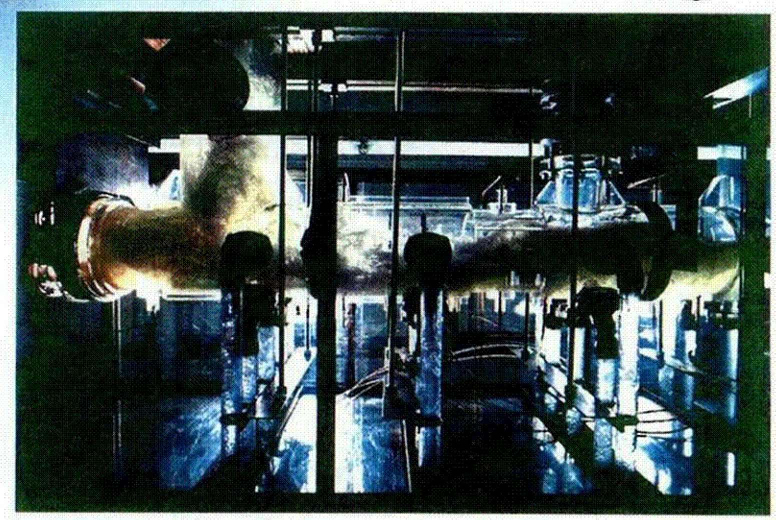
Transparent Header/Feeder Facility



Transparent Header/Feeder Facility



Transparent Header/Feeder Facility



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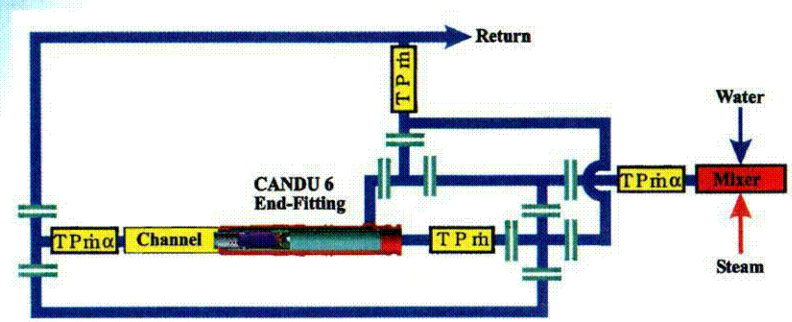
End-Fitting Characterization Facility

- Consists of an actual CANDU 6 end-fitting modified to include instrumentation
- Experiments performed to study:
  - Flow resistance through various flow paths
    - Steam
    - Liquid
    - Two-phase
  - Blowdown behaviour with different break locations
    - Break on channel end
    - Break on feeder end
    - Simulated online refueling break
  - Heat-transfer behaviour
    - Initially liquid filled then heated with steam
    - Initially steam filled then cooled with liquid water
    - Initially liquid filled then cooled with cold water
- Program has been completed

End-Fitting Characterization Facility



Component Facilities

- Data for each test archived on CD-ROM in a standardized ASCII format
- Electronic database (MS Access), developed for the RD-14M program, also contains information on the CWIT, LASH, and End-fitting Characterization facilities

Summary

- Comprehensive database of integral thermal hydraulics experiments exists for CANDU
  - Wide range of test types including LOCA, natural circulation, loss-of-flow, transition to shutdown cooling, and flow stability
  - Experiments performed over a wide range of conditions
  - Extensively used for code validation
  - Scaling effects understood and studied
- Existing integral thermal hydraulics database has been extended to ACR pressures and temperatures (RD-14/ACR)

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Summary

- **Separate effects experiments performed for major CANDU components:**
  - **Full-scale channel and end-fittings (CWIT)**
  - **Headers (LASH and Transparent Header)**
  - **End-fitting Facility**
- **Separate effects experimental programs have been completed**

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