RD-14M Facility Scaling

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Outline

- Scaling Philosophy
- Scaling Criteria
- RD-14 Design
- RD-14M Design
  - Heated Sections
  - End Fittings
  - Feeders
  - Headers
- Summary

Scaling Philosophy

- **The RD-14 and RD-14M test facilities were designed to preserve *Dynamic Similarity* with CANDU RCS based on a developed set of scaling criteria**
- **Where scaling criteria could not be applied, past experience and engineering judgment were used to provide a conservative component design**

Development of Scaling Criteria to Preserve Dynamic Similarity - 1

- Approach to Ishii and Kataoka used to develop scaling criteria to obtain dynamic similarity
- Write the governing thermal hydraulic equations in dimensionless form (mass, energy and momentum balances) using drift flux or homogeneous flow 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

Development of Scaling Criteria to Preserve Dynamic Similarity - 2

- **Limitations of scaling criteria:**
  - Scaling laws only apply if flow is 1-D, well mixed and void / quality relationship for homogeneous flow can be applied
  - If horizontal stratified, or horizontal / vertical annular flow occurs departures from similarity between reactor and loop behavior will occur

Development of Scaling Criteria to Preserve Dynamic Similarity - 3

- Key dimensionless groups include:

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 Criteria - 1

Phase change number

$$N_{pch} \equiv \left(\frac{4\delta\, q_o^{'''} \ell_o}{d\, u_o \Delta H_{fg}\, \rho} \right) \left(\frac{\Delta\rho}{\rho_g} \right)$$

Drift Flux number

$$N_d \equiv \frac{V_{gj}}{u_o}$$

Froude number

$$N_{Fr} \equiv \frac{u_o^2}{g\, \ell_o < a >_o} \frac{\rho}{\Delta\rho}$$

Density ratio group

$$N_\rho \equiv \frac{\rho_g}{\rho}$$

Friction number

$$N_f \equiv \left(\frac{f\ell}{d} \right) \left(\frac{1 + x\left(\Delta\rho / \rho_g\right)}{\left[1 + x\left(\Delta\mu / \mu_g\right)\right]^{0.25}} \right) \left(\frac{a_o}{a_i} \right)^2$$

Scaling Criteria - 2

Orifice number

$$N_o \equiv K\left[1 + x^{3/2}\left(\Delta\rho / \rho_g\right)\right]\left(\frac{a_o}{a_i}\right)^2$$

Subcooling number

$$N_{sub} \equiv \left(\frac{\Delta H_{sub}}{\Delta H_{fg}}\right)\left(\frac{\Delta\rho}{\rho_g}\right)$$

Critical Heat Flux number

$$N_q \equiv \frac{q_c'''}{\delta q_{so}'''}$$

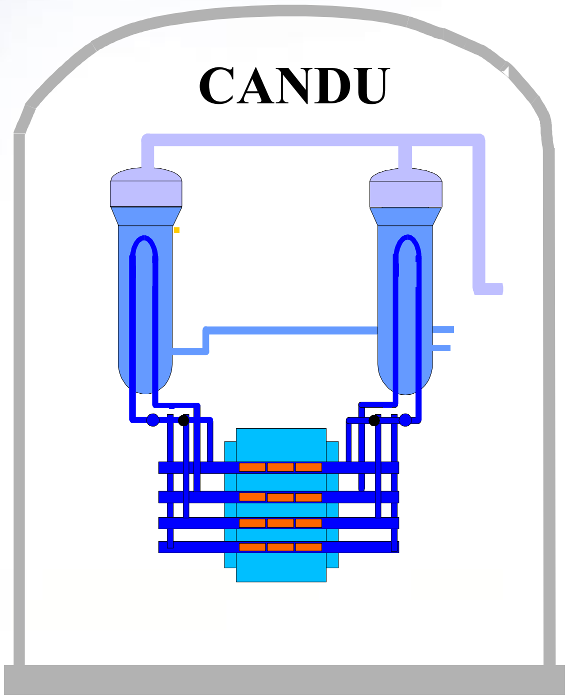
Heat-source number

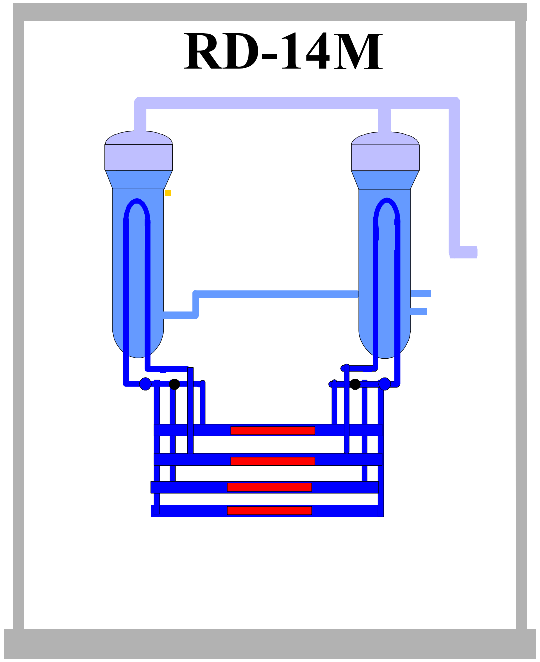
$$Q_{si} \equiv \frac{q_{si}''' \, \ell_o \, C_p}{\rho_{si} \, Cp_{si} \, u_o \, \Delta H_{sub}}$$

Time Ratio group

$$T_i^* \equiv \left(\frac{\alpha_s}{\delta^2} \frac{\ell_o}{u_o}\right)_i$$

RD-14/RD-14M Design





Full-length Heated Channels

Full-length Feeders

Full-height Steam Generators

RD-14M – Multiple Heated Channels

RD-14 Design

- **Reference Design Basis:**
  - One figure-of-eight loop with 1:1 vertical scaling and a single 5.5MW, 37-element channel per pass
- **Conducting experiments at reactor typical conditions (pressure, temperature, power and flow) and use of full-size channels and feeders ensure all scaling criteria below headers are met (except for end-fitting simulators)**
- **Steam generators designed maintain 1:1 matching of scaling criteria**
- **Engineering judgment was required in the design of above-header piping, headers and end-fittings, as not all scaling criteria could be met due to constraints**

RD-14 Above-Header Pipe Work

- The existing RD-14 pipe work was used above the headers. Scaling ratios show distortions with respect to a CANDU 600 reactor.

Scaling Ratios for Pipes Above Headers (CANDU 600 Reactor Geometry)

Description	$\left(A_I^* / N_C\right)R$	$\left(\ell_I^*\right)R$	$\left(\sin\theta_i\right)R$	$\left(N_{fi}\right)_R$	$\left(Q_i\right)_R$	$\left(M_W C_W\right)_R$
Steam Generator Inlet	4.3	0.9	-	0.34	1	1.7
Pump Suction	4.3	0.8	-	0.3	1	1.7
Pump Discharge	3.6	1.6	-	0.99	1	2.4

The deviations are not considered critical.

- **Pipe lengths are small when compared to the rest of the primary circuit**
- **Pressure drops in both a typical reactor and RD14 are comparable ($\cong$20% of total Δ P)**

RD-14 Steam Generators

The RD-14 steam generators are recirculating U tube steam generators. They closely resemble reactor boilers and have a reduced number of tubes.

RD-14 Steam Generator Characteristics

	RD-14	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

Scaling Ratios for Steam Generator Tube Bank

$\left(A_i^*/N_c\right)R$	$\left(\ell_i^*\right)R$	$\left(\sin\theta_i\right)R$	$\left(N_{fi}\right)_R$	$\left(Q_i\right)_R$	$\left(M_W C_W\right)_R$
1.2	**1.1**	**1.0**	**0.7**	**1.0**	**1.0**

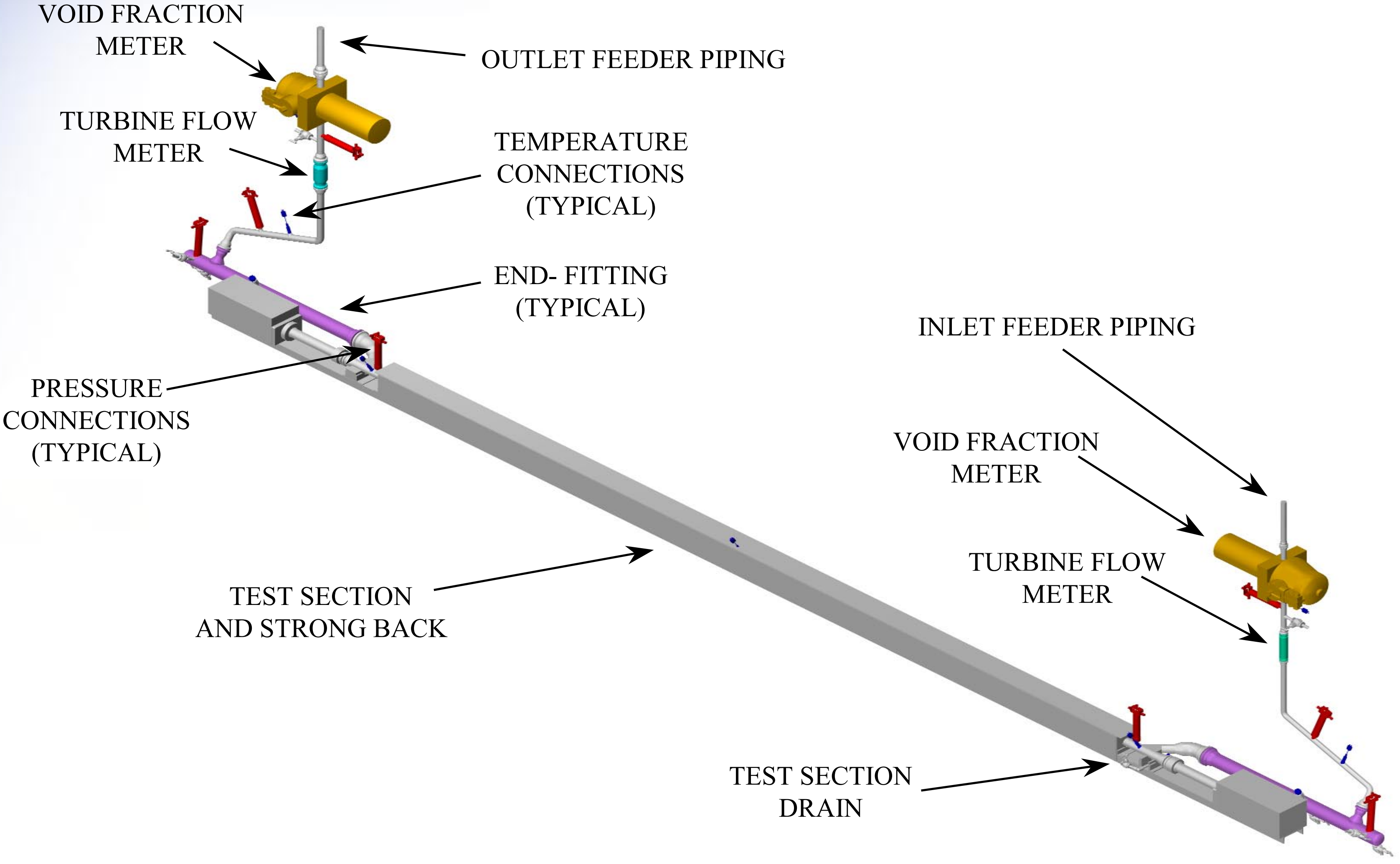
RD-14M Design – 1

- To study the interaction among parallel channels in natural circulation and LOCA transients, the RD-14 test facility was modified to a multiple channel geometry and renamed RD-14M
- The steam generators, total power, and total flow per pass from RD-14 were retained
- No significant changes from RD-14 to the above-header pipe work so the scaling for the above-header components is the same in both facilities

RD-14M Design – 2

- New design required for:
  - Channels
  - End-fittings
  - Feeders
  - Headers
- Scaling Criteria:
  - The same scaling approach and criteria used in designing RD-14, based on preserving dynamic similarity, was applied to designing RD-14M

RD-14M Channel Design – 1



RD-14M Channel Design – 2

- **Requirements:**
  - It is desirable to have as many channels as possible to simulate CANDU behavior
  - The heaters should have a ring geometry as in CANDU fuel bundles
- **Constraints:**
  - The number of heated sections is limited by existing loop specifications
    - Steam generators, pumps and flow areas scaled for a single pass of a 37 element 5.5 MW channel
  - For economic reasons, the existing heater design was used – to maintain the same element heat flux at a given power, the number of elements in a single pass should be 37

RD-14M Channel Design – 3

- **Three channel geometries satisfy the design requirements and economic and design constraints:**
  - **two 18 element channels**
  - **three 12 element channels**
  - **five 7 element channels**
- **The five channel geometry was chosen since it has weaker channel to channel interactions than the other configurations and seven element channels were used in earlier RD-12 experiments**

RD-14M Channel Design – 4

- A 7-pin, full-length design permitted excellent agreement for all dimensionless scaling groups except for the Friction number
  - Friction number for RD-14M is 29% higher than the reactor value
- Correlations for the transition to stratified flow for both 7 and 37 pin CANDU channel geometries indicate stratified flow is expected to occur at a loop mass flux which is 30% lower than in a full size channel
  - This difference is within the uncertainties of flow regime transitions

RD-14M Channel Parameters

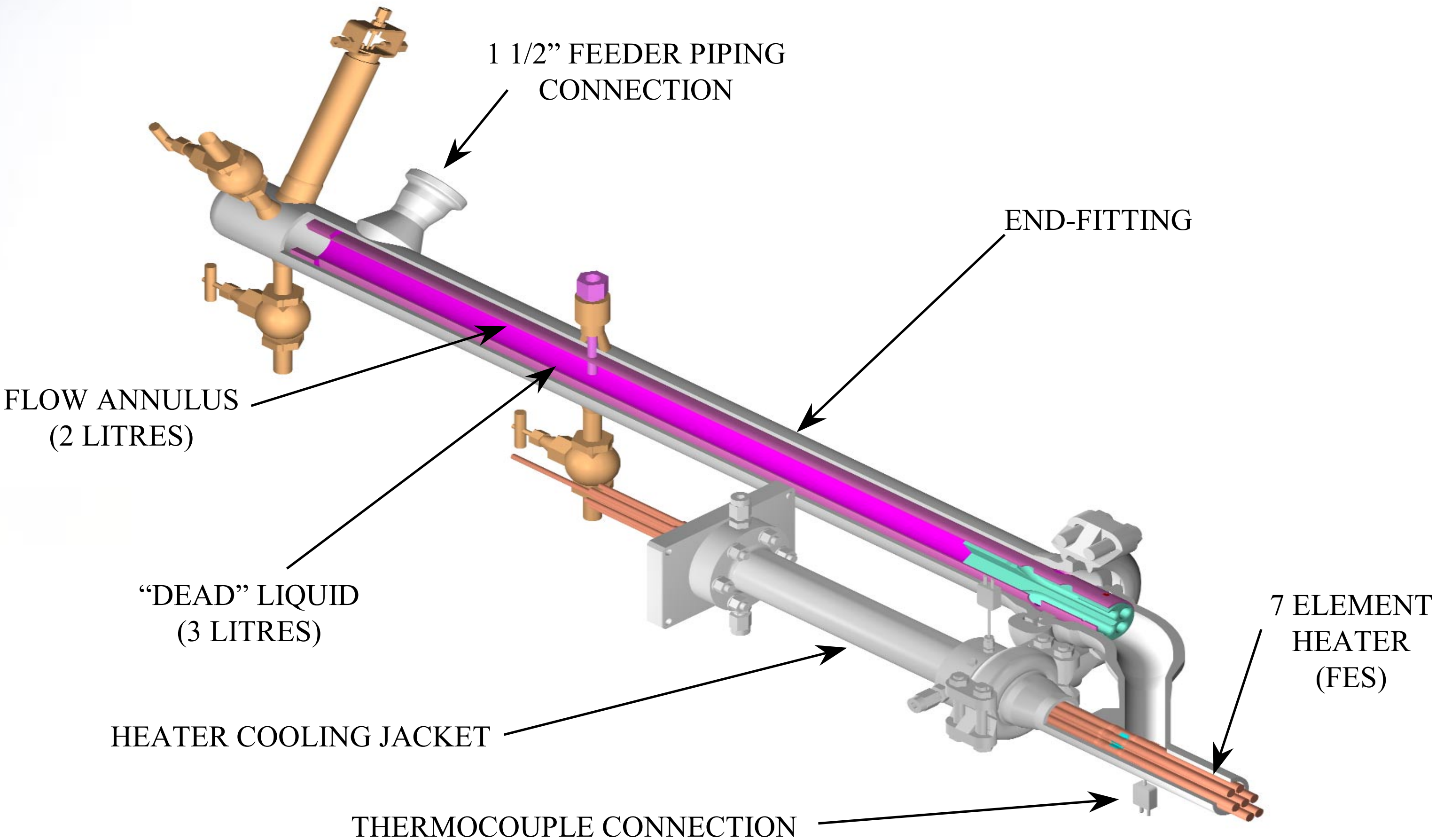
	RD-14M	CANDU
Flow tube diameter (mm)	44.8	103
Flow area (mm^2)	647.2	3421
Flow tube thickness (mm)	6.1	4.3
Hydraulic diameter (mm)	6.07	7.5
Pin outside diameter (mm)	13	13
Number of pins	7	37
Pin heat capacity (at 250°C) (kJ/m. °C))	0.38	0.37

Scaling Ratios for Channels

$(A_i)_R^+$	$(\ell^*_i)_R$	$(\mathrm{Sin}\,\theta_i)_R$	$(N_{fi})_R$	$(Q_i)_R$	$(M_W C_W)_R$
1	**1**	**1**	**1.29**	**1.01**	**1.03**

+ with reference to the number of pins

RD-14M End-Fitting Design – 1



RD-14M End-Fitting Design – 2

- In the end-fitting, the assumption of one-dimensional flow does not always hold, e.g. during natural circulation flow will stratify and multi-dimensional effects could be significant
- During blowdown and refill transient, the delay of ECC into a channel is related to fluid volume and heat storage capacity of the end-fitting
- Thermal mass determines the timing of natural circulation following a flow stagnation

RD-14M End-Fitting Design – 3

- Both fluid volumes and thermal masses should be scaled. Stagnant volumes can act as a thermal mass, during end-fitting heat up, and a potential source of channel coolant during blowdown and refill.
- Under certain natural circulation conditions, recirculation flow patterns may be established near the end-fittings. Steam produced in the channel and condensed in the end-fitting can flow back into the channel, driven by the gravity head within the end-fitting.
- To simulate the flow phenomena, L/D_H ratios should be preserved

RD-14M End-Fitting Design – 4

- Pressure, heat losses and heat capacity requirements for the end-fittings were developed by writing integral momentum and energy balances
- This led to approximate scaling rules for the end-fitting geometry
- Scaling criteria satisfied in the final design

Scaling Ratios for End-Fitting

$(K_{EF})_R$	$(V_f / A_o \ell_o)_R$	$(M_W C_W / A_o \ell_o)_R$	$(Q_{LS} / A_o)_R$
1	**1**	**1**	**0.9**

– **It should also be noted that L/D_h ratios were preserved in the end-fitting design**

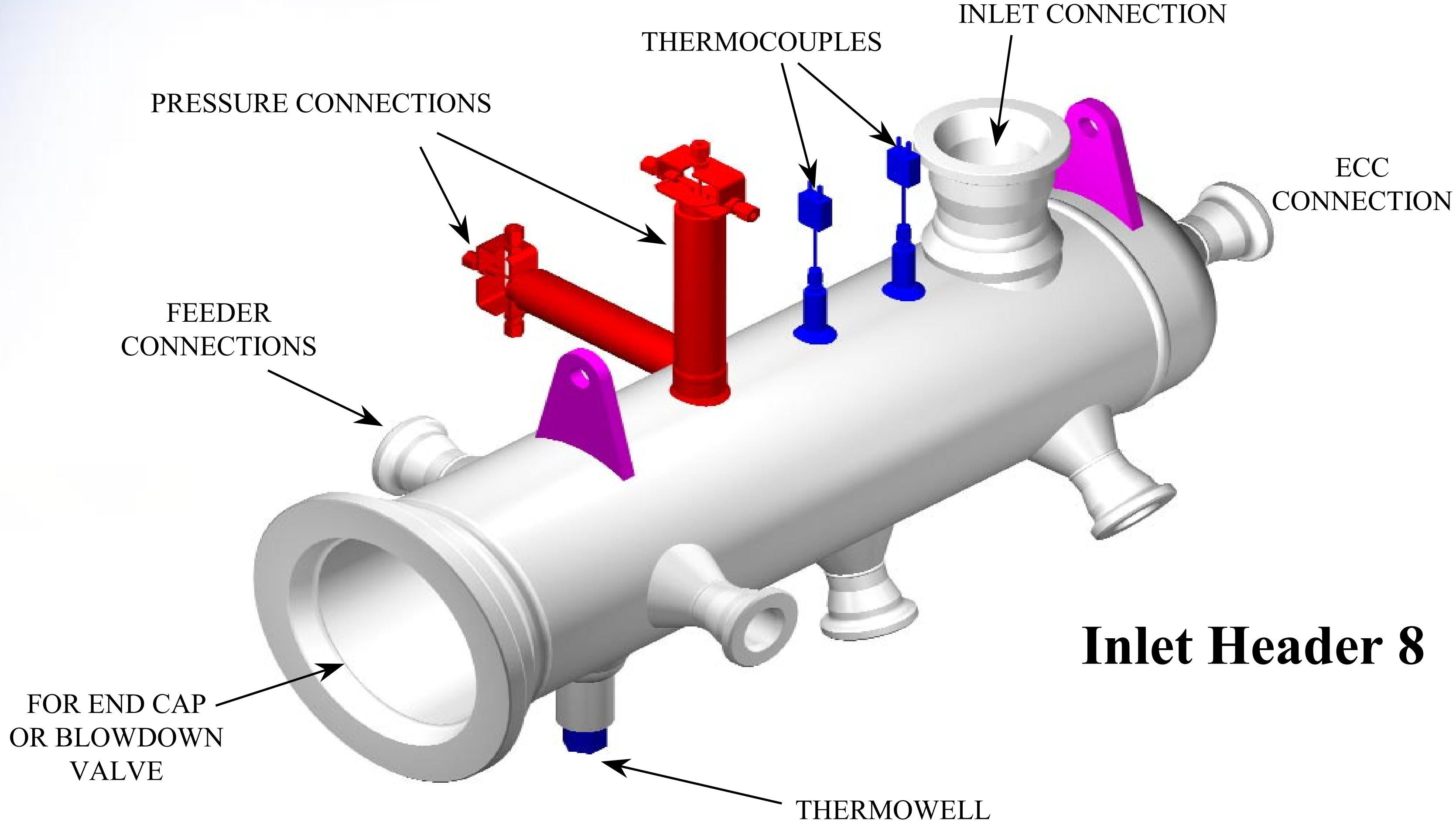
RD-14M Feeder Design

- Five CANDU reactor channel/feeder geometries were simulated in each pass:
  - one top channel (B10)
  - three middle channels (L2, M11, O5)
  - one bottom channel (X12)
- These geometries cover the full range of elevation differences, horizontal lengths, and flow restricting orifices present in a CANDU reactor
- The five RD-14M (average) channel flows and powers are equal to a CANDU (average) channel flow and power
- The nozzle angles, at header connections, cover the range found in a typical CANDU reactor
- The cross-sectional areas were not preserved between RD-14M and a CANDU

Scaling Ratios for Feeder X12

Reactor pipe nominal size (schedule 80)	Multichannel loop pipe nominal size (schedule 40)	$(A_i)_R$	$(N_{fi})_R$	$(Q_i)_R$	$(M_W C_W)_R$
2	1	1.55	0.74	1	1.14
2-1/2	1-1/4	1.86	0.53	1	0.85
3	1-1/4	1.19	1.7	1	0.98

RD-14M Header Design – 1



Inlet Header 8

RD-14M Header Design – 2

- Flow in the header is not one dimensional so the Ishii-Kataoka scaling laws are not applicable
- The flow will stratify during natural circulation, blowdown and refill. This will affect the quality of fluid supplies from the headers to the feeders.
- To simulate quality distribution, headers have the same feeder to header diameter ratio as in a typical CANDU header
- Volumes are scaled
- Header-feeder angles are also CANDU reactor typical
- Fluid flow length is shorter than in a CANDU header to accommodate these geometry requirements

RD-14M Header Design – 3

- **Similarities:**
  - Volumes scaled
  - Covers feeder nozzle geometries
  - Can investigate channel interactions
  - Can investigate the affect of nozzle location during stratified flow
- **Differences:**
  - Header mass is higher in RD-14M
  - Shorter fluid flow paths in RD-14M headers
  - Fewer channel connections (five) to a header in RD-14M

Comparison of D_2O and H_2O

Property Ratio $\left(\frac{H_2O}{D_2O}\right)$	Pressure		
	0.1 MPa	4.0 MPa	10 MPa
T_{SAT}	0.982	1.001	1.003
ΔH_{fg}	1.090	1.107	1.112
ρ_f	0.902	0.904	0.904
ρ_g / ρ_f	1.001	0.990	0.995

Component Scaling Ratios[1] - 1

Component	ℓ_R	u_R	$(N_{pch})_R$	$(N_{Fr})_R^2$	$(N_f)_R$
Channel	1	1	1	1	1
End-Fitting	0.2	0.2	N/A	~ 0.2	
Feeders	~1	~ 1	N/A	~ 1	~ 1
Headers	N/A	0.5 – 1	N/A	N/A	N/A
SG Inlet Piping	~ 1	0.3	N/A	~ 0.1	~ 0.4
Steam Generator	~ 1	1	~ 1	~ 1	~ 1
SG Outlet Piping	~ 1	0.3	N/A	~ 0.1	0.1 – 0.2
Pump	N/A	0.3 – 0.8	N/A	N/A	N/A
Pump Outlet Piping	~ 1	0.6 – 0.8	N/A	0.4 – 0.6	1.0 – 1.8

[1] – using average reactor values (Darlington, Bruce, Pt. Lepreau)

[2] – assuming homogeneous flow

Component Scaling Ratios[1] - 2

Component	$(N_O)_R$	$(T^*)_R$	$(Qsi)_R$	$(\Delta H_{sub})_R$	$(N_d)_R$ [2]	$(N_q)_R$
Channel	1	1	1	1	1	1
End-Fitting	N/A	N/A	N/A	1	~ 1	N/A
Feeders	~ 1	N/A	N/A	1	~ 1	N/A
Headers	N/A	N/A	N/A	1	~ 1	N/A
SG Inlet Piping	N/A	N/A	N/A	1	~ 1	N/A
Steam Generator	~ 1	~ 1	~ 1	1	~ 1	N/A
SG Outlet Piping	N/A	N/A	N/A	1	~ 1	N/A
Pump	N/A	N/A	N/A	1	N/A	N/A
Pump Outlet Piping	N/A	N/A	N/A	1	~ 1	N/A

1 – using average reactor values (Darlington, Bruce, Pt. Lepreau)

2 – assuming homogeneous flow

Summary

- Consideration was given to natural circulation, blowdown, and ECC transients.
- Scaling laws, consistent with those derived by Ishii and Kataoka, were developed and applied to the design of a multiple channel loop.
- Full linear dimensions and elevation changes present in a typical CANDU reactor were maintained. This permits the simulation of the reactor void distribution, caused by elevation induced flashing.

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