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Docket Number(s): PROJ0722

Plant/Facility Name: Advanced CANDU Reactor (ACR-700)

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Purpose of Meeting (copy from meeting notice): AECL technical presentation during the visit to the RD-14M Facility

NAME OF PERSON WHO ISSUED MEETING NOTICE
Belkys Sosa

TITLE
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SCALING LAWS FOR SIMULATING THE CANDU HEAT TRANSPORT SYSTEM

by

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ABSTRACT

The RD-14 test facility at Whiteshell Nuclear Research Establishment is a full-elevation model of a typical CANDU™ primary heat transport loop. It consists of two full-scale, full-power electrically heated channels, full-scale feeders and two full-height steam generators. The loop is designed so that fluid mass flux, transit times, and pressure and enthalpy distributions in the primary system are the same as in a typical power reactor in both forced and natural circulation.

To study the interaction between parallel channels in thermosiphoning and blowdown/emergency coolant injection transients, it is proposed to modify RD-14 to a multiple-channel configuration. A scaling rationale has been developed from a consideration of the one-dimensional, homogeneous, two-phase-flow conservation equations. The scaling laws show that to represent the CANDU™ system correctly, particularly under thermosiphoning conditions, the model loop must possess the full linear dimensions and elevation changes of the reactor.

The paper will describe the development of the scaling laws and their application in defining the sizes of the major loop components of the proposed multiple-channel RD-14 loop.

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NOMENCLATURE

A	Area (m^2)
C_w	Specific heat $(J/(kg.°C))$
d	Diameter (m)
e	Internal energy (J/kg)
f	D'Arcy friction factor $= \frac{\Delta p}{\rho u^2} \frac{2d}{l}$
g	Acceleration due to gravity (m/s^2)
G	Mass flux $(kg/(m^2 \cdot s))$
h	Enthalpy (J/kg)
K	Pressure loss coefficient
l	Pipe length (m)
m	Mass (kg)
m	Mass per unit flow volume (kg/m^3)
N_{fi}	Friction number $= \left(\frac{\eta}{A^*}\right)_i^2 \left(\frac{fl}{d} + K\right)_i$
N_c	Number of channels per pass
p	Pressure (N/m^2)
q_L	Pin power rating (W/m)
Re	Reynolds number
Q	Heat loss or gain per unit flow volume for pipe (W/m^3)
$\dot{Q}_f$	Heat entering fluid from wall/unit time (J/s)
Q_{LS}	Heat loss per unit time (J/s)
t	Time (s)
T	Temperature (°C)
u	Velocity (m/s)
V_f	Fluid volume (m^3)
W	Mass flow rate (kg/s)
X	Quality
z	Length coordinate (m)

Greek

α Void fraction

β Function defined by Equation (13) (kg/m^3)

Δh_{SUB} Subcooling (J/kg)

η Factor (for pipes below header = 1, for pipes above header = N_c)

Φ^2_{fo} Two phase multiplier = $(\frac{dp}{dz})_{TP} / (\frac{dp}{dz})_{fo}$

ρ Density (kg/m^3)

θ_i Upward inclination from horizontal

Subscripts

g Steam property

f Water property

fo Value if two-phase mixture flowed as liquid at same mass flow rate

gf Difference between fluid and gas properties (e.g., $h_{gf} = h_f - h_g$)

o Reference property

i Property of i'th pipe section

$(\ )_R$ Ratio between model and reactor values. $(Re)_R = \frac{Re_{model}}{Re_{reactor}}$

SAT Saturation property

W Property of pipewall

EF Property of end fitting

TP Property of two-phase flow

Superscript

* Dimensionless quantity

– Steady state variable

INTRODUCTION

The RD-14 test facility (Figure 1) is a full elevation-model of a typical CANDU™ primary heat transport loop. It consists of two full-scale, full-power electrically heated channels, full-scale headers and two full-height steam generators in a figure-of-eight configuration. The number of U tubes in the steam generators is reduced in direct proportion to the heated channels to give the correctly scaled heat transfer area. The loop is designed so that fluid mass flux, transit times and pressure and enthalpy distribution terms in the primary system of the loop are the same as those in a typical reactor under both forced and natural circulation.

To study the interaction between parallel channels in thermosiphoning and blowdown/emergency coolant injection (ECI) transients the loop will be modified to a multichannel geometry. This paper describes the scaling rationale developed for this modification. Scaling requirements for the new configuration are identified. The scaling laws are used to define the sizes of major loop components in the multichannel RD-14 loop.

SCALING REQUIREMENTS

The primary requirement of the modified loop is that it must represent reasonably well the behaviour that occurs in a reactor during thermosiphoning and blowdown/ECI transients. Ideally, dynamic similarity should exist between the reactor and its model. If this is true, known scaling laws can be applied to experimental data, and reactor behaviour can be deduced.

In constructing a scale model of single-phase flow in a reactor, the necessary scaling requirements to achieve dynamic similarity can be derived by expressing the governing thermo-fluid equations in dimensionless form. Dynamic similarity between the model and the actual reactor is assured by matching the dimensionless parameters that appear in these equations. For example, Reynolds numbers in both model and reactor must be the same. Unfortunately, the application of this method to two-phase flow is not so simple is because the governing equations for two-phase flow depend on a large number of dimensionless groups. Simultaneous matching of all dimensionless groups in a scale model is usually impossible.

However, by using a simple set of conservation equations, like those of the homogeneous equilibrium model or drift-flux model, to represent the two-phase-flow, scaling criteria can be developed. Using this assumption, Ishii and Kataoka [1] developed a scaling rationale to model a Light Water Reactor (LWR) natural circulation loop. If the void/quality equation for the two phase mixture is of the form

$$\alpha = \alpha \text{ (X, gas properties, liquid properties)} \qquad (1)$$

their scaling rules are valid. Equation (1) is obviously true for homogeneous two-phase flow, although Ishii and Kataoka suggest it may also apply to certain types of churn-turbulent flow.

In this paper the approach of Ishii and Kataoka [1] is used to develop scaling criteria for multichannel RD-14 loop. The importance of certain dimensionless groups in CANDU reactor geometries (identified by Ishii and Kataoka for LWR's) will be highlighted. Model development is described below.

DEVELOPMENT OF SCALING LAWS

Characteristic Parameters

The multichannel RD-14 test loop is assumed to consist of N_c channels per pass (Figure 2). At steady thermosiphoning conditions, with the loop operating at reactor typical temperatures and pressures, the mass flow in all channels is assumed equal.

Most of the loop can be described as several pipe lengths of uniform area connected in series and parallel. These pipe lengths can represent sections of a feeder, a riser, a heated channel, or a bank of parallel boiler tubes. Channel end fittings, and headers, cannot be represented as simple pipes and are considered separately.

If the steady thermosiphoning flow rate in the feeders and heated channels is $\bar{W}_o$, then the flow rate in pipe sections above the headers is $N_c\bar{W}_o$. If ρ_o is the saturated liquid density and A_o the flow area of the channel, then the characteristic velocity $\bar{u}_o$ can be defined as

$$\bar{u}_o = \frac{\bar{W}_o}{\rho_o A_o} \tag{2}$$

Analysis

To simplify development we will neglect interphase slip, and momentum flux terms, which are small at the low mass velocities encountered in thermosiphoning. The headers will be considered as a point source with no volume, and hence no mass energy.

Assuming one-dimensional flow, the transient conservation equations in pipe section i can be written as follows:

Mass Conservation

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial(\rho_i u_i)}{\partial z} = 0 \tag{3}$$

Momentum Balance

$$\rho_i \left(\frac{\partial u_i}{\partial t} + \frac{u_i \partial u_i}{\partial z}\right) = \frac{-\partial p_i}{\partial z} - 1_i \rho_i g \sin\theta_i + \tfrac{1}{2}\, \rho_i u_i^2 \;\; \Phi_{foi}^2 \left(\frac{fl}{d} + K\right)_i \tag{4}$$

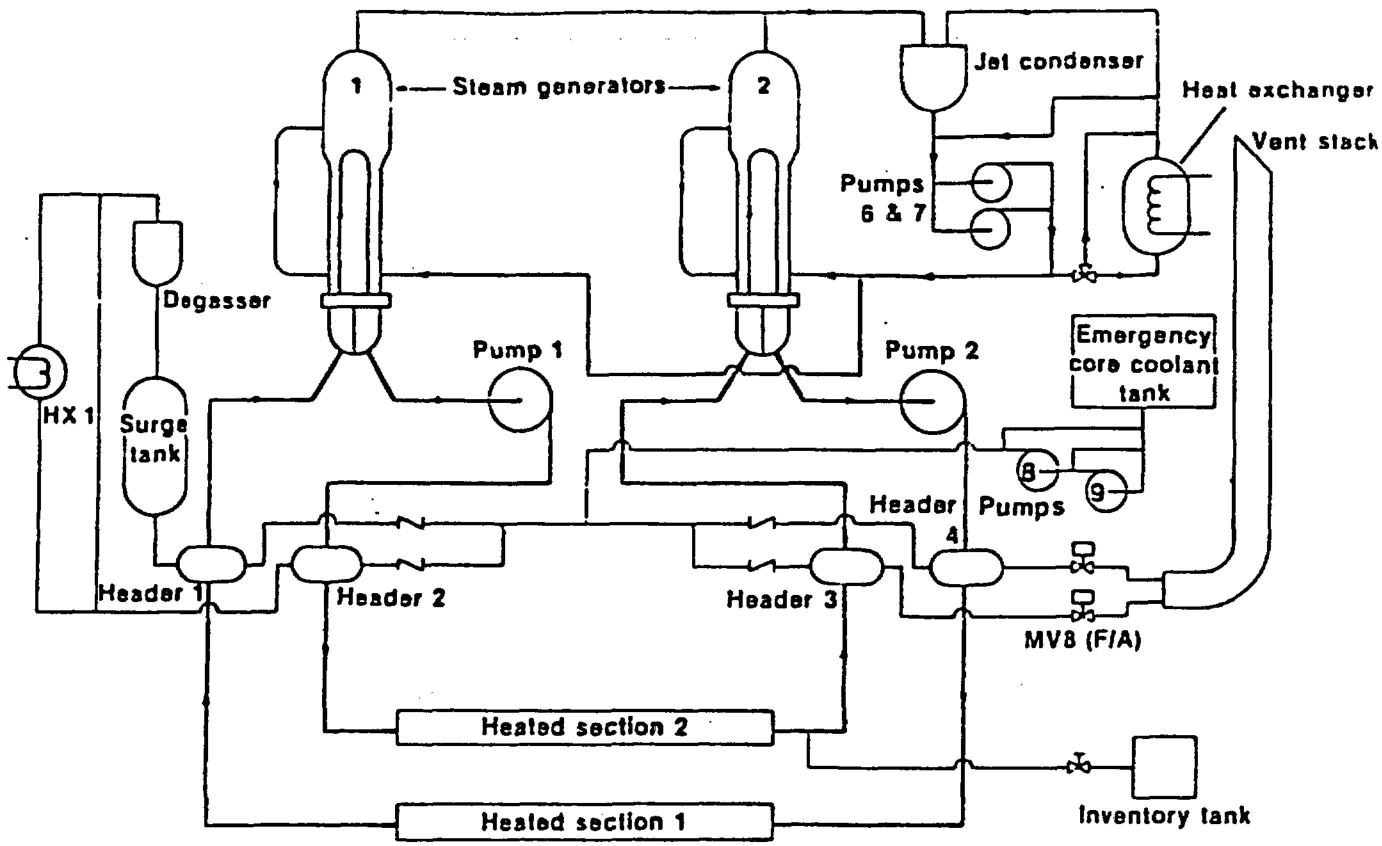


FIGURE 1: RD-14 Loop Schematic

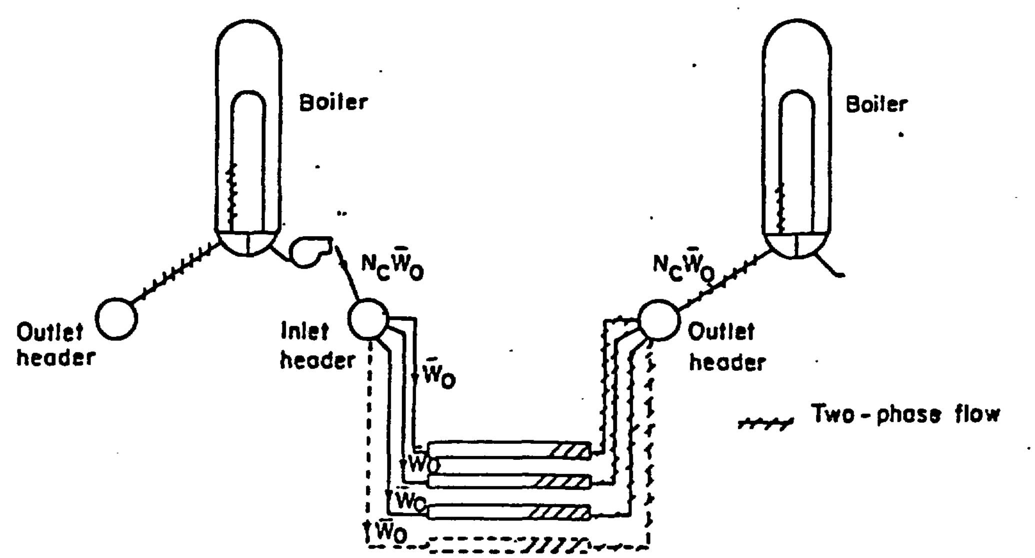


FIGURE 2: Schematic of Multichannel Facility in Steady Thermosiphoning
(Single Pass Only Shown)

Energy Balance

$$\rho_i \frac{Dh_i}{dt} - \frac{Dp}{dt} = Q_i \tag{5}$$

The mean volumetric heat source, Q_i, consists of components due to a heat source, Q_{iHS}, within the pipe section, heat loss through the pipe wall, Q_{iHL}, and the accumulated heat term Q_{iA}:

$$Q_i = Q_{iHS} - Q_{iHL} + Q_{iA} \tag{6}$$

In a transient, an important component of the volumetric heat source is due to the release of thermal energy stored in the pipe walls and fuel [1,2]. This can be written as

$$Q_{iA} = - M_{wi} C_{wi} \frac{\partial T_{wi}}{\partial t} \tag{7}$$

where M_{wi} is the wall mass per unit flow volume for pipe section i. In slow transients, the wall temperature, Tw,can be assumed as equal to the fluid temperature, T, Equation (7) becomes

$$Q_{iA} = M_{wi}\, C_{wi} \left(\frac{dT}{dp}\right)_{SAT} \frac{\partial p_i}{\partial t} \tag{8}$$

Substituting Equation (7) into (5), we get

$$\rho_i \frac{Dh_i}{dt} - \frac{Dp}{dt} = Q_i - M_{wi}\, C_{wi} \left(\frac{dT}{dp}\right)_{SAT} \frac{\partial p_i}{\partial t} \tag{9}$$

If we define the following dimensionless parameters:

$$l^* = \frac{l}{l_o},\ t^* = \frac{t\bar{u}_o}{l_o},\ A^* = \frac{A}{A_o},\ u^* = \frac{u}{\bar{u}_o},$$
$$p^* = \frac{p}{p_o},\ \rho^* = \frac{\rho}{\rho_o},\ h^* = \frac{h}{h_{gf}},\ T^* = \frac{T}{T_o}$$

Where l_o, is the reference length, p_o is the reference pressure, T_o the reference temperature and h_{gf} the latent heat of vaporization at pressure ρ_o, we can rewrite equations (3), (4) and (9) in dimensionless form.

Mass

$$\frac{\partial \rho_i^*}{\partial t^*} + \frac{\partial}{\partial z^*} (\rho_i^* u_i^*) = 0 \tag{10}$$

Momentum

$$\rho_i^* \frac{Du_i^*}{Dt^*} + \left(\frac{p_o}{\rho_o \bar{u}_o^2}\right) \frac{\partial p_i^*}{dz^*} + \rho_i^* l_i^* \left(\frac{l_o g}{\bar{u}_o^2}\right) \sin\theta_i = \frac{1}{2} \rho_i^* N_{fi}\, \Phi^2_{foi} \tag{11}$$

Energy

$$\rho_i \frac{DX_i}{Dt^*} + \left(\rho_i^* \beta^* - \frac{p_o}{\rho_o h_{gf}}\right) \frac{Dp_i^*}{DT^*} + \left[M_{wi} C_{wi} \left.\frac{dT}{dp}\right|_{SAT} \frac{p_o}{h_{gf}\rho_o}\right] \frac{\partial p_i^*}{\partial t^*} = \frac{Q_i l_o}{h_{gf}\rho_o u_o} \quad (12)$$

Where B* is defined as follows:

$$\beta^* = \left[\left(\frac{dh_g}{dp}\right)_{SAT} X + \left(\frac{dh_f}{dp}\right)_{SAT} (1-X)\right] \frac{p_o}{h_{gf}} \quad (13)$$

Auxiliary Equations

Density ρ_i is related to X_i, the quality, by the following relationship:

$$\rho_i = \rho_i\ (X_i, G_i, \text{gas properties, fluid properties}) \quad (14)$$

The two-phase friction factor can be expressed in various ways. We will assume the following form:

$$\Phi_{foi} = \Phi_{foi}\ (X_i, G_i, \text{gas properties, liquid properties}) \quad (15)$$

The equations of Dukler et al. [3], Baroczy [4] and Thom [5] are all expressed in this empirical form.

Scaling Laws

For the loop model to have the same transient response as the reactor, the nondimensional paramenters appearing as coefficients in Equations (10), (11), and (12) must be equal in both model and reactor. For example, the ratio of Reynolds number in the model to the Reynolds numbers in the reactor $(Re)_R$ must equal unity.

Therefore for dynamic similarly between the model and reactor the following scaling laws must be obeyed.

$$(\rho_i^*)_R = 1 \quad (16)$$

$$(u_i^*)_R = 1 \quad (17)$$

$$(l_i^*)_R = 1 \quad (18)$$

$$\left(\frac{A_i^*}{\eta_i}\right)_R = 1 \quad (19)$$

$$(\Phi^2_{foi})_R = 1 \quad (20)$$

$$(\sin\theta_i)_R = 1$$

$$(N_{fi})_R = 1 \quad (22)$$

$$(M_{wi}C_{wi})_R = 1 \quad (23)$$

$$\left(\frac{Q_i l_o}{h_{gf}\,\rho_o u_o}\right)_R = 1 \tag{24}$$

$$\left(\frac{g l_o}{\overline{u}_o^2}\right)_R = 1 \tag{25}$$

$$(\beta_i^*)_R = 1 \tag{26}$$

Some of the dimensionless group are automatically satisfied because of equations (10), (11), (12), (14) and (15), and the fact that the model operates at the same pressure as the reactor. If we remove the redundant equations, seven fundamental scaling laws are apparent.

$$(A_i^*)_R = \begin{cases} 1 & \text{pipe sections below headers} \\ N_c & \text{pipe sections above headers} \end{cases} \tag{27}$$

$$(l_i^*)_R = 1 \tag{28}$$

$$(\sin\theta_i)_R = 1 \tag{29}$$

$$(N_{fi})_R = 1 \tag{30}$$

$$(Q_i)_R = 1 \tag{31}$$

$$(M_{wi}C_{wi})_R = 1 \tag{32}$$

$$(l_o)_R = 1 \tag{33}$$

Equations (27) to (29) imply similarity of pipe length and areas between model and reactor. The most suprising scaling requirement is Equation (33). This implies that the model must have full-scale pipe lengths and be of full height. Ishii and Kataoka [1] identified their requirement in their scaling analysis for an LWR type system, but did not stress its importance. The full-length requirement arises because of a component in the pressure gradient term, $\frac{\partial p_i^*}{\partial z^*}$, in Equations (11) and (12). An important parameter in characterising this gradient is the gravitational group that appears in Equation (11), $\left(\frac{l_o g}{\overline{u}_o^2}\right)$, which contains the full length requirement term, l_o. If it is not met quality changes around the loop caused by elevation changes will not be reproduced. Boiling as a result of elevation change is important in determining the void distribution in a CANDU system during two-phase thermosiphoning [6,7]. Partial length scaling will reduce the importance of this effect and will generate distortions in the transient response of the system.

Equations (27) to (33) form the complete set of scaling laws. When obeyed, transient and steady-state thermosiphoning behaviour will be the same in both reactor and model. These scaling laws only apply if the homogeneous flow model, used to describe the system, is valid.

LOOP SPECIFICATIONS

Heated Sections

A CANDU reactor has up to 120 parallel channels per pass per loop. The coolant flow in each channel is approximately one hundredth of the system flow per loop. To simulate the parallel-channel behaviour of CANDU reactor it is desirable to have as many channels as possible. However, the size and number of channels in the RD-14 test facility is limited by the design of the existing loop.

Steam generators and pumps in RD-14 were scaled for a single 37-element, 5.5 MW channel per pass. Loop flow areas were similarily scaled. Thus for a multichannel geometry, the sum of the individual channel flow areas must correspond to that of a single 37-element channel. Other criteria must also be satisfied.

To maintain the same element heat flux at a given power, the total number of elements in a multichannel pass should equal the original single channel design. The heaters should also have a ring geometry as in a CANDU reactor. Three parallel channel geometries will satisfy these requirements: (a) two 18-element channels (b) three 12-element channels and (c) five 7-element channels per pair.

Very strong interactions between channels are expected to occur with the two and three channel geometries. This would not be representative of a typical CANDU reactor. The five-channel geometry was chosen for two reasons. It has weaker channel to channel interactions, and seven element channels were used in earlier RD-12 experiments.

Each channel will have the full heated length of 6 m, satisfying Equation (33). Seven electrically heated fuel element simulators (FES), as per current RD-14 design, will be used in each channel. The geometry of the FES will correspond to the seven central elements of a typical CANDU fuel bundle. Since a typical CANDU bundle contains 37 fuel elements, the flow in a seven-element channel will be reduced proportionately. Major characteristics of the heated channels are listed in Table 1. Based on this heated channel design, the scaling ratios given in Equations (27) to (32) are listed in Table 2. Certain nominal operating conditions for thermosiphoning flow have been assumed for both loop and reactor. These conditions, based on available RD-14 data, are an average pin power rating $q_L = 0.9$ kW/m, $p_o = 4$ MPa and $\bar{u}_o = 0.36$ m/s. These values correspond to a reactor channel decay power of 200 kW and a channel flow of 1 kg/s. It should also be noted that with the proposed channel design, Equation (31) requires that the average pin power rating, q_L, be the same in both loop and reactor.

Channel End Fittings

It is obvious that these end fittings cannot be represented as uniform area pipes. The previously developed scaling rules are therefore not applicable. Pressure and heat losses, plus heat capacity requirements for the end fittings can, however, be developed. To obtain approximate scaling rules for the end fitting geometry, we write integral momentum and energy balances, as shown below.

TABLE 1

HEATED CHANNEL CHARACTERISTICS

	RD-14	Reactor
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
Pin Number	7	37
Pin Heat Capacity (at 250°C) (kJ/(m.°C))	0.38	0.37

TABLE 2

VALUES OF SCALING RATIOS FOR HEATED SECTION

$(A_i^*)_R$	$(l_i^*)_R$	$(\sin\theta_i)_R$	$(N_{fi})_R$	$(Q_i)_R$	$(M_w C_w)_R$
1	1	1	1.29[a]	1.01[b]	1.03[c]

Notes:

(a) K factors are neglected.

(b) Assumes heat loss for multichannel loop is 550 W and reactor channel heat loss is 8 kW

(c) Assume heat capacity of reactor fuel and FES are 0.37 kJ/(m.°C)[10] and 0.38 kJ/(m.°C), respectively.

The frictional pressure loss in the end fitting when steady two-phase flow occurs is

$$\Delta p = \Phi_{fo}^{2} K_{EF} \frac{1}{2} \rho_o u_o^{2} \tag{34}$$

Written in dimensionless form, Equation (34) becomes

$$\Delta p^{*} = \Phi_{fo}^{2} K_{EF} (\rho_o u_o^{2}/2p_o) \tag{35}$$

But p_o, ρ_o and Φ_{fo}^2 are the same in both model and reactor. The scaling requirement becomes

$$(K_{EF})_R = 1 \tag{36}$$

The frictional pressure loss coefficient K_{EF} is expressed in terms of the velocity head of the heated channel.

The integral energy balance for the fluid inside the end fitting is

$$V_f \frac{\partial}{\partial t} (e\rho) = -W\Delta h + \dot{Q}_w \tag{37}$$

where $\dot{Q}_w$, is the energy in the form of heat entering the wall per unit time, V_f, is the fluid volume and e, the fluid internal energy.

For the end-fitting metal work the energy balance can be written as

$$-M_c C_w \left(\frac{\partial T_w}{\partial t}\right) = \dot{Q}_w + Q_{HL} \tag{38}$$

Eliminating $\dot{Q}_w$ and transforming the dimensionless variables we get

$$\Delta h = -\left(\frac{V_f}{l_o A_o}\right) \frac{\partial}{\partial t^{*}} (e^{*}\rho^{*}) - \frac{M_w C_w T_o}{l_o A_o \rho_o h g_f} \left(\frac{\partial T_w^{*}}{\partial t^{*}}\right) - \left(\frac{Q_{HL}}{\rho_o u_o A_o h_{gf}}\right) \tag{39}$$

For similarity the following scaling laws must be satisfied.

$$(V_f/A_o l_o)_R = 1 \tag{40}$$

$$(M_w C_w/A_o l_o)_R = 1 \tag{41}$$

$$(Q_{HL}/A_o)_R = 1 \tag{42}$$

Equations (40) to (42) show that fluid volume and heat capacity of the end fittings should be scaled in direct proportion to channel volume. End-fitting heat losses must be reduced in direct proportion to channel flow area.

For similarity, Equations (36) and (40) to (42) should be satisfied. End fitting scaling ratios are given in Table 3.

TABLE 3

SCALING RATIOS FOR END FITTING

$(K_{EF})_R$	$(V_f/A_o l_o)_R$	$(M_w C_w/A_o l_o)_R$	$(Q_{LS}/A_o)_R$
1	1	1	0.9[a]

Notes: (a) Reactor-end fitting heat loss was taken as 3 kW. Model end-fitting heat loss was estimated from RD-14 measurements. A value approximating to 7/37 of the RD-14 37-element channel end fitting heat loss was used.

Feeders

Five reactor-channel/feeder geometries have been selected to represent CANDU feeders; three middle channels, one top channel and one bottom channel. Channels were chosen as follows:

(1) The channels should cover the full range of elevation differences.
(2) The five-channel average powers should equal the core average power.
(3) The five-channel average flows should equal the core average flow.
(4) Feeder geometries should cover the range of pipe diameters, horizontal lengths, and flow restricting orifices present in the reactor.
(5) Nozzle angles, at header connections, should cover the range found in a reactor.

Table 4 lists relevant data for selected channel/feeder geometries or a typical CANDU reactor. Figure 3 shows the feeder geometry for reactor channel X 12.

Model feeders, where possible, will have the same lengths and geometries as reactor feeders. Diameters and wall thicknesses should be reduced according to the scaling requirements of Equations (27) and (32). To manufacture piping sections with the exact diameters and wall thicknesses specified by the scaling laws would be costly. For practical purposes, commercially available pipe sizes will be used. This will result in some scaling distortions (see Table 5).

Data from the existing RD-14 loop indicates that, at a 4 MPa operating pressure, heat losses from lagged feeders in the multichannel loop will be 5-10 kW/channel. At thermosiphoning conditions, where power levels are at decay levels, with an average pin power rating of 0.9 kW/m, 12-25% of the channel input power could be dissipated through heat losses. This is a significant heat loss when compared with reactor feeder losses.

In a reactor, feeder lines are enclosed in cabinets. At 4 MPa, and typical reactor decay power levels, heat losses are expected to be less than one percent of the channel power.

This discrepancy between the multichannel loop and the reactor will lead to a significant distortion in $(Q_i)_R$ ratios. A more serious problem is that with such high heat losses in the multichannel loop the void distribution around the loop will not be reactor typical. To avoid this problem feed pipework in the multichannel loop will be trace heated to eliminate heat losses.

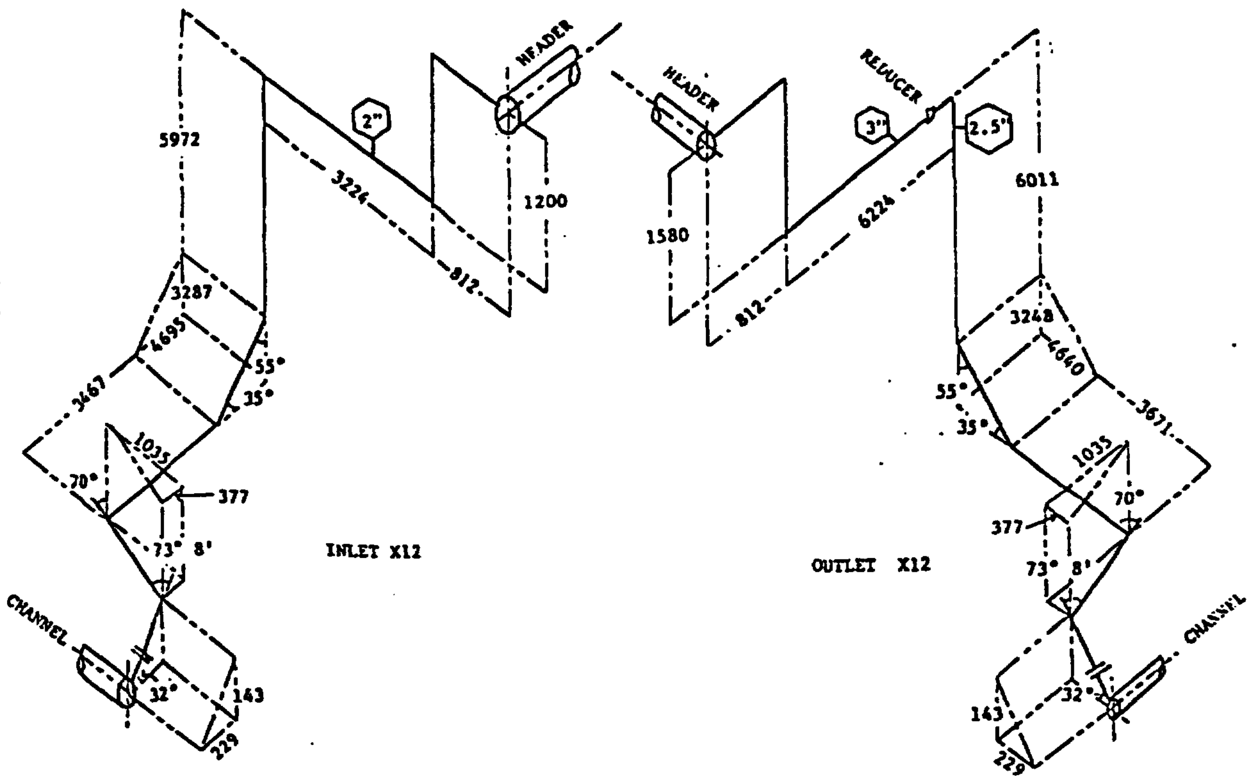


FIGURE 3: Reactor Feeder Geometry for Channel (X 12)

Pipework Above Headers

Existing RD-14 pipework will be used above the headers. Scaling ratios with respect to a CANDU 600 reactor are given in Table 6.

Significant distortions from ideality are apparent. However, the deviations are not considered critical since they will not have a major effect on loop behaviour. Primarily this is because the above header pipe lengths in both reactor and the multichannel facility are small when compared to the rest of the primary circuit. Pressure drops for the above header pipework in both the RD-14 facility and a typical reactor are comparable. (≈20% of the total loop pressure drop.)

Boilers

The RD-14 boilers are recirculating U-tube steam generators. They closely resemble reactor boilers and have a reduced number of tubes. Boiler characteristics are summarized in Table 7.

Scaling ratios are listed in Table 8. All values are close to unity.

TABLE 4

DATA ON REACTOR FEEDER/CHANNEL GEOMETRIES

Channel	Power (MW)	Flow (kg/s)	Elevation Difference[a] (m)	Header Connection (deg)	Notes
B10	4.9	19.07	+3.003	54	Outer core, upper elevation channel. No horizontal pipe sections near channel. Close to minimum restricting orifice size
L2	5.1	20.97	+0.429	54	Outer core mid-elevation channel. No horizontal pipe sections near channel. Large restricting orifice.
M1	6.5	23.6	+0.143	90	Inner core, mid-elevation high power channel. Long horizontal section near channel. No orifice.
05	6.4	24.25	-0.429	18	Inner core, mid-elevation high power channel. Representative geometry.
X12	4.8	20.20	-3.003	90	Outer core, low-elevation channel. Long horizontal section near channel. No orifice.

Notes:

(a) Measured with respect to core centre.

TABLE 5

SCALING RATIOS FOR FEEDER X 12

REACTOR PIPE NOMINAL SIZE (a)	MULTICHANNEL LOOP PIPE NOMINAL SIZE (b)	$(A_i)_R$	$(N_{fi})_R$ (c)	$(Q_i)_R$ (d)	$(M_wC_w)_R$
2	1	1.55	0.74	1	1.14
2½	1¼	1.86	0.53	1	0.85
3	1¼	1.19	1.7	1	0.98

Notes:
(a) Schedule 80 pipe
(b) Schedule 40 pipe
(c) K factor's neglected
(d) Assume Q_i=0 in reactor and multichannel loop.

TABLE 6

SCALING RATIOS FOR PIPES ABOVE HEADERS (CANDU 600 REACTOR GEOMETRY)

DESCRIPTION	$(A_i^*/N_c)_R$	$(l_i^*)_R$	$(\sin\theta_i)_R$	$(N_{fi})_R$	$(Q_i)_R$	$(M_wC_w)_R$
Steam Generator Inlet	4.3	0.9	-	0.34	1[a]	1.7
Pump Suction	4.3	0.8	-	0.3	1[a]	1.7
Pump Discharge	3.6	1.6	-	0.99	1[a]	2.4

Notes: (a) Assume Q = 0 in multichannel loop and reactor.

TABLE 7

RD-14 BOILER 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	Incaloy-800	Incaloy-800
Average tube length (m)	18.8[a]	17.5[a]

Notes: (a) Average based on total heat transfer area.

TABLE 8

SCALING RATIOS FOR BOILER TUBE BANK

$(A_i^*/N_c)_R$	$(l_i^*)_R$	$(\sin\theta_i)_R$	$(N_{fi})_R$	$(Q_i)_R$	$(M_w C_w)_R$
1.2	1.1	1.0	0.7	1.0	1.0

Headers

Flow patterns in the headers will be highly three dimensional. This means that scaling laws developed for pipe components cannot be applied.

In certain two-phase thermosiphoning transients, and during blowdown and refill in a reactor loop, the flow in the headers will most likely stratify. Stratified flow will affect the quality of fluid supplied to the channels connected to the headers.

To simulate the correct quality distribution in the multichannel loop, headers will be constructed with the same feeder to header-diameter ratio as in a typical reactor. Feeders in the multichannel loop will be positioned at angles typical of a reactor. These requirements will effectively simulate phase separation and feeder nozzle uncovering phenomena in the modified loop. However, with this geometry, scaling of fluid flow path lengths is not possible, although transit times will be maintained since volumes will be scaled.

To obtain the desired wall temperatures and stored heat terms in the modified loop, the metal mass of the headers should be correctly scaled. Given that the previous scaling rationale for the headers is followed, the headers would have to be constructed from thin piping. To satisfy pressure vessel code requirements, and to maintain structural integrity, piping of a much larger thickness must be used. The header design is shown in Figure 4.

DISCUSSION

The scaling laws developed are applicable to two-phase flows that occur in thermosiphoning and in blowdown/emergency-coolant injection transients. The scaling rationale only applies if the flow is well mixed and the void/quality relationship for homogeneous flow can be applied (Equation (14)). For separated flow behaviour, like horizontal stratified flow or horizontal/vertical annular flow, Equation (14) is not usually valid. If these flow regimes occur, departures from similarity between reactor and loop behaviour are expected. A brief discussion of some of the expected departures from homogeneous flow in horizontal and vertical loop pipework is included below.

Horizontal Channel Behaviour

The onset of stratified flow in horizontal channels is expected to be important in determining the behaviour of the test facility in thermosiphoning. Flow stratification will uncover the upper elements of fuel assemblies, leading to reduced channel to coolant heat transfer. With perfect scaling, flow stratification in the loop and reactor would occur at identical conditions.

Kowalski and Krishnan [8] made detailed studies of the transition to stratified flow in a seven-rod channel. The channel geometry used was almost identical to that proposed for heated sections in the modified multichannel loop. In their study they developed a correlation for the transition to stratified flow. The correlation agreed well with both their own experimental data and that of Aly [9] and Sawamura et al. [10]. The latter workers used a 37 rod CANDU channel geometry.

Using dimensionless variables defined previously, Kowalski and Krishnan's correlation can be written

$$\rho^* . u^* = f(X, \text{ fluid and gas properties}) \sqrt{\frac{gA_o}{d_o \bar{u}_o^2}} \qquad (43)$$

Stratified flow will occur if the left hand side of Equation (43) is less than the right hand side.

Since ρ^*, u^*, X, $\bar{u}_o$, gas and fluid properties will be equal when scaling laws are obeyed, if $\sqrt{(A_o/d_o)_R}$ is unity, stratification will occur

under similar conditions in both the loop and the reactor. The actual scaling ratio is in fact given by $\sqrt{(A_o/d_o)_R} = 0.66$. This implies that stratified flow will occur at a loop mass flux, which is approximately 30% lower than in a typical reactor. This is well within uncertainties normally associated with predictions of flow regime transitions.

Figure 5 shows the transition to stratified flow for 7- and 37-rod geometries as predicted by the Kowalski-Krishnan model. Sawamura's data [10] is also shown. There is reasonable agreement between the two curves.

Feeder Geometries

Under some conditions the penetration of water downwards into the feeders may be limited by flooding caused by steam upflow [11]. This phenomenon is expected during loop blowdown and refill. In a feeder, the minimum steam upflow, to prevent water downflow, is expected to follow an equation of the form:

$$\frac{j_g}{(gd\rho_{fg}/\rho)^{\frac{1}{2}}} = K \qquad (44)$$

where K is a constant fixed by feeder geometry. Transforming Equation (44) to a dimensionless form, we get

$$(\rho^* u^*)\mathrm{min} = f\,(x, \text{gas properties, fluid properties}) \left(gd/\bar{u}_o^2\right)^{\frac{1}{2}} \qquad (45)$$

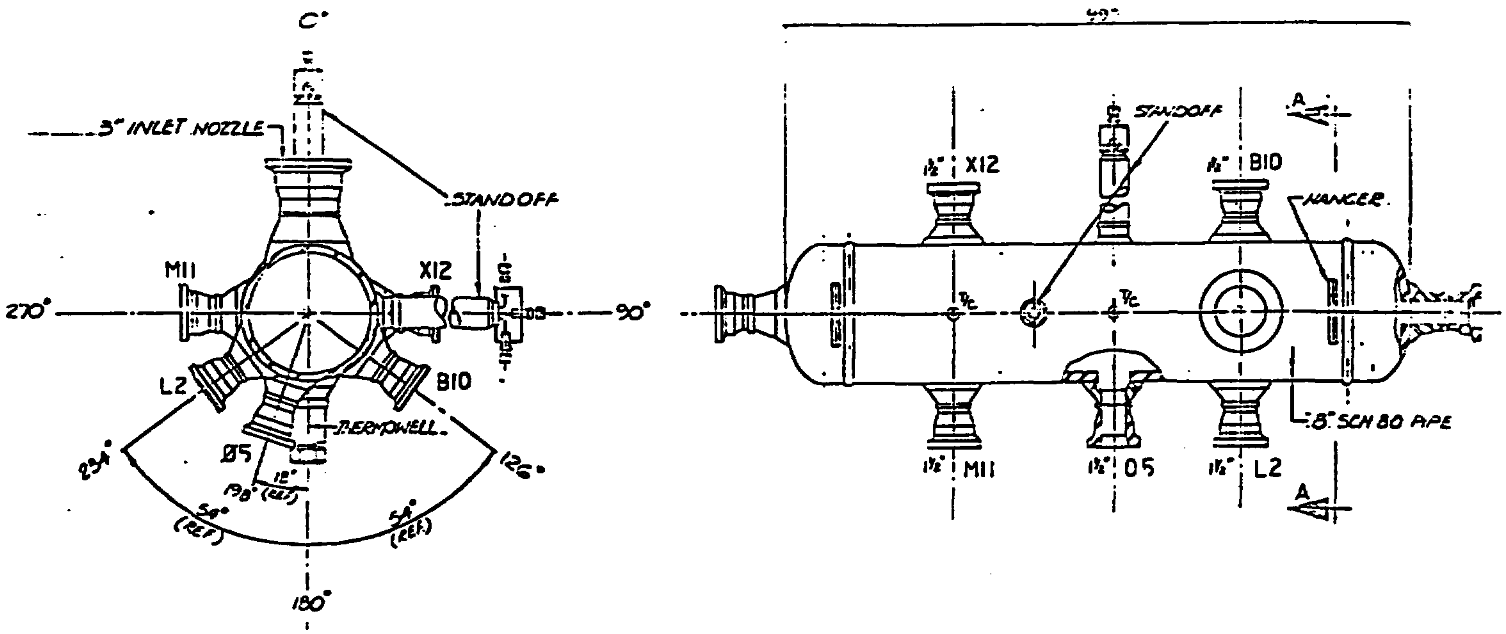
The model feeders have approximately one quarter the cross sectional area of reactor feeders. Therefore liquid downflow in the modified loop will be prevented at a steam mass flux, which is 70% of that in a typical reactor. As a consequence, channel refilling in the loop may take longer than in a reactor.

SUMMARY AND CONCLUSIONS

Scaling laws have been developed and applied to the design of a multichannel loop. Consideration has been given to themosiphoning, blow down and ECI transients. The scaling laws are consistent with those derived by Ishii and Kataoka [1].

The importance of maintaining full linear dimensions and elevation changes present in a typical CANDU reactor has been stressed. If this requirement is not met, simulation of the reactor void distribution, caused by elevation induced flashing, will not be possible in the multichannel loop.

The main features of the multichannel loop design are summarized in Table 9.



Section
'A-A'
Inlet Header

Plan
Inlet Header

FIGURE 4: Typical RD-14 Inlet Header Design

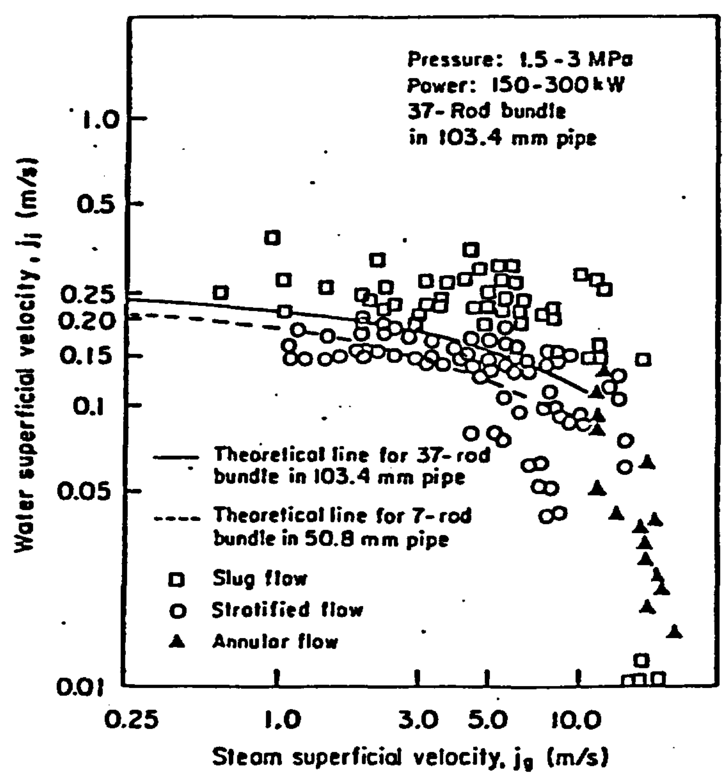


FIGURE 5: Predicted Transition to Stratified Flow for 37-Rod and 7-Rod Channel Geometries. Data of Sawamura et al. [10]

TABLE 9

DESIGN FEATURES OF PROPOSED FACILITY

Heated Channels	5 channels/pass. 7 full-heated length FES/ channel. (Model channel flow area)/(Reactor channel flow area = 7/37
End Fittings	(Model fitting metalwork mass)/(Reactor end-fitting metalwork mass) = 7/37 Model end-fitting fluid Vol.)/(Reactor end-fitting vol.) = 7/37 Model end-fitting K factor) = (Reactor end-fitting K factor)
Feeders	Model feeders = full-length scale, height scale models of typical reator feeders for one top, one bottom and three middle channels (Model feeder flow area)/(Reactor feeder flow area) = 0.2 - 0.3
Headers	Feeder nozzles at reactor-typical angles (Header to feeder diameter) R = 1
Components Above Headers	Unchanged from present build of RD-14
Heat Losses	Feeders, headers, SG inlet, exit pipework surrounded by guard heaters to reduce heat losses to reactor levels

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