162

TDAI-295

cv ref C6

THERMALHYDRAULIC DESIGN VERIFICATION FOR THE PRIMARY HEAT TRANSPORT SYSTEM

by

Wm. J. Garland
Process Analysis Section
AECL-EC

Submitted to:

1982 Simulation Symposium on Reactor
Dynamics and Plant Control

1982 April 19 and 20

THERMALHYDRAULIC DESIGN VERIFICATION
FOR THE PRIMARY HEAT TRANSPORT SYSTEM

ABSTRACT

The Primary Heat Transport System (PHTS) is, in the simplest sense, merely a system which transports fluid for the purposes of heat transfer. However, the design of the PHTS covers many aspects including chemistry, mechanics, safety analysis (for LOCA's, etc.) and process design. It is the verification of process (thermalhydraulic) design work that is the subject of this paper.

Since process design is largely based on computer simulations, verification of process design work is centered around the verification of the methodology, models and base data used by the relevant computer codes. Errors can enter the simulation from simplifications in:

a) the fundamental conservation and constitutive laws,
b) discrete approximations to continua (numerical discretization),
c) solution of the resulting systems of equations.

Verification is therefore, necessary. Discussion of the potential sources of simulation errors is expanded in the paper. The extent to which the verification of a design tool is necessary depends on the degree of accuracy required and the ramifications of approximations. Design margins are required because of operating and safety requirements, however, the existence of these margins is expensive. In recent years, the escalation of both costs and the requirements for margins has led to demands for increased simulation accuracy. These issues are also expanded in the paper. Having established the general sources of thermalhydraulic simula- tion errors, and the need for reducing those errors, the paper goes on to develop the equations describing the major thermalhydraulic characteristics of the PHTS. Key parameters, and major uncertainties, are outlined and their effect on the performance of the PHTS is illustrated.

Finally, the details of the verification procedure are developed. Although some verification of the PHTS design tools has already been done, much more remains to be done. Thermalhydraulic verification comes from three sources:

a) feedback from operating plants,
b) laboratory experiments,
c) code benchmarking.

Some of the specific needs in each of these areas is discussed. Ongoing programs in all three areas are also outlined, including a brief summary of possible future programs. Emphasis is placed on discussing the plans for obtaining feedback from the plants since that is a major current involvement of AECL.

TABLE OF CONTENTS

1.0 WHY VERIFY? - OVERVIEW

1.1 Approximations Inherent in Process Analysis
1.2 The Requirement for Increased Accuracy
1.3 Synopsis of the Contents of this Paper

2.0 WHAT TO VERIFY - THE MAIN CHARACTERS

2.1 Simple Steady State Equations
2.2 Example: CANDU 600

3.0 VERIFY - TO WHAT ACCURACY?

3.1 The Main Parameters
3.2 Design Deviation Effect on CPR
3.2.1 Primary Heat Transport System Flow
3.2.2 Primary Heat Transport Steam Generator Area
3.2.3 Steam Generator Drum Pressure
3.2.4 Reactor Outlet Header Pressure
3.2.5 The Reactor Power
3.3 Other Design Deviation Effects
3.4 Conclusions
3.5 Recommendations

4.0 VERIFY - HOW?

4.1 Feedback from the Plants
4.1.1 Experimental Design
4.1.2 Code Lock-on Procedure
4.2 Out-of Plant Experimental Data
4.2.1 Specific Needs
4.2.2 Experimental Design
4.3 Basic Code Development
4.3.1 Specific Needs

5.0 CONCLUSIONS

THERMALHYDRAULIC DESIGN VERIFICATION
FOR THE PRIMARY HEAT TRANSPORT SYSTEM

1.0 WHY VERIFY? - OVERVIEW

The Primary Heat Transport System (PHTS) is, in the simplest sense, merely a system which transports fluid for the purposes of heat transfer. However, the design of the PHTS covers many aspects including chemistry, mechanics, safety analysis (for LOCA's, etc.) and process design. It is the verification of process (thermalhydraulic) design work that is the subject of this paper.

Since process design is largely based on computer simulations, verification of process design work is centered around the verification of the methodology, models and base data used by the relevant computer codes.

1.1 The Approximations Inherent in Process Analysis

The fundamental relationships governing thermalhydraulic analyses are:

1) Conservation laws: mass, energy, momentum,
2) Constitutive laws: state equations.

This basic step of establishing mathematical statements to reflect reality is, in itself, an approximation.

All component (fluid, pipes, heat exchangers, valves, pumps) equations are derivable from these fundamental relationships. The state of the art is such that empirical relations are heavily relied on to compensate for the lack of understanding of the fundamental terms in the basic equations. For example, stress tensors are invariably reduced, ignored, or replaced by friction factors. Multiphase flow equations are invariably combined into mixture equations. This is the second level of approximation.

The third level of approximation is created because the solutions to the various approximate forms of equations that have been derived are usually not directly achievable. Discrete approximations are made to continuous systems and numerical solution techniques, guaranteed to work only for linear systems, are used (the fourth level of approximation). The final solution is thus fourfold removed from reality. Small wonder that the simplified component models used in systems analysis do not always produce perfect results.

Verification is therefore, necessary. Analysis should be coupled with experiments and operating experience for best returns. This coupling is weak compared to what it should be.

1.2 The Requirement for Increased Accuracy

The issue can be stated quite simply: We can get answers from codes but, without verification ,we don't know if the answers are correct. But why is this a problem? Just a few years ago tools like SOPHT, FIREBIRD, etc. didn't exist. So why can't we be satisfied with the improvements since then?

The answer is simple. The analysis performed for past stations is not enough for the future stations. The increasing reliance on analysis is prompted, naturally enough, by economic incentives from the design and operations point of view and by necessity from the safety point of view. The attempt to extract more and more power and performance out of a nuclear station of fixed size means the lowering of margins, both operating margins and safety margins. Overdesign is wasteful of resources and costly in capital and operation. It has been estimated that reducing the margins 1% can save $80 million over the life of a 4 unit station. However, a "small margin" design can be more costly in outages and analysis.

The incentive to get more power out of a fixed size plant has another overtone - increased complexity. Increased complexity also arises from the ever increasing safety requirements. Such complexity means that, in the design and analysis of nuclear systems, it is not possible for a designer to consider all the ramifications of his particular system without resorting to a computer code to model the interactions between systems. Although detailed models of each system are imperative; it is equally imperative to have an overall model composed of at least simplified versions of the more detailed models. The requirement to use simplified models introduces approximations and leads to errors. The cost of fixing design errors thru the backfit process is very high. The alternate cost of such errors is derating which means using higher cost replacement energy.

Finally, in view of our quality assurance program, it is inevitable that we are being asked to prove the validity of our design.

All of the above lead to the need for design analysis verification.

1.3 Synopsis of the Contents of this Paper

Having established the general sources of thermalhydraulic simulation errors, and the need for reducing those errors in the above, we proceed to develop the equations describing the major thermalhydraulic characteristics of the PHTS. Key parameters, and major uncertainties, are outlined and their effect on the performance of the PHTS is then illustrated. Finally, the details of the verification procedure being used in the CANDU 600 design work are developed.

2.0 WHAT TO VERIFY - THE MAIN CHARACTERS

The main heat transport system for all reactor systems is fundamentally simple. Heat is generated by nuclear fission, transferred to a moving heat transport medium, and carried by this medium to the steam generators for steam production. This is indicated in Figure 1.

2.1 Simple Steady State Equations

Performing a steady state energy balance around the reactor, the energy out of the reactor equals the energy going in plus the reactor energy generation. Thus:

$$Wh_o = Wh_i + Q,$$

or

$$Q = W(ho-hi), \qquad 1$$

where W = coolant mass flowrate (kg/s);
h_o = core exit enthalpy (kJ/kg);
h_i = core inlet enthalpy (kJ/kg);
Q = reactor power transferred to the coolant (kJ/s or kW).

Neglecting minor factors (such as, pump heat, piping heat losses, pump gland seal leakage and miscellaneous heat losses via auxiliary systems), the power transferred to the steam generator is Q kW. The heat transfer at any point in the steam generator is given by Fourier's law:

$$dQ = UdA\,(T_p - T_s) \qquad 2$$

where U = overall heat transfer coefficient ($kJ/m^2\,{}^oC$),
A = heat transfer area (m^2),
T_p = primary (D_2O)side temperature (°C).
T_s = secondary side (H_2O) temperature (°C).

U is a function of flow, temperature, the amount of boiling (quality), the physical layout, heat exchanger tube material and the degree of crudding or fouling in the steam generator.

Thus the total heat transfer is

$$Q = \int_Q dQ = \int_A UdA(T_p - T_s) \qquad 3$$

The D_2O and H_2O temperatures are not constant throughout the steam generator. A schematic representation of the variation is shown in Figure 2.

Using the 600 MW CANDU as an example, demineralized feedwater (H_20) enters the preheating section of the steam generator at roughly 175°C and gains heat from the exiting D_20 (~265°C at ~5 mPa) and the H_20 begins to boil. The temperature then remains essentially constant as the H_20 travels through the boiler (left to right in Figure 2). The D_20 (primary fluid) enters the boiler section of the steam generator at roughly 310°C at 10 mPa with 4% quality (ie. 4% by weight of steam). The heat transfer to the secondary side condenses the steam and the temperature subsequently drops as the D_20 travels through the steam generator tubes (right to left in Figure 2).

For the purposes of discussion, we will simplify equation 3 by assuming a temperature distribution as shown in Figure 3. Thus we have ignored the preheating section (where the H_20 temperature is less than saturation) and have assumed that no boiling occurs on the primary side. Further we have assumed that U is constant. These are crude approximations but adequate for discussion purposes.

Thus, equation 3 becomes:

$$Q = U\int_A dA\,(T_p - T_s) = UA\left(\frac{T_i+T_o}{2}\right) - UAT_s, \qquad 4$$

where T_i and T_o are the reactor inlet and outlet temperatures, respectively. Since enthalpy can be expressed as

$$h \simeq C_pT + \text{CONSTANT}, \qquad 5$$

where C_p is the heat capacity of water. Equation 4 becomes:

$$Q = \frac{UA}{C_p}\left[\frac{h_o+h_i}{2} - h_s\right] \qquad 6$$

if we assume the same properties for H_20 and D_20.

A final primary heat transport system relation is needed to complete this very approximate picture. The primary side flow is determined by a balance between the head generated by the primary pumps and the circuit head losses due to friction.

$$\Delta P_{pump} = \Delta P_{circuit} \qquad 7$$

The pump curve (head vs. flow) relationship is supplied by the pump manufacturer. It can be approximated by a power series:

$$\Delta P_{pump} = A_o + A_1W + A_2W^2 + \ldots\ldots \qquad 8$$

To a first order approximation, the circuit losses obey the classical velocity squared relationship:

$$\Delta P_{circuit} = KW^2 \qquad 9$$

where K can be a complex function of material properties and pipe geometric details.

Typical shapes for Equation 8 and 9 are shown in Figure 4. The intersection of the two curves is the operating point, defined by equation 7.

The primary heat transport approximate conditions are set, then, by the simultaneous solution of the energy balance at the core, the energy balance at the steam generator and momentum balance around the circuit. In summary:

$$Q = W(h_o - h_i) \tag{1}$$

$$Q = \frac{UA}{C_p}\left(\frac{ho+hi}{2} - h_s\right) \tag{6}$$

$$\Delta P_{pump} = \Delta P_{circuit}. \tag{7}$$

Equations 1 and 6 can be rearranged to give an expression explicit in h_i:

$$h_i = (Q/W)\left[\frac{C_p W}{UA} - \frac{1}{2}\right] + h_s. \tag{8}$$

It is constructive to look at some derivatives of this equation in order to investigate the behaviour of h_i as parameters are changed.

$$\partial h_i/\partial W = Q/2W^2 \tag{9}$$

$$\partial h_i/\partial h_s = 1 \tag{10}$$

$$\frac{\partial h_i}{\partial Q} = \frac{C_p}{UA} - \frac{1}{2W} = \frac{1}{W}\left(\frac{C_p W}{UA} - \frac{1}{2}\right) \tag{11}$$

$$\frac{\partial h_i}{\partial (C_p W/UA)} = Q/W. \tag{12}$$

Since all parameters, Q, W, C_p, A, U, etc, are all positive quantities, the reactor inlet enthalpy (and hence the inlet temperature) will go up as flow goes up, will go up as secondary side temperature and enthalpy go up and may go up or down as power changed, depending on the sign of equation 11.

The reactor outlet enthalpy, h_o, is directly related to h_i by equation 1:

$$h_o = Q/W + h_i = Q/W\left[\frac{C_p W}{UA} + \frac{1}{2}\right] + h_s. \tag{13}$$

The average enthalpy in the core and the steam generator is:

$$\bar{h} = \frac{h_o + h_i}{2} = (Q/W)\left(\frac{C_p W}{UA}\right) + h_s = \frac{Q\,C_p}{UA} + h_s. \tag{14}$$

This result is very interesting since it shows that $\bar{h}$ is not a direct function of flow. Assuming h_s and C_p/UA are fixed for a given secondary side temperature and steam generator geometry, $\bar{h}$ is a simple linear function of the reactor power, Q. Figure 5 illustrates this point and also shows the spread, or variation, in h about $\bar{h}$ given by:

$$h_o - \bar{h} = Q/W\left(\frac{C_p W}{UA} + \frac{1}{2}\right) + h_s - \frac{Q}{W}\frac{C_p W}{UA} - h_s = Q/2W. \tag{15}$$

Similarly,

$$\bar{h} - h_i = Q/2W \,. \qquad 16$$

We see that the primary side enthalpy remains above the secondary side enthalpy with just enough Δh to transfer Q kW of power.

2.2 Example: CANDU 600

Parameters:

$$\begin{aligned} Q &\simeq 2000 \text{ MW(th)} = 2\times10^6 \text{ kW(th)} \\ W &\simeq 7600 \text{ kg/s} \\ T_s &\simeq 265\,^\circ\text{C} \\ C_p &\simeq 4.25 \text{ kJ/kg}^\circ\text{C} \end{aligned} \Bigg\} \Rightarrow h_s \simeq 1125 \text{ kJ/kg}$$

$$\begin{aligned} U &\simeq 20 \text{ kJ/s}^\circ\text{C-m}^2 \\ A &= 3200 \text{ m}^2 \end{aligned} \Bigg\} \frac{UA}{C_p W} \simeq 2$$

$$P_{ROH} = 10 \text{ MPa} \,.$$

Thus from equation 8

$$h_i = 263\left[\tfrac{1}{2} - \tfrac{1}{2}\right] + h_s = h_s = 1125 \text{ kJ/kg} \qquad 17$$

and

$$h_o = h_i + Q/W = 1388 \text{ kJ/kg} \,. \qquad 18$$

The saturation enthalpy at the outlet header is roughly 1370 KJ/kg. Hence our prediction of the primary outlet conditions is that the D_2O should reach a quality of 1.6% based on a known flow of 7600 kg/s and the assumption of $h_i = h_s$. In fact, h_i is greater than h_s and the actual PHT quality should be larger than our calculation, as indeed it is. The detailed design calculations give the outlet quality at 4% with an enthalpy of ~1415 KJ/kg.

The value of UA/C_pW was chosen to be exactly 2 to cause h_i to be equal to h_s. If, through variations or uncertainties in U, A, C_p or W, this value changed then from Equation 12:

$$\frac{\partial(h_i/h_{io})}{\partial\left(\frac{C_pW}{UA}\right)\Big/\left(\frac{C_{po}W_o}{U_oA_o}\right)} = \frac{Q}{W_o}\left(\frac{C_{po}W_o}{U_oA_o}\right)\left(\frac{1}{h_{io}}\right) = 0.12\,\%/\% \,. \qquad 19$$

where the subscript, o, denotes nominal values.

From Equation 9 to 11 we can estimate the sensitivities of h_i to flow, steam enthalpy and power:

$$\frac{\partial(h_i/h_{io})}{\partial(W/W_o)} = 0.12\%/\%. \qquad 20$$

(Thus h_i changes by 0.12% when W changes 1%)

$$\frac{\partial h_i}{\partial h_s} = 1\%/\%. \qquad 21$$

$$\frac{\partial(h_i/h_{io})}{\partial(Q/Q_o)} = \frac{Q_o}{W_o h_{io}}\left(\frac{C_{po}W_o}{U_o A_o} - \frac{1}{2}\right) = 0 \text{, since } \frac{C_p W}{UA} = \frac{1}{2}. \qquad 22$$

and

$$\frac{\partial(h_o/h_{oo})}{\partial(Q/Q_o)} = \frac{Q_o}{W_o h_{oo}}\left(\frac{C_{po}W_o}{UA} + \frac{1}{2}\right) = 0.19\%/\%. \qquad 23$$

From these results we note the relative insensitivity of the enthalpy to changes in flow, power and heat transfer coefficient. The flow, however, is very sensitive to changes in enthalpy since, from Equation 8:

$$\frac{\partial(W/W_o)}{\partial(h_i/h_{io})} = \frac{1}{0.12} = 8.5. \qquad 24$$

Similarly,

$$\frac{\partial(W/W_o)}{\partial(h_o/h_{oo})} = -\frac{1}{0.12} = -8.5. \qquad 25$$

But what impact do these sensitivities have on verification? From the above, the importance of flow is obvious. If the PHT flow were known by direct measurement in an operating plant, then a major unknown becomes known and the verification process takes a giant step forward. Unfortunately, PHT gross flow is not now measured in the CANDU stations. It is inferred from power and enthalpy measurements. As the above equations show, any error in measuring enthalpy is magnified almost an order of magnitude in the flow estimate.

Also, power is not directly measurable. It is inferred from secondary side flow and enthalpy. Even enthalpy is not directly measurable. It is inferred from temperature or pressure (under saturated conditions). A detailed assessment has been made of the flow prediction error resulting from the accumulation of these errors. It was found that flow prediction errors of 1.5% are most likely, but errors as high as 6.5% could easily result in the CANDU 600 stations under unfavourable conditions.

These flow errors seem, on the surface, quite tolerable and it is not immediately obvious that any serious operating problems would be created if the flow is in error by even as much as 6.5%. To investigate the possible effect of such errors, the next section discusses likely errors in key parameters and their impact on margin to fuel dryout, the critical power ratio (CPR).

3.0 VERIFY - TO WHAT ACCURACY?

This section addresses the effect of changes in the main process parameters in the steady state. Specifically, this section addresses the following questions:

1) In what ways can we be off in our estimations of the main parameters affecting the PHT system?
3) What are the consequences of being off in these estimations and what could be done about it?

Further studies should be done to investigate the effect of changes in the various empirical correlations used and the effect of both in transient analysis.

3.1 The Main Parameters

The main parameters affecting the steady state performance of the PHT system are:

1) The steam quality of the PHT system. Specifically, the quality at the ROH (X_{ROH}) is a good indicator.
2) The pressure of the PHT system. Specifically, the pressure at the ROH (P_{ROH}) is a good indicator.
3) The pressure in the steam drum, P_{DRUM}.
4) The primary circuit flow, W.
5) The power, Q.
6) The critical power ratio, CPR.
7) The boiler area, BA.
8) The header to header pressure drop, ΔP_{H-H}.
9) The PHT pump head.
10) The PHT circuit hydraulic resistance coefficient, K_{TOTAL}.

Of these main parameters, P_{ROH}, P_{DRUM}, Q, BA, ΔP_{PUMP} and K_{TOTAL} are directly controllable while X_{ROH}, W, CPR and ΔP_{H-H} can be considered as derived from the directly controllable parameters. The only truly independent parameters for an operating plant are P_{ROH}, P_{DRUM} and Q.

3.2 Design Deviation Effect on CPR

The approach of this analysis is to start with a base case of 100% FP for a boiling figure of 8 CANDU. Perturbations in 5 parameters are made in such a way so as to reflect what would happen in the operating plant. The SOPHT code was used to generate the PHT process conditions and NUCIRC was used to calculate the CPR.

3.2.1 Primary Heat Transport System Flow

The PHT pump curve and the circuit hydraulic resistances could be different from their design values, leading to a flow that is different from its' design value. The pump curve is checked by performance testing and is guaranteed to within 15 ft in 700 ft or + 2%. The hydraulic resistance can be off by as much as ± 10% due to errors in correlations, pipe tolerances (+ 0.5%, - 9%,), etc. Low flow will cause the PHT quality to rise, leading to lower CPR. High flow will lower quality but can lead to fretting and erosion. With these sorts of errors it is easy to generate a flow error of 2%. The computer code results show that a low flow of 2% leads to a 1% derating (costing $80M) to maintain the design value of CPR. If the flow is not measured and is high or low by a few percent, then the designer is hampered in his evaluation of equipment performance. Extra design margins and CPR margins may have to be introduced. The threshold for erosion and fretting problems for a flow that is high is uncertain at this time.

Thus, there is considerable incentive to have a good estimate of PHT flow. If ΔP pump instrumentation is provided, this measurement can be related to PHT flow if the head-flow curve can be accurately obtained. Present practise is to guarantee the pump head to within 2% by off-site testing, install the pumps in the unit and trim the impellers if necessary. (Note: Accurate pump flow measurements are needed in order to determine the trim!) In addition reactor channel flows could be measured. The accuracy with which these measurements can be translated into total core flow is in question but more than a few percent error is expected.

At least two possibilities exist for direct flow measurement: 1) ultrasonic clamp-on probes (still under development) and 2) pitot probe in the flow-straightening vanes of the pump suction. Both methods should be pursued to increase the chance of obtaining an accurate flow measurement.

Ultimately, it is hoped that the flow can be measured to within ± 1/2% in the steady state. Long term measurements are necessary in addition to commissioning tests for CPR purposes. Long term measurements with a scan rate of 2 seconds are required to investigate system transients as well. As a guesstimate, an accuracy of ± 2% should be sufficient for transient analysis.

3.2.2 Primary Heat Transport System Steam Generator

The steam generator area may be different from design since extra margins are added in to account for uncertainties in design. As much as 10% margin is normal, hence the error in steam generator area is: - 0%, + 10%. High boiler area will decrease the PHT quality and lead to higher PHT flow. This in turn raises questions about fretting and erosion. Upper limits on flow velocities are not well understood and investigations are in progress at AECL.

The code results indicate that a 5% decrease in area reduces CPR by 1% and the subsequent derating is worth \$80M. Thus there is considerable incentive to place extra margin in the steam generator area, as is the usual practice, leading to the error estimates noted above. But these extra margins are very costly, as noted. In order to reduce this margin without the risk of derating, measurements are needed of the main process parameters which indicate boiler performance. Section 4 outlines the minimum list of measurements required.

3.2.3 Steam Generator Drum Pressure

The boiler drum pressure may be in error by as much as ± 2% due to measurement and control errors. This will perturb the PHT flow and quality with the usual consequences. A high drum pressure raises the PHT quality and decreases flow. A low pressure has the opposite effect.

The code results indicate that a 2% rise in drum pressure leads to a 1% derating at \$80M over the life of the station. Since a more accurate measurement and control is probably not feasible, all that can be done, is to put extra allowance in the CPR to account for the RMS error of drum pressure.

3.2.4 Reactor Outlet Header Pressure

The ROH pressure may be in error by as much as 2% due to measurement and control errors. A high pressure will suppress PHT quality and increase flow. A low pressure will have the opposite effect, with the usual consequences.

The code results indicate that a 2% drop in ROH pressure leads to a 1.3% derating at \$104M over the life of the station. As with the drum pressure, a more accurate measurement and control is probably not feasible. Therefore, all that can be done, is to put extra allowance in the CPR to account for the RMS error of the ROH pressure.

3.2.5 The Reactor Power

The reactor power may be in error by ± 5% due to simulation, measurement and control errors. This will directly perturb the quality and hence the flow in the PHT with the usual consequences.

The code results indicate that a 5% change in power leads to a 4% drop in CPR. Allowances are already factored into the CPR margins.

3.3 Other Design Deviation Effects

CPR is but one aspect of the need for accuracy. There are many other needs as well. Unfortunately, the impact of not meeting these needs is not as easily quantified and assigned a dollar value. These other needs are discussed qualitatively as follows.

If quality is present, it is important to know just how much since it influences U and K to a large degree. Also the relationship between the quality and void fraction is important for determining the swell and shrink during transients and plays a large roll in PHT stability behaviour. The inability of our codes to precisely predict PHT stability behaviour required an expensive preventative plant modification.

The transient behaviour is important because flow, temperature and pressure swings can be damaging to the components. Accurate models of the system are required so that detailed analysis of normal and abnormal events of plant operation can be analyzed and accounted for in the design of the plant. The accuracy required depends on the design margin. Tight margins require high accuracy while crude models will suffice for very robust designs.

The steam generator modelling capabilities should be enhanced. Pressure drops and flow resistances around the recirculation loop are largely unknown. Knowledge of transient behaviour, such as, swell, shrink, recirculation and heat transfer with uncovered tubes, is lacking.

For the bleed condenser, verification of the U-tube behaviour and of condensation is needed.

For the pressurizer, data on condensation and insurge and outsurge (pressure and temperature) is needed. The pressurizer behaviour is of prime importance in total plant behaviour and hence this should receive high priority.

Accurate assessments of pressure drops, two-phase flow behaviour, heat transfer details, pump head curves, etc, are required for design. Detailed equations for mass, energy and momentum balances are required throughout the system and they must be solved simultaneously in the steady state and the transient. Better empirical correlations must be found to account for complex processess like pressure drop in pipes under single and two-phase conditions, heat transfer (boiling and non boiling) etc.

The errors introduced into codes by the nodal-link discretization need a more thorough investigation. The discrete modelling of a continuous system affect the propagation of flow and pressure disturbances, the pressure distribution, and the quality distribution.

Piping and vessel heat losses need to be verified.

A comprehensive set of temperatures and pressures and valve positions during transients around the system have never been obtained. Further, valve capacities need to be verified.

3.4 Conclusions

It is concluded that the primary heat transport system is very sensitive to a few key parameters such as ROH pressure, PHT flow, drum pressure and reactor power. These parameters can strongly affect CPR but only two of them, reactor power and PHT flow, are now factored into the CPR margins.

The PHT circuit resistance can be off by 10% and, this error could lead to very substantial flow error and subsequent CPR problems if not accounted for. Since a 2% error in flow is associated with a power derating of 1%, whose cost is $80M, it is certainly desirable to minimize such errors. The present practise of adding a boiler area margin of up to 10% is conservative but costly. Detailed feedback from an operating plant could offer substantial savings.

3.5 Recommendations

The following recommendations are made:

1) In order to increase the chance of obtaining an accurate flow measurement, at least two possible flow measurement devices should be investigated:

    a) ultrasonic clamp-on probes for permanent installation.
    b) pitot probes in the pump flow straightening vanes calibrated at the pump test facility.

2) Upper limits on flow velocities should continue to be investigated.

3) Measurement devices as listed in section 4 should be installed in all stations and the design should be verified during commissioning.

4) Extra allowance in the critical power ratio, CPR, should be given for errors in process conditions. Actual allowances should be set once the station has been commissioned and the actual process conditions are measured. Thus, recommendation (3) is considered essential so that meaningful allowances can be set.

5) Tabulate as-built dimensions during construction (particularly pipe diameters).

4.0 VERIFY - HOW?

Having established why we should verify the design of the Primary Heat Transport System, what aspects are the most important to verify and to what extent verification is necessary, we can now turn to the issue of how we should verify.

In determining how, we must not ignore past experience. Considerable process design verification work has already been done. The recent work includes:

1) In 1972, a comparison of a Pickering load rejection from 75% F.P. with the old SOPHT code was done. It was concluded that better models were needed, especially for the secondary side.

2) In 1974, the new SOPHT code was used to compare with the above data. The boiler correlations still remained a problem. It was recommended that a sensitivity study be included in any particular application to ensure conservative estimates (see References 1 and 2).

3) The Bruce A relief valve opening failure was also addressed in Reference 1.

4) The time to PHT pump rundown for Douglas PT., Pickering A and Bruce A was investigated. There was no documentation.

5) In 1976, a thermosyphoning test on Bruce A was performed. Excellent agreement with SOPHT-B was obtained.

6) Comparison of SOPHT simulations and NPD boiling data.

7) Comparison to bench marks. Four standard problems have been analyzed. SOPHT and FIREBIRD compare as well as other codes but numerical diffusion seems to be a shortcoming, Reference 3.

8) Flow oscillation investigation via the RD-12 loop at WNRE, reference 4.

9) Bruce channel flow verification, reference 5.

Additional work is ongoing or is planned for the near future including:

i) Data collection from operating plants
ii) Data acquisition from the WNRE RD-12 loop
iii) Thermosyphoning using the RD-12 loop.

The above work was and is aimed at solving immediate problems and, is not derived from a comprehensive plan of attack on the verification problem. Such a plan would aid in identifying the needed design verification and provide a comprehensive plan of attack.

In developing a comprehensive verification procedure, we have adopted the philosophy of identifying the major areas. Then proposals are made for each area.

The major areas can be divided into three main headings:

1) Feedback from the plants.
2) Off-site experimental data.
3) Basic code development.

These three areas are discussed in the following.

4.1 Feedback from the Plants

Until now, feedback from the plants has been inadequate, largely due to the conflict in priorities of operations (to produce power) and design and safety (to ensure an adequate next design). Operations cannot afford the time and effort needed to carry out experiments at site or to install instruments and collect data, and rightly so. Because of this conflict of priorities, performing an experiment using an existing plant is, more often than not, doomed to failure. Without proper planning and experimental design at the plant design stage, the best that one can hope for in most cases is a post-mortem, from which usually results only an incomplete data set.

In the next sections, we identify what are our specific data needs and what probes should be included in the plant design if we are to get better data from operating plants.

4.1 Experimental Design

Although a full experimental design is still needed, a preliminary list of requirements can be drawn. In general, probes are needed for flow, pressure and temperature for the primary, secondary and pressure and inventory control systems. Heat flux detectors would also be useful. A computerized data collection and analysis centre on site would be required. To be specific, the following probes are identified:

For flow;

a) Total flow at all pumps, especially the PHT pumps;
b) Inlet and outlet feeders (all);
c) Steam generator downcomers;
d) Steam mains;
e) Risers;

f) S.G. hot leg;
g) PHT surge line;
h) PHT interconnect lines;
i) Relief lines;
j) PIC lines such as reflux, feed, bleed and spray.

For pressure and ΔP:

a) Distribution in outlet feeders;
b) Distribution in PHT main piping, including around the pumps;
c) Pressures in pressurizer, bleed condenser and PIC lines;
d) Steam generator distribution.

For temperature:

a) PHT piping to aid in estimates of heat losses;
b) T_{in} and T_{out} of reactor;
c) Pressurizer, bleed condenser and bleed cooler (T_{in} and T_{out}).

For heat flux:

a) Bleed condenser U-tubes;
b) Steam generator;
c) Piping and vessel walls for heat loss estimates.

For level:

a) Pressurizer;
b) Degasser condenser/bleed condenser;
c) D_2O storage tank;
d) S.G. drum.

Such a comprehensive experiment is not within practical reach. Thus, a "bare bones" experiment is outlined in the next sub-section.

4.1.2 Code Lock-on Procedure

Each separate plant requires a code lock-on procedure to adjust the design data to the as-built parameters. In this way, pump heads, heat transfer areas, etc., are adjusted to model each particular plant. The lock-on procedure begins with steady state measurements at various power levels and terminates with transient measurements. A possible "bare bones" procedure is outlined in Tables 1 and 2 using the CANDU 600 as an example. The procedure is severely hampered by the lack of flow measurements. Table 3 lists the main parameters which can be used for code tuning. Tables 4 and 5 give a comprehensive list of measurements needed for the tests mentioned. This gives some idea of the magnitude of the job of code tuning, the number of variables to record and the importance of coordinated data collection through a data collection system, such as a mini-computer or micro-processor.

4.2 Out-of-Plant Experimental Data

Out-of-plant experiments are needed in addition to the on-site efforts. In general, much experimentation has been done, especially in the field of two phase flow. But little is available for the specific geometrics of our stations.

4.2.1 Specific Needs

Precise, hydraulic resistance data remains ellusive. Hydraulic resistances obtained from various sources in the literature can differ by over 50%. One publication (ref. 6) shows that interference between closely spaced resistances, say two elbows, introduce additional significant errors (up to 100%) if the interference is not accounted for. Uncertainties about hydraulic resistance coupled with little information about pump performance under abnormal operating conditions, means that we cannot accurately predict PHT flow. Nor can we measure flow in the present stations. Head-flow and torque-flow pump curves for forward and reverse flow, braked and free-wheeling conditions are needed. The pump affinity laws used by all present-day codes should be evaluated.

The precise behaviour of the steam generator under steam and feedwater line break conditions is open to speculation.

Which empirical correlations should be used and where? Examples include:

a) Comprehensive heat transfer package;
b) Piping heat losses;
c) Pump heat;
d) Low flow conditions where drift flux and stratification may be important (such as in steam generators);
e) Bubble rise model in two-phase flow (such as in pressurizers and steam drums);
f) Condensation correlations.

4.2.2 Experimental Design

Given the scope of this paper, little can be said about the experiments needed. It is sufficient to say that each area is a study onto itself.

4.3 Basic Code Development

In the past, the development of design tools has been primarily for extending the scope of the code to handle areas such as new plants, and safety studies (ECC, etc.). It is proposed herein that more effort be directed to verification of the existing coding, rather than its extension.

4.3.1 Specific Needs

Some verification work has been done; more is ongoing. More still should be done. The fundamental mass, energy and momentum equations are being looked at but much remains to be done. For instance, due to the discretization process and numerical technique used in codes, momentum flux in the momentum equation is inadequately modelled. The node-link representation needs to be evaluated, as do the representation of density gradients and area changes.

Comparison to other codes and to bench mark problems is still in its infancy. Much work is needed here.

The property routines of the code need to be verified, brought up-to-date and extended.

The returns per dollar are probably greater for this area than for on-site and off-site experimentation.

5.0 CONCLUSIONS

The Primary Heat Transport System flow is identified as a major, if not the major, parameter and it is, simultaneously, the least instrumented parameter in the CANDU stations. The flow plays a major role in governing the pressure distribution, the enthalpies, temperatures and, hence, determines whether two phase flow is present or not. CPR is strongly dependent on flow and hence margin to dryout is affected. The establishment of a precise measure of flow in the PHTS would clear the way for a much improved assessment of virtually all aspects of PHTS process design.

The commissioning procedure proposed for the CANDU 600 is perhaps the best vehicle presently at our disposal to firm up our code predictions. Both laboratory testing and basic code development need to be enhanced to complete the attack on uncertainties in flow and associated PHT parameters.

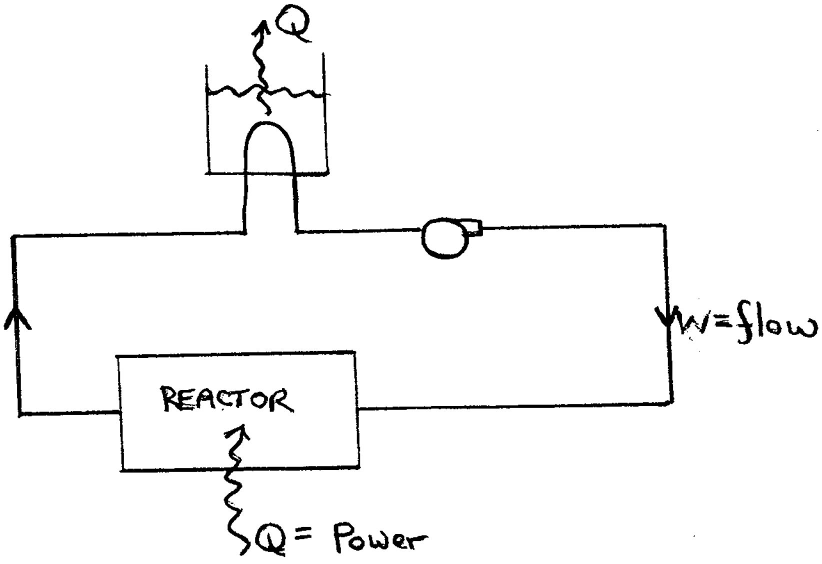

FIG. 1 PHTS SCHEMATIC

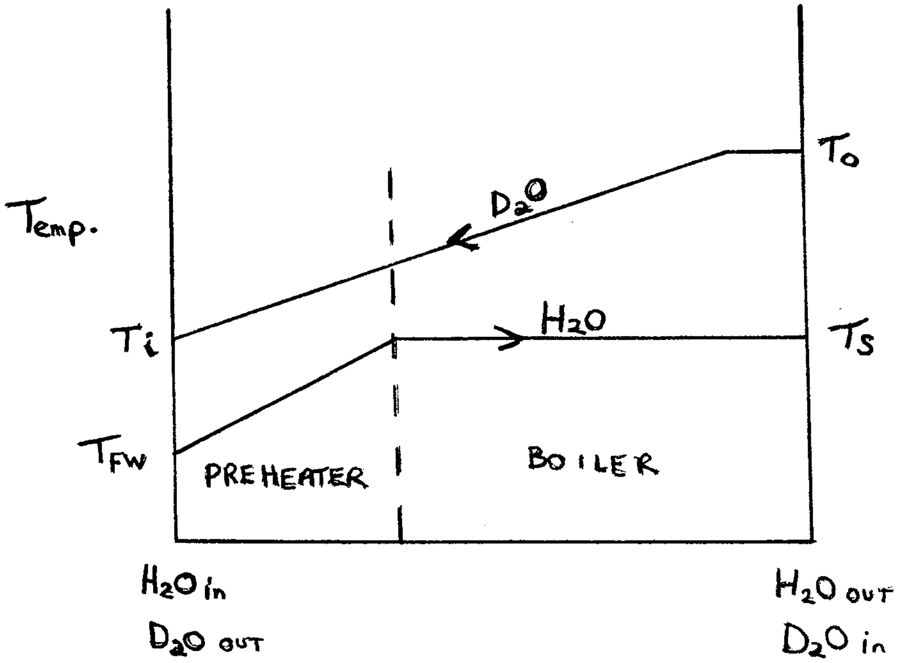

FIG. 2 STEAM GENERATOR TEMP. DISTRIBUTION

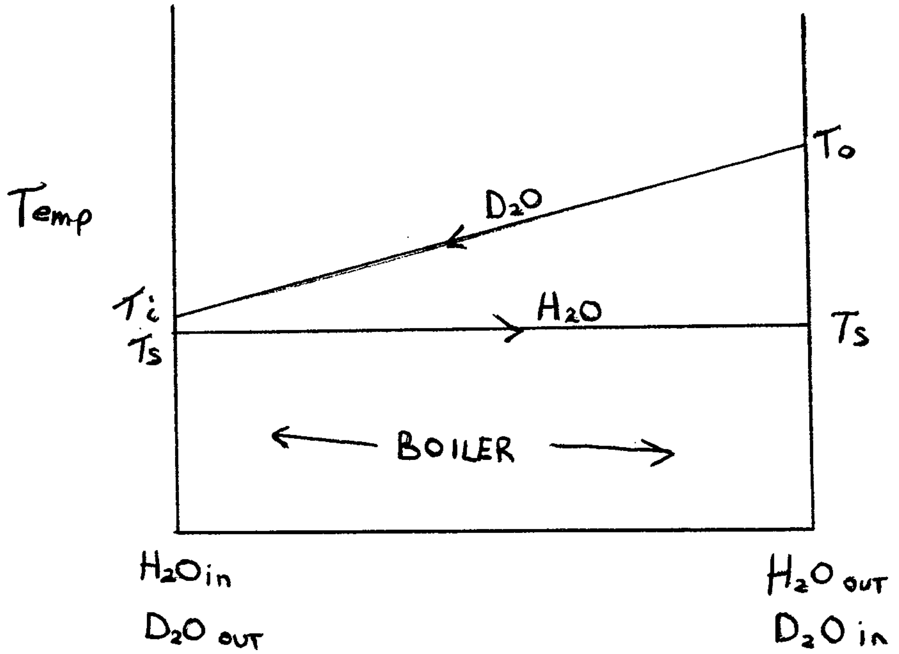

FIG. 3 SIMPLIFIED STEAM GENERATOR TEMP. DISTRIBUTION

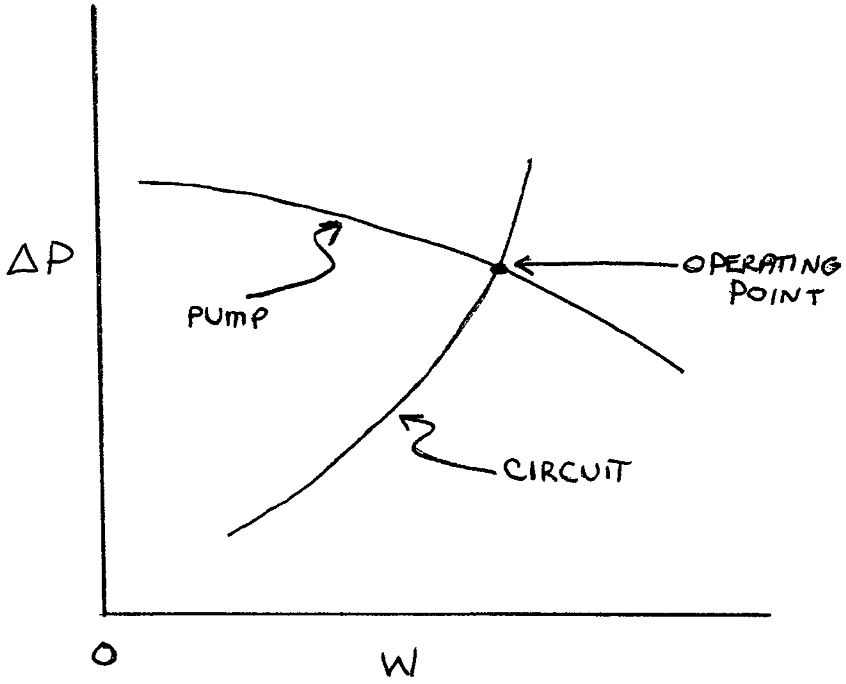

FIG. 4 CIRCUIT LOSSES AND PUMP HEAD VS. FLOW

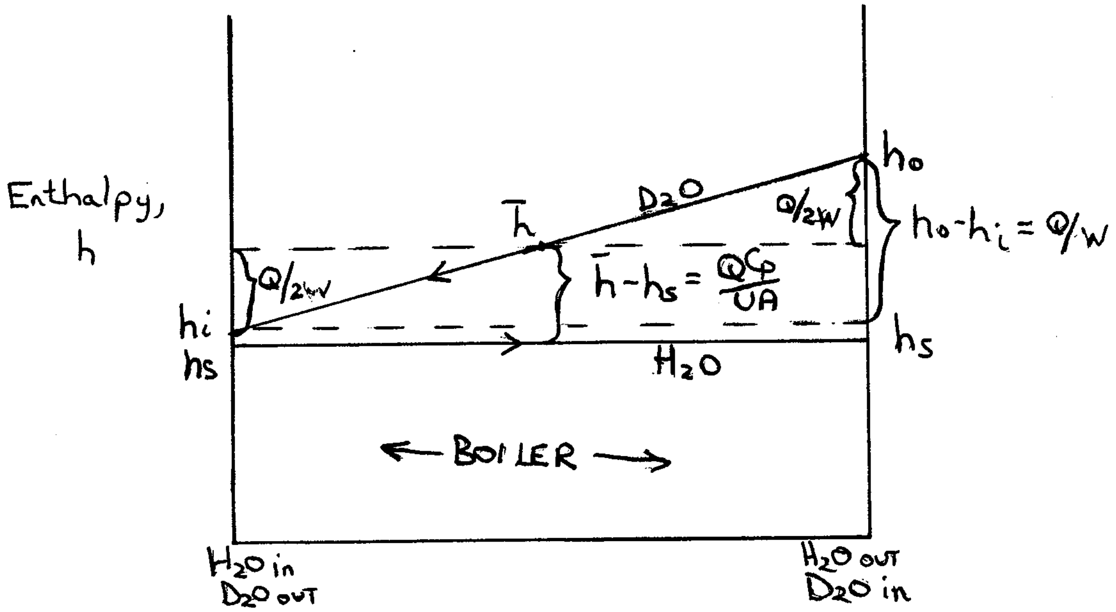

FIG. 5 ENTHALPY VARIATIONS

Table 1

Code Lock-on Procedure for CANDU 600

TEST	MEASURED VARIABLES	ANALYSIS PROCEDURE
0% F.P. Cold and Hot (Phase A or B commissioning results STEADY STATE)	PHT Temp, Flow (12 ch) ΔP_{pump}, $\Delta P_{RIH-ROH}$ (LONG SCAN RATE ACCEPTABLE)	1. Run NUCIRC at PHT temp, set $\Delta P_{RIH-ROH}$ to measured values Compare calculated flow to 12 measured flows. Adjust single phase resistance correlations to match flows. Infer core flow by ITYPE=4 run on NUCIRC using adjusted resistance. This gives one point on pump curve. Compare to manufacturer's curve. Keep curve shape but adjust magnitude if significantly different. May have to adjust external circuit resistances. 2. Run SOPHT at PHT temp. Compare flows, pump head and circuit ΔP's with data. Adjust resistances and pump curve magnitude to suit.
0% F.P. Phase A or B 1 pump/loop STEADY STATE	As per above	1. As per above
0<Power<75% eg. 5% 10% 25% 50% 75% (STEADY STATE)	PHT TEMP at RIH & ROH + 380 outlet feeders PHT FLOW (12 ch) ΔP_{pump}, $\Delta P_{RIH-ROH}$ Secondary Side Conditions Power Map, Total Power (LONG SCAN RATE ACCEPTABLE)	1. Run NUCIRC for 12 channels to compare flows for given $\Delta P_{RIH-ROH}$. Use power map.* Compare flows and ΔT with data. Adjust power map to suit 2. Run NUCIRC for rest of channels (ITYPE=2) and compare to channel flows calculated from power map* and ΔT's. Should compare within error bounds. 3. Run NUCIRC (ITYPE=4) to predict temperature. Adjust H.T. coeff. to suit. Check flows and ΔP's. 4. Run SOPHT to predict temperature. Adjust H.T. coeff. to suit. Check flows and ΔP's.

* Power map should be compared to secondary side heat balance for calibration purposes. Because of large secondary side flow measurement errors at low flows (i.e., low power), secondary side heat balances are not accurate below 50% F.P. Thus, power map calibration is not done at low powers and code readjustment may have to be done after powers greater than 50% are achieved.

Table 2

Code Lock-on Procedure for CANDU 600

TEST	MEASURED VARIABLES	ANALYSIS PROCEDURE
OOV . . 100% F.P. (STEADY STATE)	PHT TEMP at RIH & ROH and 380 outlet feeders PHT FLOW (12 ch) ΔP_{pump}, $\Delta P_{RIH-ROH}$ Pressurizer Pressure and level Secondary Side Conditions Power Map, Total Power (LONG SCAN RATE ACCEPTABLE)	5. Predict onset of void (OOV) using SOPHT with NUCIRC backup.** For given power (calibrated from secondary side measurements), can predict quality, flows (primary and secondary), RIH temp, ΔP_{H-H}, etc. Compare with, data. Cannot measure quality so if discrepancy exists, then don't know if cause is wrong quality, wrong two-phase pressure drop correlations or wrong heat transfer correlations. Iteration on tuning may be required.
TRANSIENTS		Many transients can be used to correlate to the codes. Below are two examples.
2 PUMP TRIP (one per loop)	PHT TEMP, Flow (12 ch) ΔP_{pump}, $\Delta P_{RIH-ROH}$ Power Map, Secondary Side parameters (2 SECOND SCAN RATE)	Compare trands with SOPHT. Adjust pump rundown curve, $\alpha = f_n(x)$, etc. as necessary.
LOAD REJECT	as per 2 PUMP TRIP	Compare with SOPHT and modify as indicated. In particular look at pressurizer response. This is a good check on the adiabatic compression model. May have to adjust boiler shrink to get proper PHT pressure.

** If prediction of OOV is $>$100% FP or if tests show no boiling at 100% FP, determine PHT pressure reduction to give 4% quality at 100% power and commence test from new OOV position.

Table 3 Tuning Parameters

TUNING PARAMETERS/MODELS

1. Pump Head }
   Pump Flow } Nominal values at 100% F.P.
   Pump Curve Variation as f_n (flow) or shape of curve

2. Resistance Losses around Loop - single phase
   - 2 ØΔP correlations

3. Boiler Heat Transfer Coefficient - Correlation (Variational Response)
   - Magnitude at 100% F.P. Clean
   - Crud Factor

4. Void vs Quality Relationship

5. Nodalization

6. Pressurizer Model

7. Valves - Capacity and Stroking Time

8. Stored Heat

9. Parallel Channel Modelling

10. PHT Heat Losses - Pump Heat

Table 4 List of Measurements

COMPONENT	PARAMETER	INST.NUMBER	0%FP	Up to 75%FP	00V → 100%FP	2-P TRIP & LOAD REJECT
PHT-ROH #1	Temperature	63312-T5	X	X	X	X
#3		63312-T6	X	X	X	X
#5		63312-T7	X	X	X	X
#7		63312-T8	X	X	X	X
PHT-ROH #1	Pressure	63312-P35	X	X	X	X
#3		63312-P36	X	X	X	X
#5		63312-P37	X	X	X	X
#7		63312-P38	X	X	X	X
PHT-RIH #2	Temperature	63312-T27	X	X	X	X
#4		63312-T28	X	X	X	X
#6		63312-T29	X	X	X	X
#8		63312-T30	X	X	X	X
PHT-RIH #2	Pressure	63312-P13	X	X	X	X
#4		63312-P14	X	X	X	X
#6		63312-P15	X	X	X	X
#8		63312-P16	X	X	X	X
PHT-Pump #1	Suction Pressure	63312-P9	X	X	X	X
#2		63312-P10	X	X	X	X
#3		63312-P11	X	X	X	X
#4		63312-P12	X	X	X	X
PHT-Pump #1	Head	63312-(P13-P9)	X	X	X	X
#2		63312-(P14-P10)	X	X	X	X
#3		63312-(P15-P11)	X	X	X	X
#4		63312-(P16-P12)	X	X	X	X
PHT-HD2-HD3	Pressure Drop	63312-(P13-P36)	X	X	X	X
HD4-HD1		63312-(P14-P35)	X	X	X	X
HD6-HD7		63312-(P15-P38)	X	X	X	X
HD8-HD5		63312-(P16-P37)	X	X	X	X
PHT-Outlet Feeders (380)	Temperature	63102-T1 to T380		X	X	
PHT-Instrumented Channels	Flowrate	68234-F1 to F4, D, E & F	X	X	X	X
PIC-3331-P1	Suction Pressure, Discharge	63331-P17	X	X	X	
	Pressure	63331-P3	X	X	X	
3331-P2	Suction Pressure, Discharge	63331-P18	X	X	X	
	Pressure	63331-P4	X	X	X	

Table 4 List of Measurements(Cont'd)

COMPONENT	PARAMETER	INST.NUMBER	0%FP	Up to 75%FP	00V → 100%FP	2-P TRIP & LOAD REJECT
PIC Feed Flowrate	Flowrate	63331-F10	X	X	X	X
PIC-Bleed Flowrate	Flowrate	63331-F20	X	X	X	X
		63331-F19	X	X	X	X
PIC-Pressurizer	Pressure	63332-P29		X	X	X
	Temperature	63332-T16		X	X	X
	Level	63332-L13		X	X	X
PIC-Degasser Condenser	Pressure	63332-P25 or 63332-P24		X	X	X
	Temperature	63332-T27 or 63332-T4		X	X	X
	Level	63332-L8 or 63332-L15		X	X	X
Steam Generator	Feedwater Temperature			X	X	X
	Feedwater Flowrate			X	X	X
	Steam Drum Pressure			X	X	X
	Steam Flowrate			X	X	X
	Drum Level			X	X	X
	Indicator for Blowdown			X	X	X
	Reheater Drain Temperature			X	X	X
	Reheater Drain Flowrate			X	X	X
Reactor Core	Reactor Power Map			X	X	
Feeder Cabinet	Ambient Temperature		X	X	X	
Reactor Outlet Headers	ROH-ROH Pressure Drops		X	X	X	X
Regulating/Safety Indicators	LRV	OPEN/CLOSE				X
	High Pressure Trip	ON/OFF				X
	Low Flow Trip	ON/OFF				X
	SDS1	ON/OFF				X
	SDS2	ON/OFF				X
Scan Rate			Long	Long	Long	2 S.
Long Term Storage			X	X	X	X
Type of Test: STEADY STATE/TRANSIENT			S.S.	S.S.	S.S.	T.
Length of Test			As Req'd for SS	As Req'd for SS	As Req'd for SS	120 s.

REFERENCES

1. SOPHT - A computer Model for CANDU-PHWR Heat Transport Networks and Their Control, C.Y.F. Chang and J. Skears, Nuclear Technology, Volume 35, page 591, October 1977.

2. The SOPHT Program and its Application, Y.F. Chang, Proceedings of the 1975 Simulation Symposium on Reactor Dynamics and Plant Control, May 26-27, 1975, available as CRNL-1369, October 1975.

3. Solutions to Benchmark Injection Problems with the Computer Codes FIREBIRD and NAIAD, N.J. Spinks, et al, Topical Meeting on Numerical Benchmark Techniques for Transient Two-Phase Flow, Paris, France, June 16, 1978.

4. Two Phase Flow Stability Tests in RD-12, F.W. Barclay et al, 8th Simulation Symposium on Reactor Dynamics and Plant Control, University of Toronto, March 17 and 18th, 1981.

5. Verification of Predictions of Bruce NGSA Reactor Channel Flows, J.A. Lorenc, H.G. Hunt, 8th Simulation Symposion on Reactor Dynamics and Plant Control, University of Toronto, March 17 and 18th, 1981.

6. Donald S. Miller, "Internal Flow - A Guide to Losses in Pipe and Duct Systems", British Hydromechanics Research Association, Cranfield, Bedford, England, 1971.