# Modelling Of A Pressure Gradient Across A CANDU Reactor Inlet Header

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## Abstract

In nuclear reactor safety analysis, the behavior of a postulated accident is modeled using computer codes which simulate the behaviour of the Primary Heat Transport System (HTS) under postulated accident scenarios. For simulations of the entire heat transport system, two-fluid formulations are used to predict the flow behavior during the transients with each HTS component represented as a module. Modelling of each component of the HTS as a one-dimensional module may cause some uncertainty due to three-dimensional flow and temperature effects within that component. An example of this would be a pressure gradient across the Reactor Inlet Header (RIH) in a CANDU reactor, which distribute coolant to a number of separate fuel channels. Typically there are four RIH in a CANDU reactor, each distributing the flow of heavy water into about one quarter of the fuel channels. In some CANDU designs, the flow to each RIH is provided by any 3 of 4 pumps within that quadrant (i.e., one pump in each quadrant is on standby at any given time). Each pump is connected to the RIH at different locations along its axis. This geometrical arrangement combined with the specific pump placed out of service, leads to pressure and flow differences along the header, which in turn may affect the flow characteristics of heavy water in a fuel channel. This paper outlines the empirical based methodology used to improve the one-dimensional predictions, and the validation of this model against station data.

## 1. Introduction

A simplified schematic of the Primary Heat Transport System (HTS) is shown here as Figure 1.

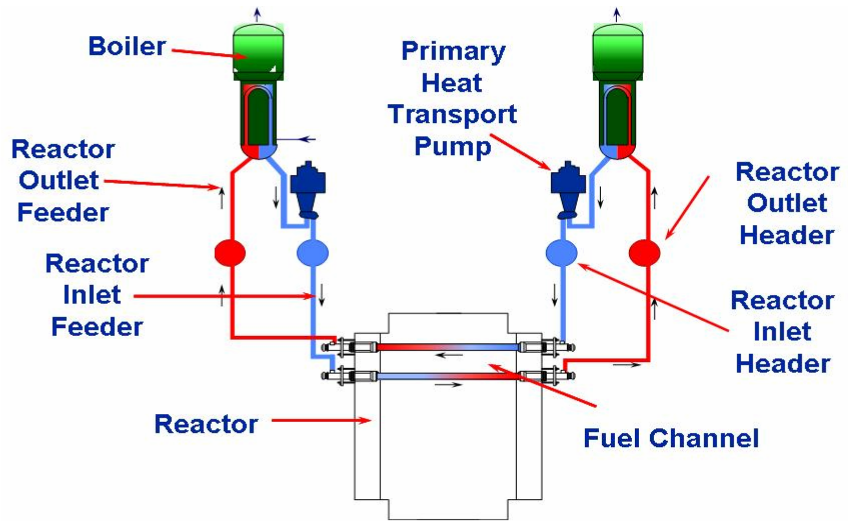


Figure 1 CANDU Heat Transport System

In nuclear safety analysis, the computer code TUF (Two Unequal Fluids) [1] simulates the behaviour of the HTS under postulated accident scenarios. TUF models each component of the HTS as a one-dimensional module however; there are three-dimensional flow and temperature effects within that component which will not be accounted for using this model. An example of this would be a pressure gradient across the RIH in a CANDU reactor, which distribute coolant to a number of separate fuel channels. Figure 2 is a representation of a typical RIH.

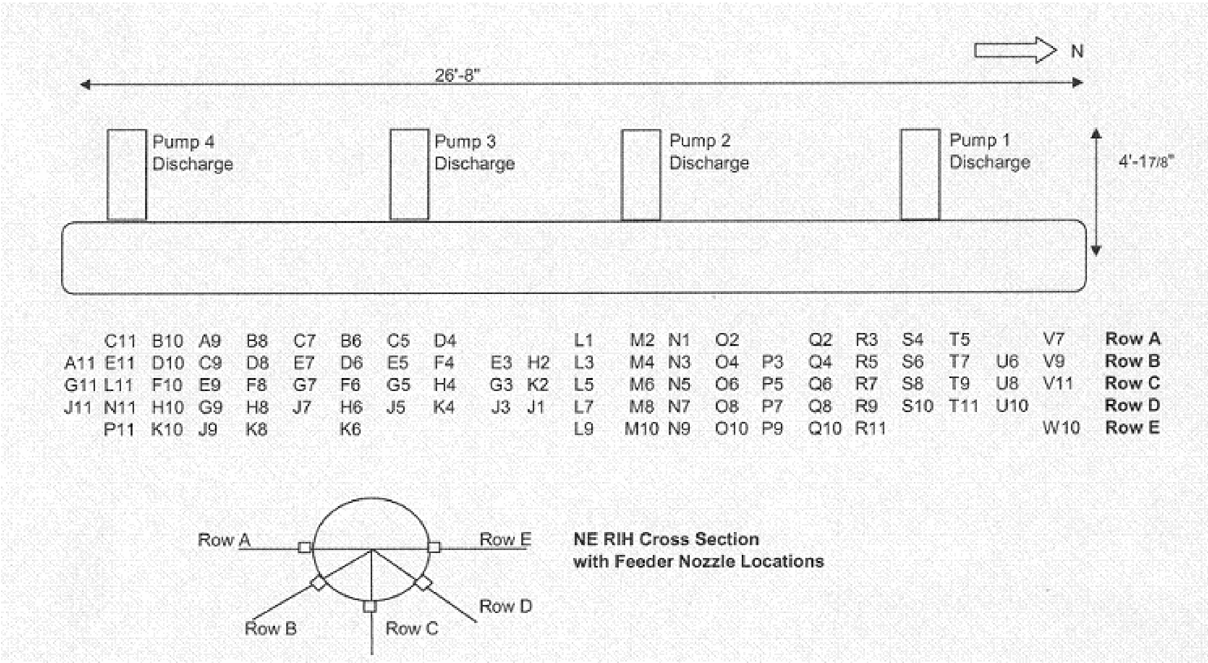


Figure 2 Heat Transport System NE Reactor Inlet Header (RIH)

Typically there are four RIH in a CANDU reactor, each distributing the flow of heavy water into one quarter of the fuel channels. As shown in Figure 2, the flow to each RIH is provided by any 3 of 4 pumps within that quadrant (i.e., one pump in each quadrant is on standby at any given time) for a Pickering B reactor. Each pump is connected to the RIH at different locations along its axis. This geometrical arrangement combined with the specific pump placed out of service, leads to a pressure and flow distribution along the header, which in turn may affect the flow distribution to each fuel channel.

A typical 1-dimensional modular TUF model is represented in Figure 3.

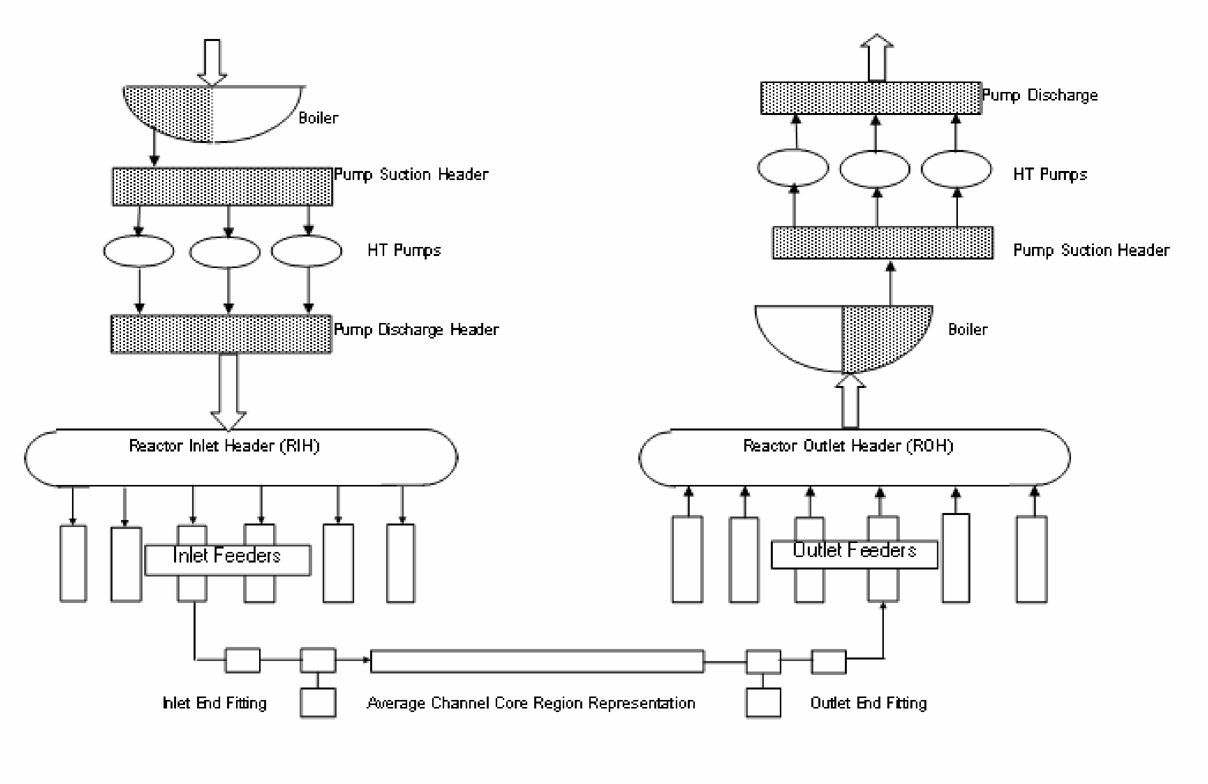


Figure 3 Typical TUF Representation of a Single Core Pass

This paper describes the development, implementation, and testing of a TUF inlet header model which attempts to model the pressure gradients along each header. The following were the main steps in the model development and testing:

- Collection of station data (Plant Information (PI) data, and pump configuration data),
- Data processing to determine the model requirements,
- Collection of design data (header drawings and axial location of fuel channels),
- Development of a TUF input model capable of predicting the header axial gradients
- Validation of the model against operating data (i.e., 3 of 4 pumps running per quadrant).

The following sections describe in more detail each of these steps.

## 2. Station data collection

To determine the accuracy of the model, it was required to collect station data for comparisons against simulations. Primarily this included review of station maintenance logs to determine pump configurations at each point in time and extraction of flow measurements. Flow measurements for Fully INstrumented fuel CHannels (FINCH) before and after a pump configuration change were required for comparison purposes. For a Pickering B reactor, there are 22 FINCHs located throughout the core, as shown in Figure 4 below.

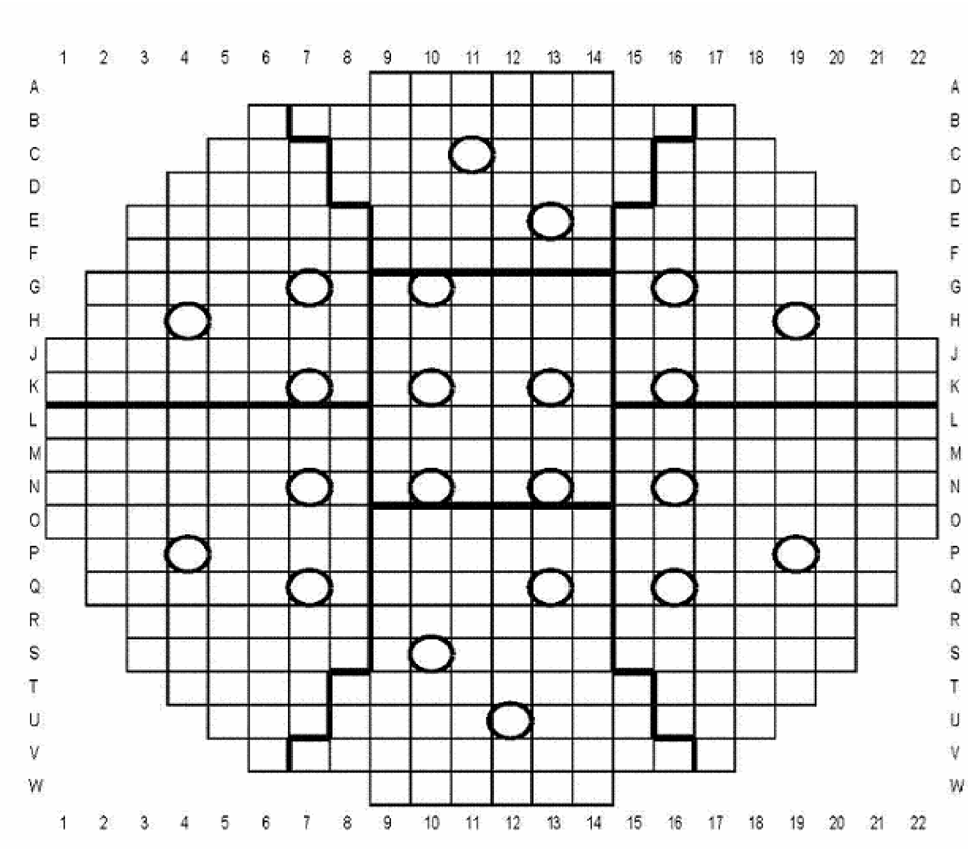


Figure 4 Pickering B Reactor Core Map Indicating FINCH locations

## 2.1 Pump configuration data

Pump Configuration data was extracted from operator logs and an Equipment Status List Database. The Heat Transport pump configurations for four units (Pickering NGS B Units 5-8) between January 2001 and December 2003 were extracted. The data collection was restricted to periods of time in which the reactor was at full power operation. The pump configurations over a three-year period are summarized in Table 1.

| Unit # | Standby Pump Change |
|---|---|
| 5 | P3 -> P2<br>P7 -> P8, P11 -> P10, P16 -> P13<br>P2 -> P3 |
| 6 | P11 -> P12<br>P12 -> P9 |
| 7 | P9 -> P12<br>P12 -> P10<br>P13 -> P15 |
| 8 | Data Not Available |

Table 1 Pump Configuration Changes

## 2.2 Plant data

Historical station data such as RIH temperatures and pressures, FINCH flows etc. are collected in the Plant Information (PI) system. FINCH flows (% of design flow), before and after a pump configuration change, were collected and trended. Figure 5 shows FINCH flow trends from Pickering B Unit 5 data, for a scenario in which the stand-by pump was changed from P16 to P13 during an outage.

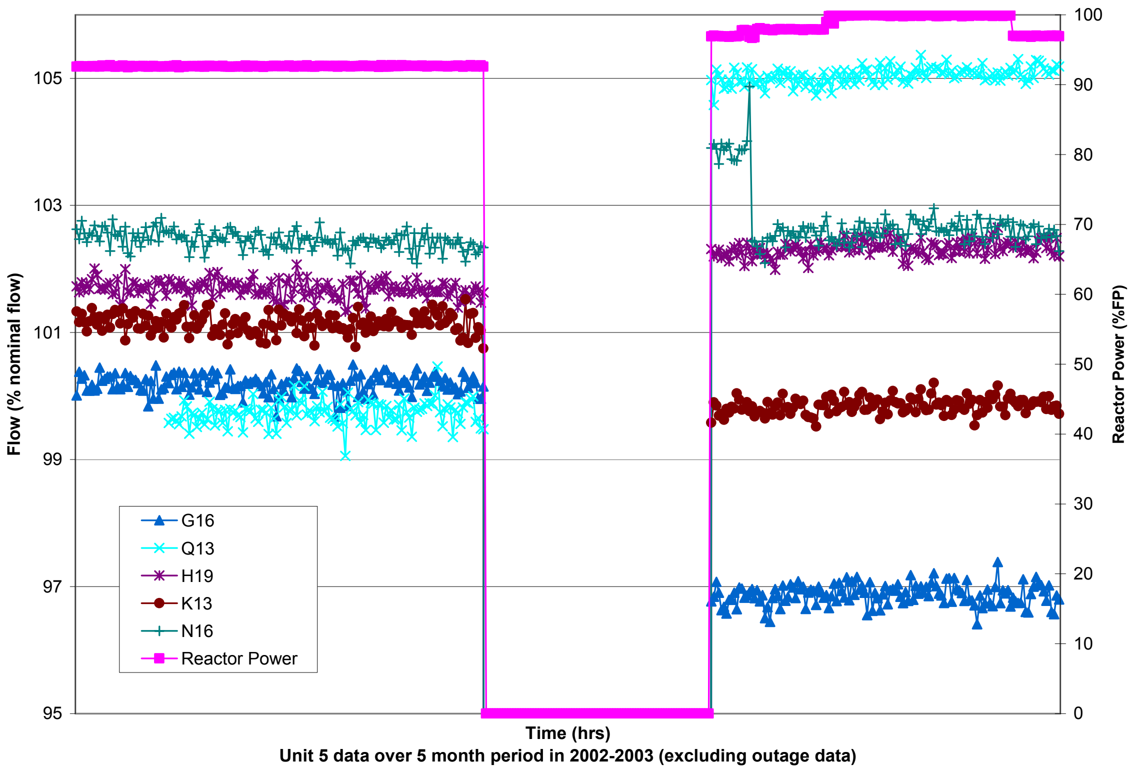


Figure 5 FINCH Flows Before and After a Pump Configuration Change for Pickering NGS B Unit 5

FINCH flow average values before and after a pump configuration changes are calculated and compared. The averages were calculated from hourly measurements for four to six days before and after the pump change. All units demonstrated variation in flows based on pump configuration changes. Table 2 contains sample data for the pump change in Unit 5 shown in Figure 5.

| FINCH Channel | Flow with P16 on Standby (% of design flow) | Flow with P13 on Standby (% of design flow) | Flow Difference (%) |
|---|---|---|---|
| G16 | 100.19 | 96.87 | -3.32 |
| Q13 | 99.73 | 105.05 | 5.32 |
| H19 | 101.69 | 102.32 | 0.63 |
| K13 | 101.14 | 99.85 | -1.29 |
| N16 | 102.45 | 102.73 | 0.28 |

Table 2 FINCH Flow Data for a Pump Configuration Change on the SW RIH

The key parameter is the percent difference in flow between channels from one pump configuration to another. Using the values shown in Table 2, the following trend information is apparent. For FINCH channel Q13, a 5.32% flow increase resulted from the change in stand-by Heat Transport pump from P16 (pump located at the rightmost end of header, corresponding to Pump 1 in Figure 2) to P13 (pump located at the leftmost end of header, corresponding to Pump 4 in Figure 2). When P16 is on standby, there is a pressure gradient in the inlet header that is higher on the left, so the channel flows from the left side of the RIH will be higher than for the channels on the right hand side. Similarly, when P13 is on standby, the pressure is higher on the right. The effect on pressure, and therefore flow gradient, is more pronounced when Heat Transport pump duty is switched between Pumps P13 and P16. However, even with more centrally placed pumps along the RIH on standby, the effect remains. Examining the data for all the units shows consistent data trends.

## 3. Model design

The typical model used in Safety Analysis was modified between the pump suction header and the core in order to capture the reactor inlet header gradient effects. This revised model included a more detailed representation of the 4 pumps in the affected quadrant as well as additional nodes to represent the axial distribution of pressure along the RIH. The revised model is shown in Figure 6 below.

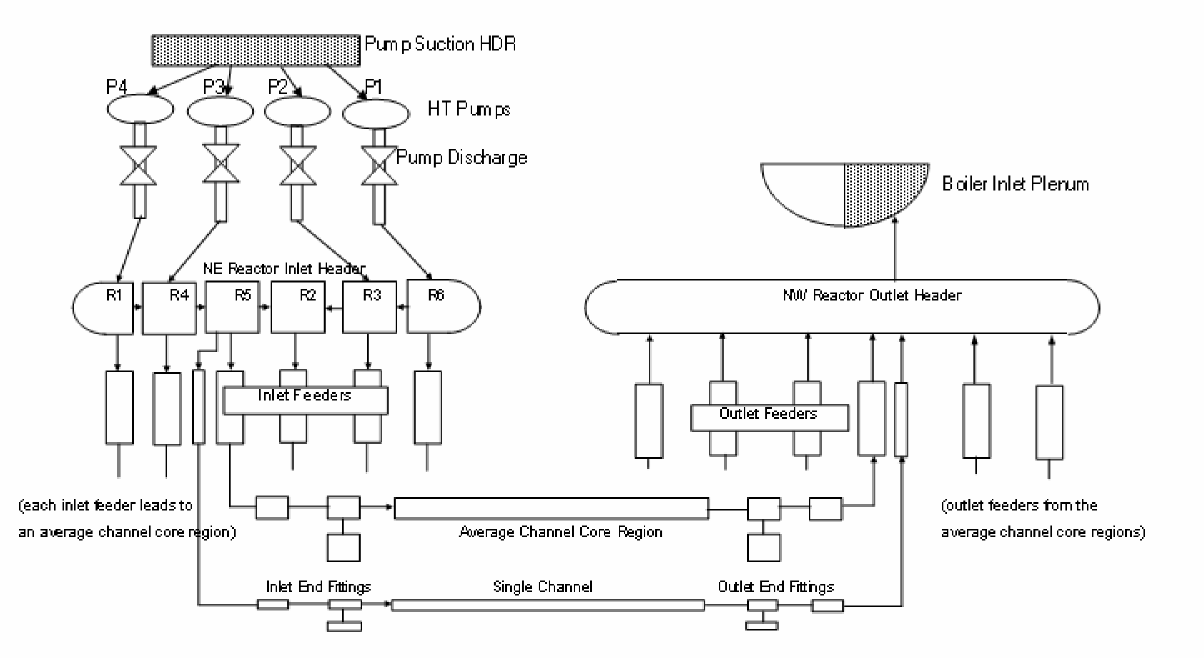


Figure 6 Detailed RIH Header Model, NE Core Pass

Starting with the North East Pump Suction Header (PSH), four Heat Transport pump links join the PSH to the corresponding four segments of the Pump Discharge Header (PDH). Only three of the four Heat Transport pumps will be providing flow during nominal operations. The PDH has four flow links into four (out of 6) RIH nodes. The North East RIH is represented by six nodes based on the six channel core regions typically used in modelling for safety analysis. Each inlet header region is linked to an inlet feeder, which in turn is linked to the inlet end fittings and finally to either a core region (represented as a region average channel) or a single channel. After the channel, the flow passes through the outlet end fittings, to the outlet feeders, and into the ROH. The flow from the ROH continues into the North West Boiler Inlet Plenum, and from there into the North West PSH, following a similar flow path through the North West core pass. It should be noted here that this model is not just a Header to Header model as is conventional. It is from Pump Suction Header to Boiler Inlet Plenum. It was required to place the boundary conditions upstream of the RIH in order to capture the effect of the pump configuration.

The structure of this model remains the same for each simulated case with the exception of the pump configuration (depending on which pump is in stand-by mode), and the single channel being modelled.

### 3.1 Heat transport pumps

Using a baseline data set, modifications (in the North East and North West core passes only) were made to include three (out of four) Heat Transport pumps discharging into a nodalized inlet header of 6 regions. The current pump data from the baseline set was used to provide the individual heat transport pump properties such as flow, torque, etc.

Three out of four pumps are in operation at all times in each core pass as per the nominal operating conditions. All flow through a stand-by pump is prevented by isolation valves. A Heat Transport pump can be put in standby mode in the revised model by increasing the frictional coefficient to a value which prohibits flow through that link.

The pump links are from the PSH to four pump discharge header regions which were based on the baseline pump discharge module data. The volume and length of the four pump discharge header regions were assumed to be approximately equal.

The four pump discharge header regions are linked to four (out of six) RIH regions based on physical pump inlet location along the header. The linkage is based on the physical layout of the pump discharge lines and their connection to the inlet header.

### 3.2 Reactor inlet header regions

The total volume and length of the six header regions are derived from the original RIH module data available in the baseline data set and are assumed to be approximately equal.

The RIH module was segmented into six nodes which correspond to the six regions previously established in the data set. Based on the connectivity of each inlet feeder along the header (i.e. its physical location of attachment along the header), each inlet feeder is assigned to one of the six header regions. The six header regions themselves are linked together with a flow diameter equivalent to the RIH diameter with a loss factor applied to flow between adjacent regions. Figure 7 shows the nodalization of the North East RIH (Header 3) and the inlet feeders for the 6 regions as per the engineering drawing, Figure 2.

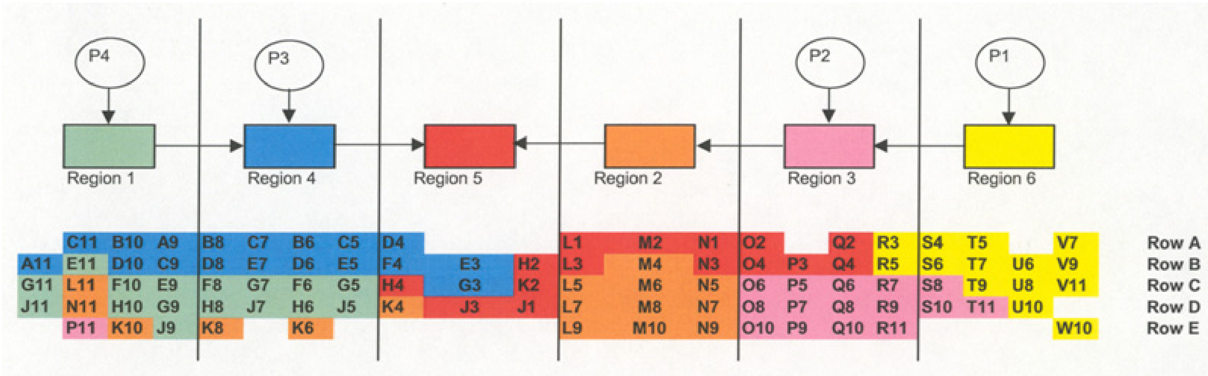


Figure 7 Pickering NGS B NE RIH Regionalized by the Existing TUF Average Channel Core Regions

## 4. Methodology

The methodology to implement and validate this model can be summarized as follows:

1. Perform a full HTS circuit reference simulation to obtain boundary conditions (Pump Suction Header and Boiler Inlet Plenum)

2. Segment the RIH according to region average channels and implement in TUF input data (this stage includes the segmentation of the pump discharge header and the addition of more pump links)

3. Perform a steady state simulation with the detailed header model for a particular single channel in a particular pump configuration (e.g. C11, Pump 3 on Stand-by).

4. Simulate a 100s zero change transient of this steady state and extract the resulting flow in the single channel at 100s.

5. The steady state and 100s zero change transient are simulated again for the same single channel in a different pump configuration (e.g. C11, Pump 2 on Stand-by) to determine the single channel flow value at 100s.

6. The resulting channel flows at 100s can then be compared to obtain a percent difference which can be compared to the station data.

7. Adjust frictional loss coefficient, K, between the RIH regions as required to match channel flow predictions to station data and repeat simulations for one set of data. The same loss coefficient is applied to each link between the regions.

8. Validate subsequent sets of data against the frictional loss coefficient determined in the previous step.

### 4.1 Simulated cases

In order to validate the model against station data, a number of pump configurations were analyzed. Based on the Pickering B pump configuration data, and the corresponding FINCH flow data (given in % of design flow), the following sets of cases were simulated for comparison to station data:

1. Unit 5 - 3312-HD3 (RIH3 North East Core Pass), Heat Transport stand-by pump switches from P3 to P2, single channels H04, C11, G07, K10, N07 and S10.

2. Unit 5 - 3312-HD4 (RIH4 North West Core Pass), Heat Transport stand-by pump switches from P7 to P8, single channels P04, Q07, G10, K07, and N10.

3. Unit 5 - 3312-HD10 (RIH10 South West Core Pass), Heat Transport stand-by pump switches from P16 to P13, single channels G16, Q13, H19, K13, and N16.

4. Unit 6 – 3312-HD9 (RIH9 SE Core Pass), HT stand-by pump switches from P11 to P12, single channels E13, N13, Q16, and U12

5. Unit 7 – 3312-HD9 (RIH9 SE Core Pass), HT stand-by pump switches from P9 to P12, single channels E13, N13, Q16, and U12

It should be noted that the model was set-up for the North East Core pass only (Set 1 above). For Sets 2, 3, 4, and 5 (involving other core passes), equivalent cases were run based on core symmetry. For example, instead of HD4 – P7 to P8 switch, Single Channel Q07, an equivalent case was run, HD3 – P3 to P4 switch, Single Channel Q06 (mirror image channel to Q07).

## 4.2 Loss factor between RIH regions

The flow redistribution due to change in pump configuration creates an axial pressure gradient along the reactor inlet header. This gradient-induced pressure drop is introduced in the detailed RIH model through an increase in the loss coefficient K along the header (axially), and implemented in the links between header regions. In order to simulate the pressure gradient along the header, the loss factor in the links between the RIH segments was optimized based on the station data available. Although this loss factor is prescribed by empirical methods, an attempt was made to determine the theoretical range of values this factor could attain.

To determine the frictional loss co-efficient to implement in the links between header regions the following calculations were required. The main assumptions utilized for the derivation of the frictional coefficient K, are as follows:

- The geometrical information, i.e. friction factor-f, flow length-L, diameter-D and area-A are based on an existing single channel TUF data set (Channel S10) and the base line TUF data set for the RIH.
- The S10 channel flow, *w*, is assumed to be 23.4 kg/s.
- The S10 channel flow is reduced by ~2 % due to change in HT pump configuration (based on the PI data for channel S10, with HT pump P2, P3 on standby respectively).
- The axial flow in the RIH is assumed to have average value between 600 kg/s and 300 kg/s. This assumption is an approximation based on current TUF calculations, and is primarily a function of the pump configuration.

Using Bernoulli's Equation in the form,

$$\Delta P = (\mathrm{K} + \mathrm{f}\frac{\mathrm{L}}{\mathrm{D}})\frac{w^2}{2A^2\rho} \quad (1)$$

We can express the pressure drop across the channel S10 (from RIH to ROH) as,

$$P_{RIH} - P_{ROH} = \sum_{i=1}^{n} (\mathrm{K_i} + \mathrm{f}\frac{\mathrm{L_i}}{\mathrm{D_i}})\frac{w_i^2}{2A_i^2\rho} \quad (2)$$

where n represents the number of links from RIH to ROH (e.g. inlet feeders, end fittings, channel, etc.).

If we assign Pump 2 on stand-by as scenario 1, and Pump 3 on stand-by as scenario 2, holding the $P_{ROH}$ constant we could combine the above equation applied to both scenarios to obtain the following formula:

$$P_{RIH1} - P_{RIH2} = \sum_{i=1}^{n} \frac{K_i + f\frac{L_i}{D_i}}{2A_i^{\,2}\rho}(\mathrm{w}_1^2 - w_2^2) = K_{tc}(\mathrm{w}_1^2 - w_2^2) \quad (3)$$

where the link variables have been combined into the constant $K_{tc}$ representing the total loss across the channel from RIH to ROH.

From the PI data, we know that the flow drops by 2% in channel S10 when going from pump 3 to pump 2 on stand-by. This implies that, going from pump 2 to pump 3 on stand-by will increase the flow by 2% which can be expressed as, $w_1=1.02w_2$.
We can now rewrite the equation as:

$$\Delta P = P_{RIH1} - P_{RIH2} = 0.04K_{tc}w_2^2 \quad (4)$$

$K_{tc}$ is calculated for each portion of the channel (i.e. inlet feeders, inlet and outlet end fittings, the channel, and outlet feeders) using the S10 single channel data to yield a final value for ΔP. This value represents the change in RIH pressure at the S10 feeder location, attributed to the change in pump configuration.

To calculate the overall K value across the header, we can use the ΔP value calculated above in the following equation,

$$\Delta P = P_{RIH1} - P_{RIH2} = (\frac{K + f\frac{L_h}{D_h}}{2A_h^{\,2}\rho})\mathrm{w}_\mathrm{h}^2 = Kw_h^2 \quad (5)$$

where K now represents the total loss along the header. Using the RIH values for flow length ($L_h$), diameter ($D_h$), area ($A_h$), etc. from the baseline dataset and a range of header flow values, $w_h$, of 300 to 600 kg/s, K is calculated in the range of 1.18 to 5.97 Pa/Pa. The total divided equally between the four RIH links gives a range of 0.29 to 1.49 Pa/Pa.

This range of values is dependant on the axial header flow which changes from region to region depending on pump configuration. Simulations were then performed over this range of modelling coefficients for all subsets of pump configuration and an optimum value of 0.85 best matched the station data results.

## 5. Results

Table 3 shows the TUF model results compared to the station data using a header region link loss factor of 0.85 Pa/Pa.

| Unit # | Standby Pump Change | FINCH ID* | Station Data Flow Change (%) | Model Prediction Flow Change (%) | % Difference |
|---|---|---|---|---|---|
| 5 | P3 -> P2 | H04 | 0.49 | 0.40 | 0.09 |
| | | C11 | 1.30 | 1.99 | 0.69 |
| | | G07 | 1.25 | 2.10 | 0.85 |
| | | K10 | 1.25 | 2.00 | 0.75 |
| | | N07 | -0.57 | -0.46 | 0.11 |
| | | S10 | -1.90 | -2.05 | 0.15 |
| | | | **Average Difference** | | **0.44 %** |
| 5 | P3 -> P4 | P03 | -1.11 | 0.14 | 1.25 |
| | | Q06 | 0.61 | 0.14 | 0.47 |
| | | H10 | -0.61 | -0.87 | 0.26 |
| | | K06 | -1.58 | 0.19 | 1.77 |
| | | N09 | 0.04 | 0.18 | 0.14 |
| | | | **Average Difference** | | **0.78%** |
| 5 | P1 -> P4 | G07 | -3.32 | -2.11 | 1.21 |
| | | Q10 | 5.32 | 2.08 | 3.24 |
| | | H04 | 0.63 | -0.41 | 1.04 |
| | | K10 | -1.29 | -3.09 | 1.80 |
| | | N07 | 0.28 | 0.41 | 0.13 |
| | | | **Average Difference** | | **1.48%** |
| 6 | P2 -> P1 | E10 | 0.97 | 0.15 | 0.82 |
| | | N09 | 1.28 | 0.22 | 1.06 |
| | | Q06 | -2.09 | 0.23 | 2.33 |
| | | U10 | -1.52 | -0.82 | 0.70 |
| | | | **Average Difference** | | **1.22 %** |
| 7 | P4 -> P1 | E10 | 3.64 | 3.01 | 0.63 |
| | | N09 | 1.64 | -0.42 | 2.06 |
| | | Q06 | -4.47 | -2.12 | 2.35 |
| | | U10 | -3.44 | -3.02 | 0.42 |
| | | | **Average Difference** | | **1.37 %** |

* - FINCH IDs are based on the symmetry of the NE RIH with the other three reactor inlet headers (NW, SE, and SW), due to the model's restriction of the NE core only.

Table 3 Simulation Results vs. Station Data

Based on these results the following is observed:

- for most FINCH channels, the proposed model captures the correct trend (in terms of increasing or decreasing flow). Specifically, the model is capable of capturing the trends for greater than 85% of the available data.

- in general, the magnitude of the flow changes with configuration change shows good agreement with the measured relative flow changes. On average, the TUF model captured the change in flow to within 1.06%. Improved agreement with these trends may be possible with further model development.

It should be noted that for changes in configuration from P1 to P4, the TUF results show the largest difference as compared to station measurements (1.48% difference in flow). This specific pump configuration change involved the largest changes in actual FINCH flows for channels G07 and Q10. It was determined that an axial gradient modelling factor of 1.5 Pa/Pa would provide a better approximation for G07 and Q10 for this pump configuration change, and can be considered within the range of analytical values (0.29 to 1.49 Pa/Pa) discussed in Section 4.2.

## 6. Model improvements

Improved agreement with station measurements would be expected if the TUF channel averaging was re-optimized considering both the flow region in the core (as is currently done) and its physical location along the header. Based on Figure 7, approximately 11 to 15 averaged channels for a single core pass would likely be required to ensure that the current core averaged locations and header regions are considered (i.e., breaking each of the existing grouped channels into 2 separate groups so their location on the header could be more accurately represented). Such increases in the number of averaged channels would be beyond the limits for the number of average channels in the current TUF code.

## 7. Conclusions

Based on this work the following is concluded:

- Realistic changes in the FINCH flows can be predicted using the detailed header model proposed in this work.
- Using a loss factor of 0.85 Pa/Pa between reactor inlet header regions, TUF predictions were generally capable of capturing the correct trends in flow as a function of pump configuration. Furthermore, the TUF predictions using this model provide reasonable approximations of the relative flow changes for different heat transport pump configurations.
- For the worst pump configuration change giving the largest changes in FINCH flows, a bounding loss factor of 1.5 is indicated. Using this conservative value, the model provides good agreement for the most challenging flow changes observed in the station data

## 8. References

[1] W.S. Liu, R.K. Leung, J.C. Luxat, "Overview of TUF Code for CANDU Reactors", Fifth International Conference on Simulation Methods in Nuclear Engineering, Montreal, Canada, September 8-11, 1996.