CANDU® 6 HTS DIAGNOSTIC AND ADJUSTMENT METHODOLOGY FOR ECONOMIC AND SAFETY-SYSTEM OPTIMIZATION

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Abstract

This paper deals with a portion of the CANDU® 6 nuclear reactor operation that track operational changes of the primary Heat Transport System (HTS) throughout its lifetime and their potential impact on Regional Overpower Protection (ROP) margin to trip. The paper offers an operational option for CANDU 6 utilities to economically optimize reactor performance. At the same time reactor safety is maintained or enhanced by keeping operational parameters well within the original design envelope. The focus is on facilitation of increased automation of an already accurate tracking of HTS operational changes, associated with periodic operational adjustments. The high adaptability of this option to nuclear utility preferences is demonstrated. Development of this option has led to improved analysis tools, enabling reactor performance optimization as well as enhanced prediction capabilities of future operational requirements for continued optimum performance and safety.

1. Introduction

This paper deals with the CANDU[1] 6 operational changes of the primary Heat Transport System (HTS) throughout its lifetime and their potential impact on Critical Channel Powers (CCP), the power at which fuel dryout occurs, and, ultimately, on Regional Overpower Protection (ROP) trip margins defining the margin between operating power and power at fuel dryout. It summarizes the current understanding to monitor, understand and adjust operational parameters of nuclear reactors. It also discusses improved analysis tools, including recent thermal-hydraulic model developments, enabling reactor performance optimization as well as prediction of future trends and requirements. The focus is on thermal-hydraulic model development used for accurate diagnostic of HTS operating changes and potentially, if needed, frequent minimal operational adjustments such that safe reactor performance continues to be ensured without unnecessary economic penalties. Tracking and adjustment methodologies are an integral part of all ROP Trip Setpoint (TSP) analyses, considering thermal-hydraulic analysis reference modeling as well as design consideration with respect to biases and uncertainties associated with methodology implementation and execution. ROP design documentation, therefore, includes a specific ROP tracking and adjustment methodology.

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[1] CANDU is a registered trade-mark of Atomic Energy of Canada Limited (AECL)

The enhanced diagnostic and adjustment methodology reported here is based on the original design principles of monitoring/detecting/tracking, anticipating, understanding and then adjusting or compensating. It has components involving thermal-hydraulic model development, analysis, assessment, maintenance, and operational changes [1], [2], [3]. The enhanced HTS diagnostic and adjustment methodology was developed, tested and in part implemented or proposed to be implemented at Canadian CANDU 6 utilities. As a result of this enhanced diagnostic and adjustment methodology, plants have an additional option, facilitating increased automation, to achieve operation at the highest operating power possible without compromising safety.

This paper deals with the key elements of this enhanced diagnostic and adjustment methodology and its routine site application and it demonstrates that it is within the original methodology design envelope. The original design tracking and adjustment methodology is enhanced by offering a more frequent optional tracking and adjustment procedure with respect to one of its tracking parameters. Further, the paper summarizes the validation of this methodology by comparison with the traditional, well accepted but more complex methodology. The traditional methodology, although accurate, is not suitable for more frequent site application due to its complexity. The diagnostic methodology may be used to investigate operational changes of the HTS by developing appropriate thermal-hydraulic models. This is achieved by a system of analysis, using several components of the NUCIRC thermal-hydraulic code, efficiently developing plant specific aging models based on appropriately chosen and validated site data. Further, the plant specific thermal-hydraulic models may be extrapolated to best-estimate or reference future operating conditions. These trends, based on thermal-hydraulic analysis, form references for future comparison with actual, measured site characteristics. The NUCIRC-code based thermal-hydraulic analysis is integrated with site measurements leading to site adjustments as necessary. In this manner, the margin to CCP can be tracked with time and as needed adjustments can be put in place to ensure that adequate margins continue to exist throughout the life of the station without unnecessary economic penalties.

2. CANDU 6 Reactor description of operational changes

Figure 1 gives a simplified presentation of the HTS components and coolant flow of a typical CANDU 6 reactor. The HTS consists of two “figure-of-8 loops” with four main HTS pumps (P1, P2, P3, P4), four steam generators (B1, B2, B3, B4), and associated headers (HD) servicing the 380 core channels (ranging from channels A09 to W14). Outlet header, purification and pressurizer interfaces are also shown.

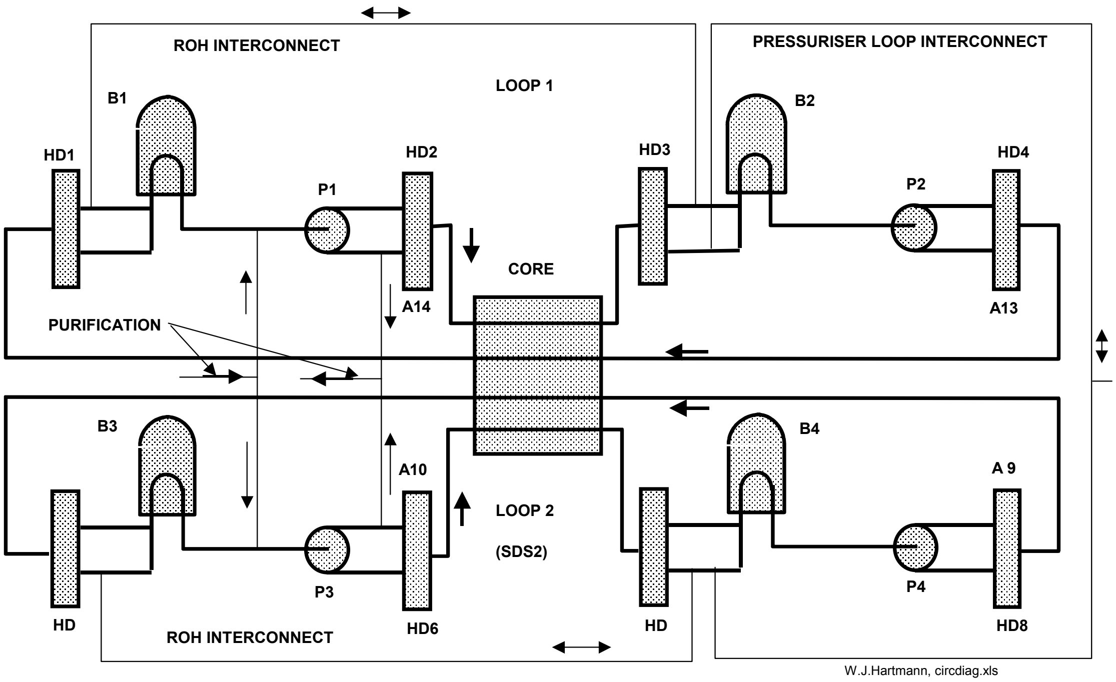

Figure 1 Typical CANDU 6 Simplified HTS Flow Diagram

Aging processes or operational preferences may cause changes to the primary HTS. These changes affect both coolant-flow and heat transfer properties of the HTS as a whole. There are several component effects, some acting to increase and some to decrease safety margins. The magnitudes of these effects vary over time, and thus the overall impact on the HTS is a complex integrated function of all mechanisms.

Operational changes can take place in a relatively short time frame, such as changes caused by utility operating preferences as well as changes in reference analytic model interpretation caused by measurement-instrumentation calibration. An example would be a relatively instantaneous change in measured inlet header temperature caused by changes in the secondary side steam generator pressure (real change in temperature) or inlet header instrumentation calibration (not a real change in temperature, only improved perception affecting the analyzed model). Operational changes may also take place over relatively long time periods and would generally be associated with plant-component aging. The following is a list of the main currently known aging processes that are occurring within the HTS that can affect CCP:

- Increase in pressure tube diameter due to irradiation creep (pressure-tube diametral creep). This reduces the hydraulic resistance in the channel, hence increases its coolant-flow, but causes a detailed redistribution of coolant flow within the bundle that can result in a reduction in dryout power. Because there is more creep in the higher power channels, there is a flow redistribution effect whereby some of the flow from the outer low power channels is redirected to the inner channels. This changes the radial flow tilt in the reactor core. Increased flow in central channels mitigates the effect of pressure tube diametral creep on CCP for the central channels, which are typically the most limiting for ROP.

- Increase in hydraulic resistance due to redistribution of iron oxides (magnetite) in the HTS. Dissolution of iron and flow accelerated corrosion (FAC) is occurring in the outlet feeders. Iron is being removed from the outlet feeders and being re-deposited in the cold part of the circuit, including the cold leg of the steam generators, the inlet feeders, and possibly the first section of the channel. The magnetite layers cause both a fouling of the inside of the steam generator tubes, leading to reduced heat transfer, and also an increase in hydraulic resistance in the steam generator tubes and inlet feeders. This has a negative effect on core flow (possibly also on core top-to-bottom flow tilt), on inlet header temperature and, consequently, on CCP.
- Erosion of the edges of flow-reducing orifices. This can lead to relative flow redistribution from inner to outer reactor core.

Considerable advances have been made to mitigate these aging characteristics, such as improving pressure tube production design and pressure tube installation orientation as well as material composition of HTS feeders. Complete elimination of these aging characteristics is, however, not possible. Therefore, a robust operational diagnostic and adjustment methodology is designed to consider both short-term and long-term operational changes with equal efficiency and accuracy. The diagnostic and adjustment methodology described in this paper addresses these requirements.

3. General Regional Overpower Protection (ROP) overview

The ROP system is designed to prevent dryout in any fuel channel during a slow loss-of-regulation event [4]. It accomplishes this through an array of detectors in the core, which are designed to actuate reactor shutdown systems (trip the reactor) if a sufficient number of neutronic-flux detector readings exceed pre-defined ROP TSPs. These TSPs are defined such that ROP will trip the reactor before any fuel channel exceeds its CCP, the power at which fuel-sheath dryout occurs. Thus changes to the CCPs due to HTS operational changes will affect the required ROP TSPs.

Figure 2 summarises the ROP analysis components and interfaces. Normal and abnormal “flux shapes” (a set of data that characterises one possible reactor configuration. The data consists of channel powers and neutronic detector responses.) are produced by a reactor core neutronics code (RFSP, [4]). Corresponding CCPs and CCP-equivalent parameter uncertainties are produced by a thermal-hydraulic code (NUCIRC, [2]) using a below-header thermal-hydraulic model as shown in Figure 3. Future reactor operating points are based on a best-estimate thermal-hydraulic model of some aging parameters such as pressure tube diametral creep (one of the most important aging parameters) and reference thermal-hydraulic models of other aging parameters, such as magnetite transfer based feeder-pipe inner roughness, feeder-orifice degradation, and steam generator fouling. Flux shapes, detector characteristics, CCPs, all with associated uncertainties, are then analysed by a statistical code (ROVER-F, [4]) to yield required ROP TSP trends. These calculations indicate that, for the data and models available, decreases in the ROP TSP are required to maintain trip effectiveness as reactors age. Figure 4 shows a typical, corresponding decrease in required ROP TSP.

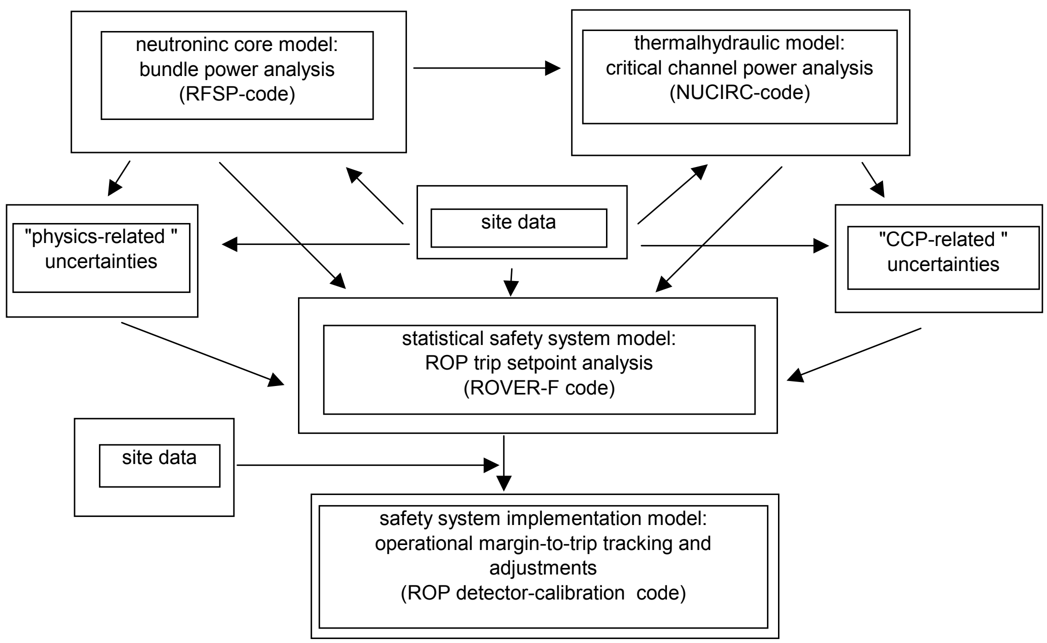

Figure 2 Simplified ROP Analysis Interfaces

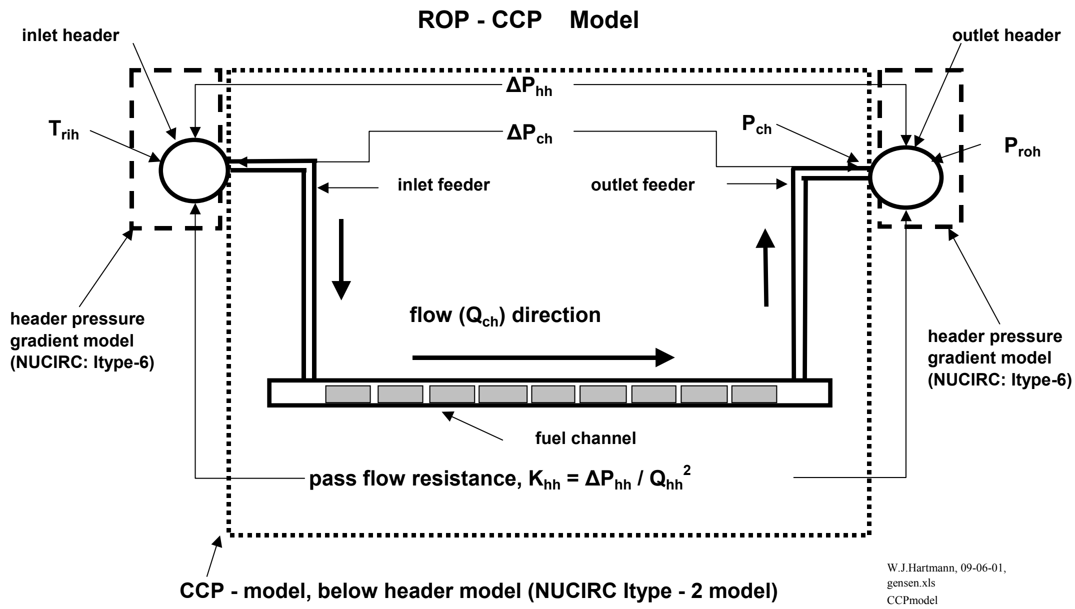

Figure 3 Simplified ROP-CCP Below-Header Hydraulic Model

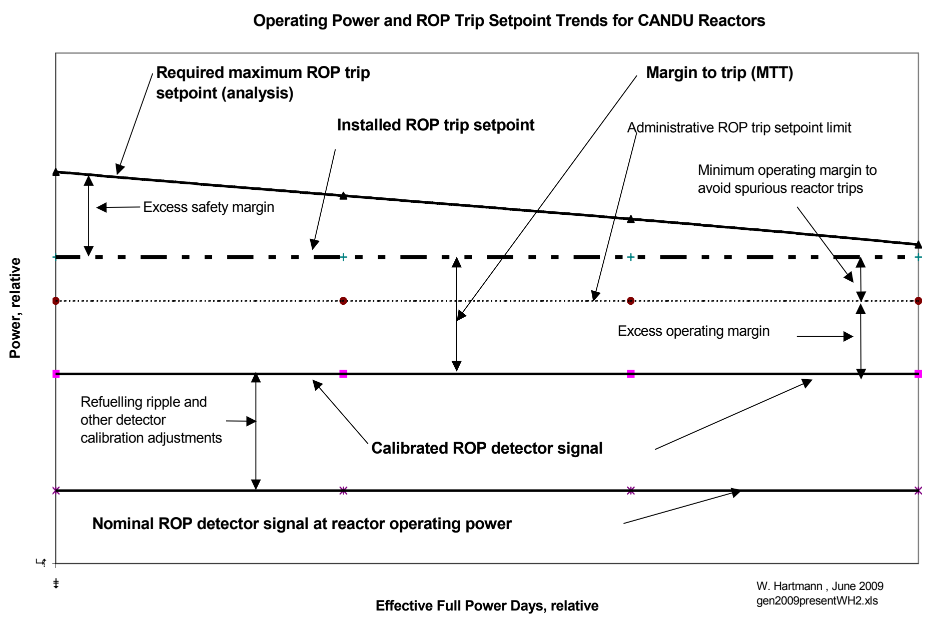

Figure 4 Summary of ROP Trip Setpoint Trends and Margins

A required ROP TSP trend, as shown in Figure 4, is then incorporated into the reactor safety system by a combination of implemented ROP TSP and neutronic-flux detector calibration as shown in Figure 2. The relative relationship between TSP and margins are also summarized in Figure 4. As long as the required ROP TSP is higher than the implemented ROP TSP an excess safety margin exists. When the required ROP TSP trend falls below the implemented ROP TSP an adjustment to the implemented ROP TSP is required to maintain the ROP safety system effectiveness. It is recognised that the system effectiveness can be achieved either by direct adjustment of the implemented ROP TSP (a direct decrease in TSP) or by detector calibration (an increase of the detector signal) adjusting the margin to trip and producing an effective ROP TSP that falls below the required ROP TSP. Here the margin to trip is defined as the difference between the calibrated detector signal and the implemented ROP TSP. For example, changes in the fuelling preferences may not produce the reference time average performance (TAP), defined as the channel refuelling power ripple, assumed in the original reference ROP analysis. A ROP TAP analysis and subsequent adjustment is then required to update ROP trip setpoints, generally performed by corresponding detector calibration. In Figure 4 it should be noted that an administrative ROP TSP is defined to fall 2% to 4% below the installed ROP TSP. This administrative limit defines a minimum operating margin to prevent spurious reactor trips and its magnitude is determined based on site preferences. The difference between this limit and the calibrated detector signal defines the excess operating margin. As also shown in Figure 4, generally, detector signals include the effect of peak channel powers due to refuelling with fresh fuel as well as other adjustments necessary to account for changes with respect to the analysed ROP TSP reference conditions.

4. Operational updates to ensure continued ROP system effectiveness

4.1 Conceptual introduction to operational ROP system update requirements

HTS temperature, pressure and flow as well as pressure tube diametral creep have long been established as the key parameters in establishing Critical Heat Flux (CHF) and CCP performance. These parameters, therefore, define the test matrix for associated laboratory tests at fuel dryout conditions. To simulate in-reactor conditions, CHF tests are performed in well-controlled test rigs in laboratory settings. In test set-ups radioactive heat sources (fuels) can be avoided and one can accurately measure local pressure, temperature, power, fuel channel and fuel geometry as well as channel coolant-flow at fuel dryout conditions. From the collected data, CHF correlations can be developed. CHF is a function of temperature, pressure, channel-flow and pressure tube diameter. For the models applied for this case, specific correlations are needed to use more easily predicted bundle average conditions for specific bundle geometries, conditions upstream in the channel need to be accounted for, and the appropriate complementary models for local quality prediction are needed. In fact, the entire hydraulic model for pressure-drop, two-phase flow condition prediction, and the CHF model need to work together in an integrated manner to have a reliable prediction. Also, the system hydraulic model needs to properly predict the boundary conditions for the individual channels as well. Thermal-hydraulic codes (such as NUCIRC), accurately predicting CCPs once the thermally-hydraulic code, by arbitrarily increasing channel power, has established local temperature, local pressure and flow associated with fuel dryout. A plant-specific thermal-hydraulic model is required for this analysis. This plant-specific thermal-hydraulic model is generally referred to as a slave channel model (see Figure 3) with plant specific geometry, together with plant specific boundary conditions, the measured HTS header conditions. For the CCP/CHF analysis to remain effective, one has to assure that this plant-specific thermal-hydraulic model remains appropriate regardless of the operational changes, due to aging or otherwise. This assurance is given by tracking measured HTS header conditions and below-header geometry followed by ROP analysis adjustments whenever the plant conditions drift from the reference conditions of the previous ROP analysis.

Therefore, the ROP/CCP thermal-hydraulic model (see Figure 3) is a below-header geometric model typically consisting of feeders, end-fittings, feeder-orifices, and pressure tubes with fuel bundles. The 4 parameters defining the site-specific characteristics of the ROP/CCP thermal-hydraulic model, therefore, can be identified as the following model boundary conditions:

1. The outlet header pressure, (P_{roh}),
2. The inlet header temperature, (T_{rih}),
3. The header-to-header differential pressure, (ΔP_{hh}), and
4. The HTS geometry below the headers.

These 4 parameters must be tracked and adjustments made whenever the operational characteristics differ from the design reference, used in a corresponding full ROP TSP reference analysis. The associated methodology is called the 4-parameter methodology and forms the basis for the original design ROP tracking and adjustment methodology.
The CHF/CCP tracking evaluations at real power plants require tracking of parameters that can easily be measured and then use a thermal-hydraulic code (NUCIRC) and associated model to derive data appropriate for the CCP evaluation at corresponding fuel dryout conditions. The following parameters can be measured at the plant and used for this purpose:

1. Outlet header pressure up to 100% FP,
2. Inlet header temperature up to 100% Full Power (FP),
3. Header-to-header differential pressure up to 100% FP,
4. Bundle power up to 100% FP (from flux mapping, physics code predictions, and secondary side thermal bulk power calibration),
5. Outlet feeder exit temperature up to 100% FP,
6. Channel flow at about 80% FP (mainly channel specific inverse heat balance, derived from 1), 2), 4), and 5) during a flow-verification or flow-resistance verification),
7. Pressure tube diameters for at least some representative channels (normalized RC1980 code [5] predictions are used for channels that were not measured, see Figure 3).

Since dryout has to be evaluated for header conditions at dryout and not at 100% FP (items 1 to 3), an appropriate adjustment factor is introduced for compensation, appropriately called the HTS variation at Trip-Power bias correction, “Ftp”, associated with a common random uncertainty. Similarly the assumed bundle-power distribution is time-average and, therefore, a channel random fuel age uncertainty is introduced for variable axial bundle power distributions associated with fuel burnup. Further, the coolant-pressure in the headers has significant gradients. The header-pressure at the points of measurement (i.e. (ΔP_{hh}) or (P_{roh}), Figure 3) generally differs from the pressure at the feeder-header interface (i.e. (ΔP_{ch}) or (P_{ch}), Figure 3). Appropriate header pressure gradient correlations for header-to-header differential pressure and outlet header pressure are obtained by the use of the NUCIRC hydraulic code (code-option: ITYPE-6, [2]). These correlations are then used to obtain channel specific equivalent pressure boundary conditions from the conditions at the measurement points.

In addition to the boundary conditions associated with the headers and the bundle powers, the ROP/CCP model needs to consider the geometric model below the headers. One of the associated geometry model components is pressure tube diameter. Pressure tube diameter is based on direct measurements for some channels and appropriately normalized predictions using an associated predictive code, currently referred to as a RC1980 type code by the industry [3], [5], for the remaining channels. Other, main below-header geometry components also affected by operational changes, including aging, are feeder roughness and inlet feeder orifice degradation. One does not have any direct measurements (with associated effects on HTS conditions or performance) for these two parameters, therefore, one has to find an appropriate surrogate for the full ROP analyses as well as subsequent tracking and adjustments methodologies as required. In the search for an appropriate surrogate one has to make sure that the surrogate only changes when there is a change in the specific below-header geometry components. Observing that changes in below-header geometry, such as changes in feeder-roughness and orifice-geometry, will change the flow, flow may be considered a potential surrogate candidate. However, it is recognised that even when feeder-roughness and orifices remain unchanged flow may change due to changes in header-to-header differential pressure (the flow driving force) due to changes in pump and steam generator characteristics (a first order, important effect) or even due to the random choice of bulk reactor power (coolant density effect, a second order, less important effect), chosen for channel inverse heat balance flow determination and verification. Basically flow is the major thermal-hydraulic code resultant dependent on all of the 4 model defining parameters described above. A better surrogate choice is internal core flow-resistance (or hydraulic-resistance) defined by

$$K_{hh}=\Delta P_{hh}/Q_{hh}^2, \quad (1)$$

where ΔP_{hh} is the header-to-header differential pressure and Q_{hh} is the corresponding HTS pass flow rate (see Figure 3). This surrogate is found to be significantly less sensitive to changes in header conditions for single-phase operation (at about 80%FP). Single-phase conditions eliminate the flow-resistance sensitivity with respect to two-phase flow (liquid and gaseous phases). Further, the internal core flow-resistance surrogate eliminates the first order differential pressure effect, as compared to the flow surrogate but may vary, for example, according to the choice of reactor power chosen for flow-verification (a second order effect in magnitude). The below-header flow-resistance or below-header hydraulic-resistance K_{hh}, therefore, historically has been chosen to be the CANDU 6 design tracking parameter, serving as a surrogate for below-header geometry [1]. Generally K_{hh} has sufficient accuracy (within analysis resolution) for most tracking purposes. However for relatively severe operational changes, such as obtained during a major primary-side steam generator cleaning, the reference flow-resistance K_{hh}, used during a channel specific flow-verification, has to be appropriately conditioned (see Section 4.4, Equation (12)). It has to be conditioned to make the flow-resistance difference between reference and site measurement independent with respect to changes in non-geometry observables as well as pressure tube diameter. Changes in non-geometry observables are variations in operating power, temperature, differential pressure, and outlet header pressure with respect to the ROP analysed reference. The conditioning adjustments, associated with this second order effect, are achieved by appropriate adjustment factors for bulk power, temperature and differential pressure (it has been found that the effect due to outlet header pressure variations is negligible), based on NUCIRC-code thermal-hydraulic calculations. This consideration yields a realistic and accurate surrogate for feeder orifice model and feeder roughness changes, relative inlet feeder roughness as compared to outlet feeder roughness being considered by appropriate uncertainties.

It is recognised that the ROP limiting channels are found in the central, high power core region. HTS performance tracking and adjustment by pass flow-resistance, therefore, is only accurate if the radial flow distribution does not change with respect to the reference analysis. The pressure tube diametral creep rate is highest in the high-power, central-channel core region and, therefore, the relative flow in the central channels increases as the pressure tube diameter ages. Therefore, due to explicit modelling of pressure tube diametral creep, the reference radial tilt increases with time. It is noted that orifice changes also affect the radial tilt since it only affects outer channels and, therefore, radial flow tilt needs to be tracked in addition to pass normalized flow-resistance and proper adjustments need to be made when the observed tilt becomes significantly different from the analytic reference [1]. Similar to radial tilt, a further analysis assumption is that the central top-to-bottom flow tilt does not change with respect to the reference. Similar to the radial flow tilt , top-to-bottom flow tilt needs to be tracked in addition to pass flow-resistance and proper adjustments need to be made when the observed tilt becomes significantly different from the analytic reference [1].

4.2 Comparison of full ROP analysis with 4 –parameter tracking and adjustment analysis

The first step in a full ROP/CCP analysis is the gathering of data associated with inlet header temperature (at 100% FP), header-to-header pressure (at 100% FP), outlet header pressure (at 100% FP), and below-header flow-resistance (at about 80% FP, single phase, the surrogate for feeder-pipe inner surface roughness) as well as representative pressure tube diameter measurements (defining hydraulic model best-estimate pressure tube diametral creep). In order to obtain a corresponding thermal-hydraulic CCP/ROP model (see Figure 3) orifice degradation and feeder roughness are adjusted until the below-header flow-resistance, radial flow tilt, and top-to-bottom flow tilt are obtained (at about 80%FP reference conditions). This thermal-hydraulic model including feeder roughness and orifice degradation is then introduced to the 100% FP ROP/CCP model and dryout powers (CCPs) calculated

(NUCIRC). This is followed by the statistical ROP TSP analysis using the ROVER-F code (as shown in Figure 2). Possibly the most important characteristic of the 4-parameter operational tracking and adjustment methodology is now apparent. The full ROP/CCP analysis is identical to the 4-parameter tracking and adjustment analysis, except for the following difference: in the full "lock-on" ROP analysis actual site data is used in the model development while in the 4-parameter analysis the full range of possible future site data is analysed before the fact. The range of possible future site data is relative to the reference parameters used in the full "reference" ROP analysis. In effect one has generated what may be called a pre-calculated multidimensional analysis response surface. During future flow-verification an appropriate CCP response can be obtained accurately without any further thermal-hydraulic analysis (NUCIRC code) from this pre-calculated analysis response surface. It is further recognised that the CCP response (change) is proportional to the ROP TSP response for the most limiting channels (or HTS pass). Historically one required that the most severe change in CCP, of the four HTS passes considered, be applied to the entire core of 380 channels. For this common change in all channels the effective ROP TSP need only be adjusted according to the change in CCP, to reflect the full ROP probabilistic analysis (ROVER-F code), which, therefore, would not be required any more for routine TSP updates. It is emphasised that the least beneficial CCP adjustment of any one pass is applied to all passes, which ensures that this approach is either as accurate as a full probabilistic analysis or conservative if the most limiting pass is not the pass with the most severe decrease in CCP. Consistent with this approach, it is noted that in the past CANDU regulators effectively have not only approved a specific ROP TSP but a range of possible ROP TSPs based on a range of possible future operating conditions. It is noted that the 4-parameter methodology does not include pressure tube diametral creep methodology updates. If pressure tube diameter measurements indicate a significant difference with respect to the best-estimate creep model, then a full ROP TSP analysis update using an appropriately updated pressure tube creep model is preferred. Generally such an update is seldom found necessary.

It is noted that the 4-parameter methodology can produce an update in TSP within about one day as opposed to a full ROP analysis update typically requiring several months. This is made possible without adjusting the installed ROP TSP but by changing the detector calibration to implement the corresponding change in ROP margin to trip. Changing the detector calibration to change the margin to trip instead of directly changing the installed ROP TSP is generally referred to as changing the effective ROP TSP. The advantage of pre-analysed and pre-approved quick updates is realised at the expense of the 4-parameter methodology always being exact or conservative with respect to the full analysis, as explained above. However, the station is generally well aware when there is a change in the most limiting pass in the 4-parameter methodology (and an associated possibility of conservative results). Consequently the station has the option to perform a full ROP analysis update, eliminating the conservatism, or continue operating with the possibility of a conservative ROP TSP. Therefore, at the beginning of plant life, when extra operating margin is available, a full ROP analysis update would not yield an economic advantage.

It should be noted that the basic 4-parameter methodology (temperature, pressure, differential-pressure, and differential pressure surrogate methodology – see Section 4.3) is generally implemented in all CANDU 6 reactors with flow-resistance tracking (or equivalent conditioned-flow tracking) a design-tracking requirement. The enhanced 4-parameter methodology (temperature, pressure, differential-pressure, and below-header flow-resistance surrogate – see Section 4.4) described here is proposed to be implemented as a more automated option at all CANDU stations.

In conclusion, the strength of enhanced 4-parameter methodology is that it is identical to the full ROP TSP analysis up to the point of the probabilistic assessment and facilitates increased automation. Further it can be demonstrated to be as accurate as, or more conservative than, the full probabilistic ROP TSP analysis.

4.3 Basic 4 –parameter ROP tracking and adjustment analysis methodology

Consistent with the ROP thermal-hydraulic model (see section 4.1), the major reference parameters for CCP and ROP TSP design calculations are pressure, temperature, differential pressure, and below-header flow-resistance. These are generally referred to as "HTS boundary conditions". The ROP TSP reference analysis accounts for measurement uncertainty and for short-term fluctuations. Further the design states that corrections, by suitable operational adjustments, must be made for longer-term changes in the HTS boundary conditions. Adjustments can be made by multiplying measurement-based changes of the parameters or the associated parameters with appropriate CCP sensitivities with respect to each parameter. Here, sensitivities are obtained by perturbation (usually in the range of the associated uncertainties) of the parameters and noting the corresponding CCP changes. These adjustments can be expressed by the general formula:

$$C_{HTS} = (P - Pref) * kP + (T - Tref) * kT + (\Delta P - \Delta Pref) * k\Delta P + (K - Kref)/Kref * kK \qquad (2)$$

where P, T, ΔP, and K refer to the parameters of outlet header pressure, inlet header temperature, header-to-header differential pressure and below-header flow-resistance and the subscript "ref" refers to the associated analysis reference (it is noted, that for ease of writing, the subscripts "roh" (reactor outlet header),"rih"(reactor inlet header), "hh"(header-to-header) have been omitted, as presented in Figure 3, but are implied). The sensitivity factors kP, kT, kΔP, and kK are associated with the parameter sensitivity with respect to the average central channel CCPs. As explained above flow-resistance can be defined by the relationship:

$$K = \Delta P / Q^2 \qquad (3)$$

It is noted that differential pressure (ΔP) (see Section 4.3 Equation (5b)) and/or HTS flow (Q) (see Section 4.4 Equation (7)) may be tracked as a surrogate instead of flow-resistance as long as specific requirements are met according to utility preferences.

The flow-resistance item accounts for changes below the headers while the first three parameters of Equation (2) account for changes above the headers (such as steam generator aging and pump characteristic changes) as well as partially for associated changes below the headers.

Equation (2) can be conditioned by K = Kref (the below-header flow-resistance does not change) to yield:

$$C_{HTS} = (P - Pref) * kP + (T - Tref) * kT + (\Delta P - \Delta Pref) * k\Delta P \quad (4)$$

For this specific condition a decrease in header-to-header differential pressure would be associated with a decrease in flow with respect to the ROP reference (analysed) flow, requiring an associated ROP TSP penalty or an equivalent calibration adjustment of the ROP detectors. However, it has been demonstrated that the flow-resistance below the headers can change due to geometric changes associated with HTS feeder and pressure tube aging. An increased flow-resistance below the headers will decrease the associated flow and will, as well, increase the differential header-to-header pressure. Depending on cause, either an increase or a decrease in differential pressure may be indicative of either a reduced or an increased coolant flow. For this reason the ROP design requires that:

> "Operationally, any change in header-to-header differential pressure, ΔP_{hh}, should be treated as adverse in terms of ROP TSP until a review of available data (pump differential pressure, instrumented channel flow, (steam generator flow-resistance, core internal resistance,) etc.) indicates the source of the change." Specifically, "when the change in ΔP_{hh} is due to a change in the core internal (hydraulic/flow) resistance" a penalty for increasing ΔP_{hh} is to be applied.

Equation (4) can be rewritten as Equation (5a) and (5b) to express these requirements:

$$C_{HTSbc} = (P - Pref) * kP + (T - Tref) * kT + (\Delta P - \Delta Pref) * (k\Delta P) \quad (5a)$$

> for flow reduction due to pump performance degradation and above-header flow-resistance increase, specifically for $\Delta P < \Delta Pref$ and $(k\Delta P)$ being positive, and

$$C_{HTSbc} = (P - Pref) * kP + (T - Tref) * kT + (\Delta P - \Delta Pref) * (-k\Delta P) \quad (5b)$$

> for flow reduction due to below-header flow-resistance increase, specifically for $\Delta P > \Delta Pref$ and $(-k\Delta P)$ being negative.

Equation (5) is generally implemented at CANDU stations and remains the best short-term ROP adjustment methodology, whenever a direct core internal (below-header) flow-resistance evaluation is impractical to be performed. A below-header flow-resistance (below-header geometry) evaluation with corresponding adjustment has to be performed whenever significant below as well as above header performance changes are evident relative to the analysed reference, since conservative adjustment results cannot be guaranteed when both types of changes are apparent. The enhanced 4-parameter methodology (Section 4.4) explicitly formalises this requirement. Adjustments may typically be performed about once every 3 days, for HTS header temperature and pressure, about once every 90 days or as needed, for pass bulk flow-resistance related issues [1], about once every year or as needed for adjustments related to radial and top-to-bottom flow tilt trends [1] (see Section 4.1), and, finally about once a decade or as needed for pressure tube diametral creep or feeder-orifice degradation issues [1] (see Section 4.1). The ROP Detector Calibration (ROPDC) methodology implements associated changes at site, as per current ROP design requirements (see Figure 2).

4.4 Enhanced 4-parameter ROP tracking and adjustment methodology

The design ROP performance is evaluated for reference thermal-hydraulic conditions. These conditions generally change during reactor operation. It has been observed that HTS operational changes include, both, above-header and below-header flow decreasing mechanisms. The enhanced or refined methodology explicitly considers change in the flow-resistance below the headers (or a surrogate such as conditioned flow) and is an implementation refinement of the general tracking and ROP TSP adjustment formulation of Equation (2), facilitating increased automation with respect to tracking and adjustment. Four adjustments are added to form the total pass-dependent integrated adjustment ($F_{PHTS}i$). The HTS pass (PHTSi, i defining the HTS pass) with most conservative adjustment being implemented for all HTS passes. This procedure is expressed in functional form as follows:

$$F_{PHTS}i = 1 / (1 + \Delta PHTSi(\text{most limiting})) \qquad (6a)$$

and

$$\Delta PHTSi = (P - Pref) * kP + (T - Tref) * kT + (\Delta P_k - \Delta Pref) * k\,\Delta P + (K - Kref) / Kref * kK \qquad (6b)$$

The subscript "k" in "ΔP_k" emphasizes that a below-header flow-resistance measurement, K, is associated with this parameter. The "ref" post-script identifies the current ROP analysis reference. The sensitivity factor kK appropriately being obtained from perturbations in feeder roughness (see Section 4.1). The ratio of Equation (6a) provides the "inverse" adjustment to the ROP TSP to ensure consistency with implementation via ROP detector calibration. (A penalty, associated with a reduction in ROP operating margin, can be achieved by either a reduction in implemented ROP TSP or an increase in ROP detector reading (calibration) resulting in a reduction in effective ROP TSP.) Typically, the most limiting pass-specific ROP adjustment is conservatively applied to all detectors.

As an equivalent alternative, to demonstrate adaptability to CANDU-utility preferences, Equation (6b), can be reformulated to yield:

$$\Delta PHTSi_Q = (P - Pref) * kP + (T - Tref) * kT + (\Delta P_k - \Delta Pref) * k\Delta P + (Q - Qrefk) / Qrefk * kQ \qquad (7)$$

where the parameters P, T, ΔP and Q, were defined earlier, Q being a surrogate for K, and the subscript "ref" refers to the associated analysis reference. The factors kP, kT, kΔP, and kQ are associated with the parameter sensitivity with respect to CCPs. Here "k" in Qrefk denotes that the flow reference is conditioned (see Section 4.1) and usually is different from the ROP analysis reference, Qref. This is necessary since the 4 basic parameters, temperature, pressure, differential pressure and below-header geometry are independent thermal-hydraulic model defining parameters (NUCIRC code model input) while flow is, to some extent dependent on all thermal-hydraulic parameters (a NUCIRC code output result). Therefore, during a flow-verification, the reference flow has to be conditioned such that its difference with respect to measured flow presents only changes with respect to below-header geometry, excluding explicitly modelled pressure tube diameter changes. A conditioned reference flow is typically obtained by thermal-hydraulic calculations (using NUCIRC) using as-found header conditions as well as other defining conditions such as bulk/channel/bundle powers at the time of the flow-verification in addition to changes in reference pressure tube diameters. The only difference between the conditioned reference and site measurement will in fact be the below-header geometry components that have not changed in the reference, making the conditioned reference flow an accurate below-header reference geometry surrogate (most important: a surrogate for feeder roughness, see Section 4.1, with kQ being obtained from perturbations in feeder roughness). This method, a variant of the method defined by Equation (6), or the method defined by Equation (6) are consistent with the strategy and the method, with some site-specific adaptation, that have been implemented at Canadian CANDU 6 stations, including the Gentilly-2 Canadian CANDU station [3] which aligns itself with Equation (7). It should be noted that the component "(Q - Qrefk) / Qrefk * kQ" (Equation (7)) may be substituted, accurately and explicitly, for the component "(K - Kref) / Kref * kK" (Equation (6b)) in the following development of the refined ROP tracking and adjustment methodology, since both formulations accurately define below-header geometry adjustments.

As discussed in Section 4.3 (see Equation (5)), the short-term four-parameter adjustment equation may be expressed as follows:

$$\Delta PHTSp = (P - Pref) * kP + (T - Tref) * kT - | (\Delta P - \Delta Pref) * k\Delta P | \quad (8)$$

Here ΔP is defined as a header-to-header differential pressure measurement at times when a corresponding flow-resistance evaluation is not done. Consistent with the design the general form of Equation (8) is still valid between flow-resistance evaluations of the refined methodology. The reference differential pressure (ΔPref) would be the one measured at the last flow-resistance evaluation update, $\Delta Pref_k$ with the corresponding flow-resistance evaluation term of Equation (6) still being valid. The fully integrated equation, obtained from Equations (6) and (8), then becomes:

$$\Delta PHTSi = \Delta PHTSp_k + (\Delta P_k - \Delta Pref) * k\Delta P + (K - Kref) / Kref * kK \quad (9)$$

where

$$\Delta PHTSp_k = (P - Pref) * kP + (T - Tref) * kT - | (\Delta P - \Delta Pref_k) * k\Delta P | \quad (10)$$

and $\Delta Pref_k$ = the reactor operating condition equivalent of ΔP_k (i.e., $\Delta Pref_k = \Delta P_k$ only when applied at the same reference operating conditions). The reference $\Delta Pref_k$ (see Equation (10)) is with respect to the preceding flow-resistance verification associated reference ΔP_k (see Equation (9)), but corrected to account for any change in reactor power from RP_k to RP. For each HTS core pass (j):

$$\Delta Pref_k(j,RP,RP_k) = \Delta P_k * (\Delta Pref\,(j,RP) / \Delta Pref\,(j,RP_k)) \quad (11)$$

where RP_k is the maximum reactor power associated with the preceding flow-resistance verification. It is the power associated with ΔP_k (it is not the single phase reactor power associated with the flow-resistance verification itself) and RP is the reactor power at the current evaluation point.

The HTS conditioned internal flow-resistance reference Kref (see Section 4.1) can be defined as:

$$Kref = Krefa * F_{RPs} * F_{Ts} * F_{\Delta Ps} \quad (12)$$

where Krefa is the single-phase analysis below-header reference flow-resistance, and the adjustment multipliers F_{RPs} , F_{Ts} and $F_{\Delta Ps}$ correspond to second order adjustments whenever the single-phase flow-resistance verification analysis reference conditions with respect to reactor power, inlet header temperature, and header-to-header differential pressure differ from measurement. These sensitivity factors are obtained from parameter perturbation calculations. These factors are second order corrections in nature and generally only required for large reactor condition perturbations such as caused by primary-side steam generator cleaning.

5. Summary and Conclusion

The enhanced HTS operational diagnostic and adjustment methodology, presented here as a ROP design implementation option, more explicitly defines the basic, historic methodology to yield a formulation that facilitates increased HTS parameter tracking and adjustment automation. This is achieved by reconsidering original design requirements to include changes in below-header hydraulic-resistance explicitly. These below-header changes are due to pressure tube diametral creep, feeder orifice degradation, and iron transport related HTS geometry changes but may also be due to other unspecified operational changes, demonstrating robustness of the refined methodology. Generally only minor adjustments are necessary to keep the CCP reference model representative of plant operating conditions. Once CCP reference model and tracking methodologies are implemented they ensure continued future safe reactor operation without unnecessary economic penalties.

The enhanced HTS diagnostic and adjustment methodology proposed and described here is considered to be of prime value as an option for further increased tracking and adjustment automation for all CANDU reactors, enhancing performance in both new and aged reactors as well as reactors after refurbishment or pressure tube retubing maintenance outages. By showing that the CCP reference model describes CANDU 6 aging well, credible predictions can be made for future reactor requirements to mitigate aging. Therefore, this proposed HTS diagnostic methodology also serves as an early warning system, allowing the operator to take timely, appropriate action to mitigate aging impacts including the development of excessive, aging related, HTS pass asymmetries. This becomes useful in developing optimal remedial-action schedules, including the determination of the optimum time for steam generator cleaning.

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