Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22, 2009

Review on ROP update methodology for CANDU-6 Plant

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1. Introduction

CANDU6, Pressurized Heavy Water Reactor (PHWR) has Regional Overpower Protection (ROP) system to prevent the sub-channel from intermittent dryout during slow loss of reactivity control event. The thermal hydraulic condition, determining ROP trip set point, experiences aging effects as time goes. To keep an appropriate safety margin, tracking of operational changes should be done.

2. Description of operational changes

Figure 1 gives a simplified presentation of the heat transport system(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.

Aging processes 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 operational margins.

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. Operational changes may also take place over relatively long time periods and would generally be associated with plant-component aging.

2.1 Pressure-tube Diametral Creep

Increase in pressure tube diameter due to irradiation 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.

2.2 Redistribution of Iron Oxide

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. 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.

2.3 Erosion of the Edges of Flow-reducing Orifices

This can lead to relative flow redistribution from inner to outer reactor core.

Considerable efforts 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, an operational diagnostic and adjustment system is designed to consider both short-term and long-term operational changes with equal efficiency and accuracy.

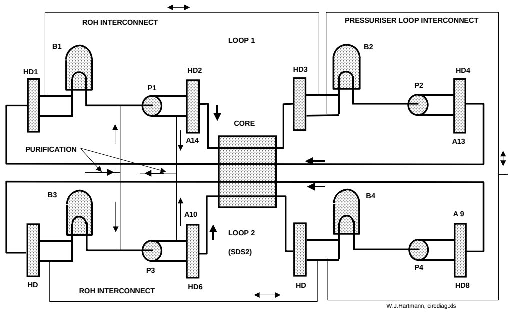

Fig. 1. Typical CANDU-6 Heat Transport System.

3. Operational updates to ensure continued ROP system effectiveness

3.1 Conceptual Introduction

Thermal-hydraulic code (such as NUCIRC), accurately predicting CCPs 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 with plant specific geometry, together with plant specific boundary conditions, the measured HTS header conditions.

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:

The outlet header pressure, (Proh),

The inlet header temperature, (Trih),
The header-to-header differential pressure, (ΔPhh), and
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.

For the first three of 4 parameters can be measured appropriately. But for the last, an appropriate surrogate for the full ROP analyses as well as subsequent tracking and adjustments methodologies as required.

A recommended surrogate choice is internal core flow-resistance (or hydraulic-resistance) defined by

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

where, ΔP_{hh} is the header-to-header differential pressure and Q_{hh} is the corresponding HTS pass flow rate. This surrogate is found to be significantly less sensitive to changes in header conditions for single-phase operation (at about 80%FP).

3.2 Basic 4-Parameter ROP Tracking and Adjustment

Consistent with the ROP thermal-hydraulic model, 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.

3.3 Enhanced 4-Parameter ROP Tracking and Adjustment

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:

$$F_{PHTS}i = 1 / (1 + \Delta PHTSi(\text{most limiting})) \qquad (3)$$

and

$$\Delta PHTSi = (P - Pref) * kP + (T - Tref) * kT + (\Delta P_k- \Delta Pref) * k\,\Delta P + (K - Kref) / Kref * kK \qquad (4)$$

The subscript "k" in "ΔP_k" emphasizes that a below-header flow-resistance measurement, K, is associated with this parameter. The ratio of Equation (3) 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.

4. Conclusions

The enhanced HTS diagnostic and adjustment system 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.

REFERENCES

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