HISTORY OF ROP MARGINS EROSION AND POWER RECOVERY AT GENTILLY-2

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Abstract

Regional Over-Power Protection (ROP) trip setpoints have a direct impact on power levels at which reactors can operate safely. An issue common to all types of nuclear power plants is the gradual decrease in operating margins as plant equipment is affected by ageing. Our experience shows that the dominant adverse ageing mechanisms in the heat transport system are associated with pressure tubes, steam generators and to a lesser degree, feeders. This paper presents the evolution of the Regional Overpower Protection Trip Setpoints since first commissioning of Gentilly-2 and the relative contribution of the various ageing mechanism which impact the safety margin and reactor power at Gentilly-2. Corrective actions to restore full power are also revisited and conclusions and lessons learned are highlighted.

1. Introduction

An issue common to all types of nuclear power plants is the gradual decrease in operating margins as plant equipment is affected by ageing.

Gentilly-2 plant first came into service in 1983 with a very large operating margin. This is reflected in the Regional Over-Power Protection (ROP) margin, which is the operating margin between the normal core power levels and overpower trip set points.

The basic safety design requirement for the ROP system is that the integrity of the Heat Transport System (HTS) be maintained if an overpower condition were to occur. This functional objective is achieved with an appreciable safety margin with ROP setpoints determined to prevent OID (Onset of Intermittent Dryout) with a 95% or 98% confidence, which initially provided a significant operating margin. Efforts were put on close monitoring and assessment of the ageing phenomena and on station specific initiative to recover eroding ROP margins.

2. History

The history of our ROP margin erosion due to ageing and margin restoration obtained from mitigating actions are illustrated in Figure 1.

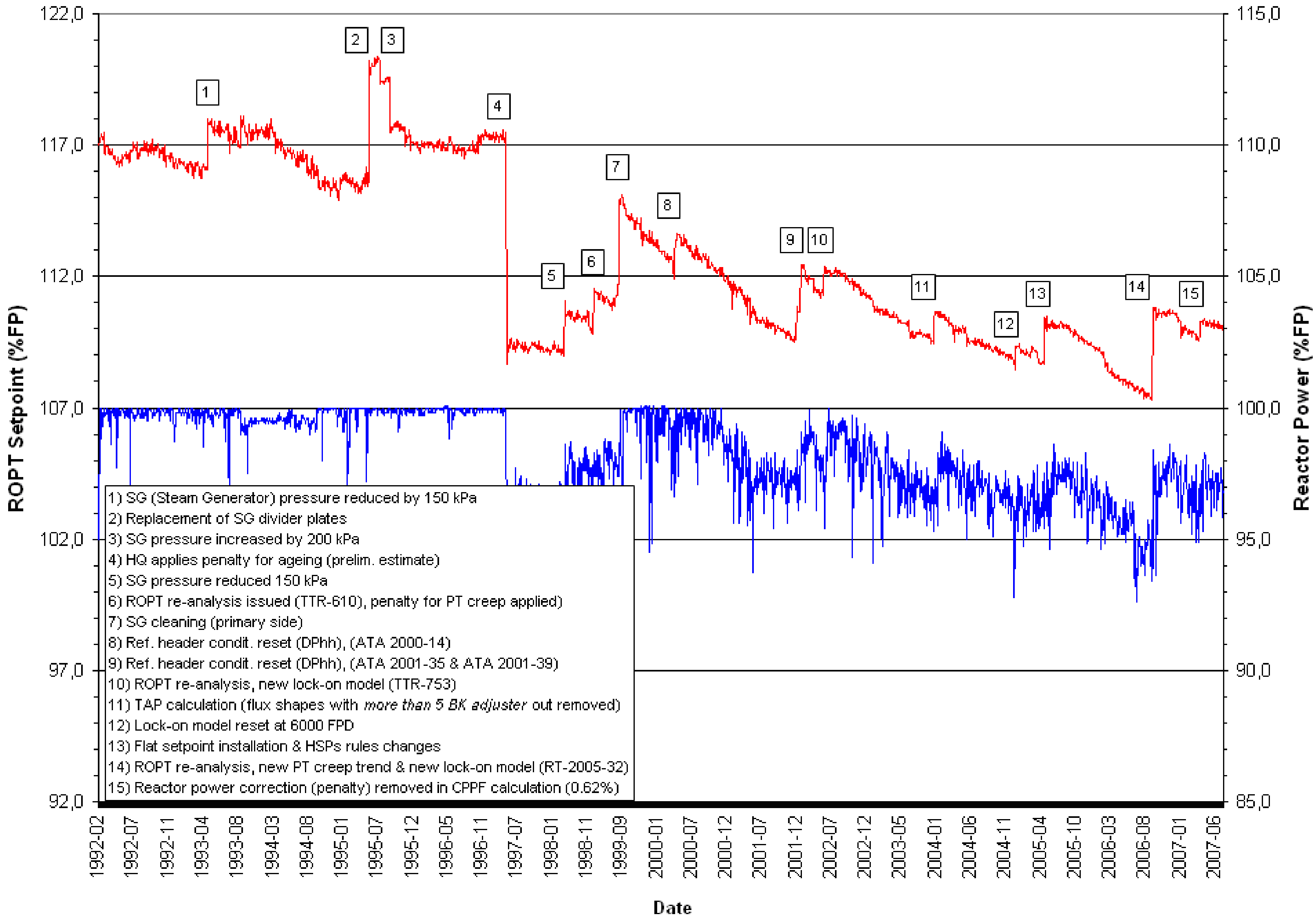

Figure 1 Gentilly-2: ROPT Effective Setpoint vs Reactor Power

Our experience shows that the dominant ageing mechanisms in the heat transport system are associated with pressure tubes, steam generators and to a lesser degree feeders. The effects of the component aging mechanism included physical effects anywhere in the HTS (e.g., geometry, wall thinning, etc.) and effects on HTS operating conditions (flows, temperatures, pressures, etc.). Other effects may impact modelling assumptions used in the ROP analysis (e.g., heat transfer coefficient, material properties, hydraulic resistance, etc.) and revision of methodologies/tools used for the analysis. Historically, HTS operating conditions has been addressed since late 1985 (after~2 years of operation) by reducing the effective ROPT (Regional Overpower Protection Trip) setpoints. This reduction of effective ROPT setpoints was implemented by normal calibration of ROP detectors after applying appropriate penalties to the (neutronic) CPPF (Channel Power Peaking Factor) value. This way we assured that the ROP system adequately protects against adverse degradation mechanisms trends or aging effects on the components and the system. The approach has been to control within a defined band, thus precluding the need to revisit or revise any related safety analyses or to recalibrate detectors. Changes from the reference values of reactor inlet header temperature (RIHT) and Reactor Outlet Header Pressure (ROHP) were translated into a penalty or gain depending of the direction in the change. Any changes of Header-to Header Pressure Drop (HHPD) relative to the reference values need to be treated like a detrimental change as increases or decreases can be the result of effects which contribute to reduce the Critical Channel Powers (CCP) and result in a penalty for the trip set points.

The history of ROP Trip Setpoint and Gentilly-2 Reactor Power revealed some important events that need to be discussed.

Over the years, Gentilly-2 has experienced a continuous increase in full power reactor inlet header temperature. Operational changes such as reducing the secondary side boiler pressure in 1993 reduced the inlet header temperature and thus increase the CCP's in each channel; that is reflected in figure 1 point 1. During the 1993 outage, inspection of the steam generator indicated that the divider plates separating the steam generator (SG) primary side inlet and outlet plenums were leaking. Tightening loose bolts in the boilers indicated that the degradation of the water tightness of the divider plate in the SG primary-side enclosure was the cause of an important fraction of the increase in reactor inlet header temperature (RIHT) at Gentilly-2. Before the 1995 annual planned outage, only a small margin was left before reaching the safe operating envelope limit of 270°C.

Replacement of the boiler divider plate done in 1995 shown in figure 1 point [2] reduced RIHT and allows restoring the secondary side boiler pressure back to nominal [shown in figure 1 point 3].

Analyses of the full-scale tests in the presence of diametral creep led Gentilly-2 to conclude that ROP setpoint penalties were required. Meanwhile the ROP detector calibration practices and monitoring have been changed in main control room, having as consequence increased ROP margin. As a result, an estimated 7% penalty was applied in 1997 (figure 1 point 4) pending the completion of ROP ageing analysis in the presence of pressure tube diametral creep. At that time the penalty estimate of 7% FP had 4% FP (Full Power) impact on reactor power.

From that point on, operating margins were reduced to a point that any reduction in the effective ROP Trip Setpoint had a direct impact on the Reactor Power (RP). Efforts were made to restore operating ROP margins.

In 1998, figure 1 point 5, secondary side heat transport system steam pressure was decreased again when it was realised that inlet header temperature needed to be limited to 265°C at full power to ensure SDS2 high pressure trip effectiveness for loss of single pump events. At Gentilly-2 this parameter is instrumented on only two of the four headers resulting in a reduced range of conditions where the setpoint can be reached in the event of loss of a single or two even numbered pumps. This action also recovered more than 1% FP in reactor power.

A significant safety assessment program was put in place to understand changes in plant condition and equipment due to ageing mechanisms to determine new ROP trip setpoints consistent with the current aged plant configuration. Updated plant data models based on observed phenomenological behaviour at Stern and at Chalk River Laboratories, full scale pressure drop and CHF tests at STERN, along with collection of station data provided accurate and reliable simulation of the plant ageing. ROP ageing analysis was performed to identify the contributions of HTS aging effects that are critical to ROP margins. The ROP analysis approach was used, with codes, models and reference data sets modified to reflect observed HTS conditions and new setpoints were installed (figure 1 point 6). Pressure tube creep was shown to have an important adverse effect on ROP Trip Setpoint. As a consequence, a correction factor was added to the detector calibration (CPPF) value in order to take into account the detrimental effect of the diametral creep of pressure tubes (i.e. bypass of coolant flow through fuel bundles) on Critical Channel Powers (CCP). At that time, the correction factor was based on a predictive model of diametral creep based on limited number of PT measurements made on CANDU-6 reactors. This model evolved with time and was readjusted as increased numbers of PT measurements were taken at Gentilly-2 over the years.

Degradation of heat transfer in the steam generator was identified to be the result of fouling of the primary side of the boiler tubes, as shown by the SIVABLAST[1] primary side cleaning of the boiler tubes completed during the 1999 annual outage [figure 1 point 7]. That activity resulted in withdrawal of a significant amount of magnetite and produced an important reduction of Reactor Inlet Header Temperature; the restored margins allowed a return to full power reactor operation.

Detailed operating data tracking was used in support of safety analysis updates. HTS operating parameters as Reactor Inlet Header Temperature (RIHT), Reactor Outlet Header Pressure (ROHP) and Header-to Header Pressure Drop (HHPD) were collected to assess trends.

Any changes of Header-to Header Pressure Drop relative to the reference values was treated like a detrimental change. With Header-to Header Pressure Drop continued reduction, analysis were completed to identify the causes and their impact on CCPs. Analyses established that changes of Header-to Header Pressure Drop (HHPD) relative to the reference ROP setpoint values were the result of magnetite redistribution along the HTS circuit which had no negative impact on CCPs. As a result, as shown in figure 1, points 8 and 9, ROP margins could be restored by redefining

[1]SIVABLAST: “Siemans vacuum blasting” method of steam generator cleaning

reference values for Header-to Header Pressure Drop (HHPD) and removing the unjustified detector calibration penalty for HHPD.

Later, additional station pressure tube inspection data taken during planned outages were used to assess models and correlations of pressure tube creep. This allowed us to reduce the impact of PT diametral creep and diametral creep uncertainties as measurements indicated that pressure tube creep rate was significantly lower at Gentilly-2 than the CANDU-6 average.

A revised PHT circuit model has been established and ROP trip set point were reanalysed and applied in figure 1 point 10. Individual penalties for RIHT, ROHP and core delta-P are then reset with new reference values. Analysis updates included the effect of primary side steam generator cleaning, measurements of HTS conditions including new diametral creep measurements, revised PT diametral strain model and final CHF correlation based on extended range of STERN Lab experimental creep data. An evaluation of the ROP trip setpoint trends up to 8000 EFPD was also provided to account for pressure tube creep increase over time. Updates were repeated as updated station data and measurements became available, as shown in figure 1 point 12.

Time Average Performance (TAP) calculation are performed on a yearly basis and applied as a correction to the ROP Trip Setpoint to correct for Gentilly-2 operating fuelling practices and for average axial tilt. TAP result in small changes in ROP trip setpoint that can go both directions as presented in figure 1 point 11.

Collapsing detector trip plateaus from 4 plateaus to uniform ROPT setpoint and changing the operating rules of using the Handswiches (HSP) positions were other initiatives that target optimisation and assured improvement of ROP margins and reactor power, shown in figure 1 point 13.

As the diametral creep has a significant impact, Gentilly-2 put a significant effort assessing this effect. In 2003, 16% of the channels had measured diametral creep rates and measurements were used to produce a probabilistic assessment of diametral strain up to design end of life. The probabilistic assessment showed that data was sufficient to describe the un-measured population of pressure tubes in Gentilly-2. This result was used to update our ROP Trip Setpoint analysis, obtaining important margin gains (figure 1 point 14).

Operating tracking was performed to support ROP Trip setpoint between setpoint analyses updates. Monthly system monitoring of the HTS boundary condition helped us to track any significant drift. An expert elicitation committee meets regularly to ensure adequacy of data tracking and bulk power calibration.

Presently, in 2009, the reactor power is limited at around 96% FP. Without any additional correction, we expected power to be limited to around 94% at refurbishment. We are presently looking at methodological improvements which could provide us between 2% to 5% additional margins.

3. Margin Erosion

The gradual decrease in operating margin as plant equipment age is mainly the result of pressure tube diametral creep, increase in reactor inlet temperature due to SG fouling and primary boiler divider plate bypass and to a lesser degree by increases in heat transport system circuit hydraulic resistance. Other causes that contributed to margin erosion come from new findings revealed by STERN experiments that impact the CHF.

Heat Transport System Ageing

PHT parameters slowly change with time due to dissolution and redeposition of magnetite in the PHT system. Fouling of steam generators (SG) and redeposition of magnetite affects mainly RIHT and HHPD.

Prior to 1994 a limited number of instrument measurements could be retrieved from the plant control computer. Among these, a large number of data were collected during the initial commissioning tests and /or during the records needed 3 times/week for calibration of the ROP shutdown systems. In 1994 Gentilly-2 installed a system which collects and logs all the process and shutdown system instrument signals on a continuous base. This provided Gentilly-2 with consistent sets of data permitting to trend the heat transport system evolution.

3.1.1 Primary Heat Transport System Flow

Figure 2 illustrates the evolution of Primary Heat Transport System Core Pass Flows in single phase (non boiling) condition.

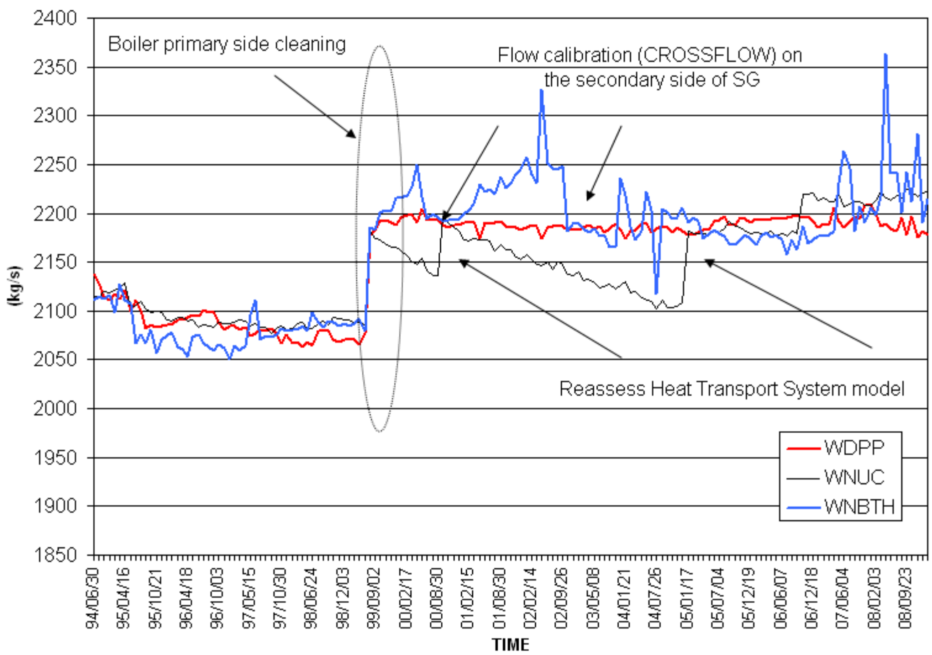

Figure 2 Primary Heat Transport System Pass Flow History

Direct measurements of core flow pass are not available. However core pass flows are inferred from heat transport pump flow (WDPP) and heat balance calculations obtained from measurements in single phase coolant conditions. Heat transport pump flow is based on manufacturer's curve and measured heat transport pump head. Core pass specific heat balance flows are based on reactor heat-balance (WNBTH). Reactor heat balance core pass flows are obtained from the sum of channel heat balance flows calculated with mapped channel powers and the primary side temperature rise across the fuel string.

Reassessing the HTS model and calculating flow with the hydraulic models for the measured header conditions (WNUC) allows tracking and identification of trends. Also CROSSFLOW ultrasonic flow measurement system produced by AMAG to measure flow on the secondary side of Steam Generators provided independent measurement.

3.1.2 Reactor Header Inlet Temperature

Figure 3 illustrates the evolution of reactor inlet header temperature at or near full power. This figure shows that reactor inlet header temperatures increases with time and that steam generator performance degradation is an important ageing mechanism in CANDU reactors.

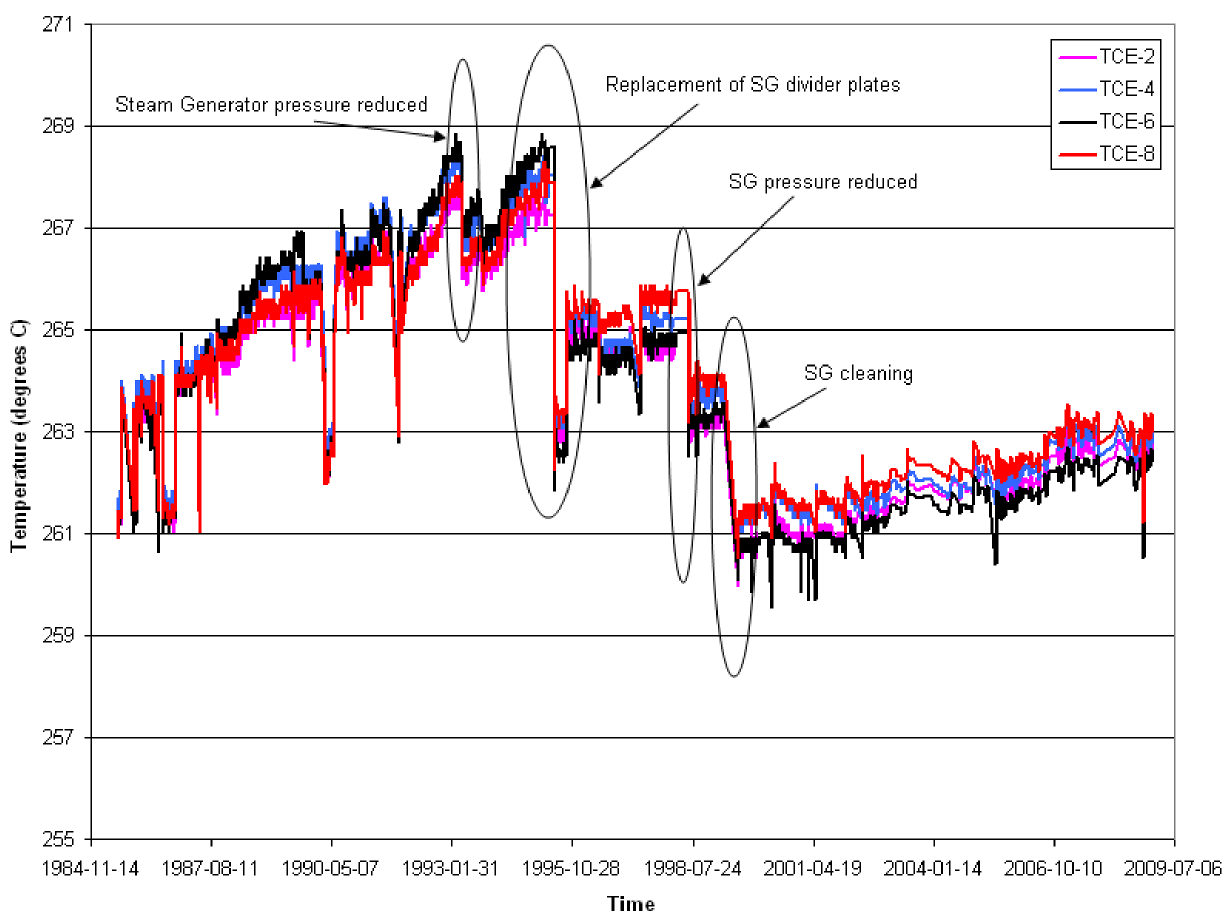

Figure 3 Gentilly-2 Reactor Inlet Header Temperature History

Up to 1993 Gentilly-2 experienced a significant continuous increase in RIH T, from 261ºC to 267ºC as a result of steam generator performance degradation. After ten years of operation increasing reactor inlet header temperatures levels raised concerns on boiler conditions and performance. In 1995 replacement of the boiler divider plate reduced the temperature by 3ºC. Primary side boiler cleaning and secondary side pressure reduction brought the temperature down to around 260ºC, after which RIH temperature increased at an averaged rate of 0.2 to 0.3ºC/yr, corresponding to the expected boiler fouling rate. Step increases in RIH T are typically observed after an outage followed by a gradual reduction back to normal but not fully to the original value. The analyses performed to date have assumed a linear increase in RIH T over the time periods reviewed, i.e., the step change which occurs after unit outages is not treated as a step change but is reflected in the overall temperature rate of increase over the entire operating period trended. We expect that the temperature will reach 264ºC at Gentilly-2 end of life.

3.1.3 Header to Header Pressure Drop

Figure 4 illustrates the evolution of header-to- header pressure drop at full or near full power (i.e. at the maximum achievable power).

In early operation, before the replacement of the boiler divider plate, header-to- header pressure drop slowly increased. During that period, the west loop and east loop trends diverged due to magnetite redistribution and asymmetries associated to outlet headers connexion to pressuriser on one side of the reactor and purification system on the other side.

Following the boiler divider plate replacement, header-to-header pressure drop decreased by 50 kPa. Primary side boiler cleaning resulted in a rise of header-to-header pressure drop of 70 kPa. After 1995 there appears to be a slow decrease, suggesting redistribution of pressure drop or a change in the header-to-header pressure drop as a result of pressure tube diametral creep. These are occurring at a rate of approximately 10 kPa/year, taking into account the period between 1995 and 1999 and after 2004.

Between 1999 and 2004 the header to header pressure drop decreased at a higher rate. After 2004, header to header pressure drop experienced also a reduction of asymmetry level between the loops.

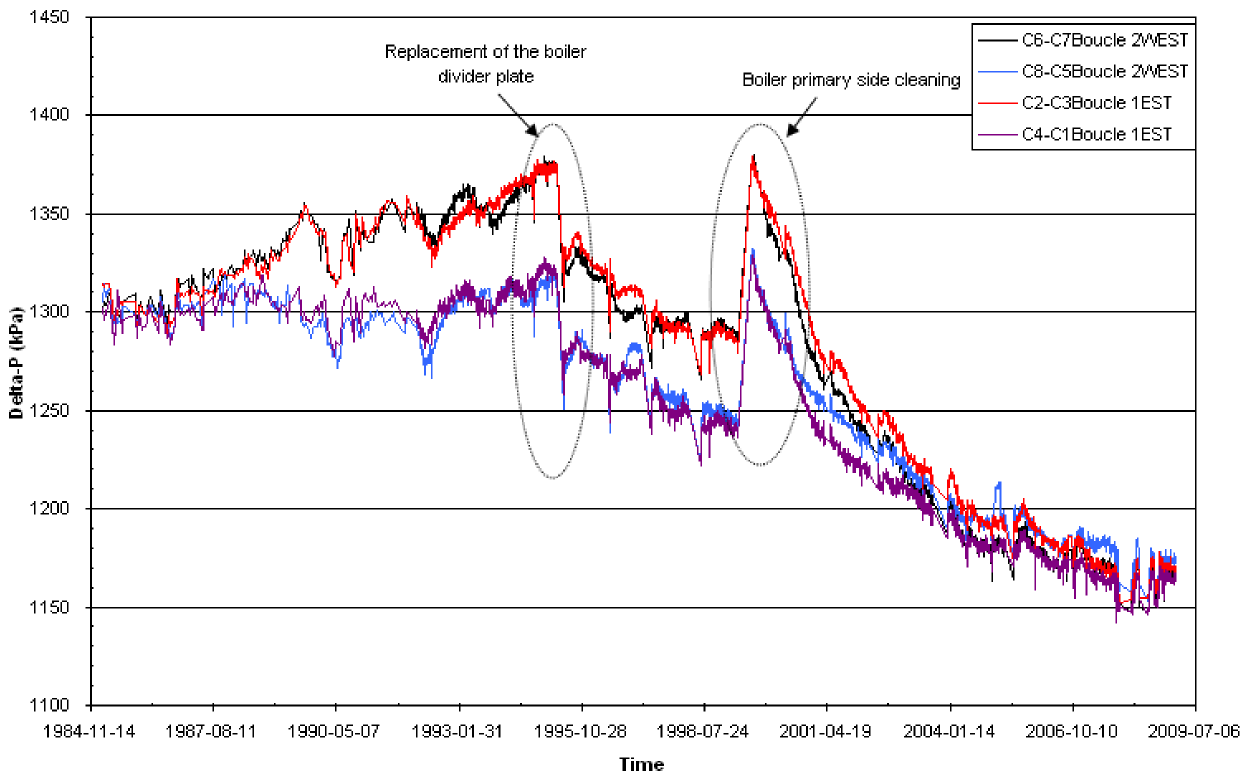

Figure 4 Header-to-Header Pressure Drop Gentilly-2 History

3.1.4 Pressure Tube Diametral Creep

Diametral creep is a continuous degradation, which affects the coolant flow in the fuel channels and reduces, at constant channel flow, the margin to critical heat flux (CHF); as a result diametral creep along with other ageing effects affects power limits and Regional Over Power (ROP) trip setpoints need to be updated to ensure that dryout is prevented with the required trip probability.

Key factors like fast neutron flux, channel temperature, internal pressure were identified as important factors in determining diametral strain levels.

At Gentilly-2, between 1987 and 2005, i.e. after 6323 EFPD irradiation creep measurements have been performed on 87 PTs. Figure 6 shows the channels inspected until 2005 at Gentilly-2. The results have revealed that there is an overall negative bias for the average creep rate of Gentilly-2 pressure tube relative to the average value calculated by AECL model, RC-1980.

Inspections were performed with different techniques i.e. CIGAR, MED or CANDE[2]. Verification for consistency between the methods has been always done for at least the most restrictive channel.

[2] CANDU: Candu Advanced Non Destructive Examination; CIGAR: Channel Inspection and Gauging Apparatus for Reactors; MED: Mesure d'expansion Diametrale (all are creep measurements methods)

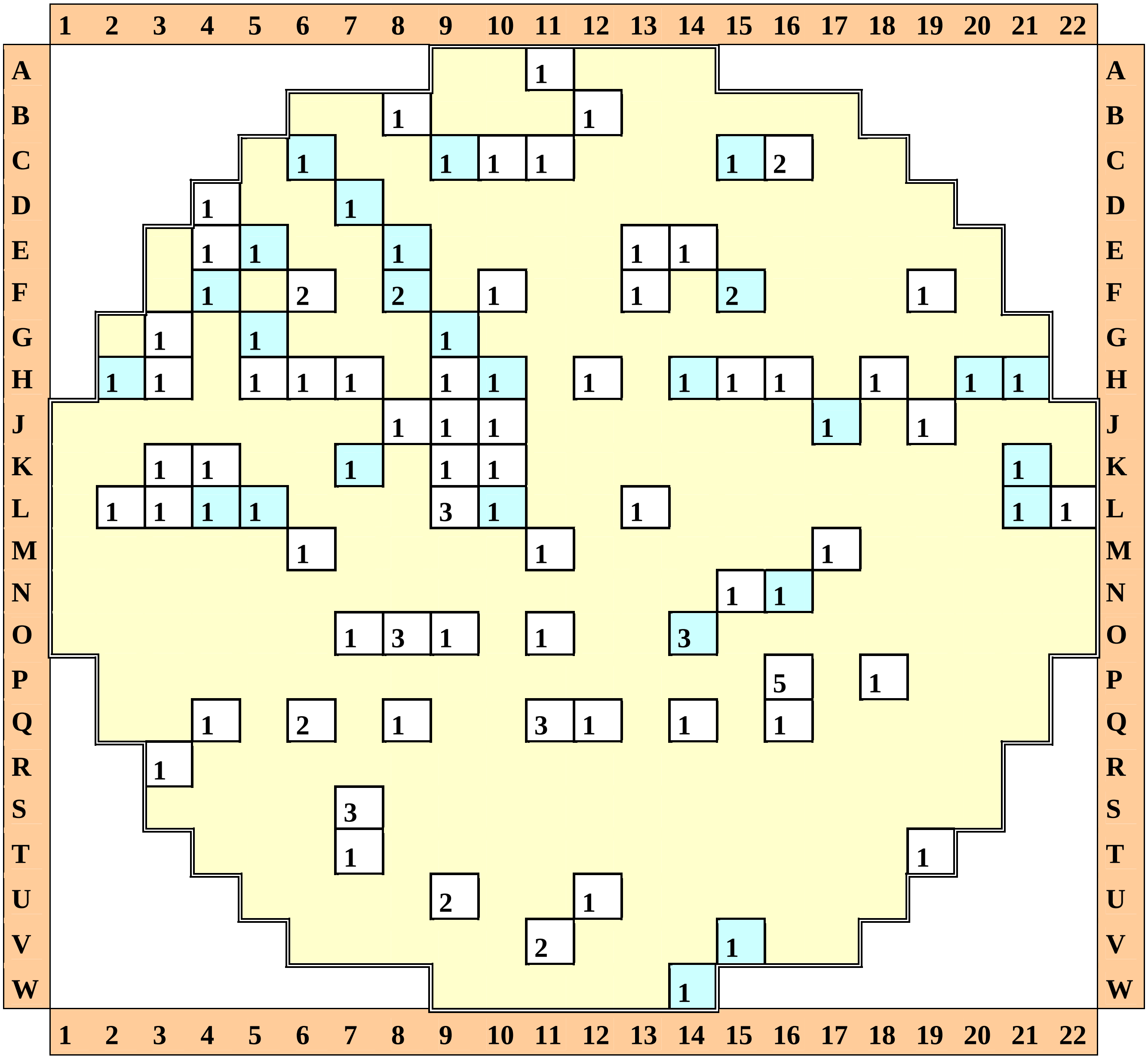

Figure 5 Measured Pressure Tubes (white and blue squares) till 2005. Numbers are indicating how many measures for each channel

Another important key factor is microscopic texture of the tube and texture variation from front–to-back ends of the tubes due to extrusion. This effect is responsible of the tube-tube variability of the creep rates and increases the uncertainties of predictions. Measurements become important as prediction models or design equation describes some "average" pressure tube and which "average" will depend on the database of measurements used to "tune" the particular equation.

The "frequency" of tubes having a given creep rate relative to the "average" creep rate is also a major factor in determining the overall uncertainty of the predictions and is a plant specific factor. Therefore it is important to characterize the distribution of creep rates within a specific reactor.

AECL developed models to predict creep strain rate as a function of the operating conditions (fast neutron flux, channel temperature, internal pressure), based on station inspection data. The last model used at Gentilly-2, RC-1980, is based on CANDU-6 station inspection data through 1997.

In parallel, the establishment of safety margins has been validated with full-scale bundle tests at diametral strain levels of up to 5.1%.

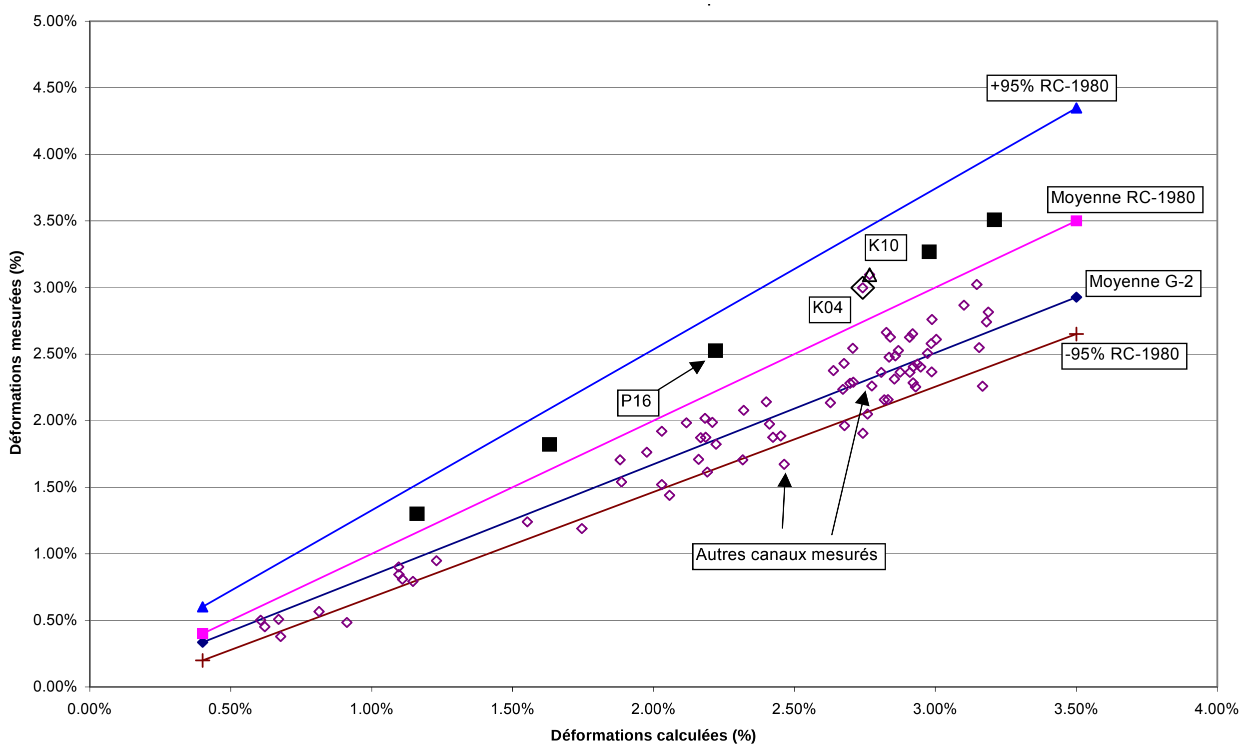

Figure 6 Pressure Tube Diametral Creep Measurements at Gentilly-2

AECL also carried out a detailed analysis for Gentilly-2, using a statistical model. This model enabled a forecast of the probable number of tubes exceeding 5.1% diametral strain at end-of-life.

Figure 6 illustrates the pressure tube measured creep strain rate against the AECL model (RC-1980). The rates of AECL model are higher on average than those of pressure tube measurements at Gentilly-2.

Methodology

As design methodology originally has not explicitly taken into account some of the ageing mechanisms as pressure tube creep, updated methodology around 1996 introduced a setpoint correction as a function of EFPD (this penalty increases with time). Methodological changes account for the effect of pressure tube creep on CHF and the contribution of pipe roughness degradation, pressure breakdown orifice erosion and other aging mechanisms identified in close observation of the heat transport system hydraulic evolution.

In 1998, the impact of heat transport system ageing on CCP and ROPT Setpoints was assessed. Before this analysis it was assumed that the functional dependence of CHF on physical properties is the same for a nominal and a crept pressure tube. After that, CCP did explicitly account for the CHF reduction due to pressure tube diametral creep. We implemented a CHF correction factor, derived from the trends observed in STERN Laboratory CHF experiment.

The Adjusted Parameter Model Methodology is a process used to quantify the magnitudes of the component-specific hydraulic and heat transfer degradation parameters of the ageing models incorporated in codes so as to accurately and reliably reproduce measured HTS operating conditions and to ensure coherence and consistency with available mechanistic models and/or empirical data of ageing phenomena. The principal feature is the de-coupling of the boiler and core pass characterisation. First, the boiler and HT pump in each core pass are adjusted through appropriate component ageing parameters to the pertinent station data. Subsequently, these adjusted boilers and HT pump models are inserted into the full-circuit model of the HTS, and the core model is adjusted through appropriate component ageing parameters to the pertinent core – pass pertinent data.

4. Power Recovery

One method of maintaining or improving ROP effectiveness is by directly increasing critical channel power (CCP) or by minimizing the effect of the ageing phenomena on CCP. Another method of increasing ROP margin is by optimising the ROP detector system for the aging conditions experienced at the plant.

The details of where gains come from depend on the systems that are in place at the station. In principle, the following things were used to maximise operating margin while ensuring that we meet the design acceptance criteria of having a reactor trip occur prior to dry-out in any fuel channel for all flux shapes with 98% probability.

Steam Generator Cleaning

Mechanical and chemical cleaning of the Steam Generators offers the possibility to improve heat transport conditions that affect critical heat flux, that is reactor inlet header temperature, and flow resistance through primary side boiler cleaning.

Gentilly-2 has experienced a continuous increase in reactor inlet header temperature as a result of steam generator degradation. In 1995, divider plates were replaced from a bolted to welded design.

Boiler cleaning resulted in a flow increase of around 4% to 6% across the 1999 outage and a decrease of more than 3°C in RIH temperatures. The step increase in flows across the outage were seen in all available site flow measurements, that is instrumented channel flow, channel heat balances, SG heat balance and Pump head/flow characteristics as shown in figures included in this article. Steam Generator cleaning was estimated in an overall recovery of 3% in CCP that translates in a 3% trip setpoints recovery.

Pressure Tube Diameter measurements

The primary reason for the reduction in ROP trip setpoint is due to the reduction in critical channel powers as the pressure tubes creep. There is a significant reduction in critical channel power due to flow by-pass from new pressure tubes to 5.1% radial creep (about 15%). Therefore, minimise the uncertainties in the analysis, particularly in pressure tube creep is the most significant contribution to the reduction in trip setpoint. This can be done through more pressure tube creep measurements and applying channel specific creep rates and uncertainties based on known quantities.

In recent ROP analysis we used “design equation” RC-1980 for comparisons between predictions and measured PT deformations rate in order to provide plant specific model prediction.

When compared to prediction of RC-1980, 93% of the inspected PTs have a lower diametral creep than predicted by the design equation RC-1980.

We concluded for Gentilly-2 that on average, correlation RC-1980 overestimates the maximum diametral creep and that a bias correction need to be applied in order to accurately predict channel maximum deformation.

We recover from reactor power by minimising the uncertainties in the analysis through more pressure tube creep measurements, applying channel specific creep rates for the measured channels and applying uncertainties based on known quantities.

Minimum ROP Operating Margin

The minimum ROP operating margin keeps the reactor from spurious trip due to variation of detectors readings. Low ROP margin has impact on reactor power, in order to maintain the minimum ROP margin; the operator should reduce the power. The minimum ROP margin was established at 6% since the beginning of Gentilly-2 operation in 1983.

The analysis of detector readings at Gentilly-2 has shown that the ROP detectors variation is small and Gentilly-2 can operate with lower ROP margin without risk. In 1997, the new rule of minimum ROP margin of 4% was implemented in main control room. As a result, Gentilly-2 has recovered 2% of power.

ROP Detector Calibration Allowance

In 1997, in order to gain 1% of ROP margin, the detector calibration allowance has been reduced from 2% to 1%. This increases the number of ROP detectors to be calibrated because of the detectors which the readings outside the range of the CPPF ±1% should be calibrated.

Uniform ROPT Setpoint

The detectors setpoints of original design were distributed on 4 plateaus; this was based on ROP analyses in 1991 for the detectors replacement project. However, the subsequent ROP analyses have shown that the HTS ageing has impacted on ROP setpoint on different ways so that the uniform setpoint is more efficient in term of ROP coverage.

During the annual outage in 2005, Gentilly-2 has modified the ROP system in order to uniformly distribute the trip setpoint for all detectors. As a result, the ROP margin has been increased around 1%.

Flux Shapes Classification and Handswiching

In 2005, the reactor configurations with more than *5 adjuster banks out* are no longer considered as normal operating condition at Gentilly-2. The implementation of clear alarms and procedures in control room conduct operator to turn the handswiches to the position HSP *"abnormal*" which have lower setpoints. Moreover, the adjuster withdraw at Gentilly-2 is under manual operating mode, the movement of these rods is controlled only by operators. This ensures that the adjuster rods could not moved automatically and the operators have enough time to react.

Since these flux shapes were limiting in previous ROP analyses, about 5% ROP margin has been recovered after removing these flux shapes from HSP-1.

Methodology

The Canadian Nuclear industry is looking at alternative analysis approaches to demonstrate that the current methodology is very conservative and there is more NOP/ROP margin that can be recovered. This initiative is being spearheaded largely by OPG and Bruce Power. In general terms, the methodology enhances the current statistical treatment in ROP trip setpoint calculation. This change allows for the quantification of the conservatism that the deterministic methods inherently have and could provide justification for more operating margin in the form of higher trip setpoints.

5. Conclusions

The present paper details the history of ROP margins at Hydro-Quebec, Nuclear Generating Station Gentilly-2 from the first commissioning. The analysis focuses on the factors of margin erosions and means of power reactor recovery. Lessons learned will be used in second life cycle, as Gentilly-2 will undertake a major refurbishment project in 2011.

6. References

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2. Identification and Mitigation of Heat Transport Ageing Mechanisms at the Gentilly-2 Generating Station, G. Hotte, M.A. Petrilli, A Baudouin, CNS Annual Conference, Toronto, October 18-21, 1998.