COMPLIANCE STRATEGY FOR STATISTICALLY BASED NEUTRON OVERPOWER PROTECTION SAFETY ANALYSIS METHODOLOGY

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Abstract

The methodology employed in the safety analysis of the slow Loss of Regulation (LOR) event in the OPG and Bruce Power CANDU reactors, referred to as Neutron Overpower Protection (NOP) analysis, is a statistically based methodology. Further enhancement to this methodology includes the use of Extreme Value Statistics (EVS) for the explicit treatment of aleatory and epistemic uncertainties, and probabilistic weighting of the initial core states. A key aspect of this enhanced NOP methodology is to demonstrate adherence, or compliance, with the analysis basis. This paper outlines a compliance strategy capable of accounting for the statistical nature of the enhanced NOP methodology.

1. Introduction

For all design basis accident analysis, a set of analysis assumptions are required as input into safety analysis, regardless of the analysis methodology. The validity of the analysis result and conclusions is maintained only if the analysis assumptions required as input to the analysis remain valid. For this reason, the general concept of the compliance strategy is to demonstrate the validity of the analysis assumptions over the appropriate range of applicability, and hence demonstrate the validity of the safety analysis conclusions, at all times, to ensure safe plant operation within the range of applicability considered.

For non-statistically based safety analysis methodology, generally known as deterministic analysis, key parameters have traditionally been set to limiting values, or safety limits. Safety limits are defined as the maximum supportable values such that the acceptance criteria continue to be met for all design basis accidents. The safety limits then define the Safe Operating Envelope (SOE) in which the reactor operates [1]. Compliance to deterministic safety analysis is maintained by ensuring the reactor operates within the SOE.

The enhanced NOP methodology utilizes Extreme Value Statistics (EVS) to propagate aleatory (i.e., operational) and epistemic (i.e., simulation) uncertainties separately to determine the required NOP safety system actuation setpoint with a high degree of confidence, as demonstrated in References [2], [3], and [4]. In this enhanced methodology, many of the required input values are not defined as a single set of values, but by a statistical distribution (i.e., a mean value, a standard deviation, and a distribution type, e.g., uniform). Some enhancement to the existing compliance process is required to account for the statistical nature of the input to the NOP methodology analysis.

More specifically, additions to the existing compliance process can be described by the following three major components:

1. Review the current relevant surveillance requirements and compliance monitoring activities for the analysis assumptions required by the enhanced NOP analysis methodology to determine the need for additional surveillance requirements.

2. Periodically collect station data to determine the parameter statistical properties, such as, mean, standard deviation, and distribution type for comparison to the analysis assumptions to determine any bias or drift in the mean value or the shape of the distribution.

3. Define guidelines to determine what constitutes a deviation from the analysis assumptions values in a non-conservative direction such that an impact assessment is required and develop a 'Compliance Tool' capable of performing an impact assessment for a given set of conditions.

The following section provides an overview of the NOP analysis methodology for the CANDU reactor in order to identify all relevant analysis assumptions. The remainder of the paper further describes the mathematical formulation of the compliance strategy and the implementation of the compliance strategy in the context of the three major components listed above.

2. Enhanced NOP Analysis Methodology

The goal of the NOP analysis is to calculate the NOP trip setpoint such that the NOP trip will occur before fuel dryout in the event of a slow loss of regulation accident with 95% probability and a 95% confidence level on three out of three logic channels. The acceptance criterion of this analysis can be stated concisely as, ***the margin to NOP trip should be less than or equal to the margin-to-dryout with 95% probability and with a confidence level of 95%***.

Briefly, the NOP analysis methodology is comprised of the following steps:

1. Simulation of initial core states representative of behaviour experienced during normal steady state operation, transient operation resulting from the normal maneuvering of reactivity devices, and flux shapes resulting from potential failures of the control system, are performed. The channel overpowers and detector readings from each core state are calculated.

2. Calculation of the Critical Channel Powers (CCPs) corresponding to each flux shape using thermal hydraulic models representing an aged condition of the Heat Transport System (HTS) as a function of Equivalent Full Power Days (EFPD).

3. A Monte Carlo statistical tool uses the input from the first two steps in combination with the key parameter uncertainties and varied operating states (i.e., fuelling ripples) to determine the required NOP trip setpoint to fulfill the acceptance criterion.

4. The required NOP trip setpoint for each flux shape is weighted within the flux shape group based on the probability of the initial core state (for example, the average zone level).

In Step 3, the calculation of the required TSP for each flux shape (TSP_{FS}) is dependent on the input to the trip setpoint calculation; namely, the critical channel powers, the nominal channel powers, the channel over powers, the required detector setting, the detector readings, and the uncertainty in each of these parameters, as per the following equation (assuming three out of three logic channels must trip to initiate the NOP trip):

$$TSP_{FS} = \min_i \left[\frac{CCP_i}{COP_i \times CP_i} \right] \times (RDS) \times \min_{CH} \left[\max_{k \in CH} (DR_k) \right] \times \left(1 - \tau^{1-\alpha} + \xi^{\beta} \right) \qquad (1)$$

Where,

CCP_i = Critical Channel Power (channel power at which the onset of intermittent dryout is predicted to occur) for channel i

CP_i = Channel Power for channel i under normal operating conditions

COP_i = Channel Over Power for channel i, given a flux perturbation of the postulated LOR

RDS = Required Detector Setting, generally given as indicated reactor power multiplied by the Channel Power Peaking Factor (CPPF)

DR_k = Detector reading at detector k on each channel CH

$\tau^{1-\alpha}$ = Uncertainty associated with the epistemic (i.e., simulation) uncertainties

ξ^{β} = Uncertainty associated with the aleatory (i.e., operational) uncertainties

To account for the lower likelihood of some initial reactivity device configurations, each TSP_{FS} is weighted appropriately within its flux shape category, and the lowest calculated trip setpoint from all the flux shape categories is defined as the required trip setpoint, $TSP_{required}$.

Station operation experiences random process variations so that at any point in time there is a true set of operating parameters which contribute to the true value of critical channel powers, nominal channel powers, channel over powers and detector readings. These true value variations lead to fluctuations in the true required trip setpoint. The true values cannot be known for the following reasons:

- Some inputs are predicted with computer codes which are subject to simulation uncertainty
- Some inputs rely on readings of instrument measurements which are subject to measurement uncertainty
- Each input may rely on operational parameters which are subject to spatial and temporal variations in the true values (operational variability)

Assumptions are therefore made in the analysis in order to estimate the true value of the required NOP trip setpoint. The analysis is designed so that the estimated required trip setpoint is less than the true value of the required trip setpoint with 95% probability at a 95% confidence.

The analysis assumptions required by the enhanced NOP analysis can be divided into two general categories of Modeling Parameter Assumptions and Operating Parameter Assumptions.

Modeling parameters are generally quantified through validation or research and development. Examples of modeling parameter assumptions made in the enhanced NOP analysis are simulation uncertainties and measurement/instrument uncertainties. The modeling uncertainties used in NOP analysis are based on the current state-of-the-art knowledge regarding computer code and model accuracy. Any research and development findings, discovery issues, or engineering changes related to modeling accuracy of the tools or instrumentation which lead to non-compliance with the analysis basis, will be assessed via existing issue resolution processes or the Engineering Change Control (ECC) process.

Operating parameters are measurable quantities readily available from station information systems. Operating parameter values employed in the analysis are derived from station operating data.

Many of the parameters considered in the analysis have more than one analysis assumption associated with them. For example, for Reactor Inlet Header (RIH) Temperature, an assumption is made for (i) the rate of change due to aging, (ii) the mean value for a given aged core state, (iii) the true value process variation expected at this state, typically characterized by a standard deviation, and/or (iv) the uncertainty in the computational estimate of a variable (i.e., measurement/instrument uncertainty or simulation uncertainty). Each of these assumptions is an operating parameter assumption (i.e., can be compared to measured data) with the exception of the instrument uncertainty that is considered a modeling parameter assumption.

Consistent with current compliance practices, only directly measurable variables (i.e., operating parameters) can be monitored relative to the analysis assumptions. The following table contains a complete listing of the operating parameter assumptions made in the enhanced NOP analysis.

Parameter	**Mean Value (μ)**	**Process Variation (σ)**	**Aging Trend**
Reactor Inlet Header (RIH) Temperature	√	√	√
Reactor Outlet Header (ROH) Pressure	√	√	N/A – controlled value
Core Flow/Pressure Drop Across the Core	√	√	√
Pressure Tube Diametral Creep (PTDC)	√	√	√
Reactor Power	√	√	N/A – controlled value
Operational Variation of NOP Detector Readings between calibration to the Required Detector Setting (RDS)	√	√	N/A – due to calibration procedure
Frequency of Initial Core States	Each flux shape is assigned a frequency of occurrence (probability) based on operating information.		
Operating States (i.e., Fuelling Ripples)	A set of operating states over multiple fuelling cycles based on operating information was considered.		

Table 1 Set of Operating Parameter Assumptions

3. Mathematical Formulation of the Compliance Strategy for the Enhanced NOP Analysis Methodology

In Reference [5] a concept is outlined which is defined as "decision making under uncertainty". This concept, also referred to as test statistics, has been employed successfully in licensing submissions such as compliance with channel power license limits [6]. The test statistics concept and its application to the enhanced NOP methodology are presented here.

A limit or acceptance criteria for safety analysis of a design basis accident is defined as L. Demonstration that results of an analysis remain below this value, given station operation at any given time, would constitute demonstration of compliance. Given the variable nature of station operation, the true outcome of an accident scenario, T, should remain less than L, for any given set of operating conditions.

In a statistical analysis with a range of possible operating states, T_x can be defined as the x^{th} percentile value (e.g., 95^{th} percentile) of probable results given exact station conditions, i.e., with no computational or measurement error. Methodology, such the enhanced NOP methodology, is then used to calculate an analysis (best estimate) result, U_x, which is the estimation of the true value, T_x. U_x cannot represent station operation exactly due to the associated computational and measurement uncertainties, u_{xy} (y representing the set of calculation, modeling and measurement uncertainties for U_x taken at a specified confidence or risk level).

To demonstrate an acceptable analysis result, it must be shown that U_x, plus the associated uncertainty term, u_{xy} remains below L with a certain confidence level. If we can show that $U_x+u_{xy} \leq L$, then we can also expect that T_x remains below L ($T_x< L$). There is of course some risk that this is not true, however, analysis is designed to minimize the risk that U_x and u_{xy} remain below L, while T_x is above L. Expressed mathematically,

$$P\{U_x+u_{xy} \leq L \mid T_x > L\} = 1 - y \tag{2}$$

where y, is the confidence level (e.g., 0.95). In this way, the level of safety is defined by x/y (e.g., the familiar 95/95 industry standard).

Applied to the enhanced NOP methodology, Equation (2) can be written as:

$$P\left\{TSP_x - \tau_{x,y} \geq L \mid TSP_x^{true} < L\right\} = 1 - y \tag{3}$$

Where,

$L =$ the installed trip setpoint,

$TSP_x^{true} =$ the true trip setpoint bounding β percent of true trip setpoints given any set of operating conditions[1],

$TSP_x =$ the calculated trip setpoint for the same set of operating conditions as the true trip setpoint, and

$\tau_{x,y} =$ the combined uncertainties present in the TSP calculation.

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[1] The true trip setpoint is a random variable which will vary with operating conditions at any given time

4. Compliance Strategy Implementation for the Enhanced NOP Analysis Methodology

Current compliance is maintained through a set of surveillance requirements to ensure operation within a set of safety limits in order to remain within the safe operating envelope. However, it is possible for an operating parameter value to be well within the safety limit, established with deterministic safety analysis, at the same time as being outside the range of conditions considered in the NOP analysis. To account for this possibility, three additions to the existing compliance process are discussed in more detail in the following sub-sections.

4.1 Additional Surveillance Requirements

The first proposed addition to the existing compliance process is to introduce additional surveillance requirements. To determine the need for additional surveillance requirements, it is required to review the current relevant surveillance requirements and compliance monitoring activities for the analysis assumptions employed in the enhanced NOP analysis methodology.

The analysis assumption values may change rapidly (e.g., a momentary reduction in ROH pressure mean value due to the spurious opening of a relief valve) or more slowly over time (e.g., a slow increase of the RIH temperature mean value over time due to HTS aging effects). Based on the nature of the expected change of the analysis assumption value, the analysis assumptions can be classified by the frequency of current and proposed monitoring, i.e., (i) on-going, (ii) periodic, or (iii) none.

In Table 1, a listing of operating parameter analysis assumptions was given. Table 2 provides the frequency of current surveillance requirements and the frequency of the proposed additional surveillance requirements for each of the operating parameter assumptions:

Parameter	Analysis Assumption Type	Current Frequency of Surveillance	Proposed Frequency of Additional Surveillance
Reactor Inlet Header (RIH) Temperature	Mean Value (μ)	**On-going** » to confirm value remains within safety limits	**On-going** » to confirm value remains within analyzed range **Periodic** » to check for drift over time
	Process Variation (σ)	**None**	**Periodic** » to check for distribution change over time
	Aging Trend	**None**	**Periodic** » to assess adequacy of modelling predictions
Reactor Outlet Header (ROH) Pressure	Mean Value (μ)	**On-going** » to confirm value remains within safety limits	**On-going** » to confirm value remains within analyzed range **Periodic** » to check for drift over time

	Process Variation (σ)	**None**	**Periodic** » to check for distribution change over time
Core Flow/Pressure Drop Across the Core	Mean Value (μ)	**On-going** » to confirm value remains within safety limits	**On-going** » to confirm value remains within analyzed range **Periodic** » to check for drift over time
	Process Variation (σ)	**None**	**Periodic** » to check for distribution change over time
	Aging Trend	**None**	**Periodic** » to assess adequacy of modelling predictions
Pressure Tube Diametral Creep (PTDC)	Mean Value (μ)	**Periodic** » pressure tube inspections during outages	**Periodic** » to assess adequacy of modelling predictions
	Process Variation (σ)	**None**	**Periodic** » to assess adequacy of modelling predictions
	Aging Trend	**Periodic** » dimensional inspection reporting following inspection campaigns	**Periodic** » to assess adequacy of modelling predictions
Reactor Power	Mean Value (μ)	**On-going** » to confirm value remains within safety limits	No additional surveillance required
	Process Variation (σ)	**None**	**Periodic** » to check for distribution change over time
Operational Variation of NOP Detector Readings between calibration to the Required Detector Setting (RDS)	Mean Value (μ)	**Periodic** » adjust indicated value equal to the RDS if the indicted value is outside the calibration band	**Periodic** » to check for drift over time
	Process Variation (σ)	**None**	**Periodic** » to check for distribution change over time
Frequency of Initial Core States	Probability assignation for each flux shape	**None**	**Periodic** » to confirm against station operating information that the assigned probabilities are conservative
Operating States (i.e., Fuelling Ripples)	Set of fuelling ripples used in analysis	**None**	**Periodic** » to confirm the set of ripples used in the analysis are conservative

Table 2 Current and Proposed Surveillance Requirements

For the analysis assumptions that are currently monitored on an on-going basis as part of the operating procedures (e.g., through panel checks), it is proposed that additional criteria are added to monitor these values to confirm they remain within their analyzed range.

To implement this, additional criteria should be employed in the surveillance requirements such that a flag is raised when a parameter value is beyond the analyzed range in a non-conservative direction. This flag would indicate that an assessment may be required to determine the impact of operating in this current state. The 'compliance tool' proposed in Section 4.3 would expedite this impact assessment.

For the analysis assumptions for which additional periodic surveillance is proposed, a periodic compliance report is discussed in the following sub-section.

4.2 Periodic Compliance Reporting

In addition to confirming that the instantaneous values remain within the analysis assumption range on a day to day basis, a periodic NOP compliance report will provide additional monitoring of the longer-term trends.

As noted in Table 2, surveillance is currently in place for many of the analysis assumptions on an on-going basis. In addition to these routine compliance monitoring activities, data collection and assessment should be documented in a periodic compliance report.

The following elements of a periodic report should be considered for each parameter in Table 2:

1. Document the source and frequency of data collected (e.g., once per hour reading of RIH temperature extracted from an online data collection system or, pressure tube dimensional inspection data collected during a bi-yearly outage)

2. Assess the collected data by performing the following steps (where applicable):

   i. Produce histogram of parameter values over the previous operating period to determine the probability distribution functions, mean values, and process variations for comparison to analysis assumption values.

   ii. Produce trend lines for parameter values over the previous operating period to determine the rate of aging (if any) for comparison to the analysis assumption values.

   iii. Confirm parameter values collected over the previous operating period remain within the same data population/acceptable range by means of statistical testing.

3. Document instances of parameter drift and changes in process variation over the previous operating period (if any) that required an impact assessment, using the compliance tool proposed in Section 4.3.

4. For the required NOP trip setpoint:

   i. To ensure compliance was maintained over the past compliance period – Use the collected data in conjunction with the compliance tool (Section 4.3) to calculate the required trip setpoints (i.e., the set of $TSP_{current}$ values corresponding to each available data point over the previous compliance period) and assess the results for any instance of non-compliance or unexpected trends in the margin to installed setpoint.

ii. To ensure compliance will be maintained over the upcoming compliance period – Use the trends of the required trip setpoints for the current operating period from step (i) to project the required NOP trip setpoint to the end of the next operating period.

iii. Figure 1 illustrates the use of data over the past compliance period given an instantaneous set of operating conditions, and a projection over the upcoming compliance period to demonstrate that compliance was maintained and will likely be maintained over the upcoming operating period.

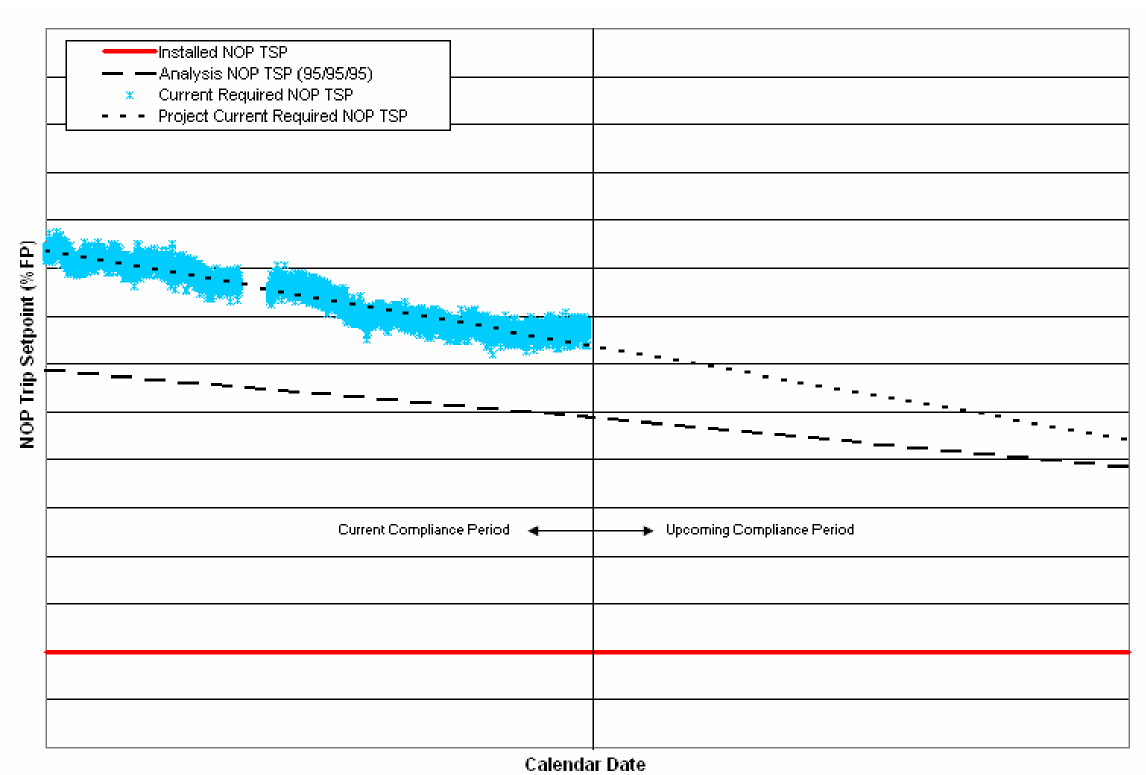

Figure 1 Demonstration of Compliance Over the Past and Upcoming Compliance Period

4.3 Impact Assessment Guidelines and Development of a Compliance Tool

The calculation of the NOP trip setpoint takes into account the process variations of the operating parameters, however a systematic drift of the operating parameter values sustained over a period of time may require compensatory actions. Impact assessments for the calculated required NOP trip setpoint are necessary for instances in which an operating parameter value is found to have drifted beyond the analysis assumption value in a non-conservative direction (as per the additional surveillance requirements proposed in Section 4.1). In this event, a process should be implemented which considers the following elements:

- Definition of parameter drift, i.e., considerations such as (i) magnitude of parameter variation considered larger than process variation, (ii) time period possible before action, and (iii) required action or penalty.

- Define a process or a tool to determine the available margin between the calculated required NOP trip setpoint and the installed NOP trip setpoint in the event of sustained drift requiring an impact assessment. The tool should be capable of considering simultaneous drift of other parameters which may be likely in response to the change in another operating parameter.

The following sub-sections provide guidelines in the event of drift in the mean values of the operating parameters.

4.3.1 Definition of Parameter Drift

It is important to distinguish between systematic change and normal parameter variation, i.e., when a parameter has entered a new operating regime or when the parameter is varying in accordance with the assumed process variation. If at any time during the compliance monitoring activities, it is found that an input parameter has drifted systematically or sporadically from the best estimate analysis assumption value in a non-conservative direction (but still remains below the safety limit) the following actions are recommended:

1. Determine the extent of parameter drift (i.e., comparison of the difference between the analysis value and the measured value with the assumed process variation).

    - For drifted parameter values within the 2σ range, the value is considered within normal process variation and therefore covered implicitly by the statistical nature of the methodology.

    - For drifted parameter values beyond the 2σ range, an impact assessment may be required depending on the amount of time the parameter remains at the drifted value in order to confirm a systematic change compared to a sporadic change. The methodology for this impact assessment is documented in the following sub-section.

2. Determine the amount of time the parameter may operate at the drifted value without significantly affecting the probability of trip before dryout.

    - For drifted parameter values within the 3σ range, a short operating period is considered acceptable before a penalty is assigned to allow for recovery of the parameter value to within an acceptable range (i.e., within 2σ). This allowable period defines the difference between a systematic change and a sporadic change in a parameter value.

    - For drifted parameter values beyond the 3σ range, an impact assessment and associated penalty should be initiated and applied immediately until corrective action is taken to return the parameter value to within an acceptable range (i.e., within 2σ). The methodology for this impact assessment and associated derivation of a penalty factor is documented in the following sub-section.

3. If required by the magnitude and length of time of parameter drift, initiate an impact assessment to determine the adequacy of NOP trip coverage.

4. Use the results of the impact assessment to derive a penalty factor, if required, for the NOP trip setpoint.

4.3.2 Impact Assessment for Sustained Parameter Drift

If the operating parameter has drifted systematically in a non-conservative direction to a new value, a means of assessing the impact is needed. A methodology is proposed for the calculation of the required NOP trip setpoint given a set of operating conditions at any point in time. A comparison can then be made to ensure the required trip setpoint remains above the installed setpoint, and hence allow for continued operation with the parameter at a new value or until the parameter can be returned to the nominal range.

As part of critical channel power calculations, sensitivity cases were considered. The CCPs are calculated for a reference thermal hydraulic model assuming reactor header conditions corresponding to nominal operating and modelling parameter values at a given aged core state. From this reference case, parameters are varied one at a time to determine the change in CCP value. Operating parameters such as reactor inlet header (RIH) temperature, reactor outlet header (ROH) pressure, header-to-header pressure drop[2], and pressure tube diametral creep are considered in the sensitivity cases. It is worthwhile to note that the range of operating conditions considered in the sensitivity cases then defines the range of applicability of this compliance tool.

The results of the sensitivity cases are used to derive the relative changes to the nominal core average CCP value (CCP_{ref}) such that for each unit of drift above/below the analyzed value, a corresponding percent change in CCP is known. Expressed mathematically:

$$\%\text{ Relative Change in CCP} = (\text{Delta CCP} / CCP_{ref}) * 100\% \qquad (4)$$

The relative change in CCP is equivalent to the relative change in the margin-to-dryout, and hence, the relative change in $TSP_{required}$. Therefore, the required trip setpoint can be expressed as

$$TSP_{current} = TSP_{required} \text{ x } (1 + \%\text{ Relative Change in CCP}) \qquad (5)$$

To determine $TSP_{required}$ the methodology outlined in Section 2 would be onerous to perform in each instance of parameter drift. However, the results of the NOP analysis generally provide the $TSP_{required}$ for more than one aged core condition (given in EFPD) such that a linear trendline between the required trip setpoint values can be used to interpolate the $TSP_{required}$ at any time.

The current trip setpoint, $TSP_{current}$ can be compared to the installed trip setpoint, $TSP_{installed}$, to assess the impact of the deviated operating parameters on the margin between required and installed trip setpoint.

This relationship could be implemented as a 'Compliance Tool' which allows a user to input the parameter values at a unique moment in time, such that the $TSP_{current}$ is automatically calculated and compared to the $TSP_{installed}$. In this way, the compliance tool is used as a

[2] Header to header pressure drop is directly proportional to FINCH flow, so that either parameter can be considered, but not both simultaneously as this would lead to double counting of the predicted change in the reference CCP.

surrogate for the full analysis (outlined in Section 2) in order to expedite impact assessments in support of plant operations.

The compliance tool may also be used on a more frequent basis as part of the fuel management and core surveillance activities to determine the required NOP setpoint adjustments (or required penalty factors via a Detector Calibration Factor) in the instance of operational parameter drift.

5. Conclusions

The enhanced NOP analysis methodology is statistical in nature and requires an appropriate compliance strategy to account for this. The three additions to the current compliance strategy documented in this paper are an enhancement to the existing compliance process via additional surveillance. It is important not to impose new compliance limits which may cause the station behaviour to deviate from the station operation data used in deriving the analysis assumption values. The strategy outlined in this paper allows for demonstration that compliance to the enhanced NOP analysis basis is maintained.

6. References

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