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Fixed Setpoints Introduce Error in Licensing Probability

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Abstract

Although we license fixed (constrained) trip setpoints to a target probability, there is no provision for error in probability calculations or how error can be minimized. Instead, we apply reverse-compliance preconditions on the accident scenario such as a uniform and slow LOR to make probability seem error-free. But how can it be? Probability is calculated from simulated pre-LOR detector readings plus uncertainties before the LOR progression is even knowable. We can conserve probability without preconditions by continuously updating field setpoint equations with on-line detector data. Programmable Digital Controllers (PDC's) in CANDU 6 plants already have variable setpoints for Steam Generator and Pressurizer Low Level. Even so, these setpoints are constrained as a ramp or step in other CANDU plants and don't exhibit unconstrained variability. Fixed setpoints penalize safety and operation margins and cause spurious trips. We nevertheless continue to design suboptimal trip setpoint comparators for all trip parameters.

Keywords: Fixed and Variable Setpoints, Licensing Probability, Error

1. Introduction

This paper focuses on Regional Overpower (ROP) probabilistic calculations because they are undoubtedly the most formal and elaborate in CANDU licensing. ROP is a network of in-core detectors placed judicially throughout the reactor and arrayed into 3 safety channels for each shutdown system. The relationship between probability and variable setpoints holds for the other trip parameters. Steam Generator and Pressurizer Low Level already have variable setpoints in CANDU plants. Even so, the setpoints are constrained as either a step or ramp and do not exhibit the correct unconstrained variability. The argument is often heard that these parameter setpoints are nevertheless "conservative". This must now be understood to also pose an increase in spurious trip frequency and premature aging related derating in the plant. The question then becomes, "are spurious trips at low power for the ion chamber high Lograte trip with a fixed setpoint or for Steam Generator Low Level with a ramped setpoint avoidable with unconstrained variable setpoints"? There is no fundamental distinction between safety and economic criteria with variable setpoints. We can also fully reconcile deterministic and probabilistic criteria. However, we continue to design over-constrained analog and digital trip setpoint comparators using under-defined safety analysis equations. Setpoints are now pseudo-solutions of these equations. No wonder they don't achieve optimal performance for either safety or spurious trip frequency.

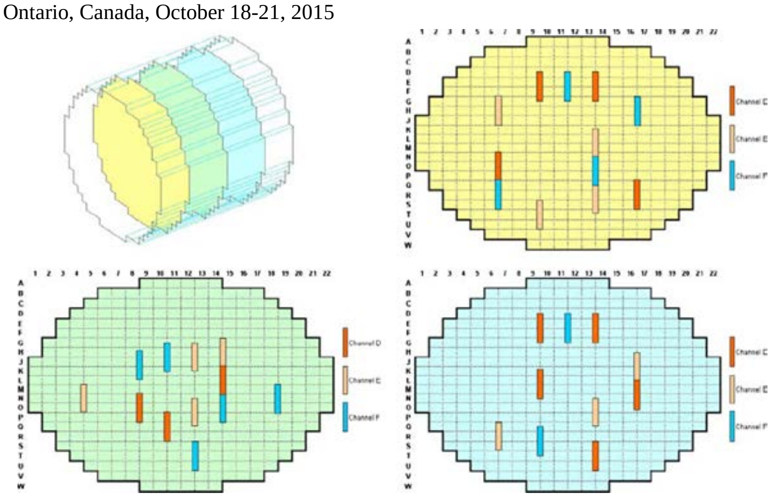

Figure 1 Typical CANDU Vertical Overpower Detectors and Channelization

2. Probability of Dryout

The dryout probability distribution Q is traditionally given by a product of the complement Normal distributions (1 - erf) for random fuel channel errors:

$$Q(x) = 1 - \prod_{j} 1 - \mathrm{erf}\left[\frac{x - \dfrac{cprl_j}{CPRL}}{\sigma_{d/o}}\right] \tag{1}$$

where:

erf	is the Normal distribution – integral of the Gaussian density
Q	is the probability distribution for dryout
$\sigma_{d/o}$	is fuel channel random dryout uncertainty
x	is the relative overpower error
j	fuel channel index
$cprl_j$	is critical power ratio of the fuel channel j
CPRL	is critical power ratio of the most limiting fuel channel

A correlated dryout error density, $\mathbf{q_c}(x)$, would need to be included by convolving it with the extremal dryout density, $\frac{dQ}{dx}$ to yield:

$$\frac{dQ'}{dx} = \int q_c(x') \frac{dQ}{dx}(x - x')dx' . \tag{2}$$

Since we are only interested in the general functional form of $\frac{dQ}{dx}$, we lose nothing in retaining Q instead of Q' as the final form.

3. Probability of Trip

The key driver of trip probability without regard to dryout, **P**, is safety margin (**SM_i**) given by:

$$\mathbf{SM_i} = \frac{\mathrm{CPRL}\boldsymbol{\Phi}_\mathbf{i}}{\boldsymbol{\Phi}_\mathbf{max}\mathbf{TSP_i}} \tag{3}$$

The safety channel trip probability distribution **P** is traditionally also given by a product of Normal distribution complements (1 - erf) for random detector errors:

$$\mathbf{P}(\mathrm{x}) = 1 - \prod_{\mathbf{i}} 1 - \mathrm{erf}\left[\frac{\mathbf{SM_i}\mathrm{x} - 1}{\sigma_{\mathrm{det}}}\right] \tag{4}$$

where:

P is the probability distribution of safety channel trip
i is detector loop designation within the safety channel
TSP_i is the trip setpoint for detector i
SM_i is the safety margin i.e. argument to trip probability before dryout (**Prob_sc**)
Φi is the reading of detector i of a particular design basis fluxshape
Φ_{max} is the maximum detector reading in the safety channel
σ_{det} detector random trip uncertainty

As with Dryout Probability, the convolution of the densities to include common errors would result in a new $\frac{d\mathbf{P'}}{dx}$ instead of $\frac{d\mathbf{P}}{dx}$. The error on **Φ**max is one example of a common random error. This is built into the licensing calculations. The form of **P** does not determine setpoint functionality.

For variable setpoints, we will see that the random detector uncertainty, σ_{det}, is 0. **P** becomes a step function. $\boldsymbol{\Phi}_{\mathbf{max}}$ may carry a non-zero correlated error. It is mathematically acceptable to have trip probability, **P**, as a step function or a Normal distribution with common (correlated) errors. The common detector calibration factor for $\boldsymbol{\Phi}_\mathbf{i}$ and $\boldsymbol{\Phi}_{\mathbf{max}}$, RP x CPPF, cancels out in $\mathbf{SM_i}$.
Note, Φ_i is any design basis fluxshape. Φ_i must apply equally whether it is a simulated snapshot for safety analysis or $\Phi_i(t)$ continuously available on-line. This point is conveniently left out from safety analysis although the safety requirements address the reactor and not safety analysis.

$$\mathbf{P_{cal}} = 1 - \prod_{\mathbf{i}} 1 - \mathbf{erf}\left[\frac{\mathbf{x} - \boldsymbol{\Phi}_\mathbf{max} / \boldsymbol{\Phi}_\mathbf{i}}{\boldsymbol{\Phi}_\mathbf{i}\boldsymbol{\sigma}_\mathbf{al}}\right]$$

Another common random error is to account for the calibration drift on the detectors. For this, d$\mathbf{P_{cal}}$/dx is convolved with d**P**/dx. This calculation occurs in the assessment code which we computes ***F***. Its purpose is for the setpoints to provide the 95% required probability. This can be conservatively correlated with fluxshape flatness ($\overline{\boldsymbol{\Phi}}_\mathbf{i} / \boldsymbol{\Phi}_\mathbf{max}$) and used to vary TSPo which has been shown for a single fluxshape only.

4. Probability of Trip Before Dryout

The equation for the probability of safety channel trip before dryout (**Prob_sc**) is:

$$\mathbf{Prob_{sc}} = \int \mathbf{P}\mathrm{d}\mathbf{Q} = \int \mathbf{P}[\mathbf{SM_i};\mathrm{x}]\frac{\mathrm{d}\mathbf{Q}}{\mathrm{dx}}\mathrm{dx} = \boldsymbol{F}[\mathbf{SM_i}] \tag{5}$$

where

P[**SM**$_i$;x]	is the safety channel trip probability distribution
Q[x]	is the dryout probability distribution
P and Q	are usually extremal of Normal distributions with convolved common densities
Prob$_{sc}$	is probability of a safety channel trip before dryout
F	transforms the input variable distribution Φ_i into **TSP**$_i$

Prob$_{sc}$ is the integral of probability of having the logic tripped (**P**) multiplied by the dryout probability increment (d**Q**) as shown in Figure 2.

The function ***F*** is symbolic in this paper. The numerical evaluation of ***F*** for fixed setpoints is performed by proprietary computer codes. The reason that it appears that ***F*** is only a function of the unknowns **SM**$_i$ and **TSP**$_i$ is that all other neutronic and thermalhydraulic data as well as the respective uncertainties are known and kept unchanged. The level and distribution of **SM**$_i$ and **TSP**$_i$ are unknown. Arbitrary setting of either of these parameters is not made. The variable setpoint methodology extracts unconstrained analytic solutions by applying ***F*** to the on-line Φ_i/Φ_{max} input data stream from the instrumentation. The resulting on-line **TSP**$_i$ output stream is sent to the analog or digital trip comparators.

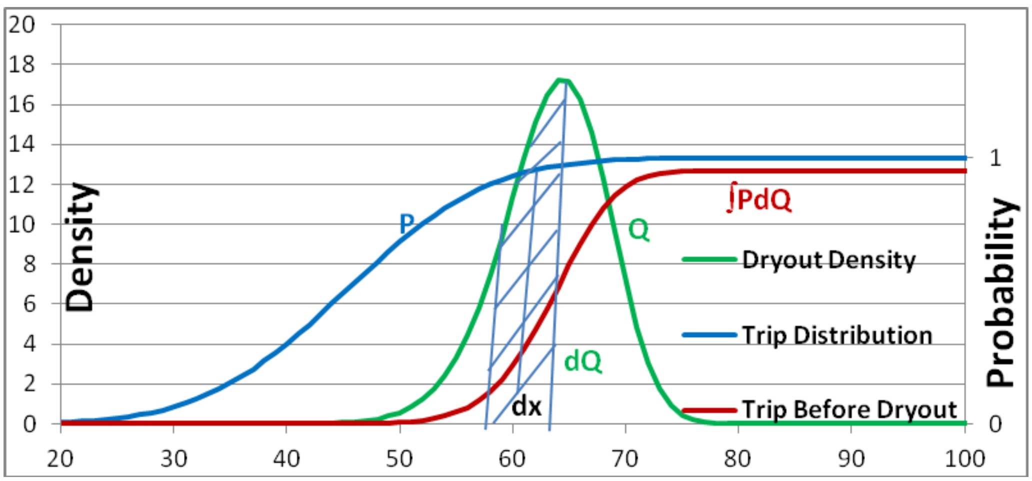

Figure 2 Probability of Trip before Dryout

It is noted **SM**$_i$ and **TSP**$_i$ cannot and must not be explicitly solved at this point by arbitrarily fixing one or the other parameter. There is insufficient information. We need more information - another equation. Fixed **TSP**$_i$ from safety analysis are arbitrarily constrained and are invalid solutions of Equation 3. **TSP**$_i$ are, nevertheless, arbitrarily taken from safety analysis, licensed and applied in the field. Variable setpoints defer determination of field setpoints until on-line readings are available. The breach of normal mathematical protocol with fixed pre-determined setpoints can only be averted with unconstrained instantaneous variable setpoints. The minimization of the error in probability justifying variable setpoints is given in Equation 11 and supplies the missing information and link.

F is now provided by probabilistic ROP codes for the fixed setpoint distribution supplied.

Note: the statistics of dryout remain unchanged from the traditional approach.

Only detector parameters shown in **bold** are unknown, but knowable, and are thus not random but real time variables in ***F***.

$\mathbf{Prob_{sc}}$, in Equation 5 seems to be a function of loop (**i**) within each safety channel, detector reading at that location ($\mathbf{\Phi_i}$), the maximum detector reading ($\mathbf{\Phi_{max}}$) in each safety channel and the yet to be determined trip setpoints ($\mathbf{TSP_i}$). CPRL offers a simple scalar linkage to the propagation of the dryout error implicit in the differential d**Q**[**x**].

The task is to find the dependence of probability on the independent parameters and isolate the condition which minimizes (or eliminates) the random detection epistemic error[1] as expressed by the differential of probability ($\Delta\mathbf{Prob}_{sc}$).

$$\Delta\mathbf{Prob_{sc}} = \sum \frac{\partial \mathbf{F}[\mathbf{SM_i}]}{\partial \mathbf{SM_i}} \Delta\mathbf{SM_i} \tag{6}$$

$$\Delta\mathbf{SM_i} = \mathbf{SM_i}\left[\frac{\Delta\mathbf{\Phi_i}}{\mathbf{\Phi_i}} - \frac{\Delta\mathbf{TSP}_i}{\mathbf{TSP}_i}\right] \tag{7}$$

The error $\Delta\mathbf{SM_i}$ can be set to zero as shown in Section 6 below. That lets the error in probability, $\Delta\mathbf{Prob}_{sc}$, also vanish. This has three consequences:

1. $\mathbf{SM_i}$ is constant (at a fixed probability), unique, optimal and invariant ($\Delta\mathbf{SM_i}$ = 0)
2. $\mathbf{Prob_{sc}}$ is also constant, optimal and invariant ($\Delta\mathbf{Prob}_{sc}$ = 0)
3. We have achieved Conservation of Probability between safety analysis and reactor data.

The analytic solution of $\mathbf{TSP_i}$ (Section 6) by setting Δ**SMi** = 0 is the basis of variable setpoints.

5. Fixed Setpoints

If $\mathbf{TSP_i}$ are kept fixed ($\Delta\mathrm{TSP}_i = 0$) as in the traditional methodology, then:

$$\Delta\mathbf{SM_i} = \frac{\mathrm{CPRL}\mathbf{\Phi_i}}{\mathbf{\Phi_{max}}\mathrm{TSP}_i}\frac{\Delta\mathbf{\Phi_i}}{\mathbf{\Phi_i}} \qquad \text{or} \qquad \frac{\Delta\mathbf{SM_i}}{\mathbf{SM_i}} = \frac{\Delta\mathbf{\Phi_i}}{\mathbf{\Phi_i}} \tag{8}$$

With fixed setpoints $\Delta\mathbf{SM_i}$ is non-zero because there is random relative error in the flux simulations i.e. $\frac{\Delta\mathbf{\Phi_i}}{\mathbf{\Phi_i}}$. The LOR evolution cannot be known at licensing time and field setpoints, because they are fixed, are not allowed to be updated in the field. We have thus created epistemic detector random error. The invariability of setpoints must impose not only a penalty in fixed setpoint level ($2\boldsymbol{\sigma}_{\mathbf{det}}$) but also in probability of covering a non-uniform LOR. We cannot just rule out these penalties as in our arbitrary and restricted definition of LOR. Fixed setpoints are not unique, optimal or invariant. They are not correct mathematically and do not apply in the field.
They are useful for fictional accident scenario using fictional data from a fictional reactor.

Fixed setpoints mean that a finite $\Delta \mathbf{SM_i}$ will have contribution to trip probability before dryout ($\Delta \mathbf{Prob_{sc}}$). That is over and beyond what was calculated in safety analysis without knowing the space-time evolution of an actual LOR. The assumption of random detector error affecting setpoints is completely due to fixed setpoints and thus avoidable.

6. Elimination of Probability Error

Let us turn the error increments (Δ) in $\frac{\Delta \mathbf{\Phi_i}}{\mathbf{\Phi_i}} - \frac{\Delta \mathbf{TSP}_i}{\mathbf{TSP}_i} = 0$ (9)

to differentials (d) and solve:

$$\int \frac{d\mathbf{\Phi_i}}{\mathbf{\Phi_i}} = \int \frac{d\mathbf{TSP}_i}{\mathbf{TSP_i}} \tag{10}$$

This gives us the slow LOR setpoint to cover an LOR exactly as in safety analysis ($\Delta \mathbf{Prob_{sc}} = \mathbf{0}$):

$$\mathbf{TSP}_i = \mathrm{TSP_o} \frac{\mathbf{\Phi_i}}{\mathbf{\Phi_{max}}}. \tag{11}$$

This form applies in safety analysis ($\mathbf{SM_i}$ = k) and on-line.

The main issue with the assumption of slow LOR is that on a ~10%/s rate of power increase, the safety margin is eaten up in the overshoot between logic trip and reactor trip about 1 s later.

To compensate for overshoot, reactor variable setpoints are decreased by the detector reading increase ($\Delta\Phi$i) in one second (Δt=1s):

That is, $\Delta \mathbf{\Phi_i} = \frac{d\mathbf{\Phi_i}}{d\mathbf{t}} \Delta \mathbf{t}$ where Δt = 1 s. (12)

$$\mathbf{TSP}_i = \mathrm{TSP_o} \frac{\mathbf{\Phi_i} - \frac{d\mathbf{\Phi_i}}{d\mathbf{t}}}{\mathbf{\Phi_{max}}} \tag{13}$$

6.1. Similarity with Ideal Gas Law Solution

A similar situation for the solution of under-defined setpoint equation is encountered in the Ideal Gas Law. The equations are given in Table 1 below.

Ideal Gas Law	Setpoint Equation
$\mathbf{PV = nRT}$	$\mathbf{SM_i} = \frac{\mathrm{CPRL}\mathbf{\Phi_i}}{\mathbf{\Phi_{max} TSP_i}}$

Table 1 Two Under-Defined Equations

These equations each apply in two different states. The thermodynamic states of the Ideal Gas Law are (before or State 1, after or State2) × (V, P,T) = (V_1, P_1,T_1) and (V_2, P_2,T_2). The solutions for the two stated processes (isentropic, isobaric) are shown in Table 2 below.

	Constant	Known Ratio	P_2	V_2	T_2
Isentropic process (Reversible adiabatic)	Entropy PV^{γ}	P_2/P_1	$P_2 = P_1$	$V_2 = V_1(P_2/P_1)^{(-1/\gamma)}$	$T_2 = T_1(P_2/P_1)^{(\gamma - 1/\gamma)}$
		V_2/V_1	$P_2 = P_1(V_2/V_1)^{-\gamma}$	$V_2 = V_1(V_2/V_1)$	$T_2 = T_1(V_2/V_1)^{(1-\gamma)}$
Isobaric process	Pressure P	V_2/V_1	$P_2 = P_1$	$V_2 = V_1(V_2/V_1)$	$T_2 = T_1(V_2/V_1)$
		T_2/T_1	$P_2 = P_1$	$V_2 = V_1(T_2/T_1)$	$T_2 = T_1(T_2/T_1)$

Table 2 Some Solutions for Ideal Gas Laws

The setpoint states are (safety analysis-SA) and (real time-r/t) × ($TSP_{i,}$ SM_i) = ($[TSP_i]_{SA}$, $[SM_i]_{SA}$) and ($[TSP_i]_{r/t}$,$[SM_i]_{r/t}$). The solutions of safety margin, $\mathbf{SM_i}$, and loop **i** setpoints, $\mathbf{TSP_i}$, for safety analysis and real time are shown for both the assumed invariance of safety margin and thus probability as well as fixed setpoints in Table 3 below. The latter represents the status of fixed setpoints from safety analysis applied exactly in the reactor. By fixing the setpoint from safety analysis we cannot maintain the licensing probability in the reactor. That is because the simulated flux is assumed to increase uniformly while the actual flux is independent and drives variable setpoints at a fixed safety margin or probability.

Invariance	Status of SM_i and $Prob_{sc}$	Solutions of TSP_i or SM_i
Probability $[Prob_{sc}]_{r/t} = [Prob_{sc}]_{SA}$	$[SMi]_{r/t} = [SM_i]_{SA} = SM_o$ $\mathcal{F}[SM_i]_{r/t} = \mathcal{F}[SM_i]_{SA} = \mathcal{F}[SM_o]$	$[TSPi]_{r/t} = TSP_o[\Phi_i/\Phi_{max}]_{r/t}$ $[TSPi]_{SA} = TSP_o[\Phi_i/\Phi_{max}]_{SA}$
Setpoint $[TSP_i]_{r/t=} [TSP_i]_{SA}$	$[SMi]_{r/t} \neq [SM_i]_{SA}$ $\mathcal{F}[SM_i]_{r/t} \neq \mathcal{F}[SM_i]_{SA}$	$[SMi]_{r/t} = [SM_i]_{SA} \dfrac{[\Phi_i/\Phi_{max}]_{r/t}}{[\Phi_i/\Phi_{max}]_{SA}}$ $[SMi]_{SA} = [SM_i]_{r/t} \dfrac{[\Phi_i/\Phi_{max}]_{SA}}{[\Phi_i/\Phi_{max}]_{r/t}}$

Table 3 Solutions for Safety Margin and Setpoints

In each case, we have one equation but several unknowns. We can simply pretend that both states are identical in these applications. For the Ideal Gas Law, we can specify more than one particular process e.g. isentropic that constrains both states because we have 4 unknowns. The safety margin equation, having only 2 unknowns/loop (TSP_i, SM_i) thus requires only one process. That process is the long forgotten requirement of "equal probability". Since probability (of trip before dryout) is $\mathbf{Prob_{sc}}$ = $[\boldsymbol{F}[\mathbf{SM_i}]]_{SA}$= $[\boldsymbol{F}[\mathbf{SM_i}]r/t$, the inverse, $[\mathbf{SM_i}]_{\mathbf{r/t}}$ = $[\mathbf{SM_i}]_{\mathbf{SA}}$ = $\boldsymbol{F}[SM_o]$ really imposes a strong condition on each loop of both states to be identical (SM_o). This links the calculated safety analysis probability imposing it on the reactor in real time. This is achieved by simply scaling the filed setpoint, $\mathbf{[TSPi]_{r/t}}$, to the actual $[\mathbf{\Phi_i}]_{\mathbf{r/t}}$. This forces the licensing probability which used $[\mathbf{\Phi_i}]_{\mathbf{SA}}$ to be identical.

To demonstrate the plausibility of these results is simple: Substitute Equation 11 into Equation 3. When we do, we end up with the following result:

$$SM_o = \frac{CPRL}{TSP_o} \tag{14}$$

The vector $\mathbf{SM_i}$ is replaced by the scalar SM_o. This result states that the safety margin for any given fluxshape and therefore the licensing probability is invariable. We achieve the same result if had whether for simulated data or on-line real time data. In other words, $\mathbf{\Phi_i}$ in safety equations refers to both:

- $[\mathbf{\Phi_i}]_{\mathbf{r/t}}$ the real time output of the detectors, and
- $[\mathbf{\Phi_i}]_{\mathbf{SA}}$ the safety analysis simulation

We cannot pick and choose one or the other – we need both. With this result, we can pre-compute licensing probability <u>but</u> we cannot pre-determine the setpoints. These need to be generated in real time. This is the step that guarantees that variable setpoints in the field carry no error but fixed setpoints must. This corresponds exactly to the principle of variable setpoint for BWR overpower. One cannot know at licensing time, when the setpoints are normally fixed, what the core flow will be at any particular time. We have always known that we cannot pre-determine BWR overpower setpoints. This principle now unifies all trip setpoints. None can be assumed to be fixed.

6.2. <u>**Economic and Safety Margins**</u>

The safety margin is not invariable i.e. is dependent on loop detector readings for fixed setpoints (usually constant). If the vector $\mathbf{TSP_i}$ is replaced by the scalar TSP, the safety margin $\mathbf{SM_i}$ remains a vector because $\mathbf{\Phi_i/\Phi_{max}}$ is the vector of detector reading distribution and beyond manipulation of safety analysts.

$$\mathbf{SM_i} = \frac{CPRL\mathbf{\Phi_i}}{\mathbf{\Phi_{max}}TSP} \tag{15}$$

Also, safety analysis normally covers 1000 flux distribution for licensing. Assuming that the fixed setpoint distribution actually matched <u>one</u> of the 1000 different fluxshapes which yields a scalar SM_o, there would be 999 others for which there would be scatter in the safety margin ratio. Scatter in $\mathbf{SM_i}$ has two other bad features which are inescapable.

- Higher values have larger contributions to licensing probability and spurious trips
- Lower values have smaller contributions to licensing probability and spurious trips

Both of these effects occur in at least 999 out of 1000 fluxshapes and simultaneously hurt both safety and operating margins. Since variable setpoints avoid scatter, they lessen both safety and operating problems. On this basis, what the ISA67.04 standard says about avoiding over-conservative setpoints also applies under-conservative setpoints.

7. Missing Probability Law

Safety Analysis data alone cannot supply unique trip setpoints – only the trip setpoint function. That is, the functional relationship between trip setpoints and detector readings. This must remain in force in safety analysis and in the field. The maximum portion of trip setpoints (TSP_o) is a part of the functional relationship and, as will be shown in a later paper, is itself dependent on a scalar function of fluxshape. Field trip setpoints can thus be generated on-line via suitable analog or digital instrumentation. What is missing in fixed setpoints is the application of proper mathematical protocol, information theory, generalized information theory and Noether's Theorem covering symmetries and conserved quantities. Conservation of Probability demands that setpoints be correlated with flux detector readings so that licensing probability from safety analysis actually applies with corresponding field variables. This is, after all, the only real licensing requirement. We should be preserving safety analysis probability not arbitrary safety analysis setpoints. Fixed setpoints guarantee that licensing probability is not preserved in the reactor. The added drop in safety and operating performance merely heighten the overall ineffectiveness of fixed setpoints.

7.1. Algebraic Solution

An additional equation solve algebraically for field trip setpoints, is to directly equate the probability calculated with safety analysis data with that using the on-line plant data stream as it becomes available in real time.

$$\mathbf{Prob}_{SC} = \boldsymbol{F}\left[\frac{\mathrm{CPRL}\cdot\boldsymbol{\Phi}_i}{\boldsymbol{\Phi}_{\mathbf{max}}\mathbf{TSP}_i}\right]_{\mathbf{SA}} = \boldsymbol{F}\left[\frac{\mathrm{CPRL}\cdot\boldsymbol{\Phi}_i\mathbf{(t)}}{\boldsymbol{\Phi}_{\mathbf{max}}\mathbf{TSP}_i}\right]_{\mathbf{r/t}} = 95\%$$

A unique solution for field setpoints is reached by taking the inverse of $\boldsymbol{F}$ and noting that there can be one Φ_i/TSP_i ratio for all detector loops in safety analysis and in real time. This directly gives us the field trip setpoint solution given by Equation 16. The same function also applies to safety analysis as shown in Equation 17. This confirms the Conservation of Probability algebraically.

$$\left[\mathbf{TSP}_i\right]_{\mathbf{r/t}} = \mathrm{TSP}_o\left[\frac{\boldsymbol{\Phi}_\mathbf{i}}{\boldsymbol{\Phi}_{\mathbf{max}}}\right]_{\mathbf{r/t}} \tag{16}$$

$$\left[\mathbf{TSP}_i\right]_{\mathbf{SA}} = \mathrm{TSP}_o\left[\frac{\boldsymbol{\Phi}_\mathbf{i}}{\boldsymbol{\Phi}_{\mathbf{max}}}\right]_{\mathbf{SA}} \tag{17}$$

8. Theoretical ROP Benchmark Expectations

To demonstrate the underlying theory, let us turn to ROP benchmarks of the past using traditional fixed setpoints. From the definition of probability of trip before dryout, Equation 5, we can derive the theoretical probability expectation function for dryout with N identical fuel channels or trip with N identical detectors. The setpoints can be worked out numerically when imposing a given probability target. The probability expectation formulae are shown below. It is left to the holders of the data to check these functions against actual benchmark results.

8.1. Benchmarks with Dryout Errors Only

$$\mathrm{Prob}_{fc} = \left[\mathrm{erf_c}\left(\frac{\mathrm{TSP}-1}{\sigma_{d/o}}\right)\right]^N \tag{18}$$

The parameters in these functions are:

Prob_{fc} is probability of trip before dryout from random fuel channel errors
TSP is the common fixed trip setpoint
$\sigma_{det} = 0$ detector random trip uncertainty assumed as zero
N is Number of fuel channels

8.2. Benchmarks with Trip Errors Only

$$\mathrm{Prob}_{det} = 1 - \left[\mathrm{erf_c}\left(\frac{1-\mathrm{TSP}}{\sigma_{det}\mathrm{TSP}}\right)\right]^N \tag{19}$$

The parameters in these functions are:

Prob_{trip} is probability of trip before dryout from random detector errors
$\sigma_{d/o} = 0$ fuel channel random dryout uncertainty assumed as zero
Prob_{det} is probability of trip before dryout from detector random errors
N is Number of detectors
σ_{det} detector random trip uncertainty

9. Conclusions

. The main overall conclusions are:

1. Fixed setpoints introduce error on probability and don’t satisfy the licensing requirement
2. Variable setpoints carry no error on probability and thus satisfy the licensing requirement

The detailed conclusions are listed below:

1. Variable setpoints are analytic functions and which can only be evaluated in the field.
2. Variable ROP trip setpoints are proportional to the detector reading distribution.
3. ROP trip setpoints and detector readings are correlated. What about causality?
   a. Variable setpoints depend on detector readings during the LOR. Reasonable.
   b. Detector readings depend on fixed trip setpoints during the LOR? Not physical.
4. If the LOR is truly uniform, ROP variable setpoints will not change.
5. If the LOR is not uniform, ROP variable setpoints are updated to reflect readings.
6. The operating margin with variable setpoints is always uniform.
7. The operating margin with fixed setpoints is very non-uniform.
8. The detector firing order is the key to optimality of variable setpoints.
   a. All detectors in each safety channel fire simultaneously.
   b. No detector trails another – best safety performance.
   c. No detector leads another – best economic performance.
9. Lack of scatter in detector firing means that safety and economic criteria are the same.
10. Trip is only meaningful for the safety channel – not individual detectors.
11. We need not assume a slow LOR because the rate of increase reduces variable setpoints.

10. Discussion

Fixed ROP trip setpoints are “frozen” to assumed LOR detector readings and lead to error in calculated licensing probability. This is due largely to two assumptions:

1. Initial detector readings are known with an uncertainty (σ_{det}).
2. Detector readings progress uniformly during the LOR.

Both of these assumptions are wrong.
The on-line detector readings before, during and after the LOR are tracked exactly ($\sigma_{det} = 0$) but ignored in fixed trip setpoints.
As a consequence:

1. There is a needless loss of $2\sigma_{det}$ in trip margin for peaky fluxshapes
2. Detector readings during a LOR are tracked and could update the setpoint distribution
3. Only fantasy enforces a uniform (regulated) power increase during a loss of regulation

Although fixed setpoints suffer a loss of $2\sigma_{det}$ in operating margin due to some unrelated limiting case, the uniformity of an LOR is determined from the reactor physics of the event and remains unaddressed. The LOR is not repeatable. Each LOR may proceed in different ways. Uniformity of the LOR is addressed neither deterministically nor probabilistically. The reactor physics of the LOR are deterministic. They are not statistical in nature. Uniformity of the LOR can only be imposed on safety analysis. Uniformity can be pre-determined no better than a weather forecast or a roll of dice. The assumption of uniformity has no longer a place in licensing given the fact that detector readings are streaming in real time and trip setpoints could be simply and safely modulated below a maximum (TSP_o) which can be pre-determined and licensed.

That is, we can calculate the probability in the field using on-line detector readings symbolically. Probability is not the same as fixed setpoints. This situation is completely averted by defining a setpoint functionality which removes the detector identity in safety margin. This translates to scaling field setpoints directly with on-line reading distribution. This is done in safety analysis to compute licensing probability. The same setpoint algorithm must be executed in real time in the field to preserve licensing probability. Fixed or constant trip setpoints was easy to implement with analog instrumentation but do not preserve licensing probability. On the other hand, variable setpoints involve a little more work in the field but do preserve licensing probability and improve both safety and economic margins. Licensing probability is what we license to preserve in safety analysis. To preserve setpoints at the expense of probability is a poor substitute.

Because licensing probability is maximized with variable setpoints ($d\mathbf{Prob}_{sc} = 0$), the nature of the error to which I refer is more of a bias or better yet an avoidable mistake. That is to say, it is one sided but would have been two sided (±) if it were truly random. The error vanishes with variable setpoints. As such, it is the undisclosed deviation in detector readings relative to a uniform LOR. This is not a statistical phenomenon. We need to stop hiding behind statistical smokescreens. This is relevant data that is deliberately disregarded for setpoints. It is a quantifiable amount during each and every LOR. There is no safety or economic reason that we slap on a one time penalty in trip margin of questionable effectiveness to attempt to cover it off. With HTS aging, trip setpoints are reduced and this error first shows up silently as derating. We have the worst of both worlds satisfying neither safety nor economy. Obviously, the fixed setpoint methodology and accompanying error analyses are too simplistic and faulty.

To make a final point on the futility of fixed setpoints, why should we have the same setpoint on all detectors to protect a very peaky fluxshape? Stated another way, why maintain pre-determined fixed setpoints that <u>allow</u> only one covering detector out of 19 per safety channel for peaky fluxshapes? Where is robustness and redundancy? Why put all the eggs in one basket?

A further reminder of the inadequacy of fixed setpoints, is reactor derating with aging. The setpoint is “fixed” for the limiting case which is all adjusters <u>out.</u> Why does this affect operating with all adjusters in? Can adjuster banks randomly appear or disappear inside the reactor? Are fluxshapes and flux detector readings truly random? Are we hiding behind probability and statistics to cover off things that seem random in the myriads of safety analysis fluxshape simulations but which are easily and clearly seen by <u>the</u> on-line detector readings? Do we really have the right to interpret that $\mathbf{\Phi_i}$ in setpoint equations refer to simulations but not actual on-line reactor readings? Since when does the abstraction take precedence over the real thing? Surely for consistency, the on-line readings should simultaneously drive both the signals and the setpoints. Safety margin ($\mathbf{SM_i}$) and licensing probability ($\mathbf{Prob_{sc}}$) become invariant or independent with respect to detector loop and detector reading.

11. <u>References</u>

[1] F.A.R. Laratta, “Variable ROP Setpoints Remove Random Epistemic Detector Error”, <u>Proceedings of the 34th Annual Conference of the Canadian Nuclear Society</u>, Toronto, Ontario, Canada, 2013 June 9 -12