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General Comment

Dear Carol,

I worked with AECL from 1974 until my retirement in 2004 and am very familiar with the generation of trip setpoints for 2 parameters in CANDU plants Regional Overpower (ROP) and low Steam Generator Level (SGL) for both shutdown systems. I do not have any experience with light water reactors, so I must use CANDU terminology which seems very compatible with ISA67.04. Overpower has fixed setpoints while SGL has variable ones. Six years ago, I started to promote a radical idea that setpoints are only pre-determinable functions of simulated parameters in safety analysis and the setpoint values can then be evaluated as the pre-determined function of the equivalent online parameters. In other words, all trip setpoints are variable in nature. Also, there can be no trip setpoints without on-line parameters. Does a non-operating reactor need a fixed setpoint for protection?

Trip setpoints should be the most general solution of the safety margin equation (e.g.SMi= CPRL DRi/(DRmax TSPi) for Overpower and SM = TSPSG - fc[RP] for Steam Generator Level) without preconditions on the accident scenario parameters (DRi/DRmax or RP) and on setpoints giving optimal probability of trip, F[SMi] = K and G[SM] = K.

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Add= P. J. Rebstock (PJR1)
M. ORR (mpO1)

Current setpoint are (with some exceptions) numerical values constrained by designers to remain fixed from safety analysis to the field. They are too inflexible to cater to multiple fluxshapes independently of safety margin. We have abandoned unconditional compliance of safety analysis to the field and do not even address criteria for optimal probability in the field. There is insufficient information in safety analysis to justify either a fixed or a particular variable solution.

Current setpoint distributions are not solutions of any safety equations but fixed to a unique fluxshape by designers.

Safety analysis is presently incapable of determining setpoints because more information is required that can be available during safety analysis. It currently lacks the equivalent of running a assessment code to adjust setpoint in real time variable setpoints but constant probability.

The imposition of fixed setpoints is what simultaneously creates economic penalties in most cases and unverifiable pre-conditions on safety analysis for others.

I am attaching three documents that make the analysis case that I make above with CANDU style analysis.

A paper given at the 2013 CNS Conference in Toronto (Section 1 - 7 in particular)
Letter on futility of determining setpoints using safety analysis alone written to CANDU utilities and CNSC
Previously unsent letter with notes on methodology and comparison to ISA67.04 warning to designers
Please read these documents and after clearing up any initial problems and questions, we can discuss and debate the matter of determining trip setpoints.

he dichotomy of fixed and variable trip setpoints is currently a dilemma and should raise questions on setpoint methodology. Who determines whether setpoints are designed as fixed or variable? What criteria must be used? Have we missed something in original fixed methodology? For example, how can we be sure the actual loss of regulation will follow exactly the one pre-simulated and assessed in safety analysis? Should we apply a further uncertainty allowance for deviation from predetermined probability calculations? How is the regulator supposed to oversee this murky process? To what extent can we make a statement of Compliance before the accident scenario unfolds?

The variable setpoint function can only be determination in safety analysis and then licensed. The setpoint evaluation is always a simple analytical process involving on-line parameters. The generation of fixed setpoints and making sure they remain fixed in the plant at those values is a traditional method from the days of analog instrumentation. Now that we can use a variety of technologies to update the setpoint distribution in the plant, is this the only or best way to achieve convergence between simulated loss of regulation and a real one? Why not force the safety analysis probability calculation to be the same as that during a loss of regulation regardless of scenario?

In short, the present probabilistic methodology is not totally wrong but it is only half right. The same

probabilistic calculation should be used in real time replacing the fixed simulated flux readings with real time ones. In this way, the setpoints are allowed to vary in a safe manner to maintain the calculated and licensed probability. Currently we do the reverse: we maintain the calculated setpoints but allow the probability to vary as a function of the parameters in the actual accident scenario.

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Attachments

Safety Analysis Alone Cannot Determine Trip Setpoints-rev

CNS Paper on Variable ROP Setpoints-pdf

Questions about Safety Analysis (1)

Safety Analysis Cannot Pre-Determine Setpoints

Frank Laratta - August-18-14

In licensing trip setpoints, originally using analog instrumentation, we have lost track of a basic mathematical dilemma – there is insufficient information during safety analysis (SA) to pre-determine fixed setpoints. Determining trip setpoints requires more "information" than can exist in safety analysis alone. We can only pre-determine "variable setpoints" as a function of monitored safety parameters. This function is then evaluated numerically to yield trip setpoints used to enforce them in real time. I will focus my discussion on the reactor or neutron overpower trips (ROP/NOP) and corroborate it with Steam Generator Low Level trips. This parameter has had differing variable setpoint designs in CANDU for decades.

The easiest way around the impasse for ROP setpoints (TSP_i) is to also symbolically consider detector readings tracked in real time $[\Phi_i]_{r/t}$. With this extension, there is enough information to solve setpoints analytically. The linkage of real time detector readings from safety analysis to real time is to set probability or safety margins equal ($[SM_i]_{SA} = [SM_i]_{r/t}$) in a functional relation. This function could calculate variable setpoints in real time via, for example, a microprocessor. Fixed setpoints are only simple estimates of achievable setpoints . To make this claim more clearly, I shall summarize the main probabilistic equations outlined in the Appendix below.

Safety margin, SM_i given in Equation 4, is the main driver of probability of trip before dryout for any single fluxshape. However, it is one equation in two unknowns (SM_i, TSPi) per instrument loop i. Pre-determined or "fixed" setpoints are, therefore, a violation of basic mathematical protocol and information theory. Setpoints cannot be fixed a priori in safety analysis because the exact starting fluxshape and evolution of the LOR in time cannot be known beforehand. What constitutes an LOR and to what probability can it be protected? This information cannot be captured from a single "fixed" pre-LOR snapshot simulation of the fluxshape at steady-state from safety analysis. This is the reason behind the superfluous restrictions of a slow and uniform LOR we now make. The reactor is not bound these restrictions. This fuzzy indeterminacy in setpoints and LOR also explains, in my view, why CNSC drafted the Risk Informed Decision Making (RIDM) document. It is a tacit recognition that the definitions of the LOR and setpoints are linked and missing.

Safety analysis can only legitimately determine TSP_o - the "maximum" allowable setpoint for the highest reading detector. However, we arbitrarily and mistakenly apply TSP_o for all detector setpoints. To arrive at a proper setpoint solution, we would need to incorporate available information to yield a "fixed" safety channel probability, say: $F[SMi]_{SA} = 95\% = F[SMi]_{r/t}$. The function F includes all other unchanged analysis inputs and uncertainties. This new process eliminates the indeterminacy by continuously providing new detector data and updating slow LOR setpoints as: $[TSP_i]_{r/t} = TSP_o\ [\Phi_i/\Phi_{max}]_{r/t}$ (Equation 5). Variable setpoints allow a simple algebraic solution that retains the calculated trip probability thus assuring compliance in the field. Variable setpoints answer definitively the troubling questions: What should the setpoint distribution be and what should it not? As an added benefit, trip margins increase by eliminating penalties of detector randomness - epistemic error each fluxshapes and the aleatory calibration contribution of limiting fluxshapes onto nominal. Random detector uncertainty is not the simulation uncertainty in safety analysis but a direct function of field setpoint distribution. Uncertainty cannot be preset independent of setpoint design. The light water reactor setpoint

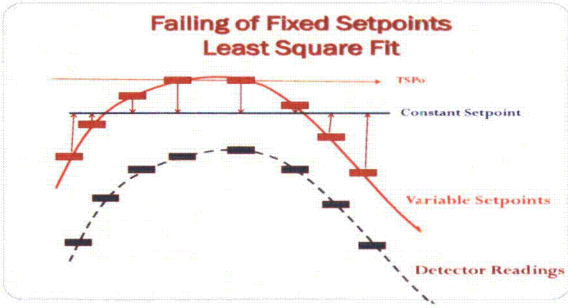
standard ISA67.04 warns designers about "over-conservatism" in defining setpoints but does not quantify or eliminate it. A similar indeterminacy affects all trip parameter setpoints.

The need for a variable setpoint for Steam Generator Low Level was recognized and reflected in the several CANDU plants. The variable setpoint curves in the CANDU 6 PDC's (Figure 1), Bruce and trip computers in DNGS are differing functions of reactor power [RP]. Fixed setpoints would otherwise cause needless lapse of safety at high power and spurious trips at low power.

I have reached these conclusions by several different analytical methods. One of these is the simple algebraic method outlined in my 2013 CNS Conference paper: **Variable ROP Setpoints Remove Random Epistemic Detector Error** and summarized in the Appendix. As corroboration of the general indeterminacy problem, setpoint design is acknowledged to be intrinsically difficult and not part of the ISA67.04 standard used to determine light water reactor trip setpoints. In addition, we can now input an arbitrary setpoint distribution into ROVER-F to yield fixed setpoints. These achieve the required licensing probability but will seriously and unnecessarily erode economic performance. The industry has never discussed adequacy of a particular setpoint design or acknowledged there may be an optimal to compare or adopt. We use the correct safety equations but admit only fixed setpoints solutions. Fixed setpoints are the result of a pseudo-statistical treatment of simulated detector readings allowing us to bypass on-line detector data during the LOR. The question becomes is a randomness what we cannot know or prefer to ignore? EVS has erroneously attempted to replace and extend prudent statistical methods to justify raising trip margins without first questioning underlying setpoint design methods. What we lacked in the past is a fundamental setpoint solution using both on-line detector data and simulations. A trip computer could easily and safely update setpoints (Equation 6) in real time at a fixed licensing probability and maximum allowable value for any rate of increase of power. In addition, Equation 6 suggests the lograte trips change setpoint functionality and remove the artificial lower bound cut-off rates of 10%/s and 15%/s on coverage of LOR from low power.

I did not fully appreciate the scale of the "indeterminacy" until 2011 and it only played a minor role in my original criticism of EVS. I tried to convey some of these sentiments in the presentation to CNSC staff "**What Really Ails ROP?**" on Jan 25, 2012 but it may have seemed to be off topic from the question at hand of EVS. I believe the setpoint indeterminacy issue has a higher priority than EVS and affects light and heavy water safety analysis world-wide. I also offer a simple algebraic method of solution and unconstrained variable setpoint designs for ROP (Equation 6) and Steam Generator Low Level (Equation 12). There are a few minor additional issues related to variable setpoints that impact licensing. We can best address them in the future.

We now prefer to penalize fixed setpoints for using simulated data while at the same ignoring available true detector readings. A fixed setpoint is a least square fit of a horizontal straight line through true data points. The scatter is from the inappropriate fitting process and not in the data.



If my conclusions on variable setpoints are rejected by the nuclear industry, what are the reasons? In addition, what is the technical basis of maintaining "fixed" ROP setpoints? Fixed setpoints reduce both operating and safety margins. Steam Generator Low Level in most CANDU reactors has long had variable setpoints. The questions then arise:

- are variable setpoints the rule or the exception for safety design?
- how exactly do fixed setpoints maximize trip probability?
- shouldn't we maintain calculated trip probability instead setpoints in the field?

Setpoints determine safety design and economic performance but should also be a balance of deterministic and valid probabilistic criteria. I welcome further discussion and correspondence.

Appendix

Safety Analysis - ROP

The calculation of probability of trip before dryout requires three basis parts:

1. probability of any fuel channel dryout (**Q[x]**) (shown for random error only)

$$\mathbf{Q(x) = 1 - \prod_{j} 1 - erf\left[\frac{x - \dfrac{cpr_j}{cprl}}{\sigma_{d/o}}\right]} \qquad \text{Equation 1}$$

2. probability safety channel trip **(P[SMi,x])** (shown for random error only):

$$\mathbf{P(x) = 1 - \prod_{i} 1 - erf\left[\frac{x - \dfrac{1}{SM_i}}{\dfrac{\sigma_{det}}{SM_i}}\right]} \qquad \text{Equation 2}$$

3. $$\mathbf{Prob_{TBD} = F[SMi] = \int P dQ = \int dP \frac{dQ}{dx} dx} \qquad \text{Equation 3}$$

where:

Prob$_{TBD}$ probability of trip before dryout

SMi safety margin (relative)

i is detector index (in safety channel)
j is fuel channel index
cpr rippled critical power ratio
cprl limiting rippled critical power ratio
CPRL generalized limiting time average critical power ratio ($CPRL^{100\%} \cdot \Phi_{max}^{100\%}$)
$\sigma_{d/o}$ fuel channel random uncertainty

Correlated error densities combine by convolution with the respective densities $\frac{dP}{dx}$ and $\frac{dQ}{dx}$.

$$\mathbf{SM_i} = \frac{\mathrm{CPRL} \cdot \Phi_i}{\Phi_{max} \mathbf{TSP_i}} \qquad \text{Equation 4}$$

where:
Φ_i normalized detector reading for loop **i**
Φ_{max} normalized detector reading for loop with highest reading
x normalized reactor overpower

Only the $\mathbf{SM_i}$ and $\mathbf{TSP_i}$ are considered the key variables because:

- $\mathbf{SM_i}$ directly drive probability
- $\mathbf{SM_i}$ and $\mathbf{TSP_i}$ are unknown
- all other licensing data remains as in the function **F** evaluated in safety analysis.

Regardless of the exact form of **F**, several conclusions follow:

1. The distribution of setpoints ($\mathbf{TSP_i}$) cannot be pre-defined uniquely
2. Only the maximum of the setpoint distribution is unique; TSP_o
   a. k is varied until probability is, say 95%
   b. TSP_o applies only to Φ_{max} for each perturbation from safety analysis
3. Pre-calculated $\mathbf{TSP_i}$ not invariant but $\frac{\Phi_i}{\mathbf{TSP_i}} = \frac{\Phi_{max}}{TSP_o}$: $[TSPi]_{SA}$ irrelevant in the field
4. Safety Analysis specifies setpoint function: it is evaluated during reactor operation
5. Setpoint for slow LOR must be continually be revised as flux changes:
   $$[\mathbf{TSP_i}]_{r/t} = TSP_o \left[\frac{\Phi_i}{\Phi_{max}} \right]_{r/t} \qquad \text{Equation 5}$$
   Aren't setpoints said to be a function of fluxshape?
6. Uniform LOR is an artifact of a single snapshot and not using actual flux for setpoints
7. For improved fast LOR or LBLOCA coverage:
   $$[\mathbf{TSP_i}]_{r/t} = TSP_o \left[\frac{\Phi_i - \frac{d\Phi_i}{dt}}{\Phi_{max}} \right]_{r/t} \qquad \text{Equation 6}$$
8. Small sample statistics should be applied to fixed setpoints for peaky fluxshapes

Real Time

Reactor trip setpoints can be solved continuously in real time with elementary algebra. We impose identical safety analysis and real time probability and a pre-calculated maximum setpoint TSPo for the maximum detector reading. As ratio $[\Phi_i / \Phi_{max}]_{r/t}$ changes, during reactor operation, $\mathbf{TSP_i}$ must change proportionally to maintain the ratio fixed:

$$\left[\frac{\mathbf{CPRL} \cdot \Phi_i}{\Phi_{max} \mathbf{TSP_i}}\right]_{SA} = \left[\frac{\mathbf{CPRL} \cdot \Phi_i}{\Phi_{max} \mathbf{TSP_i}}\right]_{r/t} \qquad \text{Equation 7}$$

For $\Phi_i = \Phi_{max}$, $\mathbf{TSP_i} = TSP_o$ for both safety analysis and real time.

$$\left[\frac{1}{\mathbf{TSP_o}}\right]_{SA} = \left[\frac{1}{\mathbf{TSP_o}}\right]_{r/t} = \frac{1}{\mathbf{TSP_o}} \qquad \text{Equation 8}$$

Safety Analysis - Steam Generator Low Level

The safety margin equation for SG Level is:

$\mathbf{SM = TSP_{SG} - f_c[RP]}$ Equation 9

Level is in absolute units - cm. (not relative)

Where: $\mathbf{TSP_{SG}}$ Steam Generator Low Level setpoint

$\mathbf{f_c[RP]}$ 35/30 minute inventory line

The measurement errors are level ($\sigma_l = \pm 10$ cm) and reactor power ($\sigma_{RP} = \pm 1.2$ **RP**%, relative) There is no intrinsic error in 35/30 min inventory lines other than measurement i.e. **SM** = 0.

$$\sqrt{\mathbf{dSM}^2} = \sqrt{|\mathbf{dTSP_{SG}}|^2 + |\mathbf{df_c[RP]}|^2} \qquad \text{Equation 10}$$

We add uncertainties by rms and make a $+2\sigma$ contribution to the low level setpoint.

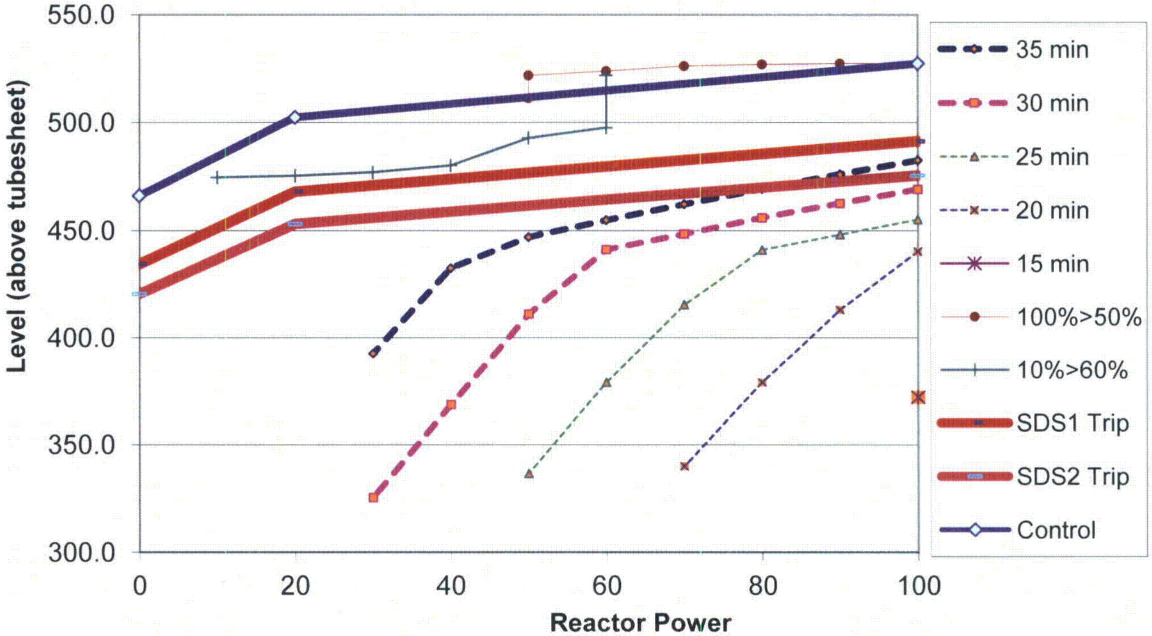
$$\mathbf{TSP_{SG}} = \mathbf{f_c[RP]} + 2\sqrt{|\mathbf{dTSP_{SG}}|^2 + |\mathbf{df_c[RP]}|^2} \qquad \text{Equation 11}$$

$$\mathbf{TSP_{SG}} = \mathbf{f_c[RP]} + 2\sqrt{10^2 + \left[1.2\%\mathbf{RP}\frac{\mathbf{df_c[RP]}}{\mathbf{dRP}}\right]^2} \qquad \text{Equation 12}$$

Note:

$\mathbf{TSP_{SG}}$ for SDS1 and SDS2 should follow the 35/30 min dashed lines ($\mathbf{f_c[RP]}$) not the solid control ramp as now in Figure 1.

Figure 1: CANDU 6 Steam Generator Level Reactor Power Diagram



Variable ROP Setpoints Remove Random Epistemic Detector Error

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Abstract

The mathematical basis of a fully automatic real-time variable setpoint design for ROP is outlined. Variable setpoints eliminate random epistemic detector error thus raising trip margin. Traditionally, snapshot detector reading simulations are used to calculate fixed setpoints making error unavoidable. With variable setpoints, only a fixed maximum setpoint level is pre-determined for the maximum reading detector. On-line detector readings prorate the maximum setpoint thus replacing detector simulations and epistemic error. Probability in real-time is compliant to that calculated for safety analysis. Also, the loss of regulation (LOR) is no longer confined to be spatially uniform and, with a feed-forward derivative term, slow.

1. Introduction

A debate has grown in the last few years with regard to raising reactor overpower (ROP) trip setpoints to delay and reduce reactor power derating due to heat transport system (HTS) aging. The Extreme Value Statistics (EVS) methodology[1] has targeted the statistical methodology for change without disclosing:

1. how over-conservatism in the setpoints design was ruled out
2. exactly which aspects of the statistical methodology require change

Industry proponents of the traditional method have reaffirmed the basis of neither the traditional method nor their disagreement with EVS.

This paper will show that real problem is a combination of:

1. the setpoint calculation and enforcement methodology
2. over-use of epistemic detector error where we have field detector data

The current design of setpoints and comparators for ROP, and other trip parameters, is inefficient for both safety and operation. The variable ROP setpoint scheme below best satisfies both safety and operational requirements. The fundamental problem with fixed setpoints is the necessity to include a random epistemic detection error for their inadequacy. The reactor doesn't need this error when using flux detector readings. Epistemic random detector error is thus absolutely avoidable if real-time detector readings are fed, as one of three components, into the setpoint leg of trip comparators. The impact of aleatory calibration error is not discussed in this paper. This error cannot be eliminated but the reduction in trip margin can be minimized. Why? Detector

readings and calibration are not random at all. Detector readings are tracked and always available to modify setpoints. Detector calibration is highly regulated and although described by an uncertainty, the process is more indiscriminate than random. We only pretend it is random in order to justify traditional assessments leading to fixed setpoints. We can then continue building logic circuits from the dawn of nuclear instrumentation. To be sure, no one is happy with the performance of current setpoint designs:

- Utilities want higher trip margins to stave off age related derating
- Regulators want Risk Informed Decision Making criteria for non-uniform/fast transients
- Designers need to redesign fuel, pressure tubes and HTS parameters on future plants.

Detector trip setpoint distributions are now very crudely imposed by designers compromising operating and safety performance. Alternatives to fixed setpoint designs are not discussed by senior designers. They, in turn, never present them to regulators or junior designers. It seems that no one has actually tried to solve the setpoint equations algebraically for unique solutions. Setpoint codes can easily model a variable setpoint circuit in Figure 1. The analysis and analog circuit is shown without needed clamps.

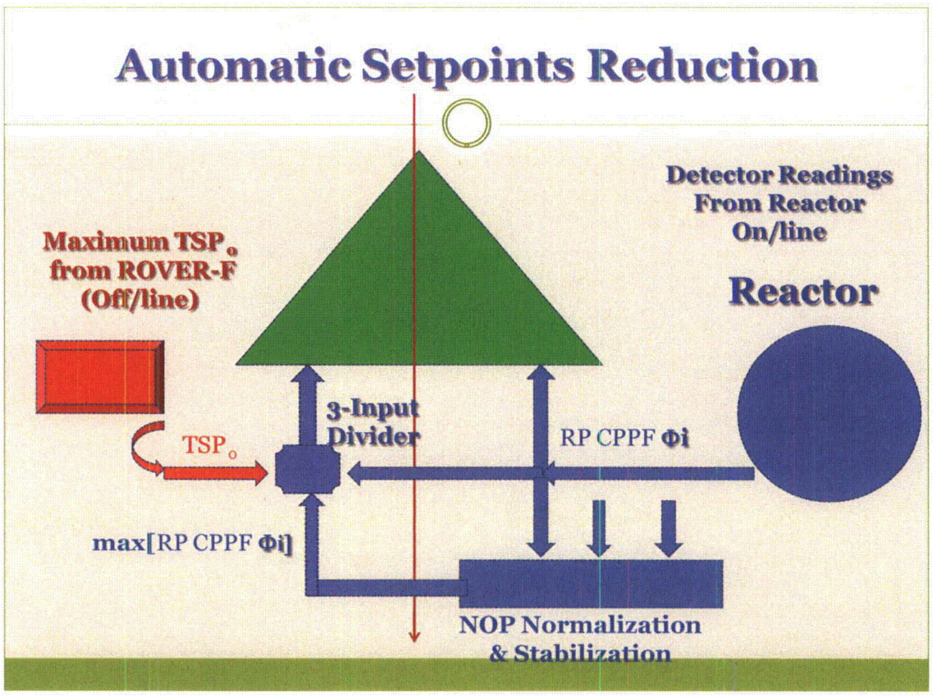

Figure 1 Variable On-line Trip Setpoints

2. ROP Deterministic Equations

To develop the needed equations for a deterministic or probabilistic approach, we need to establish trip and dryout margins and define their ratio as the safety margin for a given design basis fluxshape. The safety margin is used as the argument to the probability of trip before dryout calculations. The setpoints satisfy 98% probability on a 3/3 or w2/2 basis for licensing.

Margin to trip is: $\dfrac{\mathbf{TSP_i}}{RP \cdot CPPF \cdot \mathbf{\Phi_i^{100\%}}}$

Margin to dryout is: $\dfrac{CPRL}{RP \cdot CPPF}$

Safety Margin is: $\dfrac{\text{Margin to dryout}}{\text{Margin to trip}}$

= ***readings at dryout / readings at trip***

$$\mathbf{SMi} = \frac{CPRL \cdot \mathbf{\Phi_i^{100\%}}}{\mathbf{TSP_i}} \tag{1}$$

In licensing analysis, we explicitly run the ROP code. In the analysis for variable setpoints, we do not need to also run a real-time version of RFSP and ROVER-F (or SORO and SIMBRASS) which we don't have. We merely free up the setpoint so it can vary in real-time algebraically with detector readings in such a way as to preserve calculated probability with simulated readings. In this application, we will use real-time detector readings at any arbitrary peak detector reading continuously during operation. For this, we should preserve:

$$[CPRL/\Phi_{max}]^{sim} = [\mathbf{CPRL/\Phi_{max}}]^{r/t}. \tag{2}$$

With this addition, our safety margin equation for variable setpoints becomes:

$$\mathbf{SMi} = \frac{CPRL \cdot \mathbf{\Phi_i}}{\mathbf{\Phi_{max}} \cdot \mathbf{TSP_i}} \tag{3}$$

The importance of the safety margin (**SMi**) parameter is that it directly drives the calculation of probability of trip before dryout (**Prob$_{TBD}$**). The **SMi** equation conforms to the formulation in ISA67.04 standard for light water reactors within a CANDU convention.

Here:

TSPi	is the trip setpoint for loop **i** for any given fluxshape
RP	is normalized reactor power
CPPF	channel power peaking factor
$\Phi i^{100\%}$	normalized detector reading consistent with simulated peak detector reading
Φi	normalized detector reading for the given fluxshape at any peak detector reading

	simulated $\Phi i^{100\%}$ and on-line $\boldsymbol{\Phi i}^{data}$ is available
$\boldsymbol{\Phi_{max}}$	normalized detector reading for the given fluxshape (consistent with $CPRL^{100\%}$)
CPRL	limiting T/A critical power ratio readings at 100% reactor power

Symbols in bold are field variables available on-line. Symbols not bolded are either only simulated (CPRL) or calibration factors which can only be changed by the control room operator (RP and CPFF) manually or via monitor computer.

This equation assumes that the fuel channel determining CPPF has CPRL= CPR/CPPF. In actual reactor assessments, **SMi** has to be recalculated for each fuelling ripple distribution where the calibration to CPPF is more conservative. These recalculations are in principle identical and are fully captured by the function probabilistic function **F** (below).

It is noted that in order to calculate the probability of trip before dryout ($\mathbf{Prob_{TBD}}$),

1. probability density of dryout $\mathbf{dQ(x)/dx}$
2. probability distribution of trip $\mathbf{P(x)}$.

The probability of trip before dryout is given by:

$$\mathbf{Prob_{TBD}} = \mathbf{F[SMi]} = \int \mathbf{P[SMi]dQ} = \int \mathbf{P[SMi]}\frac{\mathbf{dQ}}{\mathrm{dx}}\mathrm{dx}$$

Where:

x abscissa is reactor power normalized to 1 at dryout

F[SMi] functional form of $\mathbf{Prob_{Trip}[SMi]}$ for a safety channel given fluxshape

Note:

The function **F** has many other inputs but we will only vary **SMi** and freeze the rest

$\mathbf{F[SMi]^{SYS}}$ is 98% probability on 3/3 or w2/2 voting logic used for licensing

The product of the distributions of trip (**P**[x]) and dryout (**Q**[x]) is **P**[x]**Q**[x] or just **PQ**:

- differential of **PQ**

  $$d(\mathbf{PQ}) = \mathbf{P}d\mathbf{Q} + \mathbf{Q}d\mathbf{P}$$

- the integral of d(**PQ**)

  $$\int_0^\infty d(\mathbf{PQ}) = \int_0^\infty \mathrm{P}d\mathrm{Q} + \mathbf{QdP} = 1$$

  The interpretation of this result is that the "probability of trip before dryout" + probability of "dryout before trip" equal unity. This gives the rationale for the functionality of **F** above.

  From this, the relationship between these two events is: $\mathbf{F[SMi]} = \int_0^\infty \mathbf{PdQ} = 1 - \int_0^\infty \mathbf{QdP}$

3. Mathematical Dilemma

To calculate setpoints, we use equation 3:

It has: 2 known values (CPRL and **Φi** from simulation)
2 unknown values (**TSPi** and **SMi**) per loop

Instantaneous **Φi** (not necessarily at 100% RP) are also available on-line in real-time via ROP instrumentation. This stream of values has thus far played a role in neither traditional nor EVS setpoint calculations.

The mathematical problem is that the trip setpoint distribution cannot be solved algebraically with only simulated **Φi** (one equation, 2 unknowns). This is why an arbitrary or non-algebraic method has been traditionally used to determine setpoints. The meaning of setpoints in the absence of field readings is meaningless. Are we trying to protect the simulated values or the reactor? Furthermore, spatially uniform and slow loss of regulation (LOR) "requirements" are imposed on the safety analysis for using readings from only one snapshot simulation. These problems apply also to EVS. These are what Risk Informed Decision Making (RIDM) requirements are attempting to address. Whatever algebraic or functional variation setpoints should have had is forever lost in this arbitrary "fixed setpoint" method. In place of a proper setpoint algebraic functionality, people merely add an aleatory type penalty in setpoints via detection epistemic uncertainty. With a real-time fully algebraic solution, this epistemic uncertainty is eliminated.

The technical definition of LOR embodied in **SMi** is now also arbitrary and problematic. In order to "determine" setpoints, we currently:

1. assume one time average simulation of $\mathbf{\Phi_i}$, **BP** (for **CCP**) and **CP** suffices
2. assume a simulation at 100% reactor power
3. assume $\mathbf{\Phi_i}^{100\%}$ is scaled until nominal dryout i.e. CPRL·$\mathbf{\Phi_i}^{100\%}$
4. assume $\mathbf{TSP_i}$ is "fixed" usually at a value TSP_o independent of fluxshape and loop
5. assume that the LOR proceeds slow in rate

Since fixed setpoints now make safety margin quite dependent on detector readings (fluxshape), the case to case and loop to loop deterministic variations hurt both operating and safety margin. The reason is that fluxshapes change but fixed setpoint do not. We create few detectors that are ahead of many others thus stranding their safety coverage participation. This penalizes the setpoints of the few detectors. Simultaneously, the margin to trip is hurt because the high reading detectors would otherwise trip first with lowered fixed setpoints. It would seem that operating and safety performance are two sides of the same coin. Another way to say this is that the probability variation will be very strong between cases with only one covering detector and those with several. This can be easily verified looking at the vast spread in case to case probability tabled in any ROP submission.

I note that safety margin is only the ratio of $\frac{\textit{readings at dryout}}{\textit{readings at trip}}$ during the LOR.

This ratio has nothing to with detector readings during steady state operation before the LOR.

3.1 Mathematical Solution

For variable setpoints, we shall make only one assumption instead of five. That is, safety margin is invariant, $1/\alpha$, and setpoints become:

$$\mathbf{TSP_i} = \alpha \frac{\Phi_i}{\Phi_{max}} \tag{4}$$

This remaining restriction can be dropped by using optimality criteria in continuous analysis.

The symbolic calculation of probability with constant safety margin in Section 6, will give us three things:

1. the value of α
2. confirmation licensing and real-time setpoints agree with Equation 4
3. link to condition required for zero epistemic detector error (Section 8)

This definition is now independent of fluxshape, detector readings or loop number. You would expect that both deterministic and probabilistic criteria would be much less variable for fluxshapes, detector readings or loop numbers. The rate of LOR will require a feed-forward extension to the variable setpoint concept which will be shown later. For now, let me note that we require only one assumption for constant safety margin instead of five. This is a better strategy with more favourable operating and safety performance. The goal should still be to have no arbitrary assumptions. Perhaps, we could explore criteria in continuous variables for optimal setpoints.

4. Probabilistic Equations

With **SMi** defined, the trip probability distribution for random errors only becomes:

$$\mathbf{Prob_{trip} = P(x) = 1 - \prod_i 1 - erf\left[\frac{x - \frac{1}{SM_i}}{\frac{\sigma_{det}}{SM_i}}\right]} \tag{5}$$

Also, the dryout probability distribution[2] for random errors only becomes:

$$\mathbf{Prob_{d/o} = Q(x) = 1 - \prod_j 1 - erf\left[\frac{x - \frac{cprl_j}{cprlo}}{\sigma_{d/o}}\right]} \tag{6}$$

The probability of trip before dryout remains:

$$\mathbf{Prob_{TBD} = F[SMi] = \int P[SMi]dQ = \int P[SMi]\frac{dQ}{dx}dx} \tag{7}$$

Where:

σ_{det} is the random detector error
cprlj is rippled cpr of fuel channel j
cprlo is most limiting rippled cpr of any fuel channel
$\sigma_{d/o}$ is the random dryout error
$\mathbf{Prob_{d/o}}$ or **Q** is probability of dryout
$\mathbf{Prob_{Trip}}$ or **P** is probability of trip
$\mathbf{Prob_{TBD}}$ Single safety channel representation shown here

The fundamental disagreements between a traditional probabilistic formulation and an EVS probabilistic formulation are:

1. Treatment of random errors (epistemic and aleatory for detection and dryout)
2. Inclusion of a fluxshape weighting (FSW) to boost limiting cases

Correlated uncertainties in traditional statistics can be included by convolution to both **P** and **Q**. This affects the distributions of **P** and **Q** but the important parameter for licensing is probability of trip before dryout ($\mathbf{Prob_{Trip}}$) which can still remain as an unspecified function **F**.

5. Current Fixed Setpoint Methodology

Traditional and EVS setpoint methodologies use a method based on "fixed" not "variable" setpoints. That is, both methods impose an arbitrary non-variable functionality to the unknown **TSPi**. The fixed setpoints are uniformly scaled until a 98% probability is achieved. This is an imposed fit and not a true algebraic solution of the equation. We do not normally solve algebraic or differential equations by predetermining the functional variation with a desired variation, doing a best fit and then dealing with the scatter by adding an uncertainty which was created by the fitting process and not the data. We have chosen to ignore measured **Φi** data which must be available for the monitoring of the ROP trip parameter itself. This directly leads to random epistemic detector error. An error, after all, is what we cannot know and not what we knowingly or unknowingly ignore.

6. Variable Setpoint Methodology

We require measured values of **Φi**, in addition to those simulated, to obtain unique and exact setpoint solutions. This supplies the missing information for a full algebraic solution of **TSPi**. However, the measured values of **Φi** are a real-time stream, i.e. **Φi(t)**. The calculation update to the setpoints would have to be in real-time as well. We shall see how the probabilistic equations are used to calculate the probability of trip before dryout. We will be in a position to fully solve symbolically the probabilistic real-time setpoint of each loop algebraically. To lighten the load

with dealing with 2 shutdown systems and 3 safety channels, let us simplify the algebra and use function **F** to calculate probability for a single safety channel. A full demonstration of variable setpoints would involve an actual licensing run at some point anyway.

Let us:

1. Assign the real-time fluxshape, $\boldsymbol{\Phi_i^{r/t}(t)}$
2. Set $\mathbf{Prob_{TBD}}$ = **F[SMi]** to 95%, with simulated readings for a single safety channel
   a. On a 2/3, w2/2, or 3/3, probability is estimated over .993, .903, .858 respectively
3. Use same function, **F[SMi]**, with real-time readings to calculate trip probability
4. Impose that the probability with simulated and real-time readings is equal

$$\mathbf{F}\left[\mathrm{CPRL}\cdot\left[\frac{\Phi_i}{\Phi_{max}\cdot \mathrm{TSP}_i}\right]^{sim}\right] = 95\% = \mathbf{F}\left[\mathrm{CPRL}\cdot\left[\frac{\boldsymbol{\Phi}_i}{\boldsymbol{\Phi}_{max}\cdot \mathbf{TSP}_i}\right]^{r/t}\right] \tag{8}$$

The arguments to **F** must be equal, for a given fluxshape at any reactor power, for simulation and real-time compliance:

$$\mathrm{CPRL}\cdot\left[\frac{\Phi_i}{\Phi_{max}\cdot \mathrm{TSP}_i}\right]^{sim} = \mathbf{F}^{-1}[95\%] = \mathrm{CPRL}\cdot\left[\frac{\boldsymbol{\Phi}_i}{\boldsymbol{\Phi}_{max}\cdot \mathbf{TSP}_i}\right]^{r/t} \tag{9}$$

F and $\mathbf{F^{-1}}$ require that ratio $\Phi i/TSPi = \Phi_{max}/TSP_o$ for each detector in real-time and also simulations. This equation could serve as a deterministic criterion on its own.

From this, we get:

$$\left[\frac{\Phi_i}{\Phi_{max}\cdot \mathrm{TSP}_i}\right]^{sim} = \left[\frac{\boldsymbol{\Phi}_i}{\boldsymbol{\Phi}_{max}\cdot \mathbf{TSP}_i}\right]^{r/t} \tag{10}$$

$$\mathbf{TSP}_i^{r/t} = \mathrm{TSP}_o\left[\frac{\boldsymbol{\Phi}_i}{\boldsymbol{\Phi}_{max}}\right]^{r/t} \tag{11}$$

The value of parameter α in our assumed variable setpoint variation in Equation 4 is TSP_o. The loop trip setpoints in real-time vary are linearly with the loop detector readings.

If we subtract the derivative (feed-forward) from **Φi** in Equation 11, we give the shutdown system ~1s to turn over an overpower transient and still not exceed the slow LOR setpoints.

$$\mathbf{TSP}_i^{r/t} = \mathrm{TSP}_0 \left[\frac{\Phi_i - \frac{d\Phi_i}{dt}}{\Phi_{max}} \right]^{r/t} \tag{12}$$

Only the constant TSP_0 comes directly from licensing calculations. This confirms the earlier statement that you cannot determine the instantaneous field setpoints until you have real-time detector reading data.

This formulation will allow the ROP code to be run for safety analysis, as usual, and supply the TSP_0 that will later be used to quickly transform and generate real-time setpoints on the fly. Sometimes, we loosely speak about required setpoint levels being a function of fluxshape when we mean the setpoint distribution. Note that this variable setpoint functionality can only reduce setpoints below a maximum value of TSP_0.

A self consistency test of Equation 11 is to see if β times the simulated readings ($\mathbf{\Phi_i}^{r/t} = \beta\Phi_i^{sim}$) and likewise maximum readings ($\mathbf{\Phi_{max}}^{r/t} = \beta\Phi_i^{sim}$) were put into the real-time $\mathbf{\Phi_i}^{r/t}$ equation, whether the $\mathbf{TSP_i}^{sim}$ would result. The right hand side becomes:

$$\mathbf{RHS} = \left[\frac{\Phi_{max} \cdot \mathrm{TSP}_i \cdot \beta\Phi_i}{\Phi_i \beta \Phi_{max}} \right]^{sim} \tag{13}$$

$$\mathbf{RHS} = \left[\mathrm{TSP}_i\right]^{sim} \tag{14}$$

With the proposed variable setpoints, the calculated SDS stationary safety margin (SM_0) and probability of trip before dryout become a stationary value for any design basis fluxshape in real-time: i.e. $\mathbf{Prob_{TBD}}^{SYS} = \mathbf{F}[SM_0] = 95\%$.

Setpoint can easily be generated in real-time with analog hardware or digital hardware every loop cycle. The stream of **Φi** is input and simultaneously transformed into an output stream of **TSPi**. Without field measurements, one could easily say that there is no real reactor to protect. The notion of protection becomes meaningless. Risk Informed Decision Making (RIDM) for trip/no trip can best be made using all available relevant plant Information. Surely, real-time measured detector readings must have as much legitimacy as those simulated for use in safety.

7. Process Trips in CANDU 6 PDC's

There is a decided similarity in variable setpoints between ROP, Pressurizer Level and Boiler Level trips in CANDU 6. The calculation of setpoint requires simple arithmetic operations without, parallel simulation, looping, convergence issues nor the requirement to explicitly calculate probability of trip before dryout. That is inherently not needed with this algorithm either. Pressurizer and Boiler Level setpoints are a function of reactor power and require 2 Programmable Digital Controllers (PDC) per safety channel. Boiler Level in Ontario plants is

established by a two tier setpoint via hardware in Bruce and a trip computer in Darlington. In any case, a single fixed setpoint is clearly inadequate. This is pretty much the pattern for all trip parameters. For example, the High Pressure trip can have a fixed level based on a slow rate less a derivative term to bring the trip quicker and avoid a transient overpressure. The Log Rate trip might better become a log trip with a switched hi/lo setpoint minus the log rate. This would make both SDS able to pick up rates below 15%/s and avoid spurious trips at very low power due to poison clouds generating log rates above 15%/s.

8. Random Epistemic Detector Error

The most interesting thing about ROP detectors is that they have absolutely no measurement error (see Equation 1). With respect to dryout, we do apply bundle and channel power uncertainties. Dryout error becomes relevant because we want to trip (before dryout) with a given probability. Knowing that we eventually trip in an LOR is not sufficient.

The formula for determining the traditional relative epistemic random detector error (and uncertainty) from commissioning data is:

$$\varepsilon_i = \frac{\Phi_i^{sim} - \Phi_i^{meas}}{\Phi_i^{sim}} \tag{15}$$

$$\sigma_{det}^{epi} = \sqrt{\frac{\sum \varepsilon_i^2}{n}} \tag{16}$$

Note:

Φ_i^{meas} in commissioning data, $\delta\Phi_i^{meas}$ resets aleatory errors by removing the calibration offsets

Φ_i^{sim} is now the basis for calculating setpoint (Φ_i^{set}) using simulations but need not be

We might ask: How else can one calculate trip setpoints?

In the field we are presented with a situation where we could use a fraction **x** of the simulated detector readings and thus **(1-x)** of on-line detector reading for setpoints.

The detector readings at the setpoint (Φ_i^{set}) become:

$$\Phi_i^{set} = (1 - x)\Phi_i^{meas} + x\Phi_i^{sim} \tag{17}$$

The error in the readings for setpoint using Equation 15 becomes:

$$\varepsilon_i^x = \frac{(1 - x)\Phi_i^{meas} + x\Phi_i^{sim} - \Phi_i^{meas}}{\Phi_i^{sim}} \tag{18}$$

Using Equation 16, we get:

$$\sum\sqrt{\frac{\varepsilon_i^2}{n}} = x\sqrt{\frac{\sum\left[\frac{\left(\Phi_i^{sim} - \Phi_i^{meas}\right)}{\Phi_i^{sim}}\right]^2}{n}} \tag{19}$$

Re-expressed, Equation 19 is:

$$\sigma_i^x = x\sigma_{det}^{epi} \tag{20}$$

It would be very difficult to actually produce simulated flux detectors in transients and apply them to both Φ_i^{set} and corresponding ε_i^x. Also, if we did possess such data, how and why would we feed it to a computer to churn out flux detector readings and error components for setpoint calculations, get them approved by management and the regulator? However, it would be very easy to use only real-time measurements to reduce setpoints during slow and fast transients.

This "hypothetical" experiment has only two practical cases:

Case 1:

No measured readings allowed in setpoint leg of comparators (only simulations), **x=1**,

$$\sigma_i^x = \sigma_{det}^{epi} \tag{21}$$

This is exactly the ransom epistemic detector error traditional design approach of fixed setpoints.

Case 2:

Only measured readings (no simulations) allowed in setpoint leg of comparators or **x=0**,

$$\sigma_i^x = 0 \tag{22}$$

Detector uncertainty is a function of **x. 1-x** is the *Information Switch* or amount of on-line information allowed to update setpoints.

If **x**=1, the epistemic detection carries the full simulation uncertainty because no amount of detection information (fluxshape) is allowed to change setpoints. If **x**=0, the epistemic detection uncertainty is zero because the full amount of detection information is allowed to update setpoints.

How does Φ_i^{set} vary with **x**?

This, in the new vernacular of variable setpoints, is like asking, when is $\frac{d\Phi_i^{set}}{dx} = 0$?

Differentiating Φ_i^{set} (Equation 17) wrt **x**, we get:

$$\Phi_i^{meas} - \Phi_i^{sim} = 0 \tag{23}$$

$$\Phi_i^{sim} = \Phi_i^{meas} \tag{24}$$

This is the same solution as setting Equation 15 to zero.

9. Conclusion

It has been shown that variable real-time ROP setpoints can be algebraically determined with the set of simulated and each set of on-line detector reading data bypassing any need for statistics. This is consistent with there being no need to carry an epistemic detector random error. Dryout, on the other hand, is not directly tracked and unknowable, to some extent, even if measured. For this reason dryout should continue to use traditional statistics. Breaking up random errors into epistemic and aleatory components but vary their statistical treatment is both arbitrary and wrong.

Only errors in maximum detector readings remain with variable setpoints. These may still use a statistical method but become correlated errors and no longer detector random. The epistemic portion of the Simulation Ratio detector error may have to be calculated a little differently than it is now. The aleatory calibration error only on maximum detector readings is also correlated and must now be calculated for each fluxshape from simulated readings, channelization and the aleatory calibration uncertainty. The hope is that the limiting cases can point to only a few detectors where it may be advantageous to calibrate a little differently.

10. References

[1] P. Sermer, G. Balog, D. Novog, E.A. Attia and M. Levice, "Monte Carlo Computation of Neutron Overpower Protection Trip Set-Points Using Extreme Value Statistics", Proceedings of 24th Annual Conference of the Canadian Nuclear Society in Toronto, 2003.

[2] F.A.R. Laratta and H.C. Chow et al., "A Probabilistic Approach to Channel-Power-Limit and Bundle-Power-Power Limit Compliance Analysis", Proceedings of 5th CNS International Simulation Conference at Montreal, 1996.

Questions and Suggested Answers for NRC

Frank Laratta - August-18-14

1. What is the main goal of safety analysis? Setpoints
   a. But, setpoints are indeterminable using safety analysis <u>alone</u>! Need real time also
2. What makes trip setpoints constant? Designers - force a solution (not <u>correct</u> or optimal)
3. What causes detector random error (epistemic and aleatory)? Having fixed setpoints
   a. $\mathbf{TSP_i = f[\varepsilon_i]}$ **BUT** $\mathbf{\varepsilon_i = g[TSP]}$
4. Are epistemic and aleatory detector errors separate? No – both removable from nominal
5. What keep fixed setpoints (necessity, desirability, optimality)? None of the above
6. Why is channel random dryout error now rightfully random? Always unknowable
7. Why are detector errors not rightfully random? Readings known in real time
8. Why is setpoint structure different between ROVER vs SIMRASS? No definition!
9. What does light water reactor standard ISA67.04 (below) warn? Determining setpoints
10. Why have Risk-Informed Decision Making worries? Setpoints require field information
11. What relates a fixed analysis point to real time continuum? Separation of Variables
12. How does trip probability now comply with safety analysis calculations? Faith
13. What are dryout and trip probability distributions? **Q** and **P** respectively
14. What is probability distribution of Trip Before Dryout? $\mathbf{Prob_{TBD} = \int PdQ}$
15. What is the main driver of $\mathbf{Prob_{TBD}}$? Safety Margin (below) - $\mathbf{Prob_{TBD} = \int PdQ = F[SM_i]}$
16. Can we build a simple pseudo real time NOP trip probability model? Yes!
17. What happens if we optimize $\mathbf{Prob_{TBD}}$? Safety Margin and $Prob_{TBD}$ fixed but setpoints variable
18. In $SM_i = \frac{CPRL \cdot \Phi_i}{\Phi_{max} \cdot TSP_i}$, what is the source of $\mathbf{\Phi_i/\Phi_{max}}$? Simulation ***and*** field measurement.
19. What is the new reality? $[SM_i]_{SA} = \left[\frac{CPRL \cdot \Phi_i}{\Phi_{max} \cdot TSP_i}\right]_{SA} = [SM_i]_{r/t} = \left[\frac{CPRL \cdot \Phi_i}{\Phi_{max} \cdot TSP_i}\right]_{r/t}$
   a. This formulation has compliance built in:
      $[SM_i]_{SA} = [SM_i]_{SA}$ and $Prob_{TBD} = F[SM_i]_{SA} = F[SM_i]_{SA}$
20. How can setpoints from simulated data achieve compliance with field data? They don't
21. Why do 'all adjusters out' determine 'power for 'all adjusters in'? Fixed setpoints
22. What does eliminating random detector error result in? All detectors trip together
23. What does ASR theory say about setpoints? Should be continuous
    a. Either TSP_i or SM_i may be fixed. Fixed TSP_i arbitrary (old instrumentation)
24. Are $\mathbf{\Phi_i}$ random (unknowable) or known in real time? Unknown but knowable in r/t

Points:

1. Consult Ujjal Mondal - COG's voting member on ISA67.04 (light water setpoints)
2. Consult a process parameter setpoint expert on boiler level
3. Epistemic and aleatory distinction in EVS is blurry:
   a. Some say no difference
   b. I say there effect can both be overcome
4. Other parameter setpoints have design and safety/economic concerns:
   a. Log rate

    b. Steam Generator[1] and Pressurizer Level
    c. High and Low HTS Pressure
    d. Low Flow
5. Setpoint functions only can be predetermined in safety analysis (variable setpoints)
    a. Setpoint values cannot be legitimately predetermined
    b. Setpoints are functions of flux?
    c. Setpoints are not points!
6. Setpoint and monitoring values must be determined in real time
7. Safety analysis paradigm is mainly incorrect
8. Some error analysis is likewise incorrect:
    a. Not everything claimed is strictly random (error on Φ_i)
    b. Modeling (epistemic) error is function of setpoint and resolvable
    c. Calibration (aleatory) error is correlated and penalizes only peaky fluxshapes
    d. Detector random error statistics should have included a χ^2 correction
9. What is different between deterministic and probabilistic criteria? None
10. What is different between safety and economic criteria? None
11. What is distinguishes errors and mistakes? Errors occur naturally, we make mistakes!

Setpoint Warning
from ISA-RP67.04.02-2009
Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation

It is prudent to evaluate setpoint calculations to assure they are not overly conservative. Overly conservative setpoints can be restrictive with respect to normal plant operation or may reduce safety by unnecessarily increasing the frequency of plant trip occurrence or safety system actuation. The evaluation should assure that there are no overlapping, redundant, or inconsistent values or assumptions. Excessive conservatism may result from the many interfaces between organizations that may have an input to the calculation. These interfaces are discussed in Section 9.

Expanded Setpoint Warning
from ISA-RP67.04.02-2009
Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation

It is prudent to evaluate setpoint calculations to assure they are not overly conservative. Note: There is no guide here for the user. It is implied but not stated that safety requirements can be satisfied in many (infinite?) ways – but the economic requirements have very many bad ones, very few good ones and perhaps only one optimum. The interplay between safety-operation is beyond these guides (ASR!). Isn't that the subject that this guide addresses? **Pre-determined setpoints, for example, are a sure way to lead to over-conservatism.** Overly conservative setpoints can be restrictive with respect to normal plant operation or may reduce safety by unnecessarily increasing the frequency of plant trip occurrence or safety system actuation. The evaluation should assure that there are no overlapping, redundant, or inconsistent values or assumptions. Excessive conservatism may result from the many interfaces between organizations that may have an input to the calculation. These interfaces are discussed in Section 9. Example, in CANDU the operating power with all adjusters inserted is set by the ROP setpoints for all adjusters withdrawn. These two events cannot happen simultaneously and ROP should easily be able to "tell" the actual fluxshape. It is a case where not reducing many detector setpoints which are unrealistically too high penalizes trip setpoints which are not allowed to change with the fluxshape (i.e. constant setpoints!).

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[1] Only process parameter planned to address specifically

Prob[S/A] = Prob[R/T]