Accounting for Human Error Probability in SIL Verification Calculations

William G. Bridges, President
Process Improvement Institute, Inc. (PII)
1321 Waterside Lane
Knoxville, TN 37922
Phone: (865) 675-3458
Fax: (865) 622-6800
e-mail: wbridges@piii.com

Harold W Thomas, PE, CFSE
Exida.com, LLC
Sellersville, PA 18195
thomashw@exida.com

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Harold W. Thomas, PE, CFSE
Exida.com, LLC
Sellersville, PA 18195
thomashw@exida.com

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Abstract

Safety Instrumented System (SIS) standards have raised the bar on using instrumented systems (formerly called interlocks, Emergency Shutdown's etc.). It introduces requirements for improved management systems to enforce independence from other Independent Protection Layers (IPLs). It requires verification that the performance of each Safety Instrumented Function (SIF) will be met during its lifetime. The performance criteria are documented as the target SIL or risk reduction factor for each SIF. This is tied to specific values of probability of failure on demand (PFD). The initial SIS standards did not include systematic human errors in the example calculation for SIL in either IEC 61508 or 61511 and current working revisions, while beginning to more rigorously acknowledge the role systematic failures play in overall performance, still fall short regarding methods to quantify. While the SIL Verification methods outlined in the standards and technical reports like ANSI/ISA TR84.00.02 facilitate consistency, as user companies seek to obtain greater risk reduction from their safety instrumented systems to satisfy their corporate risk criteria, failure to adequately address potential systematic failures can lead to overly optimistic results and a misallocation of resources intended to reduce risk

This paper shows that human error during testing, maintenance, and restoration of a SIF can potentially dominate its Probability to Fail Dangerous (PFD) value, calling into question whether the required risk reduction is indeed being met. This is especially pertinent to SIL 2 and SIL 3 requirements. Example methods for estimating the contribution of human error probability for SIL Verification calculations are provided as well as some proven approaches for controlling human factors that affect the base error rate (for a given mode of operation). It also discusses ways to prevent or else detect and recover from errors made in redundant channels (such as used in 1oo2, 1oo3, or 2oo3 voting).

1. Introduction

The failure of safety instrumented functions can be due to a number of reasons. Common terminology in the industry characterizes these failures as either random hardware failures or systematic failures. This paper mainly focuses on the systematic aspects; however, all equations presented will also include the random contribution for completeness.

Systematic failures may manifest themselves via a number of failure mechanisms such as:

- Manufacturer design Errors
- End user design errors
- Hardware installation errors
- Manufacturer software design errors
- End user programmable configuration errors
- Human error during operation and maintenance
- Management of change errors

As the list above shows, systematic error may be introduced by the manufacturer or the end user. This paper will focus on the end user, as equipment that has been properly reviewed and certified in accordance with IEC-61508 undergoes a formal work process specifically looking to minimize systematic errors. It is also likely that systematic errors that do occur will manifest themselves during the warranty period allowing appropriate response to rectify the problem to a suitable level. In addition, this equipment is expected to undergo proven in use validation by the manufacturers on a periodic basis.

Once under the control of the end user, the variability of application and control greatly increases, making their control more difficult. This paper seeks to make the reader more aware of how systematic errors may occur and how they can impact the risk reduction of safety instrumented functions.

Human error during interventions with SIS can have a detrimental effect on the availability of an SIF. There have been numerous cases where SIFs were left in bypass, etc., and an accident occurred. One of the most notable recent events was at a facility in Institute, West Virginia, USA (in 2008). A SIF was bypassed to allow startup to proceed more smoothly. Reactant was allowed in without solvent and the temperature of the newly replaced residue treater ran away and exploded, resulting in 2 fatalities and multiple injuries. In addition, it was also a near miss with respect to a potential large release of methyl isocyanate located 80 feet from the explosion. (See US CSB, 2011)

The focus of this paper will be on human interaction errors. These errors include errors in the operation of the man machine interface to the SIF (such as leaving a SIF in bypass), errors during periodic testing of the SIF, and errors during the repair of failed modules in the SIF. This last type of human error includes the simple case of inadvertently leaving a root valve on an instrument closed.

The SIS standards of the mid-1990 through today recognized that systematic human errors have a deleterious impact on the PFD of an SIF. This effect can be either errors that exist at Time Zero or systematic errors while operating. The IEC standards qualitatively covered at length the need to control such errors. In ISA-TR84.00.02-2002, an Equation 1a was provided which includes a system dangerous (D) failure/error term (F). The equation is shown below:

$$PFD_{SIF} = \sum PFD_{Si} + \sum PFD_{Ai} + \sum PFD_{Li} + \sum PFD_{PSi} + \left[\lambda_F^D x \frac{T_i}{2} \right] \quad \text{[Eq. 1a]}$$

where PFD_{SIF} is the average PFD for a SIF. The first term in the equation is the contribution of the sensors, the second term is the contribution of the final elements, the third term is the contribution of the logic solvers, the fourth term is the contribution of the power supply, and the last term is the contribution of the dangerous system failures. But as stated in ISA-TR84.00.02, for this equation:

> "…the systematic failure is modeled as an error that occurred during the specification, design, implementation, commissioning, or maintenance that resulted in the SIF component being susceptible to a random failure. Some systematic failures do not manifest themselves randomly, but exist at time 0 and remain failed throughout the mission time of the SIF. For example, if the valve actuator is specified improperly, leading to the inability to close the valve under the process pressure that occurs during the hazardous event, then the average value as shown in the above equation is not applicable. In this event, the systematic failure would be modeled using $\lambda * Ti$. When modeling systematic failures, the reader must determine which model is more appropriate for the type of failure being assessed."

This statement is accurate, but does not provide any practical guidance as to what systematic errors are most significant. In practice, most of the systematic error term results from human errors. These can include:

- Manufacturer contribution for certified equipment (Believed to be negligible relative to end user systematic errors)
- End user systematic errors:
  - Design and installation errors
  - Probability of being failed following proof test
  - Bypass during operation

Of these end user systematic errors, the dominating contribution is generally human errors that leave the protection failed at Time 0. These errors can occur during re-commissioning of an SIF following routine maintenance interventions such as:

- Leaving a root valve on an instrument closed
- Leaving a SIF in bypass, i.e.:
  - Bypassing the function due to a spurious trip and failing to remove bypass.

- Bypassing the function for startup because the system dynamics require this, however, the designers missed this need during startup mode of the process resulting in an operational bypass that requires human intervention to remove the bypass rather than an automated design that removes the bypass.
- Bypassing the final element and failing to remove bypass when the test or repair is complete

Therefore, a simple equation including the systematic error terms can replace Eq. No. 1a from ISA-TR84.00.02. The resulting improved equation is:

$$PFD_{SIF} \approx \sum PFD_{\mathrm{S}i} + \sum PFD_{Ai} + \sum PFD_{Li} + \sum PFD_{PSi} + \sum PFD_{SYS\text{-}PROCi} + \sum P_{SYS\text{-}HUMi} \qquad \text{[Eq. A]}$$

where we will now define:

$$PFD_{COMP} \approx \sum PFD_{\mathrm{S}i} + \sum PFD_{Ai} + \sum PFD_{Li} + \sum PFD_{PSi} \qquad \text{[Eq. B]}$$

and where the systematic error term is expanded using the simplified equation below

$$\mathrm{PFD_{SYSI}} = \mathrm{PFD_{SYS\text{-}PROCi}} + \mathrm{P_{SYS\text{-}HUMi}} \qquad \text{[Eq. C]}$$

The first term of Eq. C is the systematic errors and failures generated randomly by the process, such as plugging of instrument taps by process materials or contaminants, and the second term is the probability the SIF will be defeated by human error.

Further, the overall systematic human error term can be expanded and written as:

$$\mathrm{P_{SYS\text{-}HUM}} = \mathrm{P_{design\ error}} + \mathrm{P_{installation}} + \mathrm{P_{proof\ test\ error}} + \mathrm{P_{bypassed}} \qquad \text{[Eq. D]}$$

Of the four terms in this equation, the first two can be detected and corrected during initial commissioning steps for the SIF. Experience has shown that the last two terms, $\mathrm{P_{proof\ test\ error}}$ and $\mathrm{P_{bypassed}}$ are likely to dominate the $\mathrm{P_{SYS\text{-}HUM}}$, though more industry data is needed to support this observation. Making the assumption that $\mathrm{P_{SYS\text{-}HUM}}$ is dominated by $\mathrm{P_{proof\ test\ error}}$ and $\mathrm{P_{bypassed}}$, Equation D can be further simplified to:

$$\mathrm{P_{SYS\text{-}HUM}} \approx \mathrm{P_{proof\ test\ error}} + \mathrm{P_{bypassed}} \qquad \text{[Eq. E]}$$

Experienced gained from many accident investigations and also from calculations, support the contention that for high SIL designs, the human errors during interventions $\mathrm{P_{proof\ test\ error}} + \mathrm{P_{bypassed}}$, dominate the calculated $\mathrm{PFD_{SIF}}$ Unfortunately, most of the SIL verification calculations today use the truncated Eq. No. 1 (instead of 1a) from ISA-TR84.00.02:

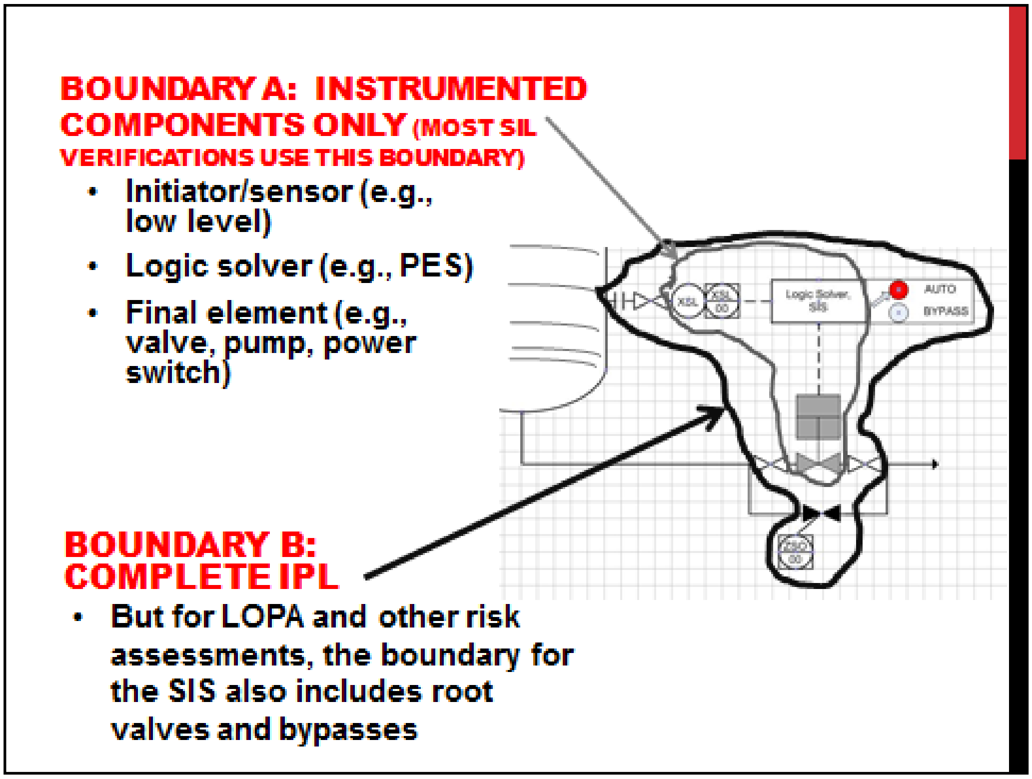
$$PFD_{SIF} = \sum PFD_{\mathrm{S}i} + \sum PFD_{Ai} + \sum PFD_{Li} + \sum PFD_{PSi} \qquad \text{[EQ. 1]}$$

As a result, most SIL Verification calculations today ignore systematic errors when quantifying their risk reduction capability. (Note that Equation B and Eq. No. 1; TR84.00.02 are the same.)

This is equivalent to saying the system boundary for an SIF only includes the instrumented components (a subsystem), or Boundary A in Figure 1, instead of including the entire independent protection layer (IPL) system, shown as Boundary B in Figure 1. In LOPA and other quantitative risk assessments, the entire IPL system must be considered. *For example, if the IPL is a PSV, then the IPL system must include upstream and downstream features, such as isolation valves. Therefore, the probability of leaving an isolation valve closed should be included as a contribution to the overall PFD of the PSV IPL system.*

This paper hopes that readers will better understand how to view and analyze the appropriate boundary for an SIF.

Figure 1: Boundary for SIF



For the remainder of this paper, we will concentrate on the effect of including the systematic human errors for calculation of PFD_{SYS}, and the effect this has on the resulting SIL. For convenience, this paper arbitrarily sets $\sum PFD_{SYS\text{-}PROC}$ = zero. This is being done so the reader can better focus on the human error aspect of systematic errors. $PFD_{SYS\text{-}PROC}$ is worthy of its own paper as its significance is generally dependent on the process fluid properties and/or ambient conditions.

The next two sections of this paper provide a basis for (1) the baseline error rate for human error during interventions and (2) the error rates given coupling of activities, such as occur with redundant systems. Following that, simple examples are provided to help show the relative impact of including systematic human error terms in the calculation of PFD_{SYS}.

2. Human Error Probability for a Single Execution of a Rule-Based Task

To calculate $P_{SYS\text{-}HUMi}$, the type of tasks must be defined and the baseline error rate for such a task needs to be established. Note that with excellent control of all of the human factors, a company can begin to approach the lower limits that have been observed for human error. Excellent control of all human factors means a robust design and implementation of management systems for each human factor are achieved with a high level of operational discipline. The first well-researched publication detailing potential lower limits of human error probability was by Alan Swain and H Guttmann (NUREG-1278, 1983) and by others. However, many times, the limits they referenced get used out of context. The lower limits in the NUREG-1278 assume excellent human factors, but such excellent control is rarely, if ever achieved. Additionally, some human errors listed by Swain and others were for a single error under highly controlled conditions, or on a "best day" instead of average error probability or rate over an average year of tasks. In general, Process Improvement Institute (PII) has found it best to use the average error probabilities as discussed in the following section.

2.1 Error Probability for Rule-Based Actions that are Not Time Dependent:

Actions that do not have to be accomplished in a specific time frame to be effective are not time dependent. It should be obvious then that these do not include response to alarms, or similar actions with time limits. Values listed below represent the lower limits for human error rates, assuming excellent control of human factors; these are expressed as the probability of making a mistake on any step:

- 1/100 - process industry; routine tasks performed 1/week to 1/day. *This rate assumes excellent control of all human factors. Most places PII visits, the workers and managers and engineers believe this is achievable, but not yet achieved.*
- 1/200 - pilots in the airline industry; routine tasks performed multiple times a day with excellent control of human factors. *This average has been measured by a few clients in the airline industry, but for obvious reasons they do not like to report this statistic.*
- 1/1000 - for a reflex (hard-wired) action, such as either proactive or minor corrective actions while driving a car, or very selective actions each day where your job depends on getting it right each time and where there are error recovery paths (such as clear visual cues) to correct the mistake. *This is about the rate of running a stop sign or stop light, given no one is in front of you at the intersection; the trouble is measuring this error rate, since you would have to recognize (after the fact) that you made the mistake.*

See the paper in this conference (Bridges and Collazo, GCPS, 2012) for more details on this topic

2.2 Adjusting the lower limit rates to estimate a baseline rate at a site

As mentioned earlier, the lower limit rates assume excellent control of human factors in the industry mentioned. Note that airline pilots have a lower error rate than what PII has measured in the process industry. This is due, in part, to the much tighter control by the airlines and regulators on factors such as fitness-for-duty (control of fatigue, control of substance abuse, etc.).

Excellent control of human factors is not achieved in many organizations; therefore the human error rates will be higher than the lower limit, perhaps much as much as 20 times higher. Table 1 provides adjustment factors for each human factor. These factors can be used to adjust the lower limit of error rate upward or downward as applicable, but the factors should not be applied independently. For instance, even in the worst situations, we have not seen an error rate for an initiating event or initial maintenance error higher than 1/5, although subsequent steps, given an initial error can have an error rate approaching 1 due to coupling or dependency.

- 1/5 - highest error rates with poor control of human factors; this high rate is typically due to high fatigue or some other physiological or psychological stress (or combination). This is the upper limit of error rates observed with poor human factors and within the process industry. *The error rates in the Isomerization Unit the day of the accident at BP Texas City Refinery (CSB, 2006) were about this rate. The operators, maintenance staff and supervisors had been working about 30 days straight (no day off) of 12 hour shifts.*

For the examples provided later in this paper ***will use a baseline error rate of 0.02 errors per step***, which is about average at the sites PII visited in the past 10 years. This could be justified based on the fact that most chemical process sites do not control overtime during turnarounds and/or do not have a system for controlling verbal communication of radios and phones. In addition, for critical steps such as re-opening and car-sealing the block valves under a relief valve after the relief valve is returned from maintenance is about 0.01 to 0.04 (CCPS 2012); plus, the average probability of making an unsafe error during maintenance of a relief is 0.02 (Bukowski, 2007-2009). Both of these tasks have multiple checks and have rigorously enforced procedures (similar to what is done when servicing a SIF and when using bypasses for an SIF) and yet the human error probability remains about 0.02.

Table 1. SUMMARY TABLE of 10 HUMAN FACTOR CATEGORIES

Based in part on: Gertman, D.; et. al., *The SPAR-H Human Reliability Analysis Method*, NUREG/CR-6883, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC, August 2005. PII has modified the list slightly to account for general industry data and terminology and to incorporate PII internal data.

Human Factor Category	Human Factor Issue/Level	Multiplier for Cognitive & Diagnosis Errors
Available Time (includes staffing Issues) – ***for responses only***	Inadequate time	P(failure)=100%
	Barely adequate time (≈2/3 x nominal)	10
	Nominal time (1x what is expected)	1
	Extra time (at least 2x nominal and >20 min)	0.1
	Expansive time (> 4 x nominal and > 20 min)	0.01
Stress/Stressors (includes staffing issues)	Extreme (threat stress)	5
	High (time pressures such as during a maintenance outage; issues at home, etc.)	2
	Nominal	1
Complexity & Task Design	Highly complex	5
	Moderately complex (requires more than one staff)	2
	Nominal	1
	Obvious diagnosis	0.2
Experience/Training	Low	10
	Nominal	1
	High	0.5
Procedures	Not available in the field as a reference, but should be	20
	Incomplete; missing this task or these steps	8
	Available and >90% accurate, but does not follow format rules ***(normal value for process industry)***	3
	Good, 95% accurate, follows >90% of format rules	1
	Diagnostic/symptom oriented	1
Human-Machine Interface (includes tools)	Missing/Misleading (violates populational stereotype; including round valve handle is facing away from worker)	20
	Poor or hard to find the right device; in the head calc	10
	Some unclear labels or displays	2
	Good	1
Fitness for Duty	Unfit (high fatigue level (>80 hrs/wk or >20 hr/day, no day off in 7-day period; or illness, etc.)	20
	Highly degraded fitness (high fatigue such as >15 hr/day, illness, injury, etc.)	10
	Degraded Fitness (>12 hr day and >72 hr/wk)	5
	Slight fatigue (>8 hr per day; ***normal value for process industry***)	2
	Nominal	1
Work Processes & Supervision	Poor	2
	Nominal	1
	Good	0.8
Work Environment	Extreme	5
	Good	1
Communcation	No communication or system interference/damage	10
	No standard for verbal communication rules ***(normal value for process industry)***	3
	Well implemented and practiced standard	1

3. Human Error Probability for Multiple Executions of a Rule-Based Task

Coupled (dependent) Error Rates: Coupling represents the probability of repeating an error (or repeating success) on a second identical task, given that an error was made on the first task. The increased probability of failure on subsequent tasks given that an error has already been made is known as dependence. The list below provides some starting point guidance on values to use:

- 1/20 to1/90 - if the same tasks are separated in time and if visual cues are not present to re-enforce the mistake path. *This error rate assumes a baseline error rate of 1/100 with excellent human factors. If the baseline error is higher, then this rate will increase as well.*
- 1/2 - if same two tasks performed back-to-back and strong visual cue is present, and if a mistake is made on the first step of the two. *This error rate assumes a baseline error of 1/100 with excellent human factors. If there the baseline error is higher, then this rate will increase as well.*
- 8/10 - if same three tasks performed back-to-back and strong visual cue is present, and if a mistake is made on the first two steps of the three.
- Two or more people become the same as one person (with respect to counting of errors from the group), if people are working together for more than three days; this is due to the trust that can rapidly build.

These factors are based on the relationships provided in NUREG-1278 and the related definitions of weak and strong coupling provided in the training course by Swain (1993) on the same topic. The following relationship is for errors of omission, such as failing to reopen a root valve or failing to return an SIF to operation, after bypassing the SIF. The values in Table 2 are based Gertman (SPAR-H, 2005 which is NUREG/CR-6883).

Table 2: Guideline for Assessing Dependence for a within-SIF Set of Identical Tasks (based partially on SPAR-H, 2005, and partially on field observations by PII)

Level of Dependence	Same Person	Actions Close in Time	Same Visual Frame of Reference (can see end point of prior task)	Worker Required to Write Something for Each Component
Zero (ZD)	No; the similar tasks are performed by different person/group	Either yes or no	Either yes or no	Either yes or no
Zero (ZD)	Yes	No; separated by several days	Either yes or no	Either yes or no
Low (LD)	Yes	Low; the similar tasks are performed on sequential days	No	Yes
Moderate (MD)	Yes	Moderate; the similar tasks are performed more than 4 hours apart	No	No
High (HD)	Yes	Yes; the similar tasks are performed within 2 hours	No	No
Complete (CD)	Yes	Yes; the similar tasks are performed within 2 hours	Yes	Either yes or no

One can readily conclude that staggering of maintenance tasks for different channels of the same SIF or for related SIFs will greatly reduce the level of dependent errors. Unfortunately, most sites PII visits do not stagger the inspection, test, or calibration of redundant channels of the same SIF or of similar SIF; the reason they cite is the cost of staggering the staff. While there is a perceived short-term higher cost, the answer may be different when lifecycle costs are analyzed.

Once the level of dependence is known, the probability of either repeat success or repeating errors on identical tasks can be estimated. For these probabilities, we use Table 3, which is a re-typing of Table 20-17 from NUREG-1278 (and the similar table in SPAR-H [Gertman, 2005]).

Table 3. Equations for Conditional Probabilities of Human Success or Failure on Task N, given probability of Success (x) or Failure (X) on Task N-1, for Different Levels of Dependence

Level of Dependence	Repeating Success Equations (but shown as error probability)	Repeating Failure Equations
Zero (ZD)	$P_{Succes@N} = x$	$P_{Failure@N} = X$
Low (LD)	$P_{Succes@N} = (1+19x)/20$	$P_{Failure@N} = (1+19X)/20$
Moderate (MD)	$P_{Succes@N} = (1+6x)/7$	$P_{Failure@N} = (1+6X)/7$
High (HD)	$P_{Succes@N} = (1+x)/2$	$P_{Failure@N} = (1+X)/2$
Complete (CD)	$P_{Succes@N} = 1.0$	$P_{Failure@N} = 1.0$

4. Illustrative examples

To illustrate the impact (sensitivity) on PFD_{SIF}, we will look at two simple cases and will not provide the details on the calculation of the component aspects of PFD_{SIF}, but instead will provide the results of PFD_{COMP} to be the value obtained by using Equation A, but without the systematic error terms (the same as using Eq. No. 1 from ISA-TR84.00.02). Then we will show a simple way to estimate the system human error term ($PFD_{SYS\text{-}HUM}$) and show the resulting impact on PFD_{SIF}. Figures 2 and 3 show a candidate SIL 1 SIF and a candidate SIL 2 SIF, respectively.

4.1 Example 1 - Illustration of Estimate of PFD_{SIF}, for a SIL 1 SIF, with and without consideration of $P_{SYS\text{-}HUM}$

For the SIL 1 SIF in Figure 2, the component PFDs were estimated using standard, simplified equations for each, and using generic data available for the components. Based on this calculation, the PFD of the SIF without consideration of discrete systematic error yielded a $PFD_{COMP} = 0.039$. It is noted that the sensor/transmitter PFD contribution is 0.025; this value will be important in the second Example included in Section 4.2.

Figure 2. Example of SIL 1 SIF (high level trip of compressor motor)

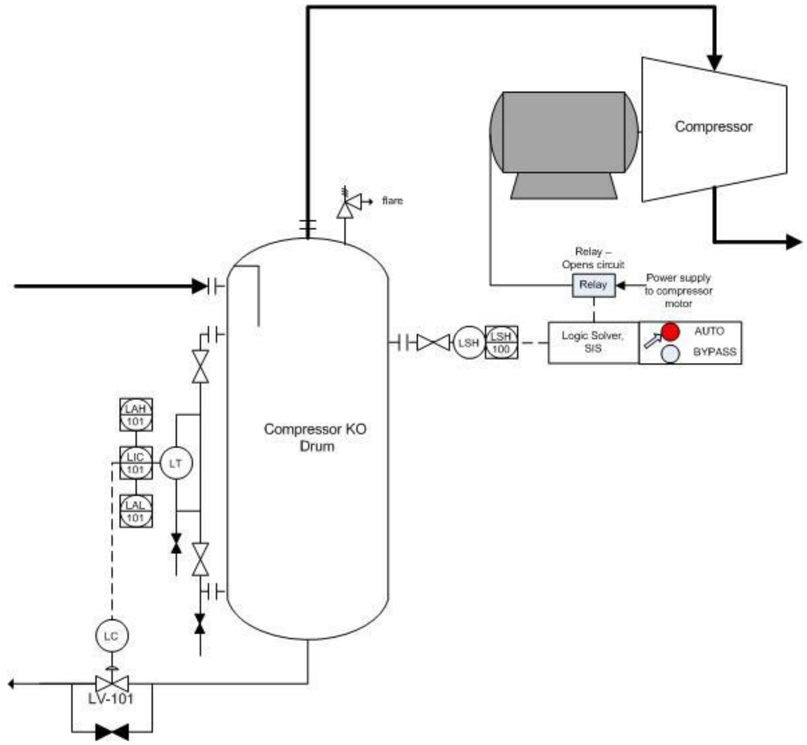
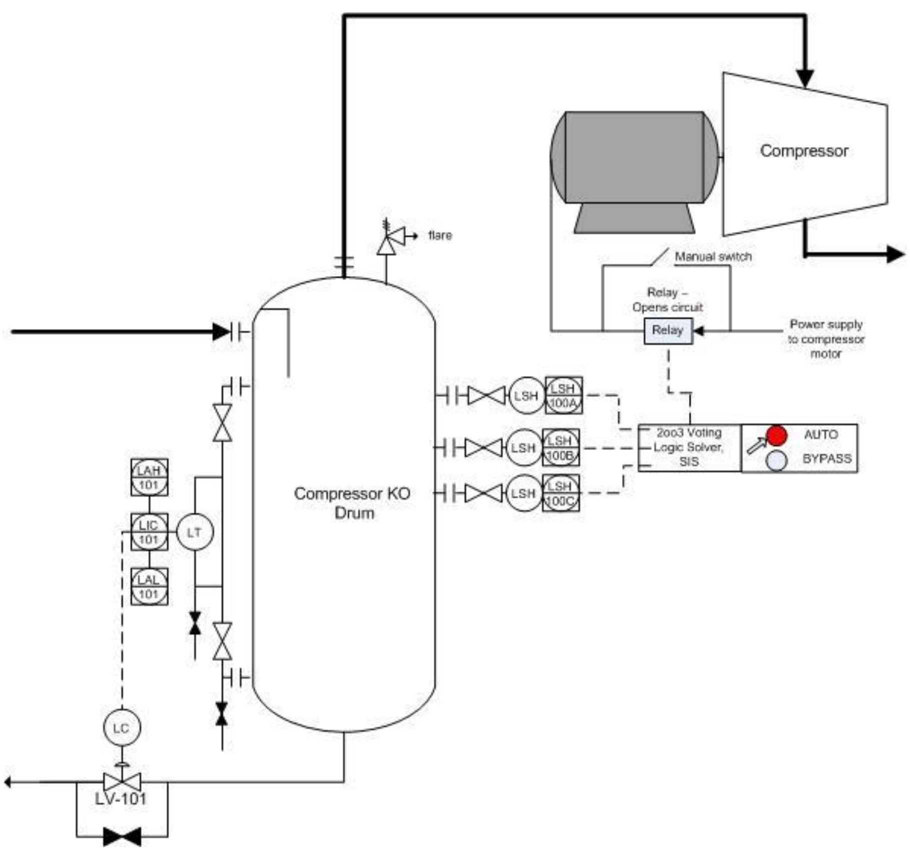


Figure 3. Example of SIL 2 SIF (high level trip of compressor motor)



For this example, the term $\sum P_{SYS\text{-}HUM}$ is next estimated by summing the

- Probability of leaving the root valve for the level switch (sensor/transmitter) closed
- Probability of leaving the entire SIF in BYPASS after maintenance or after some other human intervention (such as an inadvertent error or as a necessity during startup)
- Probability of miscalibration of the level transmitter/switch.

Since these are all independent systematic errors, the error rate will simply be 0.02 (the base error rate provided) for each mistake, or:

$$\sum P_{SYS\text{-}HUM} = 0.02 + 0.02 + 0.02 = 0.06$$

This would then give an overall failure probability for the SIF of:

$$\mathbf{PFD_{SIF} = PFD_{COMP} + P_{SYS\text{-}HUM}} = 0.039 + 0.06 = 0.099$$

Since the PFD is less than 0.1, the instrumented system for high level protection still qualifies as a SIL 1 SIF. But, suppose we wish to improve the reliability and independence of the instrumented system by using a smart sensor/transmitter for the high level switch (LSH) which will detect null movement of the sensor reading (indicating the valve is closed on the tap is plugged) or suppose we put a limit switch (or captive key system) on the root valve. There is a probability that these safeguards against human error will also fail or be bypassed by the staff, but assuming the probability of that failure is the same as other human errors for this example, 0.02, then the overall system human error is reduced, because the probability of leaving the root valve closed is now ANDed with the probability of smart sensor/transmitter or limit switch failing:

$$\sum P_{SYS\text{-}HUM} = (0.02*0.02) + 0.02 + 0.02 = 0.04$$

therefore the revised PFD of the instrument system becomes:

$$\mathbf{PFD_{SIF} = PFD_{COMP} + P_{SYS\text{-}HUM}} = 0.039 + 0.04 = 0.079$$

Sensitivity to Baseline Human Error Rate: If the baseline human error probability increases to 0.04 due to fatigue or extra stress due to schedule constraints, then even with the extra instrumentation to detect valve closure, the PFD of the systematic human error will increase substantially:

$$\sum P_{SYS\text{-}HUM} = (0.04*0.04) + 0.04 + 0.04 = 0.082$$

and the revised PFD of the instrument system becomes:

$$\mathbf{PFD_{SIF} = PFD_{COMP} + P_{SYS\text{-}HUM}} = 0.039 + 0.082 = 0.121$$

In this modified case, which is applicable to about a third of the facilities PII has visited in the past 10 years (due primarily to fatigue), the instrumented system no longer qualifies as a SIL 1.

The human error for miscalibration is very difficult to reduce, unless there are redundancy and voting of the level sensor/transmitters; then miscalibration errors can be essentially eliminated as an important contribution to human error. This case will be explored in Section 4.2 as part of Example 2.

The composite error of leaving the entire system in bypass is usually made up of (1) the inadvertent error to return the system to AUTO after maintenance and (2) the probability that the staff will make the intentional decision to leave the SIF in bypass, for perhaps a reason not anticipated by the designers. Management of change (MOC) should address the latter case, but the probability of MOC failing is the same as the error rate used already, since the error probability used was a lumped error for leaving the SIF bypassed for whatever reason. Therefore, this error rate normally cannot be reduced, even after adding repeating alarms to alert the staff that the SIF is still bypassed; the staff will hear and acknowledge the alarms, but will leave the system in bypass intentionally. Again, this will be bad only if the designers failed to anticipate this need and therefore failed to have a different IPL provided when it is necessary to bypass for operational requirements or if the MOC fails to engage the designers allowing for a proper design fix.

4.2 Example 2 - Illustration of Estimate of PFD_{SIF}, for a SIL 2 SIF, with and without consideration of $P_{SYS\text{-}HUM}$

For the SIL 2 SIF described in Figure 3, the component PFDs were estimated using standard, simplified equations for each, and using data available for component. For the case where the sensors are voted 2oo3, the PFD of the SIF without consideration of discrete systematic error yielded PFD_{COMP} = 0.008 (of which the 2oo3 voted sensor portion is 0.0025 and the 2oo3 voted logic solver is 0.003).

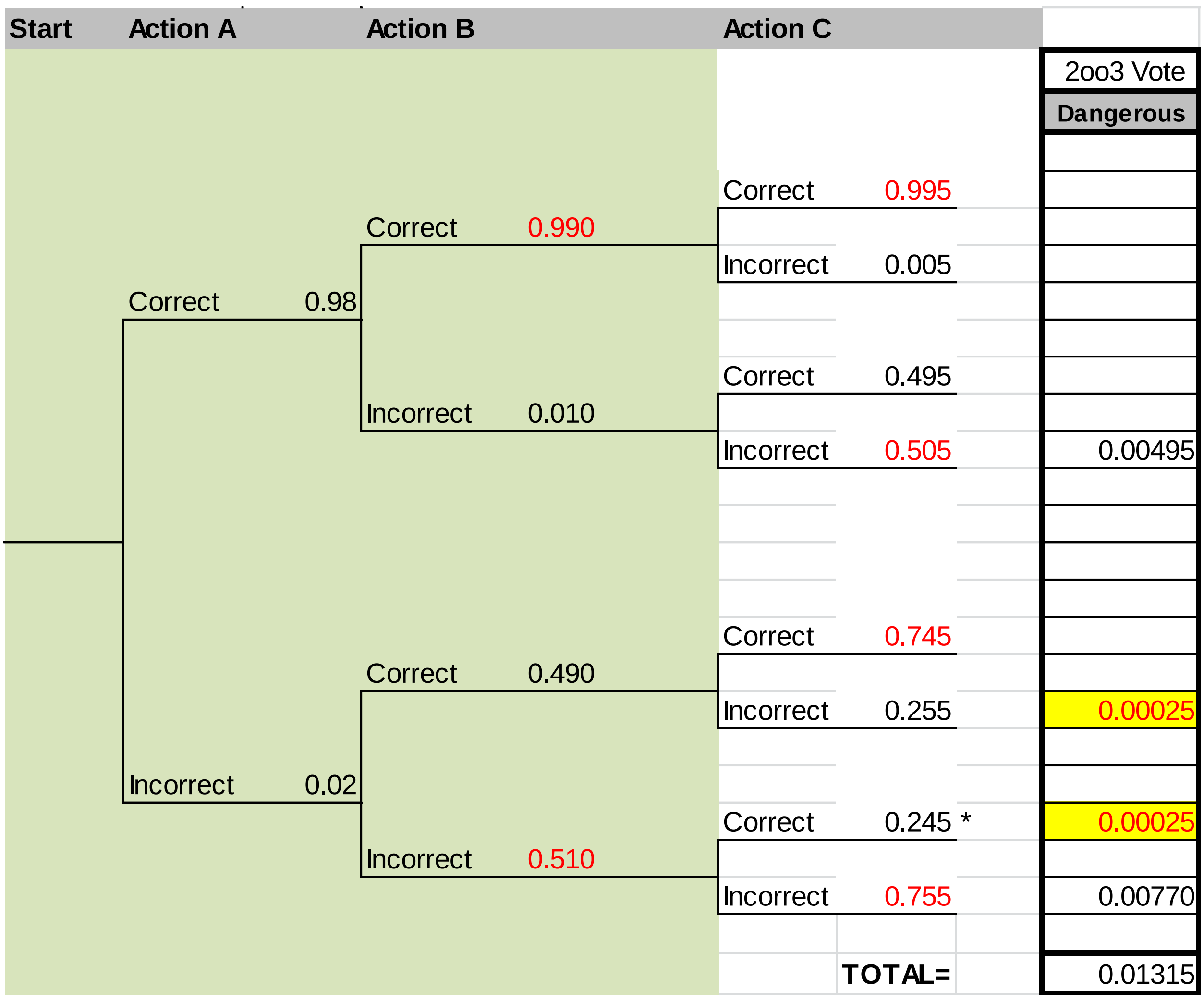
For this example, the term $\sum P_{SYS\text{-}HUM}$ is next estimated by summing the

- Probability of leaving the level sensor/transmitters 2oo3 root valves closed, causing an unsafe failure. (This calculation is shown later.
- Probability of miscalibration of the level transmitter/switch. This calculation is shown later, but for this to be significant probability, all two of the three sensors/transmitters must be miscalibrated, unless there is comparison checking, then it would require miscalibration of all three transmitters.
- Probability of leaving the entire SIF in BYPASS after maintenance or after some other human intervention such as an inadvertent error or a necessity during startup; as before, we will use the base error probability of 0.02 as a starting point.
- Probability of leaving the relay bypass closed. As before, we will use the base error probability of 0.02 as a starting point.

To aid in the calculation of the probability of leaving 2oo3 root valves closed, we use an event tree to show the conditional probabilities for leaving Valve B closed, given Valve A is open or closed, and similarly, the conditional probability of leaving Valve C closed, given Valve A or B are closed or both Valve A and B are closed. Figure 4 shows the results of this calculation. For the branch probabilities, the equations for high dependency of the human actions were used (See Table 3); this reflects the more prevalent case of the maintenance of redundant channels being maintained on the same day, by the person, and that level valves are within the visual field of the worker. From Figure 4 the result for the probability of human error of leaving 2oo3 or 3oo3 of the root valves closed is 0.0129. But, the comparison checking between sensors/transmitters will alert the workers that a root valve is closed, so the only valid path is the 3oo3 path; the 3oo3 error case is the bottom row of the event tree in Figure 4. The probability of leaving all three root valves closed is 0.0077.

From the same figure, we can also extract the conditional probability of leaving 3oo3 sensors/transmitters bypassed; assuming comparison checking is in place to note deviations and correct the problem, only the case of 3oo3 errors is credible. This represents a strong recovery path for the previous errors. The 3oo3 error case is the bottom row of the event tree in Figure 4. The probability of miscalibrating all three sensors/transmitters is 0.0077.

Figure 4. Calculation of Conditional Probability of Opening Root Valves; with the Last Column Showing the Probability of Leaving Two or Three Valves Closed (using High Dependence Equations)



$$\sum P_{SYS\text{-}HUM} = 0.0077 + 0.0077 + 0.02 + 0.02 = 0.055$$

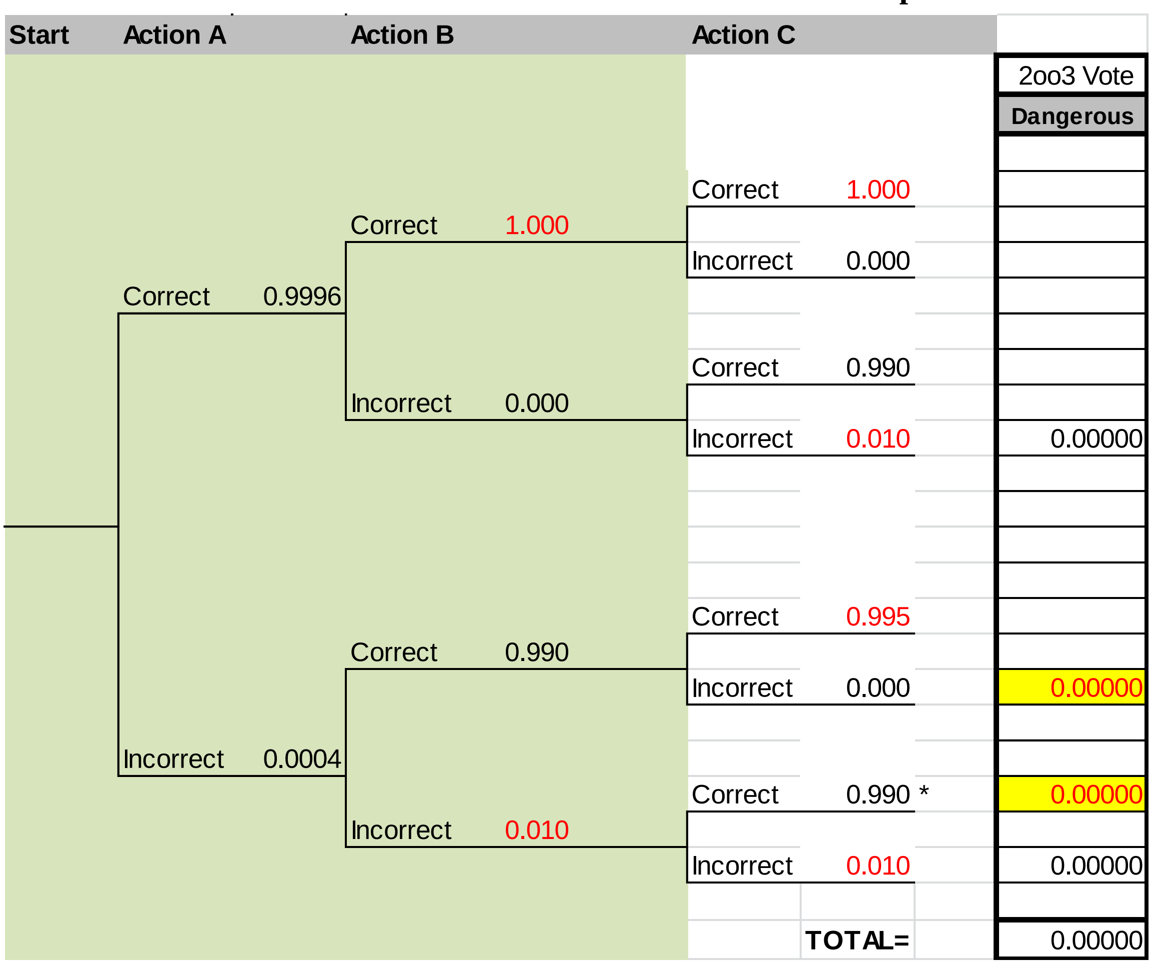
This would then give an overall failure probability for the SIF of:

$$\mathbf{PFD_{SIF} = PFD_{COMP} + P_{SYS\text{-}HUM}} = 0.008 + 0.055 = 0.063$$

Since the PFD is greater than 0.01, the instrumented system for high level protection in this example does not qualify as a SIL 2 SIF when accounting for human error probabilities related to interventions with the SIF.

One means to improve the reliability and independence of the instrumented system is to use a smart sensor/transmitter for the LSH which will detect null movement of the sensor reading, indicating the valve is closed on the tap is plugged. Another possibility is to implement a limit switch (or captive key system) on the root valve. There is a probability that these safeguards against human error will also fail or be bypassed by the staff, but assuming the probability of that failure is the same as other human errors for this example, 0.02, then the systemic human error drops to about zero as the probability of leaving the root valve closed is now ANDed with the probability of smart sensor/transmitter or limit switch failing, as shown in Figure 5 below:

Figure 5. Calculation of Conditional Probability of Opening Root Valves; with the Last Column and Last Row Showing the Probability of Leaving Three Valves Closed, and with a Limit Switch or Smart Sensor to Check that Each Root Valve is Open.



$$\sum P_{SYS\text{-}HUM} = 0.0000 + 0.0077 + 0.02 + 0.02 = 0.048$$

In this case the revised PFD of the instrument system becomes:

$$\mathbf{PFD_{SIF} = PFD_{COMP} + P_{SYS\text{-}HUM}} = 0.008 + 0.048 = 0.056$$

Since the PFD is still greater than 0.01, the instrumented system for high level protection still does not qualify as a SIL 2 SIF when accounting for human error probabilities related to interventions with the SIF. But, we have reduced the errors related to dependent failures during checking of the sensors/transmitters as much as possible.

As another alternative (instead of using smart sensors/transmitters or instead of installing limit switches on the root valves) we can reduce potential dependent human error by staggering maintenance activities across different shifts. This would drop the dependence to Low. The dependent error calculations using the Low Dependence equations of Table 3 is shown in Figure 6. From Figure 6, assuming low dependency of human error, the result for the probability of human error of leaving 3oo3 of the root valves closed in 0.00016 (assuming that comparison of sensor readings alerts the workers that one root valve is closed)

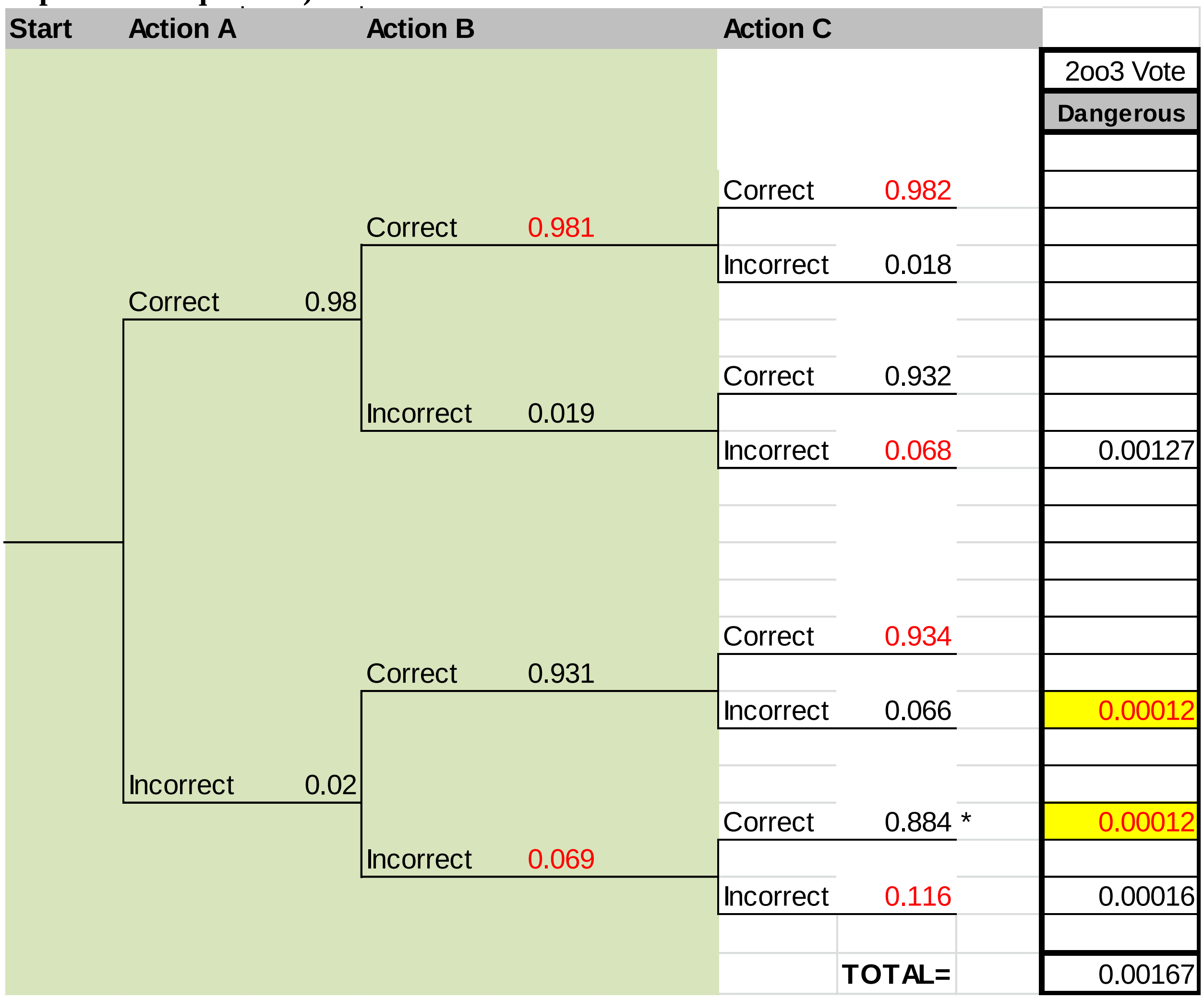
From the same figure, we can also extract the conditional probability of leaving 3oo3 sensors/transmitters. As before, only the case of 3oo3 errors is considered credible, since it was assumed that sensor comparison checking was implemented where any transmitter not miscalibrated will provide the workers an opportunity to note the deviation and take corrective action to fix the problem; this represents a strong recovery path for the previous errors. The 3oo3 error case is the bottom row of the event tree in Figure 6. The probability of miscalibrating all three sensors/transmitters is 0.00016.

$$\sum P_{SYS\text{-}HUM} = 0.00016 + 0.00016 + 0.02 + 0.02 = 0.040$$

This would then give an overall failure probability for the SIF of:

$$\mathbf{PFD_{SIF} = PFD_{COMP} + P_{SYS\text{-}HUM}} = 0.008 + 0.042 = 0.050$$

Figure 6. Calculation of Conditional Probability of Opening Root Valves; with the Last Column Showing the Probability of Leaving Two or Three Valves Closed (Using Low Dependence Equations)



Since the PFD is greater than 0.01, the instrumented system for high level protection still does not qualify as a SIL 2 SIF when accounting for human error probabilities related to interventions with the SIF. The weak link in this design is again the human error probability of leaving either the relay bypass closed or the probability of leaving the entire SIF bypassed. This is a common concern on all SIF that have system bypasses. The most effective way to drop these error rates is to eliminate the capability for bypassing the relay and to eliminate the capability for bypassing the entire SIF. Or; we can install a parallel relay with a selector switch so that one relay (and only one) is aligned in the circuit to the motor of the compressor. This will likely drop the relay systemic human error probability from 0.02 down to 0.0004 or lower. The toughest bypass to eliminate is the one for the entire SIF. This is usually only feasible on batch systems or on continuous operations that can be shut down completely for each test interval.

Sensitivity to Baseline Human Error Rate: Obviously, if the baseline human error probability increases to 0.04 due to extra fatigue or extra stress due to schedule constraints, the PFD of the systematic human error will increase substantially and the SIL 2 target becomes even less attainable. Likewise, if suitable operational discipline is adopted to reduce the baseline human error with independent performance measurement to validate the results, the human error rate will be reduced (though it is likely not possible to reduce the baseline human error probability enough to achieve a SIL 2 target, if a SIF bypass is present).

5. Acronyms Used

1oo2	One out of two voting architecture
1oo3	One out of three voting architecture
2oo3	Two out of three voting architecture
3oo3	Three out of three voting architecture
λ	Failure Rate
A	Final element
CD	Complete Dependence
COMP	Random hardware failure contributions to overall PFD
D	Dangerous
F	Failure/error term
HD	High Dependence
HRA	Human Reliability Analysis
IPL	Independent Protection Layer
LD	Low Dependence
L	Logic Solver
LOPA	Layer of Protection Analysis
MOC	Management of Change
P	Probability
PES	Programmable Electronic System
PFD	Probability of Failure (dangerous) on Demand
PII	Process Improvement Institute, Inc.
PS	Power supply
PSV	Pressure Safety Valve
S	Sensor
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIS	Safety Instrumented System
SYS	Systematic failure contributions to overall PFD
SYS-HUM	Systematic errors and failures generated by human error
SYS-PROC	Systematic errors and failures generated randomly by the process
TI	Proof Test Interval
ZD	Zero Dependence

6. Conclusion

As can be seen from the quantitative examples, systematic errors have the potential to significantly impact a SIF in a negative manner. In addition, SIL verifications performed today often do not account for this contribution to probability of failure. In such cases, it becomes increasingly likely that the risk reduction assumed by analysts (who rely upon a SIL 2 to have a PFD of 0.01 or lower) is not sufficient to satisfy corporate risk criteria when the actual risk reduction estimated for the IPL is being counted on, such as an SIF replacing a relief valve, as opposed to analyses that are simply performed on a comparative basis where consistency is more important than the actual numbers.

The paper points to the need for companies to begin:

- Accounting for systematic (and especially human systematic error probability) in SIL Verifications; otherwise the risk reduction factor from this IPL will be unrealistically optimistic.
- Taking a more in-depth look at the management systems and work process in place for operations and maintenance and their associated training and revalidation of performance.

Utilizing the mathematics presented, companies can gain insight as to the relative effectiveness of their practices and find areas where improvements can be made without adding any real cost. Just as improved human factors improve safety, this is one of those cases where improved performance if done properly with true operational discipline, should also improve reliability and plant availability.

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