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COMPUTING THE SAFETY INTEGRITY LEVEL (SIL) FOR TURBO MACHINERY PROTECTION

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Lil Kassie is presently an independent Rotating Equipment Consultant. He has been involved with the selection, sizing, installation, commissioning and maintenance of rotating equipment for over 45 years. For over 30 years he worked for BP/ Amoco in the following positions; Machinery Advisor, BP Refining - worldwide; Consultant, BP/ Amoco, US - Refining; Superintendent, Rotating Equipment Group, Amoco, Whiting Refinery, Whiting, IN. and Rotating Equipment Engineer at the same refinery. Prior to joining BP/ Amoco he worked for Ingersoll Rand Co, Philipsburg, NJ.as field engineer, in the Turbo Products Division, and for the ECI Refinery, East Chicago, IN. as Superintendent, Rotating Equipment. Lil holds a BS and MS in Mechanical Engineering from the University of Wisconsin and is presently a Member (Emeritus) on the Turbo Advisory Committee.

ABSTRACT

SIL has become the new standard by which industry, manufacturers, and end users will be held to by regulators as good engineering practice. Specifically supporting turbomachinery, the API670 "Machinery Protective Systems" (5th edition, 2014) [R1] standard has embraced such methodology.

To begin the presentation, background on risk assessment, SIL assignment, and API 670 will be reviewed. After it, common SIL assignments for various types of rotating equipment will be presented. he paper will then take a deeper look into what is important regarding the "SIL verification calculations" based on common interlocks. Such calculations are required to quantify that the probability of failure-average (PFDavg) of the system design meets the SIL assigned earlier in the risk assessment.

Since not all of the key factors that affect SIL calculations are intuitively obvious, the authors will break down the SIL calculation models and discuss each parameter in detail. After this model foundation is set, the combined effect of an interlock's design including components (i.e. data), architecture, and maintenance practices will be shown.

Lastly, various examples utilizing a cross-section of equipment configurations will help reinforce such SIL calculation principles.

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INTRODUCTION

Tutorials are a highly effective method of transferring knowledge and may be used as an important means of imparting learning. The focus of this tutorial is on the specifics of the SIL calculations. Each safety instrumented function (SIF) design must be verified through probabilistic calculations to meet their risk bases SIL target. (See ISA61511 Clause 11.9.1) The key here is to do the probabilistic calculations for each SIF which will verify safety and spurious trip performance criteria as well as optimize design to economically meet the requirements for each different function. The spurious trip discovery could be quite significant for plant production where it has been stated that up to 18% of plant trips are associated with instrumentation.

BACKGROUND ON RISK MANAGEMENT AND APPLICATION OF SIL

The SIL lifecycle starts with an operating company's hazard assessment to determine if there are any risk gaps. The original methodology was to utilize qualitative processes, but these have now been updated to more quantitative processes. A review of this progression follows in the next sections.

Qualitative Techniques for Risk Mitigation

Process Hazard Assessment (PHA) is a systematic way to identify all potential hazards for a facility so the risk team can determine how to manage each one. Generally speaking, HAZOPs are favored for their thoroughness with processes, since the whole plant is reviewed node-by-node, with a detailed set of guide words applied to each characteristic of the process. What-ifs, FMEAs, and Checklists are alternative PHA techniques used for many rotating equipment configurations.

The primary objective of the PHA studies was to identify the causes of potential safety and environmental hazards, as well as major operability problems. Based on the evaluated consequences and safeguards identified, the multi-disciplined PHA team will propose recommendations to reduce the risk and enhance operability to tolerable levels in compliance with each company's risk criteria.

Quantitative Techniques for Risk Mitigation

Use of qualitative risk ranking tools is relatively simple, but unfortunately, it lead to inconsistencies between different PHA teams as well as having the potential to under or over-estimate the risk. For lower level risks, this is not generally a significant concern, however, for higher risks there is a need for management to be able to make better informed decisions using a more consistent basis. That requires a greater level of insight and is provided by more quantitative analysis techniques that determine if there is a risk or Safety Integrity Level (SIL) gap.

In layman terms, SIL refers to "orders of 10 risk reduction" as shown in the following table:

SIL	Risk Reduction
1	> 10 factor
2	> 100 factor
3	> 1,000 factor

Table 1: SIL & Risk Reduction

After such risk targets are discovered, other Safety Life Cycle (SLC) processes are followed such as verification calculations to ensure that the Safety Instrumented Functions (SIFs) designs can achieve the necessary risk reduction.

SIL Determination Methods

There are various graphical and numerical techniques to determine the required SIL value to achieve a target risk goal. Those cited in ISA61511Application of Safety Instrumented Systems for the Process Industries [R3] follow in Table 2.

Annex	Name	Origin
A	ALARP *(As Low as Reasonably Practicable)*	UK
B	Semi-Quantitative	USA
C	Safety Layer Matrix	USA
D	Calibrated Risk Graph: Semi-Qualitative	UK
E	Risk Graph: Qualitative	Germany
F	Layer of Protection Analysis (LOPA)	USA

Table 2: Different SIL Selection Methods

Each of these methods should give roughly the same answer if they're "calibrated" to the same tolerable risk. The real choice in technique depends more on what fits best with a company's existing risk management philosophy and procedures. For each hazard, the SIL technique must take into account:

1. The corporations' tolerable limits
2. Full and mitigated consequences of each hazard
3. Root cause or initiating event frequency
4. Number and effectiveness of independent safeguards

If there's a gap between the tolerable and current hazard frequency (taking into account the applicable safeguards, but not the SIF), then added protection is required. It can be either a SIF or other layers of protection.

Common SIL Ratings for Rotating Equipment

As mentioned in the preceding section, the process of SIL assignment takes into account the end user's risk target, consequence severity, initiating cause frequency, the number of safeguards, and the application of conditional modifiers, so the final SIL requirement can vary widely.

Utilizing the experience of the authors and a broad perspective of reviews, the following Table 3 offers a glimpse of what could be expected for critical rotating equipment.

		SIL Target		
Driver	**Application**	**High**	**Low**	**Norm**
Steam turbine	Overspeed	SIL2	SIL1	SIL1
Centrifugal Compressor	Anti-Surge	SIL2	None	1 IPL
	Back flow Isolation	SIL2	None	SIL1
	High Level	SIL2	None	SIL1
Gas turbine	Light Off	SIL2	SIL1	SIL1
Turbine Generator	Overspeed	SIL2	SIL2	SIL2
Reciprocating Compressor	High Level	SIL2	None	SIL1
	HP discharge	SIL2	None	SIL1

Table 3: Common SIL Targets for Rotating Equipment

Naturally, each company must review each application individually to avoid either over- specification, or more imperative for safety, under-specification of turbomachinery SIL.

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The Complete Functional Safety Lifecycle

Once an interlock has received the "SIL branding", the ISA61511 standard requires that other SLC steps be followed diligently to ensure that both random and systematic failure is not introduced into its design and operability. Although the focus of this paper is the SIL calculations, the other steps include:

- Functional Safety Management
- Safety Requirements Specification (SRS)
- SIF Conceptual Design
- SIL Verification Calculations
- Validation Tests
- Functional Safety Assessments (FSA)
- Routine Periodic Tests / Maintenance
- Management of Change/Decommissioning

SPECIFIC APPLICATIONS OF SIL WITHIN API670

Before getting into the details of SIL verification calculations, it was felt that a review of the API670 standard's correlation to SIL would be helpful. It should also be noted that the 2014 standard is already being updated via committee at the time of this writing.

Although API Machinery Protection Standard API670 has been around since the 1980s, the November 2014 update adds over 150 pages of new content. The most notable changes are shown in the following Table 4:

Clause /Annex	Specification
8	Electronic Overspeed -More detailed discussion
9	Surge detection (New)
10	ESD (New)
K	Surge Detection (New)
L	Safety Integrity Level *(New)*
M	Spurious Shutdowns *(New)*
N	Condition Monitoring *(New)*
O	Overspeed *(New)*
P	Recip Compressors *(New)*
Q	Wireless *(New)*

Table 4: New Clauses & Annexes in API670

Such additions support a cohesive strategy with the other process and machine functional safety standards.

Emergency Shutdown Device (ESD) and API670

The Emergency Shutdown Device (ESD) detailed in clause 10 is synonymous to the SIS detailed by ISA61511. By having such a "single brain" for supporting all the critical safety functions, the first requirement of consolidating all trip demands and ensuring "proper timing and sequencing for a safe shutdown" is met.

There is latitude on whether all the shutdown logic is performed in the ESD. If such functions are included in the ESD, then it is termed "Integrated Architecture". If it is not and separate surge, monitoring, and overspeed systems are tied to the ESD through hardwiring or communications, the overall system is considered to have "distributed architecture".

Annex L – Safety Integrity Level

Annex L provides a 17-page introduction of the SIL concepts and correlates their application to turbomachinery standards. Although the risk graph methodology is not as prevalent in the USA as it is in Europe, its principles still apply to those that have standardized on LOPA as mentioned earlier.

Key takeaways from this SIL annex include:

- SIL compliance, although associated directly to the ESD logic solver, should be extended to the I/O devices
- Separation of control and safety is imperative
- SIL is determined by performance requirements set by each user, not by prescriptive methods

Such practices line up closely with those of the currently functional standards like ISA61511.

Annex M – Spurious Shutdowns

Since safe, fault tolerant methods with higher spurious trip rates may at times oppose process uptime (i.e. machine reliability), this annex "recommends some practice to reduce the risk of economic losses".

Key takeaways from this spurious trip annex include:

- Utilization of fault tolerant designs for safety and reliability
- Applying preventative diagnostics where applicable

Regarding plant impact examples, the following table truly supports such measures.

Process Application	Spurious Trip Cost
Oil & Gas Platforms	Up to $2 million/day
Polystrene	20 days to recover at $20k/day=$400k
Refinery Coker Heater	$35k/day
Refinery Catalytic Cracker	$500k
Complete Refinery	$1 million/day
Ammonia & Urea Plants	$1 million/day
Power Generation	$100k/MWhr to $MM/site
Ethylene	$1 MM getting product to spec

Table 5: Spurious Trip Cost in Process Industries [R5]

VERIFICATION –QUANTIFYING THAT SIF DESIGN MEETS THE RISK TARGET SIL

Each safety instrumented function (SIF) design must now be verified through probabilistic calculations. (See ISA61511 Clause 11.9.1) The key here is to do the probabilistic calculations for each SIF which will verify safety and spurious trip performance criteria as well as optimize design to economically meet the requirements for each different function. The spurious trip discovery could be quite significant for plant production where it has been stated that up to 18% of plant trips are associated with instrumentation.

Verification calculations are optimally performed after the conceptual design step has been completed using generic components for the SIF architectures proposed. The calculation models are based on three main techniques as discussed in the following paragraphs.

In the sections that follow, a high level tutorial of three popular methods will be reviewed. See Safety Instrumented Systems Verification - Practical Probabilistic Calculations [R5] and ISA TR.02 SIL Evaluation Techniques [R4] for more information on this subject.

Verification Technique 1: Simplified Equations

Simplified calculations have been derived using basic calculus methods where you would get the integral average of the probability function, PF(T).

For instance, for a 1oo2 component voting system:

$PF(T) \approx \lambda d * T$ (where $PF<0.1$) for one component
(T=test interval, λd = dangerous failure rate)

Then for two components where we multiply probabilities:

$PF(T, 2 \text{ devices}) \approx (\lambda d*T)(\lambda d*T) = \lambda 2d*T2$ assuming identical

The integral average function is:

$PFDavg = 1/T * \int PF(t)dt$

So if we substitute the PF(T, 2 devices) above:

$PFDavg = 1/T * \int \lambda 2d*T2\ dt$

Then if we integrate, we get:

$PFDavg = 1/T * [\lambda 2d * T3/3] = \lambda 2d * T2/3$

As an example, if $T = 2$ years, and $\lambda d=1/20$ years for a pressure switch:

$PFDavg = (1/20)2*22 /3 = 3.33E\text{-}3$, or alternatively,
Risk Reduction Factor (RRF) = 1/PFDavg = 300

That may have seemed simplified, but the complete equation, accounting for online partial testing, imperfect proof tests, and common cause can become more daunting. This is the formula for such a case and is expressed as:

$PFDavg = \lambda 2dd * (RT+TIPT/2)2$ [partial test contribution]
$+\ \lambda 2d * T2/3$ [base contribution, derived above]
$+\ \lambda 2dn * T2LT/3$ [imperfect test contribution]
$+ (\beta*\lambda d*T/2) + (\beta*\lambda dn*TLT)$ [common cause adds]

Where: λdd = Partial test failure effectiveness,
RT= Online repair time,
TIPT=Partial test frequency,
λdn = Failures never detected due to imperfect test
TLT = Lifetime (mission) time before rebuild/replace
β = Common cause, lowered w/diversity/separation

Verification Technique 2: Fault Trees

Fault tree math is another method that practitioners use to perform their SIL verification analysis. It utilizes the OR and AND gate math principles that most engineers picked up during college in general programming classes.

The math is quite simple; addition is applied to OR (symbol-) and multiplication is used for AND (symbol-) gates. These rules apply for standard probabilities, but for PFDavg, you cannot just multiple the individual component's average or you would have an optimistic answer.   To overcome such an issue, a conservative averaging of multiple time iterations of the standard probability will yield a conservative answer.

This methodology was applied to the 1oo2 example applied in the last section on simplified equations. Its graphical depiction is as follows:

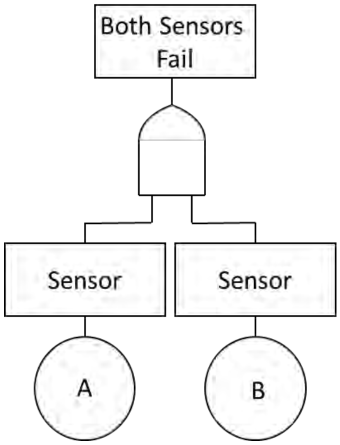

Figure 1: Fault Tree for 1oo2 Voting Sensors

In this case, again with identical components, the 1oo2 pressure switch probability would be:

$$PF(T) \approx (\lambda d * T)(\lambda d*T) = (\lambda d*T)^2.$$

The results are shown in the following table based on 1 month time increments:

Increment	T (yr)	λd	$\lambda d * T$	$(\lambda d*T)^2$
1	0.083	0.05	0.00417	0.00002
2	0.167	0.05	0.00833	0.00007
3	0.250	0.05	0.01250	0.00016
4	0.333	0.05	0.01667	0.00028
5	0.417	0.05	0.02083	0.00043
6	0.500	0.05	0.02500	0.00063
7	0.583	0.05	0.02917	0.00085
8	0.667	0.05	0.03333	0.00111
9	0.750	0.05	0.03750	0.00141
10	0.833	0.05	0.04167	0.00174
11	0.917	0.05	0.04583	0.00210
12	1.000	0.05	0.05000	0.00250
13	1.083	0.05	0.05417	0.00293
14	1.167	0.05	0.05833	0.00340
15	1.250	0.05	0.06250	0.00391
16	1.333	0.05	0.06667	0.00444
17	1.417	0.05	0.07083	0.00502
18	1.500	0.05	0.07500	0.00563
19	1.583	0.05	0.07917	0.00627
20	1.667	0.05	0.08333	0.00694
21	1.750	0.05	0.08750	0.00766
22	1.833	0.05	0.09167	0.00840
23	1.917	0.05	0.09583	0.00918
24	2.000	0.05	0.10000	0.01000
			Total	0.08507
			Avg	0.00354
			RRF	282

Table 6: Fault Tree Example PFDavg for 1oo2 Sensors

Overall, the PFDavg is comparable to the simplified example. If smaller time increments had been taken, specifically in the early periods, a closer approximation would have resulted.

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Verification Technique 3: Markov Models

Markov modeling techniques were developed by Andrey Markov, a Russian mathematician, over a 100 years ago. They utilize graphical pictorials which show the state (represented by a circle) and probability transitions (represented by an arc). These pictorials are then translated to matrix arrays which can then be solved by applying time iterations to yield discrete approximations for PFDavg.

For the 1oo2 system example we have applied in the last two section, the Markov graphic would look like this:

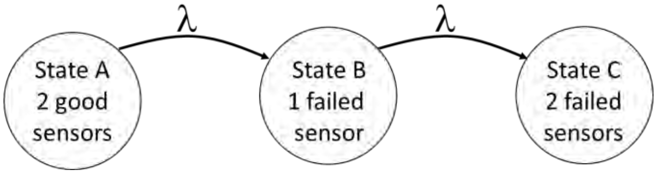

Figure 2: Markov State Diagram for 1oo2 Voting Sensors

The probability “transition matrix”, where the system degrades from state A, then to B, and finally to C would look like this:

$$\begin{bmatrix} (1\text{-}2PF) & 2PF & 0 \\ 0 & (1\text{-}PF) & PF \\ 0 & 0 & 1 \end{bmatrix}$$

The “state matrix”, which would be the current state of the system and probability in any of the states A, B, or C at different iterations would be depicted by:

$$\begin{bmatrix} SA & SB & SC \end{bmatrix}$$

Matrix multiplication is then applied to the state matrix and transition matrix. Naturally, with Microsoft Excel™, such a feat is easily accomplished utilizing 2400 increments. The result table is shown below:

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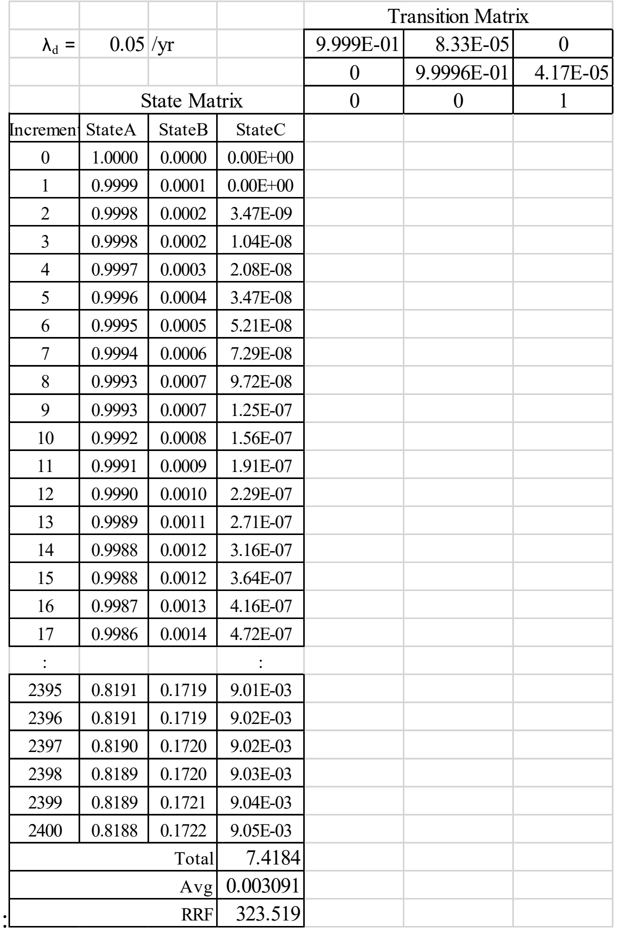

				Transition Matrix		
λ_d =	0.05	/yr		9.999E-01	8.33E-05	0
				0	9.9996E-01	4.17E-05
	State Matrix			0	0	1
Incremen	StateA	StateB	StateC			
0	1.0000	0.0000	0.00E+00			
1	0.9999	0.0001	0.00E+00			
2	0.9998	0.0002	3.47E-09			
3	0.9998	0.0002	1.04E-08			
4	0.9997	0.0003	2.08E-08			
5	0.9996	0.0004	3.47E-08			
6	0.9995	0.0005	5.21E-08			
7	0.9994	0.0006	7.29E-08			
8	0.9993	0.0007	9.72E-08			
9	0.9993	0.0007	1.25E-07			
10	0.9992	0.0008	1.56E-07			
11	0.9991	0.0009	1.91E-07			
12	0.9990	0.0010	2.29E-07			
13	0.9989	0.0011	2.71E-07			
14	0.9988	0.0012	3.16E-07			
15	0.9988	0.0012	3.64E-07			
16	0.9987	0.0013	4.16E-07			
17	0.9986	0.0014	4.72E-07			
:			:			
2395	0.8191	0.1719	9.01E-03			
2396	0.8191	0.1719	9.02E-03			
2397	0.8190	0.1720	9.02E-03			
2398	0.8189	0.1720	9.03E-03			
2399	0.8189	0.1721	9.04E-03			
2400	0.8188	0.1722	9.05E-03			
		Total	7.4184			
		Avg	0.003091			
		RRF	323.519			

Table 7: Markov Example PFDavg for 1oo2 Sensors

Once more, a comparable answer to the simplified equation is achieved.

The Complete SIF SIL Verification Calculation

As with other designs, the SIF is only as strong as its weakest component. For the calculations performed in this section, only one component was calculated. To get the complete SIF PFDavg, one must add the PFDavg of all devices. Stated in a formula, see the following:

PFDavg(Complete SIF) = PFDavg (Sensors)
+ PFDavg(Logic Solver)
+ PFDavg (Final Element)

What to Do when SIL RRF Targets are not Attained??

If calculations show that the draft design does not meet the SIL target, the choices are:

1. Shorten the testing interval, but not beyond the practical point for operations
2. Shorten the maintenance interval
2. Select better technology/equipment.
3. Add redundancy, fault tolerance, or other IPLs

The conceptual design iterations will continue until the SIL or risk reduction target is met with the overall most economical system.

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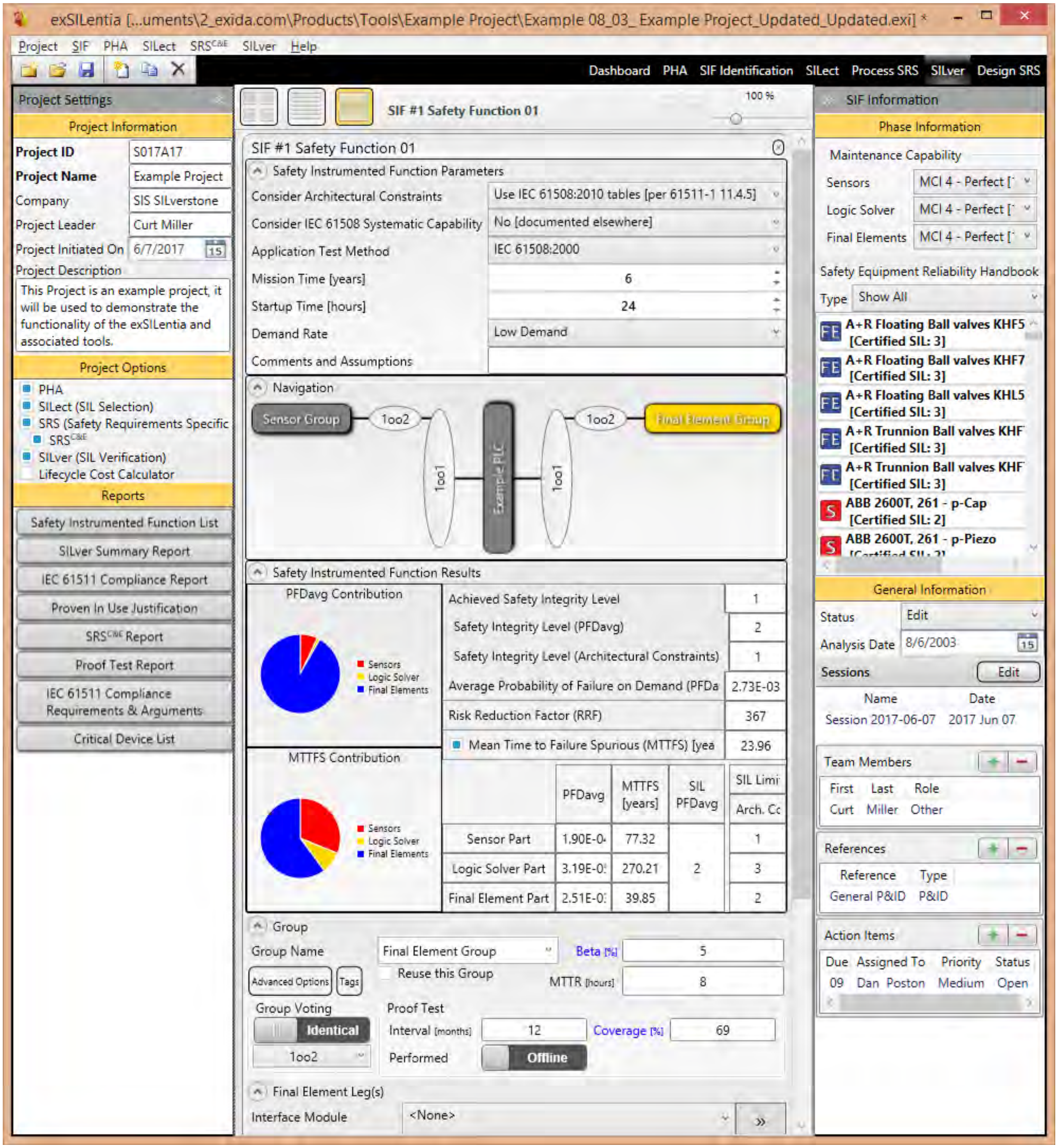
SIL Verification Calculations – Software Example

Although the SIL verification calculations can be completed by hand with techniques previously reviewed (e.g. Simplified equations, Markov models, and Fault Tree Analysis), most functional safety professionals prefer to use off-the-shelf tools. Shown below is the output of such software.



exSILentia [...uments\2_exida.com\Products\Tools\Example Project\Example 08_03_ Example Project_Updated_Updated.exi] *

Project SIF PHA SILect SRS$^{C\&E}$ SILver Help
Dashboard PHA SIF Identification SILect Process SRS SILver Design SRS

Project Settings

Project Information

Project ID	S017A17
Project Name	Example Project
Company	SIS SILverstone
Project Leader	Curt Miller
Project Initiated On	6/7/2017

Project Description

This Project is an example project, it will be used to demonstrate the functionality of the exSILentia and associated tools.

Project Options

- PHA
- SILect (SIL Selection)
- SRS (Safety Requirements Specific
  - SRS$^{C\&E}$
- SILver (SIL Verification)
- Lifecycle Cost Calculator

Reports

Safety Instrumented Function List
SILver Summary Report
IEC 61511 Compliance Report
Proven In Use Justification
SRS$^{C\&E}$ Report
Proof Test Report
IEC 61511 Compliance Requirements & Arguments
Critical Device List

SIF #1 Safety Function 01 — 100 %

SIF #1 Safety Function 01

Safety Instrumented Function Parameters

Consider Architectural Constraints	Use IEC 61508:2010 tables [per 61511-1 11.4.5]
Consider IEC 61508 Systematic Capability	No [documented elsewhere]
Application Test Method	IEC 61508:2000
Mission Time [years]	6
Startup Time [hours]	24
Demand Rate	Low Demand
Comments and Assumptions	

Navigation

Safety Instrumented Function Results

Achieved Safety Integrity Level	1
Safety Integrity Level (PFDavg)	2
Safety Integrity Level (Architectural Constraints)	1
Average Probability of Failure on Demand (PFDa	2.73E-03
Risk Reduction Factor (RRF)	367
Mean Time to Failure Spurious (MTTFS) [yea	23.96

	PFDavg	MTTFS [years]	SIL PFDavg	SIL Limi Arch. Cc
Sensor Part	1.90E-0	77.32	2	1
Logic Solver Part	3.19E-0	270.21		3
Final Element Part	2.51E-0	39.85		2

Group

Group Name	Final Element Group	Beta [%]	5
Reuse this Group		MTTR [hours]	8

Group Voting: Identical — 1oo2

Proof Test

Interval [months]	12	Coverage [%]	69
Performed	Offline		

Final Element Leg(s)

Interface Module: <None>

SIF Information

Phase Information

Maintenance Capability

Sensors	MCI 4 - Perfect [
Logic Solver	MCI 4 - Perfect [
Final Elements	MCI 4 - Perfect [

Safety Equipment Reliability Handbook

Type: Show All

- FE A+R Floating Ball valves KHF5 [Certified SIL: 3]
- FE A+R Floating Ball valves KHF7 [Certified SIL: 3]
- FE A+R Floating Ball valves KHL5 [Certified SIL: 3]
- FE A+R Trunnion Ball valves KHF [Certified SIL: 3]
- FE A+R Trunnion Ball valves KHF [Certified SIL: 3]
- S ABB 2600T, 261 - p-Cap [Certified SIL: 2]
- S ABB 2600T, 261 - p-Piezo [Certified SIL: 2]

General Information

Status	Edit
Analysis Date	8/6/2003

Sessions — Edit

Name	Date
Session 2017-06-07	2017 Jun 07

Team Members

First	Last	Role
Curt	Miller	Other

References

Reference	Type
General P&ID	P&ID

Action Items

Due	Assigned To	Priority	Status
09	Dan Poston	Medium	Open

Figure 3: SIL Verification Analysis Output

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SUMMARY OF INFORMATION REQUIRED AND COMMON ASSUMPTIONS FOR SIL CALCULATIONS

Up to this point in the paper, some general information requirements have been presented. Namely, the minimum parameters that a functional safety practitioner needs to get started as shown in the calculation techniques include:

1. Component technology (Sensor, Logic Solver, Final Elements)
2. Component Voting (Redundancy/Fault tolerance)
3. Periodic test frequency
4. Maintenance intervals

Expanded List of Key Parameters for Optimized Calculations

For precise calculations, additional parameters will have to be applied to take advantage of the full functional safety principles and technology options. A comprehensive listing with short descriptions of each are as follows:

1. ***Diagnostic Alarm Setting*** - Option applicable for analog devices only. It allows you to indicate if upon detection of an internal failure, a Failed Detected fault, the analog output is driven over range or under range.
2. ***Architectural Constraints*** – ISA61511 requirements based on failure rates, modes, & diagnostics. Use IEC61508 normally except when have "Proven In Use" justification of the SIF components (e.g. documentation)
3. ***Beta (β)-Factor*** – Common cause factor for redundant components. Generally ranges from 2-10%
4. ***Control System*** - Assumed to be independent of the current SIFs (i.e. DCS or separate PLC)
5. ***Demand Rate*** – Low if SIF tested 2+times before process demand. If activated often, may be high/continuous
6. ***Diagnostic Filtering*** – How a transmitter and PLC handle diagnosed failures
7. ***External Comparison*** – Diagnostic monitoring of the dynamic signals between the control and SIF
8. ***Interface Components*** – Must specify other devices (e.g. voltage isolators, safety barriers, modulators, etc.) in SIF loop
9. ***Mission Time*** – Operational time of component to be either replaced or refurbished to "like new
10. ***MTTR*** (Mean time to repair) - Indicates expected time to repair the equipment items in the group in case of a detected failure
11. ***Proof Test Coverage*** – No proof tests are 100% effective in finding all failures. Coverage is based upon the specific SIS components parts and testing methods applied (Exida "Proof Test Generator" was used in this analysis and the specific manufactures testing methods or better must be followed)
12. ***Proof Test Interval*** (PTI) - Period of time in which components are regularly tested. Is important in calculations
13. ***Redundancy/Voting*** – How multiple devices within a SIF react together Examples:
    a. Sensor (1oo1: Single device, 1oo2: either will cause trip, 2oo2: both needed to trip)
    b. Final Element (1oo1: Single device, 1oo2: two valves in series, 2oo2: two valves in parallel)
14. ***Startup Time*** - Time in hours required to restart the process after a shutdown.
15. ***Process Connection*** – Sensor tie-in either (1) remote seal, (2) clean, or (3) dirty tap (low, med, high pluggage)
16. ***Trip Setting*** - Depending on the low or high trip setting and the Alarm Setting and Diagnostic Filtering, a Low Failure will either be classified safe or dangerous, detected or undetected.

Common Assumptions Made for SIL Calculations

Within the parameters mentioned above, functional safety engineers will normally apply a starting basis to be confirmed. A standard listing of common assumptions includes:

1. ***Control System***: The control system is assumed to be independent of the current SIFs (e.g. DCS).
2. ***Mission Time**:* Typically assumed to be fifteen (15) to twenty (20) years
3. ***Startup Time:*** Normally assumed to be twenty-four (24) hours for most facilities.
4. ***Failure rates for SIF components***: Specific data will be applied where available. In situations where no specifics were available, "generic" data used for the calculations.
5. ***Proof Test Interval*** (PTI): Testing interval that has been used for all devices in the study as provided by the client.
6. ***Proof Test Coverages***: Estimates normally based upon reliability studies (i.e. Failure Modes, Effects, and Diagnostic Analysis) of components selected.

7. ***Beta (β)-Factor:*** In initial studies, β-factor used for multiple sensor and final element components is a conservative 10%.
8. **MTTR**: Conservative times 72 hours are generally used
9. ***Architectural Constraint Requirements:*** Each safety function must meet minimum hardware fault tolerance (HFT) based on the target SIL requirement listed in the architectural constraint table. (11.4.1) This design element was included to provide an extra layer of protection to address the uncertainty in the failure rate of the various system components.
10. ***SIL Capable Device Utilization:*** Devices that are either certified to IEC 61508 or based on "prior use" (Clause11.5.3) must be used to meet this requirement. Although many will choose certified components just because they don't have a good device reliability database and since the certified equipment comes with its own approved data, either choice will require "usability" judgment based upon current installation time accumulated and specific application details.

EXAMPLE 1: SIL VERIFICATION APPLIED TO A HIGH HORSEPOWER STEAM TURBINE

These unique SIL processes were recently utilized on a critical high horsepower turbine application and will be generally discussed so that the overall safety lifecycle can be understood.

A. Performing SIL Verification to Prove that SIL2 was Attained for the Overspeed Trip

To prove that the overspeed trip met the SIL2 risk target, reliability calculations were performed as the next step in the functional safety lifecycle. Such calculations were based on the components selected, their voting architecture, diagnostics applied, and finally, testing and replacement intervals.

The specific components that made up the overspeed trip system included the magnetic pickup sensors, logic solver (i.e. Safety PLC or SIS), the trip & throttle shutoff valve, and any interface components in between. There initially was no concern in meeting the SIL2 target since the overspeed system applied SIL3 certified electronics and the final element was partial stroke tested.

Data for the certified devices was readily available in the vender's product safety manuals. It should be noted that the two (2) commonly accepted functional safety assessment agencies include TUV and exida Certification and the standard adhered to is IEC61508 [R7].

Since the trip & throttle valve had not been certified and the manufacturer had no failure mode specific data, the SIS project engineer contracted a Failure Modes, Effects, and Diagnostics Analysis (FMEDA) from a third party consulting firm. This analysis was specific to the OEM's valve assembly and therefore resulted in a precise, yet conservative data set to be used in the SIL verification calculations. Otherwise, conservative data based on generic components would have been used and the SIL2 risk target likely would not have been met.

Another SIL2 issue surfaced when an emergency trip device (ETD) was discovered in the turbine mechanical drawings. The ETD was critical to the overspeed trip since it acted as an interface component for dumping the hydraulic power fluid. Since it could not be tested by the partial stroke apparatus, it became a SIL2 limiter and the overspeed system became degraded to SIL1. Fortunately, the design team found an alternative solution to avoid adding an inline steam valve (~ $300k).

The team utilized a commercially available software platform to perform the calculations. SIL2 results were achieved by using partial stroke testing and accounting for specific overspeed failure modes where a significant leak was required to fit the scenario stated. The results are shown in Figure 4.

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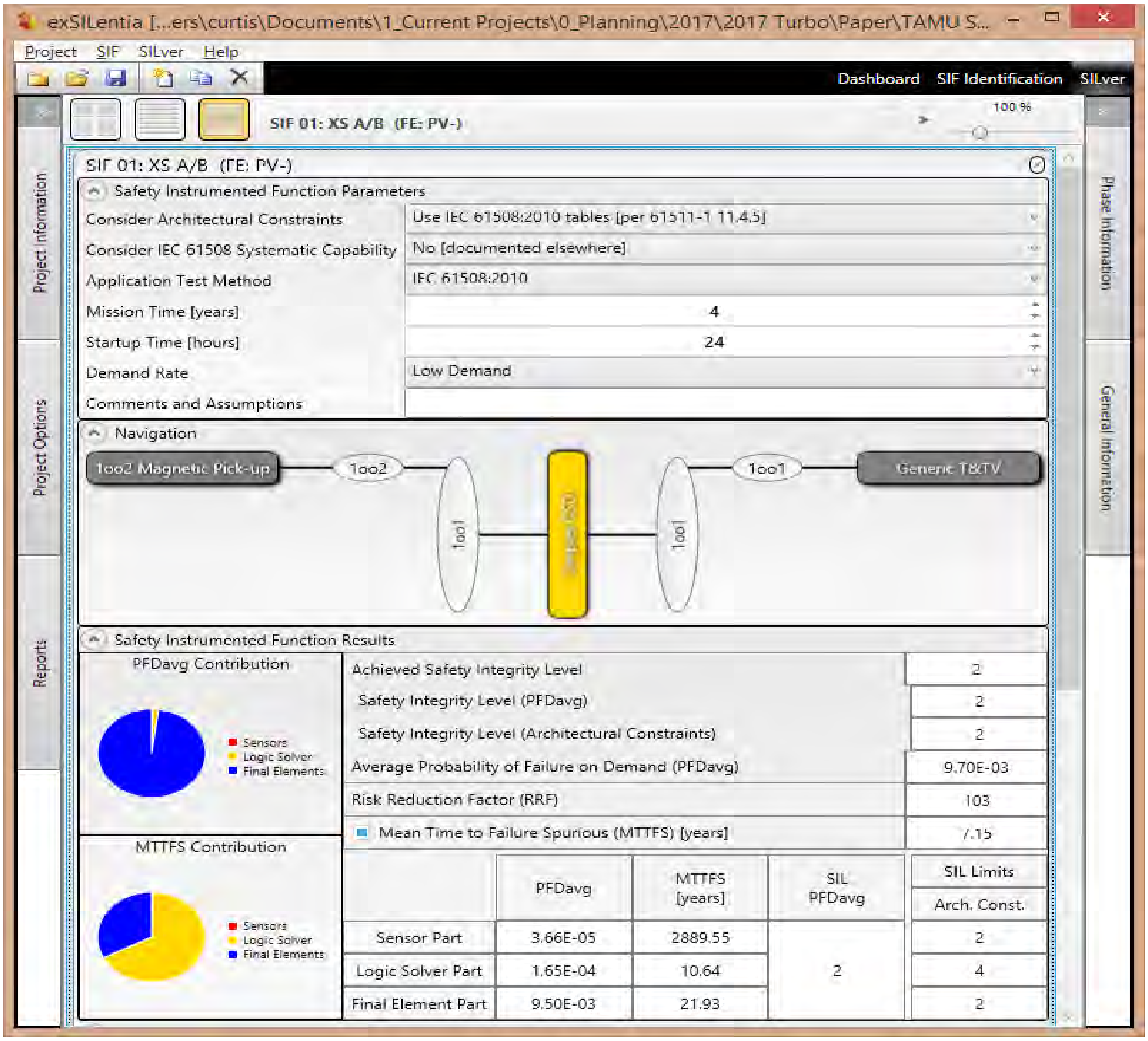

SIF 01: XS A/B (FE: PV-)

Safety Instrumented Function Parameters

Consider Architectural Constraints	Use IEC 61508:2010 tables [per 61511-1 11.4.5]
Consider IEC 61508 Systematic Capability	No [documented elsewhere]
Application Test Method	IEC 61508:2010
Mission Time [years]	4
Startup Time [hours]	24
Demand Rate	Low Demand
Comments and Assumptions	

Navigation

Safety Instrumented Function Results

Achieved Safety Integrity Level	2
Safety Integrity Level (PFDavg)	2
Safety Integrity Level (Architectural Constraints)	2
Average Probability of Failure on Demand (PFDavg)	9.70E-03
Risk Reduction Factor (RRF)	103
Mean Time to Failure Spurious (MTTFS) [years]	7.15

	PFDavg	MTTFS [years]	SIL PFDavg	SIL Limits
				Arch. Const.
Sensor Part	3.66E-05	2889.55	2	2
Logic Solver Part	1.65E-04	10.64		4
Final Element Part	9.50E-03	21.93		2

Figure 4: SIL Verification Tool Output for High HP Turbine

With the upgraded model, this overspeed trip met SIL2 and had a 7.15 year spurious trip rate.

B. Performing SIL Verification to Prove that SIL2 was Attained for the Vibration Trip

This vibration trip was another initiator for the larger turbine compressor. In this application, a major vendor had provided MTBF data for all the components in their system, but it was not granular to the level required by SIL calculations. (i.e. Not specific to failure modes (safe/dangerous) and diagnostic coverage.) Because the system was somewhat complex with a modular design, putting the data together was more cumbersome.

The table of assumption are included below in Table 8:

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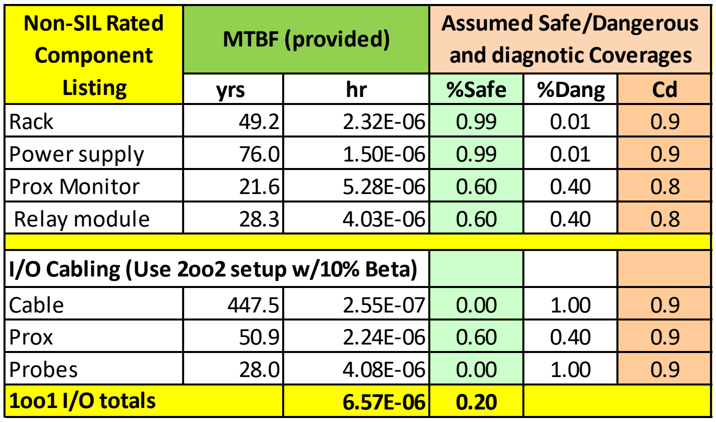
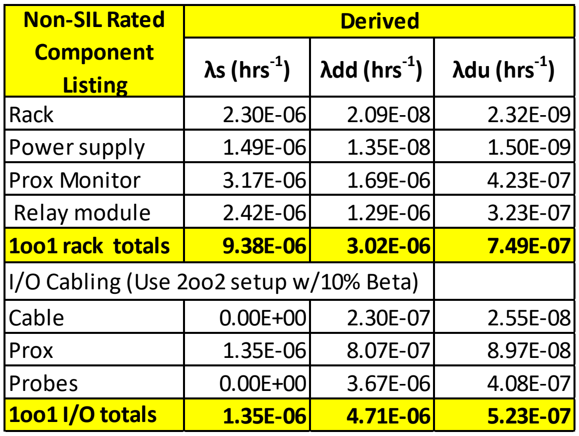


Non-SIL Rated Component Listing	MTBF (provided)		Assumed Safe/Dangerous and diagnotic Coverages		
	yrs	hr	%Safe	%Dang	Cd
Rack	49.2	2.32E-06	0.99	0.01	0.9
Power supply	76.0	1.50E-06	0.99	0.01	0.9
Prox Monitor	21.6	5.28E-06	0.60	0.40	0.8
Relay module	28.3	4.03E-06	0.60	0.40	0.8
I/O Cabling (Use 2oo2 setup w/10% Beta)					
Cable	447.5	2.55E-07	0.00	1.00	0.9
Prox	50.9	2.24E-06	0.60	0.40	0.9
Probes	28.0	4.08E-06	0.00	1.00	0.9
1oo1 I/O totals		**6.57E-06**	**0.20**		

Table 8: Vibration Data & Assumed Coverages

With the above assumptions, the derived data to be utilized in the SIL calculations is listed below in Table 9.



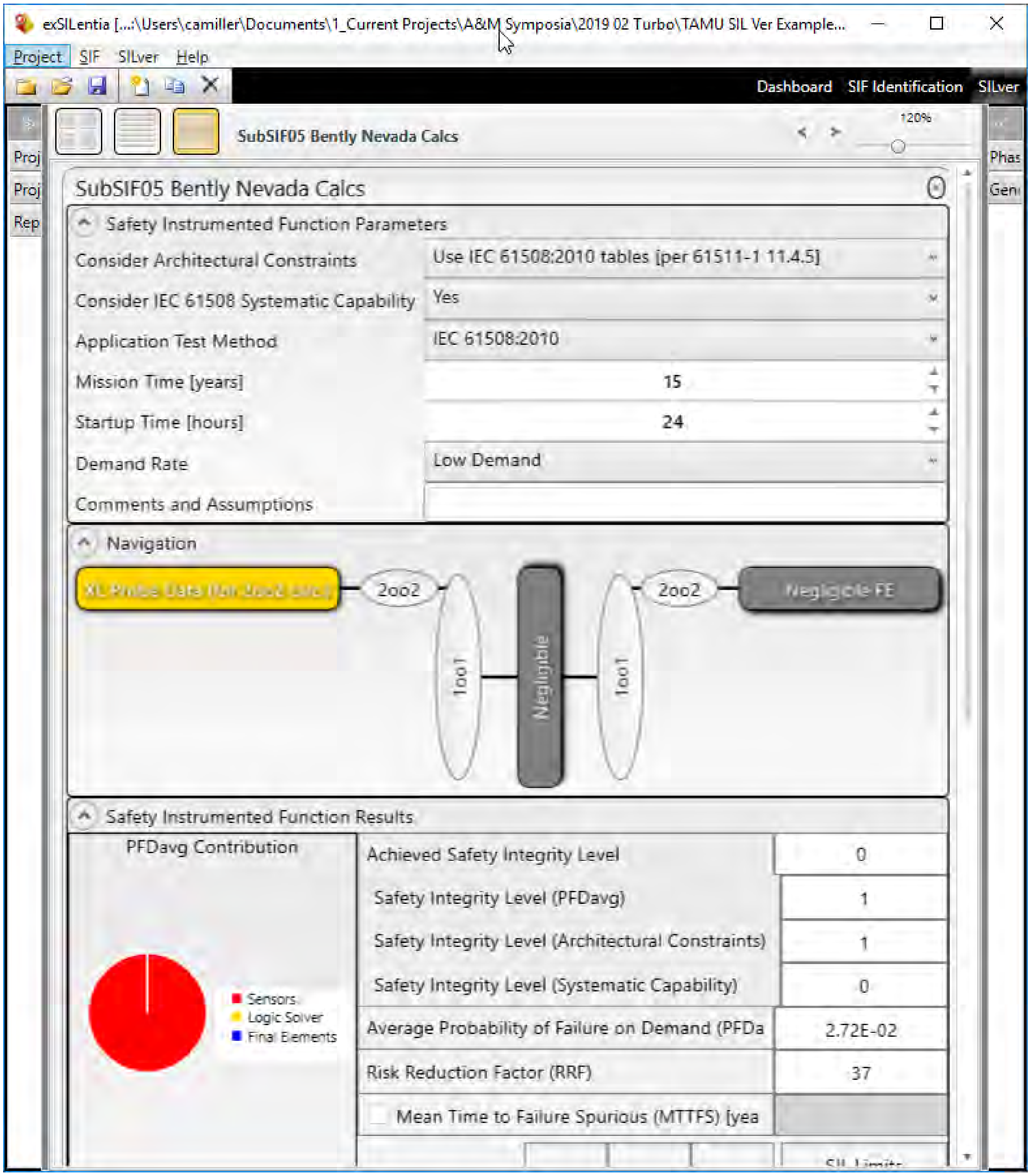
Non-SIL Rated Component Listing	Derived		
	λs (hrs^{-1})	λdd (hrs^{-1})	λdu (hrs^{-1})
Rack	2.30E-06	2.09E-08	2.32E-09
Power supply	1.49E-06	1.35E-08	1.50E-09
Prox Monitor	3.17E-06	1.69E-06	4.23E-07
Relay module	2.42E-06	1.29E-06	3.23E-07
1oo1 rack totals	**9.38E-06**	**3.02E-06**	**7.49E-07**
I/O Cabling (Use 2oo2 setup w/10% Beta)			
Cable	0.00E+00	2.30E-07	2.55E-08
Prox	1.35E-06	8.07E-07	8.97E-08
Probes	0.00E+00	3.67E-06	4.08E-07
1oo1 I/O totals	**1.35E-06**	**4.71E-06**	**5.23E-07**

Table 9: Derived Vibration Data to be Applied in Calculations

Since there was no vendor safety user's manual with detailed information to support the system components, confirmation that the assumptions made was problematic.

Now that the data was available, it was time to setup the SIL models in the software. As prescribed by the process team, any of three (3) voting high vibration groups would mitigate the scenario stated in the PHA. Effectively, the SIS voting logic was 1oo3. For the vibration monitor to send a high-high vibration, though, it took both vibration probes reading high, so it was effectively 2oo2.

Given two (2) levels of voting (i.e. one for the probes & vibration monitor, another for the SIS PLC), the SIL calculation was split up. Starting with the 2oo2 probes, a SubSIF model yielded the following PFDavg shown in Figure 5:



SubSIF05 Bently Nevada Calcs

Safety Instrumented Function Parameters

Consider Architectural Constraints	Use IEC 61508:2010 tables [per 61511-1 11.4.5]
Consider IEC 61508 Systematic Capability	Yes
Application Test Method	IEC 61508:2010
Mission Time [years]	15
Startup Time [hours]	24
Demand Rate	Low Demand
Comments and Assumptions	

Navigation

Safety Instrumented Function Results

PFDavg Contribution

Achieved Safety Integrity Level	0
Safety Integrity Level (PFDavg)	1
Safety Integrity Level (Architectural Constraints)	1
Safety Integrity Level (Systematic Capability)	0
Average Probability of Failure on Demand (PFDa	2.72E-02
Risk Reduction Factor (RRF)	37
□ Mean Time to Failure Spurious (MTTFS) [yea	

Figure 5: Vibration Example – Probe SubSIF Calculation

This sensor PFDavg result was then utilized in the full calculation where three (3) such probe groups, each representing different locations on the turbine-compressor package, were voted to trip.

The overall SIF results are shown in the following Figure 6:

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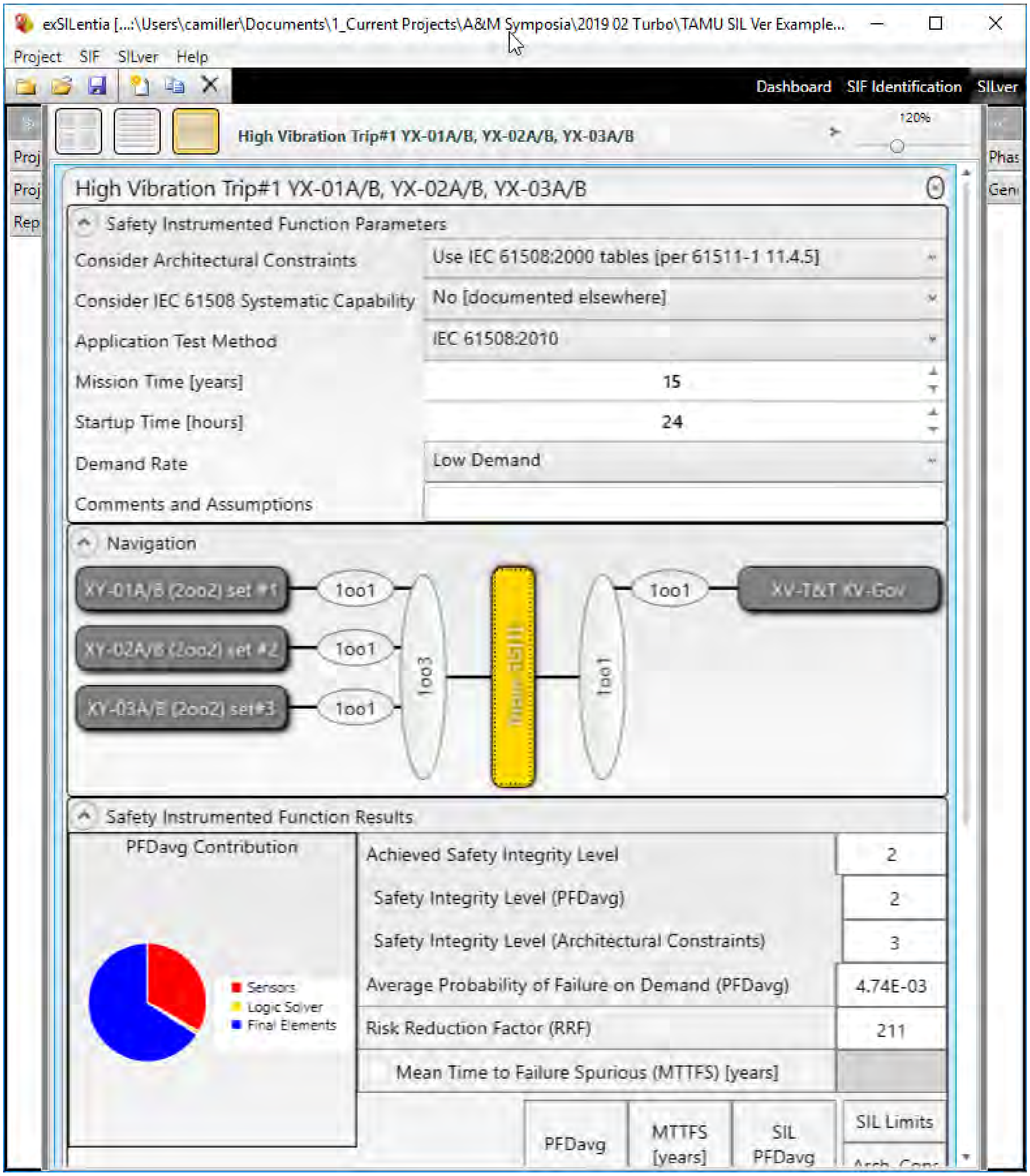

High Vibration Trip#1 YX-01A/B, YX-02A/B, YX-03A/B

Safety Instrumented Function Parameters

Consider Architectural Constraints	Use IEC 61508:2000 tables [per 61511-1 11.4.5]
Consider IEC 61508 Systematic Capability	No [documented elsewhere]
Application Test Method	IEC 61508:2010
Mission Time [years]	15
Startup Time [hours]	24
Demand Rate	Low Demand
Comments and Assumptions	

Navigation

Safety Instrumented Function Results

PFDavg Contribution

Achieved Safety Integrity Level	2
Safety Integrity Level (PFDavg)	2
Safety Integrity Level (Architectural Constraints)	3
Average Probability of Failure on Demand (PFDavg)	4.74E-03
Risk Reduction Factor (RRF)	211
Mean Time to Failure Spurious (MTTFS) [years]	

Figure 6: Vibration Example – Main Model Results

As shown, a SIL2 was met utilizing this arrangement. It should be noted, though, that vibration is typically a mitigation safeguard only. Other sensing techniques (i.e. level, pressure, anti-surge, etc.) should be applied for direct prevention purposes.

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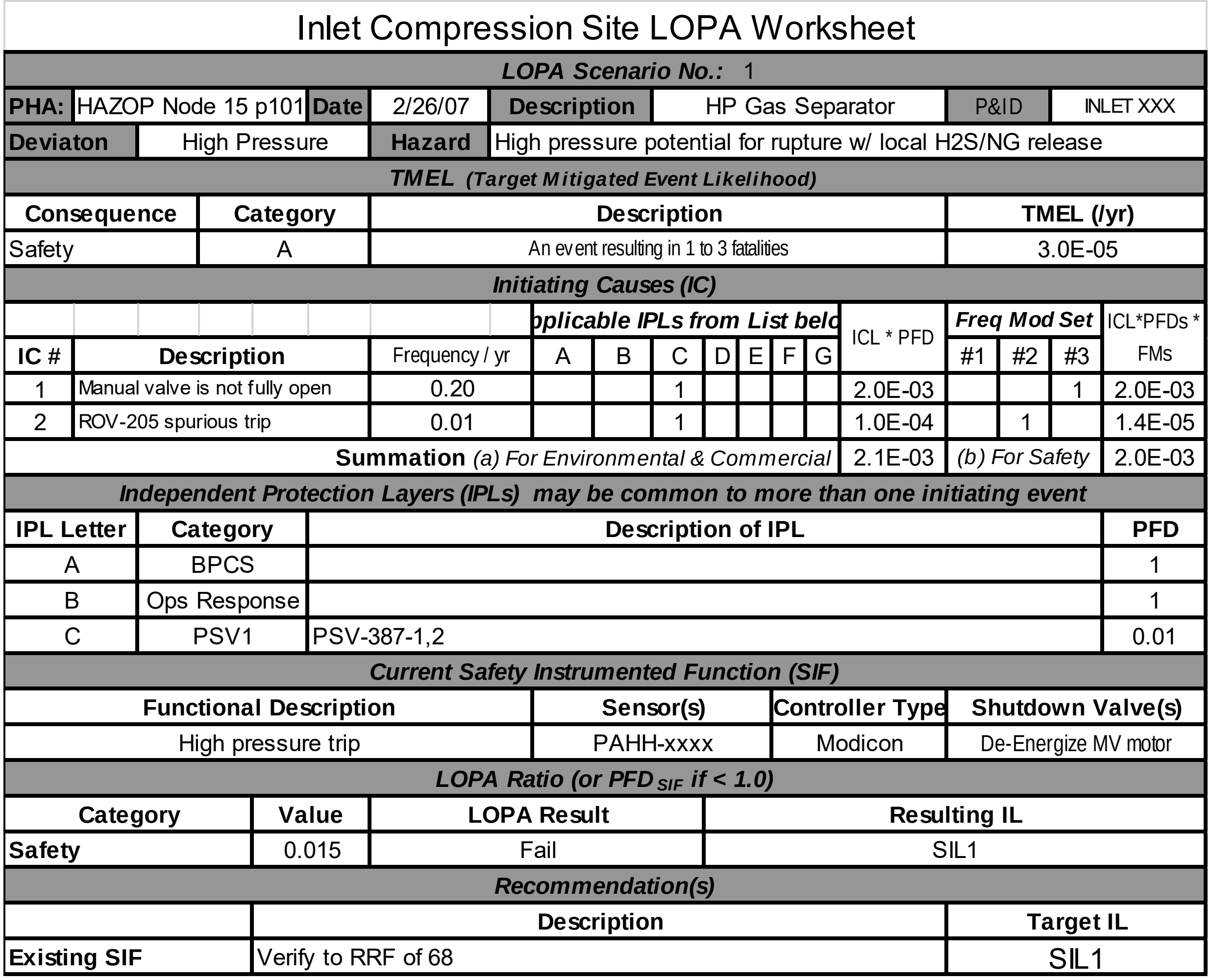
EXAMPLE 2: SIL VERIFICATION APPLIED MEDIUM VOLTAGE MOTOR FOR A HIGH PRESSURE REPROCATING COMPRESSOR TRIP

A calculation conundrum exists when data is not readily available to support the quantitative models. Such was the case when a 30-year-old vintage gas compression site was reviewed and SIL assessed utilizing the LOPA methodology as shown in the Figure below.



Inlet Compression Site LOPA Worksheet

LOPA Scenario No.: 1

PHA:	HAZOP Node 15 p101	**Date**	2/26/07	**Description**	HP Gas Separator	P&ID	INLET XXX
Deviaton	High Pressure	**Hazard**	High pressure potential for rupture w/ local H2S/NG release				

***TMEL** (Target Mitigated Event Likelihood)*

Consequence	**Category**	**Description**	**TMEL (/yr)**
Safety	A	An event resulting in 1 to 3 fatalities	3.0E-05

Initiating Causes (IC)

			pplicable IPLs from List belo							ICL * PFD	***Freq Mod Set***			ICL*PFDs * FMs
IC #	**Description**	Frequency / yr	A	B	C	D	E	F	G		#1	#2	#3	
1	Manual valve is not fully open	0.20			1					2.0E-03			1	2.0E-03
2	ROV-205 spurious trip	0.01			1					1.0E-04		1		1.4E-05
		Summation *(a) For Environmental & Commercial*								2.1E-03	*(b) For Safety*			2.0E-03

Independent Protection Layers (IPLs) may be common to more than one initiating event

IPL Letter	**Category**	**Description of IPL**	**PFD**
A	BPCS		1
B	Ops Response		1
C	PSV1	PSV-387-1,2	0.01

Current Safety Instrumented Function (SIF)

Functional Description	**Sensor(s)**	**Controller Type**	**Shutdown Valve(s)**
High pressure trip	PAHH-xxxx	Modicon	De-Energize MV motor

LOPA Ratio (or PFD$_{SIF}$ if < 1.0)

Category	**Value**	**LOPA Result**	**Resulting IL**
Safety	0.015	Fail	SIL1

Recommendation(s)

	Description	**Target IL**
Existing SIF	Verify to RRF of 68	SIL1

Figure 7: LOPA for Compressor High Pressure Trip

Due to a high SIL1 RRF target of 68, precise data was needed to support potential changes such as upgrading hardware or maintenance frequency.

The specific SIF architecture included a pressure switch tied to the DCS with a relay interface to a medium voltage contactor. This SIF structure is pictorially represented by the following Figure:

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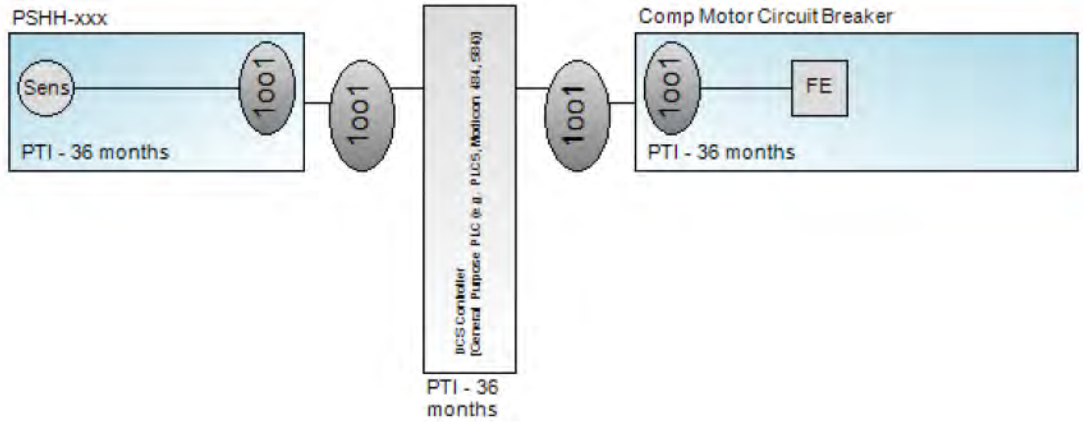


Figure 8: Compressor High Pressure Trip Architecture

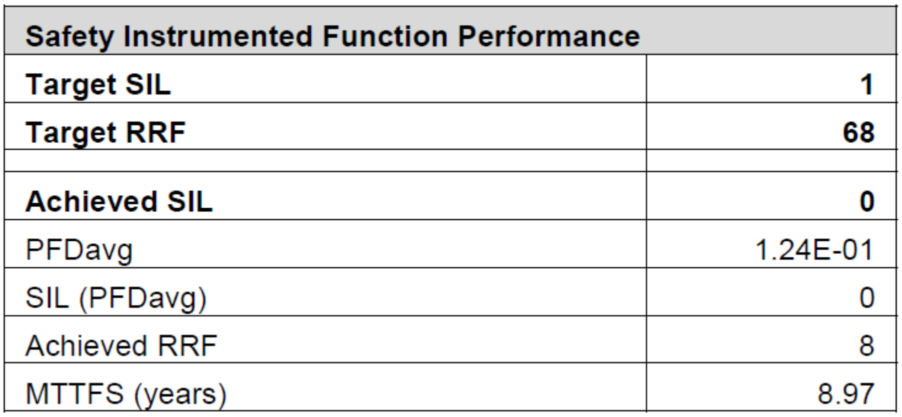
Data was available, at least in generic format, for both the pressure switch and the DCS controller, but not for the medium voltage (MV) contactor after checking with the vendor. Furthermore, neither the site nor the corporate enterprise had initiated a data collection program on similar device types, so an alternate path was required.

The MV contactor technology was studied and comparable information on a similar device provided a data basis. It was discovered that the MV contactor sequence of operation is as follows:

1. There is an electric motor that needed to be energized to charge a closing spring.
2. After charging the spring, the breaker can be operated by energizing a closing solenoid
3. The energized solenoid unlocks the closing mechanism operated by the energy stored in the closing spring.
4. When the closing spring operates the breaker, it charges an opening spring at the same time.

In other words, it can be simply modeled as an energized -to-trip (ETT) solenoid with spring contributions. The model was then updated utilizing the basis of a known ETT solenoid model.

The results of using the generic data for the pressure switch, DCS controller, and this comparable MV contactor data is shown below in Table 10:



Safety Instrumented Function Performance	
Target SIL	**1**
Target RRF	**68**
Achieved SIL	**0**
PFDavg	1.24E-01
SIL (PFDavg)	0
Achieved RRF	8
MTTFS (years)	8.97

Table 10: Compressor High Pressure Trip – Initial Results

As shown, the SIL achieved fell short with a SIL0 RRF of 8, so improvement was required. The easiest way to visualize what needed to be done was to look at the PFDavg “pie chart” contributions shown in Figure below:

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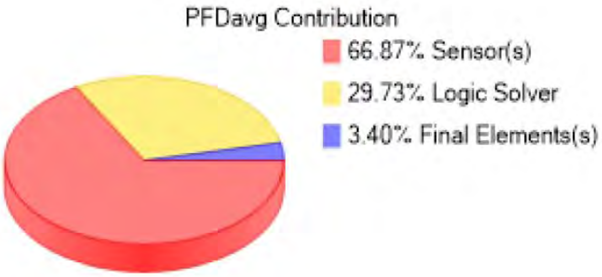
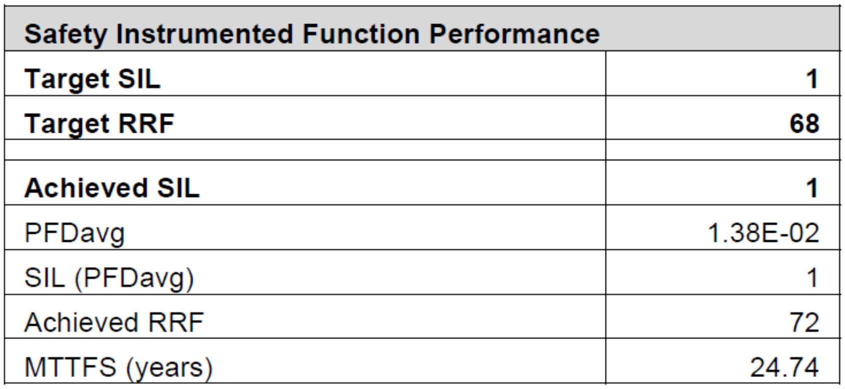


Figure 9: Compressor High Pressure Trip – PFDavg Pie Chart Showing Contribution by SIF Component

The chief culprit of the low PFDavg was the pressure switch (~67%), but and the logic solver was also suspect (~30%) relative to to the MV contactor (~3%). It was decided to upgrade both devices. The pressure switch was upgraded to a SIL assessed transmitter and the PLC to a SIL2 capable PLC.

Making such changes, the net result (shown in Table 11) then became:



Safety Instrumented Function Performance	
Target SIL	**1**
Target RRF	**68**
Achieved SIL	**1**
PFDavg	1.38E-02
SIL (PFDavg)	1
Achieved RRF	72
MTTFS (years)	24.74

Table 11: Compressor High Pressure Trip – Final Results

Hence, the SIL1 target RRF of 68 was achieved.

It should also be pointed out that the spurious trip rate (shown as MTTFS "mean time to fail safe) also benefited with the changes. What was a potential of once-in~9 years spurious trip rate was dramatically reduced to a new rate of once-in~25 years! Such a benefit further supports the SIL quantitative approaches!

EXAMPLE 3: SIL VERIFICATION APPLIED TO A PRODUCTION FIELD RECIPROCATING ENGINE

Field compressors are unique in that they are normally energized-to-trip to prevent nuisance shutdown since personnel are typically not on-site. This added dimension requires that wiring and power connection failures are included in the base design.

Based on the client's risk criteria, three (3) sets of trips initiators were reviewed for a minimum SIL1 requirement. They included high pressure, level, and temperature applications as shown in the following simplified SIF sketches in Figure:

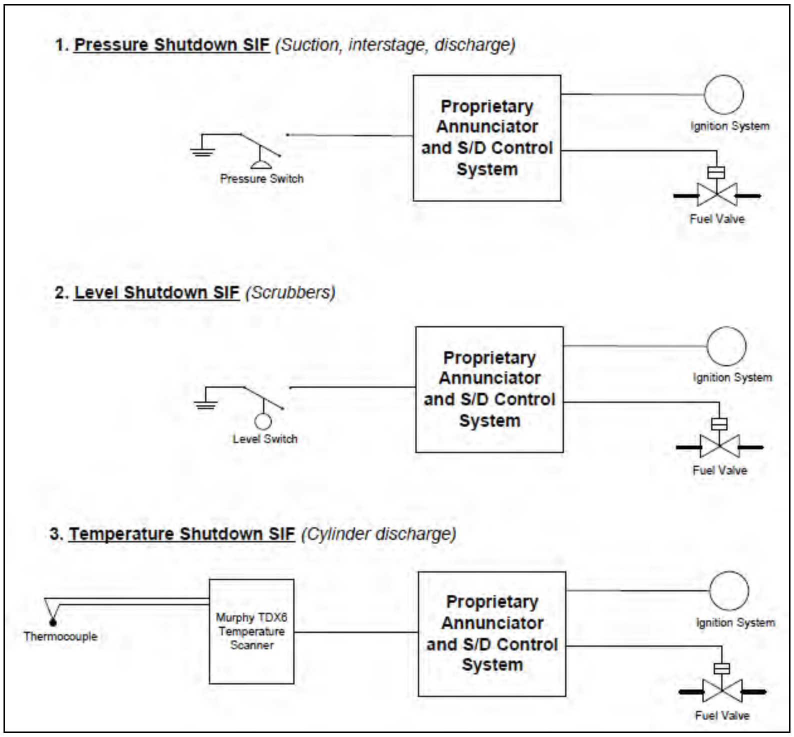

1. Pressure Shutdown SIF (Suction, interstage, discharge)
Pressure Switch
Proprietary Annunciator and S/D Control System
Ignition System
Fuel Valve
2. Level Shutdown SIF (Scrubbers)
Level Switch
Proprietary Annunciator and S/D Control System
Ignition System
Fuel Valve
3. Temperature Shutdown SIF (Cylinder discharge)
Thermocouple
Murphy TDX6 Temperature Scanner
Proprietary Annunciator and S/D Control System
Ignition System
Fuel Valve

Figure 10: Reciprocating Engine Field Compressor

Starting with the engine logic solver, the vendor had a proprietary, non-SIL design, hence there was no failure rate data readily available. It was therefore modeled as a Generic Industrial PLC (simplex) using SERH data.

Regarding the shutdown final element actions, fault tolerant design allowed either closing the fuel valve or dropping out the ignition to stop engine. Such a voting architecture is considered "1oo2". For their data, the following assumptions were applied:

- For the fuel valve: Generic air operated gate valve, driven by a Generic 3-way solenoid valve was assumed
- For the ignition circuit: Thyristor data from a component failure rate data book was applied. This was appropriate since the ignition system is a capacitor discharge (CD) type and is executed by grounding a specific SD (i.e. "shorting dot") terminal in the thyristor which likewise disconnects the alternator

The sensors then were then scrutinized. Generic pressure switch was used and an assumed dangerous failure rate of wiring/ connections as once every 100 years was added as required for the ETT design. Level switches were also applied for the level trips and a similar wiring/connections failure contribution was added.

Lastly, the temperature component makeup required finding suitable data. Generic thermocouple was applied for the elements and a Generic Analog Trip Amplifier was used to represent the temperature scanner. Since the scanner could detect an open thermocouple (executing trip), shorted TC and drift was assumed as dangerous failures within the calculations.

Based on such assumptions, all SIL1 targets were obtained as shown in the following Table.

SIF Tag	SIF Description	Target		Achieved	
		SIL	RRF	SIL	RRF
LSHH Trip	High Scrubber Level Trip	1	10	1	26
PSHH Trip	High Scrubber Pressure	1	10	1	20
TSHH Trip	High Cylinder Discharge Temperature	1	10	1	15

Table 12: Reciprocating Engine Field Compressor Results

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CONCLUSIONS

The purpose of the SIL verification process is to substantiate that our SIL targets will conclusively be met by the SIF design and post-installation periodic testing and maintenance. In the past, not all systems were created equal and gaps could unknowingly exist.

Every project that employs such quantitative SIL verification techniques will gain valuable insight on what is required to keep their system in a ready-state and hopefully avoid both dangerous events and unnecessary downtime.

Such a message was supported by the late Trevor Kletz who specifically stated:

> *"Accidents are not due to the lack of knowledge, but failure to use the knowledge we have"*

We should be keen to follow such wise advice!

ABBREVIATIONS

API – American Petroleum Institute
DCS – Distributed Control System
ESD – Emergency Shutdown Device
IEC – International Electrotechnical Commission
ISA – International Systems and Automation
FMEA – Failure Modes and Effects Analysis (PHA method)
FMEDA – Failure Modes, Effects, and Diagnostics Analysis (Component reliability technique)
FSM – Functional Safety Management
LOPA – Layer of Protection Analysis
LSHH – Level Switch High High (trip)
MTTFS – Mean time to Fail Safe (Spurious)
PFDavg – Probability of Failure Dangerous – Averaged
PSHH – Pressure Switch High High (trip)
RRF – Risk Reduction factor (RRF=1/PFDavg)
SERH – Safety Equipment Reliability Handbook (exida)
SLC – Safety Lifecycle
SIF – Safety Instrumented Function
SIL – Safety Integrity Level

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