KENEXIS

# Safety Instrumented Systems Engineering Handbook

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# About Kenexis

Kenexis is a global engineering consulting company that is focused on the implementation of engineered safeguards in process plants. Engineered safeguards are physical devices that can detect that an unwanted or out-of-control situation is occurring in the process plant and take remedial action to move the process to a safe state. Some typical examples of engineered safeguards employed in the process industries are shown below.

- Safety Instrumented Systems
- Fire and Gas Detection and Suppression Systems
- Emergency Isolation Valve Systems
- Alarm Systems
- Pressure Relief Systems
- Cyber Security Systems (Intrusion Detection and Prevention)
- Machine Safeguarding Systems

Kenexis helps our clients to deploy these systems by working as an independent expert third-party advisor who assists in the development of the design basis of these systems and validation that these systems are implemented in accordance with the design basis over their entire lifecycle. Since Kenexis does not sell or recommend any hardware or perform any detailed engineering services, Kenexis is uniquely positioned to act as an independent advisor with no conflicts of interest that might sway the direction of decisions in the development of the design basis.

Kenexis applies a risk-based approach in assisting our clients to determine their engineered safeguard needs. The risks that are posed by the processes that our clients operate can be determined and developed through Process Hazards Analyses (PHA) that Kenexis can both facilitate and actively participate in. Once the needs for engineered safeguards are identified, the design basis for those safeguards is further developed by considering the codes and standards that apply to the design of each specific safeguard along with the level of risk reduction that those safeguards are required to provide. Considering these two factors Kenexis prepares design basis documentation that defines the requirements in sufficient detail to allow equipment to be selected and purchased, but general enough to ensure that any technology or equipment vendor that is capable of meeting the technical requirements can provide an appropriate solution. Kenexis design basis documents are unique in their ability to allow end users to compare alternatives from multiple vendors and select the solution that best suits their requirements.

After the design basis is complete, our clients work with equipment vendors, systems integrators, and engineering companies to physically implement the solution. After the safeguards are implemented, Kenexis helps our clients by performing validation services and ongoing support services to ensure that the safeguards were selected, designed, and installed in accordance with the design basis documentation, and that the system design and design basis documentation are maintained in an evergreen fashion.

# About the Authors

## Kevin J. Mitchell

Mr. Kevin J. Mitchell has unparalleled experience in the risk management and process safety fields. Mr. Mitchell has been involved in hundreds of projects covering such diverse operations as oil & gas production, refining, petrochemical, specialty chemical and general manufacturing. Specializes in state-of-the-art assessment of the risk of toxic, flammable, and explosive materials on people, property, the environment, and, ultimately, the business. Uses risk assessment and Cost-Benefit Analysis to assist in making engineering and business decisions.

## Todd M. Longendelpher

Mr. Longendelpher has experience in design of safety instrumented systems and risk analysis methods. He is responsible for the development of SIL requirements and verification of SIL requirements for safety instrumented systems. He utilizes risk analysis techniques to assess existing SIS design versus potential hazards resulting in consequences. He has conducted LOPA / SIL Selection and SIL Verification activities for customers in petroleum refining, petrochemicals, and upstream oil and gas production in US and international locations. He currently oversees the implementation of SIS design at multiple upstream oil and gas production platforms in the Gulf of Mexico.

# Preface

Safety instrumented systems (SIS) form some of the most widely used and difficult to design engineered safeguards in the process industries. Prior to the release of risk-based standards for the design of SIS, designs were traditionally implemented using rules of thumb – which were quite effective, but not entirely satisfactory. After the implementation of risk-based analysis, users of SIS realized that these engineered safeguards alone had the design flexibility to allow widely diverse designs with widely diverse risk reduction capabilities. Only SIS can be designed in a good, better, and best fashion, limiting the amount of risk reduction provided to match the amount of risk reduction needed.

The downside of the flexibility that risk-based decision making provides is the large amount of complexity that subsequently is introduced to the design process. In order to make risk-based decisions, one needs to understand the risk of the chemical process, which is no small feat and typically out of the "comfort zone" of SIS designers, and also to understand the details of reliability engineering as applied to SIS design.

In the years following the release of the performance-based standards that define SIS engineering, many books, standards, technical reports, and papers have been written about the SIS Engineering process (including books and papers by the authors of this book). The authors of this book determined that it would be very valuable to distill this information down into a handbook format that will allow everyday practitioners to have a quick reference to the most salient points of the design process.

This book provides a very practical discussion of the SIS safety lifecycle and presents it in a fashion that leans toward assistance in execution of the tasks without belaboring the theoretical underpinnings of the equations and data that are presented in other books and technical reports. In addition, this book reflects the most proven and accepted methodologies for performing tasks, especially in areas where the standards allow great flexibility to the users to select from many options for complying with the standard.

For instance, the task of selecting safety integrity levels can be performed utilizing a wide variety of methods including risk graphs and layer of protection analysis. But since the vast preponderance of industry has elected to use layer of protection analysis, only this methodology will be explored in great detail.

Also, this book focuses on the SIS engineering aspects of the safety lifecycle while leaving important tasks that are out of the realm of instrumentation and control engineering to others. For instance, a good process hazards analysis is important to identifying where instrumented safeguards such as SIS are required, but execution of a PHA is typically not the responsibility of instrumentation and control engineers, and is thus discussed, but not developed in detail.

The authors of this book hope you enjoy the contents and find the information educational and useful on a day-to-day basis.

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# Introduction

Safety instrumented systems (SIS) are the most flexible and one of the most common engineered safeguards used in process plants today. The design of SIS, in accordance with current practice, is a risk based process where the selected equipment and associated maintenance and testing procedures are tailored to specific requirements of an application. This risk-based approach yields superior designs that provide the required risk reduction while minimizing cost.

SIS design has become a more complex process due to the need to understand more than traditional instrumentation and control engineering. In addition to basic concepts, SIS design requires expertise in analyzing the risks of the process under control (which necessarily requires an understanding of the process) in order to establish design targets, and also expertise in reliability engineering to ensure that the selected targets have been met.

The purpose of this book is to provide a brief overview of the Safety Lifecycle that is used to design SIS, along with general information to assist in performing the tasks that are defined in the safety lifecycle. This includes tables of data, lists of definitions and acronyms, equations, and explanations for using these resources.

## Why do I need an SIS?

Process plants create value by converting raw materials into valuable products. The processes utilized to perform this conversion often create hazardous conditions that could result in significant consequences if the processes are not adequately controlled. These conditions include:

- Flammable Materials
- Toxic Materials
- High Pressures
- High Temperatures

Control of the risks posed by process plants is performed by a combination of:

- Administrative Controls
- Engineered Safeguards

A Safety Instrumented System (SIS) is one of the safeguards used in modern petroleum and chemical processing to reduce risk to a tolerable level. It is an engineered control, and fits in with engineering safeguards, as well as administrative controls, to achieve an overall balance of safeguards that reduce risk to a tolerable level.

Common Safety Instrumented System applications include emergency shutdown systems, burner management systems for boilers and other fired devices; high integrity pressure protection systems (HIPPS) in petroleum or chemical processing facilities, as well as other industry specific applications.

## What is an SIS?

The Safety Instrumented System is an instrumentation and control system that detects out-of-control process conditions, and automatically returns the process to a safe state. It is the last line - or near last line - of defense against a chemical process hazard, and it is not part of the Basic Process Control System. The last line of defense is what differentiates a Safety Instrumented System from the Basic Process Control System, which is used for normal regulatory process control.

*Figure 1* demonstrates how Safety Instrumented Systems are different from Basic Process Control Systems, or the BPCS. In this example, pressure is a potential hazard. Pressure is normally controlled by a regulatory control loop, shown as the Basic Process Control System, which modulates a pressure control valve. An independent high-pressure shutdown function is implemented in a Safety Instrumented System. It is independent in as much as the components used in the BPCS and the SIS are separate, physically and functionally. This includes the sensor components, the logic solver, as well as the final control elements. SIS are generally independent, both physically and functionally, from the BPCS in order to ensure that any condition, which might result in an out-of-control process parameter in the BPCS, is safeguarded by the SIS, regardless of the function of the BPCS.

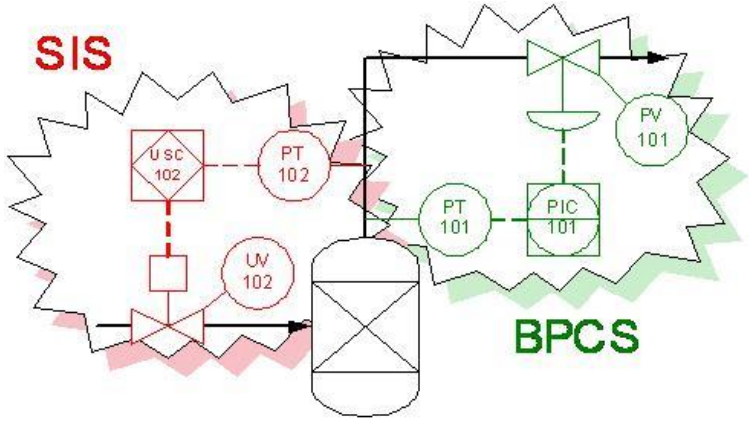



***Figure 1 – SIS versus BPCS***

The SIS will include three types of components including sensor components, a logic solver component, and final control elements. Together these components make up the Safety Instrumented System, which detects out-of-control process conditions, and automatically returns the process to a safe condition, regardless of the functioning of the Basic Process Control System. In this case, the SIS could include a programmable system, or a non-programmable system.

## Legislation and Regulation

Legal requirements for Safety Instruments Systems in the United States are derived from a variety of process safety management regulations, as well as the legislation that serve as the foundation of those regulations. While the discussion in this handbook focuses on the US, a similar framework is utilized in most regions of the world.

Regulations require compliance with recognized and generally accepted good engineering practices for safety critical controls, including SIS. These regulations require recognized and generally accepted good engineering practices to ensure that industry complies with the norms of operation that have been defined

for that industry. Regulations and standards that apply to Safety Instrumented Systems originated in the late 1980's when industry regulators, including the U.S. Occupational Safety and Health Administration (OSHA), as well as the U.S. Environmental Protection Agency (EPA), concluded that industry's performance with respect to prevention of major hazards was inadequate. This originated Process Safety Management Standards by OSHA, which were propagated in 1992 under 29 CFR 1910.119. In 1996, the EPA propagated its Accidental Release Prevention Program, or 40 CFR Part 68, which is also called Risk Management Program. This regulatory standard was substantially similar in the requirements to OSHA's Process Safety Management Standard. Largely in response to these regulations, the International Society for Automation (ISA) as well as the International Electrotechnical Commission, or IEC, developed industry standards for safety critical control systems to provide additional information on how to comply with OSHA and EPA process safety management regulations.

## Why develop SIS standards?

As was previously noted, regulations regarding process safety came about due to a perception of inadequate policies and procedures regarding safety in the process industries. Many of the lessons that have been learned from major accident investigations point to the lack of functional safety as a key cause in loss of life, as well as other property damage, and lost production incidence in the petroleum and chemical industries. Upon review of the accident history of the process industries with respect to scenarios where SIS failure contributed, several common themes developed.

- Often, no SIS was installed when it could be argued that was necessary for safety to be automated. In fact, in many of these cases no study to assess the risks posed by the process was performed at all.

- In some instances, a poor decision making process was used to determine when safety should be automated versus left to another system. This included deciding if operator intervention or the basic process control was adequate in lieu of a separate instrumented system that is dedicated to safety.

- Incident histories also point to questionable equipment selection as another cause for lack of functional safety that resulted in major accidents and losses.

- Lack of redundancy and diagnostic features of SIS was another frequent cause.

- Poor testing methods and poor determination of the frequencies for functional testing was also a cause in many of the losses that were seen related to lack of functional safety, as well as improper bypassing and equipment selection techniques.

  Together, these causes point to the need for improved practices for ensuring functional safety management is achieved. The implications of the accident data on Safety Instrumented System engineering are listed below, and incorporated into the IEC 61511 (ISA 84.00.01) standard for SIS design and implementation.

- We should select criteria for when to use alarms and operator judgment verses an automatic shutdown, using a SIS, when predefined safe operating limits have been violated and the risk is significant enough that manual means are insufficient.

- It is also important to recognize that in order to prevent major hazards, a defense in depth strategy involving multiple, independent layers of protection or safeguards is necessary to prevent major accidents. We recognize this because in some cases, safeguards can fail resulting in demands on SIS.

- We also recognize that inadequate specification of SIS is often a fundamental cause of accidents where functional safety was inadequate. This includes specification of components, system architecture, diagnostic testing, as well as functional proof tests.

- In many cases, accident data shows that bypass and defeat of safety critical systems was also a significant contributor to accident case histories.

In response to these factors, as well as other drivers in the industry, the ISA and IEC developed a Standard for SIS that addresses many of these causes. It provides a Safety Lifecycle as the foundation to address functional safety. The Safety Lifecycle includes identification, design, testing, maintenance, and management of change. It's a "Cradle-to-Grave" approach to safety that addresses fundamental problems that could occur at any step during the design, operation, maintenance, and change of a Safety Instrumented System.

In the U.S., OSHA requires industrial facilities that are covered by the Process Safety Management regulation to comply with recognized and generally accepted good engineering practices. ISA posed the question to OSHA as to whether their standard, ISA 84.00.01 for Safety Instrumented Systems, complies with OSHA's requirements for Process Safety Management. OSHA, in response to this question, agreed that the ISA standard would be one example of compliance with the mechanical integrity requirements for safety critical controls and shutdown systems. OSHA also indicated that this was only one example - it was not the only way - that a company could comply with the Process Safety Management standard requirements for mechanical integrity, as well as process safety information. Since that time most process industry operating companies have come to agree that the safety lifecycle contained in IEC 61511 (ISA 84.00.01) is the optimal methodology for managing safety instrumented system design and implementation.

## What does the standard require?

Unlike other standards and practices in use prior to the release of IEC 61511 (ISA 84.00.01), this standard does not provide a set of rules that define, in details, how a system should be designed. Instead it lays out a framework for allowing each individual user to determine what is appropriate for their specific situation. It's a performance-based approach to SIS rather than a prescriptive approach. In other words, the standard does not take the position of prescribing: what types of components, what types of architecture, what types of diagnostic testing, how often, and what functionally tests a Safety Instrumented System? Rather, the standard establishes a performance or goal-setting approach. In other words, users should select an appropriate performance target for a Safety Instrumented System function, and design the system accordingly to achieve that level of performance.

The standard defines a Safety Lifecycle with multiple steps that should be taken to achieve functional safety in a "Cradle-to-Grave" approach for functional safety management. The standard requires the selection and achievement of a target performance level. That key performance level is the Safety Integrity Level (SIL), which is selected for each Safety Instrumented Function within a SIS using risk-based approaches. The SIL is the fundamental metric for all subsequent decision making about the design of the SIS.

The standards bodies (IEC and ISA) and government regulators (e.g., OSHA in the U.S.) generally agree on the different approach to existing equipment versus new engineering design. Good engineering practice for new design would include compliance with recognized and generally accepted engineering standards, including IEC 61511. However, existing equipment could be treated slightly differently, depending on how each company decides to handle an approach to grandfathering of existing equipment. "Grandfathering" of existing equipment is allowed in the U.S. under OSHA's Process Safety Management

Standard, and is also allowed under the ISA 84.00.01 version of the IEC 61511 version of the SIS standard. The standard says, "For existing systems, designed and constructed in accordance with codes, standards, or practices prior to the issue of this standard, the owner/operator shall determine, and if any equipment is designed, maintained, inspected, tested, and operated in a safe manner." In other words, it does not prescribe that old equipment designed to previous engineering standards needs to be up to the current SIS standard; rather a system should be in place to verify that equipment is operated, tested, inspected, maintained, and designed according to safe standards of the time. The acceptability of "grandfathering" may vary depending on the location in which a SIS is employed.

## The Safety Lifecycle

*Figure 2* presents the SIS Safety Lifecycle as prescribed in IEC 61511 (ISA 84.00.01). The Safety Lifecycle includes a number of specific steps from design through operation, maintenance, testing, and even decommissioning, to address safety throughout the lifetime of a Safety Instrumented System in the petroleum or chemical process.

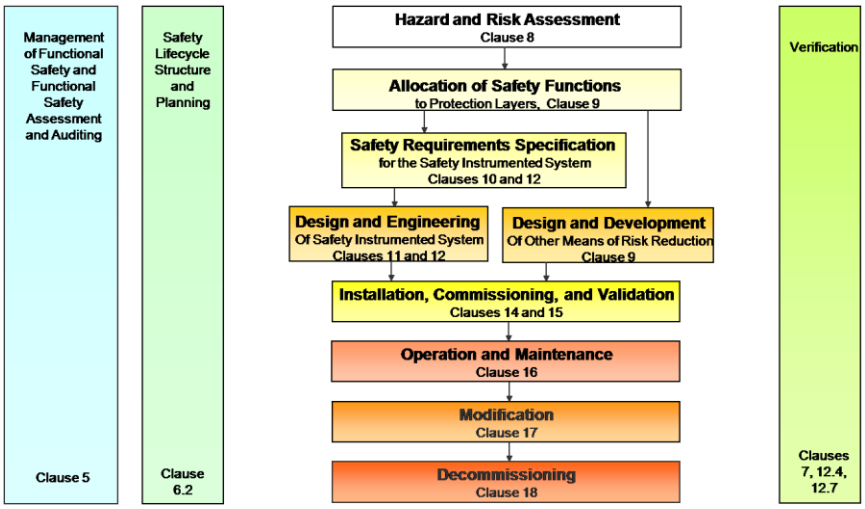



***Figure 2 – IEC 61511 Safety Lifecycle***

The first step in the Safety Lifecycle is "Hazard and Risk Assessment". The premise of this step is that to adequately design a Safety Instrumented System, we must fully understand the hazards against which that system is intended to safeguard. If we don't have an adequate understanding of those hazards, the system might be improperly designed with respect to the types of components that are used, the type of redundancy or architecture that is selected, and other factors that are pertinent to SIS engineering design.

The next step, "Allocation of Safety Functions", involves assigning certain levels of integrity to each of the safeguards that are used in the process, including Safety Instrumented Functions, as well as non-instrumented functions to achieve an overall level of safety that is acceptable to the company that is operating that process.

The third step in the Safety Lifecycle is "Safety Requirement Specifications". This is an important step to achieve overall functional safety. In the conceptual design of a process, we must make sure that the safety requirements are adequately specified prior to proceeding to other steps in the engineering design lifecycle, including detailed design, construction, installation, and commissioning. This step is where the objectives and means for achieving those objectives are defined. Once completed, the Safety Requirements Specifications (SRS) form the basis for all subsequent design and validation activities.

The steps after SRS (which are often performed in parallel by different groups) are "Detail Design and Engineering" and "Design and Development" of other non-safety instrumented system safeguards. This stage is where the information in the SRS is expanded into more detailed documentation that is used for purchase of equipment, equipment configuration, and installation. This includes tasks such as creating equipment lists, cabinet layout diagrams, internal wiring diagrams, interconnecting wiring diagrams, and PLC programs.

After the detailed design of the SIS is complete the following step is "Installation, Commissioning, and Validation" of the Safety Instrumented System itself. This stage involves factory acceptance testing (FAT), physical installation of the SIS logic solver and all of the field instrumentation, commissioning of those devices, and a validation step that will include site acceptance testing (SAT) and pre-startup acceptance testing (PSAT).

Once the SIS is installed and operational, a different phase of the lifecycle begins where the design team passes responsibility for the equipment to the operations and maintenance team of the operating company. The "Operation and Maintenance" involves the routine day-to-day interaction with a functioning system. During this phase, operations staff will respond to overt system alarms utilizing procedures written for that purpose. In addition, maintenance will repair the system in response to overt faults and also perform periodic function testing to ensure the system's proper operation.

The "Decommissioning" and "Modification" steps are very similar in nature. If changes to the SIS or to the process under control occur, measures must be taken so that the SIS is not compromised in its ability to provide the required amount of risk reduction. During this phase Management of Change (MOC) requirements apply to ensure that when changes are made to the process that are outside the SRS, those changes are adequately analyzed for potential hazards prior to implementing the change. Decommissioning is a special form of modification where analysis of the removed equipment must be analyzed with respect to its impact on the equipment that will stay in service.

There are three other steps of the Safety Lifecycle that occur over the entire length of an SIS lifetime. These steps are "Management of Functional Safety and Functional Safety Assessment and Auditing", "Safety Lifecycle Structure and Planning", and "Verification". In order to execute a functional safety project effectively, management of the entire process is important. Management tasks such as assigning tasks to qualified resources can have a bearing on the project, and thus standard requirements were set. Each step along the way, the standard requires that we verify that the outputs of each step in the Safety Lifecycle have been achieved, and are consistent with the inputs to that step of the Safety Lifecycle.

Kenexis has prepared a typical SIS design lifecycle in a slightly different representation that more closely associates itself with the actual steps that are taken during the design of a SIS. This lifecycle is shown in *Figure 3*.

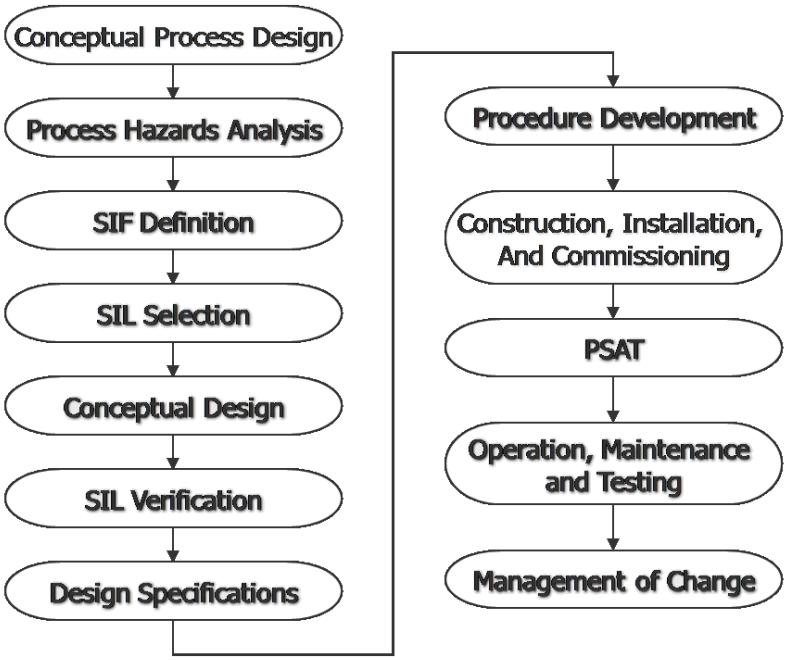
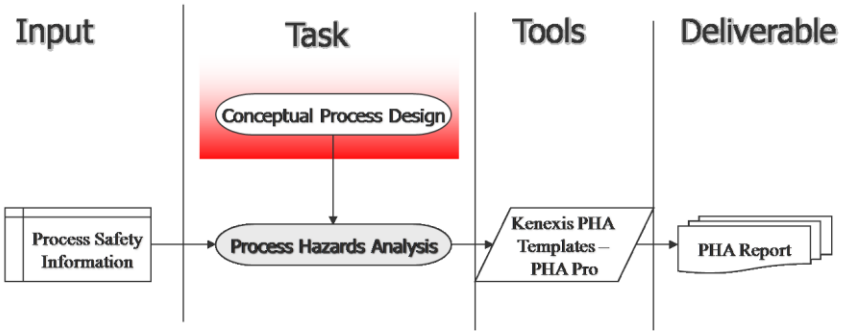



***Figure 3 – Kenexis Safety Lifecycle***

The steps in the Kenexis Safety Lifecycle are more granular than what is shown in the standard, and thus functions more effectively as a flowchart of an SIS project than does the lifecycle in IEC 61511.

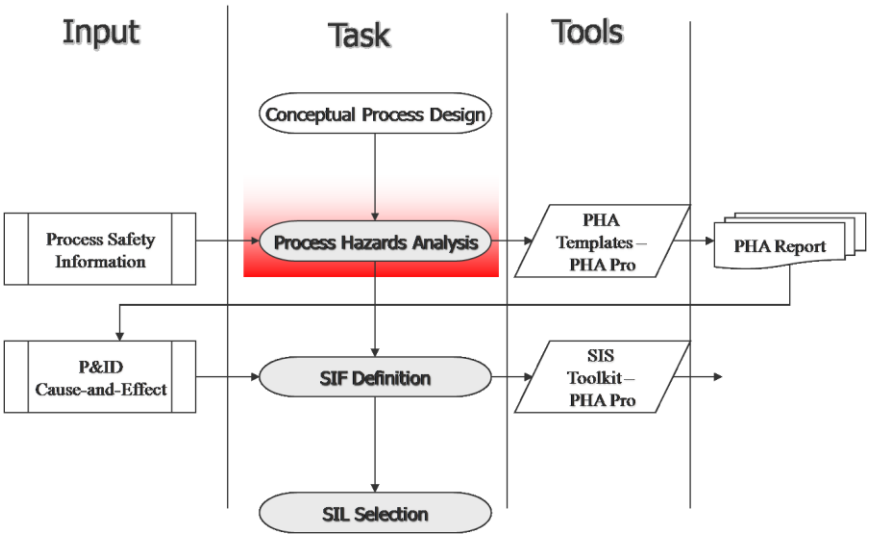
# Conceptual Process Design




Conceptual Process Design is the starting point of the Safety Lifecycle. Although it is listed as a step in IEC 61511, it is typically considered out-of-scope for Safety Instrumented Systems. This step is included in the safety lifecycle as a reference for the task that leads into the standard, and provides inputs for the first safety lifecycle task, but the standard places no requirements on the conceptual process design.

Conceptual process designs are either developed by the operating company itself, or are licensed from a company that specializes in developing processes. The conceptual design process will result in design documents that will form the basis for subsequent engineering, and also form the basis of the Process Safety Information (PSI) that will be used as an input to the process hazards analysis. PSI includes information such as piping and instrumentation diagrams (P&IDs), heat and mass balances, block flow diagrams, and safe operating limits.

# Process Hazards Analysis




Process Hazards Analysis (PHA) is a qualitative analysis of process hazards by a multi-disciplinary team. It is not a new concept. PHA has been implemented within industry for more than 15 years now. The OSHA process safety management regulation put into place in 1992 caused PHA to become much more prevalent, but most PHA methodologies were developed and implemented far earlier.

The inputs to this step of the Safety Lifecycle include Process Safety Information, such as proposed Process Flow Diagrams (PFD), Piping and Instrumentation Diagrams (P&ID), and other documentation that would be required to analyze potential deviations from normal intention of process operation. PHA involves analyzing those deviations from design intent and determining if they could result in a credible hazard. If so, the consequences of those hazards are identified, and the safeguards in place to prevent those hazards are identified. A qualitative assessment of risk is made by the PHA team, often using risk guidelines from the operating company, such as a risk matrix. If safeguards are not considered adequate, then the PHA team makes recommendations for reducing or eliminating the hazards or adding to the safeguards. The result of this step is a Process Hazards Analysis report that identifies the process hazards. The PHA report can then be used in the next step in the SIS engineering lifecycle.

With respect to SIS engineering, the primary purpose of the PHA step is to identify safeguards that are required in order to reduce risk of the process and understand what hazards those safeguards protect against. PHA is typically considered to be a single formal study such as a Hazards and Operability Study (HAZOP) whose results are documented in a single report. However, in reality PHA should be considered as a series of studies and engineering tasks that result in recommendations for potential safeguards. These tasks should include the following:

- Development of Design Packages from Process Technology Licensors and Engineering Companies
- Review of Design Standards, Codes, and Good Engineering Practice Guidelines for Specific Equipment Items
- Initial Preliminary Hazard Assessment studies, such as HAZID
- Relief System Design Basis Studies

- Alarm Rationalization Studies
- Chemical Reactivity Testing and Analysis
- Formal Process Hazards Analysis

A preliminary process design is rarely performed starting from a blank slate. Often, process design is based on proven technologies used for years. There are often process design templates from process licensors that contain important information about hazards and key safeguards. These licensor packages identify Safety Instrumented Functions that have been included by process licensors based on past experience with design and operation of the process technology. Furthermore, most process plants include a large number of common pieces of process equipment that require safeguarding through SIS. These include pumps, compressors, and fired equipment. Often, this equipment is designed and safeguarded in accordance with equipment specific standards such as the National Fire Protection Association (NFPA) standards for fired equipment including boilers, as well as the American Petroleum Institute's (API) recommended practices for designs for fired equipment, compressors, and other rotating equipment.

Other engineered safeguard design basis studies may also yield requirements for safety instrumented systems. Studies such as relief system design basis, alarm management study, or chemical reactivity study often result in recommendations for SIS especially when other means of safeguarding are determined to be inappropriate or less effective than use of SIS.

The tasks that are traditionally considered PHA are essentially "structured brainstorming" techniques where a trained facilitator generates discussion among a group of experts with regards to the hazards potentially posed by a process by leading the discussion with cues that are designed to stimulate thought. For instance, in a HAZOP the cues are deviations from design intent for a specific process section such as less flow or more level. Formal PHA studies are typically performed at several stages in the lifecycle of a process plant. In many cases the first studies are carried out using simpler techniques (e.g., checklists, HAZID) and later studies using more detailed methods such as HAZOP. At the point in time that a final PHA is performed, the great preponderance of engineered safeguards have already been documented in the plant's design and the PHA simply acts as a final check on a good design.

With respect to the SIS safety lifecycle, it is important for the selection of a SIL target to be consistent with other PHA studies performed for the process plant. In addition, the information provided in these studies can provide valuable assistance and insight during the SIL selection effort.

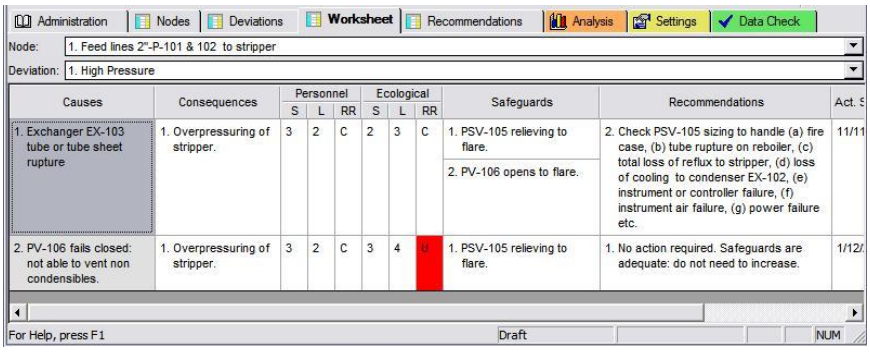


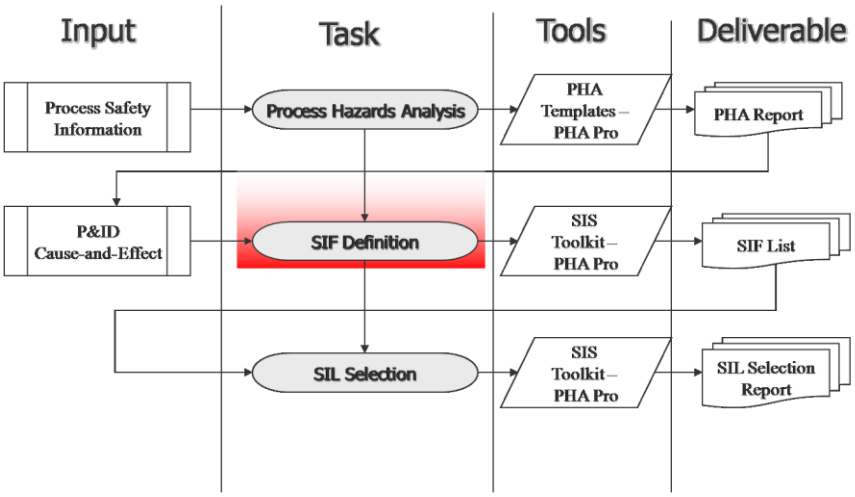

***Figure 4 Typical HAZOP-Style PHA Output***

*Figure 4* presents a typical HAZOP-Style PHA. This type of report can be dissected in order to develop information that will assist in the determination of a SIL target. For instance, hazard scenarios that are

listed are typically assigned consequence categories, the causes can often be used as initiating events, and the safeguards can be considered as independent protection layers. Also, recommendations from the PHA might identify the need for additional SIF that were not identified by other prior analysis.

In summary, this step in the safety lifecycle should not be considered as conducting a "traditional PHA", but a comprehensive series of activities to identify and understand the hazards that require safeguarding by the SIS.

# SIF Definition




The definition of safety instrumented functions (SIF) is a critical step in the SIS safety lifecycle, and the source of many errors in SIS design as a result of common misconceptions about what constitutes a SIF. SIF Definition requires an adequate understanding of hazards associated with a chemical process, and the specific instruments that are utilized to protect against those hazards. Safety Instrumented Functions are intended to protect against specific and identifiable hazards instead of general hazards, such as fire and gas explosion.

The result of SIF definition is that Safety Instrumented Function List, or SIF list. A SIF list is a compilation of the functions which must be implemented in an overall Safety Instrumented System which could include multiple Safety Instrumented Functions within the same logic solver, and using similar or identical components such as sensors and final elements. Some components might be employed in multiple SIF, as demonstrated in *Figure 5*.

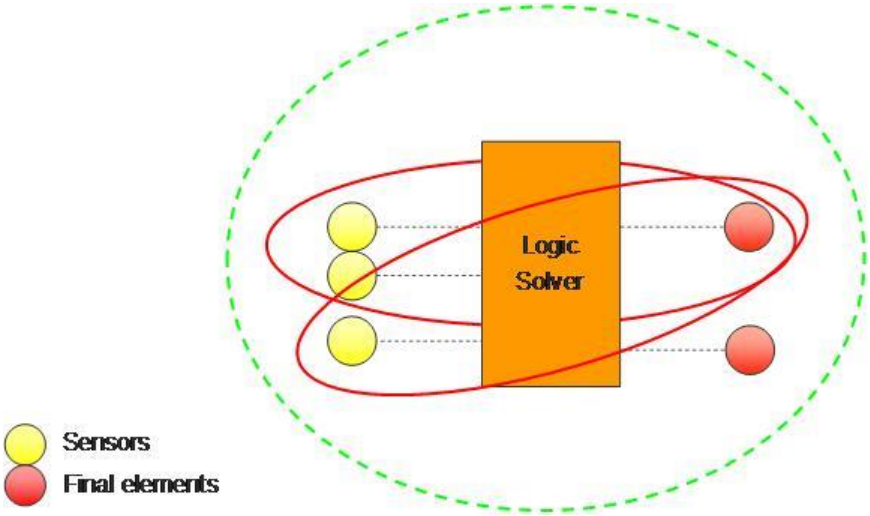



***Figure 5 SIF versus SIS***

The purpose of SIF definition is to create a list of all the functions that need to be analyzed in the remaining steps of the Safety Lifecycle including SIL selection, Safety Requirement Specification, Functional Test Procedure development, and so on. Safety Instrumented Functions are identified on a hazard-by-hazard basis, as opposed to strictly considering the functionality executed by the SIF. Therefore, it is imperative that this step is done adequately, with sufficient thought as to the hazards that are involved in the process, and the equipment or components that could be used to detect and take corrective action once those hazards are identified.

Identification of Safety Instrumented Functions is performed considering a range of design documentation including Cause and Effect Diagrams, and Piping and Instrumentation Diagrams. The SIF List is a list of all functions that needs to be analyzed. Each SIF is assigned its own Safety Integrity Level, individually, in order to represent the risk reduction required to mitigate the specific hazard associated with that function. The integrity level requires or defines the performance for that function in terms of its ability to achieve a tolerable risk target that is established by the company operating the process.

*Figure 6* presents a typical SIF list, as contained in the Kenexis SIS Design Basis Toolkit™. As shown, this list completely defines the extents of the SIF.

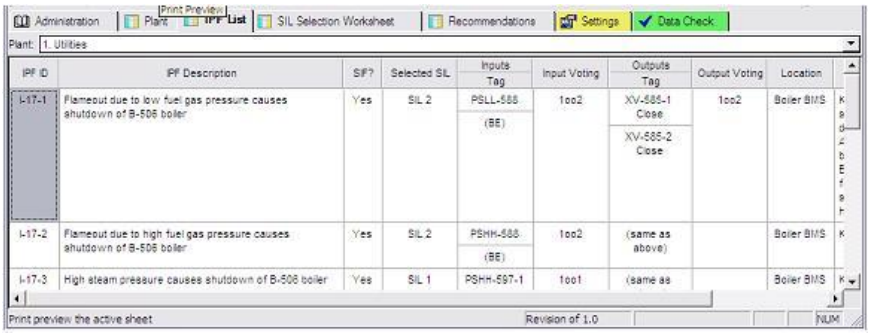



***Figure 6 Typical SIF List***

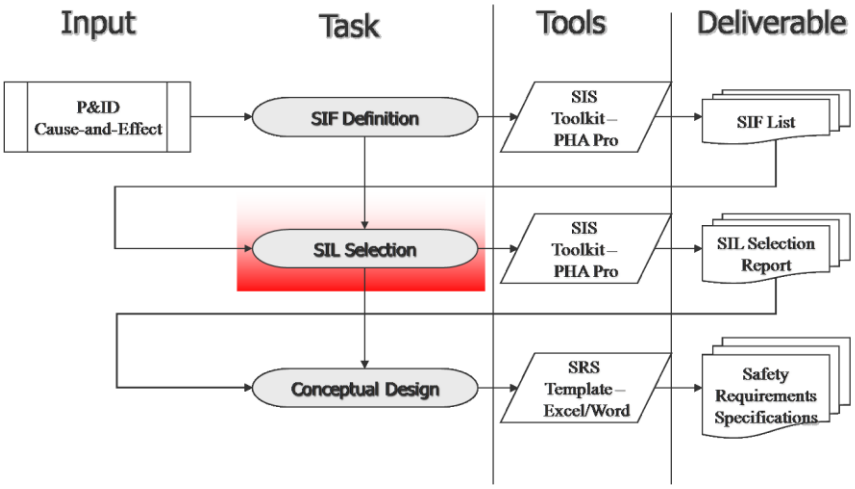
For each SIF, a description is provided that defines the intention of the function and the action that is required to move the process to a safe state. All of the safety critical inputs are listed, specifically all of the sensors that can detect the hazard being prevented. The safety critical outputs are listed, and by this what is meant is all of the outputs that are necessary and sufficient to move the process to a safe state. This is a very different concept than listing all of the outputs that are activated as per the unit's cause and effect diagram. Also, the location of the SIF is listed, designating the logic solver that is utilized to implement the SIF. In addition to listing the equipment items information concerning the voting arrangements of the equipment necessary to prevent the defined hazard is also provided.

The SIF List should define each SIF completely, including:

- Tag names for input devices
- Description of SIF intention
- Input voting
- Tag names for output devices
- Output voting
- Location of SIF logic

Additional information such as interlock numbers, P&ID drawing numbers and general notes may also be included for complete documentation purposes.

# Safety Integrity Level Selection




Once all of the functions that are in the scope of analysis have been defined in the SIF list, Safety Integrity Level (SIL) Selection is performed. At this stage, the SIFs are analyzed sequentially looking at the hazards, identifying the appropriate perimeters that affect the risk of those hazards, and selecting an appropriate SIL to achieve a desired risk tolerance threshold. It is important to remember that the purpose of SIL Selection is to define performance criteria for the system. It is not to define the SIF, but rather prescribe how much risk reduction is required of each of those SIF.

## Defining SIL

As per their definition in IEC 61511 (ISA 84.00.01) SIL are order of magnitude bands of average probability of failure on demand (PFDavg). This PFDavg also represents the amount of risk reduction of a preventive safety instrumented function can provide. The ranges for each of the four SIL levels defined in the standard are presented in *Figure 7*. This figure not only presents SIL in terms of PFDavg, but also Safety Availability and Risk Reduction Factor (RRF). Safety Availability is the complement of PFDavg (i.e., 1-PFDavg), and the RRF is the inverse of PFDavg (i.e., 1/PFDavg). All of these metrics are commonly used in industry.

| Safety Integrity Level | Safety | Probability of Failure on Demand | Risk Reduction Factor |
|---|---|---|---|
| SIL 4 | > 99.99% | 0.001% to 0.01% | 100,000 to 10,000 |
| SIL 3 | 99.9% to 99.99% | 0.01% to 0.1% | 10,000 to 1,000 |
| SIL 2 | 99% to 99.9% | 0.1% to 1% | 1,000 to 100 |
| SIL 1 | 90% to 99% | 1% to 10% | 100 to 10 |

***Figure 7 Safety Integrity Level Metrics***

SIL 1 is the lowest level of Safety Integrity that is defined by safety availability by at least 90% up to 99%, essentially providing one order of magnitude of risk reduction. SIL 2 is an order of magnitude safer than SIL 1 in terms of its safety availability. The safety availability of a SIL 2 function would be at least at least 99% and up to 99.9% safety available. SIL 3 is an order of magnitude on top of SIL 2 in terms of safety availability, and SIL 4 follows accordingly. SIL 4 is rarely - if ever - seen in the process industries, and is often reserved for application to other non-process related industries that could be covered by international standards for Safety Instrumented System design. If a SIL selection process results in a requirement for SIL 4 the user should proceed with care and obtain the assistance of experts.

## SIL Selection Process

Since SIL is a measure of the amount of risk reduction provided by a Safety Instrumented Function, SIL selection is an exercise in analyzing the risk of the hazard and determining how much risk reduction is required to achieve a tolerable level of risk. Reducing the risk can be graphically represented by this diagram contained in *Figure 8*, where at least two perimeters that affect risk are considered. Specifically, those parameters are consequence and likelihood.

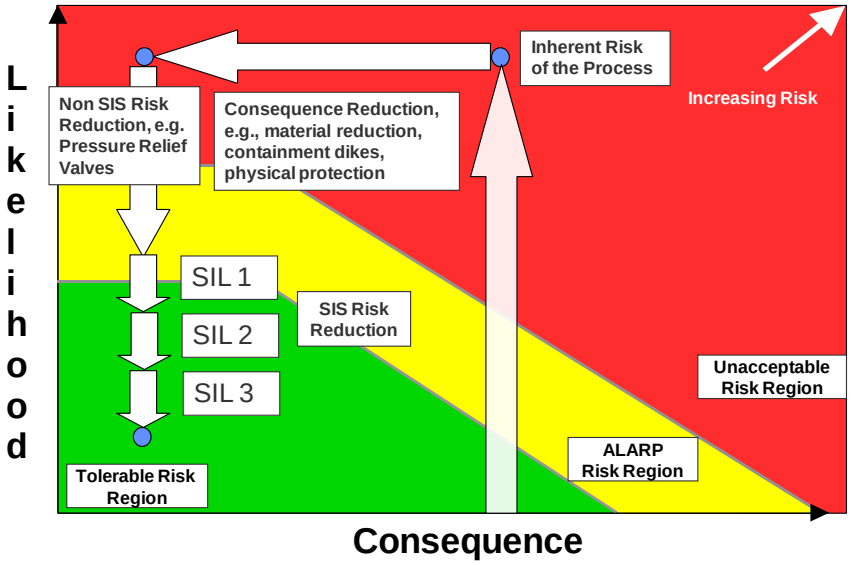



***Figure 8 Graphical SIL Selection Representation***

The consequence is the potential severity of an accident hazard. The likelihood is a representation of how often the accident is expected to occur. If one considers a single hazard within a process, it will have an inherent process risk, which is a function of its inherent consequence severity, and an inherent likelihood of that hazard occurring in absence of any other safeguards. In this diagram, increasing risk is up and to the right. This means that increasing consequence or increasing likelihood would result in an increasing risk. The risk diagram, in this case, is divided into three regions shown below:

1. An unacceptable risk region, shown in red, where risk is intolerable and must be reduced.

2. A tolerable risk region, shown in green, where risks are deemed generally tolerable without further risk reduction.

3. A region in-between the unacceptable and the tolerable risk region, shown in yellow, which is called the "ALARP", or as low as reasonably possible risk region.

In order to achieve a level of risk that is broadly acceptable, the user is required to show that risk is in the green area of this diagram.

The inherent risk can be reduced by Non-SIS risk reduction. In order to assess the risk one, is required to know and evaluate the effectiveness of all Non-SIS risk reduction measures to ensure that the risk is reduced to as low as possible before we apply the additional benefit of a SIS. Or in fact, address whether or not we need a SIS to further reduce the risk.

Non-SIS risk reduction could include consequence reduction measures, as well as likelihood reduction measures. "Consequence Reduction" could take the form of containment dikes, or physical protections such as blast walls, or blast-resistant control buildings. "Likelihood Reduction" could take the form of operators responding to safety critical alarms, or pressure relief provided by conventional over-pressure protection.

In the example shown in *Figure 8*, the benefit of all these Non-SIS layers of protection, or safeguards, is not sufficient to achieve tolerable risk. Therefore, additional risk reduction is required, and in this example, a SIL 1 level of risk reduction, a SIL 1 performance, is adequate to achieve a tolerable risk. In this example, we would specify a SIL 1 level of performance to achieve tolerable risk for a Safety Instrumented Function that protects against this hazard. Each SIL level provides a one order of magnitude decrease in the frequency of the event.

## Representing Tolerable Risk for SIL Selection

For the purposes of performing SIL selection, companies often, represent their risk tolerance in terms of either risk matrices or Tolerable Maximum Event Likelihood (TMEL) Tables. *Figure 9* shows an example risk matrix and *Figure 10* contains a consequence categorization table that includes TMEL figures for each consequence category. These risk tools are utilized for day-to-day risk engineering tasks, and are calibrated against corporations' tolerable risk guidelines. Calibration details for these example risk tools are contained in *Appendix H*.

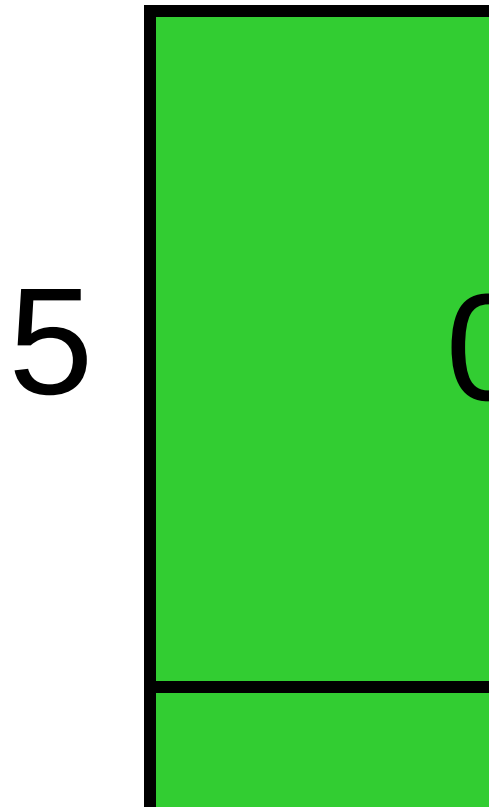



***Figure 9 Calibrated Risk Matrix***

| S | Category | Safety | Environment | Commercial | TMEL |
|---|---|---|---|---|---|
| 0 | None | No significant safety consequence | None | None | N/A |
| 1 | Very Low | Minor injury - first aid | Small release with minimal clean up requirements | $50,000 | 1E-02 |
| 2 | Low | Lost time injury not requiring extended hospitalization | Moderate release limited to onsite damage with moderate clean up effort | $500,000 | 1E-03 |
| 3 | Moderate | Severe injury (extended hospitalization, dismemberment) | Large release with limited offsite impact requires significant onsite clean up | $5 Million | 1E-04 |
| 4 | High | Single fatality | Large release offsite on extensive clean up and damage to sensitive areas | $50 Million | 1E-05 |
| 5 | Very High | Multiple fatalities | Very large release off site with extensive clean of and permanent damage to several sensitive areas | $500 Million | 1E-06 |

***Figure 10 Consequence Category Table with TMEL***

*Figure 11* shows an example likelihood category table which would be used in combination with the consequence table when using the Risk Matrix approach.

| Likelihood | Description | Recurrence Period |
|---|---|---|
| 0 | None | N/A |
| 1 | Very Unlikely | 1,000 years |
| 2 | Unlikely | 100 years |
| 3 | Occasional | 10 years |
| 4 | Frequent | 1 year |
| 5 | Very Frequent | 0.1 year |

***Figure 11 Likelihood Category Table***

While a wide variety of techniques can be used to select the required SIL, Layer of Protection Analysis (LOPA) is by far the most common method due to its ease of use and effectiveness. LOPA can employ either the Risk Matrix or TMEL table approach to represent risk. When a risk matrix is used, the analysis strictly employs orders of magnitude (i.e., the "exponents") and is referred to as "Implicit" LOPA, whereas then the TMEL table is used, risk figures are calculated using the actual frequency and probability figures and is referred to as "Explicit" LOPA.

When performing an Implicit LOPA, the category of the consequence is selected, and the category of the initiating event is selected. It is important to remember that the selected likelihood needs to reflect the frequency of the initiating event, not the ultimate consequence. This is different than how risk is ranked in other PHA studies such as HAZOP where the frequency of ultimate consequence is ranked. The intersection of the consequence and the likelihood categories on the risk matrix contains the number of orders of magnitude of risk reduction that are required to make the risk of a particular hazard tolerable.

When using the TMEL table approach, only the consequence category needs to be determined. Each category of consequence is associated with a TMEL. This TMEL is the frequency at which a consequence of that magnitude is tolerable. When using Explicit LOPA, initiating events are quantified based on their frequencies. *Appendix C* contains a list of typical initiating event frequencies.

## Layer of Protection Analysis

The benefit of layers of protection can be accounted for in a separate Layer of Protection analysis, where we look at the potential effectiveness of each of these protection layers.

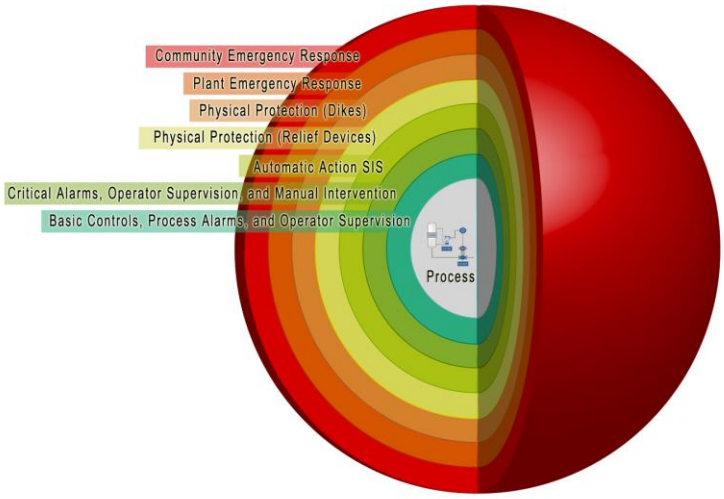



***Figure 12 Layers of Protection***

*Figure 12* presents a graphical depiction of the concept of layer of protection analysis, where each concentric sphere contains the process risk with it. In order for a process hazard to escape it will need to go through all of the layers.

The process industries utilize a number of independent protection layers as part of typical plant designs. Some common protection layers, along with probabilities of failure of those layers can be found in *Appendix D*. Figure 13 displays some protection layers that are common in the process industries. This most common protection layer is operator response based on alarms indicating a process has been moved from its normal window of operation to a potentially unsafe state. Safety instrumented systems are the layer of protection for which we would want to establish a SIL.

Pressure relief devices, or simple mechanical devices, to reduce the risk of hazards such as over-pressure are also common. In addition, other safeguards that are in this case not related to prevention of an accident, but rather mitigation of the potential consequences of an accident, including plant emergency response, are also often available.

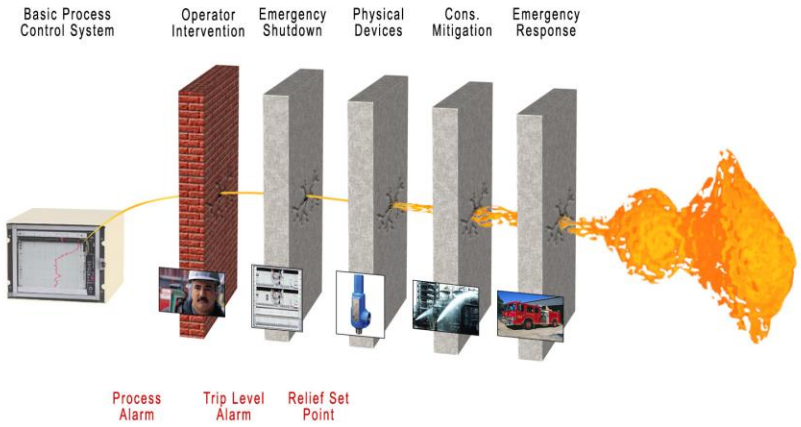



***Figure 13 Layers of Protection***

The philosophy of layers of protection acknowledges that one or more of these layers could fail when a demand condition is placed upon it. And as such, some accidents with potentially high consequence severities, as well as high likelihoods, could require more than one robust SIS design, or other layers of protection to reduce the risk to a tolerable level. We account for the protection layers in a separate Layer of Protection analysis where we verify that each of the protection layers is independent of all other protection layers, is specifically designed to prevent the hazard that has been identified, and is effective. In other words, it's equivalent to at least 1 order of magnitude reduction in risk, or no more than 10% probability of failure when a demand is placed upon it.

Explicit and implicit varieties of LOPA handle the effectiveness of protection layers in a slightly different way, which are mathematically equivalent. When using TMEL targets as the basis for tolerable risk, the frequency of the unwanted accident must be calculated and compared against the target. This frequency calculation is done by multiplying the initiating event frequency by the probability of failure on demand of all of the independent protection layers that act against that specific initiating event. If multiple initiating events are present, then the resultant frequencies should be summed. The selected performance target for the SIF is then calculated as the maximum probability of failure that the SIF would be allowed to yet still to achieve the TMEL.

When using a risk matrix to contain tolerable risk, the required number of orders of magnitude of risk reduction is taken from the matrix. Each credit for an independent protection layer reduces the risk by 1 order of magnitude. Mathematically speaking, this means that each credit is equivalent to a PFD of $1x10^{-1}$. Thus the SIL target selected for the SIF is the required number of orders of magnitude of risk reduction minus the number of protection layer credits. The subtraction of protection layers is equivalent to multiplication of probabilities because multiplying numbers or adding their exponents yields the same result.

The equations that are used to determine the required SIL (additionally the required RRF when TMEL is used) are shown below:

*Implicit (Risk Matrix) LOPA*

$$SIL = RR(S,L) - \sum IPLCredit$$

Where,

SIL= The selected safety integrity level

RR(S,L) is the required amount of risk reduction (in terms of required orders of magnitude of risk reduction, obtained from the calibrated risk graph

∑(IPLCredit) is the sum of all of the credits for all of the valid independent protection layers

IPL Credit to PFD Conversion:

$PFD = 0.1^{Credits}$

(1 credit = PFD = 0.1 ; 2 credit = PFD = 0.01 ; 3 credit = PFD = 0.001)

*Explicit (TMEL) LOPA*

$$SIL = \frac{F(event, No - SIS)}{TMEL}$$

$$F(event, No - SIS) = \sum_i (IE_i * \prod_j IPLPFD_{ij})$$

Where,

SIL= The selected safety integrity level

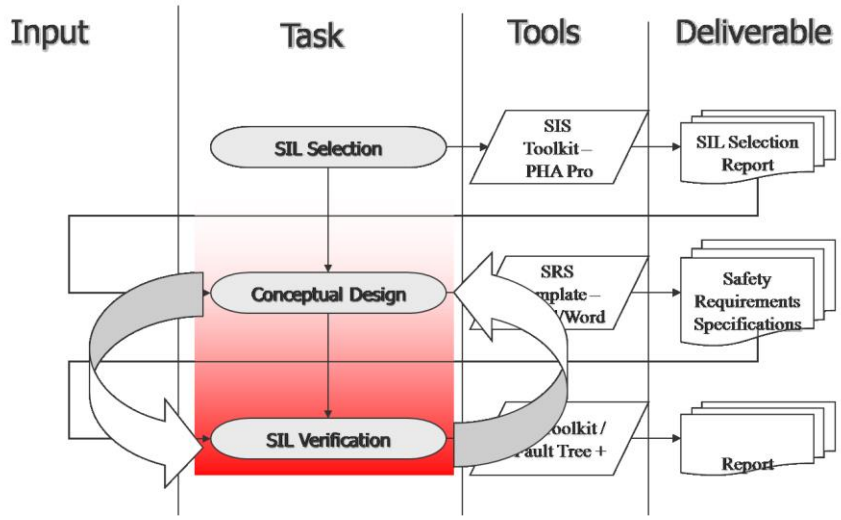
TMEL (Total Mitigated Event Likelihood) is the frequency at which the event is tolerable, obtained from the calibrated risk matrix and is based on the severity of the event.

F(event, No – SIS) is the frequency of the event occurring without a Safety Instrumented System installed to protect against it.

IE is the frequency of the initiating event.

Π(IPLPFD) is the Product of the probability of failure on demands for all of the valid independent protection layers for each Initiating Event.

# Conceptual Design / SIL Verification




After Safety Integrity Levels have been selected for each of the indentified Safety Instrumented Functions, the next tasks in the SIS Safety Lifecycle that need to be accomplished are "Conceptual Design of the Safety Instrumented System" and "SIL Verification". This stage is where verification that each of the required SILs has been achieved by the system that has been designed is accomplished.

These two steps really go hand-in-hand, and often they are iterative in nature. The typical starting point is a Conceptual Design of the SIF that is either based on prior experience with the application, or engineering judgment based on the required SIL. This design is then evaluated in order to determine whether the SIL has been achieved. The Conceptual Design is then modified in an iterative fashion until all facets of the SIL rating have been achieved by the design; including, component type, architecture, fault tolerance, functional testing, and diagnostic capabilities. The purpose of conceptual design evaluation is to determine whether the equipment, and how it is maintained, is appropriate for the selected SIL. The result is a set of functional specifications of the system that can be used in detailed design engineering (i.e., safety requirements specifications).

As shown in *Figure 14,* there are several parameters in the design of a SIS that could potentially affect the achieved SIL. These are the selection of the components, the fault tolerance of the design (which is dependant on the architecture that has been selected), the functional testing interval of the system (and its components), the potential for common cause failures to defeat any fault tolerant design features, as well as any diagnostics that are incorporated into the design of the system components.

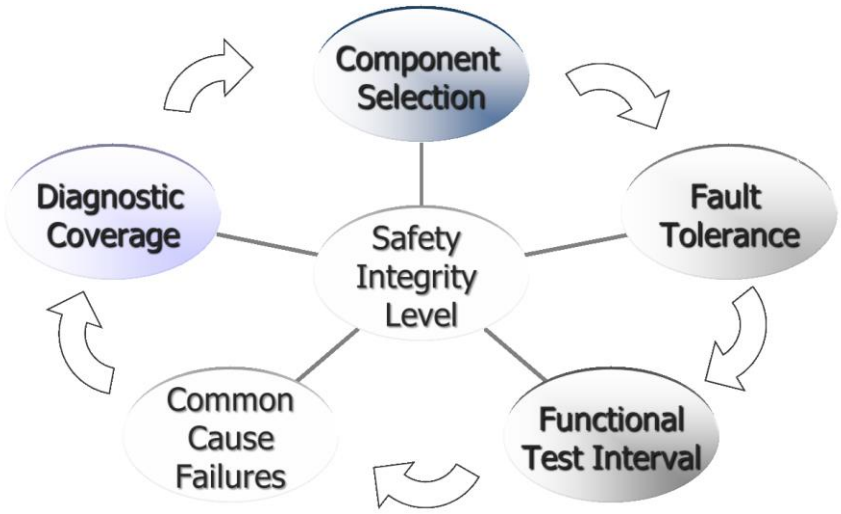



***Figure 14 Parameters Impacting Achieved SIL***

## Component Selection

The component selection process considers both qualitative and quantitative aspects of the components set of properties. The qualitative aspects include:

- Suitability for the selected application
- Suitability for use in safety

The former criterion speaks to the component's ability to accurately react in the specific process application, and the latter criterion speaks to the component's reliability for safety applications. Both of these criteria are critical, and neither can be ignored.

For a device to be suitable for a specific application, the principles that the device employs must have a proven history of effective performance in a specific application. For instance, vortex meters and magnetic ("Mag") meters both measure flow, but cannot be interchanged in all applications because their effectiveness is not equal in all cases, and is very dependent on the substance being measured. This is a critical consideration when employing "certified" equipment. Even if equipment is "certified" for IEC 61508 compliance, it still cannot be used unless an assessment is made by the users that the technology the device employs is suitable for the application.

In order for a device to be "suitable for safety", the user must either have successful "prior use" experience with the device or it must be manufactured in accordance with industry recognized standards for suppliers of Safety Instrumented System components; specifically IEC 61508. This is typically verified by an independent third party certification. These measures are meant to speak to suitable "reliability" of the device. In the case of "prior use", the end user analyzes past performance of the device to determine acceptability, and in the case of "certification" it is assumed that the highly controlled design and manufacturing processes will yield high reliability.

In addition to the two qualitative criteria, the technology of the device will also play a role in what equipment is selected. Decisions between programmable technologies, as opposed to hard-wired electromechanical devices, are typically made by balancing the low cost of small hard-wired systems with

the decreased cost and engineering effort associated with large programmable systems. In addition, the technology will also affect other quantitative parameters that will be discussed later in this section such as failure rate, safe failure fraction, and diagnostic coverage.

## Fault Tolerance

Fault tolerance is the ability of the SIS to be able to perform its intended actions (and not perform unintended actions) in the presence of failure of one or more of the SIS components. Fault tolerance is typically achieved through the use of multiple redundant components that are arranged to "vote" upon action of the SIF. This arrangement of multiple redundant components is referred to as the "architecture" of a SIF subsystem. Some voting architectures would potentially result in loss of safety upon failure of a component, while others could potentially increase the level of safety if one or more of components in the architecture failed.

The most common architectures employed as SIS subsystems are listed below. In general, these figures are described in M-out-of-N systems, where M is the number of components that must function in order to take the safety action and N is the total number of components.

One-out-of-One (simplex)

One-out-of-Two

Two-out-of-Two

Two-out-of-Three

The 1oo1 architecture is a single, individual component, and serves as the baseline in comparing the various available SIS architectures. The 1oo2 arrangement is the "safest" of the options, meaning it provides the lowest probability of failure on demand. In this arrangement, if either of two transmitters "votes" to shutdown, the shutdown action is taken. The 1oo2 arrangement provides one degree of fault tolerance with respect to "dangerous" failures, but none with respect to spurious failures. In fact, the 1oo2 arrangement will result in a spurious failure twice as often as the rate resulting from a single device. The 2oo2 arrangement provides one degree of fault tolerance to spurious failures, but none to safety. As a result, its PFDavg is twice that of a single component (i.e., more dangerous), but has a nuisance trip rate that is an order of magnitude lower. Finally, 2oo3 offers a compromise between 1oo2 and 2oo2. This arrangement has both lower PFDavg and lower spurious trip rate than a single device, but is neither as safe as 1oo2 nor as spurious trip resistant as 2oo2.

In addition to the quantitative impacts of architecture, SIL levels require the achievement of "Architectural Constraints" which are essentially restrictions on the minimum fault tolerance that must be supplied for any given subsystem. Generally, Safety Integrity Level 1 requires no fault tolerance unless it is necessary to achieve the desired probability in PFDavg target. Safety Integrity Level 2 requires at least one degree of fault tolerance, which could be achieved by, for example, a 1oo2 voting architecture. A detailed discussion of achieving minimum fault tolerance, along with the minimum fault tolerance tables out of IEC 61511 and IEC 61508 is included in *Appendix F*.

## Functional Test Interval

Functional testing of a SIF decreases its probability of failure, and increases its effective SIL, by effectively reducing the fraction of time that a SIF is in the failed state. When a test of a SIF is performed, any latent failures in the system are identified and subsequently repaired. As the test interval becomes shorter (i.e., testing is more frequent), a failed SIF will not remain in that failed state for as long a period of time, reducing unavailability. *Figure 15* demonstrates this concept from the unreliability perspective. The curves in the graph show unreliability which is essentially the probability of failure. As time increases, the unreliability increases until a test is performed. After the test confirms successful operation of the system (or results in repair of failed components) the probability of failure then returns to zero. If a system is tested more frequently it does not travel as far up the unreliability curve before being reset to zero.

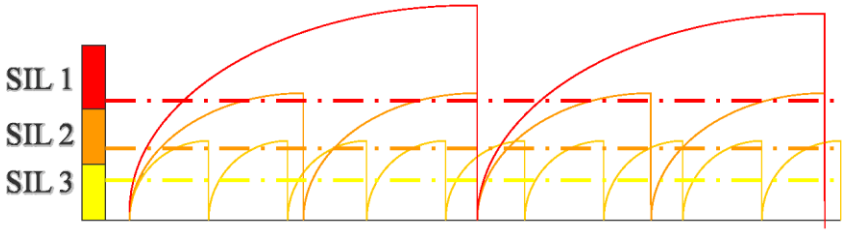



***Figure 15 Impact of Test Interval on SIL***

## Common Cause Failures

Common Cause recognizes that a potential single event or stress on a SIF could result in multiple simultaneous failures of SIF components. For example, two or more sensors could fail at the same time if their process taps were plugged. Common Cause Failures are often handled using an analysis of Common Cause Failure percentages that affects the achieved SIL. This is called the Beta Factor Method. Common Cause Failures can be eliminated, or substantially reduced, by using not only redundant architectures, but by diverse types of equipment within a redundant architecture.

## Diagnostic Coverage

Diagnostic Coverage is another factor that allows achievement of potentially higher SIL targets. Diagnostics are essentially proof tests of an individual SIS component that occur rapidly and automatically, but only detect some of the potential failures of the device. The fraction of the failures that can be detected is referred to as the diagnostic coverage.

Diagnostics decrease the overall probability of failure of a SIF by effectively reducing the dangerous failure rate. If a dangerous failure of an SIF component is detected by diagnostics, it can then be converted into a safe failure by configuring the SIF to automatically go to safe state in the presence of a detected failure.

## PFD Calculation

The overall probability of failure calculation, which considers all of the previously described factors, is performed using reliability models such as fault tree analysis, simplified equations, or Markov models to

evaluate each SIF. Industry standards require quantitative verification that the selected SIL targets were achieved for the selected design. While each of the potential methods for performing SIL verification calculations have their strengths and weaknesses, the simplified equation options is primarily used by industry practitioners where possible. In cases where the situation that is being modeled cannot be described using the standard set of simplified equations, more robust – but difficult to employ – tools, such as fault tree analysis are used to support the simplified equations.

Calculation of the overall PFDavg of a SIF begins with use of one of the equations shown below for each subsystem – sensor, logic solver, and final element. The equations used considering the specific failure rates of the analyzed device and the proposed test interval of the subsystem. Some typical failure rates for common instrumentation that is used in safety applications is given in *Appendix G*. The following section contains simplified equations for most common SIS subsystem architectures. More details regarding the equations can be found in *Appendix E*.

## Simplified Equations

**Equations for Probability of Failure on Demand**

**1oo1** $$\mathrm{PFD}_{\mathrm{avg}} = \left[\lambda^{DU} \times \frac{\mathrm{TI}}{2}\right]$$

**1oo1D-NT** $$\mathrm{PFD}_{\mathrm{avg}} = \left[\lambda^{DU} \times \frac{\mathrm{TI}}{2}\right] + \left[\lambda^{SD} + \lambda^{DD} x MTTR\right]$$

**1oo2** $$\mathrm{PFD}_{\mathrm{avg}} = \left[\left(\lambda^{DU}\right)^2 \times \frac{TI^2}{3}\right] + \left[\beta \times \lambda^{DU} \times \frac{TI}{2}\right]$$

**2oo2** $$\mathrm{PFD}_{\mathrm{avg}} = \left[\lambda^{DU} \times TI\right]$$

**2oo3** $$\mathrm{PFD}_{\mathrm{avg}} = \left[(\lambda^{DU})^2 \times (TI)^2\right] + \left[\beta \times \lambda^{DU} \times \frac{TI}{2}\right]$$

**Equations for Spurious Trip Rate (STR)**

**1oo1** $$STR = \lambda^{S} + \lambda^{DD}$$

**1oo1D-NT** $$STR = \lambda^{SU}$$

**1oo2** $$STR = 2(\lambda^{S} + \lambda^{DD})$$

**2oo2** $$STR = \left[2(\lambda^{S} + \lambda^{DD})^2 \times MTTR\right] + \left[\beta\left(\lambda^{S} + \lambda^{DD}\right)\right]$$

**2oo3** $$STR = \left[6(\lambda^{S} + \lambda^{DD})^2 \times MTTR\right] + \left[\beta\left(\lambda^{S} + \lambda^{DD}\right)\right]$$

# Safety Requirements Specifications

The "Safety Requirements Specifications" task is the next step in the Safety Lifecycle. The Safety Requirements Specifications (SRS) development occurs at the end of the Conceptual Design/SIL Verification phase – after the proposed design has been confirmed to achieve its target. The objective of the SRS is to define both functional and performance related requirements for the SRS. The SRS is prepared in enough detail that the functionality of the entire SIS (particularly the logic solver) is defined in sufficient rigor that detailed design engineering tasks can proceed (typically by a different group than prepare the SRS package).

The IEC 61511 / ISA 84.00.01-2004 standard provides a listing of the information that should be documented, or at least considered during this phase. This information includes the following items:

- A description of all the safety instrumented functions necessary to achieve the required functional safety
- Requirements to identify and take account of common cause failures
- A definition of the safe state of the process for each identified safety instrumented function
- A definition of any individually safe process states which, when occurring concurrently, create a separate hazard (for example, overload of emergency storage, multiple relief to flare system)
- The assumed sources of demand and demand rate on the safety instrumented function
- Requirement for proof-test intervals
- Response time requirements for the SIS to bring the process to a safe state
- The safety integrity level and mode of operation (demand/continuous) for each safety instrumented function
- A description of SIS process measurements and their trip points
- A description of SIS process output actions and the criteria for successful operation, for example, requirements for tight shut-off valves
- The functional relationship between process inputs and outputs, including logic, mathematical functions and any required permissives
- Requirements for manual shutdown
- Requirements relating to energize or de-energize to trip
- Requirements for resetting the SIS after a shutdown
- Maximum allowable spurious trip rate
- Failure modes and desired response of the SIS (for example, alarms, automatic shutdown)
- Any specific requirements related to the procedures for starting up and restarting the SIS

- All interfaces between the SIS and any other system (including the BPCS and operators)
- A description of the modes of operation of the plant and identification of the safety instrumented functions required to operate within each mode
- The application software safety requirements
- Requirements for overrides/inhibits/bypasses including how they will be cleared
- The specification of any action necessary to achieve or maintain a safe state in the event of fault(s) being detected in the SIS. Any such action shall be determined taking account of all relevant human factors
- The mean time to repair which is feasible for the SIS, taking into account the travel time, location, spares holding, service contracts, environmental constraints
- Identification of the dangerous combinations of output states of the SIS that need to be avoided
- The extremes of all environmental conditions that are likely to be encountered by the SIS shall be identified. This may require consideration of the following: temperature, humidity, contaminants, grounding, electromagnetic interference/radiofrequency interference (EMI/RFI), shock/vibration, electrostatic discharge, electrical area classification, flooding, lightning, and other related factors
- Identification of normal and abnormal modes for both the plant as a whole (for example, plant start-up) and individual plant operational procedures (for example, equipment maintenance, sensor calibration and/or repair). Additional safety instrumented functions may be required to support these modes of operation
- Definition of the requirements for any safety instrumented function necessary to survive a major accident event, for example, time required for a valve to remain operational in the event of a fire

While all of the information described above must be developed to fully define a SIS, it is not good practice to attempt to combine all of the information into a single document. Often, engineers who are new to SIS, have not had significant experience in specification of instrumentation and control system, and use a reading of the standards as their only basis for how to specify control systems erroneously attempt to use IEC 61511 / ISA 84.00.01 as a design guideline instead of the collection of requirements that it is. This often results in an SRS document that uses the list of bullet items shown above as an "outline" and then proceeds to "fill in the blank" for each SIF. This process usually yields poor results. The documents are difficult for systems integrators and equipment vendors to use, as they do not present a comprehensive view of the system, and also include large amounts of repetitive data that is not useful to system designers, and often does not get updated when subsequent changes occur.

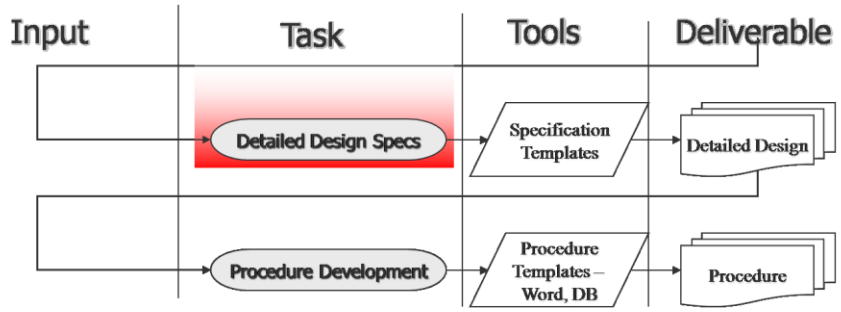
A much better approach is to provide a more comprehensive package that describes an entire SIS. This type of package typically contains a functional logic description, often in the concise and easy-to-use cause and effect diagram format. A collection of requirements that are uniformly applied to all SIF – such as bypass requirements and failure response actions are best contained in a single "general requirements" document. Finally, complexities of the system that are unique to a single SIF and too complicated to be explained in the context of the functional logic description (e.g., cause and effect diagram) can be described in a specific notes document.

Using this methodology, a holistic system view is provided, repetition of information is minimized, and information that is not relevant to the users of the SRS package (such as SIL selection details) are not

included. Instead, the general requirements section simply refers to the other project documents in which this additional information is contained.

Once the SRS package has been prepared, it can be provided to detailed design contractors and equipment vendors. These groups can then implement a system that is consistent with the Safety Integrity Levels that were selected in previous Safety Lifecycle steps. A good SRS package will allow contractors and vendors to provide equipment bids and perform their detailed design tasks with minimal additional input from the SIS design basis team.

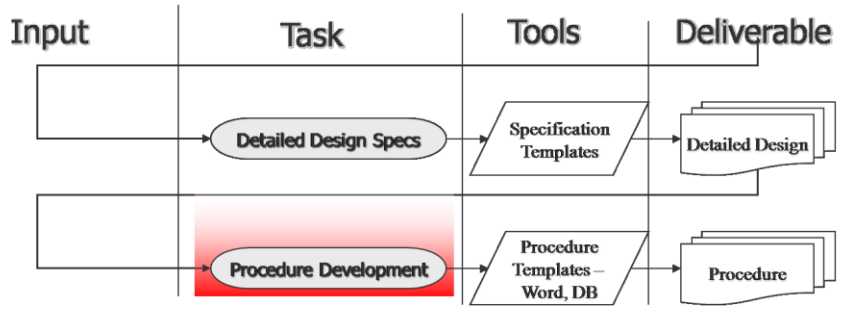
# Detailed Design and Specifications




The "Detailed Engineering Design and Specification" phase occurs after the SIS Design Basis team has completed the Safety Requirements Specification, which then serves as the basis for all subsequent design tasks. In this step, the design of a SIS is very similar to the design of other non-safety related control systems. Some of the tasks that are performed during this phase include the following:

- Development of instrumentation specifications and requisitions
- Development of loop sheets
- Development of logic solver system input/output lists
- Development of logic solver system cabinet layout
- Development of logic solver cabinet internal wiring diagrams
- Preparation of interconnecting wiring diagrams and cable schedules
- Development of PLC programs

# Procedure Development




The next step in the Safety Lifecycle is "Procedure Development". By this we mean Operations Procedures, as well as procedures for maintenance and testing of the Safety Instrumented System.

Procedures should address various modes of operations of the Safety Instrumented System, including startup, bypass, and reset operations. Procedures should address manual response to detected failures of the Safety Instrumented System. Procedures should also include maintenance and testing requirements of the Safety Instrumented System, and functional testing requirements to achieve the required Safety Integrity Level. The functional test interval must be consistent with the Safety Requirements Specifications that were identified earlier in the Safety Lifecycle.

Before procedures can be written, the end user must establish the preferred philosophy of how the SIS will get tested, maintained and operated. Seemingly minor details can have a major impact on SIS effectiveness.

The end user must determine how each function will be periodically tested. Generally it is preferable to conduct a full functional test whenever practical, which simultaneously tests all components of the SIF starting with the sensing device, through the logic solver and out to the final element. An example of a full functional test is to isolate a pressure transmitter from the process impulse lines, connect a hand pump to the transmitter test port, pressure the sensor to the trip point and confirm the function activated at the correct value. If special requirements exist for the final element (for example, a valve that must achieve Class VI bubble-tight shutoff) the test can be designed to confirm this has also been achieved.

A full functional test has the best chance at discovering covert failures. This, in turn, makes it much easier for the end user to achieve the dangerous failure rate claimed as part of the SIL verification calculations. When a full functional test is not performed the SIL verification calculations must be modified to account for non-ideal test conditions.

An example of an inferior test practice is to connect a signal simulator to the field terminals and drive a signal to the I/O card. This only reveals a small portion of the overall failures in a typical sensing device, those portions related to the line integrity, signal ranging and logic. It does nothing to reveal failure sensor failure modes related to impulse lines, sensing element, transmitter circuit board, transmitter internal settings, firmware and software.

When establishing bypass philosophy, the end user should take into account human factors; in most major accidents accidental or intentional bypassing are cited as key contributing factors.

There is recognized value in being able to temporarily place a sensing element in bypass. If the sensor needs recalibration, maintenance or replacement, a sensor bypass can allow those activities without

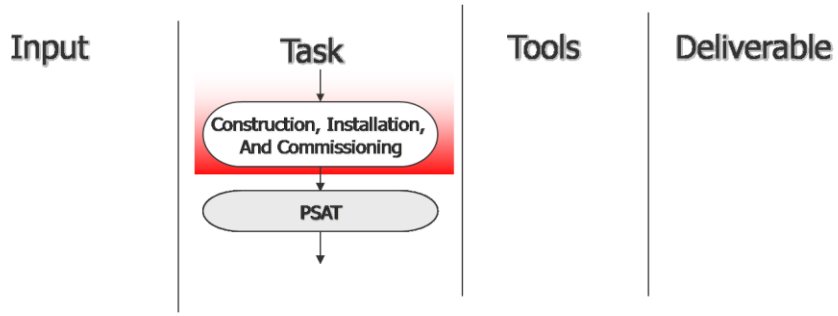
requiring a shutdown. The bypass can be done via software or a hardwired switch, although software is usually more convenient.

When software bypasses are in place and can be activated through the DCS, the SIS-DCS communication must be carefully designed to ensure that the SIS can quickly go from "bypass enabled" to "normal" mode without the operator being required to remove each bypassed sensor by hand. Also, SIS-DCS communication diagnostics must be used that will allow the SIS to function properly in the case of a communication loss between the systems.

The SIS interface should be designed so that the operator, instrument technician and engineer are not capable of bypassing outputs (final elements). Most outputs are activated by multiple different sensors. For example, in a fired heater the fuel supply valves may be closed because of high firebox pressure, high/low fuel gas pressure, high temperature, oxygen/combustible analyzer and fan failures. An abnormal condition in any of these different variables can require the activation of a shutdown. If an output is bypassed, it is effectively bypassing ALL of this critical interlocks simultaneously.

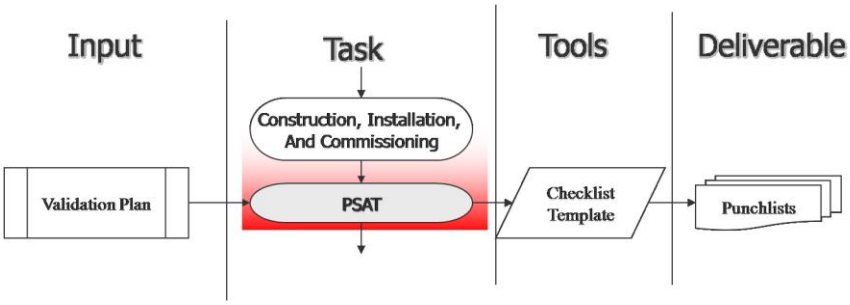
Testing and bypassing philosophy are only two of the many important protocols to establish when considering SIS design. When making these decisions, the user should be aware of their impact on the effectiveness of the system. Whatever philosophy is chosen, the decisions should be made during the early part of the design phase and then implemented in testing procedures.

# Construction, Installation, and Commissioning




The next step of the Safety Lifecycle is the "Construction, Installation, and Commissioning". This step is very similar to other standard (non-SIS) control systems' design, commissioning, and startup activities. It involves purchasing equipment, on-site installation, importing and loading software programs, and connecting wiring. This must be done prior to Pre-Startup Acceptance Testing.

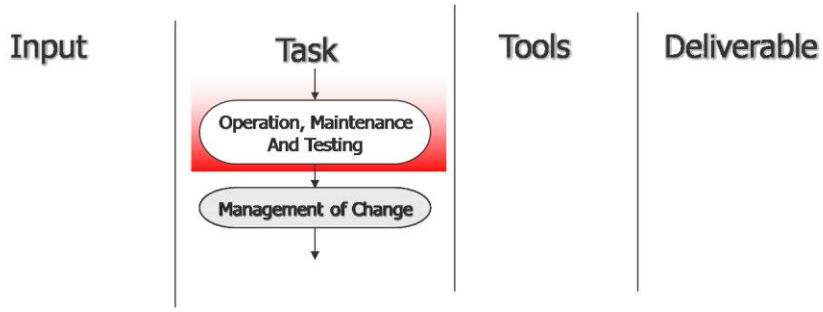
# Pre-Startup Acceptance Testing




"Pre-Startup Acceptance Testing" (PSAT) is the next step in the Safety Lifecycle. In this step, the requirement is to verify that the installed equipment and software conform to the Safety Requirement Specifications (SRS). This is an activity that takes place on site during the commission, installation, and startup activities. Design engineers review the hardware and software to ensure all the requirements that were established in the Safety Requirements Specification were achieved. Relevant deviations should be noted and corrected prior to placing the equipment in service. In addition, a full-functional test of the system is generally required during pre-startup acceptance testing to prove that the system behaves as it was specified in the Safety Requirement Specification.

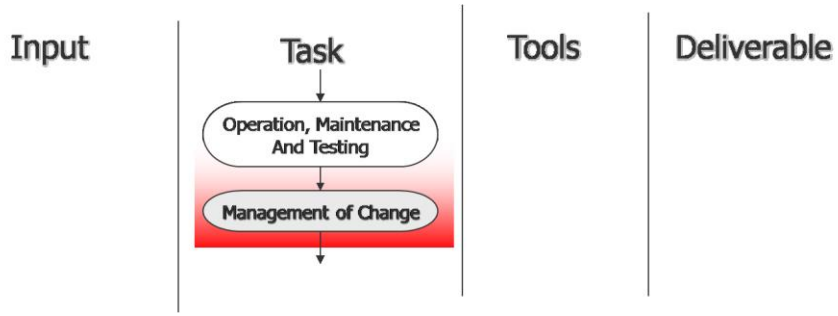
The correct method of conducting a PSAT is to confirm the design is in accordance with the SRS. This is because the SRS contains the critical design decisions, preferences and requirements that form the basis of a well-designed system. If a SIS integrator has misinterpreted a requirement within the SRS, the PSAT is the last chance for the design defect to be discovered and corrected before the system becomes operational. This is also a good reason why a third party who is independent of the SIS integrator, and who has a thorough understanding of the SRS requirements, should conduct the PSAT. The third party will be able to provide an independent assessment of the design and can confirm that the system has been implemented with all of the end user's requirements.

# Operations and Maintenance




The next step is "Operation And Maintenance". During this phase, if all goes as planned, very little activity will occur with respect to the SIS. SIS-related activities include periodic functional testing of the SIS and responding to overt faults of the SIS that are detected with diagnostics. This response will typically include the repair of the failed subsystems.

# Management of Change




Management of Change (MOC) occurs when changes are proposed to the Safety Instrumented System, that are not like-in-kind changes. Site Management of Change procedures should be followed to adequately evaluate and address those changes prior to implementation, in order to identify any potential hazards that could result from those changes. This step is important to ensure that the modifications are consistent with the Safety Requirements Specification (SRS), and preserve the required Safety Integrity Levels.

When a change occurs in the system the new components are likely to have different failure rates and diagnostic coverage from the original. If this is true, the existing SIL verification calculations are incorrect and verifying that the new components are capable of achieving the required SIL is the first step in the MOC process. Depending on the new component, the new Safety Instrumented Function (SIF) design may be able to achieve the existing SIL or it may not. If it does not the testing frequency may be adjusted, additional instrumentation may be required or other portions of the SIF may require modification.

After the new SIL verification calculations are complete, the hardware should be reviewed to make sure it is able to meet all requirements determined as part of the SRS. If the new hardware has additional requirements, or does not meet some of the existing SRS requirements, the SRS must be modified to account for this.

Sometimes other factors require an MOC for part of the SIS. For example, if corporate risk tolerance guidelines change it could affect the implementation of many SIFs. In such a case the SIL selection process must be reviewed to establish (or confirm) SILs for the functions. If a quantitative risk analysis is performed that supplies more accurate information about a specific hazard the SIF for the function may change in relation to the analysis results. A final example is where a protection layer claimed during SIL selection is less (or more) effective than claimed, based on updated data. When this occurs the SIL selection results must be reviewed to determine new SILs for the affected functions. Any of the examples mentioned could require instrument addition, instrument modification or new functional test intervals.

For this reason the SIL selection reports should be reviewed and revalidated periodically (at the same frequency that is suggested for PHA revalidations – five years) to ensure that the selected SILs are consistent with current corporate philosophy, industry best practices and most accurate modeling data.

# Conclusions

Safety Instrumented Systems are used in process plants to reduce risk – not to eliminate risk – but to reduce it to what is deemed to be a tolerable level by the operator of that plant. In the United States, regulations from OSHA, as well as EPA, govern the design, testing, maintenance, and operation of Safety Instrumented Systems. You should know the requirements of these regulations before you begin a Safety Instrumented System design project. Most companies have some type of program for design and implementation of Safety Instrumented Systems. Increasingly, companies are conforming to the SIS engineering standards from ISA and IEC. The new standards are performance-based, rather than prescriptive. They require you to set performance levels, or goals, to be achieved by SIS engineering design, rather than prescribing what that design should look like.

This handbook has presented a summary of the SIS Engineering Design Lifecycle. Before your facility implements this lifecycle, it should be carefully considered and understood. Safety Instrumented Functions in existing or new process designs require analysis to identify the functions, and address Safety Integrity Level requirements for each function. Safety Integrity Levels can be optimized to account for likely initiating events and reasonable safeguards, thereby identifying a design that meets safety objectives without unnecessary equipment and instrumentation.

Replacement of existing hardware is not required by the standards, and in many cases, is not warranted. An analysis of Safety Integrity Level requirements is necessary, and in some cases – in fact, many cases – existing equipment can be demonstrated to achieve the Safety Integrity Level targets that are required by your company.

Although in many cases existing equipment is sufficient to achieve Safety Integrity Levels, for some functions equipment modification or addition may be necessary. This additional cost is always minimized by implementing these changes at the start of the design phase. Many "horror stories" describing the difficulty of implementing IEC 61511 / ISA 84.00.01 are because it was implemented in the middle of an extensive project, or after the field design was finalized. Just like with proper process design, proper Safety Instrumented System design should be done at the start of the project, not as an afterthought.

# Appendix A – Acronyms

| | |
|---|---|
| BPCS | Basic Process Control System |
| CMS | Consequence Mitigation System |
| DCS | Distributed Control System |
| EPA | Environmental Protection Agency (USA) |
| HAZOP | Hazards and Operability Study |
| HSE | Health, Safety, and Environmental |
| HSE | Health and Safety Executive (UK) |
| IEC | International Electrotechnical Commission |
| ISA | International Society for Automation |
| IPL | Independent Protection Layer |
| HIPPS | High Integrity Pressure Protection System |
| LOPA | Layer of Protection Analysis |
| NFPA | National Fire Protection Association |
| OSHA | Occupational Safety and Health Administration (USA) |
| PFD | Probability of Failure on Demand |
| P&ID | Piping and Instrumentation Diagram |
| PHA | Process Hazards Analysis |
| PLC | Programmable Logic Controller |
| PRV | Pressure Relief Valve |
| PSV | Pressure Safety Valve |
| SIL | Safety Integrity Level |
| SIS | Safety Instrumented System |
| SOP | Standard Operating Procedure |
| TMEL | Target Maximum Event Likelihood |

# Appendix B – Definitions

| | |
|---|---|
| % Safe Failures | Means the factor used to divide the overall failure rate for a device into safe failures (i.e., failures of a device that tend toward initiating a trip condition) and dangerous failures (i.e., failures of a device that tend toward inhibiting a trip condition). This is different from the Safe Failure Fraction (SFF) as defined by IEC 61508 and IEC 61511 that includes dangerous failures that can be detected. |
| Architectural Constraints | Limitations imposed on the components and architecture selected for implementation of a safety-instrumented function, regardless of the performance calculated for a subsystem in terms of $PFD_{avg}$. Constraints are specified (in IEC 61508-2-Table 2 and IEC 61511-Table 5) and require minimum degrees fault tolerance. Architectural constraints are established according to the required SIL of the subsystem (i.e., sensors, logic solvers, final elements), "type" of components used, and Safe Failure Fraction (SFF) of the subsystem's components. Type A components are simple devices not incorporating microprocessors whose failure modes are well understood, and Type B devices are complex devices such as those incorporating microprocessors. |
| Availability | Is the calculated probability that a device is operating successfully at a given moment in time. This is a measure of the "uptime", that considers detectability and repairability of the failure in addition to its failure rate. |
| Beta Factor (β) | The percent of the failures for a specified device that attributed to common cause failure modes. |
| Common Cause | Refers to failures that render two or more devices in a failed state based on a single failure event. The single failure event may be either internal or external to the system |
| Cd | Diagnostic coverage of dangerous failures. The ability of a system to detect and diagnose failures that have or will cause a device to fail to a dangerous state. |
| Cs | Diagnostic coverage of safe failures. The ability of a system to detect and diagnose failures that have or will cause a device to fail to a safe state. |
| Diagnostic Coverage | A measure of a system's ability to self-detect failures. For SIS with active fault detection capabilities, this is a ratio between the failure rate for detected failures to the failure rate for all failures in the system. |
| Demand | A condition or event that requires the SIS to take action to prevent a hazardous event from occurring. |

| | |
|---|---|
| DTT | Deenergize-To-Trip means SIS outputs and devices are energized under normal operation. Removal of the source of power (e.g., electricity, air) causes a trip. |
| ETT | Energize-To-Trip. SIS outputs and devices are de-energized under normal operation. Application of power (e.g., electricity, air) causes a trip. |
| Failure Category | A device can fail in any one of four failure categories that describe the direction of the failure (safe or dangerous) and the ability of the failure to be diagnosed: Safe Detected (SD), Dangerous Detected (DD), Safe Undetected (SU), and Dangerous Undetected (DU) as per ISA TR84.0.02 |
| Fault Tolerance | Ability of a subsystem (sensors, logic solvers, final elements) to continue to perform a required function in the presence a limited number of equipment faults. |
| Fail-safe | The capability of a Safety Instrumented Function to go to a predetermined safe state in the event of a specific malfunction, especially loss of electrical or pneumatic energy. |
| FMEDA | Failure Modes Effects and Diagnostics Analysis means an analysis of the failure modes for an equipment item, the effects of those failure modes, and the ability of the device to diagnose failures. This is a method for determining failure rates, Safe Failure Fraction (SFF), and diagnostic coverage, requirements for certification of equipment to the requirements of IEC 61508. |
| MTTF | Mean Time to Failure is the average amount of time that elapses between putting a system into service and when that system fails. |
| $MTTF^{SPURIOUS}$ | Mean Time to Fail Spurious is the average time until a failure of the system causes a process trip when no actual trip conditions are present. This is called a spurious trip because it implies a failure of the instrumentation and control system, but one in the "safe" direction. |
| MTTR | Mean Time to Repair is the calculated average time to repair a failed component from the time of detection to the time to complete the repair and restore the component to service. |
| Proof Test Coverage | The percentage failures that are detected and repaired during the proof test of equipment. A 100% proof test coverage means the system is restored to full working order, and theoretical zero probability of failure immediately after the system is restored to service. |
| Proof Test Interval | The time interval between proof tests of an equipment item or function. |
| PFD | Probability of Failure on Demand means the probability that a Safety Instrumented Function will fail dangerously, and not be |

| | |
|---|---|
| | able to perform its safety function when required. PFD can be determined as an average probability or maximum probability over a specified time period, which is usually the proof test interval. IEC 61508/61511 and ISA 84.01 use average PFD as the system metric upon which the achieved SIL for a Safety Instrumented Function is defined. PFD is related to the amount of risk reduction that is provided by a Safety Instrumented Function. |
| Random Hardware Failure | A failure occurring at random time, which results from one or more of the possible degradation mechanisms in the hardware. Random hardware failures are not the result of human failures in the design, programming, or maintenance of the device. |
| Redundancy | The use of multiple components to perform the same function. Redundancy can be implemented by identical elements (identical redundancy) or by diverse elements (diverse redundancy). Redundancy is primarily used to improve reliability or availability. |
| Reliability | Is the probability that a device can perform its intended function under stated conditions for a given period of time without failure. |
| RRF | Risk Reduction Factor for a Safety Instrumented Function is the mathematical inverse of PFDavg of that function. It is a measure of the amount of risk reduction provided by a Safety Instrumented Function given that the function is used in a preventive manner and has 100% diagnostic coverage of the process conditions that will result in a process hazard. RRF equal to 100 implies that the Safety Instrumented Function provides a calculated risk reduction of a factor of 100. |
| SFF | Safe Failure Fraction means the fraction of the overall failure rate of a device that results in either a safe failure or a diagnosed (i.e., detected) unsafe failure. The safe failure fraction calculation includes detectable dangerous failures when those failures are annunciated and either a repair occurs or the process is shutdown upon detection of the fault. This term is strictly defined in IEC 61508 and is a critical portion of safety equipment certification processes. |
| SIF | A safety instrumented function (SIF) is a set of specific actions to be taken under specific circumstances, which will move the chemical process from a potentially unsafe state to a safe state.<br><br>In order to adequately define a SIF, the following six considerations need to be addressed:<br><br>i. The hazard that is being prevented or mitigated by the SIF<br><br>ii. Initiating event(s) or causes of the hazard<br><br>iii. Inputs, or ways to detect all initiating events |

iv. Logic connecting inputs and outputs

v. Outputs, or actions needed to bring the process into a safe state

Timing required to bring the process into a safe state once the potential hazard is detected by the inputs

SIL — Safety Integrity Level is a quantitative measure of the effectiveness of a Safety Instrumented Function. SIL is defined by ISA 84.00.01 and IEC 61511/61508 as order of magnitude bands of PFD as shown below.

| Safety Integrity Level (SIL) | Average Probability of Failure on Demand ($PFD_{avg}$) | Risk Reduction Factor |
|---|---|---|
| 4 | $10^{-4}$ to $10^{-5}$ | 10,000 to 100,000 |
| 3 | $10^{-3}$ to $10^{-4}$ | 1,000 to 10,000 |
| 2 | $10^{-2}$ to $10^{-3}$ | 100 to 1,000 |
| 1 | $10^{-1}$ to $10^{-2}$ | 10 to 100 |

Safety Instrumented System is the implementation of one or more Safety Instrumented Functions. A SIS is a system composed of any combination of sensor(s), logic solver(s), and final element(s).

Refers to the shutdown of the process for reasons not associated with a problem in the process that the SIS is designed to protect (e.g., the trip resulted due to a hardware fault, software fault, transient, ground plane interference, etc.). Other terms used include nuisance trip and false shutdown.

Redundant system (e.g., m out of n, one out of two [1oo2] to trip, two out of three [2oo3] to trip, etc.) which requires at least m of n channels to be in agreement before the SIS can take action.

# Appendix C – Typical Initiating Event Frequencies

Some common independent protection layers and typical effectiveness credits are shown below.

| **Initiating Event** | **Likelihood of Failure (Events per Year)** |
|---|---|
| BPCS instrument loop failure, including sensor, controller, and final element. Includes equipment failure as well as operational error.<br>Note: IEC 61511 limits the likelihood of BPCS failure to no less than 9E-2/yr (IEC, 2003) | $10^{-1}$ |
| Operator error to execute routine procedure, assuming well trained, unstressed, not fatigued. | $10^{-2}$<br>per opportunity |
| Failure of preparation for maintenance or return of plant from maintenance LOTO (lock-out tag-out) procedure failure | $10^{-3}$<br>per opportunity |
| Pump Failure (single pump normally running) due to mechanical problems. Does not include loss of power. | $10^{-1}$<br>(or higher based on site experience) |
| Compressor or blower failure due to mechanical problems. Does not include loss of power. | $10^{-1}$<br>(or higher based on site experience) |
| Regulator (e.g., self-contained pressure regulator) failure | $10^{-1}$ |
| Cooling water failure (redundant CW pumps, diverse drivers) | $10^{-1}$ |
| Loss of Power (redundant power supplies) | $10^{-1}$ |
| Fixed Equipment Failure (E.g. exchanger tube failure) | $10^{-2}$ |
| Pressure vessel failure | $10^{-6}$ |
| Piping failure – 100 meter section – Full Breach | $10^{-5}$ |
| Piping leak – 100 m | $10^{-3}$ |
| Atmospheric tank failure | $10^{-3}$ |
| Gasket / packing blowout | $10^{-2}$ |
| Unloading / loading hose failure | $10^{-1}$ |
| Other Initiating Events | Develop using experience of team |

# Appendix D – Typical Protection Layers

Some common independent protection layers and typical effectiveness credits are shown below.

**Suggested Risk Reduction for Independent Protection Layers**

| IPL | Further Restrictions on Considering as IPL | IPL (Typical) |
|---|---|---|
| Operator Intervention using Operating Procedures | The action should be independent from the initiating cause and any other IPL. If an operator action is the initiating cause, no IPL should be assigned to any operator action that solely relies on the same operator to recognize problem and quickly correct it. If the initiating cause is the BPCS, no IPL should be assigned to any operator action that solely relies on BPCS information display (e.g., process conditions, indications). | |
| | Process Related Rounds and Inspections. Frequency of operator rounds should be sufficient to detect potential incident. If recognition of process variable is required, the operator should log specific values from sensors or valves independent of the initiating cause. Log should show unacceptable out-of-range values. SOP should describe response to out-of-range values. | 1 |
| | Observational. Frequency of operator rounds should be sufficient to detect potential incident and mitigate ultimate scenario. Impending incident should be obvious to operator through normal visual or hearing range, i.e. loud noise, high vibration, serious leaking, etc. | 1 |
| | Review: Independent, supervisory review and sign-off that work is complete and correct prior to start-up or returning component to service. | 1 |
| | Action: An operator action that uses a different operator, relying on independent observation. | 1 |
| | Corrective Action: An operator action taken based on a scenario where the event propagation is sufficiently slow that the operator has enough time to recognize the error and to correct it. | 1 |
| | Alarm: The alarm with operator response should be examined to ensure that it is independent from the initiating cause and any other IPL. This includes not only independent field instrumentation but also an independent channel in the BPCS and independent of the operator (different operator). Only one BPCS-based alarm or BPCS function can be used as an IPL.<br>The IPL credit associated with alarms with operator response is based on the amount of time available for action and the location of the response. See Operator Time Restrictions Table for more information. | See Table 6 |
| Basic Process Control System (BPCS) | The BPCS should be independent of the initiating cause and any other IPL. If the initiating cause is a BPCS control loop, another control loop within the BPCS should not be designated as an IPL, unless a detailed study of the BPCS is performed to ensure sufficient independence and redundancy in order to address common cause failure. The IPL credit associated with a BPCS IPL is limited to 1 per IEC 61511. | |
| | Control loops normal action will mitigate the scenario. The BPCS IPL should run in automatic mode during all operational phases where the accident scenario exists. | 1 |
| | BPCS interlocks (interlocks NOT implemented in a separate, dedicated logic solver) where all causes can be verified as independent of failure of the BPCS logic solver | 1 |
| | BPCS interlocks (interlocks NOT implemented in a separate, dedicated logic solver) where all causes can NOT be verified as independent of failure of the BPCS logic solver | 0 |

| IPL | Further Restrictions on Considering as IPL | IPL (Typical) |
|---|---|---|
| Other/Local | The IPL should be independent of initiating cause and any other IPL. It should be designed to mitigate the scenario. | |
| Check Valve | Single check valve. | (none) |
| | Dual check valves in series. | 1 |
| Flame Arrester | Should be designed to mitigate the scenario. | 1 or 2 |
| Vacuum Breaker | Should be designed to mitigate the scenario. | 1 or 2 |
| Restrictive Orifice | Should be designed to mitigate the scenario. | 1 or 2 |
| Pressure Regulator | Should be designed to mitigate the scenario. | 1 |
| Special Personnel Protection Equipment | Special personnel protection equipment that is not normally worn by operation or maintenance personnel, but is part of an established procedure. This PPE would include wire mesh gloves, fire suits, respirators, self-contained breathing apparatus, etc. The user of the equipment should be trained in the use of the PPE. | 1 |
| Safety Instrumented System | Should be independent of the BPCS. IPL credit is based on the SIL that is achieved by the complete functional loop. | |
| | SIL 1 | 1 |
| | SIL 2 | 2 |
| | SIL 3 | 3 |

## Suggested Risk Reduction for Operator Response as an IPL

For all listings in the table below. The alarm and operator response should be evaluated to ensure that the components and actions are independent from the initiating cause. In all cases, the alarm should not be operator re-settable. The operator response time should consider the time it takes to recognize the alarm, to diagnose the problem, and to fully initiate action. This is compared to the process time which considers how rapidly the process moves from the alarm condition to the incident condition.

| Time (min) | Where | How Many | Restrictions | IPL (Typical) |
|---|---|---|---|---|
| <10 | Any | Any | Operator should troubleshoot the alarm and determine appropriate response. | (none) |
| 2 to 10 | Control Room | Single Operator | Drilled response, also known as a "**never exceed, never deviate**" response. If the alarm is received, the operator should execute a specific action every time without delay. Staffing should also be adequate so that there is an operator present at all times to respond to the alarm. If the operator response is to troubleshoot the alarm, less than 10 minutes is not an adequate amount of time and no IPL credit should be taken. | 1 |
| >10 | Control Room | Single Operator | Operator action is complicated, i.e. large number of alarms generated by initiating cause and the response is not clear or documented. | (none) |
| >10 | Control Room | Single Operator | The operator is trained on alarm response, has procedures available to examine and practices the action periodically. | 1 |
| >10 | Control Room | Two Operators | All operators listed should receive the same information. Both operators can make independent responses, which completely mitigate the event. Alarm should not be operator re-settable. The operators are trained on alarm response, have procedures available to examine and practices the action periodically. | 2 |
| >30 | Field | Single Operator | The operator is trained on alarm response, has procedures available to examine and practices the action periodically. | 1 |
| >30 | Field | Two Operators | All operators listed should receive the same information. Both operators can make independent responses, which should completely mitigate the event. Alarm should not be operator re-settable. The operator is trained on alarm response, has procedures available to examine and practices the action periodically. | 2 |

## Table 7 : Suggested Risk Reduction for Consequence Mitigation Systems (CMS)

| CMS | Further Restrictions on Considering as IPL | IPL (Typical) |
|---|---|---|
| Pressure Relief Valve | Clean Service. PRV should be sized to completely mitigate the scenario. | 2 |
| | More than one PRV is available to mitigate overpressure scenario. Each PRV listed should be capable of independently relieving the overpressure. Each PRV should be sized to completely mitigate the scenario. | 2 or 3 |
| | More than one PRV is available, but more than one is required to mitigate the full load. This includes staged release PRVs. To achieve higher credit than 1 IPL, the PRV calculations should be reviewed to determine whether the load can be successfully handled by each PRV, based on the specific scenario under review. | 1 |
| | Plugging Service, i.e. prone to plugging, polymerization, deposition, or has a history of failure to operate properly when tested. An unprotected PRV used in a plugging service is not considered sufficient for consideration as an IPL. | (none) |
| | Plugging Service, i.e. prone to plugging, polymerization, deposition, or has a history of failure to operate properly when tested. Redundant Pressure Relief Valves with separate process connections. Each PRV should be sized to completely mitigate the event. | 1 |
| | Plugging Service, i.e. prone to plugging, polymerization, deposition, or has a history of failure to operate properly when tested. Pressure Relief Valve with integrated rupture disk. PRV should be sized to completely mitigate the scenario. | 1 |
| | Plugging Service, i.e. prone to plugging, polymerization, deposition, or has a history of failure to operate properly when tested. Pressure Relief Valve with integrated rupture disk with purging. PRV should be sized to completely mitigate the scenario. | 1 or 2 |
| Vessel Rupture Disk | Should be designed to mitigate scenario. Release should be evaluated for potential risk. | 2 |
| Blast-wall/Bunker | Process-related blast wall. This is not related to the control room design. The blast wall is typically designed to direct/contain the explosion away from the main process unit. | Seek Guidance |

# Appendix E – PFDavg and Spurious Trip Rate Simplified Equations

This section contains simplified equations, generally as presented in ISA technical report 84.00.02 for the calculation of the average probability of failure on demand for SIF and SIF subsystems. The correct application of these equations is contingent upon the following assumptions about the system design:

**General Assumptions Applying to Calculation Methods**

- The sensor failure rate is comprised of all components of the sensor. This includes sensing element, other internal electronic and pneumatic systems, and transmitter. It also includes field wiring and interposing terminations and/or termination assemblies, up to but not including the input module of the logic solver.

- Sensor failure rates listed in this book generally do NOT include special external components such as isolation barriers, external signal conditioners, external signal transducers, signal repeaters and other similar hardware. If these devices are utilized their failure rates should be determined and incorporated with the sensor failure rate to determine the failure rate of all components within the sensor loop.

- The logic solver failure rate is comprised of all components of the SIS control system. This includes input and output I/O modules, processor(s), power supplies and other equipment that can affect the functionality of the SIF.

- The final element interface failure rate is comprised of all components of the final element interface. This includes output module of the logic solver to the electronic component(s) used in the SIF.

- The final element failure rate is comprised of all components between the final element interface and the final control element used to affect a safe state in the process (e.g., typically process valve(s) or motors).

- Failure rates for final element and final element interface devices listed in this book generally do NOT include special external components such as isolation barriers, external transducers, repeaters and other similar hardware. If these devices are utilized their failure rates should be determined and incorporated with the failure rate of the other components within the final element loop.

- Failure rates included in calculations are constant over the functional test period. Wear-in and wear-out failures are not included in the calculations.

- Failure rates for redundant components used within a Sensor Voting Group are identical. Failure rates are for a single element of the system. If the voting configuration is 2oo3 transmitters, the failure rate should NOT be three times the single transmitter value.

- The Test Interval (TI) happens much more frequently than the device Mean Time To Failure (MTTF).

- The Mean Time To Repair (MTTR) is assumed to include both the time to detect and the time to repair (i.e., Mean Time to Detect is assumed to be very short) be shorter than the Mean Time To Failure (MTTF) in this procedure.

- A successful test, or any kind of maintenance done to the system is 100% effective, i.e., a full functional test results in a "good as new system".

- Final elements are designed, configured and installed to fail in the safe state. As an example, a valve that must close to stop steam supply to a reboiler is designed fail closed.

- Failures of prime drivers that operate equipment such as pumps, blowers, compressors, (i.e., electrical motors or turbine drivers) are assumed to be to the de-energized state, and failures of prime drivers are not included in the PFD or MTTFS calculations.

- When power supply failures occur they place the system in a de-energized condition. When a dangerous detected failure occurs, either the SIS takes immediate automatic action to move the process to a safe state before a demand occurs, or the logic solver annunciates the failure and degrades to a mode of operation where the process continues to be monitored and the SIS is capable of taking the safety action automatically, if required to do so.

- Unless otherwise noted, it is assumed that when equipment diagnostics detect a hardware failure, the SIS will either take automatic action to move the process to a safe state before a demand occurs, (i.e., instantaneous or with minimal delay), or the logic solver will annunciate the failure and degrade to a mode of operation where the process continues to be monitored and the SIS is capable of taking the safety action automatically if a demand were placed upon it during the period of time prior to restoring the system to a fully functional status.

**Simplified Equations for $PFD_{avg}$**

A SIF may be considered to be composed of four key components, or subsystems: The sensor, the logic solver, the final element and the final element interface.

The sensor is the subsystem that detects and relays a process parameter to the SIS. Examples of sensors include a pressure transmitter, a level switch or a thermocouple. When there are multiple sensors that vote to take a safety action, the sensor subsystem consists of all the sensing elements.

The logic solver is the subsystem that executes the logic to take safety action. The logic solver is often some type of PLC, although if a relay, or network of relays, is used instead of a PLC then those relays could be considered a logic solver and modeled accordingly.

The final element is the subsystem that takes action to place the process in a safe state, and that is in close contact to the process. An example of a final element is a valve that stops fuel gas supply to a heater, or a compressor "Trip and Throttle" valve that stops a compressor turbine. It is frequently the output of the SIS that "touches" the process.

The final element interface is the subsystem that is frequently used to interface between the logic solver and the final element. Examples include a solenoid valve that directs the safety valve to vent its air, or an electromechanical relay contact that stops a motor.

Although one could model the final element to include the interface as part of the final element failure rate, there are times when it is simpler to think of the interface separately from the final element. For example, if there is a single solenoid that closes two valves (in series) as part of the safety function. The solenoid effectively votes 1oo1 but the valves effectively vote 1oo2.

$PFD_{avg}$ is calculated separately for sensor, final element, final element interface, and logic solver portions of the SIF. The overall $PFD_{avg}$ for the SIF being evaluated is obtained by summing the individual components. The result is the $PFD_{avg}$ for the Safety Instrumented Function.

$$\mathrm{PFD}_{avg,SIF} = PFD_{avg,Sensor} + PFD_{avg,LogicSolver} + PFD_{avg,FinalElement} + PFD_{avg,FinalElementInterface}$$

For simple systems, the PFD formulae to use for each subsystem depend on the voting arrangement within that subsystem. Thus, for a given function you may need to insert the 2oo3 voting formula for the sensors, the 1oo1 voting formula for the logic solver subsystem, and the 1oo2 voting formula for the final element and final element interface subsystems.

**1oo1**

$$\mathrm{PFD}_{\mathrm{avg}} = \left[ \lambda^{DU} \times \frac{\mathrm{TI}}{2} \right]$$

$\lambda^{\mathbf{DU}}$ is the dangerous undetected failure rate

**TI** is the time interval between full functional tests of the subsystem.

**1oo1D-NT**

$$\mathrm{PFD}_{\mathrm{avg}} = \left[ \lambda^{DU} \times \frac{\mathrm{TI}}{2} \right] + \left[ \lambda^{SD} + \lambda^{DD} x MTTR \right]$$

$\lambda^{\mathbf{DU}}$ is the dangerous undetected failure rate

$\lambda^{\mathbf{DD}}$ is the dangerous detected failure rate

$\lambda^{\mathbf{SD}}$ is the **safe** detected failure rate

**TI** is the time interval between full functional tests of the component **MTTR** is the mean time to repair any detected failure of the component (safe or dangerous). An MTTR of 72 hours is often assumed, although each site should review their maintenance practices to ascertain whether or not that is practical

This equation assumes that a safe detected or dangerous detected failures of a single component, or channel, in a redundant system results in a alarm condition only (i.e., the system is configured such that diagnosed fault conditions DO NOT place that component, or channel, in a vote to trip condition). Repair actions are assumed to immediately commence and be completed within the MTTR.

**1oo2**

$$\mathrm{PFD}_{\mathrm{avg}} = \left[ \left(\lambda^{DU}\right)^2 \times \frac{TI^{\,2}}{3} \right] + \left[ \beta \times \lambda^{DU} \times \frac{TI}{2} \right]$$

$\lambda^{\mathbf{DU}}$ is the dangerous undetected failure rate

**TI** is the time interval between full functional tests of the component $\beta$ is a parameter with a value between 0 and 1 that represents the fraction of failures that result in all redundant components within a subsystem to be disabled. It is also referred to as the common cause failure fraction. Common cause only affects subsystems with redundant components. Conservative $\beta$ values are 0.1 for sensors and 0.05 for

final elements, unless otherwise specified. Variables that affect common cause include environmental conditions, unanticipated external events and systematic failures.

This equation assumes that a dangerous detected failure of a single component, or channel, in a redundant system results in a trip of the system (i.e., the system is configured such that diagnosed fault conditions place that component, or channel, in a vote to trip condition).

Note: It is an acceptable alternative method to use FTA, and to approximate the first term in this equation using Boolean Mathematics.

**2oo2**

$$\mathrm{PFD}_{\mathrm{avg}} = \left[\lambda^{DU} \times TI\right]$$

$\lambda^{\mathbf{DU}}$ is the dangerous undetected failure rate

**TI** is the time interval between full functional tests of the component

This equation assumes that a dangerous detected failure of a single component, or channel, in a redundant system results in a vote to trip the system (i.e., the system is configured such that diagnosed fault conditions place that component, or channel, in a vote to trip condition)

**2oo3**

$$\mathrm{PFD}_{\mathrm{avg}} = \left[(\lambda^{DU})^2 \times (TI)^2\right] + \left[\beta \times \lambda^{DU} \times \frac{TI}{2}\right]$$

$\lambda^{\mathbf{DU}}$ is the dangerous undetected failure rate

**TI** is the time interval between full functional tests of the component

$\beta$ is a parameter with a value between 0 and 1 that represents the fraction of failures that result in all redundant components within a subsystem to be disabled. It is also referred to as the common cause failure fraction. Common cause only affects subsystems with redundant components. Conservative $\beta$ values are 0.1 for sensors and 0.05 for final elements, unless otherwise specified. Variables that affect common cause include environmental conditions, unanticipated external events and systematic failures.

This equation assumes that a dangerous detected failure of a single component, or channel, in a redundant system results in a vote to trip of the system (i.e., the system is configured such that diagnosed fault conditions place that component, or channel, in a vote to trip condition).

Note: It is an acceptable alternative method to use FTA, and to approximate the first term in this equation using Boolean Mathematics.

**Group Voting Calculations**

Occasionally a subsystem will contain two or more groups of sensors of a non-identical type. As an example, consider a process vessel where low level is a potential hazard, and two DP level transmitters voted 2oo2 could activate the safety function. If that vessel also has a single float level transmitter that independently activates the same function, what is the correct method to determine the overall subsystem PFD?

For a SIF where redundancy across groups is of a non-identical type, then the overall PFD calculations depends on how the groups of sensors are voted. If any single ONE of the sensor groups can independently activate the function, the group logic voting is called 1ooX. If ALL of the sensor groups must vote to activate the function in order to take action, the group logic voting is called XooX.

Once the group logic voting is determined, the calculation of the overall subsystem PFD is straightforward. Equations for the sensor subsystem are:

1ooX Group Logic $$\mathrm{PFD}_{\mathrm{avg}_S} = \prod \mathrm{PFD}_{\mathrm{avg}_{\mathrm{Si}}}$$

XooX Group Logic $$\mathrm{PFD}_{\mathrm{avg}_S} = \sum \mathrm{PFD}_{\mathrm{avg}_{\mathrm{Si}}} - \prod PFD_{avg\,Si}$$

When two or more logic solvers are defined for a SIF, the overall PFDavg calculation for the logic solver subsystem is:

$$\mathrm{PFD}_{\mathrm{avg}_{LS}} = \sum \mathrm{PFD}_{\mathrm{avg}_{\mathrm{LSi}}}$$

When two or more final element groups have been defined for a SIF where redundancy across groups is of a non-identical type, then the overall PFD calculations for the final element subsystem are:

1ooX Group Logic $$\mathrm{PFD}_{\mathrm{avg}_{FE}} = \prod \mathrm{PFD}_{\mathrm{avg}_{\mathrm{FEi}}}$$

XooX Group Logic $$\mathrm{PFD}_{\mathrm{avg}_{FE}} = \sum \mathrm{PFD}_{\mathrm{avg}_{\mathrm{FEi}}} - \prod PFD_{avg\,FEi}$$

**Calculate Achieved Risk Reduction Factor**

The achieved Risk Reduction Factor (RRF) for a SIF is the mathematical inverse of the $PFD_{avg}$ for that SIF. It represents a number corresponding to the factor that the SIF reduces the likelihood of the hazardous event that the SIF intended to prevent.

$$RRF = \frac{1}{PFD_{avg}}$$

**Calculate Spurious Trip Rate STR**

For a SIS the first factor considered is often the PFD, which indicates the likelihood of the system being unavailable when a demand is placed upon it. However, another critical concept in the design of an effective SIS is the frequency at which it shuts the system down accidentally because of a random hardware failure in one or more of the components.

Random hardware failures that place the system in a safe or shutdown state are called "spurious trips," "nuisance trips," or "safe failures." However, in the real word no "safe" failure is truly safe because it often creates a severe process disturbance, and could mean the restart of a complicated and hazardous piece of equipment such as a fired heater or compressor. Because so many accidents occur during unit startups and shutdowns, the minimization of spurious trips is critical to the safe operation of a process plant.

The Spurious Trip Rate is the frequency (measured in per unit time) at which a component in the system will fail and cause a spurious trip. The inverse of the Spurious Trip Rate is called the Mean Time to Failure Spurious ($MTTF^S$), which is the average time between spurious trips for that component or system.

STR is calculated separately for sensor, final element (including final element interface), and logic solver (including power supply) portions of the SIF. The overall STR for the SIF being evaluated is obtained by summing the individual components. The result is the STR for the Safety Instrumented Function.

$$STR_{SIF} = \sum STR_{Si} + \sum STR_{LSi} + \sum STR_{FEi}$$

Note:

$$MTTF^{Spurious} = \frac{1}{STR}$$

**1oo1**

$$STR = \lambda^{S} + \lambda^{DD}$$

$\lambda^S$ is the safe failure rate for the component, including both safe detected $\lambda^{SD}$ and safe undetected $\lambda^{SU}$ failures

$\lambda^{DD}$ is the dangerous detected failure rate for the component

This equation assumes that a safe detected or dangerous detected failure of a single component, or channel, results in a trip of the non-redundant system (i.e., the system is configured such that diagnosed fault conditions place that component, or channel, in a vote to trip condition).

**1oo1D-NT**

$$STR = \lambda^{SU}$$

$\lambda^{SU}$ is the safe undetected failure rate for the component.

This equation assumes that a safe detected or dangerous detected failures of a single component, or channel, in a redundant system results in a alarm condition only (i.e., the system is configured such that diagnosed fault conditions DO NOT place that component, or channel, in a vote to trip condition).

**1oo2**

$$STR = 2(\lambda^S + \lambda^{DD})$$

$\lambda^S$ is the safe failure rate for the component, including both safe detected $\lambda^{SD}$ and safe undetected $\lambda^{SU}$ failures

$\lambda^{DD}$ is the dangerous detected failure rate for the component

This equation assumes that a safe detected or dangerous detected failure of a single component, or channel, results in a trip of the redundant system (i.e., the system is configured such that diagnosed fault conditions place that component, or channel, in a vote to trip condition).

**2oo2**

$$STR = \left[2(\lambda^S + \lambda^{DD})^2 \times MTTR\right] + \left[\beta\left(\lambda^S + \lambda^{DD}\right)\right]$$

$\lambda^S$ is the safe failure rate for the component, including both safe detected $\lambda^{SD}$ and safe undetected $\lambda^{SU}$ failures

$\lambda^{DD}$ is the dangerous detected failure rate for the component

MTTR is the mean time to repair any detected failure of the component (safe or dangerous). An MTTR of 72 hours is often assumed, although each site should review their maintenance practices to ascertain whether or not that is practical

$\beta$ is a parameter with a value between 0 and 1 that represents the fraction of failures that result in all redundant components within a subsystem to be disabled. It is also referred to as the common cause failure fraction. Common cause only affects subsystems with redundant components. Conservative $\beta$ values are 0.1 for sensors and 0.05 for final elements, unless otherwise specified. Variables that affect common cause include environmental conditions, unanticipated external events and systematic failures.

**2oo3**

$$STR = \left[6(\lambda^S + \lambda^{DD})^2 \times MTTR\right] + \left[\beta\left(\lambda^S + \lambda^{DD}\right)\right]$$

$\lambda^S$ is the safe failure rate for the component, including both safe detected $\lambda^{SD}$ and safe undetected $\lambda^{SU}$ failures

$\lambda^{DD}$ is the dangerous detected failure rate for the component

MTTR is the mean time to repair any detected failure of the component (safe or dangerous). An MTTR of 72 hours is often assumed, although each site should review their maintenance practices to ascertain whether or not that is practical

$\beta$ is a parameter with a value between 0 and 1 that represents the fraction of failures that result in all redundant components within a subsystem to be disabled. It is also referred to as the common cause failure fraction. Common cause only affects subsystems with redundant components. Conservative $\beta$ values are 0.1 for sensors and 0.05 for final elements, unless otherwise specified. Variables that affect common cause include environmental conditions, unanticipated external events and systematic failures.

# Appendix F – Minimum Fault Tolerance Tables

**Calculate Fault Tolerance Achieved**

Fault tolerance is an expression of the number of faults that a component, a subsystem, an overall SIF can tolerate and continue to perform its intended function in the presence of such faults. Practically speaking, it is measured as an integer number being either 0 (zero degrees of fault tolerance), 1 (one degree of fault tolerance), or 2 (two degrees of fault tolerance). A simplex (non-redundant) system has, by definition, zero degrees of fault tolerance.

For each SIF, the achieved fault tolerance is calculated once for the sensor subsystem, once for the logic solver subsystem, and once for the final element subsystem. These results are compared to the required minimum fault tolerance levels that are specified in IEC 61511 to determine if the required minimum fault tolerance has been achieved. The required minimum fault tolerance per IEC 61511 is a function of the required SIL level and is shown below.

| **Target SIL** | **Required Minimum Fault Tolerance** |
|---|---|
| SIL 1 | 0 |
| SIL 2 | 1 |
| SIL 3 | 2 |

The achieved fault tolerance for each Sensor Group is a function of its architecture (voting):

| **Sub-system Architecture (Voting)** | **Achieved Fault Tolerance** |
|---|---|
| 1oo1 | 0 |
| 1oo1D-NT | 0 |
| 1oo2 | 1 |
| 2oo2 | 0 |
| 2oo3 | 1 |
| 1oo3 | 2 |

If the SIF contains multiple sensor groups (for example, 2oo3 voting on pressure and 1oo2 voting on flow), another step is required to determine achieved fault tolerance. Achieved fault tolerance for a Sensor sub-system is calculated as follows:

| **Sensor Group Logic** | **Achieved Fault Tolerance for Sensor Sub-system** |
|---|---|
| 1oo1 | (no adjustment) |
| 1ooX | Achieved Fault tolerance for the Sensor Subsystem is equal to the mathematical sum of Achieved Fault Tolerance in the Sensor Sub-system plus the number of groups within the Sensor Sub-system less 1. |
| XooX | Achieved Fault tolerance for the Sensor Sub-system is equal to the lowest achieved fault tolerance for any group within the Sensor Sub-system. |

Achieved fault tolerance for each Final Element Group and Final Element sub-system is calculated in the same manner. Achieved Fault Tolerance for the Logic Solver sub-system is typically specified by the manufacturer.

If the achieved fault tolerance does not satisfy the required minimum fault tolerance per IEC 61511, then an alternative procedure for calculating minimum fault tolerance requirements is permitted (and should be used). The IEC 61508 standard defines minimum fault tolerance requirements as follows. Type B devices are described as any device containing a micro-processor. Type A devices are all other devices.

| **Type A Devices** | | | |
|---|---|---|---|
| Safe Failure Fraction | Required Minimum Hardware Fault Tolerance to claim given SIL Achieved | | |
| | 0 | 1 | 2 |
| < 60 % | SIL 1 | SIL 2 | SIL 3 |
| 60 % to 90 % | SIL 2 | SIL 3 | SIL 4 * |
| 90 % to 99 % | SIL 3 | SIL 4 * | SIL 4 * |
| > 99% | SIL 3 | SIL 4 * | SIL 4 * |
| **Type B Devices** | | | |
| Safe Failure Fraction | Required Minimum Hardware Fault Tolerance to claim given SIL Achieved | | |
| | 0 | 1 | 2 |
| < 60 % | Not allowed | SIL 1 | SIL 2 |
| 60 % to 90 % | SIL 1 | SIL 2 | SIL 3 |
| 90 % to 99 % | SIL 2 | SIL 3 | SIL 4 * |
| > 99% | SIL 3 | SIL 4 * | SIL 4 * |

These tables replace the previous table taken from IEC 61511 and are used as an alternate test of achieved fault tolerance. If either IEC 61511 or IEC-61508 requirements for minimum fault tolerance are satisfied, then the conceptual design is suitable and the report can claim the SIL that was required has been achieved.

If required minimum hardware fault tolerance is not satisfied with the above procedure, a recommendation may be necessary to increase hardware fault tolerance in order to claim the achievement of a given SIL. The Project Engineer in consultation with the Project Manager should determine if a claim of proven in use is desirable to reduce the required minimum fault tolerance by one. For all subsystems, except PE logic solvers, the minimum fault tolerance can be reduced by one if the devices used comply with the following

- Hardware selected based on "prior use" (Proven in Use) rather than certification;
- Only allows process related parameter adjustment;
- Adjustments are protected;
- Required SIL of SIF is less than SIL 4.

The Project Engineer should use a standard worksheet for gathering information from the specific client to claim proven in use. The Project Engineer should not claim proven in use based on service history other than the specific customer for which it is desired to make the claim. The standard worksheet is attached.

For the logic solver subsystem, regardless of achieved PFD all Programmable Electronic (PE) logic solvers shall be limited to claim no more than SIL 1 unless the vendor has supplied a certification that the system is capable of SIL 2 or higher performance. This includes single channel as well as redundant (hot standby) type PE logic solvers. Where achievement of SIL 3 is required, certification shall be per a qualified independent authority such as TUV.

# Appendix G –SIS Component Failure Data

This appendix contains typical failure rate data for components that are commonly used in SIS in the process industries. This is intended to represent "typical" performance of these devices, selected, installed, and maintained in a way that is appropriate for their process service. The data is based on a review of a large number of publicly available databases, and numerous confidential data sources from process industry operating companies. All of the data reflects actual process operation, and no "predictive" techniques. These values are for informational purposes, and should not be used in verification calculations unless reviewed against plant operation and historical records of failure rates at a specific process facility.

The failure characteristics shown in the tables presented below include overall failure rate (all modes of failure) in terms of failure per hour, the safe failure percentage, safe diagnostic coverage factor [C(S)], and dangerous coverage factor [C(D)]. It is important to note that the tables provide "Safe Failure Percentage" not "Safe Failure Fraction". As discussed in other sections of this book, the Safe Failure Fraction (as defined in IEC 61511) includes both inherently safe and also diagnosed dangerous failures as safe. The Safe Failure Percentage is more useful for calculation purposes and includes only those failures that are inherently safe.

## Sensor Data

| Item | Failure Rate (per hour) | Safe Failure Percent | C(S) | C(D) |
|---|---|---|---|---|
| Pneumatic Pressure Switch | 2.37E-5 | 83.5 | 0.0 | 0.0 |
| Pneumatic Relay with Pilot | 9.20E-7 | 13.0 | 0.0 | 0.0 |
| Pressure Switch | 6.50E-6 | 41.0 | 0.0 | 0.0 |
| Pressure Transmitter – High Trip | 1.50E-6 | 10.0 | 100.0 | 55.6 |
| Pressure Transmitter – Low Trip | 1.50E-6 | 50.0 | 100.0 | 20.0 |
| Turbine Meter – High Trip | 1.50E-5 | 3.0 | 0.0 | 89.0 |
| Turbine Meter – Low Trip | 1.50E-5 | 90.0 | 97.0 | 0.0 |
| RTD | 4.90E-8 | 81.6 | 100.0 | 0.0 |
| Temperature Switch | 4.00E-6 | 40.0 | 0.0 | 0.0 |
| Temperature Transmitter – High Trip | 5.00E-6 | 30.0 | 100.0 | 50 |
| Temperature Transmitter – Low Trip | 5.00E-6 | 50.0 | 100.0 | 20.0 |
| Thermocouple – High Trip | 1.20E-6 | 0.0 | 100.0 | 97.0 |
| Thermocouple – Low Trip | 1.20E-6 | 95.0 | 100.0 | 0.0 |
| Level Sensor – Capacitance | 4.00E-6 | 50.0 | 0.0 | 0.0 |
| Level Switch – Float/Displacer | 5.00E-6 | 60.0 | 0.0 | 0.0 |
| Level Switch – Piezo-Electric – High Trip | 6.00E-7 | 30.0 | 0.0 | 66.7 |
| Level Switch – Piezo-Electric – Low Trip | 6.00E-7 | 67.0 | 0.0 | 0.0 |
| Level Switch – Pneumatic | 9.00E-7 | 50.0 | 0.0 | 0.0 |
| Level Transmitter – Displacement – High Trip | 7.00E-6 | 10.0 | 100.0 | 50.0 |
| Level Transmitter – Displacement – Low Trip | 7.00E-6 | 60.0 | 100.0 | 10.0 |
| Level Transmitter – Magnetostrictive – High Trip | 1.80E-6 | 50.0 | 100.0 | 50.0 |
| Level Transmitter – Magnetostrictive – Low Trip | 1.80E-6 | 50.0 | 0.0 | 25.0 |
| Level Transmitter – Radar – High Trip | 1.20E-6 | 50.0 | 100.0 | 35.0 |
| Level Transmitter – Radar – Low Trip | 1.20E-6 | 60.0 | 100.0 | 25.0 |
| Flow Switch | 8.00E-6 | 60.0 | 0.0 | 0.0 |
| Flow Transmitter – Coriolis Meter – High Trip | 3.70E-6 | 20.0 | 100.0 | 50.0 |
| Flow Transmitter – Coriolis Meter – Low Trip | 3.70E-6 | 50.0 | 100.0 | 25.0 |
| Flow Transmitter – Magnetostrictive Meter – High Trip | 3.30E-6 | 20.0 | 100.0 | 50.0 |
| Flow Transmitter – Magnetostrictive Meter – Low Trip | 3.30E-6 | 50.0 | 100.0 | 25.0 |
| Flow Transmitter – Vortex Shedding – High Trip | 3.50E-6 | 20.0 | 100.0 | 50.0 |
| Flow Transmitter – Vortex Shedding – Low Trip | 3.50E-6 | 50.0 | 100.0 | 20.0 |
| Flame Scanner – Burner | 6.00E-6 | 50.0 | 0.0 | 0.0 |
| Current Transmitter | 8.30E-6 | 60.0 | 0.0 | 0.0 |
| Proximity Switch | 3.00E-7 | 50.0 | 0.0 | 0.0 |
| Speed Transmitter | 2.00E-6 | 23.0 | 0.0 | 0.0 |

## Logic Solver Data

** Obtain Data from Equipment Vendor

## Final Element Interface Data

| Item | Failure Rate (per hour) | Safe Failure Percent | C(S) | C(D) |
|---|---|---|---|---|
| I/P Transducer | 4.00E-6 | 40.0 | 0.0 | 0.0 |
| Interposing Relay | 2.00E-7 | 20.0 | 0.0 | 0.0 |
| Pneumatic Regulator | 3.00E-6 | 80.0 | 0.0 | 0.0 |
| Solenoid Valve – 2-Way – Deenergize to Trip | 4.00E-6 | 60.0 | 0.0 | 0.0 |
| Solenoid Valve – 3-Way – Deenergize to Trip | 2.00E-6 | 60.0 | 0.0 | 0.0 |
| Solenoid Valve – 3-Way – Energize to Trip | 1.00E-5 | 20.0 | 0.0 | 91.0 |

## Final Element Data

| Item | Failure Rate (per hour) | Safe Failure Percent‡ | C(S) | C(D) |
|---|---|---|---|---|
| Air Operated Ball Valve | 3.00E-6 | 60.0 | 0.0 | 0.0 |
| Air Operated Butterfly Valve | 3.00E-6 | 55.0 | 0.0 | 0.0 |
| Air Operated Gate Valve | 2.00E-6 | 40.0 | 0.0 | 0.0 |
| Air Operated Globe Valve | 2.50E-6 | 55.0 | 0.0 | 0.0 |
| Hydraulic Operated Ball Valve | 3.00E-6 | 55.0 | 0.0 | 0.0 |
| Hydraulic Operated Slide Valve | 5.00E-6 | 50.0 | 0.0 | 0.0 |
| Motor Operated Valve | 5.00E-6 | 10.0 | 0.0 | 0.0 |
| Motor Starter Circuit/Contactor | 1.50E-6 | 80.0 | 0.0 | 0.0 |
| Stack Damper (Fired Heaters) | 6.00E-6 | 55.0 | 0.0 | 0.0 |
| Trip and Throttle Valve | 3.80E-6 | 39.0 | 0.0 | 0.0 |

# Appendix H – Example Risk Criteria

One of the most important, yet difficult aspects of the SIS Safety Lifecycle (and risk analysis) is determining the level of risk that is acceptable in any specific situations. While tolerability of risk can be represented in many ways, they all typically refer back to single metric called "Individual Risk of Fatality" (IR). All other representations of tolerable risk, which are subsequently utilized for risk management tasks, such as SIL selection, are derived from this single value. Figures that are employed by various organizations for tolerable IR vary, but commonly fall within a fairly narrow range. *Figure F.1* provides IR data with respect to some national criteria while *Figure F.2* presents data utilized by some operating companies in the process industries. IR is typically represented as a range, where the beginning of the range (highest frequency) represents the frequency at which risk is not tolerable under any circumstance, and the end of the range (lowest frequency) represents that point at which risk is negligible. In the middle, risk should be reduced "As Low As Reasonable Possible".

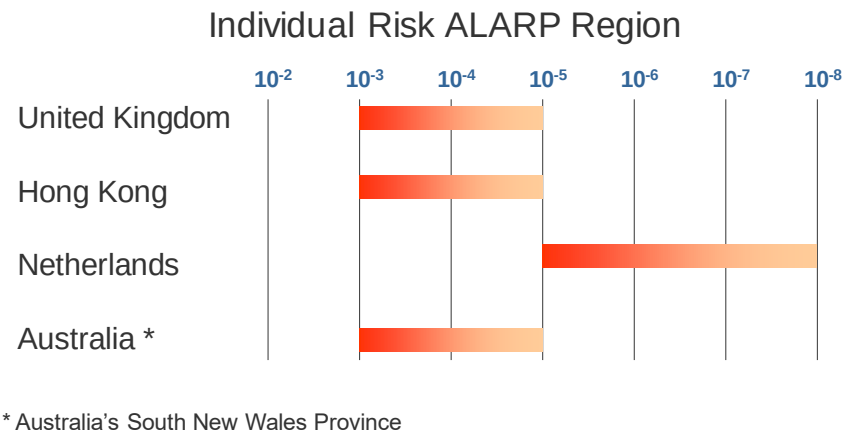



***Figure F.1 National Risk Tolerance Criteria***

For the purposes of SIL selection, a number of tolerable risk figures are calculated using a calibration process for the selected tolerable risk representation. The two most common approaches for representing tolerable risk for SIL selection are the risk matrix and the TMEL table. The risk matrix provides a two-dimensional representation of risk in terms of consequence and likelihood. Each intersection contains a numeric figure that represents the number of orders of magnitude of risk reduction required to make the risk of a particular hazard tolerable. The TMEL table, on the other hand, is consequence based. For each category of consequence the TMEL contains a "Target Maximum Event Likelihood" (TMEL) that is tolerable for a specific hazard. It should be noted that both of these approaches provide a single metric that typically falls into the middle of the ALARP range, and represents the tolerability of a single hazard, as opposed to the sum of all hazards to which an individual is exposed.

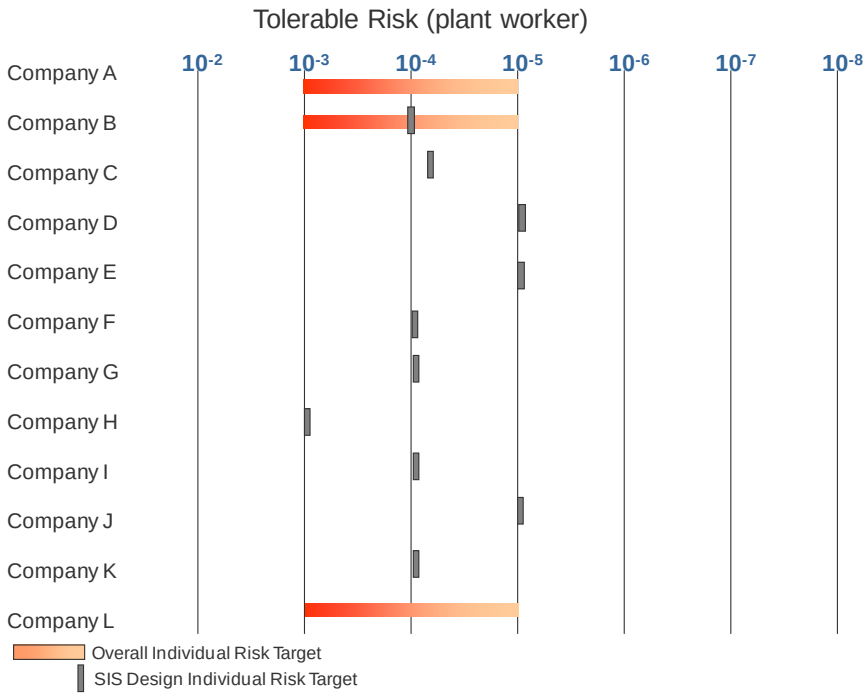



***Figure F.2 Operating Company Risk Tolerance Criteria***

At this point it is important to explain the correlation between the ALARP range of IR which represents tolerable risk to an individual and the single point TMEL which represents tolerable which represents risk that is tolerable for a specific hazard. ALARP ranges are based on correlating risks posed by common hazards against a societal perception of the tolerability of those risks. Consider *Figure F.3*.

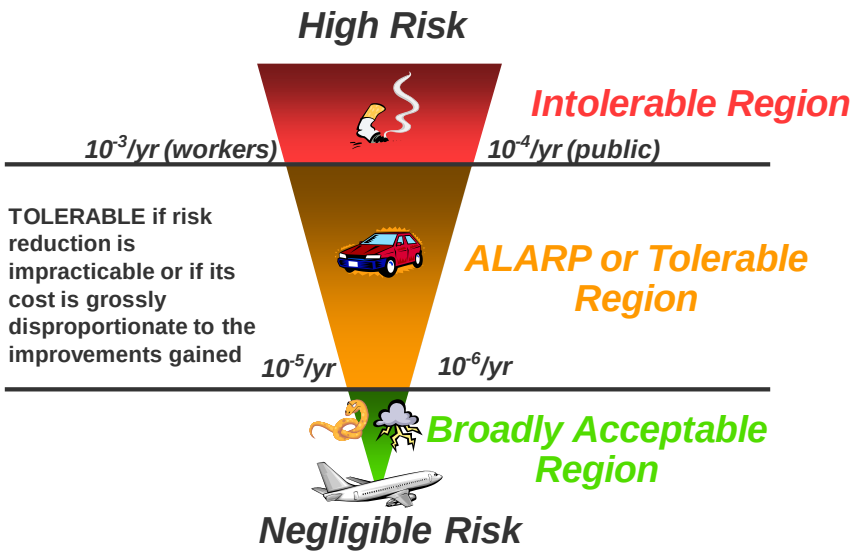



***Figure F.3 ALARP Conceptual Representation***

*Figure F.3* plots situations to which people are often exposed along with judgments regarding to tolerability of that risk

While the ALARP range is an excellent tool for representation of tolerable risk, it cannot be directly applied to SIS engineering or other engineer tasks for two reasons. First, ALARP is a range, when engineering necessarily requires a single point as a design target. Second, ALARP represents IR, which is considers the sum of all risks to which a single individual is exposed, whereas SIS engineering requires a target for prevention of a single hazard to which many people are exposed, but not continually.

The first step in converting ALARP to TMEL is fairly straightforward, converting the range to a single point. Conservatism and prudence typically result in the selection of the middle of the range as the target point. The high frequency end of the range is not conservative enough while the low frequency end of the range will require significant additional spending on risk reduction measures. In the case of *Figure F.3*, this will result in a figure of $1x10^{-4}$ per year.

The second step is complex and esoteric, but after the effort required to understand the conversion, no effort is actually require to modify the figures. Individual risk applies to the sum of all risks to which a specific individual is exposed, whereas TMEL defines that tolerability of a specific incident. In order to correlate the two, one needs to consider that an individual is exposed to multiple hazards simultaneously at all times, but not exposed to any specific hazards for a significantly long duration. In general, these two factors tend to cancel each other out. It can be speculated that at any point in time a worker might be exposed to ten different hazards that are protected against by SIS. Also, that same worker is only at work about 25% of his calendar year, thus being exposed to any specific hazard (as the worker will continually change location throughout the work day) for a shorter duration. As a result, the selected IR target figure is typically used directly as the TMEL figure for an event which is expected to result in a fatality.

Once the TMEL target has been selected, one is required to use this figure to calibrate tables and matrices that are used for subsequent engineering tasks. In the following figures, typical risk tolerance criteria will be developed using a scenario-based fatality TMEL of $1x10^{-5}$ per year. The first step is a set up a table that defines categories of consequence and assign TMEL targets for each category. The table is presented in *Figure F.4*. The "anchor point" of the table is severity rating 4 which represents a single fatality. For this row, the TMEL value of $1x10^{-5}$ can be used directly. The TMEL targets for the rows above and below are decreased and increased by an order of magnitude, respectively, based on the establishment of categories that are one order of magnitude changes in consequence severity.

| S | Category | Long Description | TMEL-S |
|---|---|---|---|
| 0 | None | No significant safety consequence | N/A |
| 1 | Very Low | Minor injury - first aid | 1E-02 |
| 2 | Low | Lost time injury not requiring extended hospitalization | 1E-03 |
| 3 | Moderate | Severe injury (extended hospitalization, dismemberment) | 1E-04 |
| 4 | High | Single fatality | 1E-05 |
| 5 | Very High | Multiple fatalities | 1E-06 |

***Figure F.4 Safety Consequence Category Table***

The table in *Figure F.4* is based on safety consequences only. In many cases it is important to consider other types of losses, such as commercial losses and environmental damage. In order to do so, each type of consequence should have a column where an equivalent loss is described. In order to do so, one must make decisions about equivalency of different loss type. For instance, what financial value of commercial loss is equivalent to one fatality? Based on US litigation settlement averages at the time of the writing of this book, a major process company can expect to settle a third party wrongful death lawsuit for about $50 million depending on the circumstances surrounding the incident. As such, $50 million can be placed

in the "fatality" severity row of the table, and orders of magnitude changes in the value for other rows. Environmental losses can be considered similarly. The final result is shown in *Table F.5*.

| S | Category | Safety | Environment | Commercial | TMEL |
|---|---|---|---|---|---|
| 0 | None | No significant safety consequence | None | None | N/A |
| 1 | Very Low | Minor injury - first aid | Small release with minimal clean up requirements | $50,000 | 1E-02 |
| 2 | Low | Lost time injury not requiring extended hospitalization | Moderate release limited to onsite damage with moderate clean up effort | $500,000 | 1E-03 |
| 3 | Moderate | Severe injury (extended hospitalization, dismemberment) | Large release with limited offsite impact requires significant onsite clean up | $5 Million | 1E-04 |
| 4 | High | Single fatality | Large release offsite on extensive clean up and damage to sensitive areas | $50 Million | 1E-05 |
| 5 | Very High | Multiple fatalities | Very large release off site with extensive clean of and permanent damage to several sensitive areas | $500 Million | 1E-06 |

***Figure F.5 Unified Consequence Category Table***

If a risk matrix approach is utilized to represent tolerability of risk, another table that represents categories of likelihood should be developed. Again, this table should include categories that are order of magnitude bands of frequency. *Figure F.6* presents such a table.

| Likelihood | Description | Recurrence Period |
|---|---|---|
| 0 | None | N/A |
| 1 | Very Unlikely | 1,000 years |
| 2 | Unlikely | 100 years |
| 3 | Occasional | 10 years |
| 4 | Frequent | 1 year |
| 5 | Very Frequent | 0.1 year |

***Figure F.6 Likelihood Category Table***

It is important to note that these tables represent categories that are bands of risk, while the development of the tables shows a single point (i.e., frequent is once per year). When developing such tables for use in actual projects that entire range for a category must be defined. This can be done using worst-case or prototypical. For instances, a "worst case" calibration would imply that the "frequent range" is once per year to once in 10 years. A prototypical range would imply that 1 per year is the middle of the range, making the recurrence period range 0.3 years to 3 years. Prototypical calibration will typically lead to results that are not excessively conservative.

Given that the consequence and likelihood tables have been completed, a risk matrix is built that includes all of the intersections of all of the likelihood and consequence categories. The amount of risk reduction required for each intersection is then calculated based on the TMEL value for an "anchor point" along with the knowledge that the likelihood and consequence categories are order of magnitude changes. As with the development of the TMEL table for consequence, a tolerability for an event whose expected consequence is a single fatality is utilized for the calibration. Since the TMEL for this consequence is 1x10-5, then an event that occurs once per year that results in a single fatality will require five (5) orders of magnitude of risk reduction to make tolerable. Therefore in the intersection of consequence = fatality and likelihood = 1 year should contain the value 5. In the matrix shown in *Figure F.7*, this intersection is 4-4. The rest of the table is then completed based on the definition that each category spans one order of

magnitude, meaning that for each move up or down, left or right, results in a change in the number in the cell by one (1).

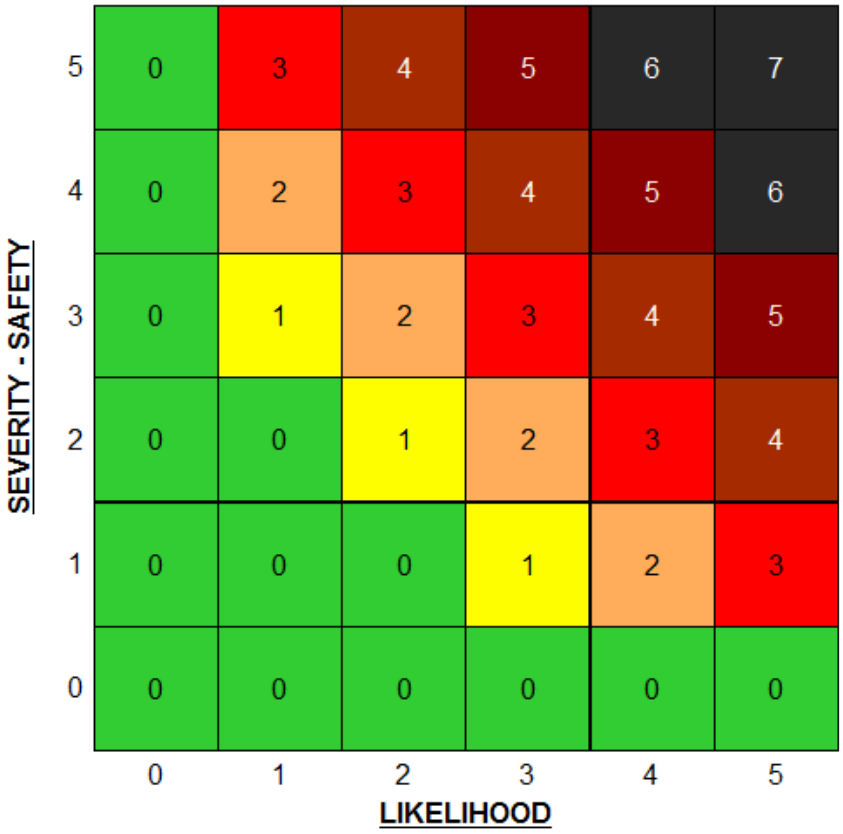



***Figure F.7 – Calibrated Risk Matrix***

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