SIL MANUAL

SAFETY INSTRUMENTED SYSTEMS

Plant Engineering and Maintenance
according to IEC 61508 and IEC 61511 Standards

- Safety Integrity Levels
- Reliability and Probability of Failure on Demand
- Redundant System Architectures
- Risk Reduction
- IEC 61508 and IEC 61511 compendiums

GM INTERNATIONAL
TECHNOLOGY FOR SAFETY

3rd Edition

SAFETY INSTRUMENTED SYSTEMS

Manual for
Plant Engineering
and Maintenance

With reference to

IEC 61508 Standard for Functional Safety of Electrical / Electronic / Programmable Electronic Safety-Related Systems

and

IEC 61511 Safety Instrumented Systems for the Process Industry

3rd Edition

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Why this manual was written

G.M. International designs, manufactures and sells SIL2 and SIL 3 certified Intrinsically Safe Interfaces for use in Hazardous Locations; these products are intended to prevent accidents before they occur, thus reducing risk and enhancing safety in a very wide variety of applications.

This manual is a practical aid for the analysis, installation and maintenance of safety instrumented systems and associated components and will hopefully serve as a guide for understanding procedures and transposing them into practice.

It represents our effort to share the results we have come to after many years of research and field experience, with anyone willing to approach Safety Related Systems.

Who this manual is for

This manual is not intended for safety reliability specialists, but for the thousands of professionals employed in process industries who work with safety instrumented systems and who are expected to follow the appropriate industry standards.
Aren't the standards alone enough? The answer depends upon the knowledge and experience of the individual and the company.

The growing demand for experts in a critical sector like functional safety, underlies the urgency of a greater awareness and comprehension of all subjects presented herein.

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Chapter 1 Presentation of IEC 61508, IEC 61511 and other safety related standards

Safety-related systems serve the function of protecting equipments and industrial processes where danger may occur in case of failure. These systems are not part of the process control system since their purpose is to bring the plant to a safe state in case of malfunctioning.
Until a few years ago these systems, for example ESD systems (Emergency Shut-Down), were being designed in compliance with the respective standards in force in the different countries, with no reference to a general normative. This condition is now changing with the introduction of the IEC 61508 and IEC 61511.
With these Standards, the most important benefits for the final user are:

- A more technical and scientific method in formulating requirements, and specifications in designing process.
- A more accurate definition of risk.
- A more valid designing of safety-related system.
- An easier and wider demonstration of safety-related system's effectiveness.
- A far more cost-effective implementation of safety-related system.
- An easier evaluation and effectiveness of maintenance operations.

The number of manufacturers of equipments complying with this standard is expected to grow. Information provided by the manufacturers allow the integration of their products into safety-related systems.

IEC 61508 is an international standard for the "functional safety" of electrical, electronic, and programmable electronics equipment.
At present, in Europe, EN 61508 has been issued but not yet acknowledged as European Directive.
This standard started in the mid 1980s when the International Electrotechnical Committee Advisory Committee of Safety (IEC ACOS) set up a task force to consider standardization issues raised by the use of a programmable electronic system (PES).
At that time, many regulatory bodies forbade the use of any software-based equipment in safety critical applications.

Work began within IEC SC65A/Working Group 10 on a standard for PES used in safety-related systems. The group merged with Working Group 9 where a standard on software safety was in progress.
The combined group treated safety as a system issue.

IEC 61508 is divided into seven parts.
The first three are required for compliance (normative), the others are supporting information (informative) which provide further guidance information.

- **Part 1:** General requirements. (Normative)
- **Part 2:** Requirements for electrical/electronic/programmable electronic safety-related systems. (Normative)
- **Part 3:** Software requirements. (Normative)
- **Part 4:** Definitions and abbreviations. (Informative)
- **Part 5:** Examples of methods for the determination of safety integrity levels. (Informative)
- **Part 6:** Guidelines on the application of Parts 2 and 3. (Informative)
- **Part 7:** Overview of techniques and measures. (Informative)

Parts 1, 3, 4 and 5 were approved in 1998. Parts 2, 6 and 7 were approved in February 2000. The relationship between technical requirements presented in parts 1, 2 and 3 and the supporting information in parts 4 through 7 is shown in Figure 1, in the following page.

Although the standard has been criticized for the “extensive” documentation requirements and use of unproven “statistical” techniques, in many industries it represents a great step forward.
The standard focuses attention on risk-based safety-related systems design, which should result in far more cost-effective implementations.
It also requires the attention to details that is vital to any safe system design.

Because of these features and the large degree of international acceptance for a single set of documents, many consider the standard to be major advance for the technical world.

Our experience of SIL 2 and SIL 3 hardware and software design, has shown how the suggested techniques in the standard are indeed a valid guidance for reducing "dangerous undetected failures" which is the correct path towards increasing safety integrity levels for any safety-related system.

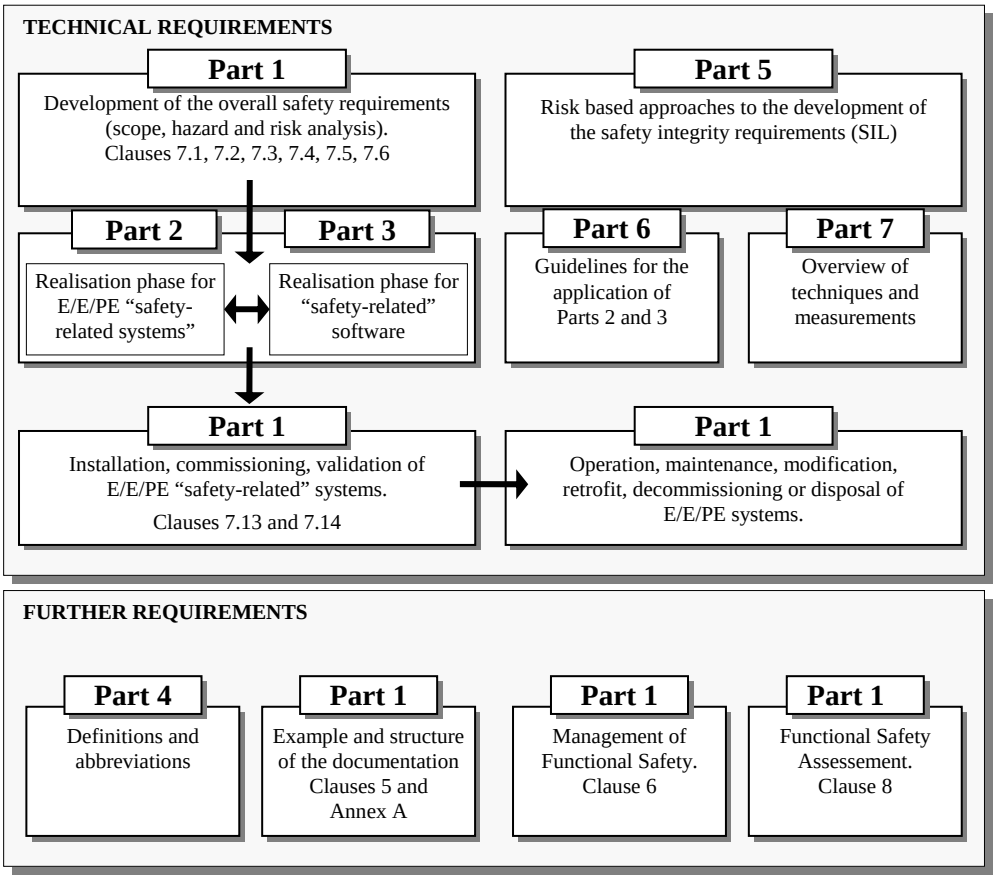

Figure 1, IEC 61508 requirements

1.1 Scope of the IEC 61508

There is a **primary** safety, (which deals with risks, as electric discharges generated by an electric equipment), a **functional** safety (to which this standard specifically refers), which depends on the measures of risk reduction adopted in the system under control, or EUC (Equipment Under Control), and a **derived** safety which deals with the indirect consequences of an EUC, which does not perform as expected, for example providing a drug with a wrong recipe which might kill instead of healing.
However, the principles of this standard can also be generally applied to other aspects of safety not specifically referring to its functionality.

IEC 61508 is one of the main publications, on safety matters, of IEC (International Electrotechnical Commission). As such, it is a document which involves many industries and applications.
It involves, for example, the PED directive (Pressured Equipment Directive) and the protection method "b" for non electrical equipments of ATEX (mechanic), as well as the new normative (not yet approved) EN 50495 (Safety devices required for safe functioning of equipment with respect to explosion risks), in which, for the first time in ATEX standard, functional safety integrity levels are used (SIL levels) as protection system.

The main purpose of IEC 61508 is to provide the basis for the preparation of specific safety standards for plant and industrial sectors.
A second scope of the standard is to help the development of safety-related systems E/E/PE (Electrical/Electronic/Programmable Electronic) where specific standards do not exist.
Starting from 2002, two new specific standards directly referring to IEC 61508 were introduced: IEC 61511 for process control industries and IEC 62061 (EN 954) Safety of Machinery.

IEC 61508 covers safety-related systems when one or more of such systems incorporate electrical/electronic/programmable electronic devices.
These devices can include anything from electrical relays and switches to Programmable Logic Controllers (PLCs) and all the way up to complicated computer-driven overall safety systems.
The standard specifically covers possible hazards created when failures of safety functions performed by E/E/PE safety-related systems occur.
The overall program to insure that a safety-related E/E/PE system brings about a safe state, when called upon to do so, is defined as "**functional safety**".

IEC 61508 does not cover safety issues like electric shock, hazardous falls, long-term exposure to a toxic substance, etc.; these issues are covered by other standards like ATEX or similar.
IEC 61508 also does not cover low safety E/E/PE systems where a single E/E/PE system is capable of providing the necessary risk reduction and the required safety integrity level of the E/E/PE system is less than SIL 1.

IEC 61508 is concerned with the E/E/PE safety-related systems whose failure could affect the safety of persons and/or the environment. However, it is recognized that the methods of IEC 61508 also may be applied to business loss and asset protection cases.

Note:
Difficulties may be found in the first reading of the standard, which requires attention and undertaking, attitudes not always available after a long and exhausting working day.
Starting from Part 4 (Definitions and abbreviations) can be very useful for the comprehension of the whole standard.

1.1.1 Safety

When considering an industrial process, it is recognized that there is an inherent risk of operation. Sometimes things do go wrong.
The standard defines Safety as "**freedom from unacceptable risk of harm**".

IEC 61508 goes on defining the level of safety as "*a level of how far safety is to be pursued in a given context, assessed by reference to an acceptable risk, based on current values of society*".
When evaluating safety, the frequency of an accident and the consequences (costs) of an accident are both taken into consideration.
Risk is defined as the probable rate of occurrence of a hazard causing harm and its degree of severity. Thus, risk evaluation includes a combination of frequency and cost.

Generally, risk (R) is the result of multiplication between the frequency of accidents (F) and their consequences (C).

$$R = F \times C$$

Example:

If the consequences of an accident are estimated to be 100'000'000 $ and the frequency of the accident is estimated to be once every 10 years (probability of an accident is 0.1 for a time interval of one year).

The inherent risk is stated to be 10'000'000 $ per year (10 = 0,1 x 100).

Note that the concept of inherent risk refers to a context with no protections.

The present industrial world, with the necessity of larger productions and lower costs, has certainly increased the probability of severe accidents.
Beyond damages to persons and environment, created by an accident, legal expenses costs, fines, commercial losses caused by plant shutdown and by bad reputation, have to be considered. Risk reduction is therefore mandatory.

Note:
From an ethical point of view, it could be objected that "damages to things" or "death of one or more persons", as mentioned in IEC 61508, should not be quantified only in economic terms. Although, beyond this being the regular procedure for insurance companies, it responds to a normative criterion of uniformity to generalize the methods of calculation.
The evaluation of human resources, as well as human factors is not a subject of this standard.

Following are the first 6 definitions available in Part 4 of the standard:

- **Hazard**
  Potential source of harm.
  Note: The term includes danger to persons arising within a short time scale (e.g. fire and explosion) and also those that have a long-term effect on a person's health (e.g. release of a toxic substance).
- **Hazardous situation**
  Circumstance in which a person is exposed to hazard/s
- **Hazardous event**
  Hazardous situation which resolves in a harm.
- **Risk**
  Combination of the probability of occurrence of harm and its severity.
- **Tolerable risk**
  Accepatble Risk in a given context based on the current values of society.
- **Residual risk**
  Risk remaining after protective measurements have been taken.

1.1.2 IEC 61508: Brief description.

Part 1

Part 1 covers basic requirements of the standard and provides a detailed presentation of the safety lifecycle. This section is considered to be the most important, as it provides overall requirements for documentation, compliance, management of functional safety, and functional safety assessment.
Three annexes provide examples of documentation structure (Annex A), a personnel competency evaluation (Annex B), and a bibliography (Annex C).

Part 2

Part 2 covers the hardware requirements for safety-related systems.
Many consider this part, along with Part 3, to be the key area for those developing products for the safety market.
Part 2 is written with respect to the entire system but many requirements are directly applicable to safety-related hardware products development.
It covers a detailed safety lifecycle for hardware as well as specific aspects of assessing functional safety for the hardware and has also detailed requirements for techniques to deal with “control of failures during operation” in Annex A (required for compliance).
This annex covers hardware fault tolerance, diagnostic capability requirements and limitations, and systematic safety integrity issues for hardware.
Annex B (required for compliance) contains a listing of “techniques and measures” for “avoidance of systematic failures during different phases of the lifecycle”. This covers design, analysis, and review procedures required by the standard.
Annex C (required for compliance) discusses the calculation of the diagnostic coverage factor (what fraction of failures are identified by the hardware) and the safe failure fraction (what fraction of failures lead to a safe rather than hazardous state).

Part 3

Part 3 covers software requirements for IEC 61508. It applies to any software used in or to develop a safety-related system. This software is specifically named safety-related. This part provides details of the software safety lifecycle, a process to be used during development.
Annex A (required for compliance) provides a listing of “techniques and measures” used for software development where different development techniques are chosen depending on the SIL level of the software.

Annex B (required for compliance) has nine detailed tables of design, coding standards, analysis and testing techniques that are to be used in the safety-related software development, depending on the SIL level and, in some cases, the choice of the development team.

Part 4

Part 4 contains definitions and abbreviations used throughout all parts of the standard. This section is extremely useful both to those new to the standard and to those already familiar with it, as a reference to the precise meaning of terms in the standard.

Part 5

Part 5 includes informative Annexes A through E which contain discussions and example methods for risk, safety integrity, tolerable risk, and SIL level selection. It presents several techniques of SIL selection including both quantitative and qualitative methods. The quantitative method in Annex C is based on calculating the frequency of the hazardous event from failure rate data or appropriate predictive methods combined with an assessment of the magnitude of the consequence compared to the level of risk that can be tolerated in the given situation.
The qualitative risk graph and severity matrixes essentially address the same frequency and magnitude components, only with general categories rather than numbers before comparing the situation with the tolerable risk level.

Part 6

Part 6 provides guidelines on the application of Part 2 and 3 via informative Annexes A through E. Annex A gives a brief overview of Part 2 and 3 as well as example flowcharts of detailed procedures to help with implementation. Annex B provides example techniques for calculating probabilities of failure for the safety-related system with tables of calculation results.
Equations that approximate various example architectures are presented, although reliability block diagrams are used and these can be confusing in multiple failure mode situations.
Annex C shows detailed calculation of diagnostic coverage factor based on FMEDA (Failure Modes, Effects, and Diagnostics Analysis) techniques.
Annex D shows a method for estimating the effect of common cause modes of failure (beta factor) in redundant hardware architecture.
This method lists relevant parameters and provides a method of calculation.
Annex E shows examples applying the software integrity level table of part 3 for two different safety software cases.

Part 7

Part 7 contains important information for those doing product development work on equipment to be certified per IEC 61508.
Annex A addresses control of random hardware failures. It contains a reasonable level of details on various methods and techniques useful for preventing or maintaining safety in the presence of component failures.
Annex B covers the avoidance of systematic failures through the different phases of the safety lifecycle.
Annex C provides a reasonably detailed overview of techniques for achieving high software safety integrity.
Annex D covers a probabilities-based approach for SIL level determination of already proven software.

Note:
Some information contained in this chapter have been excerpted with permission from *"Safety Instrumented Systems: Design, Analysis, and Justification, 2nd Edition,"*,

1.2 Other safety-related standards

Safety Instrumented Systems (SIS) are designed to respond to the conditions of a plant, which may be hazardous in themselves, or potentially hazardous if no action is taken, and must generate the correct output to prevent, or mitigate, the hazardous event. The proper design and operation of such systems are described in various standards, guidelines, recommended practices, and regulations.
Setting specifications, electing technologies, levels of redundancy, safety integrity levels, test intervals, etc. is not always an easy straightforward matter.
Various industry standards were written to assist those in the process industry tasked with proper selection, design, operation, and maintenance of systems.
Following the standard requirements is not a sufficient condition for making a plant safe. There are, in fact, no guarantees that by following the related standards, a safe process is realized.
Although, by not following them, a very probable result is an unsafe process.

1.2.1 HSE- PES

"*Programmable Electronic Systems In Safety Related Applications*", Part 1 and 2, UK Health & Safety Executive, 1987. This document was the first of its kind and was published by the HSE. Although it is focused on software programmable systems, the concepts presented applied to other technologies as well.
It deals with quantitative and qualitative evaluation methods, together with many design checklists. Part 1 – "An Introductory Guide" – is only 17 pages and was intended primarily for managers. Part 2 – "General Technical Guidelines" – is 167 pages and was intended primarily for engineers.
They were both excellent documents, although they did not appear to be well known outside U.K: however, considering the material covered, they would appear to have been used as the foundation for many of the more recent documents.

1.2.2 DIN (V) 19250

This German draft standard is titled: "*Fundamental safety aspects to be considered for measurement and control equipment.*", last issued 1994.
It has been influent in the preparation of Part 5 of IEC 61508 risk analysis examples. This standard was intended to provide guidance to standardization committees that wish to define rules for carrying out risk analysis process using the risk graph, leading to the appropriate "class" (abbreviated to AK).

AK Risk classes are of the same nature as Safety Integrity Levels (SILs) of IEC 61508. Whereas IEC 61508 defines four safety integrity levels, DIN 19250 defines eight requirements classes and correspondences between the two categorizations may be derived.
The cited DIN standard is now replaced by the IEC 61508.

1.2.3 AIChE - CCPS

"*Guidelines for Safe Automation of Chemical Processes*", 1993.
The American Institute of Chemical Engineers formed the "Center for Chemical Process Safety (CCPS), after the severe accident of Bhopal India. Since then, the CCPS has released several dozens textbooks on various design and safety-related topics for the process industry.
In particular, the text covers the design of Distributed Control Systems (DCS) and Safety Interlock Systems (SIS) and contains other very useful background information. The book took several years to be written and was the effort of several individuals belonging to user companies (e.g. no vendors).

1.2.4 ISA-SP84.01 - 1996

This American standard titled "*Application of Safety Instrumented Systems for the Process Industries*" is specific for process industries and addresses the application of safety instrumented systems (SIS) and not equipment under control (EUC) as described in the IEC 61508.
It defines the full lifecycle assuming that risk analysis and determination of SIL levels, had already been carried out.
The standard does not cover non-SIS and restricts itself to good practice in the provision of safety instrumented systems, from specification to decommissioning. The ISA SP84 committee worked for more than 10 years developing this standard. The scope of this document underwent many changes through the years. It was originally intended as a U.S. standard focusing only on programmable logic boxes (and not the field devices).
The scope eventually expanded to include other logic box technologies as well as field devices.
ANSI/ISA-84.01-1996 stated it would be re-released in five year intervals to account for new developments. Rather than rewriting the ISA SP84's standard from scratch, the committee decided to adopt the IEC 61511 standard.
The new three-part standard is designated as ANSI/ISA-84.00.01-2004,
Part 1-3 (IEC 615011).

1.2.5 API RTP 556

"*Recommended Practice for Instrumentation and Control Systems for Fired Heaters and Steam Generators*", American Petroleum Institute, 1997.
This recommended practice has sections covering shutdown systems for fired heaters, steam generators, carbon monoxide or waste gas steam generators, gas turbine exhausts, fired steam generators, and unfired waste heat steam generators. While intended for use in refineries, the document states that it is "applicable without change, in chemical plants, gasoline plants and similar installations".

1.2.6 NFPA 85

"*Boiler and Combustion Systems Hazard Code*", (first edition in 1997) National Fire Protection Association, 2004.
NFPA 85 is the most recognized standard worldwide for combustion safety systems. It is a very prescriptive standard with specific design requirements and covers:

- Single Burner Boiler Operation.
- Multiple Burners Boilers.
- Pulverized Fuel Systems.
- Stocker Operation.
- Atmospheric Fluidizer-Bed Boiler Operation.
- Heat Recovery Steam Generator System.

The purpose of NFPA 85 is to provide safe operation and to prevent uncontrolled fires, explosions and implosions. Some of the key requirements of this standard relate to the burner management system logic.
The NEPA is not involved with the enforcement of this standard.
However, insurance companies, regulatory agencies, and company standards often require compliance. Many countries and companies require compliance with NFPA 85 for Burner Management Systems (BMS).
There is a considerable debate as to whether a BMS is a safety instrumented system (SIS). Obviously there are those that believe it is, as the definitions of both systems are very similar.
The NFPA 85 does not address Safety Integrity Levels.
However, members of various standard committees are trying to harmonize the various standards.

1.2.7 IEC 61511 – 2004 (ANSI/ISA-84.00.01-2004)

This international standard titled "*Functional Safety: Safety Instrumented Systems for the Process Industry Sector*", was developed as a Process Sector

implementation of the IEC 61508. The standard is primarily concerned with SIS for process industry sectors like sensors, logic solvers and final elements which are included as part of the SIS.
It also deals with the interface between the SIS and other safety systems requiring a process hazard and risk assessment to be carried out.
The standard consists of three parts:
Part 1: Frame work, definitions, systems, hardware and software requirements
Part 2: Guidelines in the application of the IEC 61511-1.
Part 3: Examples methods for determining safety integrity in the application of Hazard & Risk Analysis.

1.2.8 API RP 14C

"*Recommended Practice for Design, Installation, and Testing of Basic Surface Safety Systems for Offshore Production Platforms*", American Petroleum Institute, 2001. This prescriptive recommended practice is based on "proven practices" and covers the design, installation, and testing of surface safety systems on offshore production platforms. It is intended for design engineers and operating personnel.

Note:
Contents of Sections 1.2.1, 1.2.3, 1.2.5, 1.2.6, 1.2.8 have been excerpted with permission from "*Safety Instrumented Systems: Design, Analysis, and Justification, 2nd Edition,"*, Copyright 2006 © by ISA

1.2.9 Risk of relevant accidents, in EEC and Italian Standards

SEVESO I
EEC directive nr. 82/501, also called Seveso I, deals with risks of accidents connected with certain industrial processes.
SEVESO II
EEC directive nr. 96/82/CE, also called Seveso II, deals with the control of relevant hazardous events connected with specific dangerous substances.
SEVESO III
EEC directive 2003/105/CE, also called Seveso III, improves directive 96/82/CE.

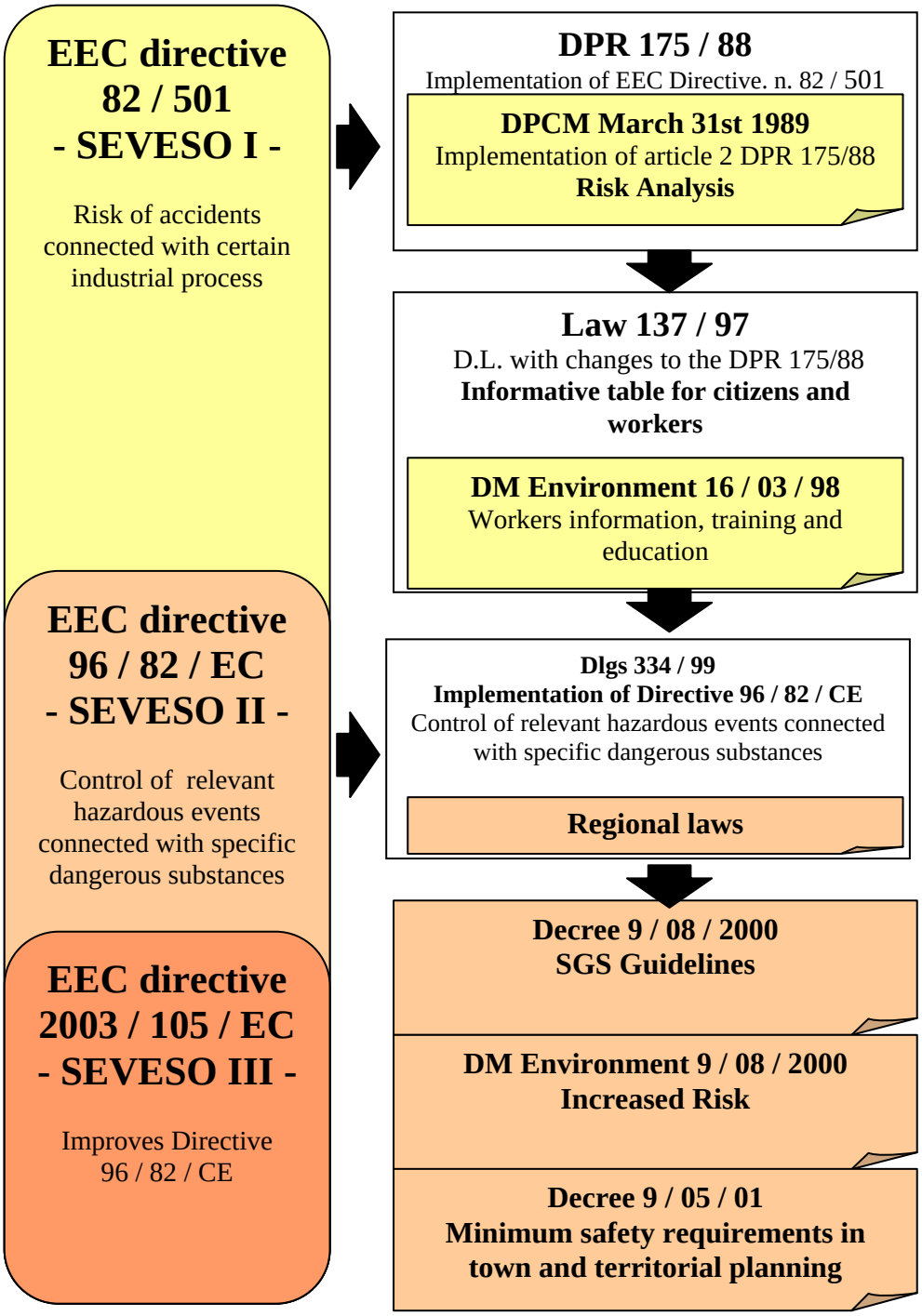

Figure 2, Legislation for risk of relevant hazardous events in the EEC and Italy

Chapter 2 Prevention and mitigation layers for hazardous events

Accidents rarely have a single cause and are usually a combination of improbable events that people initially assumed as independent and unlikely to happen at the same time.
A tragic example is the one occurred to a pesticide plant in Bhopal (India). It was December 3, 1984 and the unexpected leakage of more than 40 tons of methyl isocyanate (MIC) immediately killed almost 4000 people and caused illnesses and death to many thousands more.

Figure 3, Bhopal Disaster.
1976 Union Carbide plant: 20 thousand deaths and almost 200 thousand injured

Although operative procedures prescribed the tank to be refrigerated at a temperature below 5°C, the alarm was set at 11°C.
At that time, the refrigerating system was switched off due to bad economic conditions and the material was stored at the temperature of 20°C. The alarm set was therefore moved from 11°C to 20°C (**first cause**). The plant was in shut down for maintenance.
A worker was tasked to wash some clogged pipes and filters.
Blind flanges were not installed as required by the procedures in case of cleaning of the pipes (**second cause**) and water leaked past the valves into the tank containing MIC. Temperature and pressure gauges indicated abnormal conditions but were ignored, because thought to be inaccurate (**third cause**).
A vent scrubber, which could have neutralized the MIC release into the atmosphere, was not working because it was presumed not to be necessary while production was suspended (**fourth cause**).

But the vent scrubber would not have been able to handle that size of dangerous release anyway (**fifth cause**).

The flare tower, although insufficient for the task (**sixth cause**), could have burned off part of the material, but it was out of service for maintenance (**seventh cause**).
The material could have been vented to nearby tanks, but the gauges erroneously showed them as partially filled (**eight cause**).

A water curtain was available to neutralize a release in the atmosphere, but the MIC was vented from a stack that was 33 meters above the ground level, too high to be reached by the water curtain. Workers became aware of the MIC release because of the irritation to their eyes and throats.
Their complaints to the management, at that time, were ignored.
Workers panicked and fled ignoring the availability of 4 buses that were intended for emergency evacuation of the employees.
The plant supervisor could not find his oxygen mask and broke a leg while trying to climb over the boundary fence.
When the plant manager was later informed of the accident he did not believe the fact, by stating that the gas release could not be from his plant, nothing could ever happen to the plant, especially a MIC release, because the plant was not in operation.

Investigations of several industrial accidents proved that many of them happen during an interruption of production while an operator was trying to maintain or restart production.

In each case, the company's safety procedures were violated or jeopardized.

The best and most redundant safety layers can be defeated by poor or conflicting management practices.
If all prevention layers are effective (e.g. strong and solid), failures cannot spread from one to another.
In reality, these layers are not strong and solid, but more like Swiss cheese. The holes are caused by flaws in management, design specifications, engineering, operations, procedures, improperly performed maintenance, and other errors.
Not only there are holes in each layer, but these holes are constantly moving, increasing, ad decreasing, as well as appearing and disappearing.
It is clear that if these "holes" line up properly, a failure can propagate through all layers causing a hazardous event.

Supposing these holes are not present, the SIL levels (PFDavg) of each layer can be multiplied. This means that three SIL 1 layers could lead to SIL 3. Unfortunately this is just theory, due to the imperfections mentioned above. However, increasing the level of the three layers (SIL 2 and SIL 3), makes the achieving of a SIL 3 global level much more probable.

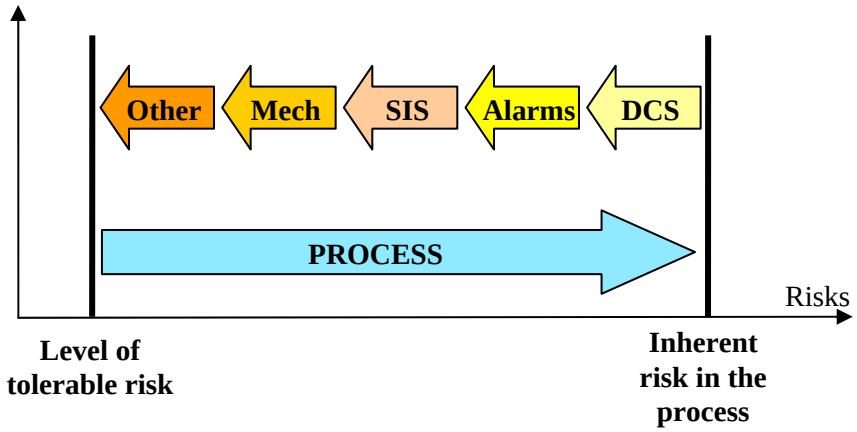

Figure 4, Risk reduction with several prevention layers

As already seen, risk is a function of the probability (or **frequency**) of a hazardous event and of its severity (or **consequence**).
In an industrial plant the various layers are planned to reduce one or the other.
Prevention layers are used to reduce the probability of the hazardous event, while mitigation layers are implemented to reduce the damaging consequences of an already happened hazardous event.
Prevention layers of an industrial plant are usually four and other four are the mitigation layers.
In this chapter ten layers are specified (5 for prevention + 5 for mitigation).
This is not relevant if not for a better comprehension and identification of the functions of the different layers.

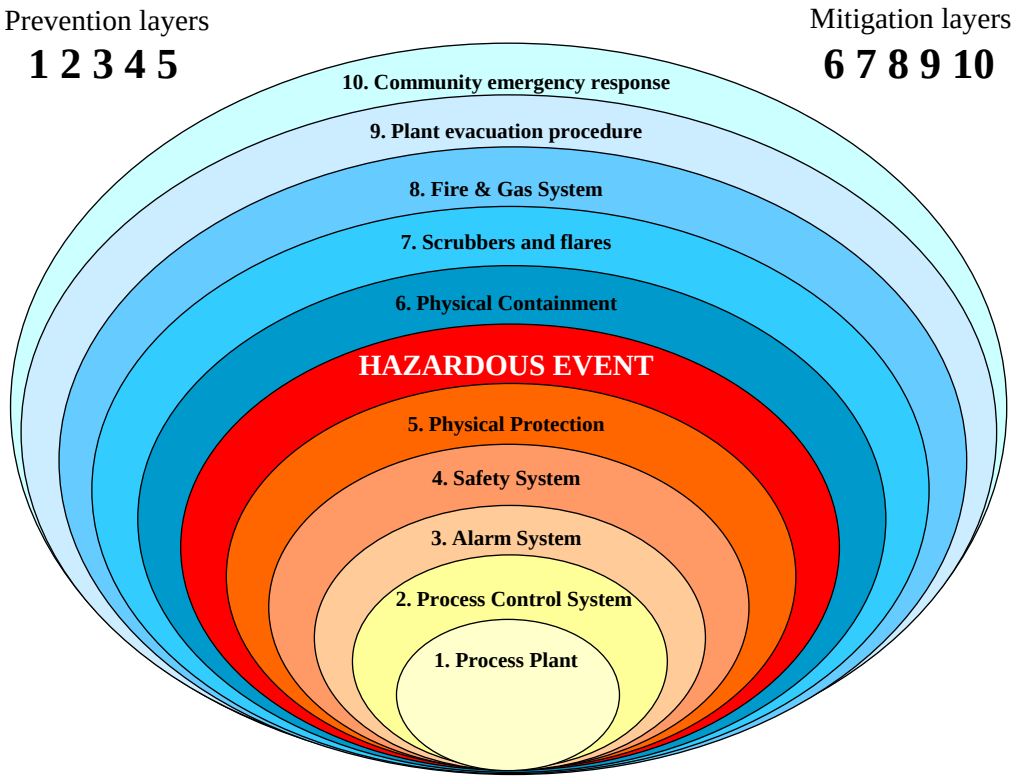

Figure 5, Prevention and mitigation layers of the hazardous event

2.1 Plants and processes in their environmental context

Industrial plants and processes must always be designed taking safety issues into consideration. This is why HAZOP (Hazard and Operability studies) or other safety reviews, such as fault tree analysis and various checklists, what-if, etc., should always be performed.
Trevor Kletz [1] points out that: "*time is usually better spent looking for all the sources of hazard, than in quantifying with even greater precision those we have already found*".

[1] Trevor Kletz, D. Sc., F. Eng., member of HSE and process safety consultant, has published more than one hundred papers and nine books on loss prevention and process safety.

In the NASA space program almost 35% of actual in-flight malfunctions had not been identified during the analysis.
The main requirement of an industrial process is to be safe, not forgetting the rule that "what is not there cannot be damaged", which means that it is important to make the process as simple as possible.
Safe processes and systems may be more expensive, but offer greater advantages to the final user throughout the life of the plant.
Risk reduction may result in a simplification and therefore in a reduction of costs. For example the problem of children remaining trapped and suffocated while playing in refrigerators has lead the industry to the use of magnetic latches, which are simpler, less expensive and much safer.

Figure 6, Refinery

Layer 1 takes into consideration all processes, plants and activities which may generate hazardous situations. All these represent the environmental context to which each safety matter refers to.

Arguments which are taken in to evaluation are:

- Area's classification.
- Stocking plants.
- Production plants.
- Storage plants.
- Hot fluid plants.
- Cold fluid plants.
- Electric plants.
- Auxiliary fluid plants.
- Organizational structure of the layer.

Teams of expert engineers working on this layer are:

- Team Leader
- Project Engineer
- Quality Assurance Engineer
- Machinery Engineer
- Mechanical Engineer
- Electrical Engineer
- Safety Engineer
- Maintenance Engineer

The application field can be chemical, petro-chemical, pharmaceutical, food, cement, and power generation plants.

Legislative directives and construction standards can include: ATEX, PED, IECEx, CPD, IEC, ISO, IEEE, CENELEC, DIN, CEI, UNI, ISA, ANSI, UL, FM, ASME, NEPA, AIChE, CCPS, etc.

2.2 Process Control System

The process control system is the second safety layer.
It controls the plant for an optimization of fuel usage, production quality, etc.
It attempts to keep all process variables, such as pressure, temperature, range, level, flow, within safe limits.
For this reason, this layer can be considered a safety prevention layer. However a failure in the control system may also initiate a hazardous event.
Automation does not eliminate the need of human intervention.
Experience has demonstrated that operators' actions may result in lowered alertness and vigilance, and lead to over-reliance on automated systems. Long periods of passive monitoring can make operators unprepared to act in emergency.
One way to solve this problem is to involve operators in safety analysis and design decisions up front. Involve operators more, not less.

A good knowledge of processes and plant structures at various levels is important in order to organize a satisfactory process control, and this means:

- Management level: Management decisions, and organization of the information.
- Productive level: Operative decisions and elaborated information.
- Field level: Elaborated commands and direct information.
- Plant level: Direct controls and direct information.

Figure 7, Control room

Layer 2 takes into consideration all process instrumentation controls and alarms, such as:

- Instrumentation management.
- Operability analysis.
- Wired systems management.
- Computerized systems management.
- Alarms management.
- Diagnostic management.
- Surveillance management.
- Organizational structure of the layer.

2.3 Alarm system

Monitoring and alarm systems should:

- Detect problems as soon as possible, to a low enough level to ensure that corrective actions can be taken before reaching hazardous conditions.
- Be independent from the control devices they are monitoring, which means they should not fail even if the system they are monitoring fails.
- Add as little complexity as possible.
- Be easy to maintain, check, and calibrate.

Alarm and monitoring systems are considered to be the safety layers in which the operators are actively involved: not everything can be automated.
However this is a double-edged sword because:

- Operators may not believe that rare events, alarmed by the system, are real or genuine.
- Operators may take wrong decisions, and fail to act, because overloaded with multiple alarms.

"*Accidents are not due to lack of knowledge, but failure to use the knowledge we already have*"[2].

An alarm system that provides a lot of information may "confuse" the operators instead of helping them.
A recent investigation has shown that during emergencies, people are about the worst thing to rely on, no matter how well trained they may be.

Note 1:
Some people might consider operating and maintenance procedures of a plant as an independent protection layer. This is a rather controversial subject.
For example, an inspection to detect corrosion and degradation of a vessel may help prevent accidents.
Procedures which limit the operability of a certain unit below the safety limits, or preventive maintenance actions, may help reduce accidents.
However all procedures may be violated (intentionally or not), especially in presence of pressures to reduce the costs or the number of the personnel involved. If the procedures are to be accounted as protection safety "layers", they must be documented, the people have to be trained to follow them, and their use must be regularly audited in order to avoid the operators forgetting them.

Note 2:
Some plant engineers include in the control system (layer 2) critical alarms, such as the ones that alert a possible system shut down by the SIS, if proper corrective actions are not taken.
Normally, if the safety alarms are supervised by specific control operators and are generated by independent instrumentation from the process control system, it is right to consider critical alarms as a separate layer (layer 3).
If instead a competent technician is not available (and this happens often due to economic reasons) or a separation of the instrumentation does not exist, layer 3 should be included into layer 2. In this case however, operator negligence must be considered as common factor in the failure analysis.

Note 3:
Many safety specialists consider layer 3 together with layer 4. For this reason the considerations accounted on layer 4 can be applied to layer 3.

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[2] "*What Went Wrong?: Case Histories of Process Plant Disasters*",
Trevor A. Kletz, Gulf Publishing, 1998

2.4 Emergency Shutdown system

If the control system (DCS) and the operators fail to act, the automatic shutdown system (ESD) takes action. These systems are always completely separated, with their own sensors, logic systems and final elements.
Safety systems are designed to:

- Allow the process to move forward in a safe way when specified conditions require so;
- Automatically take the process to a safe state if specified conditions are violated;
- Take action to mitigate the consequences, of an industrial hazard.

Note:
It is important to distinguish between a safety instrumented function (SIF) and a safety instrumented system (SIS).
A SIF refers to a single safety function (for example a high or low pressure trip), while a SIS may include hundreds of SIFs.
Many SIFs include only one sensor (or transmitter) and one final element (valve).

Figure 8, Offshore platform

Layer 4 considers all instrumentation controls and safety instrumented systems. It is structured for instrumentation protection of safety conditions.
However, the main concern for a safety system should not only be focused on how the system operates, but rather on how it fails. This is the underlying reason why dormant safety systems (ESD, F&G) differ from active control systems (DCS) and why SISs have unique design considerations.

Emergency Shut Down includes:

- Safety instrumentation ESD
- Safety analysis ESD
- Wired safety systems ESD
- Computerized safety systems ESD
- Safety interlock management ESD
- Diagnostic management ESD
- Safety surveillance ESD
- Organizational structure of layer

2.5 Physical protection and release devices

Release valves and rupture discs are one mean of physical protection that could be used to prevent, for example, an overpressure condition. While this may prevent a vessel from exploding due to a high pressure condition, the release of dangerous substances in the atmosphere may result in a secondary hazardous event (such as release of toxic material) or a violation of the environmental protection laws.

Figure 9, Release valves

Layer 5 considers all the passive physical protections such as release valves and includes:

- Containment devices.
- Discharge devices.
- Conveyances.
- Organizational structure of the layer.

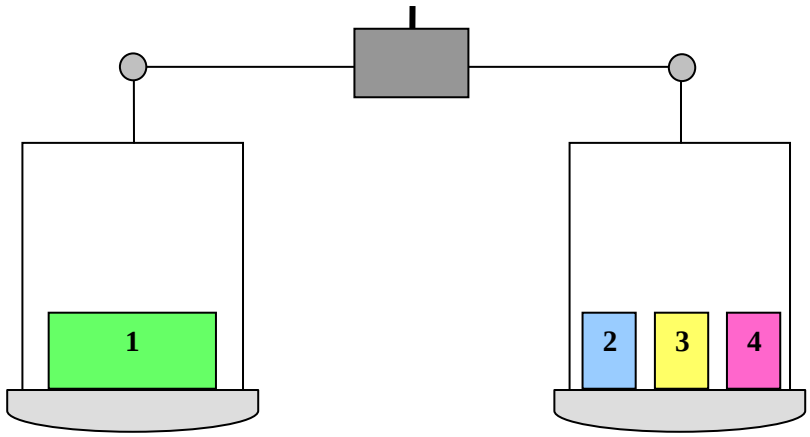
Considerations on protection levels:

HAZOP studies consider all evaluative activities that, by means of a systematic analytical approach carried out by a team of experts, have lead to a quantitative determination of potential risk levels for each specific portion of the process (node).
Such considerations should be taken in consideration of the following:

- Evaluation of the risk level.
- Evaluation of the plant's structures.
- Evaluation of the control instrumentation.
- Evaluation of the safety instrumentation.
- Evaluation of the physical protections.
- Evaluation of the prevention levels.
- HAZOP organization structure.

As show in Figure 10, the expert's goal is to balance the possible levels of risk levels with the respective levels of prevention.
If the scale leans towards the risks, it means there is not enough prevention. Vice versa, if it leans towards the prevention, it means excessive energies (costs) are invested.

This can also be applied on a general basis, with prevention and mitigation layers.



RISK

1. Environmental context Plants and Processes

PREVENTION

2. Control System

3. Safety Instrumented System

4. Prevention Physical Protections

Figure 10, Optimal safety scale

2.6 Physical protections and containment systems

Mitigation layers are implemented to reduce the severity or consequences of a hazardous event once it has already occurred. They may contain, disperse or neutralize the release of a dangerous substance.
This layer considers all passive containment physical protections.
It is designed to perform the first important actions of mitigation for a dangerous event in consequence of specific out of control plant situations. Any deficiency in this layer may lead to the propagation of hazard consequences inside the productive sites.

For example fuel tank dikes can be placed to contain the possible outflow of material. However, holding process fluid within dikes may introduce secondary hazards. Therefore it will be necessary to activate the F&G system (Fire & Gas).

Nuclear reactors are usually set in a proper containment structure
(in Chernobyl a specific structure was not available).
The control room of a plant which produces TNT is usually surrounded by a reinforced concrete wall, 7 meters in depth, with a roof made of light material that would be able to “fly away” with no harm to persons in case of explosion.

An explosion proof box (e.g. Nema 7 type) allows a safe explosion into its structure, but does not allow the propagation outside.

Figure 11, Hydrant cannon

2.7 Physical protections and dispersion systems

Scrubbers are designed to neutralize the release of dangerous substances
Flare towers are designed to burn off dangerous gas substances in excess.
Note that in Bhopal these two devices were present but not functioning during the maintenance phase the plant was in at the time.
Moreover they were not dimensioned to handle a release of such quantity.
In other analysis, the seventh layer is included in the sixth one.

Figure 12, Refinery flare tower

2.8 Physical protections and Fire & Gas neutralizing systems

F&G systems are neutralizing systems composed of sensors, a logic solver, and final elements designed to detect any combustible gas, toxic gas, or fire and:

- Alarm the condition.
- Take the process to a safe state.
- Take actions to mitigate the consequences of a hazardous event.

Sensors may consist of heat, smoke, flame, and/or gas and fire detectors, together with manual call boxes.
Logic systems can be, DCSs, conventional PLCs, Safety PLCs, special purpose PLCs, or specific multi-loop F&G systems. Final elements may consist of flashing / strobe lights, horns, sirens, phone notification system, fire

extinguishing systems, exploding squibs, deluge systems, suppression system, and/or process shutdowns.
Sometimes the F&G system is part of the ESD system. The main difference between the two is that the ESD systems operate normally-energized and de-energize for trip (to take action), while the F&G systems operate at the contrary, which means they are normally de-energize and energize for trip.
The reason for this is actually rather simple: ESD systems are designed to bring the plan to a safe state, which usually means stopping the production.
Nuisance trips (shutting the plant down when nothing is actually wrong) are economically expensive, due to lost production downtime, but are not generally catastrophic.

F&G systems are designed to protect equipment and people. Spurious operation of these systems can damage equipment and possibly result in casualties.The risk for people caused by a nuisance alarm, for example, with the release of Halon or CO_2 in a control room during normal operation, is not tolerated: this is why the system is normally de-energized.
Indeed the solenoid valves of a F&G system are driven (powered) directly by the safety PLC and, if required, the intrinsic safety isolated barriers, between the PLC and the solenoid, are powered by the loop.
For this reason the barrier will remain unpowered for most of its life.
Because of this, the input line diagnostic circuit of the barrier cannot constantly monitor the continuity of the lines.
To solve this very delicate situation, for F&G application, GM International has developed a special solenoid driver circuit which has a continuously active diagnostic circuit, while the safety function is driven by the safety PLC only (loop powered). By doing so, the mandatory feature of having zero nuisance trips is achieved together with a continuous monitoring of the input lines. To obtain a good SIL level for the safety function of these barriers it is necessary to use 1oo2 architecture, because for ND circuits the PFDavg for 1oo1 architectures is usually too high (see Chapter 5).

The analysis of this layer includes:

- Containment structures
- F&G safety instrumentations
- Analysis for the safety containments
- Wired F&G safety systems
- Computerized F&G safety systems
- F&G operating time management
- F&G diagnostic management
- F&G safety surveillance
- Organization structure of the layer.

Note:

Some plant safety engineers consider layers 6, 7 and 8 as one unique containment layer, because they state that all containment devices must be handled and managed with the same criteria and procedures.

2.9 Internal emergency plan (evacuation procedures)

Although evacuation plans are not a physical system (apart from sirens), but a set of procedures, they can be assimilated to a real layer. Failures in the procedures indeed may cause a risk for the overall safety.
Evacuation alarms are usually announced with the sound of a siren; proper means of transport are available for the safety of the personnel.
In Bhopal the sound of the siren signal had the undesired effect to attract people from outside the plant, raising the number of casualties and injuries.

The analysis of this layer includes:

- Internal scenarios analysis
- Internal emergency plan
- Internal intervention equipments
- Internal organizational structure

This layer is essentially made up of an internal organizational structure, with skilled and trained staff together with specific equipments, which are promptly used to mitigate the effects of a hazardous event inside and outside of the plant.

2.10 External emergency plan (evacuation procedures)

This is a very delicate issue. It may happen that the plant management voluntarily hides the possible hazard for the people and the environment to the authorities and citizens living around the facilities.
The external community must be instead informed about any possible hazard, and an emergency plan must be carefully prepared.
This layer considers the sequential actions to be taken in case of an emergency situation that may involve the outskirts of the plant.
It is an organized communitarian structure of authorized bodies that intervenes with coordinated actions to mitigate the dangerous effects for the residential community and for the environment.

It is obvious that inadequate responses, or the inefficiency of intervention, may lead to severe consequences, like the ones occurred in Bhopal.

Evacuation procedures should consider:

- Evaluation of external community impact
- Mapping of the area exposed to the risk
- Evaluation of intervention levels
- Organizational structure of the plan

The implementation of these procedures has to consider:

- Analysis of the external scenarios
- External emergency plan
- External intervention department
- External organizational structure

Chapter 3 Basic concepts for a better comprehension of safety standards

Some fundamental concepts for understanding safety related argumentations are presented here to ease the comprehension of Part 6 of IEC 61508, which concerns guidelines on the application of Part 2 and 3.
Some of these concepts are used in the previous Parts of IEC 61508 and for this reason, they are here recalled.
This chapter is not a complete and exhaustive presentation of all the treated subjects, but rather a manual, to "refresh" some specific arguments, or basic equations for the calculation of MTBF, PFDavg, SFF, SIL levels, etc.
Other subjects like HAZOP, FMEDA, etc., are presented at Chapter 5.

3.1 Reliability and Unreliability

3.1.1 Reliability

Reliability is a measure of success and is defined by engineers as:
"The probability that a component part, equipment, or system will satisfactorily perform its intended function when required to do so, under given circumstances, such as design limits, environmental conditions, limitations as to operating time, and frequency and thoroughness of maintenance for a specified period of time".

This definition includes four important aspects:

- The device's "intended function" must be known.
- "When the device is required to function" must be judged.
- "Satisfactory performance" must be determined.
- "Specified design limits" must be known.

All four aspects must be addressed when defining a situation to be a success or a failure.

The first aspect concerns the clear definition of what the device is asked to do, and nothing else.
The second aspect concerns the requested operability: when it will be requested to do so, not in another moment or in any moment but "on demand".
The third aspect deals with the evaluation of what the device has to do with good performances, in order to honor the demand in an acceptable way.
The forth aspect regards operability conditions in which the device works, e.g. design limits, temperature limits, etc.

The four aspects together define the terms in which reliability is evaluated.
Reliability is valid for those conditions and not for others.
If conditions change, reliability can change too.
Mathematically, reliability (R) is:
"The probability that a device will be successful in the time interval from time 0 to time t".

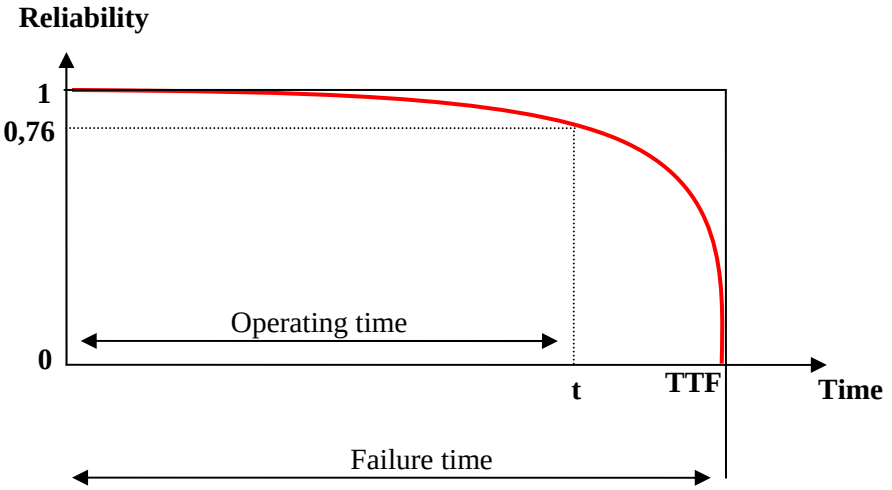


Figure 13, Reliability Figure of a device

Reliability equals the probability that TTF, failure time, is greater than t, operating time interval.
The graph in Figure 13 shows device reliability as a function of time. Increasing the time interval from 0 to TTF (estimated failure time, or TTF-Time To Fail, where the device is estimated to fail with probability close to 100%) reliability changes from 1 to 0.
At time t probability will be 76%; in other words, the operability without failure from 0 to t is 0.76.
Calculating reliabilities for a time t greater than TTF has no meaning.

Example:

A newly manufactured and successfully tested washing machine operates properly when put into service at time t = 0 (success = 1).

Since the machine will eventually fail, the probability of success for an infinite time interval is zero. Thus, all reliability functions start at a unitary probability and decrease to a probability of zero (failure).

Note 1:

Reliability is a function of operating time. A statement such as "System reliability is 0.95" is meaningless because the time interval is unknown. The statement "Reliability equals 0.98 for a mission time of 10,000 hrs" instead, makes perfect sense.

Note 2:

The reliability function graph indicated in Figure 13 is just a simple example. Reliability functions considered in this manual assume an exponential decay of failure probability, similar to those indicated below in Figure 14, where the concept of TTF, as defined limit value, is not applicable because mathematically a reliability equal to zero is never reached.

This family of curves represents the reliability function characterized by a **constant failure rate**.

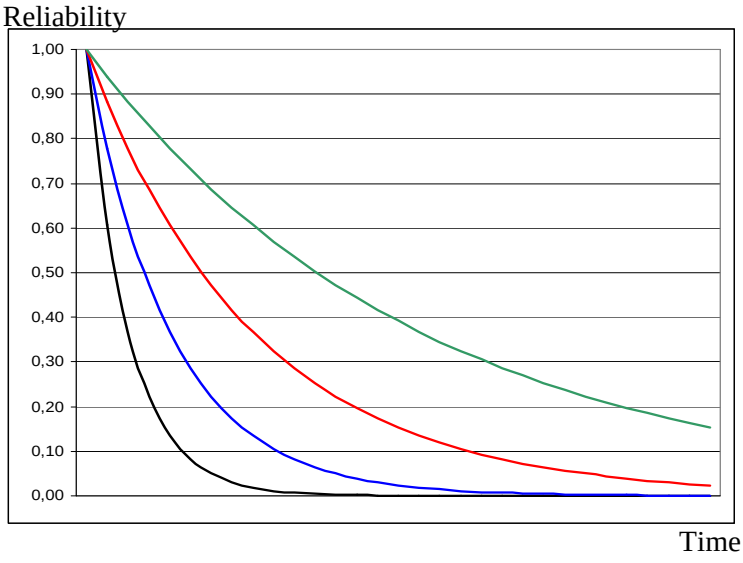


Figure 14, Device Reliability Function with exponential decay

These curves are represented mathematically by the general equation:

$$R(t) = e^{-\lambda t}$$

and have different values of λ (failure rate). They are defined at constant failure rate because the ratio between the calculated values at equal time intervals is constant:

$$\frac{R(t+\delta)}{R(t)} = f(\delta)$$

The ratio between two values of the function (the rate) depends on the time difference delta and not on the time in which the values are calculated. In other words, being δ the value of the ratio, or rate, the time is constant.
This is better defined by the following equation:

$$\frac{e^{-\lambda(t+\delta)}}{e^{-\lambda t}} = e^{-\lambda\delta}$$

in which the ratio does not depend on the time but on the value of interval δ.

Note:
It is useful to remind that representing the function of this family in a graph with logarithmic scale for values and linear scale for time, the functions will be straight.

Reliability is an important measure for those devices which are not repairable, like airplanes. Washing machines or industrial control systems are repairable and MTTF (Mean time to failure) is more likely to be used instead.

3.1.2 Unreliability

Unreliability is the measure of failure; it is defined as “the probability that a device will fail in the time interval from 0 to t”.

$$\text{Unreliability } U(t) = 1 - \text{Reliability } (t)$$

It starts with probability zero and increases up to probability one.

Example:

A controller has a reliability of 0,99 for a mission of 10,000 hrs.
What is its unreliability for the same mission time?

Unreliability = 1 – 0,99 = 0,01

A property of exponential reliability curves is the constant failure rate for values of $\lambda << 1$.
Mathematically, unreliability is defined as:

$$U(t) = 1 - R(t) = 1 - e^{-\lambda t}$$

Applying Mc Laurin's expansion equation, unreliability can also be expressed by the following:

$$U(t) = 1 - \sum_{0}^{\infty} \frac{-(\lambda t)^n}{n!} = 1 - \left[1 - \frac{\lambda}{1!} t + \frac{\lambda^2}{2!} t^2 - \frac{\lambda^3}{3!} t^3 + \ldots \right]$$

To be noticed that terms beyond λ^2 are very small, and therefore the equation can be approximated to the easier:

$$U(t) = 1 - 1 + \lambda t = \lambda t$$

This can save calculation time, however remember that approximation degrades with higher values of failure rates and interval times.

Further considerations can be made on the mean time to failure (MTTF).
Supposing a number of n devices to be analyzed with known failure rates λ and a population of n units, after time t, the number of failed units is n_F:

$$n_F = n \times \lambda \times t$$

the mean time between failures:

$$t_F = \frac{t}{n_F} = \frac{t}{n \times \lambda \times t} = \frac{1}{n \times \lambda}$$

considering just one component, n = 1, the mean time is:

$$MTTF = \frac{1}{\lambda} \quad (\text{for } \lambda << 1).$$

3.2 Availability and unavailability

Reliability assumes that the device, or system, will work successfully throughout the whole considered time interval, during which no repairs are allowed.
The term availability is introduced in order to evaluate systems which instead may be repaired and indicates the “probability that a device will be successful at a specific time t”.
If the system, or device, works, then it is available. It is not important (as it was in reliability) if it has been repaired in the past, or if it has been operating with success from the beginning without any repairing.

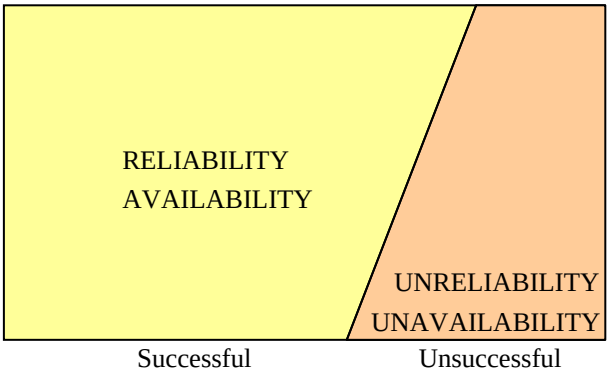


Figure 15, Venn diagram of successful-unsuccessful operations of a device

Availability is a function of failure rate, repair time, and operating time.
A good device’s availability is close to 1.

Unavailability on the other side is a measure of failure for repairable systems. It is defined as “the probability that a device is unsuccessful at time t”.

$$\text{Unavailability} = 1 - \text{Availability} = \frac{\text{Operating Time}}{\text{Operating Time} + \text{Repair Time}}$$

Example 1:
A device had a mission time of 50,000 hrs without failures, with an average repair time of 8 hrs.

Availability is: $\frac{50000}{50008} = 0.99984 = 99.984\,\%$

Example 2:
A transmitter has availability of 0.99 (99%), its unavailability (or probability to lose its availability) is 1 – 0.99 = 0.01 (1%).

As soon as the concepts of MTTF (Mean Time To Failure), and MTTR (Mean Time To Repair) will be defined in Section 3.3, the following formula will be explained:

$$\text{Availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{\text{MTTF}}{\text{MTBF}}$$

Example 3:
The availability of a transmitter which has MTTF = 2,000,000 hrs,

and MTTR = 10 hrs is: $\frac{2000000}{(2000000 + 10)} = 99.9995\,\%$

Moreover the following are valid:

$$\text{Unavailability} = 1 - \text{Availability} = 1 - \frac{\mu}{\mu + \lambda} = \frac{\lambda}{\lambda + \mu}$$

Since $\mu >> \lambda$:

$$\text{Unavailability} = \frac{\lambda}{\mu}$$

Example 4:
The transmitter of the previous example has a failure rate (λ) equal to:

$\frac{1}{2000010} = 0,0000005$ per hour and a repair rate of 0.1 / hrs

Availability is: $\frac{0,1}{(0,1 + 0,0000005)} = 0,999995 = 99,9995\,\%$

3.2.1 Ambiguity of the term “availability”

To measure and compare performances of different systems it is necessary to have common comparison terms like reliability or availability.

However, a device can fail in two different modes: safe and dangerous. Availability does not distinguish between the two and may therefore be misleading if considered the only measure of a system’s performance.
For example in the case of a 4-20 mA transmitter that is known to fail once every 5 years, it is very important to know the mode of the experienced failures, since a safe one can cause a nuisance trip, while the dangerous one may indeed cause a hazardous situation.

Difficulties in the comprehension of the term availability may also derive from the fact that even a very small difference in measure is very meaningful when evaluating the system.
For example, 99% and 99,99% are very close numbers but indeed, the availability differs for two orders of magnitude.

There are other situations in a plant generating ambiguity in the comprehension of the term availability:

- The plant works perfectly and so the safety instrumented system.
- The safety system experiences a safe failure (nuisance trip), the production has been stopped and SIS is available.
- The SIS has experienced a dangerous failure. The plant is available and production continues, but the SIS is not available and consequently it cannot bring the process to a safe state, shutting down the plant, if demanded.

In these cases the term availability for the productive plant and for the SIS will not have the same valence.

Availability time (hours)	**Repair time (hours)**	**Availability (%)**
1000	10	99
10000	10	99,9
100000	10	99,99
1000000	10	99,999

What does an availability of 99,99% for a specific component or system really stand for? That the component or system could stop working one time ..

- .. every month with a repair time of 4.3 minutes.
- .. every year with a repair time of 53 minutes.
- .. every 10 years with a repair time of 8.8 hours.

In all cases the availability is 99,99% , but from the plant manager's point of view it would rather be more interesting to have information about the number of nuisance trips that the plant could have in 5, 10, or 20 years.

Indeed, even if the repair time was a few minutes, the shutdown and startup of the plant have high costs. The final user wants to know how frequently this can happen. For this reasons, knowing MTTF (the average time to a functional failure) contributes to a more detailed overview.

The Risk Reduction Factor (RRF)[1] can also be used to qualify the performance of a safety system or of a component:

$$RRF = \frac{1}{PFDavg}$$

PFDavg	Safety availability (1 – PFDavg)	RRF (1 / PFDavg)
0.1	90 %	10
0.01	99 %	100
0.001	99.9 %	1000
0.0001	99.99 %	10000

The difference between 0.1 and 0.001 may pass unobserved, as well as between 99% and 99.99%, while the difference between 10 and 1000 is immediately evident to everybody.

Both reliability and availability of a safety instrumented system are in relation with the average value of PFD (PFDavg), also called average probability of failure on demand.

[1] RRF: see Sections 5.3 and 6.2

PFDavg and RRF are expressed as:

$$\text{PFDavg} = \frac{\text{Frequency of tolerable accidents}}{\text{Frequency of accidents without protections}}$$

$$\text{RRF} = \frac{1}{\text{PFDavg}} = \frac{\text{Frequency of accidents without protection}}{\text{Frequency of tolerable accidents}}$$

The calculation of PFDavg can be found in the following Sections.

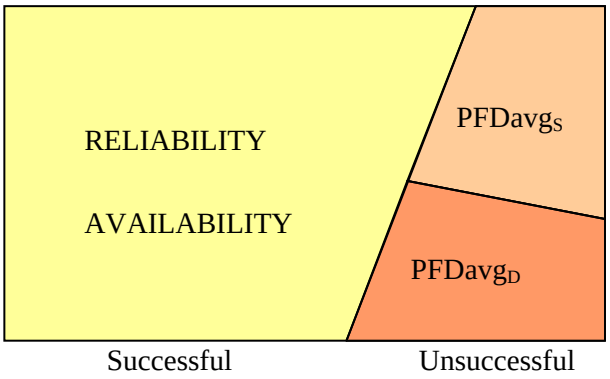


Figure 16, Venn diagram for successful and unsuccessful operation of a device

$$\text{Total Availability} = 1 - \text{PFDavg}_s - \text{PFDavg}_D$$

$$\text{Safety Availability} = 1 - \text{PFDavg}_D$$

Where:

- PFDavg$_s$: average probability on demand to the SIS for safe failures.
- PFDavg$_d$: average probability on demand to the SIS for dangerous failures.

Example:

A SIF is characterized as follows:

$\text{PFDavg}_S = 0.001/\,yr$; $\text{PFDavg}_D = 0.0001/\,yr$

Total availability = 1 – (0.001 + 0.0001) = 0.9989 = 99.89 %

Safety Availability = 1 – 0.0001 = 0.9999 = 99.99 %

3.2.2 Achievable Availability

For maintenance engineers, what has been said so far about availability is correct but the delay caused by the operators and the acquisition of the spare material was not yet taken into account.
For this reason Achievable Availability considers the average time between two maintenance intervals as operating time.
In achieved availability, the mean time between maintenance (MTBM) is used as a measure of uptime and includes both unplanned and planned maintenance. The expected mean system down time includes *unplanned* and *planned (preventive/predictive)* maintenance, but does *not* include supply or maintenance resources delays.
Achieved availability fulfills the need to distinguish availability when planned maintenance shutdowns are included, whereby it assumes zero supply and maintenance resources delay times.

$$\text{Achievable Availability} = \frac{\text{MTBM}}{\text{MTBM} + \text{MSD}_1}$$

- MTBM: Mean time between maintenance.
- MSD_1: Expected mean system down time.

The calculation of Achieved Availability is used to program the maintenance turnaround (shutdown) of the plant, supposing all the required spare parts for the operations to be in stock.

3.2.3 Operational Availability

$$\text{Operational Availability} = \frac{\text{MTBM}}{\text{MTBM} + \text{MSD}_2}$$

Operational availability is similar to achieved availability, but in the expected mean downtime of the operational availability also the spare parts supply delay and the delay of maintenance resources are included.
This calculation is required to isolate the total effectiveness and efficiency of maintenance operations.

Note:
MTBM and MSD can be expressed in man hours or in calendar days.

3.3 MTTF, MTTR, MTBF and their relations

MTBF (Mean Time Between Failure) is a term which applies only to repairable devices or systems. Like MTTF (Mean Time To Failure) and MTTR (Mean Time To Repair) it is an average value.
MTBF is the time between failures and implies that a component has failed and then has been repaired.
Mathematically:

$$MTBF = MTTF + MTTR$$

$$MTTF = MTBF - MTTR$$

Usually component or system suppliers for a SIF provide the value of MTBF and not MTTF. Being MTTR usually much smaller than MTTF, the two terms MTBF and MTTF have approximately the same value.
However the measurement of successful operation is better described by MTTF instead of MTBF.

Example:

An electronic device has the following data:

MTBF = 3,000,000 hrs;
Average Repair Time = 8 hrs.

MTTF = 2,999,992 hrs

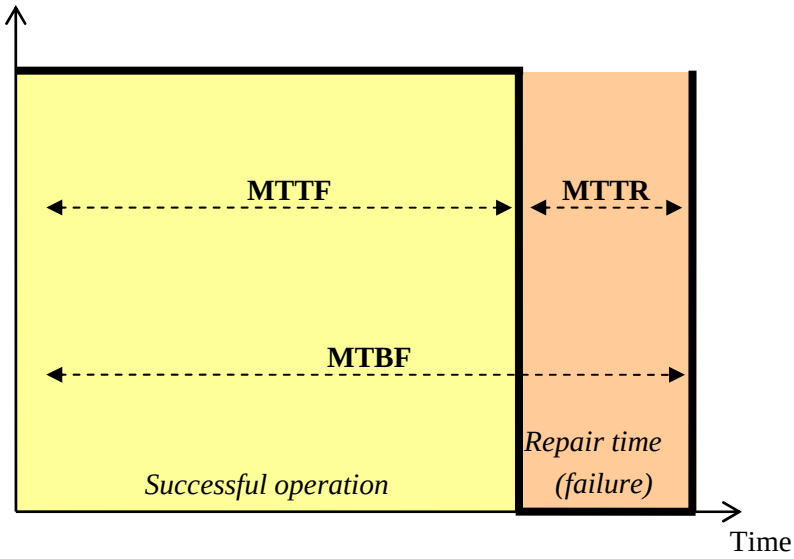


Figure 17, Schematic representation of MTTF, MTTR, MTBF

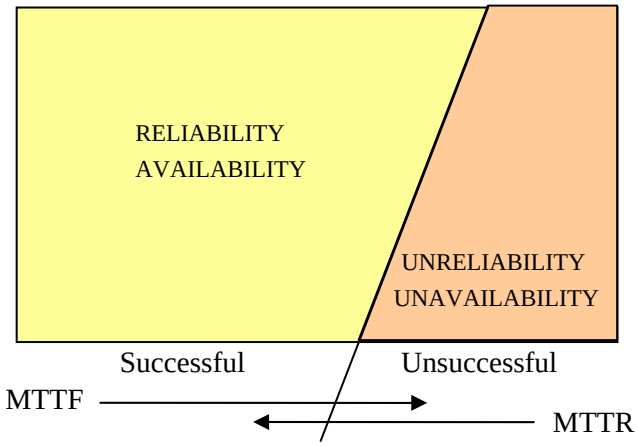


Figure 18, Venn Diagram: Reliability-Unreliability; Availability-Unreliability and relations with MTTF and MTTR

Many people consider MTBF to be the estimated life of the device, but this is not true.

For example, MTBF = 1000 yrs is a number perfectly valid for an electronic device, even though nobody expects the device to last for 1000 years.
The number means that out of a total of 1000 devices, one device is supposed to fail within a one year period.

A classical example that illustrates how MTBF and life are not the same is a match. When using dry matches and the proper technique to light them, a few failures can occur. Therefore the failure rate (failures per unit time) is generally a low value.
The reciprocal, MTBF, is a large number, for example several minutes. But a match's operating life lasts only a few seconds.

As discussed at Section 3.4.2 at page 48, SIS failure rates can be divided in:

- "**safe**", which do not have the potential to put the system in an hazardous, or fail to function, state;
- "**dangerous**" which have the potential to put the system in an hazardous, or fail to function, state.

The total failure rate is therefore given by the sum of the two:

$$\lambda_{TOT} = \lambda_S + \lambda_D$$

This separation is always necessary for both single components and systems.
For a system in fact, safe failures may initiate nuisance trips that may also shutdown the plant when nothing is actually wrong. Granted, there is nothing "safe" about a nuisance trip, they tend to be expensive in terms of loss of production. When systems suffer too many safe failures, people lose confidence in them, and the system may be bypassed as a result.
Remember that the availability of a bypassed system is zero.
Accidents can happen because sensors or systems are placed in bypass while the process instead is allowed to run.

Consequently it is possible to calculate:

- $MTBF_{TOT} = \frac{1}{\lambda_{TOT}}$
  (general component or system reliability indicator)
- $MTBF_S = \frac{1}{\lambda_S}$
  (nuisance trip indicator, caused by safe failures).
- $MTBF_D = \frac{1}{\lambda_D}$
  (safety unavailability indicator)

Example:

Suppose $\lambda_S = 0.1$ / year and $\lambda_D = 0.01$ / year:

$$MTBF_{TOT} = \frac{1}{0.101} = 9.9 \text{ yrs}\,;\ MTBF_S = \frac{1}{0.1} = 10 \text{ yrs}\,;\ MTBF_D = \frac{1}{0.01} = 100 \text{ yrs}$$

This simple example shows how nuisance trips can be more expensive than those caused by dangerous failures. It is therefore also very important to pay attention to so-called "safe" failures.

3.4 Failure Rate

Failure rate, often called “hazard rate” by reliability engineers, is a commonly used measure of reliability. It indicates the number of failures per unit time, for a quantity of components exposed to failure.

$$\text{Failure Rate} = \lambda = \frac{\text{Failures per unit time}}{\text{Number of components exposed to functional failure}}$$

It is common practice to use units of “failure per billion” $1x10^{-9}$ per hour, known as FIT: Failure In Time ($1x10^{-9}$ per hour).
A failure rate of 20 FIT means both that

- there are 20 probabilities of failure in a billion working hours,
- there is a probability of functional safety failure equal to 20 billionth per working hour.

Example 1:

An Integrated Circuit (IC), in specified working conditions of 40 °C, has shown 7 functional failures for one billion hours mission.
This IC has a failure rate of 7 FIT ($7x10^{-9}$ per hr).

Example 2:

300 industrial I/O modules have been operating in a plant for 7 years. 5 failures have occurred. The average failure rate for this group of modules is:

$$\lambda = \frac{5}{300 \times 7 \times 8760} = 0.000000271798 = 272\,\text{FIT} = 272 \times 10^{-9} \text{ per hour}$$

To simplify and approximate the calculation it is possible to assume 10000 hrs per year instead of 8760:

$$\lambda = \frac{5}{300 \times 7 \times 10000} = 0,00000023809 = 238\,\text{FIT} = 238 \times 10^{-9} \text{ per hour}$$

Other people prefer to use years instead of hours as unit time, so in the above example the result is:

$$\lambda = \frac{5}{300 \times 7} = 0.00238 \text{ per year.}$$

“FIT per hour” is usually the best indication for very low failure rates, while “failures per year” is preferred when dealing with high failure rates.

Example 3:

In the previous example the failure rate of the I/O modules is 272 FIT.
What is the MTTF of the modules?

$$\text{MTTF} = \frac{1}{272 \times 10^{-9}} = 3676470\,\text{hrs} = 420\ \text{yrs}$$

The failure probability of an electrical device decreases exponentially in time, as previously discussed and, with approximation, is:

$$P \approx \lambda \times t$$

Example 4:

A device, with exponential probability of failure, has a failure rate of 500 FIT.
How many probabilities of failure are there in one year?

$$P \approx \lambda \times t \approx 0{,}0000005 \times 8760 = 0{,}00434 / yr$$

3.4.1 Components with constant failure rate

Figure 19 presents the famous "bathtub curve", generally accepted to represent the reliability of electronic devices. Mechanical devices tend to have slightly different curves.
The left portion of the curve shows the impact of "infant mortality"; the right portion shows the "wear out" failures.
A constant failure rate is represented by the middle flat portion of the curve.
This assumption tends to simplify the math involved, but until the industry comes up with more accurate models and data, the simplification can be accepted.

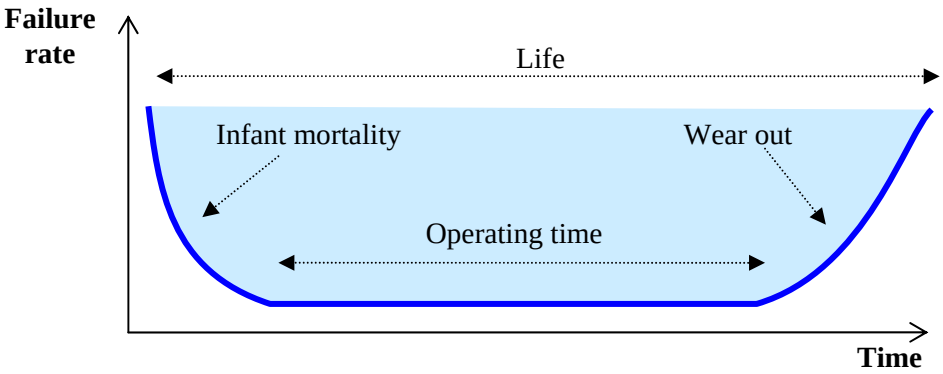


Figure 19, Example of failure rate function of time (life) (bathtub curve)

The failure rate is the reciprocal of MTTF:

$$\lambda = \frac{1}{MTTF} \qquad MTTF = \frac{1}{\lambda}$$

For repair times much smaller than success time:

$$\lambda = \frac{1}{MTBF} \qquad MTBF = \frac{1}{\lambda}$$

Example:

Supposing λ = 0,000000238 FIT/ hr, calculate the approximate value of MTBF:

$$MTTF(MTBF) = \frac{1}{\frac{0.000000238}{10000}} = 420\,\text{yrs}$$

All reliability analyses for a device or system are based on the device, or system, failure rate data.

In any engineering discipline, the ability of recognizing the required degree of accuracy is essential. Simplifications and approximations are useful when they reduce complexity and allow a model to become understandable.
Therefore the judgment, and consequent technical decisions, in many situations should follow the experience and the logic sense of expert engineers. More detailed calculations could result in a waste of time.

One simple example: if the risk analysis made for a specific SIF of a SIS, has indicated that the required risk reduction factor (RRF) is 45, further studies to obtain a value of 55 are meaningless because both indicate a coherent value with level SIL 1 (RRF from 10 to 100).

3.4.2 Failure rate Categories

It is assumed that component failure rates are constant and, in non redundant PEC equipment, statistically independent. While these assumptions are not always realistic, they are reasonable and conservative for the “useful life” period of the electronic components used in PEC equipments.
Failures are first grouped into the two significant categories: safe and dangerous.

$$\lambda_{TOT} = \lambda_S + \lambda_D$$

Dangerous failures are those which cause the loss of the system’s functional safety (or safe state). In a normally-energized system (like ESD) safe failures are defined as those that erroneously de-energize the output. Dangerous failures instead prevent the output from being de-energized. For example, in a DI (digital input circuit) with relay output, it has been defined that the safe state, in case of circuit functional failure, is a ND relay (normally de-energized). Dangerous failures in this case are the ones that prevent the relay from being de-energized.

Each failure category is further partitioned into failures that are detected by the on-line diagnostics versus the ones that are not.

- Failures (Detected);
- Failures (Undetected);

$$\lambda_D = \lambda_{DD} + \lambda_{DU}$$
$$\lambda_S = \lambda_{SD} + \lambda_{SU}$$
$$\lambda_{TOT} = \lambda_{DD} + \lambda_{DU} + \lambda_{SD} + \lambda_{SU}$$

Where:

λ_{DD}: dangerous detected failure rates;
λ_{DU}: dangerous undetected failure rates;
λ_{SD}: safe detected failure rates;
λ_{SU}: safe undetected failure rates;

Failure rate categories are used to calculate the value of SFF (Safe Failure Fraction, see 6.4.3 at page 158), which is important for calculating Safety Integrity Levels (SIL).

$$SFF = \frac{\sum \lambda_{DD} + \sum \lambda_{SD} + \sum \lambda_{SU}}{\sum \lambda_{DD} + \sum \lambda_{DU} + \sum \lambda_{SD} + \sum \lambda_{SU}} = 1 - \frac{\sum \lambda_{DU}}{\sum \lambda_{DD} + \sum \lambda_{DU} + \sum \lambda_{SD} + \sum \lambda_{SU}}$$

From this simple expression it is evident that to increase the percentage value of the SFF, and consequently the SIL level, it is necessary to decrease the value of λ_{DU} (dangerous undetected failures).

Example:
Suppose the following values:
λ_{DD} = 0.14 / year; λ_{DU} = 0.04 / year; λ_{SD} = 0.22 / year; λ_{SU} = 0.5 / year

$$SFF = 1 - \frac{0.04}{0.9} = 0.955 = 96\%$$

In case of λ_{DU} = 0.4 /year:

$$SFF = 1 - \frac{0.4}{1.26} = 0.682 = 68\%$$

By defining the term C, "diagnostic coverage" as the built-in self testing capability of a system, it is also possible to define the probability that a failure will be detected given that it occurs, by the diagnostic coverage factors C_D and C_S in the following equations:

$$\lambda_{DD} = C_D \times \lambda_D$$
$$\lambda_{DU} = (1 - C_D) \times \lambda_D$$
$$\lambda_{SD} = C_S \times \lambda_S$$
$$\lambda_{SU} = (1 - C_S) \times \lambda_S$$

Where:

- C_S : diagnostic coverage of safe failures
- C_D : diagnostic coverage of dangerous failures

A coverage factor must be obtained for each component in the system in order to separate detected from undetected failures.

3.4.3 Dependent, or common cause, failures

Part "4" of IEC 61508 standard defines a common cause failure as a "*failure, which is the result of one or more events, causing coincident failures of two or more separate channels in a multiple channel system, leading to system failure*".

These failures have a significant effect on reliability and safety of a SIS, and therefore must be considered in the reliability and safety model.

The four failure rate categories can be further specified in:

- **SDN** - (Safe, detected, normal cause).
- **SDC** - (Safe, detected, common cause).
- **SUN** - (Safe, undetected, normal).
- **SUC** - (Safe, undetected, common cause).
- **DDN** - (Dangerous, detected, normal).
- **DDC** - (Dangerous, detected, common cause).
- **DUN** - (Dangerous, undetected, normal).
- **DUC** - (Dangerous, undetected, common cause).

3.4.4 Common cause failures and Beta factor

The Beta model divides component failure rates in:

- **normal** mode failure rate λ_N (fault of one component only);
- **common** mode failure rate λ_C (fault of two or more components);

β	**(1 – β)**
Two or more components fault for stress	one component fault for stress
Common cause	Normal cause
$\lambda_C = \beta \times \lambda$	$\lambda_N = (1-\beta) \times \lambda$

Figure 20, Failure rates subdivision in common and normal mode (Beta factor)

The rectangle's total area represents failure rate (λ).
On the left, the stress is strong enough to produce a failure of two or more components as consequence of the same cause.
To put the two groups in relation, the following equations are used:

$$\lambda_C = \beta \times \lambda$$
$$\lambda_N = (1-\beta) \times \lambda$$

The four failure rate categories SU, SD, DU and DD are divided into the Beta model as follow:

$$\lambda_{SDN} = (1-\beta) \times \lambda_{SD}$$
$$\lambda_{SDC} = \beta \times \lambda_{SD}$$
$$\lambda_{SUN} = (1-\beta) \times \lambda_{SU}$$
$$\lambda_{SUC} = \beta \times \lambda_{SU}$$
$$\lambda_{DDN} = (1-\beta) \times \lambda_{DD}$$
$$\lambda_{DDC} = \beta \times \lambda_{DD}$$
$$\lambda_{DUN} = (1-\beta) \times \lambda_{DU}$$
$$\lambda_{DUC} = \beta \times \lambda_{DU}$$

The values of beta factor can be different for each group and their calculation is not simple, therefore usually only one value is used.

3.5 Safety analysis for SIL level selection: Modeling methods

There are a number of methods available for estimating the performance of systems. Some of the more commonly used are:

- Reliability block diagrams.
- Fault tree analysis.
- Markov diagrams.

The first two models combine the probability of component failures to obtain the probability of failure for the entire system.
Markov modeling involves transition diagrams and matrix math which consider the conditions of the single components and evaluate the probability basing on state transitions.

3.5.1 Reliability block diagrams

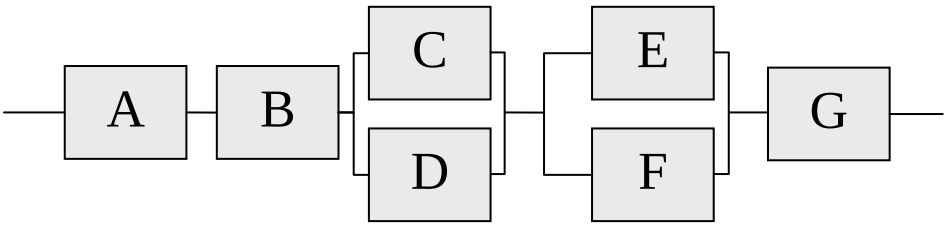


Figure 21, Example of reliability block diagrams

These diagrams help clarifying configuration and operation of the analyzed system by represent the function composition with only reference to the reliability of the components.
Generally, block diagrams and their associated math do not handle time dependent variables such as repair time, test interval, diagnostics, and more complex redundant systems.

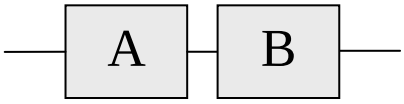
3.5.1.1 Basic theory

For blocks connected in series, a fault in any one of them, determines a fault in the chain. In such systems the probability of success (reliability) is determined for first and consequently the probability of unsuccess (unreliability). Assuming:

R_A = block A reliability = 0,99
U_A = block A unreliability = 0,01
R_B = block B reliability = 0,98
U_B = block B unreliability = 0,02
R_S = system reliability
U_S = system unreliability

There is a 0.99 probability that block A is successful and 0.01 (=1- 0.99) that the block is not successful (fault); then there is a 0,98 probability that B is successful and 0,02 that it is not:

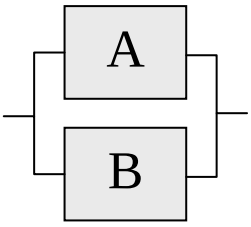
$R_S = 0.99 \times 0.98 = 0.9702 = 97.02\%$
$U_S = 1 - R_S = 1 - 0.9702 = 0.0298 = 2.98\%$



$$R_S = R_A \times R_B$$
$$U_S = 1-(1-U_A)\times(1-U_B) = U_A + U_B - U_A \times U_B$$

Being $U_A \times U_B << U_A + U_B$ it can be said that in case blocks are connected in **series**, reliabilities are multiplied and unreliabilities are added.

$$R_S = \prod R_X$$
$$U_S = 1 - R_S$$



For blocks connected in **parallel** the behavior is the opposite: reliabilities are added and unreliabilities are multiplied.

$$U_S = \prod U_X$$
$$R_S = 1 - U_S$$

In Figure 21, the system fails if either A or B or G, or the parallels C-D or E-F fail; each parallel fails if both blocks fail.
Supposing probability values of single blocks to be very low, the calculation of reliability and unreliability values, end up in additions and multiplications of probability of failure for single blocks.
Probabilities of blocks A, B and G, are added, while probabilities of
C, D, E and F are multiplied, and consequently the total system probability of failure (unreliability) is:

$$P_S = P_A + P_B + P_G + (P_C \times P_D) + (P_E \times P_F)$$

3.5.2 Fault tree analysis

Fault Tree Analysis (FTA) is a top-down qualitative approach originally used to identify failures in complex systems.
A fault tree analysis begins with the "top event" which is the result of a number of basic events that contribute to, or initiate, the system failure.
The logic of a fault tree is displayed by the symbols that represent the basic events and gates that logically relate those events.
Each common fault tree symbol represents a type of event or a logical relationship.
The fault tree method is used to find combination of failures that may cause problems and helps the analyst focus on one failure type at a time, by identifying which parts of a system are related to a particular failure.
Fault tree analysis can be a very powerful tool for analyzing the frequency or probability of an accident or failure of a piece of equipment when simple probability math alone cannot determine the outcome.
This type of analysis not only represents the way events are logically related but can also quantify the probability of those events. Additional analyses allow the determining of various parameters such as the importance, uncertainty and sensitivity of the system.

This type of analysis can provide elements for the determination of SIL level as required in a SIS.

3.5.2.1 Symbols and examples of fault tree events

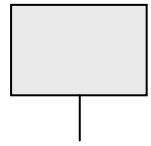
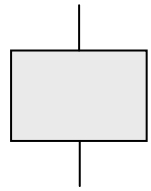
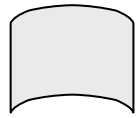
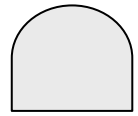
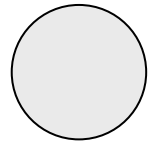
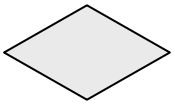
	**Top event or resulting fault:** **Unwanted event subject of the analysis**
	**Intermediate event:** A failure state as consequence of other events which operates through logic gates
	**OR gate:** The output of an OR gate is active if any of the inputs are active. Quantitatively output probabilities are calculated adding input probabilities.
	**AND gate**: The output of an AND gate is active if all the inputs are active. Quantitatively output probabilities are calculated multiplying input probabilities.
	**Basic event**: A basic fault or an event which does not require further analysis because its failure rate can be determined.
	**Undeveloped event:** An event or fault which does not require further development, often because its probability is very low.

Figure 22, Typical fault tree symbols

Figure 22 shows some of the symbols commonly used in fault trees to describe the logical relationships in a related model.
There are other symbols like NAND, NOR and others for voting relations like diamonds, used to indicate an incomplete event, that are not of interest to the analysis. Triangles for transfer In or Out. The hexagon symbol is called an inhibit gate and it is functionally similar to a two-input AND gate except that it indicates an event that is not necessarily a direct cause.

To understand their use, the following two examples are presented:

Example 1:
Analysis of a power supply system made of two independent power supplies. The system includes two independent paralleled power supplies, constructed with different techniques, to avoid common cause failures ($\beta = 0$).

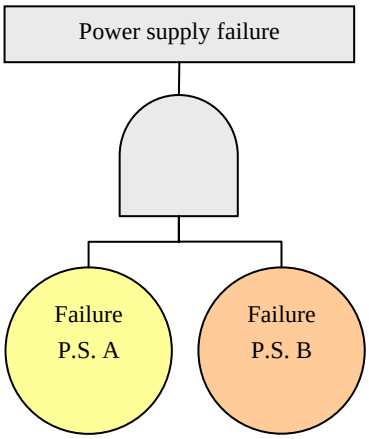


Figure 23, Fault tree events for a power supply system (example 1)

Failure probability for A is 0.02 / year, and 0.1/ year for B.
What is the probability of system failure in one year of continuous operation?

P = 0.02 x 0.1 = 0.002 / year

Example 2:
Analysis of a power supply system made of two identical power supplies connected in parallel, made by the same supplier and independently wired.

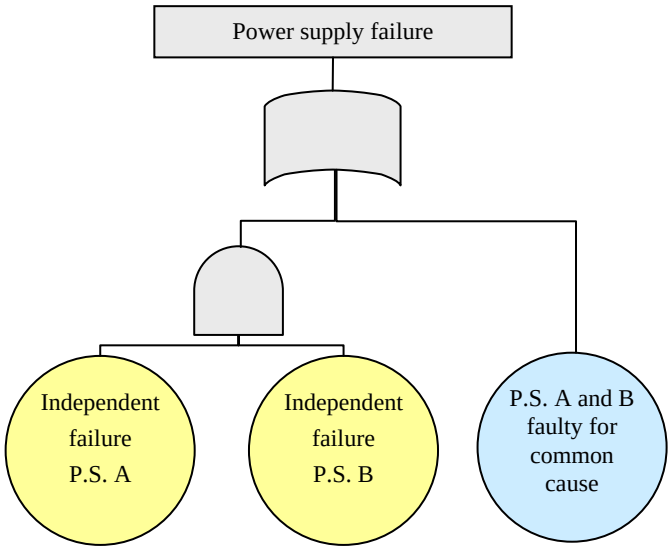


Figure 24, Fault tree events for a power supply system (example 2)

Failures probability for A and B are 0.02 / year, and 5% of failures are due to common causes ($\beta = 0.05$).
What is the probability of system failure in one year of continuous operation?

P(A) for independent failure = 0.02 x (1-0.05) = 0.019 / year.

The same is for P(B) = 0.019 / year.

The probability that A and B will fail for common cause is 5% of the failure rate because independent failures and common cause failures are mutually exclusive. Therefore:

P(AB) for common cause = 0.02 – 0.019 = 0.001 / year.

The probability that B will fail independently, is the difference between its probability and the one of common cause:

P(B) for independent failure = 0.02 – 0.001 = 0.019 / year.

The probability at the output of AND gate is the multiplication of the two input probabilities:

P(A) and P(B) independent = 0.019 x 0.019 = 0.000361 / year.

Because the inputs at OR gate are mutually exclusive, the output probability is the addition of the two input probabilities:

P(system) = 0.001 + 0.000361 = 0.001361 / year.

Note:

If the system is evaluated without common cases ($\beta = 0$), the probability of failure is 0.02 x 0.02 = 0.0004.

Adding 5% of common cause increases the probability of system failures of 3.4 times (0.001361 / 0.0004 = 3.4).

3.5.3 Markov diagrams

Markov diagrams are the most used in reliability and safety calculation.
It is therefore useful that also "non reliability engineers" gain some knowledge on this subject.
These diagrams are recommended by IEC 61508, IEC 61511, and also by the draft standard ATEX prEN 50495 ("*Safety devices required for safe functioning of equipment with respect to explosion risks*").

Andrei Andreyevich Markov (1856-1922), a Russian mathematician, studied probability while teaching at San Petersburg University in the late 1800s.
He defined the "Markov process" in which the future variable is determined by the present variable being dependent from the predecessor.
This process, explicated through diagrams, is used for reliability calculations of complex architectures where block diagrams are not practicable.

The presented diagrams work with a discrete time variable. This method can be conveniently applied to the failure/repair process since combinations of failures create discrete system states. In addition, the failure / repair process moves between discrete states only as a result of its current state and failure.

The scope is to determine the probability that a system results to be in a certain state at time t + 1, knowing its probability at time t and the transition rate between the states.

The diagrams describe the system using two symbols only:

- **States**, shown as circles;
- **Transition**, shown as oriented arcs.

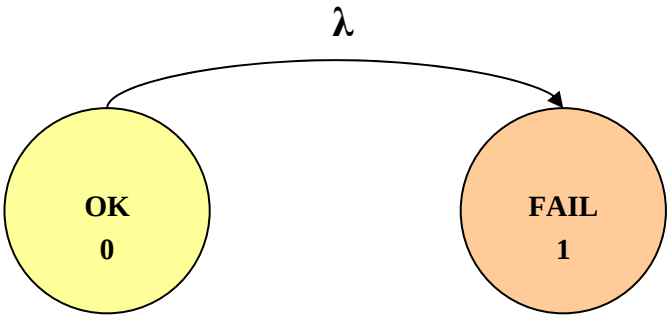


Figure 25, Markov model for a system with two states and one transition (single non-repairable component)

States are labeled starting from "0" and are sometime associated with a brief description, while arrows are associated with formulae or rate values.
The probability of the system to change its state is indicated in the arrow connecting the two states.

Figure 25 shows a single non repairable device diagram, and indicates that:

- there are only two states in the system: 0 (Success) and 1 (Failure)
- only one transition is possible from 0 to 1 with λ failure rate.

Each state has its own probability: P0 and P1.

For example a time interval of one hour and λ = 0.1 per hr are supposed.
Initially the system starts from state 0 (Ok) and P0 = 1, P1 = 0. After one hour, it has completed an entire cycle, (in this particular case consisting of only one transition), and the percentage λ of the 0 state probability has added to the probability of state 1:

$P0(1) = (1 - \lambda) \times P0(0)$
$P1(1) = P1(0) + \lambda \times P0(0)$

The following Table shows the system evolution in the first 10 cycles, while the graphic represents the two probabilities after a great number of cycles.

Probability of system being in state	
0 – OK (device is successful)	**1 – FAIL (device has failed)**
1.00	0.00
0.90	0.10
0.81	0.19
0.73	0.27
0.66	0.34
0.59	0.41
0.53	0.47
0.48	0.52
0.43	0.57
0.39	0.61
0.35	0.65

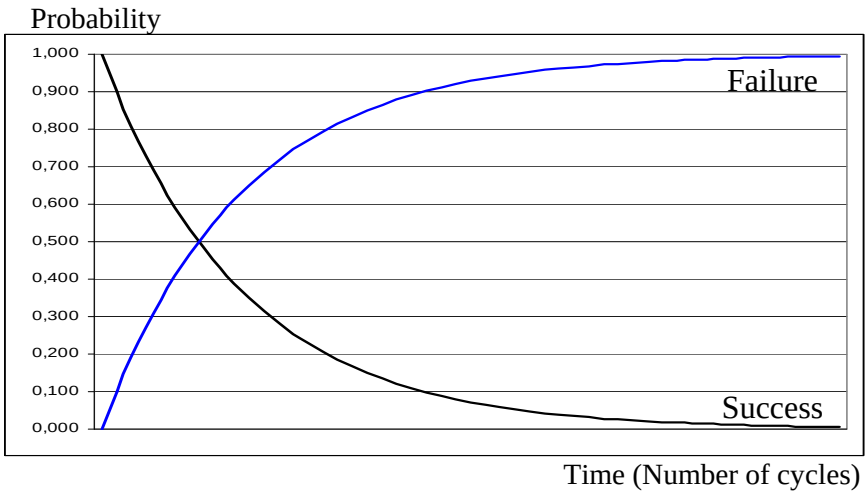


Figure 26, States probabilities for great number of cycles for a single non-repairable device

Repeating the process infinitely the probability of the system being in state 0 tends to zero, while the probability of the system being in the state 1 tends to one.

This is explained by the existence of an "absorbing state" P1, in which it is possible to arrive but not get out.

The graphic obtained represents the system reliability and unreliability with constant failure rate λ.

A single repairable device with one failure mode, two states and two transitions, is shown in Figure 27.

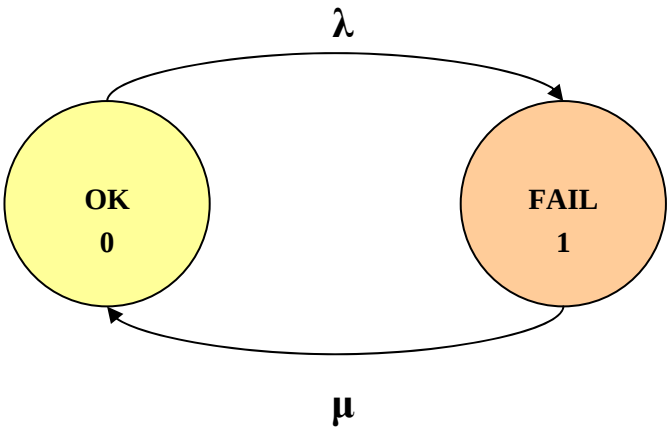


Figure 27, Markov model for a system with two states and two transitions (single repairable device)

In this system there are two possible transitions:

- from 0 to 1 with failure rate λ and
- from 1 to 0 with repair rate μ.

Initially, the system starts from the state 0 (Ok) and P0 = 1, P1 = 0. After one hour, the system has completed one entire cycle, (in this particular case two transitions) and the probabilities of each state are:

$P0(1) = (1 - \lambda) \times P0(0) + \mu \times P1(0)$
$P1(1) = \lambda \times P0(0) + (1 - \mu) \times P0(1)$

After each cycle, a λ percentage of P0 probability has moved to P1 and a μ percentage of P1 probability has moved to P0.

The following Table shows the system evolution after the first 10 cycles, assuming a time interval of one hour, λ = 0.1 per hr, μ = 0.3 per hr. The graphic represents the two probabilities after a great number of cycles.

Probability of system being in state	
0 – OK (device is successful)	**1 – FAIL (device has failed)**
1,00	0,00
0,90	0,10
0,84	0,14
0,81	0,19
0,77	0,23
0,74	0,26

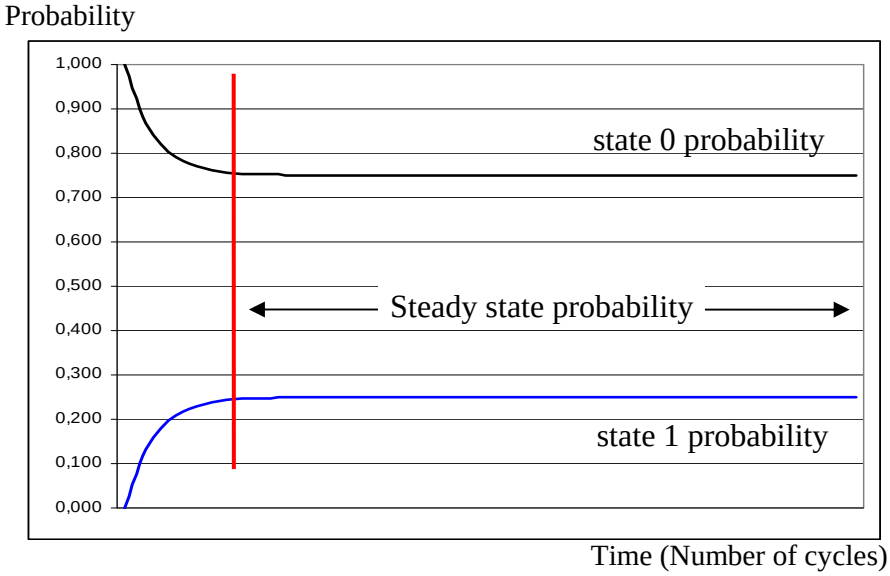


Figure 28, States probability for great number of cycles and for a single repairable device

Repeating the process infinitely, the probability of the system to be in state 0 tends to 0.75, while the probability of the system to be in state 1 tends to 0.25. This because, in this case, from state 0 and state 1 it is possible to "get out" and consequently the system finds an equilibrium when the probability contributions, exchanged between the states, are equal (c).

The graphic obtained represents the system availability and unavailability with constant failure rate λ, and constant repair rate μ.

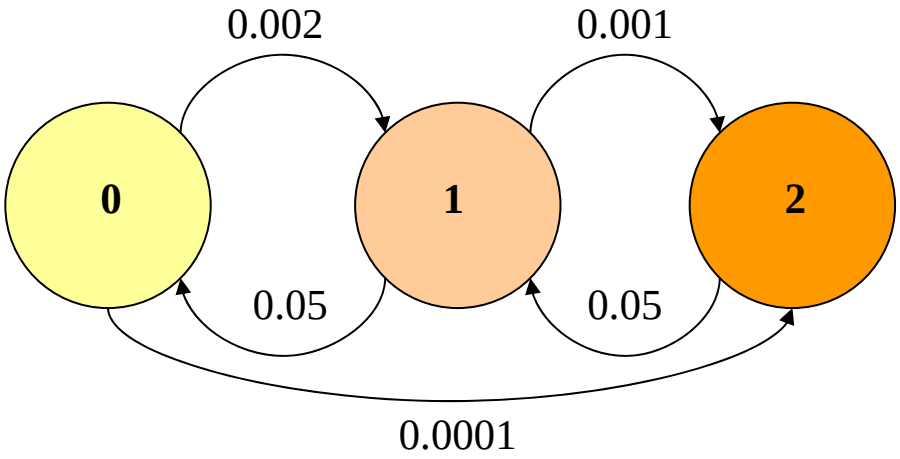


Figure 29, Markov diagram for a system with 3 states and 5 transitions

Figure 29 above represents a system with 3 states and 5 transitions. Single probability rate values are indicated on the arcs.
The diagram regards two devices (subsystems), in a 1oo2 architecture, in which common failure rates are also taken into account.

The following rate values are assumed:

- λ_N normal failure rate 0.0010 per hr
- μ repair rate 0.0500 per hr
- λ_C common failure rate 0.0001 per hr

There are 3 states:

- 0 – Successful both subsystem are functioning successfully
- 1 – Fail 1 one of the two subsystems has failed
- 2 – Fail 2 both subsystems have failed

and 5 transitions:

- 0 → 1: one of the two components fails with failure rate 2 x λ_N (2 because two are the components that can fail in the 0 state)
- 0 → 2: both subsystems can fail for common causes with failure rate λ_C
- 1 → 0: the component which has failed is repaired with repair rate μ (in state 1, one subsystem only fails)
- 1 → 2: The second component fails with failure rate λ_N (only one because the other, in state 1, is already in fail state)
- 2 → 1: one of the two failed subsystems are repaired with repair rate μ.

It is assumed that repairs will be done one at a time, this to justify the absence of the transition between 2 and 0 states, and its consequent null rate value.

The following Table represents the calculation of the transitions. Rows indicate the starting state, columns the arrival state, and in the cells the value of rates associated with the transitions.

	To state 0	**To state 1**	**To state 2**
From state 0		0.0020	0.0001
From state 1	0.0500		0.0010
From state 2	0.0000	0.0500	

The table has 3 rows and 3 columns and consequently 9 transition rate values.
In general, for n states, the Table has n rows and n columns with n^2 transition rate values.
Cells on the principal diagonal (from top left to bottom right) do not contain values so far: in the diagram they are not indicated.
These values represent the rate of the state transition towards itself.
Moreover the sum of state transition rates is always unitary, because it has to cover the total transitions of such state.
This allows the calculation of the state transition towards itself, in such a way that the sum of each row is always unitary.
The following Table is consequently obtained:

	To state 0	**To state 1**	**To state 2**
From state 0	0.9979	0.0020	0.0001
From state 1	0.0500	0.9490	0.0010
From state 2	0.0000	0.0500	0.9500

At this point the Table is complete and it contains all transition rates. Null values would indicate that the transition is not possible.

Obtained values can be used to create the so called, **transition matrix P**.

The following Table shows the probabilities of the system to be in one of the three states at a given time:

System probability to be in state		
State 0	State 1	State 2
1.000	0.000	0.000

This table, called **state matrix**, is usually indicated as **S**, and contains, in this moment, the initial state when the system starts with probability 1 of being in state 0.
It is now interesting to understand how state probabilities will change at the next cycle. If, for example, at time t = 123 hr, state probabilities were [0.8; 0.1; 0.1], what will they be at t +1 (124 hr)?

These values are indicated by the following three equations:

$$S_0^{124} = 0{,}9979 \times S_0^{123} + 0{,}0020 \times S_1^{123} + 0{,}0001 \times S_2^{123}$$
$$S_1^{124} = 0{,}0500 \times S_0^{123} + 0{,}9490 \times S_1^{123} + 0{,}0010 \times S_2^{123}$$
$$S_2^{124} = 0{,}0000 \times S_0^{123} + 0{,}0500 \times S_1^{123} + 0{,}9500 \times S_2^{123}$$

Observing the first equation, for instance, it can be noted that the system's probability at time 124 hr to be in state 0, is the result of three contributions:

- 0.9979 rate to have no transition (0 → 0)
- 0.0020 rate to have the transition 1 → 0
- 0.0001 rate to have the transition 2 → 0

Markov diagrams allow the calculation of state probabilities at a given time t+1 when the probability at time t+0 and the matrix of transition rates is known. The three equations can be mathematically expressed as:

$$\left[S_0^{124}\ S_1^{124}\ S_2^{124}\right] = \left[S_0^{123}\ S_1^{123}\ S_2^{123}\right] \times \begin{bmatrix} P_{00} & P_{01} & P_{02} \\ P_{10} & P_{11} & P_{12} \\ P_{20} & P_{21} & P_{22} \end{bmatrix}$$

or with the equivalent matrix expression:

$$S^{124} = S^{123} \times P$$

The use of matrixes is simplified by the use of dedicated software that handles the calculations after entering correct input parameters.

The results of the first 10 cycles are presented in the following Table together with the graph for a great number of cycles.
In the diagram, the scale for state S0 is different from the one of states S1 and S2 for better representing their values.

System probability to be in state		
0 - Success	**1 – Fail 1**	**2 – Fail 2**
1.000	0.000	0.000
0.998	0.002	0.000
0.996	0.004	0.000
0.994	0.006	0.000
0.992	0.007	0.000
0.990	0.009	0.000
0.989	0.011	0.001
0.987	0.012	0.001
0.986	0.013	0.001
0.984	0.015	0.001
0.983	0.016	0.001

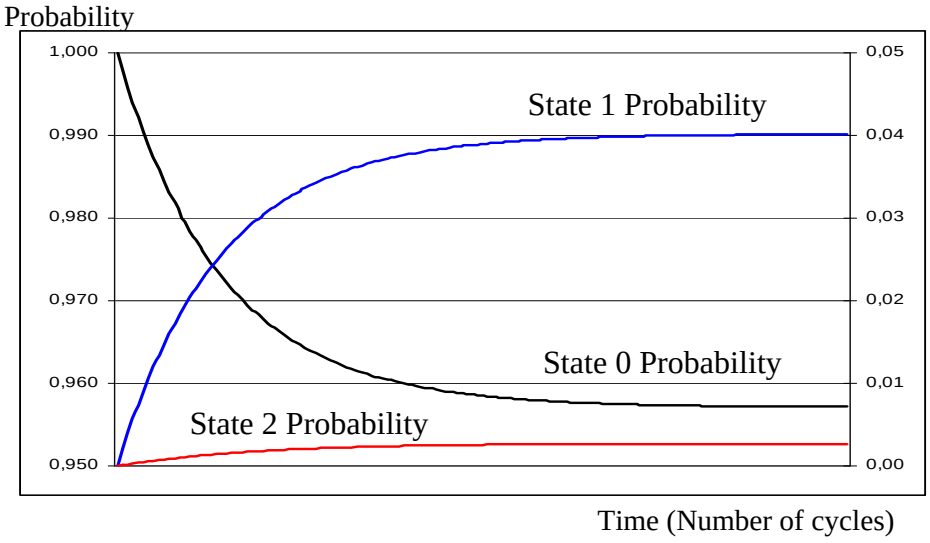


Figure 30, State probability for a great number of cycles:
3 states and 5 transitions repairable device

The states tend to:

- 0.957 for State 0
  (both components working – system working successfully)
- 0.040 for State 1
  (one component working – system working successfully)
- 0.003 for State 2
  (both components fail – system fails)

In the steady state the system has:

- 99.7% probability of functioning successfully
  (with one or two operative components)
- 0.3% probability to fail
  (with both components failed)

The system steady (or limit) state can be calculated with suitable software.

Note: The presence of limit states indicates there are no absorbing states.

The Markov approach to reliability modeling of control system, or SIS, is not only flexible enough to account for the realities of the industrial environment, but can also reveal unexpected failure states. The construction of the Markov model can be a valuable qualitative reliability tool.
A Markov model can be applied to time-dependent conditions.
Time can be viewed in two different ways: discrete or continuous.
A discrete time model changes (as seen before) once every “time increment”. The time increment depends on the model. It may be once an hour, 10 times an hour, once a day, once a week, or some other suitable time increment.
In continuous time models, the same concepts are used. As in calculus, the time increment is reduced to the limit approaching zero.
In reliability and safety modeling, the discrete time approach works well.
Then, assuming constant failure rates the calculation is simplified.
More elaborated calculations allow to obtain the average values for time persistence in the states and to calculate MTTF, as for systems with multi irreversible failure modes (where there are more than one failure state unrepairable), and the probability percentage of such states.

Figure 31 and Figure 32 show, as example, two Markov diagrams with multi failure modes indicated in a single diagram.
Diagram in Figure 32 indicate all successful operating safety system conditions in presence of one or more component failures.
The functional safety probability for each state is calculated taking in consideration the repair rate of each state.

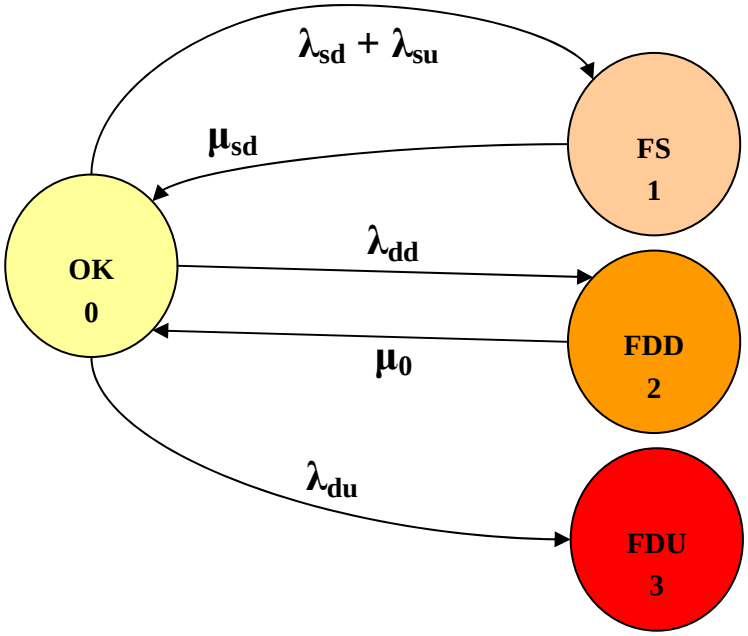


Figure 31, Markov diagram for 1oo1 architecture

To simplify Markov diagrams usually some assumption are taken like:

- Constant failure and repair rates.
- Independent failure modes.
- Only a single failure is relevant for the system under exam. With this assumption consequent failures are not relevant. Indeed if the system fails for a single or a multiple failure the result is the same for the safety function. This approach is conservative because in a safety system redundant components are always present.
- Diagnostic time is much lower than repair time.
- The model is analyzed for the time between two T-proof intervals; therefore periodic test repair rates are not included.
- The repair maintenance policy allows repairing hazardous faults in the system without stopping the process.
- The model assumes that during the T-proof test, defective components are repaired or changed “as new”.
- For redundant components it is assumed common cause failures are the same for both units.

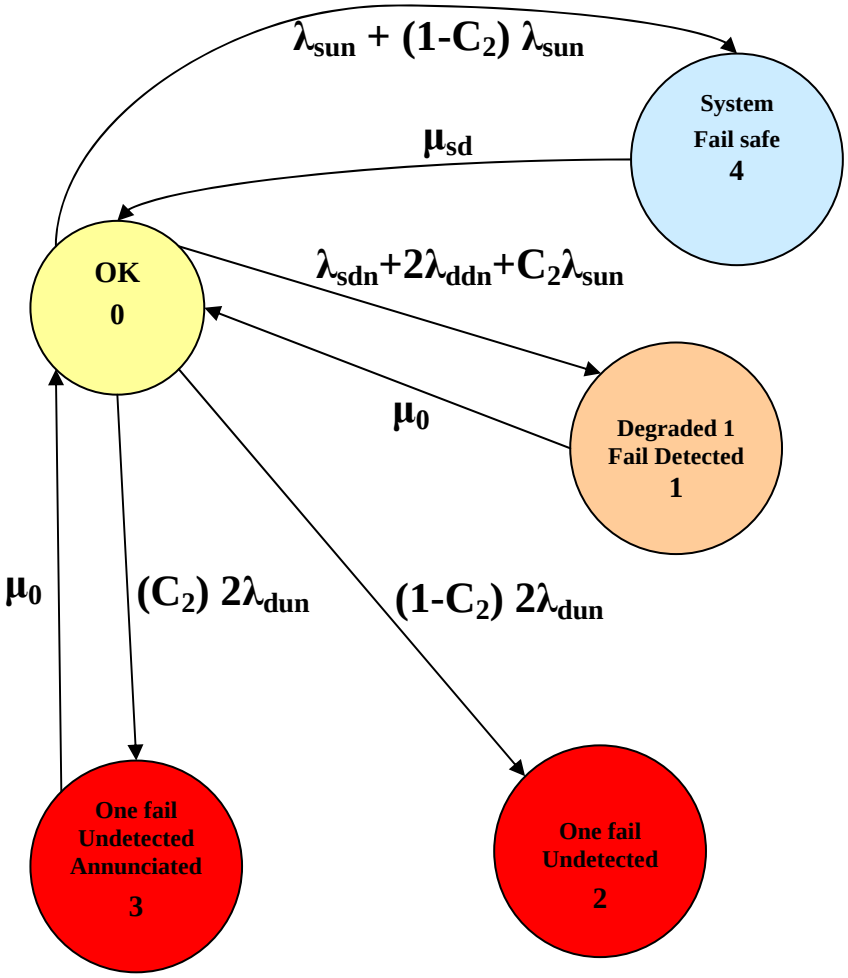


Figure 32, Markov diagram for 1oo2 architecture

Chapter 4 Consequence Analysis of relevant accidents involving chemical substances

4.1 Analysis of risks from the release of chemical substances

Before conducting a consequence analysis of any hazardous event it is necessary to consider the consequences which could derive from the release of chemical substances.

Figure 33 shows an event tree diagram for the release of hazardous chemicals, for a gas release and for a liquid/liquefied gas release.

If the release of a chemical substance occurs, the consequence may result directly from the release event, as for example in BLEVE/Fireball[1], or physical explosions.

It is also possible to have a release of chemical substances in the atmosphere only, which may cause damages later depending on their chemical/physical properties.
Two possible consequences, coincident with the initial release event, are physical explosions and/or the BLEVEs with the resulting fireballs.

[1] BLEVE: Boiling Liquid Expanding Vapor Explosion (see Section 4.2.4).

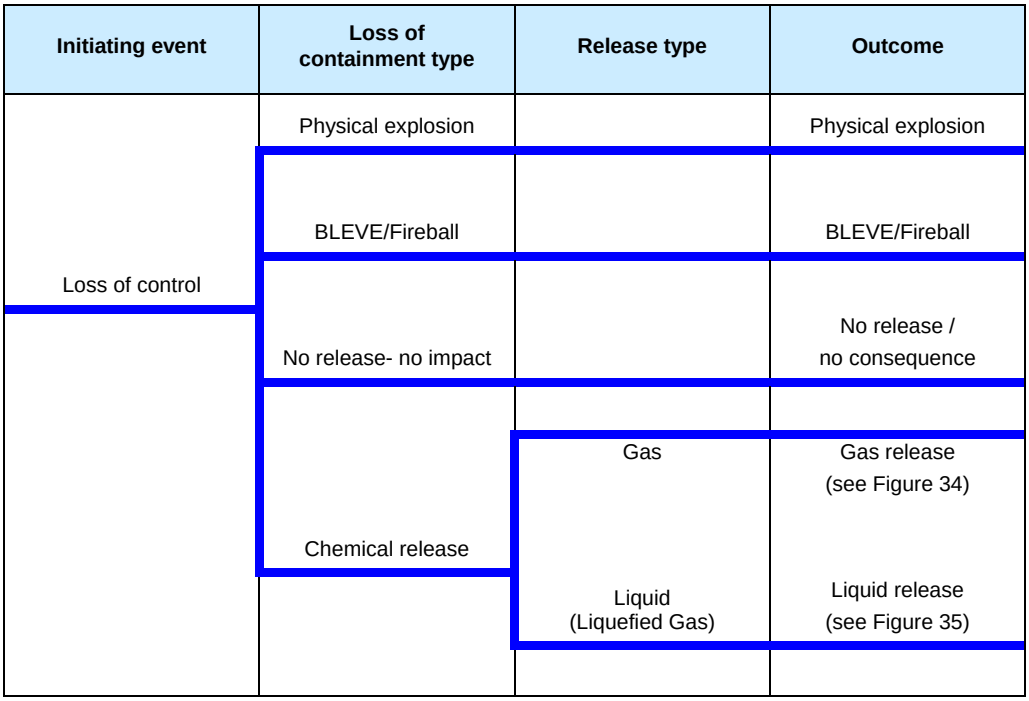


Figure 33, Event tree diagram for simplified loss of chemical containment

A pressure vessel, stimulated beyond its nominal designed pressure, can undergo a catastrophic failure creating a physical explosion.
Such event is called by the media euphemistically as an “energy release”.
If the substances released as the result of a physical explosion are flammable, a fireball may also occur.

If the accident involves a flammable liquid spill, followed by ignition, with the resulting fire of the whole tank, a BLEVE/Fireball may occur.
If the loss of containment event does not cause a fire or an immediate explosion, the chemical substances contained in the process will be spread into the atmosphere.

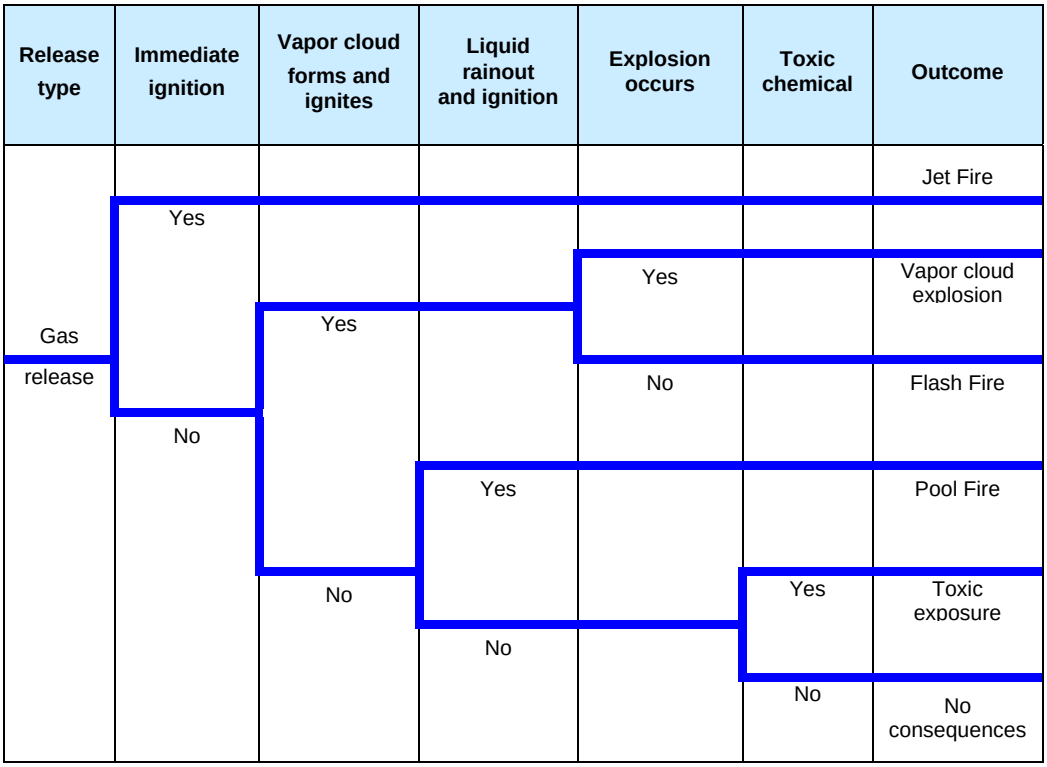


Figure 34, Event tree for gas release

The effects of this kind of release may be involved in a variety of effects depending on:

- Release conditions
- Thermodynamic conditions
- Release nature (liquid, gas, liquefied gas)

Consequences strongly depend on the conditions mentioned above and could have a large impact on what incident outcomes are possible.

If the released substances are high pressure gas or liquids that instantly flash into a gas upon release, a jet fire ignition will occur if the gas is immediately ignited. In the absence of immediate ignition, a large vapor cloud may form. Delayed ignition of the vapor cloud may cause an explosion (VCE, Vapor Cloud Explosion) with the resulting blast overpressure and shock wave.
Depending on the characteristics of the released material and the surrounding environment, a vapor cloud may not result in an explosion after ignition.

In this case the cloud could burn in a slower laminar fashion, causing a flash fire which has a strong thermal effect, but does not cause a blast wave.

The difference between these two combustion modalities depends on the complex phenomenon of flame propagation velocity, which requires a complex modeling to predict with any accuracy.
Even if any ignition does not happen, the non-ignited toxic cloud of gas will spread and disperse, with risks for workers and nearby residents.
Non-ignited gas releases, and in some cases the combustion products of the ignited release, can have a detrimental effect on the surrounding environment.

Possible incident outcomes, as the result of a liquid or liquefied gas discharge, mostly depend on the behavior of the liquid upon release:

1) Immediate vaporization of liquid.
2) Rapid vaporization of the liquid with substantial formation of a liquid pool.
3) Slow or negligible vaporization with significant liquid pooling.

In case 1) the event tree shown in Figure 33 will unfold.
In cases 2) and 3) the event tree shown in Figure 34 better represents the possible outcomes of the release.

Figure 35 shows that the outcomes from a liquid release, with vapor cloud formation, are largely similar to the ones resulting from a release with direct formation of a vapor cloud.
The cloud formation can result from either rapid vaporization or slow evaporation of a pool. In the case where a pool of liquid is formed and ignited, a pool fire will result. If the pool is not ignited, evaporation of the liquid may lead to a harmful exposure hazard downwind, if the material is toxic. Moreover this can also contaminate groundwater even if is not ignited.
In both the vapor and liquid release cases, a potential exists that released substances will be carried away from the source of the release as an aerosol or as a gas cloud, which will then cool, collect, and rain out of the atmosphere to collect in a pool.
The hazards associated with such condensation pool are essentially the same as the hazards from the direct spill of a liquid, except that they are a quite long distance from the release source.
Due to this, a secondary containment, will most likely, not help mitigating their consequences.

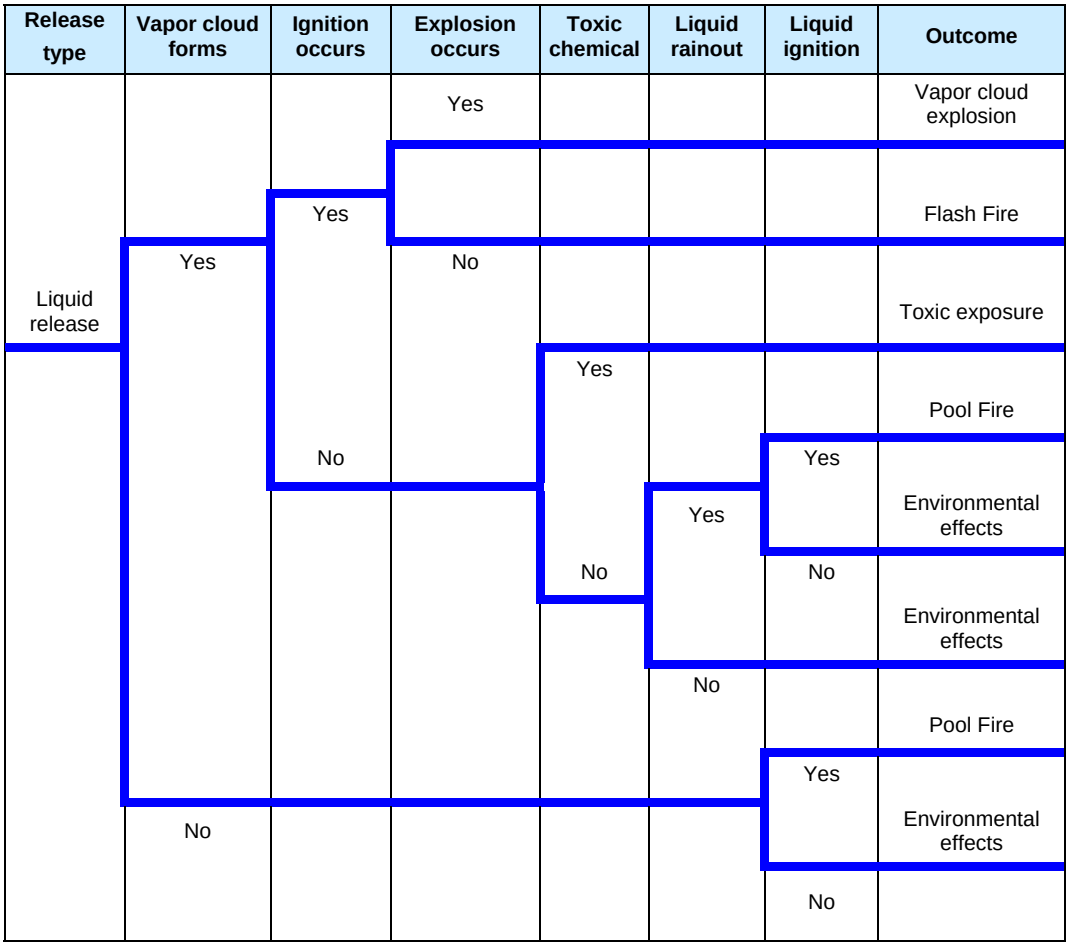


Figure 35, Event tree for liquid release

4.2 Flammability effects

All the incident outcomes so far analyzed, pose flammability hazards to people and properties because of combustion thermal energy released. Thermal energy released from a fire is primarily radiated from the portions of the flame that are in a direct line of sight of the receptor, not obscured by smoke or other potentially shielding equipments.
Not all the fires produce visible flames: an example is the daytime combustion of hydrogen fires, which is not visible, but releases an intense irradiative heat. The irradiation heat transfer mechanism dominates the entity flammability hazard to cause damages.
Although the heat transfer mechanisms, for conduction and convection effects, are negligible, they can play a potential role when the combustion gas products are blown, by any wind, toward elevated structures present during the incident.
The ability of the fire to injure people and damage properties is a function of thermal radiation that the receptor can absorb.
The quantity of thermal energy absorbed by the receptor can vary with the location, orientation toward the flame surface, amount of smoke present, humidity and the other atmospheric conditions.
Protections of equipment in buildings and behind purpose-built thermal radiation shields can reduce the magnitude of thermal energy absorbed. The consequences of a fire are typically described in terms of the distance (end point) to a specific level of thermal radiation flux, measured in Kw/m^2. For instance, the World Bank figures indicate that a direct skin exposure to a thermal radiation of $5Kw/m^2$ for 40 seconds causes serious third-degree burns.

4.2.1 Pool fire

Spilled flammable liquids generate a pool fire if ignited. The magnitude of the effect zone created by a pool fire depends on the size of the flame it generates, which in turn depends on the size of the spill surface and the properties of the released fluid.
The flame's footprint is determined by the containment of the liquid spill, which is often controlled by means of dikes or curbs present.
If the release is not confined, the flammable liquid will spread on an area depending on the viscosity of the liquid and on the characteristics of the surface, as for example its porosity.
The height of the flame depends on the characteristics of the burning fluid, while its vapor tension and heat of vaporization will determine the rate at which the liquid will volatilize and contribute to the oxidation reaction.

Figure 36, Example of Pool fire

Higher vapor tensions, and low vaporization heat, causes more intense vaporization to occur and therefore faster reaction and more thermal energy released.
The thermal combustion energy of the liquid determines the quantity of energy released per unit of liquid. Other properties such as flame propagation speed and adiabatic flame temperature are also important to evaluate the thermal effects of a pool fire.
How completely a material is combusted will determine the quantity of the smoke a fire generates.
The amount of smoke produced by a fire is important because its energy is only radiated from the visible part of the flame.
If smoke is obscuring a significant part of the flame, its transmitted energy will be greatly decreased. For instance, if a diesel fuel pool fire and a liquid natural gas (LNG) have the same dimensions, the LNG fire will have a much larger effect zone.
The reason is that the diesel pool fire produces a lot of smoke which obstructs the energy radiation. Atmospheric factors such as wind speed may also influence the flame height by causing the flame to tilt.
Another important effect of incomplete combustion is the toxic nature of many of the partial burned compounds that can be formed.
Although a complete combustion releases more heat, the toxic effects of the combustion products (CO_2 and H_2O) is minor.

However, the soot and other various toxic partial oxidation products from incomplete combustion can widely disperse in a pool fire, creating potentially serious impacts.

4.2.2 Jet fire

A jet fire occurs when high-pressure flammable material is ignited in the moment of being released from its container.
The kinetic energy of the physical release under pressure helps both to mix the material with the oxygen in the air and to spread the resulting flame. The dimension of the flame is mainly set by the surrounding conditions of the release point.
When a material under high pressure is released from a hole, its exit velocity is mainly function of the pressure and the hole's size.
The greater the distance from the hole, the more oxygen is present in the mixture as air is entrained in the jet.
As the upper flammability limit threshold is crossed, fuel and air react, releasing the energy of combustion. As combustion is continued, entrained air, unburned fuel, and combustion products continue to move in the direction of the release because of the momentum generated by the release.
The area influenced by a jet fire (also known as a torch fire) is determined, like that of a pool fire, by a combination of the physical characteristics of the released substance, and the chemical properties of the burning material. The effect zone of a jet fire is proportional to the size of the flame that is generated.
In the determination of the consequences of a jet fire, properties such as heat of combustion also play a factor.

Figure 37, A jet fire

4.2.3 Flash fire

A flash fire occurs with the ignition of a cloud of flammable vapor when the flame velocity of propagation is too slow to produce an explosive shock wave. When the combustion of an air and gas mixture is ignited, a flame front travels from the point of ignition in all directions where the mixture (fuel-air) concentration is within flammable limits. The velocity of propagation of the flame front determines the type of damage caused by this event.
If the fire front burns in a laminar fashion, with a flame front traveling at a sub-sonic velocity, a flash fire occurs.
If the fire front reaches the sonic velocity, an overpressure is not developed. The consequences in a flash-fire scenario are mainly connected to the heat of combustion being absorbed by receptors in the effect zone.
For a flash-fire, the effect zone is limited to the flame envelope, or the area where mixture is within the flammable limits.
A flash fire would not produce the overpressure shock wave as the one produced by a vapor cloud explosion. Thus there will be no equipment damaged caused by shock wave or by projectiles. Moreover the duration of a flash fire is shorter compared to a pool fire or jet fire, and consequently the harms are also lower.
Despite a lower harm to equipments and properties, the flash fire may be severe to persons when compared to a vapor cloud explosion. It is possible that any person in the flammable envelop remains fatally injured.

Figure 38, Example of Flash fire

4.2.4 Fireball / BLEVE

A fireball occurs when a sudden and widespread release of flammable gas or volatile liquid that is stored under pressure coupled with an immediate ignition. It differs from a jet fire by the shorter duration of the event and the different geometry and shape of the flame.
When a vessel containing a flammable gas or volatile liquid breaks, the highly pressurized material rapidly expands to atmospheric pressure and the first result is the quick dispersion of the flammable material.
During the expansion, the release will entrain large quantity of air. If the material in the vessel is a volatile liquid, this process also causes an aerosol to form with the dispersion of liquid droplets away from the release as a result of vapor expansion.
Right after the initial release, the expanding vapor cloud will entrain enough air to reach the upper flammability limit. If at this point a source of ignition is present, the vapor cloud will rapidly combust.
Ignition sources are frequent, after catastrophic pressure vessel ruptures, because of flying metal fragments and the heat generated by the rupture process. As the ignited cloud combusts, it continues to expand further.
The combination of an expanding flame front; relatively clean, smoke-free, combustion and rapid reaction creates a fire that travels a substantial distance away from the release source and produces intense heat.
When the cloud reaches the latter stage of its combustion, the density of the fireball drops because of the high temperature of the combustion products.
When this occurs, the cloud becomes buoyant and lifts off the ground. This is the reason for the “mushroom cloud” that always accompanies a fireball. The boiling liquid expanding vapor explosion (BLEVE) is a specific type of fireball, but the two are not synonymous.
While BLEVEs result in fireballs, not all fireballs are the result of BLEVEs. These occur when vessels which contain a liquid under pressure come in direct contact with an external flame. This contact can result from the vessel being engulfed in flame or from a jet fire impinging onto the vessel surface. As the liquid inside the vessel absorbs heat of the external fire, the liquid begins to boil, increasing the pressure inside the vessel to the set pressure of the relief valve(s). The heat of the external fire, concentrates in the parts of the vessel where the interior wall is not “wet” with the process liquid.
Since the process liquid is not present to carry heat away from the vessel wall, the temperature in this region (usually near the interface of the boiling liquid) will rise dramatically causing the vessel wall to overheat and become weak.

A short time after this, the vessel will lose its structural integrity, and a rupture will occur. After the vessel ruptures, the result will be a fireball, as described previously, ignited by the external fire.

Figure 39, Example of fireball

4.2.5 Explosion effects

The consequences of an explosion hazard are connected with the effects caused by the explosion's blast wave.
On a fundamental level, the blast wave is simply a thin shell of compressed gas that travels away from the source of the explosion as a three-dimensional wave.
The magnitude of the blast wave is typically defined by its peak overpressure, or the difference in pressure between the highest pressure point in the "shell" and the ambient atmospheric pressure.
A blast wave also has other parameters that describe its effect, such as duration and impulse, but the simple use of peak overpressure is the most common method for describing and classifying explosion effects. The correlation of explosion parameters, such as peak overpressure, to the damage sustained by persons, equipments, and structures has been the subject of a great amount of detailed studies. Reviews of accidental explosions and explosion studies have shown that 5.0 PSI (0.35 ATM) overpressure can cause substantial damage to most typical process equipments, and as a little as 0.5 PSI (0.035 ATM) overpressure can cause glass breakage. Projectiles and collapsing buildings are the main contributors to an explosion's impact on people.
The method for estimating the vulnerability of humans and structures to explosion effects can be found in American Petroleum Institute's Recommended Practice 752 "*Management of hazards associated with locations of process plant buildings, the effects of nuclear weapons*", and the

CCPS's "*Guidelines for evaluating process plant buildings for external explosions and fire*".

4.2.5.1 Vapor cloud explosions

As already discussed, the ignition of a flammable fuel-air mixture cloud will either cause a flash fire or a vapor cloud explosion.
While a flash fire results from a laminar flame front that is slower than the speed of sound, a vapor cloud explosion results from a flame front that is turbulent and exceeds sonic velocity.
The explosion potential of a flammable release depends on:

- properties of the released material,
- energy of the ignition source,
- confinement and obstacle density in the area of the release.

Flame turbulence is typically formed by the interaction of the flame front and obstacles such as process structures or equipments. As the location of a vapor cloud explosion becomes more congested and confined, the likelihood of an explosion will increase.
Generally, four primary conditions are required for a vapor cloud explosion:

- The material must be released in the proper temperature and pressure range.
- The ignition must be delayed enough to allow the fuel and oxidant material (air) to mix.
- A sufficient fraction of the cloud must be in the flammable range, with more homogeneous mixtures causing stronger explosions.
- There must be a mechanism for generating turbulence, which could include the release itself, or external turbulence induced by objects in the area.

These four elements are important both for estimating the consequences of a vapor cloud explosion and for designing a method of protection against one.
Blast effects caused by a vapor cloud explosion vary greatly and depend primarily on the resulting flame speed.
Highly reactive materials such as acetylene and ethylene oxide are much more likely to lead to a vapor cloud explosion than low-reactivity materials such as propane because they can produce higher flame speeds.
Many models have been proposed and used for analyzing the effects of explosions. They range from the simplistic single-point TNT equivalency model to three-dimensional computational fluid dynamics that consider the attenuation and reflection of the blast wave due to obstacles in the blast path.
Explosion models most commonly used for the rough explosion magnitude

estimate, required for selecting SIL levels, include TNT equivalency, TNO multi-energy, and Baker-Strehlow-Tang.

Figure 40, Example of a vapor cloud explosion (BLEVE)

4.2.5.2 Physical explosions

Explosions can be caused either by ignition of flammable materials, as discussed previously, or by the sudden catastrophic rupture of a high pressure vessel.
The blast wave created by the high pressure vessel rupture is often called a physical explosion. Even if the causes of these explosions are different, the effects are essentially the same.
In a physical explosion, the blast wave happens when the potential energy that is stored as high pressure in the vessel, is transferred to kinetic energy when the material stored in the vessel is released.
A fireball may also occur if the released material is flammable and is immediately ignited.
A treatment on how to handle the effects of a physical explosion can be found in the "*Guidelines for Chemical Process Quantitative Analysis*" edited by CCPS.
The most used model for physical explosions is the same as the TNT equivalent model, except that it uses an alternate method to determine the energy that contributes to the blast wave.
When performing a TNT equivalency analysis of a flammable material, the heat of combustion of the material is used to determine the amount of energy released. In case of physical explosion, the amount of work required to compress the gas from ambient conditions to the conditions under which the release occurs is assumed to be the energy contributing to the blast.

4.3 Toxic hazard: Dispersion modeling

Although the release of toxic chemicals may produce little, if any, property damage, it may result in a significant impact on the workforce and any surrounding off-site population (see Bhopal page 15).
The effect of a toxic release will be caused by the biological reactivity of the toxic chemical substance, and not by any primarily energetic reaction that occurs. As such, we can identify the effects of a toxic chemical release by first determining what concentration of the material will be present in areas downwind of the release and then what biological toxic effects these concentrations have. This analysis of the concentration of materials downwind of releases is called dispersion modeling.

Toxic effect zones are determined by the followings parameters:

- Release quantity
- Duration of release
- Source geometry
- Elevation/orientation of the release
- Initial density of the release
- Prevailing atmospheric conditions
- Surrounding terrain
- Limiting concentration (endpoint)

The most critical parameters are briefly discussed in the following paragraphs, with special emphasis on their influence on the process of estimating the distance of downwind dispersion effects.
The release quantity refers to the quantity of a hazardous chemical material that is released when an accident occurs. The release quantity is the single most important factor in determining dispersion effect distances. If the duration of the release is long, it may consider the release rate instead of the released quantity.
In general, larger quantities lead to larger dispersion distances. However, the dispersion distance does not increase linearly with quantity of release rate.
For gaseous and liquefied gas releases, the vapor release rate will be the same as the discharge rate. However, for liquids, the vapor release rate is governed by the evaporation rate of the liquid and will always be less than the total liquid release rate.
The duration-of-release parameter depends on the situation that causes the release as well as the physical characteristics of the release. Most dispersion models use one of the following two extreme cases:

- The release is assumed to either occur continuously, in which case the material is released at a constant rate for a long time, or

- Instantaneously, in which case the entire quantity of material is released at once. (e.g. pressurized storage tank rupture)

Under the instantaneous release assumption, the duration of the release should be very short, and the total quantity of chemical released during the accident contributes to the dispersion hazard.
Under the continuous release assumption, the release rate is the most important parameter because the downwind concentration profile of the released material will come to a steady state.
The continuous addition of more material will only maintain the concentration profile at constant level, but will not extend it further downwind.
Among the atmospheric conditions which influence the release, there is the wind speed and the stability of the atmosphere: a weak wind will slow the dilution and therefore will enlarge the area of influence; moreover the toxic cloud will move slower using more time to reach the final concentration of balance.
Atmospheric conditions that impact the effect zone of a toxic release include atmospheric stability and wind speed. A lower wind speed leads to slower dilution and, hence, larger hazard areas. Lower wind speed also means that the vapor cloud will travel more slowly and take longer to establish a steady-state concentration profile. Atmospheric stability refers to the vertical mixing of the air to disperse a released chemical. These are classified as Pasquill Stability Classes, which range from A (highly instable), to F (highly stable) [2]. Generally the late afternoon hours are typically categorized as A or B, whereas the calm hours of the night or early morning are usually in the E or F categories. The stability determines the velocity of dispersion, and therefore F stability usually leads to very large dispersion distances because very little vertical mixing is occurring.
With everything equal, the difference in the dispersion distance for F stability and A stability can easily be an order of magnitude.
The prevailing wind direction at the time of any release will determine in what direction a vapor cloud will move as well as the specific population and property that may be impacted.

[2] F. Pasquill and F.B. Smith, *Atmospheric Diffusion*, 3rd ed., John Wiley & Sons, Ltd., New York, 1983.

The limiting concentration or endpoint is the cutoff point for the parameter of interest, usually the point where effects such as injury or death are expected to end. For instance, when modeling a release of Hydrogen Sulfide (H_2S), an analyst might wish to determine the size of the effect zone in which the value Immediately Dangerous to Life and Health (IDLH) is exceeded.
In this case, the limiting concentration would be 100 ppm. As one would expect, limiting concentration affects the dispersion distance inversely, with lower limiting concentrations leading to large dispersion distances.
As with source release rates and dispersion distances, the effect is not linear.
The benchmarks used to determine the effect of toxic chemicals include Emergency Response Planning Guidelines (ERPGs), which were established by the American Industrial Hygiene Association (AIHA).
Another such set of benchmarks is the Immediately Dangerous to Life and Health (IDLH) levels suggested by the U.S. National Institute of Occupational Safety and Health (NIOSH).

It is important to distinguish between concentrations at which there will be some observable effect and concentrations at which one can expect serious ill effects and potential fatalities (Bhopal).
Typically, the concentration at which one can expect fatalities are significantly higher (nearly 100 times in some chemicals) than the suggested ERPGs or IDLHs.
Information on the toxic effects of various compounds can be found in many different places. One basic starting point is the Material Safety Data Sheet (MSDS) for a substance.
This information is required by law in The United States, and it can be readily found in databases accessible through the World Wide Web at numerous public sites, including *http://siri.uvm.edu* maintained by the University of Vermont and the Vermont Safety Information Resources Inc.

Specific IDLH database information as well as other toxicity data can be found through the U.S. National Institute of Occupational Safety and Health Web site at *http://www.cdc.gov/niosh/database.html*.

Chapter 5 Safety Instrumented Systems (SIS)

5.1 Introduction

Safety Instrumented Systems (SIS) are frequently used to reduce process hazards in production plants. For each potentially dangerous process a design is done to detect the situation and automatically take action to prevent or mitigate the hazardous event.
Each safety function is called Safety Instrumented Function (SIF).
For each SIF, the required Risk Reduction Factor (RRF) is determined.
A number of SIFs, associated with a particular process, are typically implemented within a single SIS.

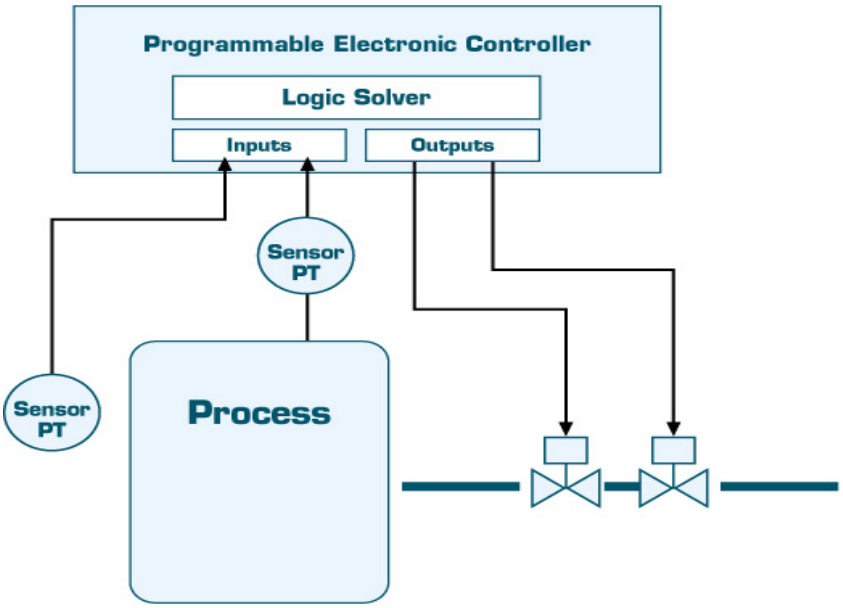


Figure 41, Example of a small SIS

A simple SIS is shown in Figure 41 together with a logic solver in a safety instrumented function.

SIS have many implemented safety functions, one for each potentially dangerous condition, in a single logic solver, which collects and analyzes data information from sensors to determine if a dangerous condition occurs, and consequently to start a shutdown sequence to bring the process to a safe state.
Typically these control systems are called “safety-related systems”.
A potentially dangerous condition is called “demand”.

The majority of SIS are based on the concept of de-energizing to trip, meaning that, in normal working conditions, input and output are energized and the programmed action to prevent or mitigate the dangerous event consists in the opening of a connection by de-energizing an electric circuit. This action is called “trip”.

A SIS is composed of process connections, sensors, logic solver, and final elements. Sensors may be temperature/pressure measurement devices, flame detectors, toxic gas detectors, emergency switches or many other devices. Final elements range from simple solenoid valves to large control valves with their associated actuators.

One type of logic solver is a programmable logic controller (PEC) which consists of input circuitry, a logic solver and output circuitry.
The logic solver is implemented using a microprocessor and software. Different types of input output circuitry exist to interface either analog and discrete sensors or final elements.
Particular SIS are:

- **ESD:** Emergency Safety Shutdown system;
- **BMS:** Burner Management System;
- **F&G:** Fire and Gas system.

A SIS includes instrumentation and/or controls installed to prevent or mitigate hazardous conditions, or to bring the process to a safe state, in presence of a safety demand. This can happen if specific process conditions are violated, e.g. pressure, level, temperature alarms. SIS are used for any kind of process in which hazard and risk analysis require their use.

SIS availability depends on:

- Failure rate and failure mode of components or sub-systems
- Component architectures (1oo1, 1oo2D, 2oo2, 2oo3, etc)
- Voting circuits
- Diagnostic coverage
- Periodic testing frequency

5.2 Safety requirements

SIS functional safety requirements specify:

- logics and actions that a SIS has to comply with;
- process actions a SIS has to perform;
- process conditions to initiate such actions, including manual shutdown, power supply failure, etc.;
- requested SIL level and required performance to achieve it.

IEC 61511 standard specifies requirements that shall be sufficient to design the SIS and shall include the following:

- A description of all the necessary SIFs 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 SIF.
- A definition of any individually safe process state which, when occurring concurrently, creates a separate hazard (e.g. overload of emergency storage, multiple relief to flare system).
- The assumed sources of demand and demand rate of each SIF.
- Requirements for proof-test intervals.
- Response time requirements for the SIF to bring the process to a safe state.
- The SIL and mode of operation (demand/continuous) for each SIF.
- A description of process measurements and their trip point.
- A description of process output actions and the criteria for successful operation (e.g. requirements for tight shut-off valves).
- The functional relationship between process input and output, including logic, mathematical functions, and any required permissions.
- Requirements for manual shutdown.
- Requirements relating to energize or de-energize to trip.
- Requirements for resetting the SIF after a shutdown.
- Maximum allowable spurious trip rate.
- Failure modes and desired response of the SIF.
- Any specific requirements related to the procedures for starting up and restarting the SIF.
- All interfaces between the SIS and any other system, including BPCS and operators.
- A description of the modes of operation of the plant and identification of the SIFs required for operating within each mode.
- Application software safety requirements (listed below).
- 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 SIF.
- The mean time to repair which is feasible for the SIF.
- Identification of the dangerous combinations of output states of the SIS that need to be avoided.
- Identification of the extremes of all environmental conditions which are likely to be encountered by the SIS.
- Identification of normal and abnormal modes for both the plant as a whole (e.g. plant startup) and individual plant operational procedures.
- Definition of requirements for any safety instrumented function necessary to survive a major accident event (e.g. the time required for a valve to remain operational in the event of a fire).

Sub clause 12.2 of the standard provides requirements for the specification of the application software safety requirements.
It is essential for the application software specifications to be consistent with the safety requirements listed below:

- An application software safety requirements specification shall be developed.
- The input to the specification of the software safety requirements for each SIS subsystem shall include:
  - specified safety requirements of the SIF;
  - requirements resulting from the SIS architecture;
  - any requirements of safety planning.
- The specification of the requirements for application software safety shall be sufficiently detailed to allow the design and implementation to achieve the required safety integrity and to allow an assessment of the functional safety to be carried out.
- The application software developer shall review the information in the specification to ensure that the requirements are unambiguous, consistent and understandable.
- The specified requirements for software safety should be expressed and structured in such a way that they are clear, verifiable, testable, modifiable and traceable.
- The application software safety requirements specification shall provide information allowing proper equipment selection.

5.3 Average Probability of Failure on Demand (PFDavg), Safety Integrity Levels (SIL)

Assigning a SIL level to a SIF is a decision to be taken in consequence of process hazard and risk analysis. It is based on the value of risk reduction, or how the risk has to be reduced to reach an acceptable level.
SIS design requirements, from operability to maintenance, must be verified and compared to the SIL level initially assigned.

Table 1, extracted from IEC 61508 and IEC 61511 standards, is used to calculate the SIL level of SIF single components, and consequently the SIL level of the entire safety function.

SIL Safety Integrity Level	PFDavg Average probability of failure on demand per year (low demand)	RRF Risk reduction factor	PFDavg Average probability of failure on demand per hour (high demand)
SIL 4	**$\geq 10^{-5}$ to $< 10^{-4}$**	**100000 to 10000**	**$\geq 10^{-9}$ to $< 10^{-8}$**
SIL 3	**$\geq 10^{-4}$ to $< 10^{-3}$**	**10000 to 1000**	**$\geq 10^{-8}$ to $< 10^{-7}$**
SIL 2	**$\geq 10^{-3}$ to $< 10^{-2}$**	**1000 to 100**	**$\geq 10^{-7}$ to $< 10^{-6}$**
SIL 1	**$\geq 10^{-2}$ to $< 10^{-1}$**	**100 to 10**	**$\geq 10^{-6}$ to $< 10^{-5}$**

Table 1, Safety Integrity Levels and Probability of Failure on Demand according IEC 61508 and IEC 61511 standards

This chapter describes the calculation of PFDavg, and its concerns.
Table 2 lists the simplified equations, used to calculate the values of PFDavg for different subsystems or component architectures, with different values of TI (periodic test time interval).

Note that the following equations do not yet take common cause (β) and diagnostic coverage factors (C) into account, since they will be treated later on in the chapter.

Architecture	PFDavg TI = 1 year	PFDavg TI = 3 years	PFDavg TI = 5 years	PFDavg TI = 10 years
1oo1	$\frac{\lambda_{DU}}{2}$	$3\times\frac{\lambda_{DU}}{2}$	$5\times\frac{\lambda_{DU}}{2}$	$10\times\frac{\lambda_{DU}}{2}$
1oo2	$\frac{\lambda_{DU}^{\ 2}}{3}$	$9\times\frac{\lambda_{DU}^{\ 2}}{3}$	$25\times\frac{\lambda_{DU}^{\ 2}}{3}$	$100\times\frac{\lambda_{DU}^{\ 2}}{3}$
2oo2	λ_{DU}	$3\times\lambda_{DU}$	$5\times\lambda_{DU}$	$10\times\lambda_{DU}$
2oo3	$\lambda_{DU}^{\ 2}$	$9\times\lambda_{DU}^{\ 2}$	$25\times\lambda_{DU}^{\ 2}$	$100\times\lambda_{DU}^{\ 2}$
1oo3	$\frac{\lambda_{DU}^{\ 3}}{4}$	$27\times\frac{\lambda_{DU}^{\ 3}}{4}$	$125\times\frac{\lambda_{DU}^{\ 3}}{4}$	$1000\times\frac{\lambda_{DU}^{\ 3}}{4}$
2oo4	$\lambda_{DU}^{\ 3}$	$27\times\lambda_{DU}^{\ 3}$	$125\times\lambda_{DU}^{\ 3}$	$1000\times\lambda_{DU}^{\ 3}$

Table 2, Simplified equations for PFDavg calculation

Figure 42 shows PFD (blue) PFDavg (red) at different periodic tests (TI).

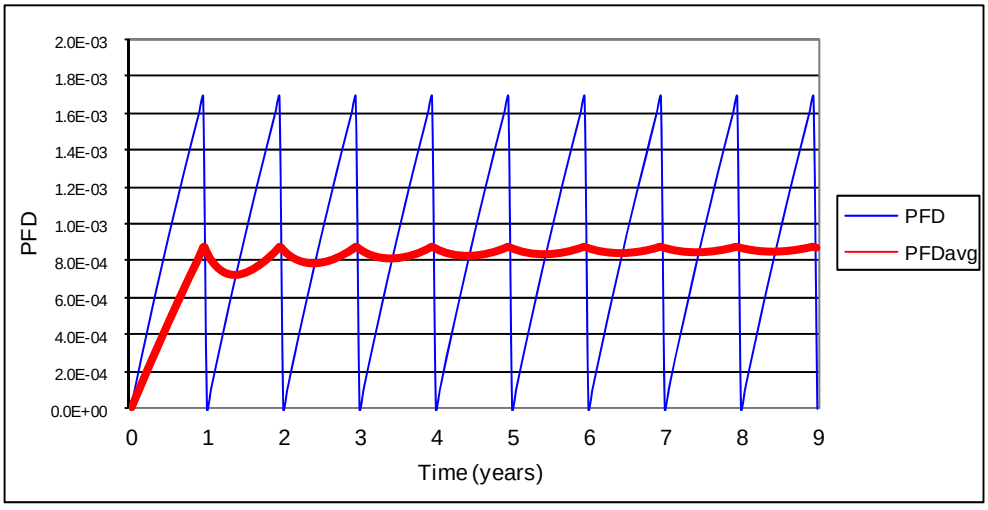


Figure 42, PFD and PFDavg at different T-proof intervals (1oo1 architecture)

The following example highlights calculations for PFDavg and SIL level for SIF components, and finally for the total SIF.

Example:

Calculate MTBF, MTBFs for spurious trips, PFDavg, RRF, and possible SIL level of the following SIF, which includes a transmitter, a barrier, a safety PLC, and a valve as final element, for one year T-proof test interval, and for a 1oo1 architecture.

The following values are assumed:

Tx:	MTBF = 102 yrs;	λ_{DU} = 0,00080 / yr;	λ_{DD} = 0,0010 / yr;	λ_S = 0,00800 / yr
Barrier:	MTBF = 314 yrs;	λ_{DU} = 0,00019 / yr;	λ_{DD} = 0,0014 / yr;	λ_S = 0,00159 / yr
PLC:	MTBF = 685 yrs;	λ_{DU} = 0,00001 / yr;	λ_{DD} = 0,0001 / yr;	λ_S = 0,00135 / yr
Supply:	MTBF = 167 yrs;	λ_{DU} = 0,00070 / yr;	λ_{DD} = 0,0000 / yr;	λ_S = 0,00530 / yr
Valve:	MTBF = 12 yrs;	λ_{DU} = 0,02183 / yr;	λ_{DD} = 0,0200 / yr;	λ_S = 0,04150 / yr

Where:

- λ: total failure rate = $\lambda_{SD} + \lambda_{SU} + \lambda_{DD} + \lambda_{DU}$;
- MTBF: Mean time between failure;
- PFDavg: Average probability of failure on demand per year;
- RRF: Risk reduction factor;
- SFF: Safe Failure Fraction, see Section 6.4.3 at page 158.

Sub-system	MTBF (yr)	λ / yr = 1/MTBF	MTBFs = 1/ λ_S (yr)	λ_S / yr	λ_{DD} / yr	λ_{DU} / yr	PFDavg 1oo1 = $\lambda_{DU}/2$	% of total PFDavg	RRF = 1/PFDavg	SFF	SIL Level
Tx	102	0.00980	125	0.00800	0.0010	0.00080	0.000400	3.40 %	2500	91.8 %	SIL 2
Barrier D1014S	314	0.00318	629	0.00159	0.0014	0.00019	0.000095	0.81 %	10526	94.0 %	SIL 3
PLC	685	0.00146	741	0.00135	0.0001	0.00001	0.000005	0.04 %	200000	99.3 %	SIL 3
Valve *	12	0.08333	24	0.04150	0.0200	0.02183	0.010915	92.87 %	92	73.8 %	SIL 1
Power Supply	167	0.00600	189	0.00530	0.0000	0.00070	0.000350	2.97 %	2857	88.3 %	SIL 3
Total (SIF)	**10**	**0.10377**	**17**	**0.05774**	**0.0225**	**0.02353**	**0.011765**	**100 %**	**85**	-	**SIL 1**

Table 3, 1oo1 system architecture and TI of 1 year

* Because the Valve is not SIL rated, the standard allows to assume $\lambda_S = \lambda_d = \lambda_{tot}/2$. Therefore it is necessary to perform a Partial Stroking Test (PST) with a diagnostic coverage of at least 52% (**λ_{du} / λ_s *100**) to bring the SIL Level to SIL 1.

Consideration 1

Even if in the SIF there are SIL 2 and SIL 3 components, the allowed SIL level for the SIF is SIL 1 only, because the RRF does not reach 100.
How is it possible to obtain a SIL 2 level for the SIF?
Two solutions:

- Using two redundant valves in 1oo2 architecture with 5% β factor: the valve's PFDavg value changes from 0.0109 / yr to 0.000545 / yr. But this solution may not be practically possible.
  (see Section 5.4.2 at page 102 for details on β factor)
- A more simple solution consists in connecting two identical valves in series using suitable bypasses. In case of periodic testing, one valve continues to serve the process while the other can be tested. By doing so, the T-proof test interval could be lowered to 4 months instead of one year, for one valve only, thus lowering PFDavg, and improving RRF (as shown in Table 4).
  This also leads the SIF to SIL 2 level with a higher RRF.
  The result is obtained applying a Partial Stroking Test (PST) to the valve, as shown in Table 3 (see Section 5.6.2 at page 130 for details).

Using the 2nd solution, values in the table will be modified into the following:

Sub-system	MTBF (yr)	λ = 1/MTBF per yr	MTBFs = 1/ λ_S (yr)	λ_S / yr	λ_{DD} / yr	λ_{DU} / yr	PFDavg 1oo1 = $\lambda_{DU}/2$	% of total PFDavg	RRF = 1/PFDavg	SFF	SIL Level
Tx	102	0.00980	125	0.00800	0.0010	0.00080	0.000400	8.98 %	2500	91.8 %	SIL 2
Barrier D1014S	314	0.00318	629	0.00159	0.0014	0.00019	0.000095	2.13 %	10526	94.0 %	SIL 3
PLC	685	0.00146	741	0.00135	0.0001	0.00001	0.000005	0.11 %	200000	99.3 %	SIL 3
Valve *	36	0.02750	73	0.01370	0.0066	0.00720	0.003602	80.91 %	278	73.8 %	SIL 2
Power Supply	167	0.00600	189	0.00530	0.0000	0.00070	0.000350	7.86 %	2857	88.3 %	SIL 3
Total (SIF)	**21**	**0.04794**	**33**	**0.02994**	**0.00910**	**0.00890**	**0.004452**	**100 %**	**225**	**-**	**SIL 2**

Table 4, 1oo1 system architecture and TI of 1 year except for valve

* Performing the Valve's T-proof test more frequently (every 4 months in this case) increases the RRF value and consequently the SIL Level.

Consideration 2

Each subsystem's PFDavg has a percentage value in relation to the total. Component manufacturers list in their functional safety manual, the value of PFDavg obtained by authorized certification bodies like TUV, EXIDA, FM. These bodies apply a conventional "weighing" of the PFDavg of the component in consequence of its importance in the entire loop, as reported in the following Table:

Subsystem	PFDavg 1oo1 (%)
Transmitter	20 %
Barrier	10 %
PLC	25 %
Valve	35 %
Power Supply	10%
Total (SIF)	100 %

Table 5, PFDavg "weighing" for 1oo1 system architecture

These criteria are not mentioned in any safety-related standard, but are applied by approval bodies basing on their experience.
In any case, project engineers can use different criteria, for a specific SIF under investigation, when assigning PFDavg percentages to the components.
For example, IS barriers are supposed to use no more than 10 % of the total PFDavg available for the SIF. This means that SIL 3 qualified barriers have to have PFDavg values listed in Table 1 for SIL 4 level (multiplication factor between SILs levels is 10).
When inspecting component safety manuals, it is important to verify that the PFDavg value is "balanced" within the desired safety function.
Data reported in the previous examples refer to GM barrier model D1014.
The percentage used for SIL 3 level is 2.13 % of the total value requested to the SIF.
These "weighing" criteria are not mandatory and a design engineer may decide to use 20% instead of 10% for a specific SIL level of a SIF.
Because the required safety integrity level of the SIF is SIL 2, the mentioned barrier can be used on a SIL 2 level for 10 years T-proof time interval instead of one year.
Indeed, multiplying by 10 the PFDavg of one year, the result is a value of 0.001, which is lower than 10% of the value indicated in the table 1 for a SIL 2 level (0.01).

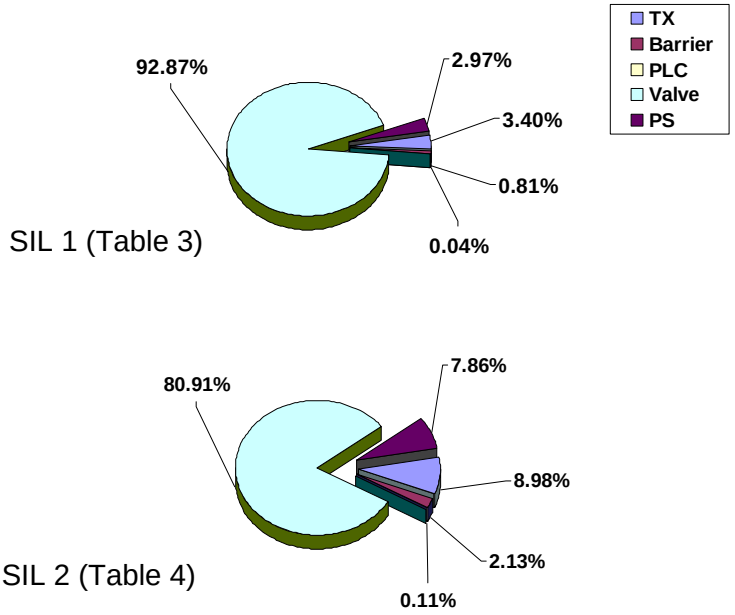


Figure 43, PFDavg distribution within the SIF

Consideration 3

The SIF has a safety integrity level SIL 2, a MTBF of 21 yrs, a MTBFs of 33 yrs, and a safety shutdown every 112 yrs (1 / λ_{DU} SIF) providing the periodic tests are performed according the following table:

Subsystem	T-proof test time interval
Transmitter	1 yrs
Barrier	10 yrs
PLC	20 yrs
Valve	4 months

Table 6, 1oo1 system architecture and T-proof test interval optimization

All the above is valid only if the periodic manual tests are carried out regularly, and with an effectiveness of 100% or very close to it. This means that the tests have to be able to detect almost all the λ_{DU} of single SIF components. Practically these percentages, which have to be clearly identified in the component functional safety manual by the manufacturer, can vary from 50 % to 99 % depending on the type of test.

Without these percentage values, maintenance engineers could not calculate the new value of PFDavg of the SIF. Equations which take into consideration PFDavg corrections with percentage of tests effectiveness are presented in this chapter at Section 5.4.3.1 for to be used by design and maintenance engineers.

Reliability data, detailed description with results of periodic testing and percentage of tests effectiveness, must be included in the component functional safety manual; otherwise they have to be requested to the supplier.

Consideration 4

What actions should be taken when reliability data, for the single components of the SIF, are not available?
This may be the case of mechanical components like valves, actuators, or other similar devices.
Standards do not help much in these cases. Usually MTBF data is available from the component's supplier, or can be found into plant maintenance reports. Starting from MTBF it is possible to calculate the total failure rate, $\lambda = 1 / MTBF$.
A good conservative suggestion is to use the total failure rate as dangerous undetected. However, a more practicable way is to follow suggestions discussed at point 5.6.2 using, where possible, the valve's "Partial Stroking Test" which can reveal up to 80% of effectiveness bringing dangerous undetected failures from 100% (λ) to 20% (λ_{DU}).
By doing so, a higher SIL level can be more easily achieved.

5.4 System architectures

5.4.1 Introduction

A set of widely known system / component architectures are now briefly presented.

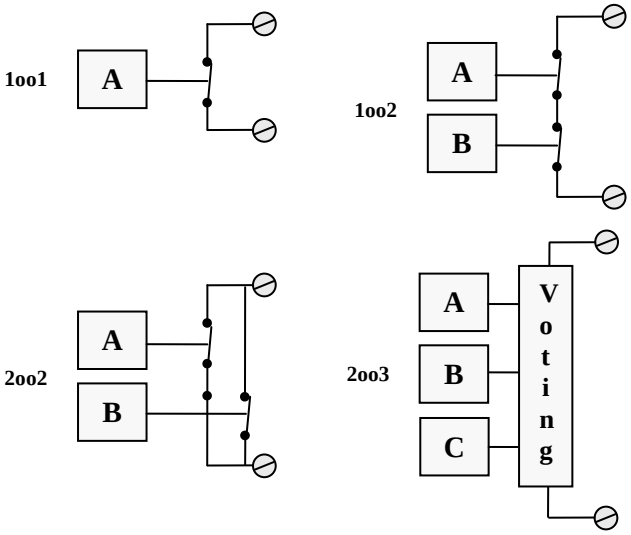


Figure 44, Schematic diagrams of some system architectures

Supposing a device in 1oo1 architecture, with a probability of safe failure of 0.04 / yr, and a probability of dangerous failure of 0.02 / yr: in the following table the value of PFDavg is compared between different system architectures.

Architecture	Probability of safe failure per year	$MTTF_S$ (yrs)	Probability of dangerous failure per year	$MTTF_D$ (yrs)
1oo1	0.0400	25	0.0200	50
1oo2	0.0800	12.5	0.0004	2500
2oo2	0.0016	625	0.0400	25
2oo3	0.0048	208	0.0012	833

Table 7, The impact of redundancy

5.4.1.1 1oo1 Architecture (one-out-of-one)

Starting with a base case of a simplex (non redundant) system referred to as 1oo1 (one-out-of-one) an example of a safe failure consists of a relay contact opening and de-energizing the system causing a nuisance trip.
Assuming a failure probability in this mode of 0.04 / yr, it means that in a given time period (e.g. 1 year) the system has a 4 % probability of suffering a nuisance trip. The system can be thought as 4 systems out of 100 causing a nuisance trip within a year or 1 system in 25 causing a nuisance trip, or a $MTTF_S$ of 25 years.
An example of a dangerous failure would be where the relay contacts are welded shut and won't operate when needed. An example of a dangerous failure would be where the relay contacts are welded shut and won't operate when required.
Assuming a failure probability in this mode of 0.02 / yr it means that, in a given time period (e.g. 1 yr):

- the system has a 2% probability / yr of not operating properly on demand
- or two systems out of 100 not responding in a year
- or one system out of 50 non responding in a year
- or a $MTTF_D$ (danger) of 50 years (1 / 0.02).

5.4.1.2 1oo2 Architecture (one-out-of-two)

Dual 1oo2 system architecture has the outputs wired in series, assuming closed and energized contacts. One out of two means the system only needs one channel to perform a shutdown.
If both channels can shut the system down, and there is twice as much hardware, there are twice as many nuisance trips. Therefore, probability moves from 0.04 to 0.08/ yr, that is 8 systems out of 100 causing nuisance trips within a year, or $MTTF_S$ (safe) of 12,5 years.

In the dangerous mode, this system fails to function only if both channels fail dangerously at the same time. If one is stuck, the other can still de-energize and shutdown the system. What is the probability of two simultaneous failures? 0.02 x 0.02 = 0.0004 / yrs. That is like 4 systems out of 10,000 not responding in a year, or 1 in 2,500, or a system with 1 probability of failure in 2500 yrs, or $MTTF_D$ (danger) = 2,500 yrs.

In other words, a 1oo2 system architecture is very safe (the probability of a dangerous system failure is very small), but the system suffers twice as many nuisance trips as a 1oo1 system, which is not desirable from a loss of production standpoint.

5.4.1.3 2oo2 architecture (two-out-of-two)

Dual 2oo2 system architecture has the outputs wired in parallel. Here, both channels must de-energize in order to perform a shutdown.
This system fails to function if a single channel has a dangerous failure. Since the system has twice as much hardware as a simplex (1oo1) system, it has twice as many dangerous failures. Therefore the 0.02 probability / year doubles to 0.04 / yr, or 4 systems out of 100 not responding in a year, or one in 25, or $MTTF_D$ = 25 yrs.

For this system to have a nuisance trip, both channels have to suffer safe failures at the same time. As before, the probability of two simultaneous failures is 0.04 x 0.04 = 0.0016 / yr.
This is like 16 systems out of 10000 causing a nuisance trip within a year, or 1 system in 625 years, or $MTTF_S$ = 1 / 0.0016 = 625 yrs.

So 2oo2 system architectures protects against nuisance trips (probability of safe failure is very small), but the system is less safe than simplex 1oo1, which is not desirable from a safety standpoint. This is not to imply that 2oo2 systems are “bad” or should not be used. If the PFDavg, which is the number we are concerned about from a safety standpoint, meets the overall safety requirements, then the design is acceptable.

5.4.1.4 1oo3 (one-out-of-three) Triple modular architecture

(TMR) systems, was very common in the mid 80s, because early computer based systems had limited diagnostic.
For instance, if there were only two signals and they disagreed, it wasn’t always possible to determine which one was correct. Adding the third channel solved the problem.
Triple Modular Redundancy is used where functional safety for a long period (5-10 yr) is required without having to stop equipments for maintenance.
This is the case of large rotating machines like gas turbines, compressors, etc.
Another application for TMR is when it is required to obtain SIL 3 safety level when only SIL 1 devices are available.

5.4.1.5 2oo3 Architecture (two-out-of-three) and 1oo2D (one-out-of-two with diagnostics)

2oo3 system architecture is a majority voting system.
Whatever two or more channels say, that is what the system does.
What initially surprises people is that 2oo3 system has a higher nuisance trip rate than a 2oo2 system, and greater probability of a fail to function failure than a 1oo2 system.
However the system architectures 1oo2 and 2oo2 are not good for both safety failure and nuisance trip, while 2oo3 system architecture is good for both types of failures (safe and dangerous).

Thanks to the improvements made in hardware and software failures in the dual redundant computer-based systems can now be diagnosed well enough to tell which of two channels is correct if they disagree. The industry refers to this newer dual design as 1oo2D.
These systems are certified by independent agencies (e.g. TUV and FM) to the same performance levels as the TMR systems.
Unfortunately, safety certifications do not cover nuisance trip performance.
Therefore TMR vendors criticize 1oo2D systems on this issue.
However, it must be noticed that because of the continuous improvement of safety PLC technology, some 1oo2D safety PLC systems have now good nuisance trip performances too.

The advantages of 2oo3 or 1oo3 architectures are still great when dealing with not intelligent devices like thermocouples, RTDs, contact, relays, pressure switches, and other similar components.

Example

A very good thermocouple has MTBF = 500 years and $PFDavg|_{1yr} = 0.0005$.
Total Failure rate λ is 1/MTBF = 0.002. λ_{DU} can be assumed $\lambda/2 = 0.001$.
Using 3 thermocouples in 2oo3:

$\lambda = 0.006$
MTBF = 166 yrs
PFDavg = 0.000001 / yr (see Table 2 at page 92)
$PFDavg|_{\beta=10\%} = 0.00005$ / yr (see Table 8 at page 102)

Finally, the advantages of each system architecture must be compared to its costs for a correct and complete evaluation.

5.4.2 Common cause factor (β) and PFDavg for redundant architectures

Chapters 3.4.3 and 3.4.4 briefly introduce the concept of dependent, or common cause, failures. The values of β factors are not simple to calculate and usually the same value is used for a component or for the electric part of the SIF. For example a value is used for Transmitter, Barrier and PLC while, a different β value can be used for the final elements.
Guidelines for calculation can be found in IEC 61508 Part 6 Annex D.
β factor must be considered when a redundancy of components, or subsystems, is required in order to lower the value of PFDavg.
Simplified equations, shown at Section 5.3, do not consider the contribution of β factor. These equations corrected with β appear as the following:

Architecture	Simplified equation	Simplified equation with β factor
1oo2	$\frac{1}{3}\times(\lambda_{DU}\times TI)^2$	$\frac{1}{3}\times\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^2+\frac{1}{2}\times(\beta\times\lambda_{DU}\times TI)$
1oo2D	$\frac{1}{3}\times(\lambda_{DU}\times TI)^2$	$\frac{1}{3}\times\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^2+\frac{1}{2}\times(\beta\times\lambda_{DU}\times TI)$
2oo2	$\lambda_{DU}\times TI$	$\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]+\frac{1}{2}\times(\beta\times\lambda_{DU}\times TI)$
2oo3	$(\lambda_{DU}\times TI)^2$	$\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^2+\frac{1}{2}\times(\beta\times\lambda_{DU}\times TI)$
1oo3	$\frac{1}{4}\times(\lambda_{DU}\times TI)^3$	$\frac{1}{4}\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^3+\frac{1}{2}\times(\beta\times\lambda_{DU}\times TI)$

Table 8, PFDavg formulae considering Beta Factor

Typical values of β range from 1% to 10%.

The second term of the equations is the PFDavg value contribution due to β factor, derived from the 1oo1 (simplex) architecture.

As it can be seen in the following example, the second term (β dependent) has a much higher value compared to the first one. Therefore in a redundant system, β factor limits the reduction of PFDavg value to about 100 times for β = 0.01 (1%) or 20 times for β = 0.05 (5%) the value for the 1oo1 architecture.

Example:

λdu = 0.01 / yr;
TI = 1 yr;
β = 0.05

For 1oo2 the equation is:

$$\frac{1}{3}\times\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^2+\frac{1}{2}\times(\beta\times\lambda_{DU}\times TI)=$$

$$=\frac{1}{3}\times\left[0.95\times0.01\right]^2+\frac{1}{2}\times(0.05\times0.01\times1)=$$

$$=0.00003+0.00025=0.00028\,/\,yr$$

Comparisons

PFDavg	RRF
1oo1 = 0.005 / yr	1oo1 = 200
1oo2 = 0.00003 / yr (no β factor)	1oo2 = 33333 = 200 x 166.6
1oo2 = 0.00082 / yr (1% β factor)	1oo2 = 12195 = 200 x 61
1oo2 = 0.00028 / yr (5% β factor)	1oo2 = 3571 = 200 x 17.8
1oo2 = 0.00053 / yr (10% β factor)	1oo2 = 1897 = 200 x 9.48

Considerations

- Without β factor, PFDavg of 1oo2 architecture is 166.6 times better than PFDavg value of 1oo1 architecture.
- With 1% β factor, PFDavg of 1oo2 architecture is 61 times better than PFDavg value of 1oo1 architecture.
- With 5% β factor, PFDavg of 1oo2 architecture is 17.8 times better than PFDavg value of 1oo1 architecture.
- With 10% β factor, PFDavg of 1oo2 architecture is 9.48 times better than PFDavg value of 1oo1 architecture.

5.4.3 1oo1 system architecture

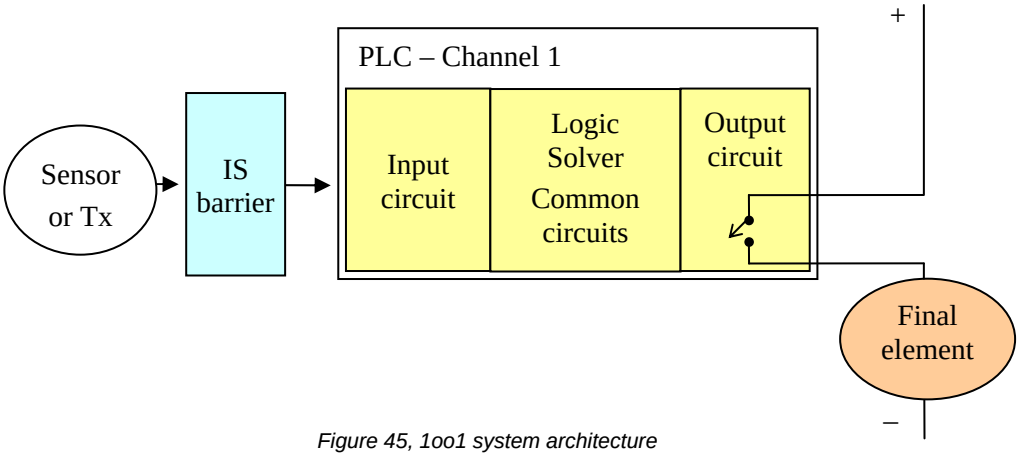


Figure 45, 1oo1 system architecture

Figure 45 shows a 1oo1 minimum system architecture, which could be a single safety SIF representing a safety loop, including a sensor / transmitter in hazardous location, an intrinsic safety barrier interface, connected in series with a safety PLC control loop, which drives an actuator or a final element (e.g. valve).
The system can fail dangerously for detected or undetected failures λ_{DD} and λ_{DU}.

$$PFDavg = \lambda_{DD} \times RT + \lambda_{DU} \times \frac{TI}{2}$$

Where:

- RT: repair time in hrs, conventionally = 8 hrs.
- TI: "T-proof test interval" (time interval between two periodic manual proof tests), usually 1, 3, 5 or 10 yr. (1 yr = 8760 hr).

For 1 yr T-proof :

$$PFDavg = \lambda_{DD} \times 8 + \lambda_{DU} \times 4380$$

Very often the value of λ_{DD} x 8 is much less that λ_{DU} x 4380 and with approximation:

$$PFDavg = \lambda_{DU} \times \frac{TI}{2}$$

The calculation of PFDavg has to be carried out for all SIF components, therefore total system PFDavg :

PFDavg system =
PFDavg sensor +
PFDavg barrier +
PFDavg PLC controller +
PFDavg actuator/valve

Example:
Let's assume a failure rate, for dangerous undetected failures, (λ_{DU}) of 250 FIT / hr ≈ 0,0025 / yr

for TI = 1 yr: PFDavg = 0,0125 / yr
for TI = 3 yr: PFDavg = 0,0375 / 3 yr
for TI = 5 yr: PFDavg = 0,0626 / 5 yr

System MTTF (MTBF) calculation is obtained:

$$\text{MTBF(system)} = \frac{1}{\sum \lambda_{TOT}}$$

$$\lambda_{TOT} = \lambda_{SENSOR} + \lambda_{BARRIER} + \lambda_{CONTROLLER} + \lambda_{VALVE}$$

Remembering that any single component failure rate has to be subdivided into the four basic categories:

$$\lambda = \lambda_{DD} + \lambda_{DU} + \lambda_{SD} + \lambda_{SU}$$

Where:
λ_{DD}: dangerous detected failure rates;
λ_{DU}: dangerous undetected failure rates;
λ_{SD}: safe detected failure rates;
λ_{SU}: safe undetected failure rates;

For systems where the majority of safe failures are detected the MTBFs for nuisance trips can be calculated:

$$\text{MTBF}_S = \frac{1}{\lambda_{S\ TOT}}$$

$$\lambda_{TOT} = \lambda_{S\,SENSOR} + \lambda_{S\,BARRIER} + \lambda_{S\,CONTROLLER} + \lambda_{S\,VALVE}$$

5.4.3.1 Effectiveness of manual periodic tests influence on PFDavg calculation for 1oo1 system architecture

When the effectiveness of periodic a proof test, to reveal dangerous failures, is 100%, the simplified equation for PFDavg, is:

$$PFDavg = \lambda_{DU} \times \frac{TI}{2}$$

Otherwise, when the effectiveness is not 100%, the equation is:

$$PFDavg = (Et \times \lambda_{DU} \times \frac{TI}{2}) + \left[(1 - Et) \times \lambda_{DU} \times \frac{SL}{2} \right]$$

where:

Et: periodic testing effectiveness to reveal dangerous failures (e.g. 90%)

SL: system lifetime. The system lifetime may be the time the system is completely tested, replaced, or the lifetime of the plant if the system is never fully tested or replaced.

for TI = 1 yr and SL = 12 years, the PFDavg simplified equation is:

$$PFDavg\Big|_{TI=1,SL=12} = (Et \times \frac{\lambda_{DU}}{2}) + \left[(1 - Et) \times \lambda_{DU} \times \frac{12}{2} \right]$$

Example 1:

λ_{DU} = 0.01 / yr

TI = 1.yr

Et = 90% = 0.9

SL = 12 yr

At first installation (brand new system):

PFDavg = 0.01 / 2 = 0.005 / yr

RRF = 1 / PFDavg = 1 / 0.005 = **200 (SIL 2)**

After one year:

PFDavg = (0.9 x 0.01 / 2) + (0.1 x 0.01 x 6) = 0.0105

RRF = 1 / PFDavg = 1 / 0.0105 = **95 (SIL 1)**

After one year, as well as after each periodic proof test, the SIL level has moved from SIL 2 to SIL 1.

Example 2:

λ_{DU} = 0.01 / yr

TI = 1 yr

Et = 99% = 0.99

SL = 12 yr

After one year:

PFDavg = (0.99 x 0.01 / 2) + (0.01 x 0.01 x 6) = 0.0056

RRF = 1 / PFDavg = 1 / 0.006 = **178 (SIL 2)**

After one year, as well as after each periodic test, SIL level is still SIL 2.

5.4.3.2 Influence on PFDavg calculation due to manual test duration in 1oo1 system architecture

To test a safety system online (while the process is still running), a portion of the safety system must be placed in bypass in order to prevent shutting something down. The length of the manual proof test duration can have a significant impact on the overall performance of a safety system.
During the test, a simplex 1oo1 system must be taken offline.
Its availability during the test is zero. Redundant systems, however, do not have to be completely placed in bypass for testing. A leg, or slice, or a dual redundant system can be placed in bypass one at a time.
In fact a dual system is reduced to simplex during a test, and a triplicate system is reduced to dual.

As consequence the simplified equation:

$$PFDavg = \lambda_{DU} \times \frac{TI}{2}$$

shall be modified to:

$$PFDavg = \lambda_{DU} \times \frac{TI}{2} + \frac{TD}{TI}$$

where TI is the proof test interval and TD the test duration.

Example 1:

λ_{DU} = 0.002/ yr

TI = 1 yr

TD = 8 hr

PFDavg = 0.001 + 0.0009 = 0.0019;
RRF = 1/ 0.0019 = 526 (suitable for SIL 2 level)

Example 2:

λ_{DU} = 0.002/ yr

TI = 1 yr

TD = 96 hr

PFDavg = 0.001 + 0.01 = 0.011;
RRF = 1/ 0.011 = 90 (suitable for SIL 1 level)

The combination of both, effectiveness and test duration, brings to the following PFDavg equation:

$$PFDavg = (Et \times \frac{\lambda_{DU}}{2}) + \frac{TD}{TI} + \left[(1 - Et) \times \lambda_{DU} \times \frac{SL}{2} \right]$$

5.4.3.3 PFDavg interpretation

The IEC 61508 standard requires a probabilistic evaluation of each set of equipment, or group of these, used for risk reduction purpose in safety-related systems. Different orders of magnitude risk reduction levels are achieved on the average probability of failure on demand (PFDavg), often called average probability of dangerous failure.
A number of different methods have been used to calculate this probability. Among the most popular are fault tree analyses, reliability block diagrams, simplified equations, derived using a number of different ways, and Markov models.
For those who use Markov models, different solution techniques are used.
The fundamental problem is that these different methods give results that vary by 2X for same set of parameters.
Fortunately for 1oo1 (simplex) architectures the results are the same.

Part of the problem may be the different interpretation of the meaning of PFDavg as unreliability indicator, or indicator of safety unavailability.

PFDavg as Unreliability indicator

For this consideration, the unreliability function is calculated as a function of time interval, for a specified mission time usually equal to a “proof test” interval, for industrial equipments.
Then the function is averaged over the entire mission time.
This model is used for safety-related systems with the assumption that the system is periodically inspected and tested.
It is also assumed that the periodic proof test will detect all failed components and the system will be renewed to perfect condition.
Therefore the unreliability function is perfect for the problem.
The system may fail right after the inspection, right before the inspection or at any time between. Therefore the PFDavg is the average value of the unreliability function plotted over the inspection period.

Figure 42 at page 92 shows this interpretation, and the simplified equation is:

$$PFDavg = \lambda_{DU} \times \frac{TI}{2}$$

PFDavg as Safety unavailability indicator

PFDavg is interpreted as steady state unavailability of the safety system. SIS unavailability is determined by the unavailability of all its components.
For a system architecture 1oo1:

$$\text{Availability} = \frac{\mu}{\mu + \lambda}$$

$$\text{Unavailability} = 1 - \text{Availability} = 1 - \frac{\mu}{\mu + \lambda} = \frac{\lambda}{\mu + \lambda}$$

because $\mu >> \lambda$:

$$\text{Total unavailability} = \frac{\lambda}{\mu}$$

$$\text{Safety Unavailability} = \frac{\lambda_{DU}}{\mu}$$

remembering that:

$$\text{Safety Availability} = 1 - \text{PFDavg}$$

therefore

$$\text{Safety Unavailability} = 1 - (1 - \text{PFDavg}) = \text{PFDavg}$$

Assuming that the failures are not detected during normal operation (typical for type A components), it is argued that the average time to restore includes detection time plus actual repair time. The average detection time equals one half the inspection period, TI (T-proof test period) assuming that failures are equally likely at any time.
If the actual repair time is insignificant compared to the inspection period (TI), the average “repair” time (“mean time to restoration” in IEC 61508) is:

$$MTTR = TI / 2$$
and
$$\mu = 2 / TI$$

Substituting the above equation into the Safety Unavailability equation:

$$U = \lambda_{du} / \mu$$
we obtain

$$PFDavg = \lambda_{du}\, TI / 2$$

the same results as per the unreliability approach.

The identical approximations of the two equations lead many to conclude that either method, unreliability averaged or unavailability, may be used to calculate PFDavg for 1oo1 architecture.
However, the equations are different for systems with redundancy in the safety function.[1]
PFDavg calculation of redundant components, depends primarily on the contribution of β factor (common cause factor, see chapter 5.4.2 at page 102). This means that, independently from the used architecture, the PFDavg value is β multiplied by PFDavg of a simplex (1oo1) architecture, for which the unreliability and unavailability approaches have the same results.

Finally, when a risk reduction factor (RRF) has been determined for a specific SIF, and because its reverse is PFDavg, it is immediately possible to calculate the maximum repair time allowed for that specific safety function.

Example:

RRF = 1000; PFDavg = 0.001/year

Simplifying one year = 10.000 Hrs

The maximum repair time allowed in one year is about 10 hours.

This for all components included in the SIF, typically:
transmitter + barrier + logic solver + final element + power supply.

This time, usually indicated MTR (mean time to restore), refers to the average (unplanned) system downtime including delays for maintenance and supply resources.

MTR is an appropriate measure when maintenance and supply resources are included as requirement for the maintainability.

For SIL safety functions, the maintainability is a must.
As shown at 5.4.3.2 at page 107 the repair time can degrade the SIL level very easily.
Typically, for a SIL 2 safety function this time is considered from 8 to 10 hrs per year, while for a SIL 3 function it is about 1 hr per year.

[1] "*What is a PFDavg?*" Julia V. Bukowski, Jan Rouvroye and William M. Goble

5.4.4 1oo2 architecture

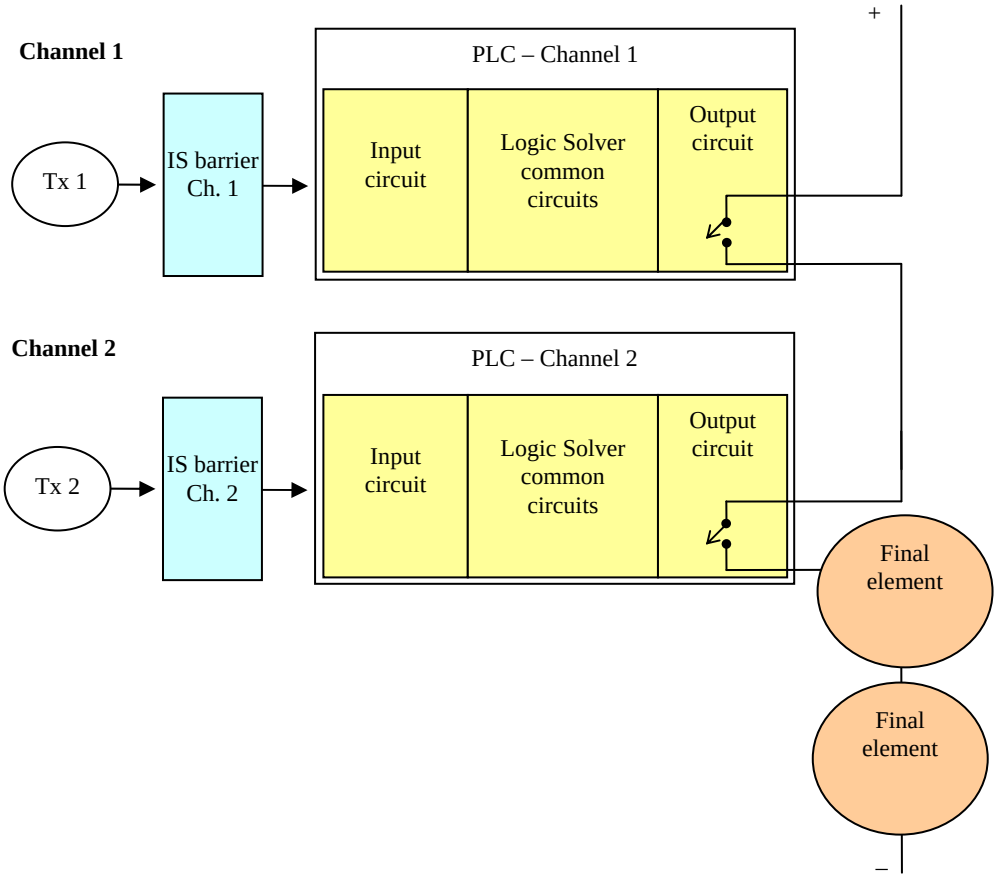


Figure 46, 1oo2 system architecture

1oo2 system architecture uses two channels, each with sensor / transmitter, IS barrier, and PLC control circuit in parallel, driving two final elements connected in series.
The system can fail dangerously for detected or undetected failures λ_{DD} and λ_{DU}.

As already described, this system architecture is used to minimize the effects of dangerous undetected failures λ_{DU}.
In the dangerous mode, this system would fail to function only if both channels were to fail dangerously at the same time.
1oo2 system has a low probability of failure on demand for safety, but twice as much probability of nuisance trips, compared to simplex system, because it has twice as much hardware.
PFDavg equation is the following:

$$\begin{aligned}&\text{PFDavg} = \\ &= \lambda_{DUC} \times \frac{TI}{2} + \lambda_{DDC} \times RT + (\lambda_{DDN} \times RT)^2 + \\ &+ \frac{(\lambda_{DDN} \times RT \times \lambda_{DUN} \times TI)^2}{2} + \frac{(\lambda_{DUN} \times TI)^2}{3}\end{aligned}$$

For systems with low common dangerous failure rates (λ_{DUC} and λ_{DDC}) and low repair time (RT) (conventionally RT is 8 hr, = 0,001 / yr), simplified equation is, as already seen in Table 2:

$$\text{PFDavg} = \frac{(\lambda_{DU} \times TI)^2}{3}$$

TI, “T-proof test” interval between two periodic manual proof tests, is usually of 1, 3, 5, or 10 years.

For TI of 1 yr:

$$\text{PFDavg}\big|_{TI=1} = \frac{\lambda_{DU}{}^2}{3}$$

Example

Considering the same data used in the 1oo1 architecture example at page 93 and introducing a β factor of 5% (0.05) on redundant sub-systems:

Tx:	MTBF = 102 yrs;	λ_{DU} = 0,00080 / yr;	λ_{DD} = 0,0010 / yr;	λ_S = 0,00800 / yr
Barrier:	MTBF = 314 yrs;	λ_{DU} = 0,00019 / yr;	λ_{DD} = 0,0014 / yr;	λ_S = 0,00159 / yr
PLC:	MTBF = 685 yrs;	λ_{DU} = 0,00001 / yr;	λ_{DD} = 0,0001 / yr;	λ_S = 0,00135 / yr
Supply:	MTBF = 167 yrs;	λ_{DU} = 0,00070 / yr;	λ_{DD} = 0,0000 / yr;	λ_S = 0,00530 / yr
Valve:	MTBF = 12 yrs;	λ_{DU} = 0,02183 / yr;	λ_{DD} = 0,0200 / yr;	λ_S = 0,04150 / yr

Subsystem	PFDavg 1oo1	RRF 1oo1	MTBFs 1oo1	PFDavg 1oo2[2]	RRF 1oo2	MTBFs 1oo2	SFF	SIL Level
Tx *	0.000400	2500	125	0.00002019	49528	62.5	91.8 %	SIL 3
Barrier D1014D *	0.000095	10526	629	0.00000476	210051	314.4	94.0 %	SIL 4
PLC	0.000005	200000	741	0.00000500	200000	741	99.3 %	SIL 3
Valve *	0.010915	92	24	0.00068768	1454	12	73.8 %	SIL 3
Power Supply *	0.000350	2857	189	0.00001765	56670	94.3	88.3 %	SIL 3
Total (SIF)	**0.011765**	**85**	**17**	**0.00073528**	**1360**	**8.5**	**-**	**SIL 3**

Table 9, 1oo2 system architecture and TI = 1 year

* Subsystems are in 1oo2 Architecture (obtained with two equal devices). Note that only one barrier is needed since G.M. International D1014D offers two completely independent channels with no common parts.

Note 1:

The Table highlights advantages of 1oo2 system architecture on 1oo1. Safety integrity level of the SIF has moved from SIL 1 to SIL 3 maintaining the same T-proof test time interval of 1 year.

Note 2:

Using such system configuration, the risk reduction factor is highly increased. If a SIL 2 level is required instead of SIL 3, it would be possible to extend the T-proof test time interval (TI).
Table 10 shows how the 1oo2 SIF would change for TI = 3, 5 and 10 years.

[2] See simplified equation with β factor at Section 5.4.2, page 112

System	PFDavg 1oo2	RRF	Max SIL level
1oo2$\|_{TI=1}$	0.00073528	1360	SIL 3
1oo2$\|_{TI=3}$	0.00220582	453	SIL 2
1oo2$\|_{TI=5}$	0.003676377	272	SIL 2
1oo2$\|_{TI=10}$	0.007352755	136	SIL 2

Table 10, 1oo2 SIF changes for TI = 3, 5 and 10 years

Consideration:

In case SIL 2 level is tolerable, the periodic test time interval can be safely extended to almost 10 yrs and some components may be used in a 1oo1 architecture (Tx, Barrier, PLC), while the power supplies are to be preferably redundant with N+1 modules.
A 1oo2 simple system architecture application is shown in Figure 47a where two contact repeaters type D1032D and D1033D, SIL 2, are used to obtain a SIL 3 level.
While in Figure 47b, two single isolator repeaters D1014D, rated SIL 3, obtain either a SIL 3 for 10 years or a SIL 4 for 1 year.
Indeed the D1014D module is made of two single completely independent channels, without any common components, including two independent power supply circuits.
Therefore it can be considered, and used, as two single independent circuits like two D1014S. This is why the unit D1014D can be used in SIL3 SIF with 10 years T-proof test interval or in SIL 4 SIF with 1 year T-proof.

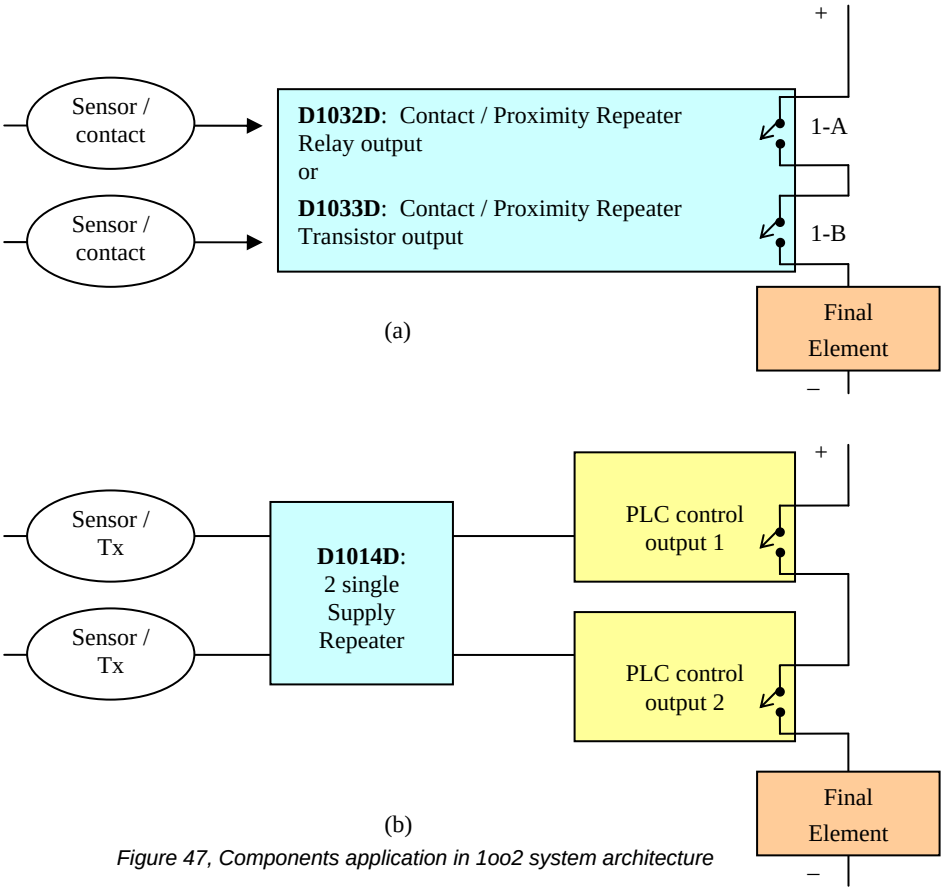
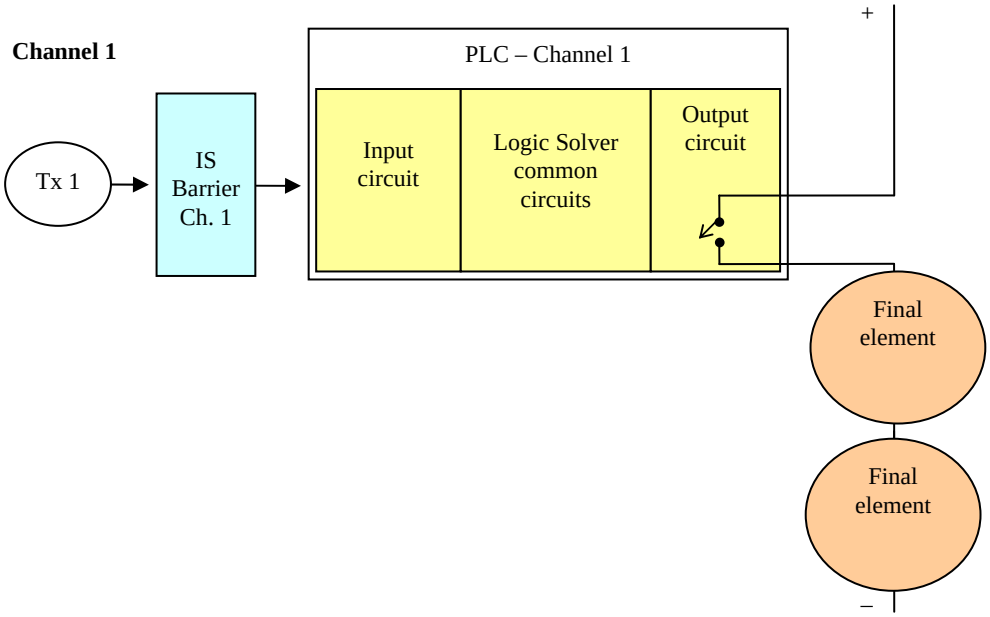


Figure 47, Components application in 1oo2 system architecture

5.4.4.1 1oo2 architecture for Final Element only



Subsystem	PFDavg 1oo1	RRF 1oo1	MTBFs 1oo1	PFDavg 1oo2[3]	RRF 1oo2	MTBFs 1oo2	SFF	SIL Level
Tx	0.000400	2500	125	0.000400	2500	125	91.8 %	SIL 2
Barrier D1014D	0.000095	10526	629	0.000095	10526	629	94.0 %	SIL 3
PLC	0.000005	200000	741	0.000005	200000	741	99.3 %	SIL 3
Valve	0.010915	92	24	0.00068768	1454	12	73.8 %	SIL 3
Power Supply	0.000350	2857	189	0.00001765	56670	189	88.3 %	SIL 2
Total (SIF)	**0.011765**	**85**	**17**	**0.00120533**	**829**	**10**	**-**	**SIL 2**

Table 11, 1oo2 system architecture for Valve only

The valve's redundancy allows the SIF to reach SIL 2 level with a more than satisfactory RRF value.

[3] See simplified equation with β factor at Section 5.4.2, page 112

5.4.5 2oo3 system architecture

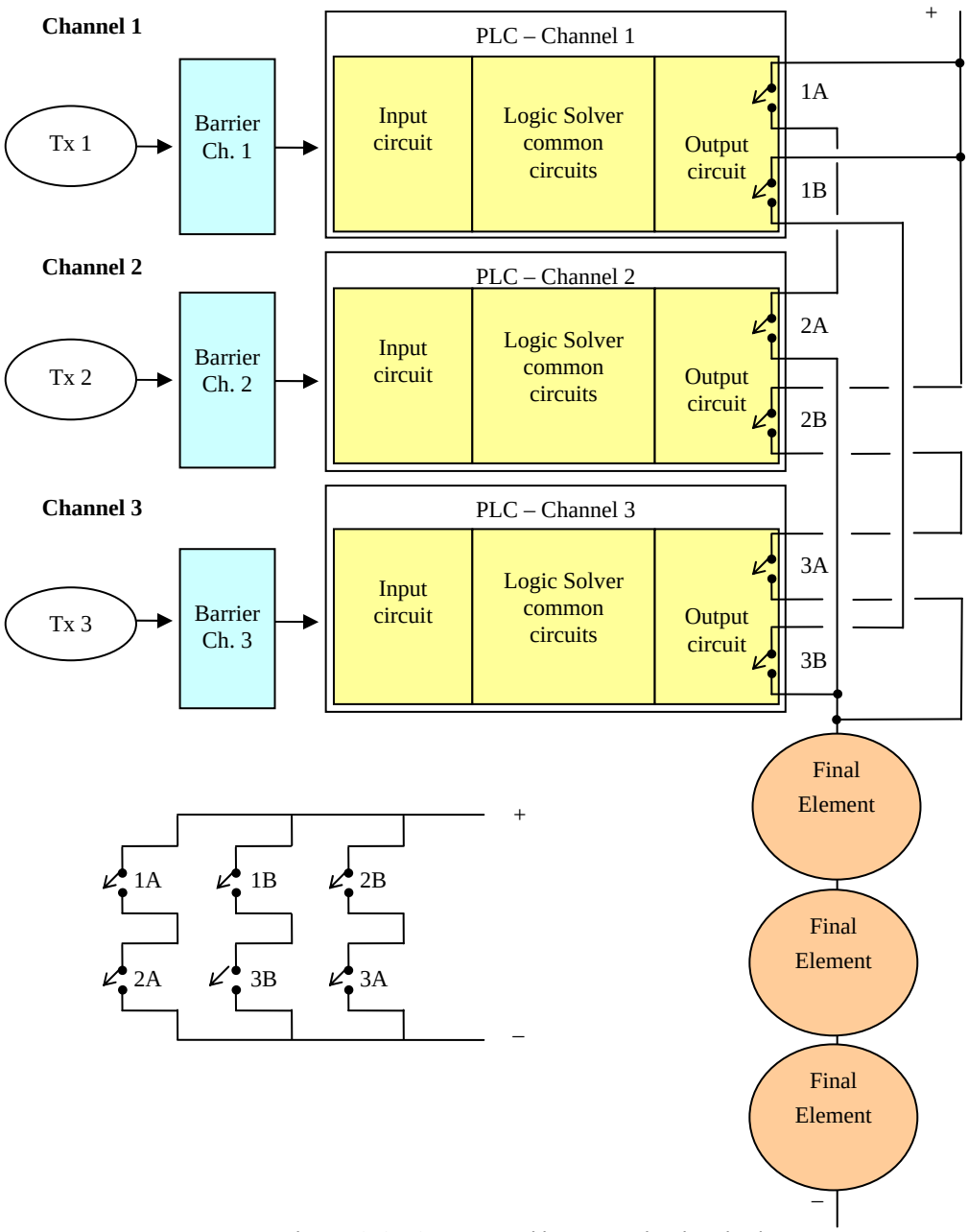


Figure 48, 2oo3 system architecture and voting circuit

An architecture designed to tolerate both “safe” and “dangerous” failures is 2oo3 (two out-of-three).
It provides both safety and high availability with three controller units. Two outputs from each controller unit are required for each output channel. The two outputs from the three controllers are wired in a “voting circuit”, which determines the actual output. This output will equal the “majority”.
When two sets of outputs conduct, the load is energized.
When two sets of outputs are off, the load is de-energized.
A close examination of the voting circuit shows that it will tolerate a failure of either failure mode: dangerous (short circuit) or safe (open circuit).
When the unit fails creating an open circuit, the system effectively degrades to 1oo2 architecture. If one unit fails creating a short circuit, the system effectively degrades to 2oo2.
In both cases the system remains in successful operation.

2oo3 PFDavg equation is:

$$\text{PFDavg} = \lambda_{DUC} \times \frac{\text{TI}}{2} + 3 \times \lambda_{DDC} \times \text{RT} + 3 \times \left[\left(\lambda_{DDN} \times \text{RT} \right)^2 + \frac{\left(\lambda_{DDN} \times \text{RT} \times \lambda_{DUN} \times \text{TI} \right)^2}{2} + \frac{\left(\lambda_{DUN} \times \text{TI} \right)^2}{3} \right]$$

For systems with low values of common failures (λ_{DUC} and λ_{DDC}), and low repair time[4] (RT) the equation can be simplified to:

$$\text{PFDavg} = {\lambda_{DU}}^2 \times TI^2$$

$$\text{PFDavg}\big|_{\text{TI}=1} = {\lambda_{DU}}^2$$

It can be observed that 2oo3 PFDavg value is 3 times greater than 1oo2 PFDavg, therefore the value of risk reduction factor (RRF) will be lower compared to 1oo2 architecture.

[4] Conventionally, Repair Time (RT) is 8 hours = 0,001 / yr

Example

Considering the same data used in the 1oo1 architecture example at page 93 and introducing a β factor of 5% (0.05) on redundant sub-systems:

Tx:	MTBF = 102 yrs;	λ_{DU} = 0,00080 / yr;	λ_{DD} = 0,0010 / yr;	λ_S = 0,00800 / yr
Barrier:	MTBF = 314 yrs;	λ_{DU} = 0,00019 / yr;	λ_{DD} = 0,0014 / yr;	λ_S = 0,00159 / yr
PLC:	MTBF = 685 yrs;	λ_{DU} = 0,00001 / yr;	λ_{DD} = 0,0001 / yr;	λ_S = 0,00135 / yr
Supply:	MTBF = 167 yrs;	λ_{DU} = 0,00070 / yr;	λ_{DD} = 0,0000 / yr;	λ_S = 0,00530 / yr
Valve:	MTBF = 12 yrs;	λ_{DU} = 0,02183 / yr;	λ_{DD} = 0,0200 / yr;	λ_S = 0,04150 / yr

Subsystem	PFDavg 1oo1	RRF 1oo1	MTBFs 1oo1	PFDavg 2oo3[5]	RRF 2oo3	MTBFs 2oo3	SFF	SIL Level
Tx *	0.000400	2500	125	0.00002058	48597	2893518	91.8 %	SIL 3
Barrier D1014D *	0.000095	10526	629	0.00000478	209092	73250735	94.0 %	SIL 4
PLC	0.000005	200000	741	0.00000500	200000	741	99.3 %	SIL 3
Valve *	0.010915	92	24	0.00097584	1025	107525	73.8 %	SIL 3
Power Supply *	0.000350	2857	189	0.00001794	55734	6592566	88.3 %	SIL 3
Total (SIF)	**0.011765**	**85**	**17**	**0.00102414**	**976**	**55546**	**-**	**SIL 2**

Table 12, 2oo3 system architecture and TI of 1 year

* Subsystems are in 2oo3 Architecture (obtained with three equal devices). Note that only two barriers are needed since G.M. International D1014D offers two completely independent channels with no common parts.

Note 1:

Table 12 highlights advantages of 2oo3 system architecture on 1oo1. Safety integrity level of the SIF has in fact moved from SIL 1 to SIL 2 maintaining the same T-proof test time interval of 1 year.
The very high value of RRF shows how SIL 2 can be easily maintained even with longer TI intervals.

[5] See simplified equation with β factor at Section 5.4.2, page 112

Note:
A simple application of 2oo3 system architecture is shown in Figure 49. This has been shown to indicate the possibility to use relay output contacts (GM International D1032 or D1033 units) in order to obtain the 2oo3 voting circuit. The final element will be driven only if at least two contact repeater units are operating correctly. SIF has a SIL 3 level.

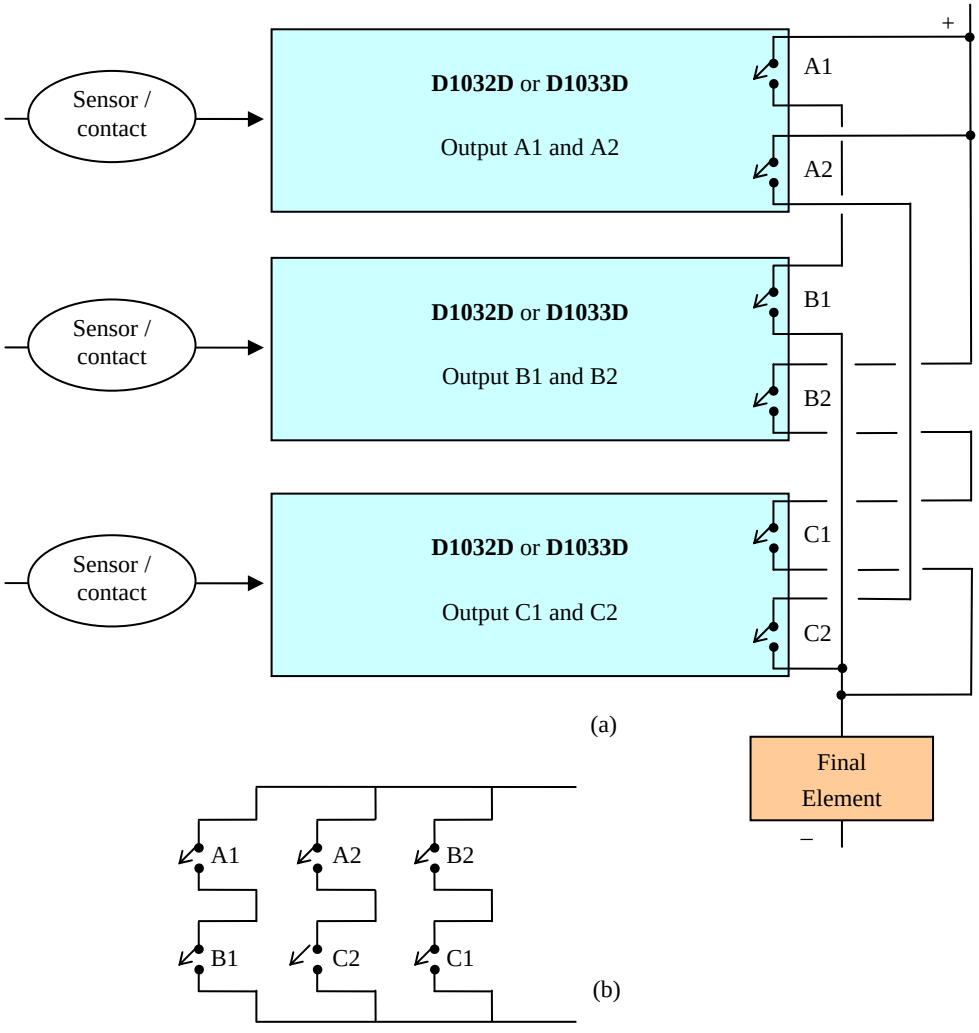


Figure 49, Example of 2oo3 (a) architecture and voting circuit (b)

5.4.6 Comparison between system architectures

Table 3 below shows the comparison between SIF values of system architectures which have been previously analyzed.

SIF Architecture	$MTBF_S$ (yr)	PFDavg	RRF	Maximum SIL Level
1oo1	17	0.011765	85	SIL 1
1oo2	8.5	0.000735	1360	SIL 3
2oo3	55546	0.001024	976	SIL 2

Table 13, Comparison between system architectures

Observations:

- Redundant architectures increase SIL level.
- 2oo3 architecture is justified primarily because of the high value of $MTBF_S$, which means that production facilities will almost never be interrupted for spurious (safe) trips.
- 1oo2 architecture is more simple, cost effective, and with a better risk reduction factor.

Considerations:

- If the required level is **SIL 1**, system architecture 1oo1 allows a test time interval (TI) of 10 yrs, while 2oo2 allows SIL 1 for 5 yrs only.
- If specified safety integrity level is **SIL 2**, system architecture 1oo1 allows a test time interval (TI) of 1 yr, while 2oo2 cannot be used.
- If the required level is **SIL 3**, system architecture 1oo2 allows a test time interval (TI) for 5 yrs, while 2oo3 allows SIL 3 for 3 yrs only.
- Architectures 1oo1 and 2oo2 cannot be used.

In order to confirm the SIL level for all components, calculation of SFF values has to be carried out separately, and compared with the appropriate Tables 2 and 3 of the IEC 61508-1.

Following are comparison tables for PFDavg values, in different system architectures, and different T-proof test intervals, assuming a constant value for dangerous failure rate (λdu = 0.01/yr), and constant Mean Time To Repair (MTTR = 8 hrs = 0.0009 yrs):

Architecture	λdu/yr	PFDavg	RRF	Possible SIL level
1oo1	0.01	0.005900000	169	SIL 2
1oo2	0.01	0.000042350	23613	SIL 4
2oo2	0.01	0.010900000	92	SIL 1
2oo3	0.01	0.000127049	7871	SIL 3

Table 14, TI = 1 yr, TD = 0.0009 yr

Architecture	λdu/yr	PFDavg	RRF	Possible SIL level
1oo1	0.01	0.015300000	65	SIL 1
1oo2	0.01	0.000309005	3236	SIL 3
2oo2	0.01	0.030300000	33	SIL 1
2oo3	0.01	0.000927016	1079	SIL 3

Table 15, TI = 3 yr, TD = 0.0009 yr

Architecture	λdu/yr	PFDavg	RRF	Possible SIL level
1oo1	0.01	0.025180	39	SIL 1
1oo2	0.01	0.000842	1187	SIL 3
2oo2	0.01	0.050180	20	SIL 1
2oo3	0.01	0.002527	396	SIL 2

Table 16, TI = 5 yr, TD = 0.0009 yr

Architecture	λdu/yr	PFDavg	RRF	Possible SIL level
1oo1	0.01	0.050090	20	SIL 1
1oo2	0.01	0.003342	299	SIL 2
2oo2	0.01	0.100090	10	SIL 0
2oo3	0.01	0.010027	99	SIL 1

Table 17, TI = 10 yr, TD = 0.0009 yr

5.5 Summary of simplified equations

MTTFs: Mean Time to Safe Failure

1oo1: $$MTTF_S = \frac{1}{\lambda_S}$$

1oo2: $$MTTF_S = \frac{1}{2 \times \lambda_S}$$

2oo2: $$MTTF_S = \frac{1}{2 \times \lambda_S^2 \times MTTR}$$

2oo3: $$MTTF_S = \frac{1}{6 \times \lambda_S^2 \times MTTR}$$

Note: These formulae are valid when MTBF >> MTTR or 1/MTTR >> λ.
MTBFs can be assimilated to MTTFs when repair time is negligible compared to mission time.
MTTR: Mean Time To Repair, if not specified, is expressed in hours.

PFDavg

1oo1:

$$PFDavg = \lambda_{DU} \times \frac{TI}{2}$$

1oo2:

$$PFDavg = \lambda_{DU_1} \times \lambda_{DU_2} \times \frac{TI^2}{3} \qquad (\lambda_{DU_1} \neq \lambda_{DU_2})$$

$$PFDavg = \lambda_{DU}^2 \times \frac{TI^2}{3} \qquad (\lambda_{DU_1} = \lambda_{DU_2})$$

1oo3:

$$PFDavg = \lambda_{DU_1} \times \lambda_{DU_2} \times \lambda_{DU_3} \times \frac{TI^3}{4} \qquad (\lambda_{DU_1} \neq \lambda_{DU_2} \neq \lambda_{DU_3})$$

$$PFDavg = \lambda_{DU}{}^3 \times \frac{TI^3}{4} \qquad (\lambda_{DU_1} = \lambda_{DU_2} = \lambda_{DU_3})$$

2oo2:

$$PFDavg = \left(\lambda_{DU_1} + \lambda_{DU_2}\right) \times \frac{TI}{2} \qquad (\lambda_{DU_1} \neq \lambda_{DU_2})$$

$$PFDavg = \lambda_{DU} \times TI \qquad (\lambda_{DU_1} = \lambda_{DU_2})$$

2oo3:

$$PFDavg = \left(\lambda_{DU_1} \times \lambda_{DU_2} + \lambda_{DU_1} \times \lambda_{DU_3} + \lambda_{DU_2} \times \lambda_{DU_3}\right) \times \frac{TI^2}{3} \qquad (\lambda_{DU_1} \neq \lambda_{DU_2} \neq \lambda_{DU_3})$$

$$PFDavg = \lambda_{DU}{}^2 \times TI^2 \qquad (\lambda_{DU_1} = \lambda_{DU_2} = \lambda_{DU_3})$$

2oo4:

$$PFDavg = \left[\left(\lambda_{DU_1} \times \lambda_{DU_2} \times \lambda_{DU_3}\right) + \left(\lambda_{DU_1} \times \lambda_{DU_2} \times \lambda_{DU_4}\right) + \left(\lambda_{DU_1} \times \lambda_{DU_3} \times \lambda_{DU_4}\right) + \left(\lambda_{DU_2} \times \lambda_{DU_3} \times \lambda_{DU_4}\right)\right] \times \frac{TI^3}{4}$$

$$(\lambda_{DU_1} \neq \lambda_{DU_2} \neq \lambda_{DU_3} \neq \lambda_{DU_4})$$

$$PFDavg = \lambda_{DU}{}^3 \times TI^3 \qquad (\lambda_{DU_1} = \lambda_{DU_2} = \lambda_{DU_3} = \lambda_{DU_4})$$

Note:
PFDavg formulae extracted from: "*Easily Assess Complex Safety Loops*"
Lawrence Beckman - Chemical Engineering Progress, March 2001

5.5.1 Influence of time interval and duration of periodic tests, on PFDavg, for redundant equal components

1oo1: $$PFDavg = \lambda_{DU} \times \frac{TI}{2} + \left(\frac{TD}{TI}\right)$$

1oo2: $$PFDavg = \lambda_{DU}{}^2 \times \frac{TI^2}{3} + \left(2 \times TD \times \lambda_{DU} \times \frac{\frac{TI}{2} + MTTR}{TI}\right)$$

2oo2: $$PFDavg = \lambda_{DU} \times TI + \left(\frac{TD}{TI}\right)$$

2oo3: $$PFDavg = \lambda_{DU}{}^2 \times TI^2 + \left(6 \times TD \times \lambda_{DU} \times \frac{\frac{TI}{2} + MTTR}{TI}\right)$$

Where:
TI = T-proof test interval in years;
TD = Test duration in years.

5.5.2 Application exercises using simplified equations

Example 1

With two ON-OFF shutdown valves in system configuration 1oo2, assuming the following data, calculate PFDavg value for TI of 1 yr.

All failures are considered dangerous undetected and time to replace the valve negligible compared to operating time.

Valve 1: $MTTF_D = 30$ yr, $\lambda_{DU1} = 0.033$ / yr;

Valve 2: $MTTF_D = 50$ yr, $\lambda_{DU2} = 0.020$ / yr;

Solenoid: $MTTF_D = 40$ yr, $\lambda_{DU3} = 0.025$ / yr;

For each valve-solenoid the common failure rate (λ_c) is:

$\lambda_{DU1c} = \lambda_{DU1} + \lambda_{DU3} = 0.058$;

$\lambda_{DU2c} = \lambda_{DU2} + \lambda_{DU3} = 0.045$;

PFDavg for 1oo2 architecture:

$$\text{PFDavg} = \frac{\lambda du_{1C} \times \lambda du_{2C} \times TI^2}{3} = \frac{(0.058 \times 0.045 \times 1)}{3} = 0.0009 / \text{yr}$$

Suitable for **SIL 3** level applications.

Example 2

Calculate PFDavg value for 2oo3 system architecture of three different thermocouples, TI of 1 yr. All failures are considered dangerous and time to replace thermocouples negligible compared with operating time.

TC 1: $MTTF_D = 500$ yr, $\lambda_{DU1} = 0.002$ / yr;
TC 2: $MTTF_D = 100$ yr, $\lambda_{DU2} = 0.010$ / yr;
TC 3: $MTTF_D = 50$ yr, $\lambda_{DU3} = 0.020$ / yr;

$$\text{PFDavg} =$$

$$= (\lambda_{DU1} \times \lambda_{DU2} + \lambda_{DU1} \times \lambda_{DU3} + \lambda_{DU2} \times \lambda_{DU3}) \times \frac{TI^3}{3} =$$

$$= (0.002 \times 0.01 + 0.002 \times 0.02 + 0.01 \times 0.02) \times \frac{1}{3} =$$

$$= 0.000086 / \text{yr}$$

Suitable for **SIL 3** level applications.

Example 3

Calculate PFDavg of a safety loop including valves of example 1, and thermocouples of examples 2, in a safety loop and a PES with PFDavg = 0.0005/ yr (suitable for SIL 3 level):

$$\text{PFDavg} = 0.0009 + 0.0002 + 0.0005 = 0.0016 / \text{yr}$$

Suitable for **SIL 2** level applications

Note:
Examples 1,2 ,3 extracted from: "*Easily Assess Complex Safety Loops*" Lawrence Beckman - Chemical Engineering Progress, March 2001

5.6 Use of valves in Safety Instrumented Systems

5.6.1 Bypass examples and possibilities of on-line periodic proof testing for SIS shutdown valves, or other field devices used in 1oo1 system architecture

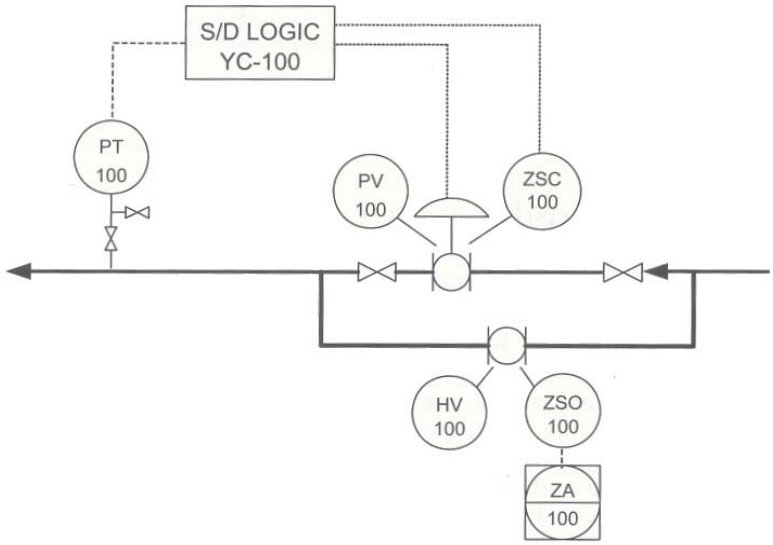


Figure 50, P&I diagram with online bypass valve for periodic proof testing

Figure 50 shows an example of installation that would allow online testing. In order to test the system, bypass valve HV-100 would be operated and the signal to transmitter PT-100 changed to simulate a trip.

The main trip valve PV-100 should close at the specified set point of PT-100. Some form of feedback (e.g. a limit switch) could be used to verify that the valve PV-100 has in fact closed fully.

One way to test a low pressure sensing device would be to close the process isolation valve and vent the signal to the device (if environmentally feasible) until it activate. One should have the means to detect that the system responds at the value documented in the requirements specification.
If a valve opens for a shutdown, a normally chained opened block valve could be installed upstream of the actuated valve. This block valve could then be closed, and the shutdown valve could be opened for testing. After testing, everything must be returned to their original positions.

The use of manual bypass switches, to disable shutdown valves from closing, should be discouraged (as they may be measured) but used if it is not practical to install a bypass around the valve.

In some cases it may not be possible to test or shutdown the final element (e.g. a compressor, pump, or large valve).
In these cases, some form of bypass may need to be installed in order to ensure that the final element will not activate when the sensing element and logic are tested. For example, in the case of a compressor, the final shutdown relay may be energized and the signal from the shutdown relay to the compressor starter bypassed.

If manually-operated bypass switches are to be installed, only one switch should be operated at a time. Active bypasses should be alarmed in some manner. Some bypasses may be necessary in order to allow plant startup (e.g. low level or low flow). These bypasses may need to be controlled by timers that allow the shutdown functions to be re-established after a fixed time. Procedures must be developed and followed on the use of bypasses.
Any defect identified during testing must be reported and repairs schedule based on the criticality of the system. Redundant systems must also be tested in order to assure that all components are fully functional.

During periodic testing, procedures listed in functional safety manuals, must be performed carefully. These manuals must list the percentage of effectiveness of each testing procedure, to reveal undetected failures which are not detectable during normal operation (λ_{DU}).

5.6.2 Partial Stroking Test (PST) for valves

In Chemical process Industry, and large Petroleum Refineries, it was usual to pull and repair valves during maintenance turnaround, (when the plant is stopped for maintenance).
Valves often represent the weakest link in a system. The traditional choice to improve performance includes redundancy and/or more frequent manual testing. With valves, both choices are often financially and operationally unattractive. Redundant valves, especially large ones, can dramatically increase overall costs. The space required for extra valves may also not be present in an existing facility. Frequent full stroke testing of valves (e.g. quarterly) is usually not possible in continuous processes that are intended to run for years between maintenance turnarounds. One solution gaining in popularity is partial stroke testing of valve. In fact, many vendors now offer packaged solutions.

The probability of a valve failing to perform its designed function increases with age and this probability can be treated as a linear function over time.
Now there are several ways to collect the data on SIS valves since BPCS valve performance data is readily available on DCS.
DCS collects loop performance data, like transmitter or valve response, for a short time, and the information is sent to their systems analysis group who generate a performance signature for all the components in the loop.
At different load conditions signatures point the problem as process or tuning valve behavior, guiding the engineer to likely problem area.
Valve responses typically indicate problem areas so the technician can focus and seek on line solution. When valves are in open or closed position they are saturated and treated as open loop.

The PST can be manual or automatic. It consists in exiting the valve with small steps and verifying the movements and their delay time, during normal operation (in line). This type of testing allow to test up to 80% of dangerous failures reducing the value of PFDavg, and consequently increasing the SIL level, without having to increase the frequency of periodic manual testing.
The frequency of such testing (PST) also plays an important role in monitor the valve integrity, as between tests little information is obtained about the valve's condition, and only a theoretical prediction can be expressed of the valve functioning correctly on demand. Therefore it follows that the higher the testing frequency and the higher the diagnostic coverage factor of the test (which express test effectiveness).

Usually, for valves which are not SIL qualified, all failures are considered dangerous. For example assume valve MTBF = 40 yr:

$$PFDavg\big|_{TI=1} = \frac{\frac{1}{40}}{2} = \frac{0.025}{2} = 0.0125$$

$$RRF = \frac{1}{0.0125} = 80 \text{ (SIL 1)}$$

PST introduce a diagnostic coverage factor which could range from 70% to 80%. A 100% diagnostic coverage factor is obtained only with a full stroke test (FST) and leakage test.

PFDavg equation could be modified as follows:

$$PFDavg = \left(C \times \lambda \times \frac{TI_I}{2} \right) + \left[(1-C) \times \lambda \times \frac{TI}{2} \right]$$

where:

C: Diagnostic coverage factor.
TI_I: Partial stroke test interval
TI: Full stroke test interval with a diagnostic coverage factor of 99% or 100%

Assuming:

TI: 1 yr
TI_I: 1 month (1/12 yr = 0.083 yr)
C: 80% = 0.8
λ: 1/40 = 0.025 / yr

$$PFDavg = (0.8 \times 0.025 \times 0.0415) + (0.2 \times 0.025 \times 0.5) = 0.00333$$

$$RRF = \frac{1}{0.00333} = 300 \text{ (SIL 2)}$$

Applying to the valve in the previous example, with RRF = 80 (SIL 1), a PST once a month, during normal operation, it can achieve RRF = 300 (SIL 2).

5.6.2.1 Advantages and risk in the use of Partial Stroking Tests

The advantage of an automatic partial stroke test (either manual or automatic), as already explained, is the capability to increase the diagnostic coverage, which can achieve up to 80 %, while the process is still running, and without interfering SIS availability.
That is possible only if software, with historic information on valve performance, is available.

Since a PST does not affect the production, it can provide an insight into the performance of the valve, between two FST. In facts PST on a SIS valves offers great help to manual full stroke test (FST), where the valve is fully closed and opened.
To be able to fully evaluate the PST advantages it is important:

- To define which effectiveness, or diagnostic coverage factors, the test will provide, in order to calculate the PFDavg.
- To be able to evaluate spurious trip probability introduced by the frequent tests.

The main disadvantages are indeed the possible nuisance trips.
For this reason valve vendors recommend to test just the valve movement and the delay. Testing other parameters inline may increase the probability of spurious trips.

5.6.2.2 Technologies to help PST

Valve vendors have introduced smart positioners and new software for PST.
The new software offers every type of data on valve behavior providing much information which normally were obtainable with a full stroke test only.
The usual technique is to bleed the air supply or pulse the solenoid valve until the desired travel, in the specified time, is achieved.
Thus partial stroke is produced by controlled air signal, travel and timing while collecting several samples of status of the valve.

The data is automatically analyzed and compared against the base line performance, results, and any disparities, may indicate that the valve is unable to complete its function to fully open or close.
The operator gets a failure alarm.

5.6.3 Full Stroke Test of valves (FST)

This test usually includes:

- Complete opening of the valve and response time recording;
- Complete closing of the valve and response time recording;
- Leak test when fully closed;

Test results are witnessed and recorded by maintenance operators, and used to increase the diagnostic coverage factor, which can reach up to 95%.
The time interval between two FST enters in the PFDavg calculation.
The ideal time interval should be 5 or 10 years, but this depends from type of process and application. SIL 3 valves are now available on the market. These

valves are SIL 3 for one year FST time interval, therefore their use should be encouraged in SIL 2 applications with 5, or more, years test time interval.
This also should be added to the criteria when selecting a proper valve for use in a specific SIF of a SIS.

Final considerations

So far industry leaders are promoting the benefits of PST in SIS applications and DCS vendors are thinking the benefits of advanced process control, optimization and online loop performance leaving the end users to wonder whether the two will take action to benefit the customer in ownership costs.
Valve vendors should always supply complete FMEDA information about their products, with all failure rates data, to allow design and maintenance engineers to reduce redundant components, bypasses costs, and increasing test time intervals.

5.7 SIS Conceptual Design [6]

The conceptual design must comply with any relevant company standards. A summary of the company guidelines relating to SIL and hardware is:

SIL	Sensors	Logic Solver	Final Elements
3	Redundant sensors required, either 1oo2 or 2oo3 depending on spurious trip requirements	Redundant safety PLC required	1oo2 voting required
2	Redundancy may or may not be required. Initial option is not to have redundancy. Select redundancy if warranted by PFDavg calculations	Safety PLC required	Redundancy may or may not be required. Initial option is not to have redundancy. Select redundancy if warranted by PFDavg calculations
1	Single sensor	Non-redundant PLC or relay logic	Single device

Table 18, SIS design guidelines based on SIL

[6] Contents of Sections 5.7, 5.8, and 5.9 are excerpted with permission from “Safety Instrumented Systems: Design, Analysis, and Justification, 2nd Edition,", Copyright 2006 © by ISA

Based on the criteria in Table 18, the proposed system is shown in Figure 51.

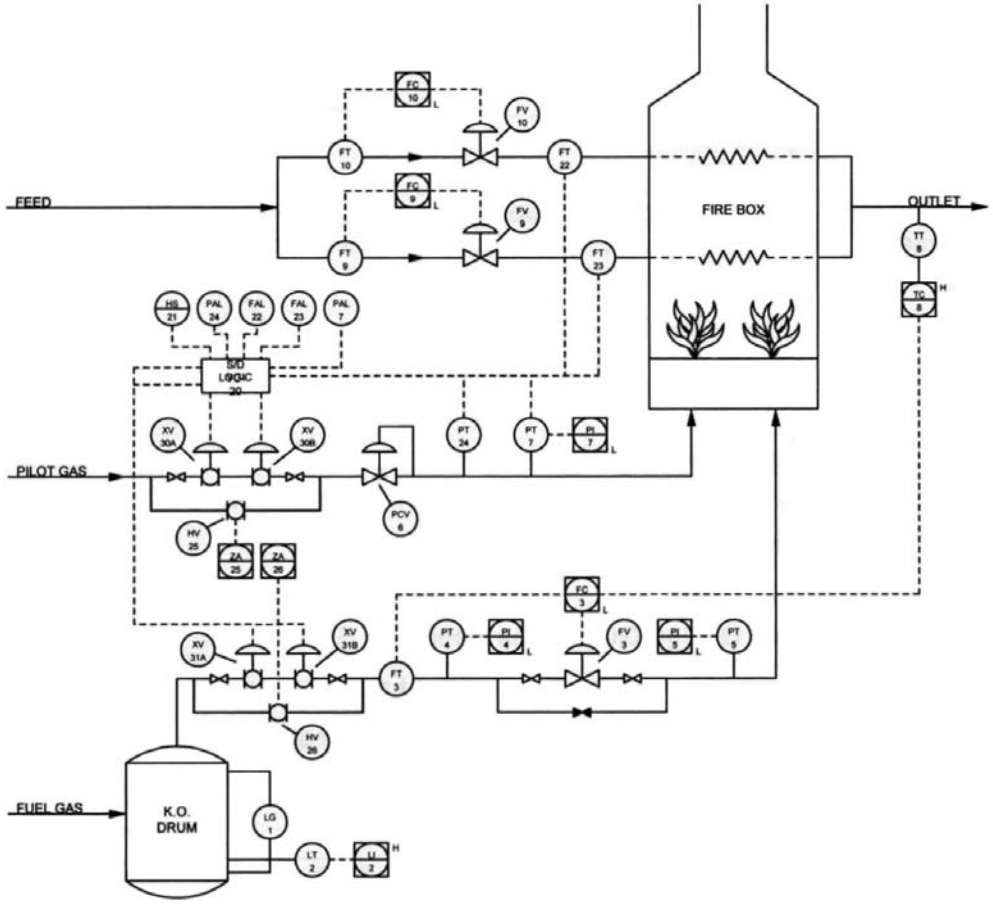


Figure 51, Proposed safety instrumented functions (SIFs)

5.7.1 Conceptual Design Requirements

The conceptual design builds on and supplements the safety requirement specification (SRS), which consists of functional specifications (what the system does), and integrity specifications (how well it does it).
Key information required by the engineering contractor in order to complete the detailed engineering package should be provided. The design should also adhere to the company standards and procedures. There should be no contradiction between the SRS and the conceptual design requirements.
Table 19 below summarizes the basic conceptual design requirements.

System architecture:	The Logic Solver shall be a redundant, certified safety PLC. The cabinet shall be located in the main control building. 1oo2 voting is required for pilot gas pressure transmitters, as well as fuel and pilot gas shutdown valves. Verification is required that this design meets the corresponding SIL level requirements. Figure 51 is a sketch of the overall configuration.
Minimize common causes:	Wiring from the 1oo2 valves and transmitters to the SIS is to be segregated from BPCS wiring. Need of separate uninterruptible power supplies (UPS) to power the SIS. All transmitters must have separate taps.
Environmental conditions:	Area classification is Class 1, Group D, Div. 2 (Europe IIB, Zone 2). Hydrogen sulfide gas is in the environment around the furnace. The ambient temperature can fall to -35°C during the winter.
Power supplies:	110 V, 60 Hz power is available from two separate UPS systems located in the main control room.
Grounding:	Ensure that company grounding standards for instruments and power systems are followed.
Bypasses:	Bypass valves are required to be installed around the pair of trip valves for the pilot gas and fuel gas trip valves for on-line testing. An alarm in the BPCS is required to indicate that a bypass valve has opened. No other bypasses are required.
Application software	Ladder logic to be used for all programs in the SIS.
Security:	The existing company security requirements for access to and modification of the SIS logic shall be followed.
Operators interface	Shutdown and diagnostic alarms are to be wired to an existing hardwired enunciator. Bypass alarms are to be connected to the BPCS.

Table 19, Conceptual design summary

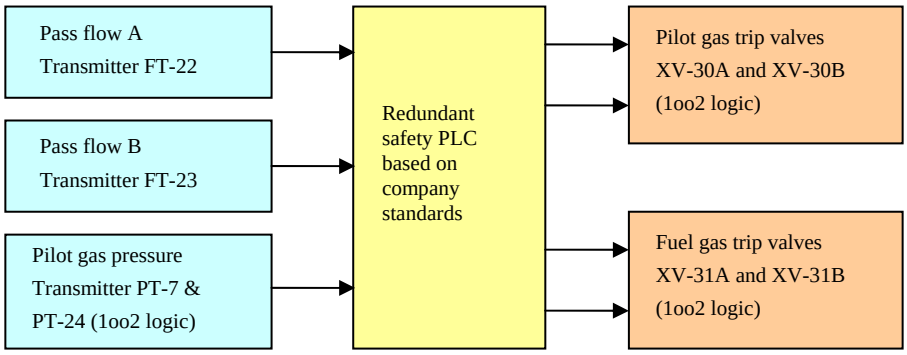


Figure 52, Proposed conceptual SIS design

5.8 Lifecycles cost analysis

Table 20 summarizes the lifecycle costs analysis.

Lifecycle costs (20 years)	Material ($)	Labor ($)	Total cost/item ($)	Subtotal ($)
Initial Fixed Costs				
Safety classification		1,000	1,000	
SRS/Design specifications		3,000	3,000	
Detailed design and engineering		20,000	20,000	
Sensors	24,000		24,000	
Final elements	6,000		6,000	
Logic system	30,000		30,000	
Misc. – Power, wiring, jb's	4,000		4,000	
Initial training		5,000	5,000	
FAT (Factory Acceptance Test) - Installation - PSAT (Pre-Startup Acceptance Testing)	4,000	16,000	20,000	
Startup and corrections	1,000	2,000	3,000	
Fixed costs subtotal				116,000
Annual Costs				
Ongoing training		1,000	1,000	
Engineering charges	1,000	1,000	2,000	
Service agreement		1,000	1,000	
Fixed operation and maintenance costs		1,000	1,000	
Spares	4,000		4,000	
Online testing		8,000	8,000	
Repair costs	1,000	500	1,500	
Hazard cost				
Spurious trips costs			8,000	
Annual costs subtotal				26,500
Present value for annual costs (20 years, 5% interest rate)				330,249
Total Lifecycle Costs				**446,249**

Table 20, Lifecycle costs summary

5.9 Conceptual Design and SIL Level

It is important to verify that each SIF meets the SIL level requirements. In this case there are three functions (i.e. low pass flow A, low pass flow B, and low pilot gas pressure). The low pilot gas pressure SIF requires SIL 3 level and the pass flow SIF requires SIL 2 level.
Only the SIL 3 SIF will be analyzed here.
The equations listed in section 5.5 are used for the calculations.
A block diagram of the conceptual pilot gas shutdown SIF is shown in Figure 53.

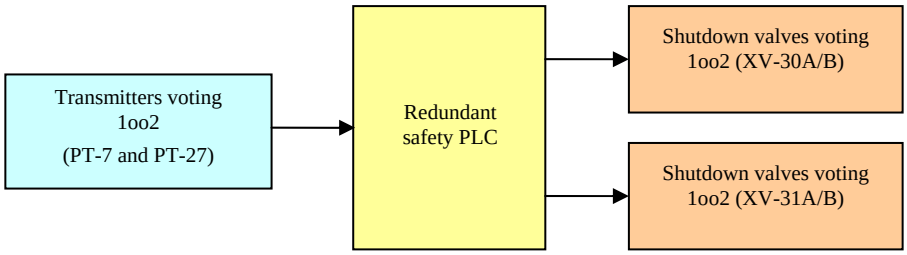


Figure 53, Block Diagram for Pilot Gas Shutdown SIF

Assuming:

- MTTR: 8 hr
- Average demand rate: 1 per yr
- Manual test interval (TI): 3 months
- Common cause β factor: 5%
- Transmitter diagnostics using comparison: 90%

Item	Dangerous undetected failure rate λ_D	Safe failure rate λ_S
Transmitter PT-7, PT-24	0.01 (1/100 yrs)	0.02 (1/50 yrs)
Valves and solenoids XV-30A/B, XV-31A/B	0.02 (1/50 yrs)	0.1 (1/10 yrs)
Safety PLC	See note 1	See note 1
Note 1: PFD_{avg} and $MTTF_S$ for the redundant safety PLC are supplied by the vendor		

Table 21, Failure Rate Data (Failures per year)

PFDavg Calculations for one year periodic test interval (TI):

PFDavg (sensors) =

$$= \frac{\text{Failure rate} \times 10\% \text{ Undetected failures} \times 5\% \text{ Common cause} \times \text{Test interval}}{2} =$$

$$= \frac{0.1 \times 0.1 \times 0.5 \times 0.25}{2} =$$

$$= 0.00000625$$

PFDavg (Valve, solenoids) =

$$= \frac{\text{Q.ty} \times \text{Failure Rate} \times 5\% \text{ Common cause} \times \text{Test interval}}{2} =$$

$$= \frac{2 \times 0.02 \times 0.05 \times 0.25}{2} =$$

$$= 0.00025$$

PFDavg (Safety redundant PLC) = 0.00005

PFDavg (Total) = 0.000306

The maximum allowed value for SIL 3 level is 0.001; therefore the conceptual design satisfies the safety requirements. The risk reduction factor (RRF=1/PFDavg) for the system is 3300, which is between the range of 1000 and 10000 for SIL 3.

$MTTF_S$ Calculations:

All field devices are included in nuisance trip calculations.

$$MTTF_S \text{ (Sensors)} = \frac{1}{4 \times 0.02} = 12.5 \text{ yrs}$$

$$MTTF_S \text{ (Valve, solenoids)} = \frac{1}{4 \times 0.01} = 25 \text{ yrs}$$

$$MTTF_S \text{ (Safety redundant PLC)} = \frac{1}{0.01} = 100 \text{ yrs}$$

$MTTF_S$ (Total) = 2 yrs

A nuisance trip is expected to occur, on average, every two years.

Chapter 6 IEC 61508: Fundamental concepts

6.1 Overall safety lifecycle

The standard is based on two fundamental concepts:

- safety lifecycles;
- safety integrity levels (SIL).

A safety lifecycle is defined as an engineering process that includes all the necessary steps to achieve the required functional safety.
The basic philosophy behind the safety lifecycle is to develop and document a safety plan, execute it and document its execution (showing that the plan has been met) and continue to follow it through to decommissioning with appropriate documentation throughout the life of the system.
Changes along the way must similarly follow the pattern of planning, execution, validation, and documentation.

The safety lifecycle referred to in IEC 61508 is shown in Figure 54.

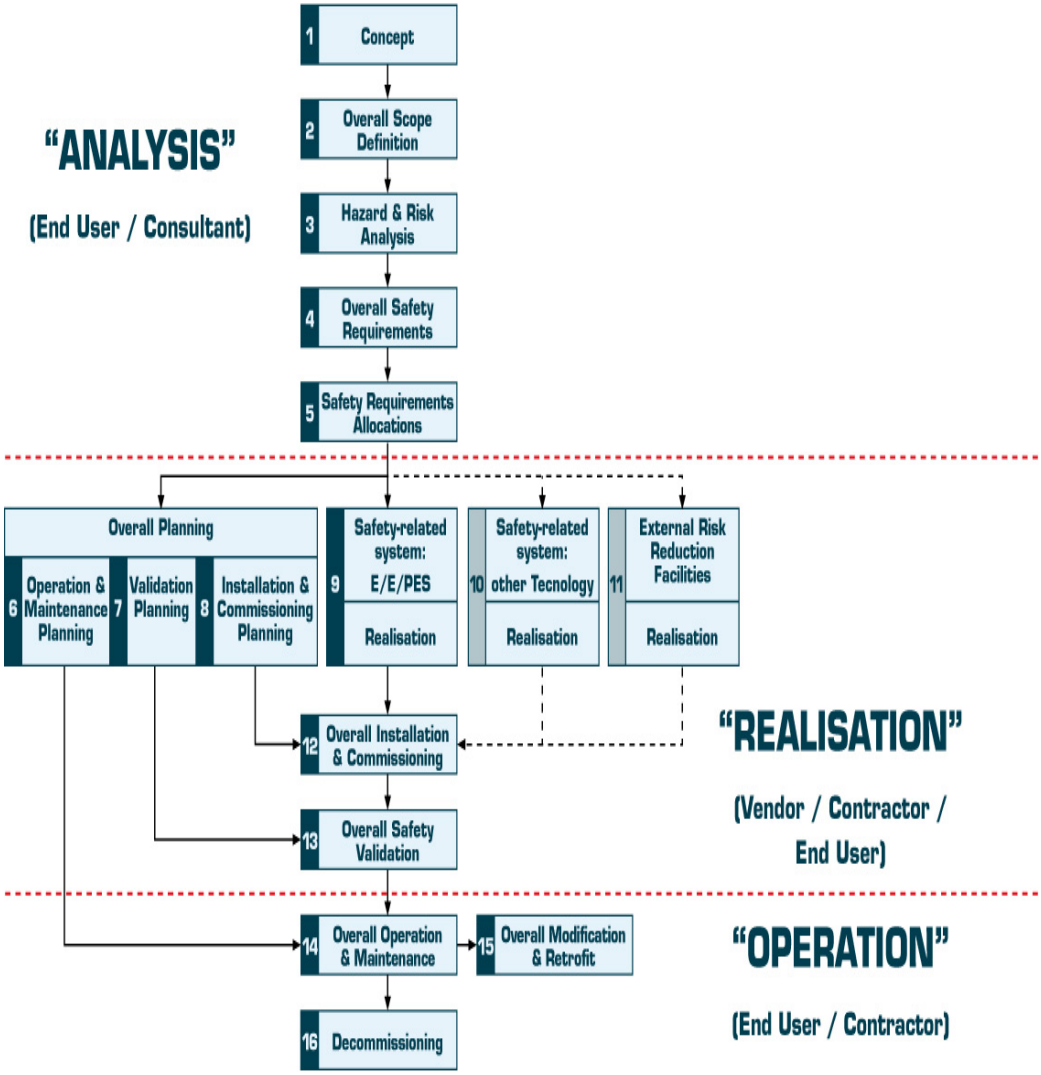


Figure 54, Overall safety lifecycle according to IEC 61508

6.2 Safety Integrity Levels

A Safety Integrity Levels (SIL) is defined as a relative level of risk reduction provided by a safety function. IEC 61508 defines four SIL levels.
SIL 1, has the lowest level of risk reduction while SIL 4, the highest.
Table 1 shows SIL levels for low and high demand modes of operation.

$$PFDavg = \frac{\text{Tolerable accident frequency}}{\text{Frequency of accidents without protections}} = \frac{1}{RRF}$$

SIL Safety integrity level	PFDavg Average probability of failure on demand per year (low demand)	RRF Reduction factor of the risk	PFDavg Average probability of failure on demand per hour (high demand)
SIL 4	**$\geq 10^{-5}$ to $< 10^{-4}$**	**100000 to 10000**	**$\geq 10^{-9}$ to $< 10^{-8}$**
SIL 3	**$\geq 10^{-4}$ to $< 10^{-3}$**	**10000 to 1000**	**$\geq 10^{-8}$ to $< 10^{-7}$**
SIL 2	**$\geq 10^{-3}$ to $< 10^{-2}$**	**1000 to 100**	**$\geq 10^{-7}$ to $< 10^{-6}$**
SIL 1	**$\geq 10^{-2}$ to $< 10^{-1}$**	**100 to 10**	**$\geq 10^{-6}$ to $< 10^{-5}$**

Table 1, Safety Integrity Levels and Probability of Failure on Demand according IEC 61508 and IEC 61511

Operating modes (defined in Part 4 of the standard) are:

- **Low demand mode:**
  frequency of demands for operation made on a safety-related system is not greater than one per year and not greater than twice the proof test frequency.
- **High demand mode** or **continuous mode:**
  frequency of demands for operation made on a safety-related system is greater than one per year and greater than twice the proof test's frequency.

Note:
the frequency of proof tests refers to how often the safety-related system is completely tested and insured to be fully operational.

While continuous mode appears to be more stringent than demand mode, it should be remembered that the units for the continuous mode are “per hour”. Demand mode units assume a time interval of roughly one year per definition. Considering the fact that there are about 10000 hours in a year (actually 8760), the two modes are approximately the same in terms of safety matrix.

Basically speaking, functional safety is achieved by properly designing a Safety Instrumented System (SIS) to carry out a Safety Instrumented Function (SIF) at a reliability indicated by the Safety Integrity Level (SIL).
The concepts of risk and safety integrity are further discussed in Part 5 of the standard.

6.3 Part “1”: General requirements

6.3.1 Scope

IEC 61508 standard covers safety-related systems when one or more of such systems incorporate electrical/electronic/programmable electronic devices. These include relay-based systems, inherently safe solid-state logic based systems, and, perhaps most importantly, programmable systems based on microcomputer technology.
The standard specifically covers possible hazards created when failures of the safety functions, performed by E/E/PE safety-related systems, occur.
Functional safety is the overall program to ensure that a safety-related E/E/PE system brings about a safe state when it is called upon to do so and is different from safety issues.
For example, IEC 61508 does not cover safety issues like electric shock, long-term exposure to toxic substances, etc. that are covered by other standards.
IEC 61508 also does not cover low safety E/E/PE systems where a single E/E/PE system is capable of providing the necessary risk reduction and the required safety integrity of the E/E/PE system is less than safety integrity level 1, (e.g. the E/E/PE system is only reliable 90 % of the time or less).

IEC 61508 is concerned with the E/E/PE safety-related systems whose failures could affect the safety of persons and/or the environment.
However, it is recognized that the methods of IEC 61508 may apply to business loss and asset’s protection as well.
Human beings may be considered as part of safety-related system, although specific human factor requirements are not treated in detail in the standard.

The standard also specifically avoids the concept of “fail safe” because of the high level of complexity involved with the E/E/PE systems considered.

In regard to this, it is useful to mention an event occurred in Italy in 2002 in an industrial plant highly protected with more than one safety-related systems, (SIL 3 level): in August the plant was almost closed due to holydays, but having received an urgent material request, a young plant manager, decided to set some process control in manual position, in order to complete the production order with the help of just a few workers.
A vessel devoted to the purification of 14 tons of raw organically peroxide exploded, resulting in the top cover blown away up to 50 meters in the air.
Eye witnesses have seen the fireball reach over 100 meters in height.
The vessel cover fell on an energy distribution cabinet nearby without consequences. The hazardous event was not as bad as it could have been.
But, was it possible to stop this inexperienced manager to do such a risky work, forbidden by all user manuals?

Not all accidents caused by human factors are sudden and unpredictable: the disaster in Chernobyl in 1986 for example.
Although IEC 61508 does not take in consideration human factors yet, the personnel in charge of plant safety should take those factors into account, even simply basing on their personal experience.

6.3.2 Compliance

IEC 61508 states that:
“*To conform to this standard it shall be demonstrated that the requirements have been satisfied to the required criteria specified (e.g. Safety Integrity Level) and therefore, for each clause or sub-clause, all the objectives have been met.*”
In practice, a demonstration of compliance often involves the listing of all of the requirements with an explanation of how each of them has been met.
This applies to both products developed to meet IEC 61508 and specific application projects wishing to claim compliance.
Because this standard is technically only a standard and not a law, compliance is not always legally required.
However, in many instances, compliance is identified as best practice and thus can be cited in liability cases. Also, many countries are incorporating IEC 61508, or large parts of it, directly into their safety codes, so in those instances it will indeed become law.
Finally, many industry and government contracts for safety equipments, or systems, and services, specifically require compliance with IEC 61508.

So, although IEC 61508 originated as a standard, its wide acceptance has lead to legally required compliance in nearly all relevant cases.

The language of conformance in the standard is quite precise: if an item is listed as "*shall be…*", or "*must…*" it is required for compliance.
If an item is listed as "*may be…*" it is not specifically required for compliance, but clear reasoning must be shown to justify its omission.

6.3.3 Documentation (Clause 5)

Documentation used in safety-related systems must specify the necessary information such that safety lifecycle activities can be performed.
The documentation must also provide enough information so that the management of the functional safety verification and assessment activities can effectively be accomplished.

This translates into specific documentation requirements that must:

- have sufficient information to effectively perform each phase of the safety lifecycle, as well as the associated verification activities;
- have sufficient information to properly manage functional safety and support functional safety assessment;
- be accurate and precise;
- be easy to understand;
- suit the purpose for which it was intended;
- be accessible and maintainable;
- have titles or names indicating the scope of the contents;
- have a good table of contents and index;
- have a good version control system, sufficient to identify different versions of each document and indicate revisions, amendments, reviews, and approvals.

6.3.4 Management of Functional Safety (Clause 6)

Managing functional safety includes taking on various activities and responsibilities to insure that the functional safety objectives are achieved and maintained. These activities must be documented, typically in a document called the functional safety management (FSM) plan.

The FSM plan should consider:

- The overall strategy and methods for achieving functional safety, together with evaluation methods and the way in which the process is communicated within the organization.
- The identification of the people, departments, and organizations that are responsible for carrying out and reviewing the applicable overall, E/E/PES, or software safety lifecycle phases (including, where relevant, licensing authorities or safety regulatory bodies).
- The safety lifecycles phases to be used.
- The documentation structure.
- The measures and techniques used to meet requirements.
- The functional safety assessment activities to be performed and the safety lifecycles phases where they will be performed.
- The procedures for follow-up and resolution of recommendations arising from hazard and risk analysis, functional safety assessment, verification and validation activities, etc.
- The procedures for ensuring that personnel are competent.
- The procedures for ensuring that hazardous accidents (or near misses) are analyzed, and that actions are taken to avoid repetition.
- The procedures for analyzing operations and maintenance performance, including periodic functional safety inspections and audit; the inspection frequency and level of independence of personnel to perform the inspection/audit should be documented.
- The procedures for management of changes.

All those responsible for managing functional safety activities must be informed and aware of their responsibilities.
Suppliers providing products or services in support of any safety lifecycle phase shall deliver products or services as specified by those responsible for that phase and have an appropriate quality management system.

6.3.5 Overall Safety Lifecycle Requirements (Clause 7)

The safety lifecycle can be viewed as a logical "identify-analyze-design-verify" closed loop (Figure 55). The intended result is the optimum design where risk reduction provided by safety-related systems matches the risk reduction needed by the process.

Figure 55, Close loop view of the safety lifecycles

The safety life cycle concept derives from studies done by HSE (Health and Safety Executive) in the United Kingdom. The HSE studied accidents involving industrial control systems and classified accident causes as shown in Figure 56 [1].

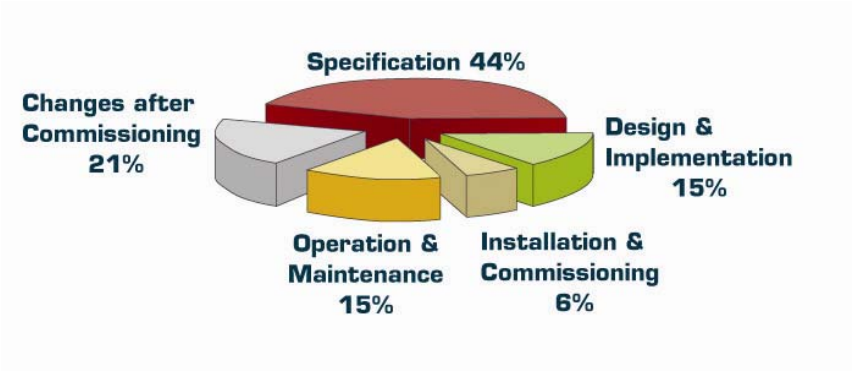


Figure 56, Results of system failure cause study: HSE "Out of Control"

[1] "*Out of Control, Why control systems go wrong and how to prevent failure*." HSE (HSG238) 2003.

6.3.6 HSE Findings

The HSE examined 34 accidents that were the direct result of control and safety system failures in a variety of different industries.
Their findings are summarized in Figure 56.
The majority of accidents (44%) were due to incorrect and incomplete specifications. Specifications consist of both functional (e.g. what the system should do) and integrity specification (e.g. how well it should do it).

There are many examples of functional specification errors.
Trevor Kletz has a documented a case where a computer controlled a controller and an exothermic reactor.
When material was added to the reactor the flow of cooling water needed to increase. However, the system was also programmed so that for any fault in the plant - and many things were categorized as a fault- the output would freeze at its last known value.
Fate would have it that these two conflicting conditions happened at the same time. Material was added to the reactor and then the system detected a low gear box oil level. The flow of cooling water did not increase so the reactor overheated and discharged its contents.
The system did exactly what it was programmed to do.
This was not an hardware failure.
The author concludes: "*accidents are not due to lack of knowledge, but failure to use the knowledge we already have*[2]".

The next largest portion of problems (21%) is due to changes after commissioning. Operation and maintenance problems were found to be responsible for 15% of accidents. Therefore the 36% of accidents are responsibilities of the end user.
Design and implementation errors were accounted for 15% of problems. This is about the only errors that are responsibility of the vendor or system integrator.
There have been cases where specifications were correct, but the system supplier did not meet at least one of the requirements and was not thoroughly tested in order to reveal that fault.

[2] "*What Went Wrong?: Case Histories of Process Plant Disasters*",
Trevor A. Kletz, Gulf Publishing, 1998

6.3.7 The concept of safety lifecycle in IEC 61508

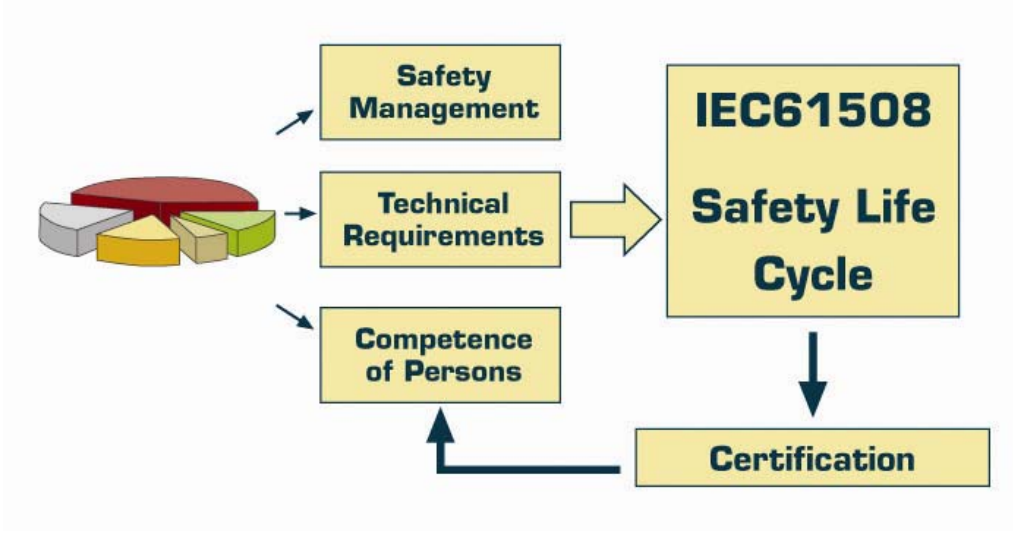


Figure 57, Origin of the safety lifecycles

The first part of the safety lifecycle, also known as *analysis portion*, includes:

- Concept and scope of the system or equipment under control (EUC).
- Hazard and Risk Analysis to identify both hazard and the events that can lead to them, including:
  - Operability (HAZOP) studies, (Computer HAZOP).
  - LOPA (Layers of Protection Analysis)
  - Criticality Analysis.
- Creation of overall safety requirements and identification of specific safety functions to prevent the identified hazards.
- Allocation of safety requirements, e.g. assigning the safety function to an E/E/PE safety-related system, an external risk reduction facility, or a safety-related system of different technology. This also includes assigning a safety integrity level (SIL), or risk reduction factor, to each safety function (SIF).

These first phases are shown in Figure 58.

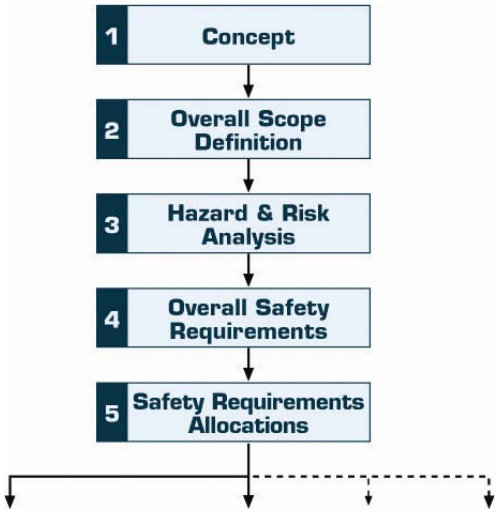


Figure 58, First portion of the overall safety lifecycles

The safety lifecycle continues in Figure 59. The safety system must be designed to meet the target safety integrity level as defined in the risk analysis phase.

This requires that a probability calculation be done to verify that the design can meet SIL level, either in demand, or continuous mode.

The system must also meet detailed hardware and software implementation requirements given in Part 2 and Part 3. One of the most significant is SFF (Safe Failure Fraction), see Part 2.

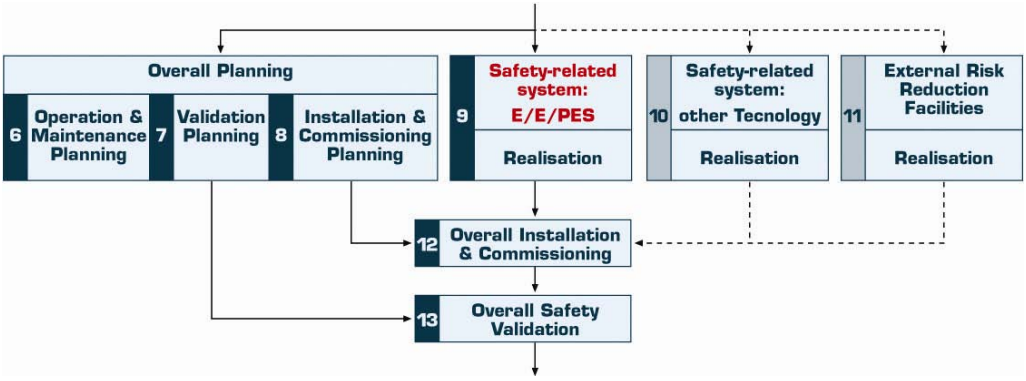


Figure 59, Realization activities in the overall safety lifecycles

There are more detailed subsections of the overall safety lifecycle called E/E/PE lifecycle, which explain the activities in box 9 above.

The E/E/PES lifecycle is shown in Figure 60.
These activities are detailed in Part 2 of the standard.

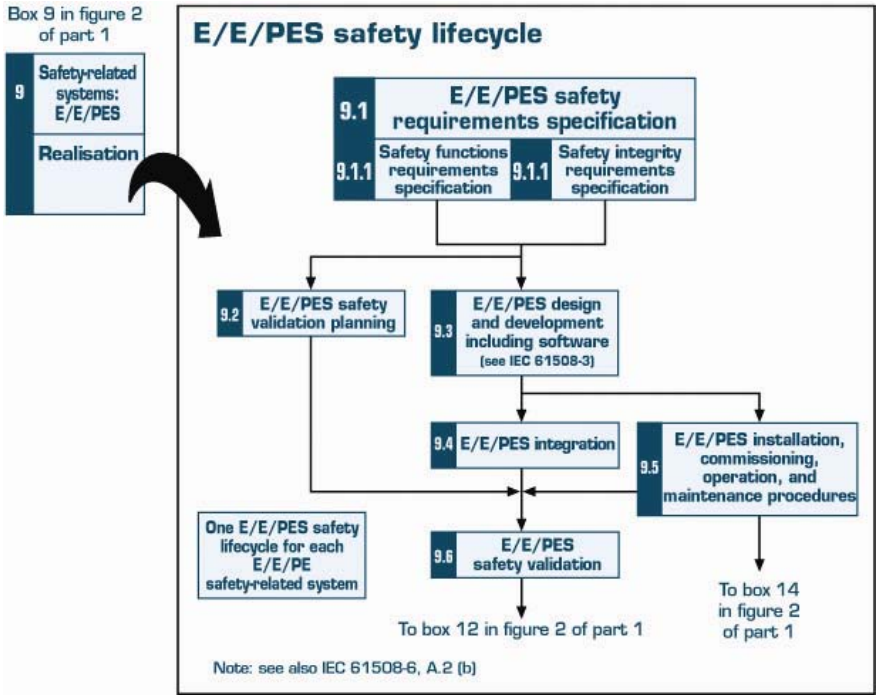


Figure 60, E/E/PES safety lifecycle in realization phase (Part 2)

The final operation phases of overall safety lifecycle are shown in Figure 61.

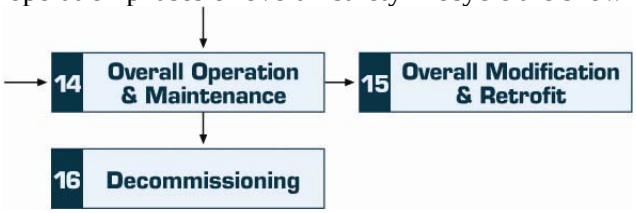


Figure 61, Operation and Maintenance phases of the overall safety lifecycle

In summary, the safety lifecycle generally lays out the different activities required to achieve functional safety and compliance with the standard.

6.3.8 Functional Safety Assessment (Clause 8)

Part 1 also describes required functional safety assessment activities, which have the objective to investigate and arrive at a conclusion regarding the level of safety achieved by safety-related system.
The process requires that one or more competent persons are appointed to carry out a functional safety assessment. These individuals must be suitably independent of those responsible for the functional safety being assessed, depending on the SIL level and consequences involved, as shown in Table 22 and Table 23. Note: (HR = Highly recommended; NR = Not recommended)

Minimum level of independence	Consequence A Minor injury; (e.g. temporary loss of function)	Consequence B Serious permanent injury to one or more persons; death to one person	Consequence C Death to several people	Consequence D Many people killed
Independent person	HR	HR	NR	NR
Independent department	-	HR	HR	NR
Independent organization	-	-	HR	HR

Table 22, Assessment independence level, as a function of consequences

Minimum level of independence	SIL 1	SIL 2	SIL 3	SIL 4
Independent person	HR	HR	NR	NR
Independent department	-	HR	HR	NR
Independent organization	-	-	HR	HR

Table 23, Assessment independence level for E/E/PE and software lifecycle activities

The functional safety assessment shall include all phases of the safety lifecycle and consider the lifecycle activities carried out and the outputs obtained. The assessment may be done in parts after each activity or group of activities. The main requirement is that the assessment be done before the safety-related system is needed to protect against a hazard.

The functional safety assessment must consider:

- All work done since the previous functional safety assessment.
- The plans for implementing further functional safety assessments.
- The recommendations of the previous assessment including a check to verify that the changes have been made.

Functional safety assessment activities shall be consistent and planned. The plan must specify the personnel who will perform the assessment, their level of independence, and the competency required.
The assessment plan must also state the scope of the assessment, outputs of the assessment, any safety bodies involved, and the resources required. At the conclusion of the functional safety assessment, recommendations shall indicate acceptance, qualified acceptance, or rejection.

6.3.9 Example documentation structure (Annex A)

The documentation has to contain enough information to effectively perform each phase of the safety lifecycle (Clause 7), manage functional safety (Clause 6), and allow functional safety assessments (Clause 8).
However, IEC61508 does not specify a particular documentation structure.
Users have flexibility in choosing their own documentation structure as long as it meets the criteria described earlier.
An example set of documents for a safety lifecycle project is shown below:

Safety lifecycle phase	Information
Safety requirements	Safety Requirements Specification (safety functions and safety integrity)
E/E/PES validation planning	Validation Plan
E/E/PES Design and development E/E/PES Architecture Hardware architecture Hardware modules design Component construction and/or procurements	 Architecture Design Description (hardware and software) Specifications (integration tests) Hardware Architecture Design Description Detail Design Specification(s) Hardware modules Report (hardware modules test)
Programmable electronics integration	Integration Report
E/E/PES operation and maintenance procedures E/E/PES safety validation	Operation and Maintenance Instructions Validation Report
E/E/PES modification	E/E/PES modification procedures Modification Request Modification Report Modification Log
Concerning all phases	Safety Plan Verification Plan and Report Functional Safety Assessment Plan and Report

Table 24, Documentation examples

6.3.10 Competence of persons (Annex B)

IEC 61508 specifically states: "*All persons involved in any overall, E/E/PES or software safety lifecycle activity, including management activities, should have the appropriate training, technical knowledge, experience and qualifications relevant to the specific duties they have to perform*".

It is suggested that a number of things are taken into consideration in the evaluation of personnel, such as:

- Engineering knowledge in the application.
- Engineering knowledge appropriate to the technology.
- Safety engineering knowledge appropriate to the technology.
- Knowledge of the legal and safety regulatory framework.
- The consequences of safety-related system failure.
- The assigned safety integrity level of safety functions in a project.
- The experience and its relevance to the job.

The training, experience, and qualifications of all persons should be documented.
For example, the TUV Certified Functional Safety Expert (CFSE) program was designed to help companies show personnel competency in several different safety specialties: details can be found at *http://www.cfse.org/*.

6.4 Part "2": Hardware Requirements

IEC 61508 Part 2 covers specific requirements for safety-related hardware. As in other parts of the standard, a safety lifecycle is to be used as the basic of requirement compliance. Figure 54 (here repeated) shows the general safety lifecycle model.

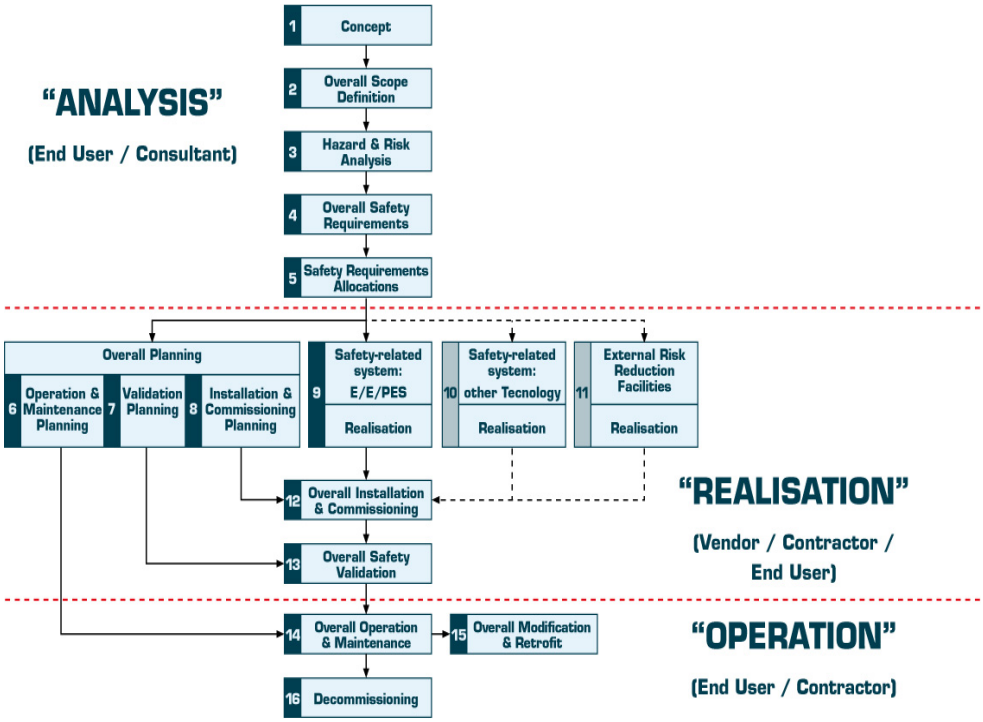


Figure 54, Overall safety lifecycle according to IEC 61508

The hardware safety lifecycle is an expanded plan of Phase 9 of the overall safety lifecycle from Part 1 that is focused on the design of the control hardware for safety-related systems.
As for the overall safety lifecycle, there are requirements for a functional safety management plan and safety requirements specifications including all variation and assessment activities. (see Figure 54).

Safety requirements specifications (described in Clause 7.2) shall include details on both the safety functions and the safety integrity level of the function. Some of these safety function details are:

- How safe state is achieved
- Operator interface
- Required E/E/PES behavior or modes
- Response time
- Operating modes of equipment under control
- Start-up requirements

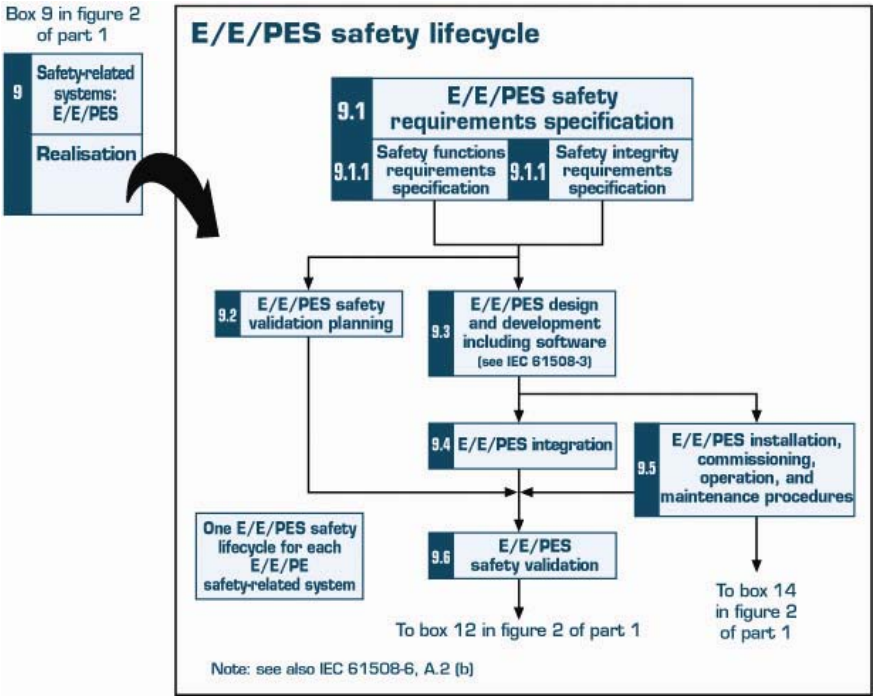


Figure 60, E/E/PES safety lifecycle in realization phase (Part 2)

Some of the safety integrity level details are:

- SIL level for each function
- Environmental extremes
- High or low demand class for each function
- Electromagnetic immunity limits

One particular aspect of the hardware design and development requirements (Clause 7.4) is the limit on the safety integrity level achievable by any particular level of fault tolerant safety redundancy.
These are shown in Table 25 and Table 26 for various fractions of failure.

SFF	Hardware fault tolerance 0	Hardware fault tolerance 1	Hardware fault tolerance 2
< 60%	SIL 1	SIL 2	SIL3
60% - < 90%	SIL 2	SIL 3	SIL 4
90% - < 99%	SIL 3	SIL 4	SIL 4
> 99%	SIL 3	SIL 4	SIL 4

Table 25, SFF (Safe Failure Fraction) for A type components

Note:
A hardware fault tolerance of N means that N + 1 faults could cause a loss of the safety function.

Type A components are described as simple devices with well-known failure modes and a solid history of operation.
Type B devices are complex components with potentially unknown failure modes, e.g. microprocessors, ASICs, etc.
Table 25 and Table 26 represent the limits on the use of single or multiple architectures in higher SIL levels. This is appropriate based on the level of uncertainty present in the failure data as well as in the SIL calculations themselves.

SFF	Hardware fault tolerance 0	Hardware fault tolerance 1	Hardware fault tolerance 2
< 60%	Not allowed	SIL 1	SIL2
60% - < 90%	SIL 1	SIL 2	SIL 3
90% - < 99%	SIL 2	SIL 3	SIL 4
> 99%	SIL 3	SIL 4	SIL 4

Table 26, SFF (Safe Failure Fraction) for B type components

Note:
the separate phase especially devoted to integrating the software and hardware before validating the safety of the combined system (described in Clause 7.5). Operation and maintenance procedures and documentation are described in Clause 7.6, while validation, modification, and verification phase details, are provided in the remaining parts of Clause 7.

The relations and fields of application between Parts 2 and 3 of IEC 61508 are highlighted in Figure 62. Hardware and software are often part of the same safety-related system.

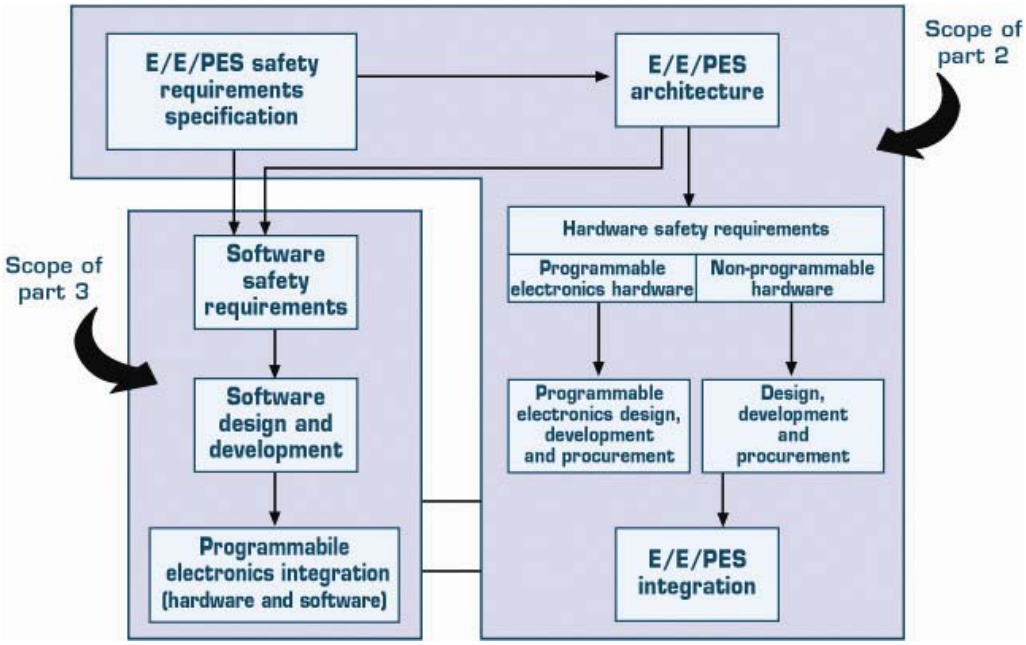


Figure 62, Relation between Parts 2 and 3 of IEC 61508

6.4.1 Control of Failure during Operation (Annex A)

This annex limits the claims that can be made for self diagnostic capabilities and also recommends methods of failure control. Numerous types of failures are addressed including random, systematic, environmental, and operational failures. It should be noted that following these methods is not enough for a given system to meet a specific SIL level.

6.4.2 Avoidance of Systematic Failures during different phases of the Lifecycle (Annex B)

Here, numerous tables present recommended techniques for different lifecycle phases to achieve different SILs levels. Again, simply using these techniques does not guarantee a system will achieve a specific SIL level.

6.4.3 Diagnostic Coverage and Safe Failure Fraction (Annex C)

Here, a basic procedure is described for calculating the fraction of failures that can be self diagnosed and the fraction that results in a safe state.

Note: SFF is calculated for each device, component, or subsystem used in the SIF. Each device is made of n components, each of them has a failure rate λ.

$$\lambda_D = \lambda_{DD} + \lambda_{DU}$$
$$\lambda_S = \lambda_{SD} + \lambda_{SU}$$
$$\lambda_{TOT} = \lambda_{DD} + \lambda_{DU} + \lambda_{SD} + \lambda_{SU}$$

The FMEDA analysis (Failure Mode, Effects and Diagnostic Analysis) allows the classifying of failure rates.

$$SFF = \frac{\sum \lambda_{DD} + \sum \lambda_{SD} + \sum \lambda_{SU}}{\sum \lambda_{DD} + \sum \lambda_{DU} + \sum \lambda_{SD} + \sum \lambda_{SU}} = 1 - \frac{\sum \lambda_{DU}}{\sum \lambda_{DD} + \sum \lambda_{DU} + \sum \lambda_{SD} + \sum \lambda_{SU}}$$

Where:

λ_{DD}: dangerous detected failure rates;
λ_{DU}: dangerous undetected failure rates;
λ_{SD}: safe detected failure rates;
λ_{SU}: safe undetected failure rates;

6.5 Part “3”: Software requirements

IEC 61508 Part 3 covers specific requirements for safety-related software.
As in other parts of the standard, a safety lifecycle is to be used as the basis of requirements compliance. Figure 54 shows the general safety lifecycle model.
Figure 63 shows the software safety lifecycle which is an expanded plan for Phase 9 of the overall safety lifecycle from Part 1 and is closely linked with the hardware lifecycle.
As for the overall safety lifecycle, there are requirements for a functional safety management plan and safety requirements specification, including all verification and assessment activities.
Here the functional safety is addressed in the context of a software quality management system (QMS) in Clause 6.
A detailed functional safety plan is presented as part of the QMS.
As in other parts of the standard, the same key features of change management, demonstration, and documentation are presented.

6.5.1 Software Functional Safety Plan (Clause 6)

A software functional safety plan (either as a part of other documentation or as a separate document) shall define the strategy of the software procurement, development, integration, verification, validation, and modifications required for the SIL level of the safety-related system.
The plan must specify a configuration management system which must:

- Establish baseline software and document the (partial) integration testing that justifies the baseline.
- Guarantee that all necessary activities have been carried out to demonstrate that the required software safety integrity has been achieved.
- Accurately maintain all documentation and source codes including:
  - Safety analysis
  - Requirements
  - Software specifications and design documents
  - Software source code modules
  - Test plans and results
  - Commercial off the shelf (COTS)
  - Pre-existing software components which are to be incorporated into the E/E/PES safety-related system
  - All tools and development environments which are used to create or test, or carry out any action, on the software of E/E/PES safety-related system.

- Prevent unauthorized modifications.
- Document modification/change requests.
- Analyze the proposed modification.
- Approve or reject the modification request.
- Manage software changes to ensure that the specified requirements for software safety are satisfied.
- Formally document the release of safety-related software.

Master copies of the software and all documentation should be maintained throughout the operational lifetime of the released software.

6.5.2 Software Safety Lifecycles (Clause 7)

IEC 61508 has a considerable but appropriate number of requirements for safety critical software put forth in the details of the software safety lifecycle framework.
The major phases of the software safety lifecycle are shown in Figure 63.

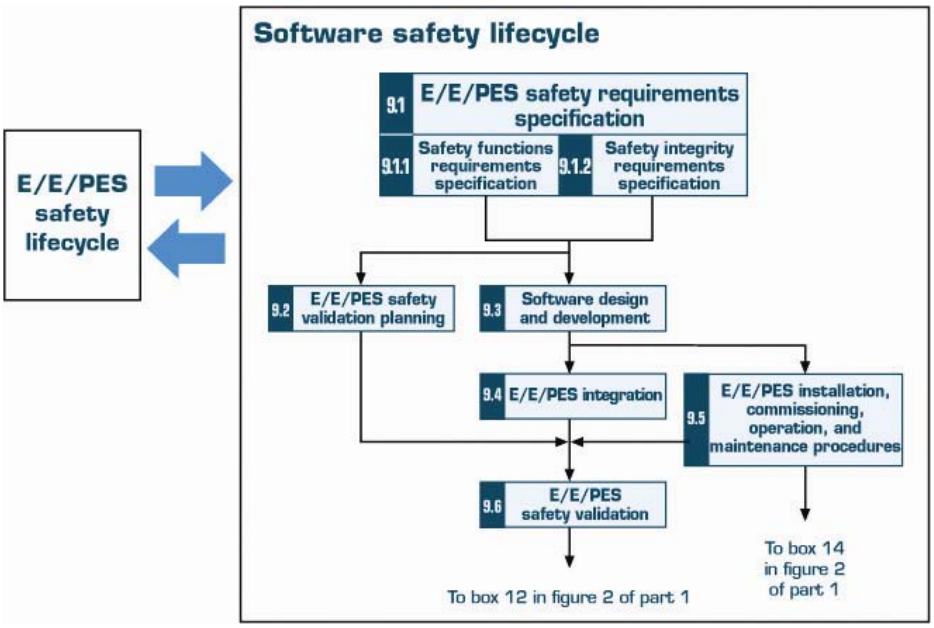


Figure 63, Safety lifecycle of software in realization phase

Part 3 requires that a process (such as the safety lifecycle) for the development of software shall be selected and specified during safety planning.
Note that the exact process is not specified and it may be customized according to company preference.
Appropriate quality and safety assurance procedures must be included. Each step of the software safety life cycle must be divided into elementary activities with the functions, inputs and outputs specified for each phase. The standard has complete details of example software safety lifecycle. During each step of process, appropriate "techniques and measures" must be used.
Part 3, Annexes A and B, give recommendations from a list of software techniques. The standard says: "*If at any stage of the software safety lifecycle, a change is required pertaining to an earlier lifecycle phase, then that earlier safety lifecycle phase, and the following phases shall be repeated*".

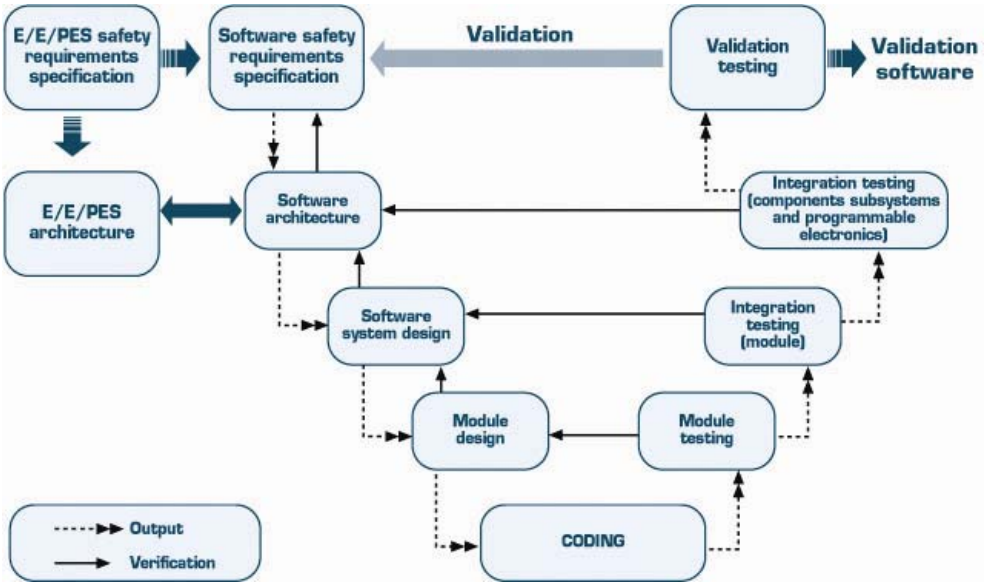


Figure 64, Software safety integrity and the development lifecycle (V-Model)

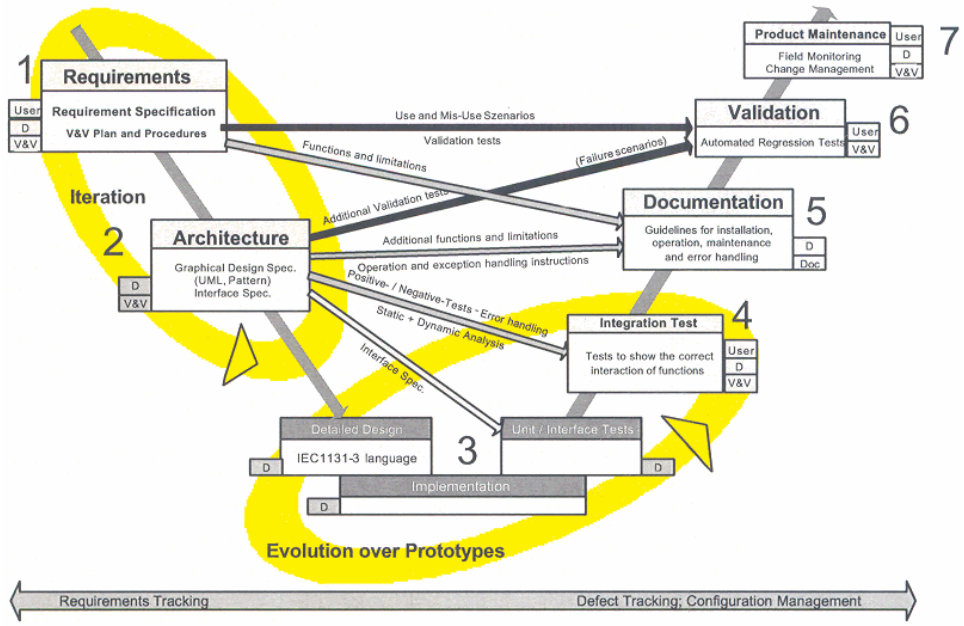


Figure 65, Iterative V- Model for software development: EXIDA

6.5.3 Software Safety Requirements Specification (Clause 7.2)

Functional safety requirements for software must be specified.
This can be done in a separate document or as part of another document.
The specification of the requirements for software safety shall be derived from the specified safety requirements of the safety-related system and any requirements of safety planning.
The requirements for software safety shall be sufficiently detailed to allow design and implementation and to allow a functional safety assessment.
Software developers should review the document to verify that it contains sufficient details. It should be noted that this is often another iterative process.
The requirements must be clear, precise, verifiable, testable, maintainable, and feasible. The requirements must also be appropriate for the safety integrity level and traceable back to the specification of the safety requirements of the safety-related system.
Terminology must be clear and understandable by those using the document.
All modes of operation for the safety-related system must be listed.
The requirements must detail any relevant constraints between the hardware and the software. Since the software is often called upon to perform much of the online diagnostics, the requirements must detail all self-monitoring software, any diagnostic tests performed on the hardware, periodic testing of critical functions and means of online testing of safety functions.
If the software also performs non-safety functions, means to insure that the software safety is not compromised (non-interfering) must also be specified.

6.5.4 Software safety validation planning (Clause 7.3)

A plan must be set up to demonstrate that the software satisfies the safety requirements set out in the specification. A combination of analysis and testing techniques is allowed and the chosen techniques must be specified in the plan which must consider:

- Required equipment.
- When the validation will be carried out.
- Who will be in charge of the validation.
- The modes of operation to be validated including:
  - start up
  - teach
  - automatic
  - manual
  - semi-automatic
  - steady state of operation

- reset
- shut down
- maintenance.

- Reasonably foreseeable abnormal conditions.
- Identification of the safety-related software that needs to be validated.
- Specific reference to the specified requirements for software safety.
- Expected results and pass/fail criteria.

The plan must show how the assessment will be done, who will review the plan, and the assessor's level of independence.

6.5.5 Software design and development (Clause 7.4)

Design methods shall be chosen such as to support abstraction, modularity, information hiding, and other good software engineering practices.
The design method shall allow clear and un-ambiguous expressions of functionality, data flow, sequencing, and time-dependent data, timing constraints, concurrency, data structures, design assumptions, and their dependencies. During design, the overall complexity of the design, its testability, and the ability to make safe modifications shall be considered.

The entire design is considered safety-related even if non-safety functions are included unless sufficient independence between safety and non-safety can be demonstrated.
If different safety integrity levels are part of the design, the overall design is only valid for the least stringent SIL of the component parts.
The design must include software functions to execute proof tests and all online diagnostic tests as specified in the requirements.
Software diagnostics shall include monitoring of control flow and data flow.
The architectural design defines the major components and sub-systems of the software.
The architectural design description must include:

- Description of the function(s) assigned to each component
- Interconnections of these components.
- The "techniques and measures" necessary during the software safety lifecycle phases to satisfy requirements for software safety at the required safety integrity level including software design strategies for fault tolerance and/or fault avoidance (redundancy/diversity).
- The software safety integrity level of the subsystem/component;
- All software/hardware interactions and their significance;
- The design features for maintaining the safety integrity of all data;

- Software architecture integration tests to ensure that the software architecture satisfies the requirements for software.

It is assumed and permitted that iteration occurs between the design and the requirements phases.
Any resulting changes in requirements must be documented and approved. Support tools and programming languages must meet the safety integrity needs of the software.
A set of integrated tools, including languages, compilers, configuration management tools, and, when applicable, automatic testing tools, shall be selected for the required safety integrity level.
Detailed design and coding shall follow the software safety life cycle.
Coding standards shall be employed and must specify good programming practice, prohibit unsafe language features, and specify procedures for source code documentation including:

- Legal entity.
- Description.
- Inputs and outputs.
- Configuration management history.

The software code must be:

- Readable, understandable and testable.
- Able to satisfy the specified requirements.
- Reviewed.
- Tested as specified during software design.

6.5.6 Integration and testing (Clause 7.5)

Tests of the integration between the hardware and software are created during the design and development phases and specify the following:

- Test cases and test data in manageable integration sets.
- Test environment, tools, and configuration.
- Test criteria.
- Procedures for corrective action on failure of test.

The integration testing results shall state each test and the pass/fail results.

6.5.7 Software safety validation (Clause 7.7)

Software validation is done as an overall check to insure that the software design meets the software safety requirements and must include the appropriate documentation. The validation may be done as part of overall system validation or it may be done separately for the software.

Testing must be the primary method of validation with analysis used only to supplement. All tools used in the validation must be calibrated and an approved, quality system must be in place.
If validation is done separately for the software, the validation must follow the software safety validation plan.
For each safety function, the validation effort shall document:

- A record of the validation activities.
- The version of the software safety validation plan.
- The safety function being validated with reference to planned test.
- Test environment (tools and equipment).
- The results of the validation activity with discrepancies, if any.

If discrepancies occur, a change request must be created and an analysis must be done to determine if the validation may continue.

6.5.8 Operation and modification (Clause 7.6 and 7.8)

Software modification requires authorization under the procedures specified during safety planning and must insure that the required safety integrity level is maintained. The authorization must address:

- The hazard that may be affected.
- The proposed change.
- The reason for changing.

The modification process starts with an analysis on the impact of the proposed software modification on functional safety.
The analysis will determine how much of the safety lifecycle must be repeated.

6.5.8.1 How to document future software modifications in a sub-system according IEC 61508 and IEC 61511

Software modifications require impact analyses to be carried out according IEC 61508.

Types of interferences and tests to be considered are:

- Input interference: will the input still be valid to the safety related module?
- Temporal interference: does the change affect the routine in a way that could interfere with safety? (loops, recursion).
- Data interference: can the change alter or corrupt safety critical data? (shared memory, pointers).

- Code interference: can the change corrupt executable code in memory?
- Resource interference: can the change prevent or delay access to a required resource (memory, semaphore, etc.)?
- Violation of Criticality assumptions: does the change affect the justification of independence used in the criticality analysis? Tests shall be done in accordance with the SIL level requirements of IEC 61508-3 (Table A.5 requires for SIL 2).
- Dynamic analysis and testing.
- Functional and black box testing.
- Boundary value analysis.
- Equivalence classes and input partition testing.

6.5.9 Software verification (Clause 7.9)

The software verification process tests and evaluates the results of the software safety life cycle phases to insure they are correct and consistent with the input information to those phases.
Verification of the steps used in the software safety life cycle must be performed according to the plan and must be done concurrently with design and development. The verification plan must indicate the activities performed and the items to be verified (documents, reviews, etc.).
A verification report must include an explanation of all activities and results.
Verification must be performed on:

- Software safety requirements.
- Software architecture design.
- Software system design.
- Software module design.
- Software source code.
- Data.
- Software module testing.
- Software integration testing.
- Hardware integration testing.
- Software safety requirements testing (software validation).

6.5.10 Software Functional Safety Assessment (Clause 8)

The software assessment process is similar to the other assessment processes in the standard. Techniques and measures relevant to this assessment are listed in Annexes A and B as well as in Part 1 of the standard.

6.5.11 Guide to the selection of techniques and measures (Annexes “A” and “B”)

Annex A provides ten tables of different techniques relevant to the:

- Software safety requirements specification
- Software design and development: Software architecture design
- Software design and development: Support tools and programming languages
- Software design and development: Detailed design
- Software design and development: Software module testing and integration
- Programmable electronic integration
- Software Safety validation
- Modification
- Software verification
- Functional safety assessment

All the different techniques are “recommended” or “highly recommended” according to the SIL levels required. Some techniques may be used alone or in combination with other techniques to prove the compliance with the standard.

Annex “B” provides nine tables with detailed techniques for:

- Design and coding standards
- Dynamic analysis and testing
- Functional and “black box” testing
- Failure analysis
- Modeling
- Performance testing
- Semi-formal methods
- Statistic analysis
- Modular approach

These tables are also referenced in the tables from Annex A.

6.6 Part "4": Definitions and abbreviations

Part 4 of the IEC 61508 contains the abbreviations and definitions used throughout the entire document. This part is extremely useful, both to who is reading the standard for the first time and to who has already a good knowledge of it.

6.7 Part "5": Safety Integrity Level determination

Part "5" is primarily composed of Annexes A, B, C, D, E which describe key concepts as well as various methods of SIL level selection and verifications.

6.7.1 Risk Reduction – General concepts

When considering an industrial process, it is recognized that there is an inherent risk of operation. Things do go wrong.
Safety is defined in the IEC 61508 as "freedom from unacceptable risk of harm". The standard goes on defining the level of safety as "a level of how far safety is to be pursued in a given context, assessed by reference to an acceptable risk, based on current values of society".

When evaluating safety, the frequency of an accident and the consequences (the costs) of an accident are both taken into consideration.
Risk is defined as the probable rate of occurrence of a hazard causing harm and the degree of severity of the harm. Thus, risk evaluation includes a combination of frequency and cost.
For example, if the consequences of an accident are estimated ten million dollars and the frequency of the accident is estimated to be once per ten years (probability of an accident is 0.1 for a time interval of one year).

Then the inherent risk is stated to be one million dollars per year.
Frequently it is judged that risk inherent in operating an industrial process is unacceptable high, corporate rules, government regulations, laws, insurance company rules, or public opinion may require a lower level risk.
This leads to the concept of "tolerable risk".
When inherent risk, perceived or actual, is high than "tolerable risk", then risk reduction is required.

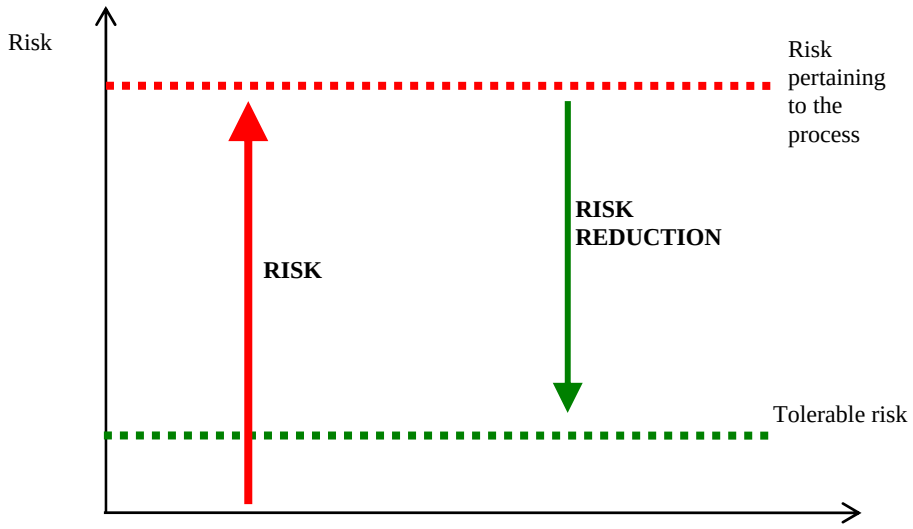


Figure 66, Basic concept of risk reduction

A proactive study called “process hazard analysis” (PHA) is requested in the United States by the OSHA Process Safety Management and EPA Risk Management Plan legislation.
But also the “Seveso Directive” I – II – III (96/82/EC) deals in detail with similar requirements on process operators in the European Community.
A wide variety of PHA methods are used in process plants.
The type used depends on the complexity of the process under study, the amount of experience that an organization has with the process, and whether the plant is new or undergoing a review.
However, the best known process of hazard analysis is HAZOP (HAZard and OPerability study). HAZOP was used for the first time by ICI in the 70s).
A HAZOP study uses guide word combinations to help a team of experts identify failure scenarios that can cause process accidents and operability problems.
First, the team breaks the entire process into smaller, more manageable sections called “nodes”. Nodes are typically chosen by looking at the natural process equipment and function brakes present in the overall system. Similarly, a set of guide words such as “too much pressure”, “too little flow”, etc., is chosen to support the review.
The team then systematically applies the guide word combinations to each part of each node to identify which hazards are present, whether there are existing safeguards, and if any additional safeguards are needed. HAZOP studies are most effective when the process is complex and unique.

A “checklist study” is a type of PHA in which a team of process experts asks a list of questions (see Chapter 10) that may identify process hazards.
This type of analysis is very effective when the process under study is small or when there are many identical or very similar processes. For example, checklists PHA studies are often used for LPG distribution facilities and chlorine injection process in municipal water treatment plants.

Another PHA method is the FMEA or the FMEDA (Failure Mode Effects and Diagnostic Analysis) which has the scope to analyze causes of malfunctioning and the effect of these on the entire system in exam.

6.7.1.1 Risk Reduction Factor (RRF)

While the risks inherent to the plant activity and the tolerable risk are always difficult to estimate, the risk reduction factor is relatively easy to determine:

$$RRF = \frac{\text{Frequency of accidents without protection}}{\text{Frequency of tolerable accidents}}$$

Risk reduction factor can be expressed as a more than unitary number.

Example:
Considering a risk estimate, without protections, of 1 million dollars per year and a company’s dedicated budget of 10.000 $ per year, a risk reduction factor of 100 (equivalent to SIL 2 level) is required.

SIL Safety Integrity Level	PFDavg Average probability of failure on demand per year (low demand)	(1-PFDavg) Safety availability	RRF Risk Reduction Factor	PFDavg Average probability of failure on demand per hour (high demand)
SIL 4	$\geq 10^{-5}$ to $< 10^{-4}$	99.99 to 99.999 %	100000 to 10000	$\geq 10^{-9}$ to $< 10^{-8}$
SIL 3	$\geq 10^{-4}$ to $< 10^{-3}$	99.9 to 99.99 %	10000 to 1000	$\geq 10^{-8}$ to $< 10^{-7}$
SIL 2	$\geq 10^{-3}$ to $< 10^{-2}$	99 to 99.9 %	1000 to 100	$\geq 10^{-7}$ to $< 10^{-6}$
SIL 1	$\geq 10^{-2}$ to $< 10^{-1}$	90 to 99 %	100 to 10	$\geq 10^{-6}$ to $< 10^{-5}$

Table 27, Risk reduction factor, as function of SIL levels and Availability

6.7.1.2 HAZOP report example

Debutanizer Column Node: Reboiler Section

Dev	Cause	Consequence	Safeguards	Recommendations
1.0	**More pressure**			
1.1	Column steam reboiler pressure control fails, causing excessive heat input	Column overpressure and potential mechanical failure of the vessel and release of its contents	Pressure relief valve, operator intervention to high-pressure alarms, mechanical design of vessel	Install SIF to stop reboiler steam flow upon high column pressure
1.2	Steam reboiler tube leak causes high-pressure steam to enter vessel	Column overpressure and potential mechanical failure of the vessel and release of its contents	Pressure relief valve, operator intervention to high-pressure alarms	See item 1.1
2.0	**Less flow**			
2.1	Low flow through bottoms pump causes pump failure and subsequent seal failure	Pump seal fails and releases flammable material	Low outlet flow Pump Shutdown SIS	Existing safeguards adequate

Table 28, Example of typical HAZOP report

Note that “Dev” stands for “deviation” which refers to the guide word in question as it is applied to the specific section of the node under consideration.

Note:
Required safety functions (SIF) are usually indicated in the P&ID (piping and instrumentation diagrams) or in the PFD (process flow diagram). SIF identifications, based on the project documents, require the knowledge of the control process engineering, and risk analysis.

However, although the SIF can be included in the basic package (basic engineering design package), they are often not different from the basic control functions, and this may complicate their identification.

6.7.2 Risk and safety integrity: general concepts (Annex A)

This Annex describes the required safety actions to bridge the gap between the current level of risk in the system and the level that can be tolerated in the given situation. This necessary risk reduction is noted to include contributions from E/E/PE safety-related systems, other safety-related systems, and external risk reduction methods.
Elements of safety integrity relating to both the hardware and the overall systematic safety integrity are sometimes difficult to assess.
This is part of the basis for SIL only referring to the order of magnitude of risk reduction for a safety-related system.
One of the process plant design's goal is to have a facility inherently safe.
The introduction of the concept of *inherent safety*[3] is credited to Trevor Kletz which has stated: "*What you don't have, can't leak*"[4].
Hopefully the design of a process can eliminate many hazards, such as unnecessary intermediate products storage, using safer catalysts, etc.
Risk assessment consists of ranking the risk of hazardous events that has been identified in the hazard analysis.

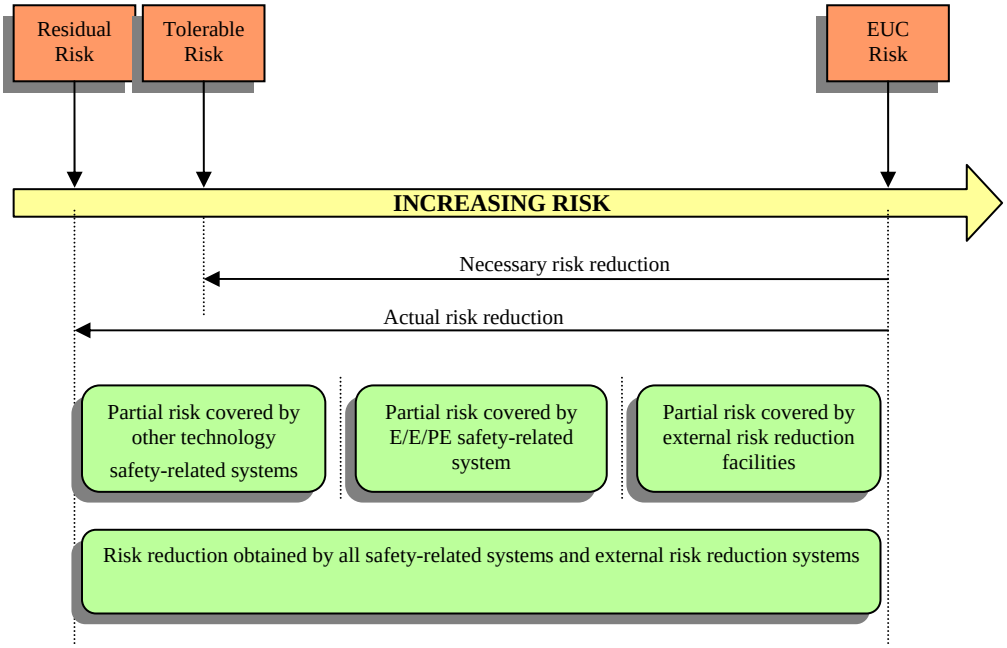


Figure 67, General concepts of risk reduction, according to IEC 61508

[3] "*Cheaper, safer plants*" T. Kletz (1984) IChemE
[4] "*Chemistry & Industry*" T. Kletz (1978) page 278

The terms “tolerable risk” and “acceptable risk” are both frequently used.
It is also said that if accidents can be tolerated, they are never accepted.

6.7.3 ALARP and tolerable risk concepts (Annex “B”)

Annex B describes the concept of a finite level of tolerable risk based on the benefits derived from undertaking that risk in the context of the norms of society. It further describes the reduction of existing risk to a level “As Low As Reasonably Practicable” or ALARP (see Figure 68).
This level again takes into account the benefits derived from the risk as well as the costs to reduce the risk even further.

Accidents are usually a combination of rare events that people initially assumed independent and that would not happen at the same time.

Each person or organization takes risky decisions every day.
Risks are taken or avoided depending on possible gain, pleasure or simply for spirit of adventure. Risks that aren’t immediately refused aren’t necessarily accepted. They could become so in case of higher revenue.
A man who is waiting to cross the street could wait until the risk, represented by traffic, diminishes. At the same manner during the design phase of a production plant with hazardous processes, the risk could be accepted by using E/E/PES safety-related systems.
Moreover an acceptable risk for a person could be unacceptable for another one. For example, risks taken in financial investments.
This also means that the acceptance of a risk involves ethical and moral values which go beyond the mere risk assessment.
Laws in various states require that the reduction of risks is practiced as far as reasonably possible.

“As Low As Reasonably Practicable” or ALARP does not mean as much as possible, but that the costs of risk reduction must be taken into consideration. This system was used the first time in a nuclear tolerable risk evaluation in England in 1988 by HSE[5], to be then extended from nuclear to every industrial field.
The ALARP principle states that there is a level of risk that is intolerable. Above this level risks cannot be justified on any grounds. Below this level instead is the ALARP region where risks can be undertaken only if a suitable benefit can be achieved.

[5] “*The Tolerability of Risk from Nuclear Power Stations*” (HSE 1988) Revised 1992

In the ALARP region, risks are only tolerable if risk reduction is impracticable or if the cost of risk reduction is greatly outweighed by the benefit of the risk reduction that is gained.
Below the ALARP region is the broadly acceptable region where the risks are so low that no consideration of them is warranted, and detailed work is needed to demonstrate ALARP because the risk is negligible, or so low, that no risk reduction is likely to be cost-effective. A cost-benefits analysis of risk reduction in this region is not meaningful.
This ALARP principle can be used with a range of different numeric risk levels defining the boundaries of the ALARP region.

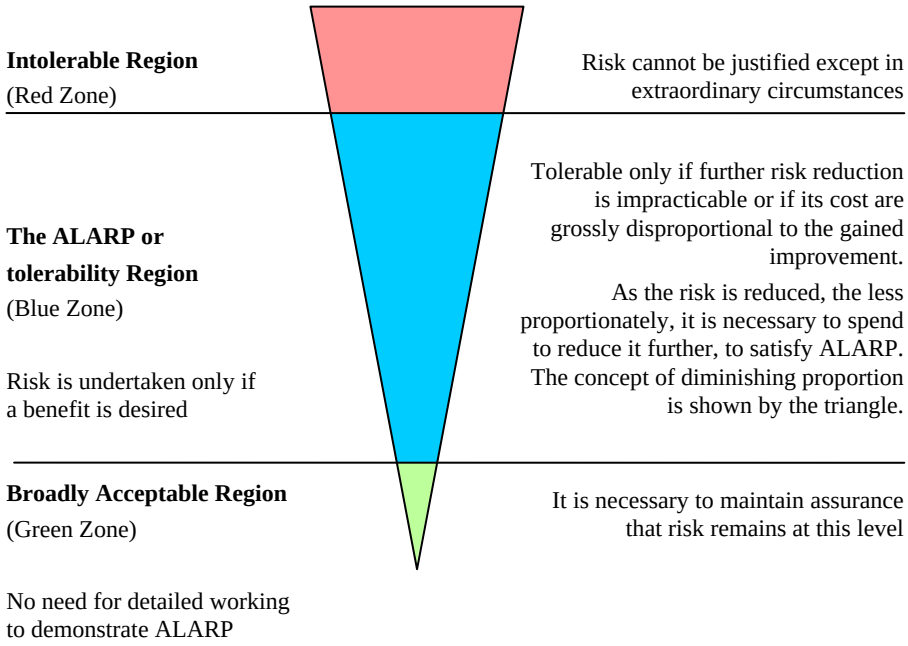


Figure 68, Risk and ALARP zone

To summarize this diagram, it can be said that if a risk is in the intolerable region (red), the plant, the process or its operations cannot be installed or performed. The risk must be reduced at least to the ALARP region (blue). In the broadly acceptable region (green) risk is considered low but it does not mean that it can be accepted or refused without considering costs, compared to benefits. In other words, potential benefits must be proven, evaluated and found appropriate to the scope.
The down shaped triangle means that costs for the risk reduction generally increase with the risk. High risks correspond to high reduction costs.

Risk reduction is not always expensive. For example, the installation of a traffic light, close to a school, is not a big cost compared to its benefit.

6.7.4 Tolerable Risk decisions based on financial considerations

Performing an explicit analysis of costs and benefits of a risk reduction project, is essential to determine the amount of risk reduction that an organization can justify.
The ALARP principle states that there is a zone in which process risk should be reduced if reasonably possible. In practice, “reasonable” means cost-effective. The best way to determine if a risk reduction project is cost-effective is to calculate the ratio of benefits to costs of a project on a financial basis: if the ratio is greater than one, then the project is cost-effective.
Although this process may seem simple, its application presents pitfalls, the largest of which is determining the benefits of risk reduction which are generally the sum of the decrease in the probability of the following harmful outcomes:

- Property damage
- Business interruption
- Environmental contamination
- Injuries, or severe illnesses, to workers and neighbors
- Fatalities to workers and neighbors.

Calculating a financial benefit for the first two items is not too difficult.
However, calculating the benefit of decreases in fatalities, injuries, illnesses, and environmental damage, in financial terms, requires difficult and subtle trade-offs to be made.
Many organizations simply refuse to perform this type of analysis.
Evaluation criteria of human life are not always easy to perform, but are regularly done by insurance companies.
A calculation method frequently used for the evaluation of total costs is the one which adds all the possible hazardous events, calculated by multiplying the frequency of the events for the cost and the consequences.

$$F_{TOT} = \frac{F_{IND}}{PLL^{\alpha}}$$

Where:

- F_{TOT} : Tolerable frequency of a specific event.
- F_{IND} : Tolerable frequency of fatality of an individual (individual risk).
- PLL : Probable Loss of Life for a specific event.
- α : Risk reversion factor used to weight high-consequence events more heavily.

Example 1:

A process plant has an individual risk criterion of 4×10^{-4} per year.
A SIS is being considered to prevent an explosion of the process vessel at the plant. Calculations have shown that the probable loss of life due to the explosion would be 2 persons. Based on the probable loss of life and individual risk criterion, what is the tolerance frequency of the explosion event?

Assuming α = 1, the tolerable frequency of the event is calculated by dividing the individual risk criterion by the expected number of fatalities, or probable loss of life (PLL).

$$F_{TOT} = \frac{4\times10^{-4}}{2} = 2\times10^{-4} = 0.0002 / yr$$

Once it has been established that the frequency of the unwanted event is below the tolerable level, (ALARP blue zone), the benefits and costs of potential risk reduction projects are calculated using the following equation.

$$\frac{\text{Benefits}}{\text{Costs}} = \frac{F_{NO\,SIS}\times EV_{NO\,SIS} - F_{SIS}\times EV_{SIS}}{COST_{SIS} + COST_{NT}}$$

Where:

- B-C ratio : The ratio of benefits to costs
- $F_{NO\text{-}SIS}$: Frequency of the unwanted event without a SIS.
- $EV_{NO\text{-}SIS}$: Total expected value of loss of the event without a SIS.
- F_{SIS} : Frequency of the unwanted event with a SIS.
- EV_{SIS} : Total expected value of loss of the event with a SIS.
- $COST_{SIS}$: Total lifecycle cost of the SIS (annualized).
- $COST_{NT}$: Cost incurred due to nuisance trip (annualized)

If the benefit-to-cost ratio is greater than one, the project should be implemented: this corresponds to the middle ALARP region where the risk is reduced based on its practicability.

Example 2:

A SIS is being installed to prevent a fire that will cost the company $1,000,000. The frequency prior to application of SIS has been calculated in one every 10 years.

After SIS installation the expected frequency is one every 1000 years, and its annualized cost is approximately $66.000.
Cost for nuisance trip is negligible, being F&G normally de-energized.
What is the benefit-to-cost ratio for the F&G project?

The Benefits/Costs relation will be:

$$\text{Benefits} = (\frac{1}{10} \times 1000000) - (\frac{1}{1000} \times 1000000) = 99000$$

$$\text{Costs} = (66000 + 0) = 66000$$

$$\frac{\text{Benefits}}{\text{Costs}} = \frac{99000}{66000} = 1.5$$

A benefit-to-cost ratio of 1.5 means that for every $1 of investment the plant owner can expect $1.5 in return.

Note that margin of error in such calculations is typically greater than 10%.

The ALARP principle requires the cost-benefit analysis to be used to determine if risk reduction projects should be funded when they fall into the ALARP region. By the HSE, risk levels were set so that most process risks fall into this intermediate region. As such, most risk reduction decisions will require a cost-benefit analysis. Since this is true, cost-benefit analysis should be built into the SIL level selection process.
Several companies have found that, for the most part, the tolerable risk guidelines they have set on a moral-legal basis are almost never used because the financial aspect of the risk reduction project always justifies a greater amount of risk reduction.
Risk caused by third-party liability of personnel injury is insignificant in comparison to other losses such as property damage, business interruption, and company reputation. For refineries, property damage losses always dominate, and for upstream refining operations business interruption losses always rule.
Studies have found that making risk reduction engineering decisions based on personal risk level alone is inadequate because it ignores the major risk to the corporations, which is financial.
Unfortunately human life cost is primarily determined by insurance companies.

If a worker dies, insurance pays a certain amount of money, if a manager dies they pay more, but for their families the compensation will never be enough.

6.7.5 Quantitative method for SIL determination (Annex “C”)

This quantitative method is based on calculating a frequency of a hazard and the magnitude of its consequences to determine the difference between the existing and tolerable risk.
First the frequency of the initiating event is determined based on either local operating experience, failure rate database references for similar equipment in similar environments, or detailed analytical estimation. Then the probabilities that the initiating event will actually lead to the hazard are evaluated and combined with the initiating event to determine a hazard frequency. In parallel, the consequence of the hazard is calculated.
Finally, the frequency and consequence of the hazard are assessed relatively to the tolerable risk and a SIL level is selected to bridge any gap.
Tolerable risk frequency is in numerical form: for example a specific consequence should not be greater than 1 every 10000 years.
SIL levels instead are determined from 1 to 4 as in Table 27 at page 171.
An example of calculation is shown in Figure 69 below.

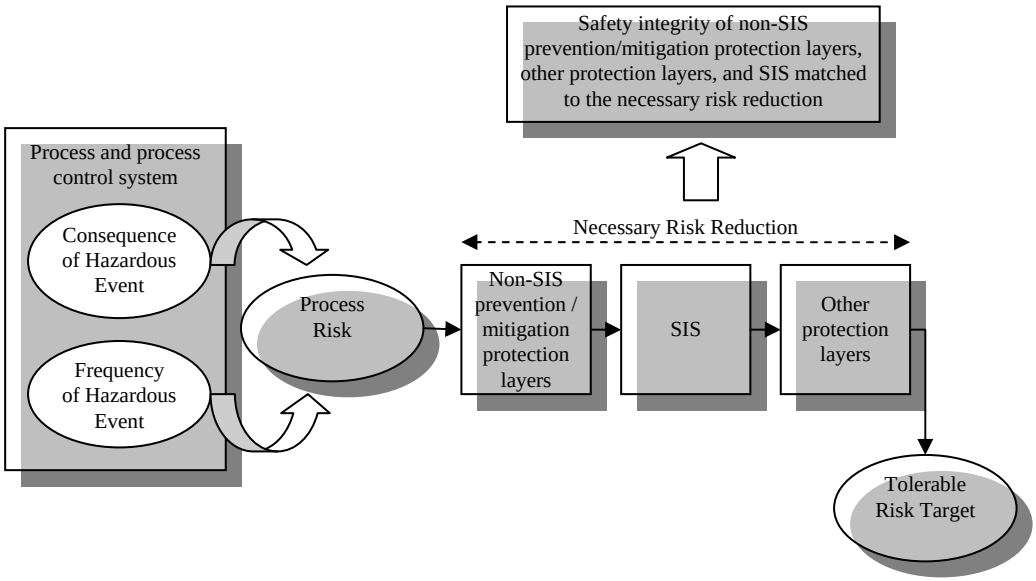


Figure 69, Example of safety integrity level calculation

It has already been stated that:

$$RRF = \frac{\text{Frequency of accidents without protections}}{\text{Frequency of tolerable accidents}}$$

and that:

$$PFDavg \leq \frac{F_T}{F_{NP}}$$

where:

- PFDavg: Average probability of failure on demand to the safety-related system, which is also the measure of safety integrity for low demand mode safety-related systems.
- F_T: Tolerable frequency of hazardous event.
- F_{NP}: Demand frequency to the safety-related system without installation of protective devices.

Frequency	Catastrophic consequences	Critical consequences	Marginal consequences	Unimportant consequences
Frequent	I	I	I	II
Probable	I	I	II	III
Occasional	I	II	III	III
Remote	II	III	III	IV
Improbable	III	III	IV	IV
Incredible	IV	IV	IV	IV

Table 29, Hazardous events classification

Class of risk	Interpretation
I	Intolerable risk
II	Undesired risk, tolerable only if the risk reduction is not possible or if the costs are excessively high compared to the benefit obtained
III	Tolerable risk if the cost of its reduction exceeds the benefit obtained
IV	Unimportant risk

Table 30, Interpretation of the classes of risk

It can be immediately noticed that the determination of the F_{NP} value for the EUC is important, because of its relation with the PFDavg and consequently with the SIL level of the safety-related system.

Steps to calculate the SIL level (when the consequences C say steady) are indicated below, referring to Figure 69:

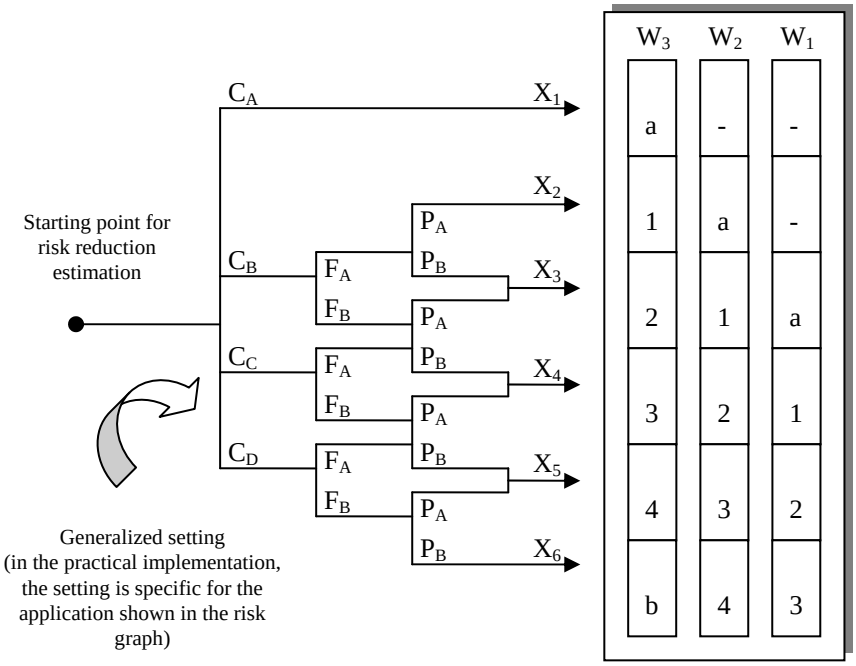
- Determine risk frequency elements in the EUC without protection (F_{NP}).
- Determine the consequences C without adding any protection.
- Determine, with Table 29, if a tolerable risk is reached for the F_{NP} frequency and the consequence C. If with Table 29 a class I risk is reached, a further risk reduction is necessary. Class IV and III risks are to be considered tolerable. Class II risks require a further examination.
- Determine the probability of the failed intervention for the safety-related system protection (PFDavg) to obtain the necessary risk reduction. In the specific case with C steady, PDFavg = (F_T / F_{NP}) = necessary risk reduction.

The SIL level can be obtained from Table 27 at page 171.

If, for example, the PFDavg is between 10^{-2} and 10^{-3},
the level of risk reduction is SIL 2.

6.7.6 Qualitative method: Risk graph (Annex “D”)

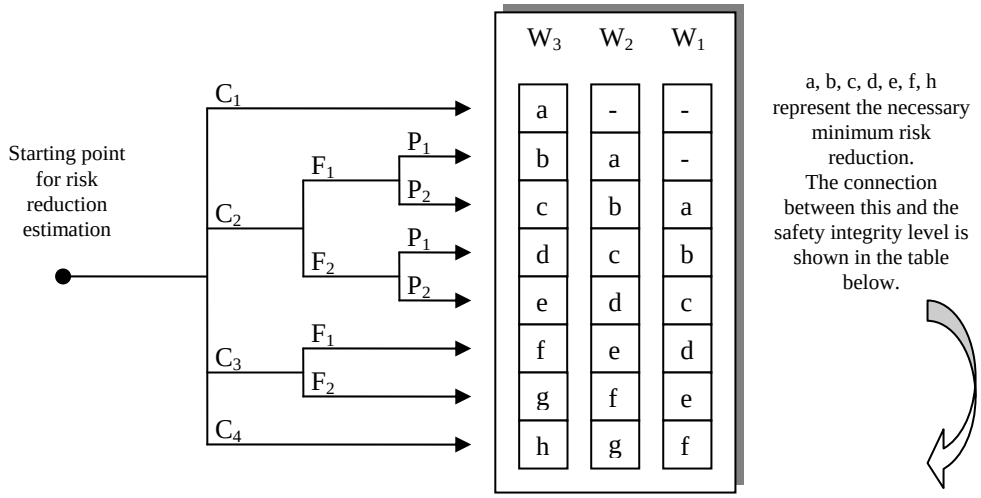
This method assigns a category both to the frequency and to the severity of an hazard to assess the relative risk to a tolerable level.



C	Consequence of the risk
F	Exposure and frequency of the risk
P	Possibility of avoiding an hazardous risk
W	Probability of an unwanted event

-	No safety requirement
a	No special safety requirement
b	Only one E/E/PES is not sufficient
1, 2, 3, 4	Safety Integrity Level (SIL)

Figure 70, Risk graph: general scheme



C	Consequence risk parameter
F	Exposure and frequency of the risk
P	Possibility of avoiding an hazardous event
W	Probability of an unwanted event
a .. h	Evaluation of the risk reduction required for the SRS

Minimum necessary risk reduction	Safety integrity level
-	No safety requirements
a	No special safety requirements
b, c	1
d	2
e, f	3
g	4
h	An E/E/PE SRS is not sufficient

Figure 71, Risk graph: example (illustrates general principles only)

Parameter of the risk		Classification	Comments
Consequences **C**	C1	Minor injuries	The system has been designed to deal with cases of injuries and deaths of people. Other classification schemes should be designed for damages to things and environment. For the interpretation of C1, C2, C3, C4, it must be taken into consideration the accidents and the average recovery process.
	C2	Permanent and severe injuries to several persons; death of one person	
	C3	Death of several persons	
	C4	Death of many persons	
Frequency and exposure time to the dangerous zone **F**	F1	From rare to frequent exposure to a dangerous zone	The system has been designed to deal cases of injuries and deaths of people. Other classification schemes should be designed for damages to things and environment.
	F2	From frequent to continuous exposure to a dangerous zone	
Possibility to avoid the hazardous event **P**	P1	Possible in some conditions	These parameters must be taken into consideration: - functioning of the process (supervised by non skilled or skilled staff or not supervised). - Way of development of the hazardous event (suddenly, quickly or slowly). - ease in identifying the hazard (immediately, detected by technical measurements or without technical measurements). - protection from the hazardous event (possible or not possible escape routes, or only possible in certain conditions). - effective safety experience (experience which might exist in another EUC, in EUC similar or which might not exist.).
	P2	Almost impossible	
Possibility of an unwanted event **W**	W1	A quite low probability that the unwanted event could happen and only very few of them could happen	The scope of W factor is to estimate the frequency that the unwanted event may happen without any safety-related system, but including any external protection system. If few or any experience is available on the EUC, or on the EUC control system, or on similar EUC systems, the estimate of the W factor may be calculated. In this case, the worst condition must be expected.
	W2	A low probability that the unwanted event could happen and only some of them could happen	
	W3	A relatively high probability for the unwanted event to happen and a frequent probability of the unwanted event to happen	

Table 31, Data regarding the example in Figure 71

6.7.7 Determination of the SIL level: qualitative method, Hazardous event severity matrix (Annex "E")

The quantitative method described in Annex "C" of the IEC 61508, useful in the calculation of the SIL level, is not applicable where the risk cannot be quantified.
This Annex describes the qualitative method of the severity matrixes of the hazardous event. This method allows the determination of a SIL integrity level of a E/E/PE system, once the risk factors of the EUC and of its control system are known. Figure 71 and Figure 70 describe a model of risk particularly suitable to be analyzed with such a method.
Note that risk matrixes are not treated in this manual.
Part 6 provides more detailed explanations and examples on how to comply with Parts 2 and 3. This part is made up of almost only annexes.

6.7.8 Layer of Protection Analysis (LOPA)

Layer of protection analysis (LOPA) is a special form of event tree analysis, which is optimized for the purpose of determining the frequency of an unwanted event, which can be prevented by one or more protection layers.
By comparing the resulting frequency to the tolerable risk frequency it is possible to finally select the proper safety integrity level.

6.7.8.1 Example using LOPA

A vessel is used to store Hexane, a combustible material (see Figure 72).
The level in the vessel is controlled by a level controller (LC) which operates the level valve (LV): if the vessel is overfilled, hexane is released through a liquid vent (PSV) and be contained within a dike.
A hazard analysis was performed and determined that the level controller may fail, liquid may be released outside of the dike, an ignition source may ignite the hexane and there may be a possible fatality (see Figure 73).
The company wants to determine if the existing facility will meet their corporate risk criteria, or how extensive the changes will need to be in case any changes are required (such as adding a standalone safety system).

The company established a yearly tolerable risk limit for a fire of 1×10^{-4} and 1×10^{-5} for a fatality. The initiating event for this scenario will be a failure of the control system, which was estimated in 1×10^{-1}. The only existing safety layer would be the dike, which had an estimated PFD of 1×10^{-2}.
Alarms and operator action were not accounted for because, in this instance, the control system was the initiating event, therefore no alarms would be generated. The organization took a conservative view that if material was

released outside of the dike, the likelihood of it finding an ignition source would be 100%. However, the area was not always manned. The probability of someone in the area actually being killed by a fire, as opposed to merely injured, was estimated at 50%.

Figure 73 shows an event tree for this scenario.
The probability of a fire is represented by the combination of probabilities of the bottom three rows, which amounts to 1×10^{-3} (0.1x0.01x1.0).
The probability of a fatality is represented by the bottom row, which amounts to 2.5×10^{-4} (0.1x0.01x1.0x0.5x0.5).

Knowing that the corporate risk target for a fire is 1×10^{-4}, it can be seen that the risk target is not being met by a factor of 10 ($1 \times 10^{-3} / 1 \times 10^{-4}$).
Knowing that the corporate risk target for a fatality is 1×10^{-5}, it can be seen that the risk target is not being met by a factor of 25 ($2.5 \times 10^{-4} / 1 \times 10^{-5}$).

Therefore, the existing design does not meet either corporate risk targets and a change is warranted.
One possible solution would be to install a separate high level shutdown function. Such a function would need to reduce the risk by at least a factor of 25 in order to meet the overall criteria.
A risk reduction factor (RRF) of 25 falls within the SIL 1 range (10-100).
However, obviously not any SIL 1 system will be appropriate.

Table 32 shows a sample worksheet for documenting this scenario.

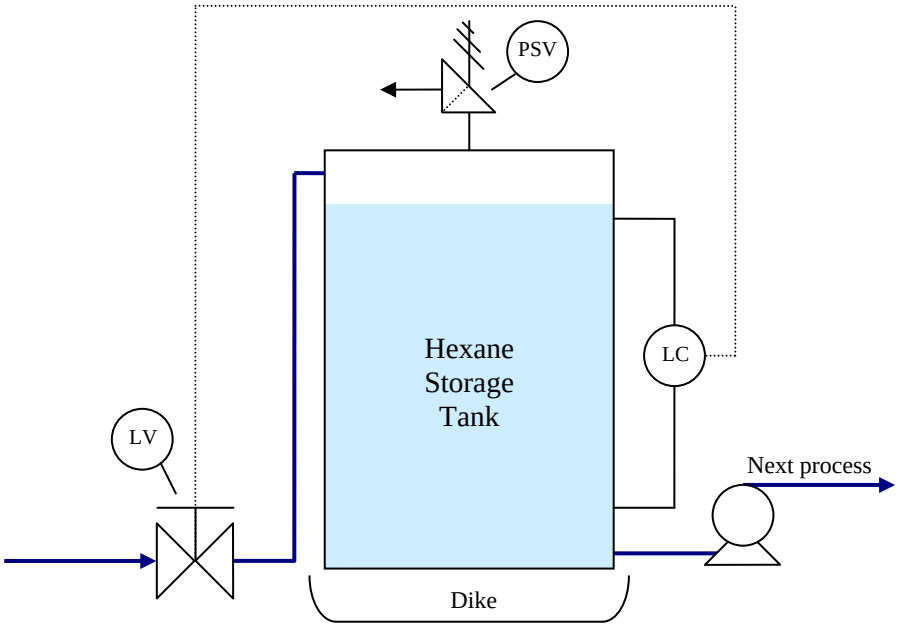


Figure 72, Sample Process for LOPA Example

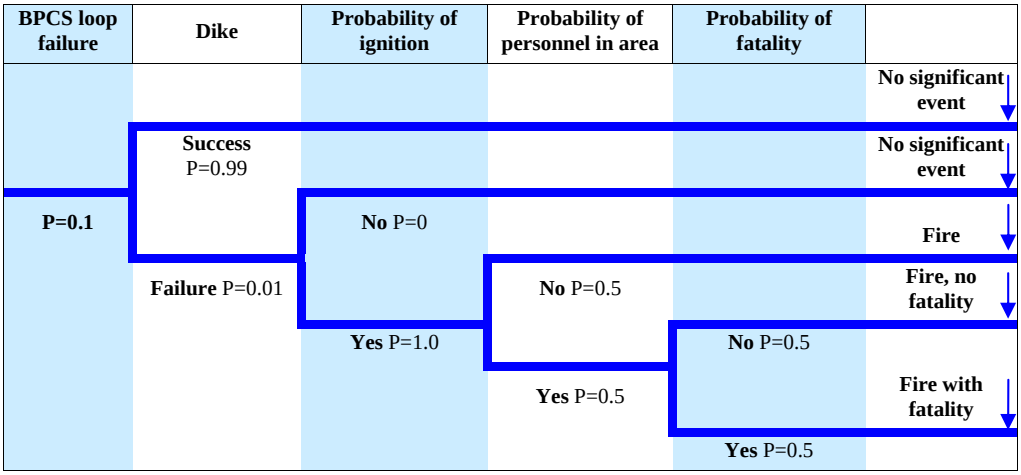


Figure 73, Event tree for LOPA example

LOPA WORKSHEET			
Scenario Number	**Equipment Number**	**Scenario Title:** Hexane Surge Tank Overflow. Spill not contained by the dike	
Date	**Description**	**Probability**	**Frequency (per year)**
Consequence Description/Category	Release of hexane outside the dike due to tank overflow and failure of dike with potential for ignition and fatality		
Risk tolerance Criteria (Category or Frequency)	Maximum tolerable risk of serious fire Maximum tolerable risk of fatal injury		$< 1 \times 10^{-4}$ $< 1 \times 10^{-5}$
Initiating Event (typically a frequency)	BPCS loop failure		1×10^{-1}
Enabling Event or Condition		N/A	
Conditional Modifiers (if applicable)			
	Probability of ignition	1	
	Probability of personnel in area	0.5	
	Probability of fatal injury	0.5	
	Other	N/A	
Frequency of unmitigated consequence			2.5×10^{-2}
Independent Protection Layers			
	Dike (existing)	1×10^{-2}	
Safeguards (non-IPLs)			
	Human action not an IPL as it depends upon BPCS generated alarm. (BPCS failure considered as initiating event)		
Total PFD for all IPLs		1×10^{-2}	
Frequency of Mitigated Consequence			2.5×10^{-4}
Risk Tolerance Criteria Met? (Yes/No): No. SIF required			
Action required:	Add SIF with PFD of at least 4×10^{-2} (Risk Reduction Factor > 25) Responsible Group / Person: Engineering / J.Q. Public, by July 2005 Maintain dike as an IPL (inspection, maintenance, etc)		
Notes:	Add action items to action tracking database		

Table 32, Sample LOPA Example

6.8 Part "6": Guidelines in the application of Parts 2 and 3

6.8.1 Application of Parts 2 and 3 (Annex "A")

Annex "A" is informative.
It shows flow charts of the expected implementation of both parts and provides on overall view of the requirements.

6.8.2 Example technique for evaluating probabilities of hardware failure (Annex "B")

Annex "B" shows an example for evaluating probabilities of failure with many tables showing results for particular architectures for selected values of diagnostic coverage and common cause beta factors.
Methods used for these calculations are approximation formulas based on reliability blocks diagrams. These methods consider the hardware as a chain made up of sensors, logic boxes such as barriers and PLC and final control elements, and indicate several configuration architectures.
For further details see Chapter 3.

6.8.3 Diagnostic Coverage calculation and Safe Failure Fraction: Worked example (Annex "C")

Annex "C" is informative.
It deals with the FMEDA technique (Failure Modes, Effect, and Diagnostics Analysis) for calculating the diagnostic coverage factor.

6.8.3.1 FMEDA (Failure Mode Effect and Diagnostic Analysis): Calculation Method

FMEDA is a systematic method to:

- identify and evaluate the effect of different failure modes,
- determine action that eliminate or reduce the possibility of failure,
- prove the system in exam.

FMEDA is an extension of FMEA (Failure Modes, Effect Analysis).

It combines the FMEA analysis technique, expanding it to identify any possible online diagnostic technique and the relevant failure modes for the designing of the safety-related systems.

It is a recommended technique to generate each category of rates of failure in the system model (safe detectable, safe not detectable, hazardous detectable, hazardous not detectable, high failure mode, low failure mode).
The FMEDA format is an extension of the FMEA standard format, obtained by the law MIL STD 1629[6].
To this issue, more attention will be dedicated, for the importance of this analysis technique, almost unique, to set the SIL level and the PFDavg in the electric-electronic devices used in the safety-related system.
Let's assume to analyze a module which performs its function by interfacing devices with an officer in the control room.
For all the components of the electric circuit in exam, an analysis is being performed as shown in Table 33. The table, for brevity reasons shows the analysis of only some components.

The premises for the analysis are the following:

- Output value lower than downscale: safe detected failure (SD)
- Output value within 4% of the range: safe undetected failure (SU)
- Output value higher than 4% of the range, but within the range: dangerous undetected (DU)
- Output value higher than upscale: dangerous detected failure (DD)

[6] "*Procedures for Performing a Failure Mode, Effects and Criticality Analysis*" MIL-STD-1629, 1998

ID	Component type	λ (FIT)	% of failure rate	Simulated failure type	Effect on output signal	λ_{SD} (FIT)	λ_{SU} (FIT)	λ_{DD} (FIT)	λ_{DU} (FIT)
C1A	Cond. MC 10 nF 50V 10 % x 7R 0805 SMD	31.8	80 20	Open Short	SD SU	25.4	6.36		
C2A	Cond. MC 10 nF 50V 10 % x 7R 0805 SMD	31.8	80 20	Open Short	DU SU		6.36		15.4
C12A	Cond. MC 10 nF 50V 10 % x 7R 0805 SMD	28.6	80 20	Open Short	DD SU		5.72	22.8	
R48A	Res.TF392KR 1/8 W 1% 100 ppm 0805 SMD	9.6	20 40 15 25	Open Short 0,5 x R 2 x R	SU SD SD SD	3.88 1.46 2.43	1.94		
R52A	Res. TF 1 KR 1/8 W 1% 100 ppm 0805 SMD	9.6	50 50	Open Short	DU DD SU SU		1.46 2.43	3.88	1.94
T1A	Tras. EF16 1p/1s 45/95s Vds 90 V Ids 300 mA 2.8/12.6 mH		50 50	Open Short	SD DD	8.9		8.9	
TR5A	Trans. 2N7002 Nmos Vds 60V Ids 300 mA Rds 0,5R SOT23 SMD	25	50 50	Open Short	SD SU	12.5	12.5		
TR7A	Trans. 2N7002 Nmos Vds 60V Ids 300 mA Rds 0,5R SOT23 SMD	25	50 50	Open Short	DU DD			12.5	7.5
IC3A	Integ. TLC272 Ampl. Operat. S08 SMD	2.7	40 40 20	Open Short Unstable	SD SU DU		1.08 1.08		15.4 0.054
IC4A	Integ. TLC272 Ampl. Operat. S08 SMD	2.7	40 40 20	Open Short Unstable	SU SD DU	1.08	1.08		 0.054
					Total Failure Rates	**55.65**	**40.01**	**48.16**	**24.95**

Table 33, Example of FMEDA analysis

As already seen, Table 33 for brevity reasons will account the analysis of only some components, while the real table would be longer, including the analysis of each single component. The premises for the analysis could be:

- The first column shows the identification of the components as shown in the electric diagram.
- The second column shows the type of component.
- The third column shows the failure rate of the component.
- The fourth column shows the percentage of the failure rates for each failure mode shown in the fifth column.
- The fifth column shows the failure modes of the component.
- The sixth column shows the effect of the failure as a function of the variation of the output signal, as stated above. The output status is therefore verified, by simulating the failure and consequently it is possible to classify the type of failure (SD, SU, DD, DU).
- Columns seven, eight, nine, and ten indicate the values of the failure rates related to the effects of the simulated fault.

The last row of the table shows total values in regard to the module in exam.

To verify how useful the FMEDA analysis is, the SFF value has to be calculated, by using all the given data.
It will be seen how this can be increased during the designing phase.
Assuming:

$$SFF = 1 - \frac{\lambda du}{\lambda dd + \lambda du + \lambda sd + \lambda su} = 1 - \frac{39,95}{183,77} = 78\% \,(SIL2)$$

The total rate of dangerous undetected failures (λ_{DU}) must be decreased.

Two hardware changes can be performed to accomplish this task:

- Capacitor C2A (10 nF) has a relevant contribution to the “du” failure rates when it fails due to the opening of a circuit. By using two capacitors in parallel, each of 5 nF, when one of the two opens the other will be available. It has been proved that in this case the failure is not classified as “du” but as “su”.
- The same reasoning is applicable to the resistor R52 (1KΩ) which generates the hazardous failure at the opening of the circuit. Two resistors 2KΩ can be connected in parallel. Although the amount on the total value is low, because the resistors used are metallic and with a few probabilities to open, it’s worth doing it.

Once these changes are performed, for a λ_{DU} = 12,61 FIT, the SFF value increases to 93% (suitable for SIL 3)

The same consideration can be made for the PFDavg = (8760 x λ_{DU})/2, and calculating the PFDavg value in the two examples, which means for λdu = 39,95 FIT and, in the second case, λ_{DU} = 12,61 FIT.

1) PFDavg = 1,75 10^{-4}
2) PFDavg = 0,55 10^{-4} (three times better and suitable for SIL 3)

6.8.4 Methodology to quantify the effect of the common failures of the hardware in the E/E/PE multichannel systems (Enclosure “D”)

Enclosure “D” is informative.

It illustrates the common mode in the redundant systems. A diagram is provided together with the estimate methods of the beta factor to be used in the derived calculation.

6.8.5 Applicative example of the integrity software table of Part 3 (Enclosure “E”)

Enclosure “E” is informative.

It provides an example for the use of the table for the SIL of the software in Part 3. Twenty tables are illustrated with detailed examples for the SIL 2 and SIL 3.

6.9 Part 7: Overview of techniques and measures

Part "7" provides descriptions and an explanation of the many engineering techniques presented earlier in the standard.

6.9.1 Overview of techniques and measures for E/E/PES: control of random hardware failures (Annex "A")

Annex "A" is informative. It addresses random hardware failures and contains methods and techniques useful to prevent or maintain safety in the presence of component failures. The explanations hereby presented support many of the techniques in the hardware tables of Part 2.

6.9.2 Overview of techniques and measures for E/E/PES: avoidance of systematic failures (Annex "B")

Annex "B" is informative. It deals the method of annulment of the systematic failures both in the hardware and software systems and it refers to Parts 2 and 3. It is structured in accordance with the safety lifecycle and deals with many important issues for the key phases.

6.9.3 Overview of techniques and measures for achieving software safety integrity (Annex "C")

Annex "C" is informative. It gives a comprehensive view on the techniques to reach an high safety integrity of the software. Many of these techniques include detailed project phases of the lifecycles. The architecture of the project is also discussed, as well as the design instruments and the programming languages. The Annex examines the verifications, modifications and assessment of functional safety of the lifecycle phases.

6.9.4 A probabilistic approach to determining software safety integrity for pre-developed software (Annex "D")

Annex "D" is informative. It designs a probabilistic approach to determine the SIL level in a already designed software. This Enclosure is addressed to the many systems which try to use software already written and tested. It lists several tests to set the SIL level of software based on statistic analysis.

Chapter 7 IEC 61511 Safety Instrumented Systems for process industry

IEC 61511 has been developed as a process sector implementation of IEC 61508 and is based on two concepts, which are fundamental to its application: the **safety lifecycle** and **safety integrity levels**.

The safety lifecycle forms the central framework which links together most of the concepts in this international standard.
It is a good engineering procedure for the designing of safety-instrumented systems (SIS).
In the safety lifecycle, process risks are evaluated and SIS performance requirements are established (availability and risk reduction).

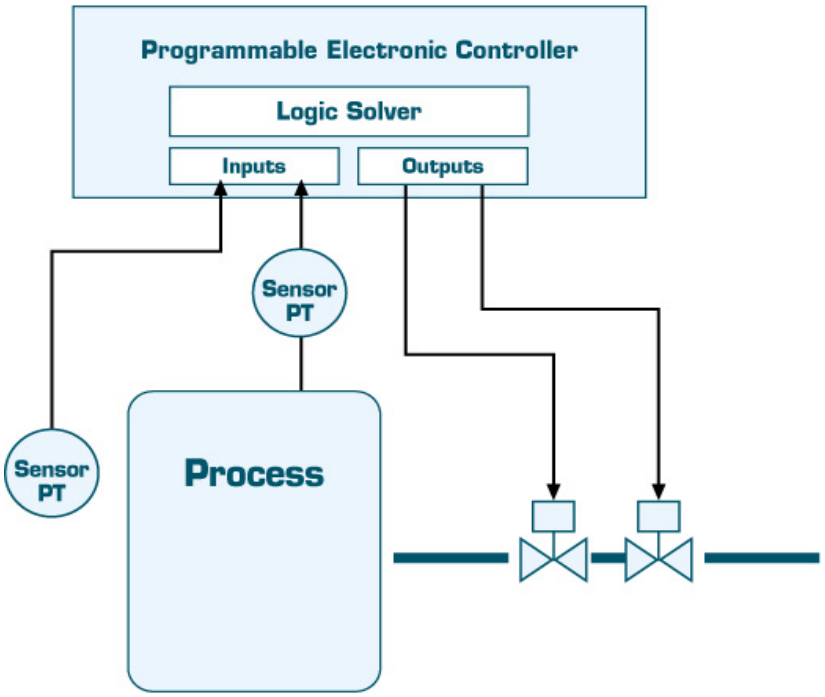


Figure 74, Safety Instrumented System (SIS)

Layers of protection are designed and analyzed. Finally, a SIS, if needed, is optimally designed to meet the particular process risk.
Safety integrity levels are order of magnitude levels of risk reduction. There are four SILs defined in the standard, just as in IEC 61508. SIL 1 has the lowest level of risk reduction, while SIL 4 the highest.
The standard suggests that applications which require the use of a single safety instrumented function of SIL 4 are rare in the process industry and that they shall be avoided where reasonably practicable.
IEC 61511 is primarily concerned with safety-instrumented systems for the process industry sector (sensors, logic solvers and final elements are included as part of the SIS). It also deals with the interface between safety-instrumented systems and other safety systems in requiring that a process hazard and risk assessment are carried out.

7.1 Part 1: Framework, definitions, system, hardware and software requirements

Part 1 specifies requirements for system architecture and hardware configuration, application software, and system integration.
This includes sections on:

- management of functional safety,
- safety lifecycle requirements,
- verification,
- process hazard and risk analysis,
- safety functions allocation to protection layers.

These last two sections only contain general and not detailed requirements.

Furthermore, there are sections on:

- SIS safety requirements specification,
- SIS design and engineering,
- Requirements for application software,
- Selection criteria for utility software containing a detailed safety lifecycle overview for application software.

Finally there are sections on:

- Factory acceptance testing,
- SIS installation and commissioning,
- SIS operation and maintenance,
- SIS decommissioning,
- Information requirements.

Parts 1, 2, 3 and 4 of IEC 61508 have thus been combined into Part 1 of IEC 61511. IEC61511-1 has sections on:

- Scope,
- References,
- Abbreviations,
- Definitions (process sector specific),
- Conformance.

The relationship between IEC 61508 and IEC 61511 is also defined in Part 1, as shown in Figure 75. The key differences between the two standards are discussed in Annex A.

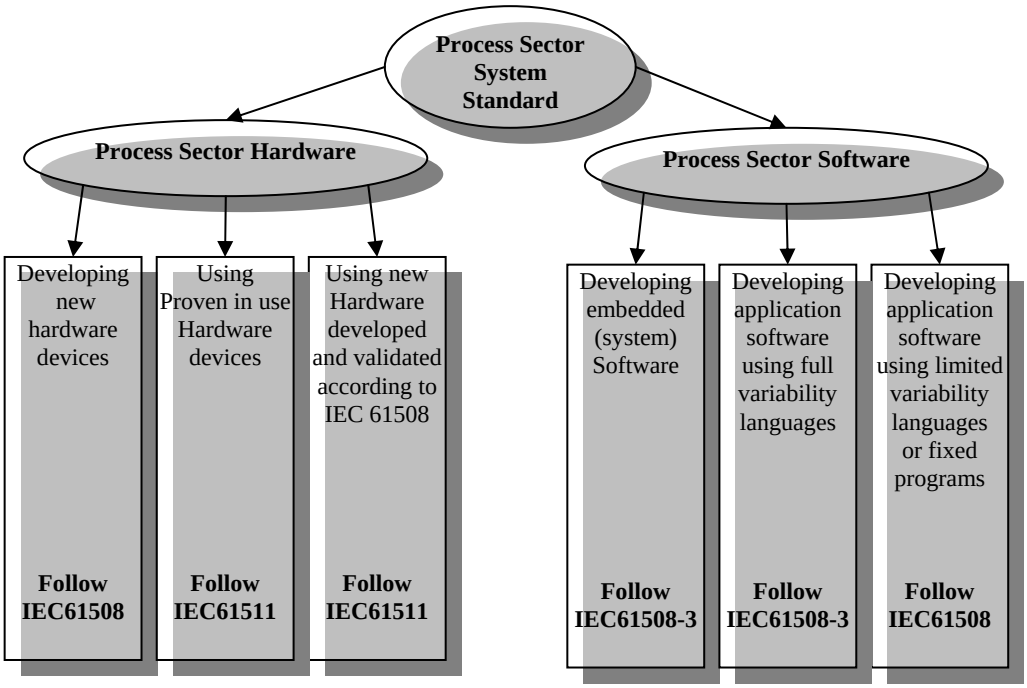


Figure 75, Relationship between IEC 61508 and IEC 61511

7.2 Part 2: Guidelines in the application of IEC 61511

Part "2" contains (as for Part 1) six informative annexes and sections on:

- scope
- definitions
- abbreviations

Part 2 contains general information and guidelines on IEC 61511-1.

Annex A sets out the functional steps in the application of the IEC 61511-1 requirements of:

- Clause 5 (functional safety management)
- Clause 6 (safety lifecycle requirements)
- Clause 7 (software requirements)

In this way, this part of IEC 61511 corresponds to Part 6 of IEC 61508.

Annex B refers to example techniques for calculating the probabilities of failure on demand, either from IEC 61508, Part 6 Annex B or ISA TR84.0.02.

Annex C provides an example of the application of IEC 61511, Part 1 in a chemical company, i.e. a typical SIS architecture development.

Annex D provides three examples of the application of IEC 61511, Part 1, related to various aspects of application programming. It gives information on attributes of a programming language for SIS, an example of the development of application code for a process sector programmable electronic SIS, and an example that illustrates how a major SIS logic solver manufacturer/integrator develops safety application software for customers.

Annex E provides an example of a safety PLC manufacturer's approach in developing a programmable logic solver certified to IEC 61508 for the process sector.

Annex F contains an overview of relevant safety techniques and measures relevant to Part 1, 2, and 3 of this standard, shortly stating, aim, description and references of the specific technique. It only gives an overview of additional process sector references. For other techniques it refers to IEC 61508, Part 7.

7.3 Part 3: Guidelines in the application of hazard and risk analysis

This part of IEC 61511 contains guidelines in the area of determining safety integrity level (SIL) in hazard and risk analysis, and for this reason corresponds to Part 5 of IEC 61508.
The information is intended to provide a broad overview of the wide range of global methods used to do hazards and risk analyses. It provides information on the underlying concepts of risk and the relationship of risk to safety integrity and a number of methods that should enable the safety integrity levels for the Safety Instrumented Functions to be determined.

IEC 61511, Part 3 consists of a clause on the underlying concepts of risk and the relationship of risk to safety integrity (general guidance); see Figure 69 at page 179.
Furthermore there are several informative annexes, of which:

- Annex A covers the ALARP principle and tolerable risk concepts.
- Annexes B, C, D, E, and F covers quantitative and qualitative methods (Safety Matrix Method):
  - Calibrated risk graph (semi qualitative)
  - risk graph (qualitative)
  - Layer Of Protection Analysis (semi-quantitative) are described.

All methods have been simplified in order to illustrate the underlying principles. The information provided is not of sufficient detail to implement any of these approaches.
Overall, IEC 61511 is considered a standard for users (as shown in Figure 75). It is expected that engineering companies and instrumentation users will find the most value from this document.

Chapter 8 Proven-in-use assessment

8.1 Defining the term “proven-in-use” according IEC 61508-7

Proving-in-use means using field experience from different applications to prove that the safety-related system will work according to its specification.

This is accomplished by the use of components or sub-systems, which have been shown by experience to have no, or only unimportant, faults when used, essentially unchanged, over a sufficient period of time in numerous different applications.

For proven by use to apply, the following requirements must have been fulfilled:

- Unchanged specification.
- 10 systems in different applications.
- 100.000 operating hours and a test of at least 1 year of service history.

Proof is given through documentation of a vendor and/or operating company. This documentation must at least contain:

- Exact designation of the system and its components, including version control for hardware and software.
- User and time of operation.
- Operating hours.
- Procedures for the selection of the system and application procedure to the proof.
- Procedures for fault detection and fault registration as well as fault removal.

8.2 “Proven-in-use” requirements according to IEC 61511-1

According to IEC 61511-1 First Edition 2003-01 section 11.4.4, for all sub-systems (e.g. sensor, final elements and non-PE logic solver) except PE logic solvers, the minimum fault tolerance specified in Table 6 of this standard may be reduced by one of the devices under consideration complying with all of the following:

- Device’s hardware is selected on the basis of prior use;
- the device allows adjustment of process-related parameters only, e.g., measuring range etc.;
- the adjustment of process-related parameters of the device is protected, e.g., jumper, password;
- the function has a SIL requirement lower than 4.

	MHFT* **Does not meet 11.4.4 requirements**	**MHFT*** **Meets 11.4.4 requirements**
SIL 1	0	0
SIL 2	1	0
SIL 3	2	1
SIL 4	Special requirements apply. See IEC 61508	Special requirements apply. See IEC 61508

Table 34, Extracted from IEC 61511-1 Edition 2003-01: Minimum tolerance to hardware failure of final element sensors and logic solvers non-PE

* MHFT: Minimum Hardware Fault Tolerance.

This means that if the requirements of section 11.4.4 of IEC 61511-1 First Edition 2003-01 are fulfilled, a hardware fault tolerance of 0 is sufficient for SIL 2 (sub-) systems with a SFF of 60% to < 90%.

Note:
Some certification bodies (e.g. EXIDA) do not take in exam subsystems which have a SFF lower than 80%.

8.3 Required information for a proven-in-use proof of a sub-system

It frequently happens that the manufacturer of a device, apparatus, or sub system has to certify (or prove) that its product was already sold and installed for years in accordance to IEC 61508 and IEC 61511.
The following information is therefore required:

- Current hardware and software version of the considered devices.
- Number of sold devices with current version of the hardware and software.
- Number of failures of the sold devices with current version of the hardware and software.
- Indication of the operating hours (counted six months after the months the devices were sold) of the considered devices with current version of the hardware and software.
- Indication of all currently available versions of hardware and software on the market.
- List of at least 10 different applications of the devices with current version of hardware and software.
- Quality system certification.
- Description (procedure) of how the field feedback tracking is done.
- Description (procedure) about the used version and configuration management system according the requirements of IEC 61508.
- Description (procedure) about the modification process according the requirements of IEC 61508.
- Description of the adjustment possibilities of process-related parameters of the considered devices and related protection mechanisms.
- Features/configurations of the considered devices, which cannot be used by the user for safety applications
- Description of why this features/configurations do not interfere with the considered safety function (FMEDA).
- Fault scenarios of the used sensor elements.

Chapter 9 Functional safety manual

A safety manual must be provided for each device, sensor, controller or final element that is part of a safety-related system and for which it is necessary to prove the compatibility with IEC 61508 and IEC 61511.
The purpose of this short chapter is to provide a "checklist" of requirements for such safety manual.

A safety manual is a document provided to the users of a product that specifies their responsibilities for installation and operation in order to maintain the designed safety level.
The manufacturer of a product is required to provide such manual by the mentioned standards. Moreover, many users consider the document to be a pre-sales document as they want to see if there are serious limitations in the use of a product before purchasing it.

9.1 Requirements

IEC 61508 requires that manufacturers:

- Advice procedures required for a test to detect known "dangerous failures" as identified by the FMEDA of the product. The procedures must include a statement that results of such testing be recorded.
  Any tools required must be identified. The expected skill level of those in charge of accomplishing the task must be specified.
  Diagnostic coverage factor for the specified test must be stated.
- Advice procedures to repair or replace the product. This must include a statement that all failures must be reported to the manufacturer. Any tools required must be identified. The expected skill level of those doing the work must also be specified.
- Advice any necessary installation and site acceptance test procedures required in order to achieve safety.
- If firmware upgrade is possible in the product, procedures must be given with any needed tools identified. The expected skill level of those doing the work must be specified.
- The safety manual must contain estimated failure rates (or a reference to the FMEDA report) and an estimate of the beta factor for use when redundant devices are designed into the safety instrumented function.

Note: Although not required, this would be a good place to include a discussion of impulse line clogging and common cause implications of that. The achievable SIL must be stated (or a reference to the FMEDA report).

- If there are any unknown product lifetime limits, these must be stated. Otherwise a statement that there are no known wear-out mechanisms. **Note:** Although not required, it may be advisable to make some statements about product lifetime even if there are no known wear-out mechanisms.
- All required parameter setting assumed for safety must be stated.
- Any application limitations and environmental limits must be stated (or a reference pointing to another document).
- Worst case diagnostic test time must be stated for the claimed diagnostic test coverage.

IEC 61508-2, in section 7.4.7.3, specifies the following information which shall be available for each safety-related subsystem:

- A functional specification of those functions and interfaces of the sub-system which can be used by the safety functions.
- The estimated rates of failure (due to random hardware failures), in any modes which could cause a dangerous failure of the E/E/PE safety-related system, which are detected by the diagnostic tests.
- Any limits on the subsystem environment which could be observed in order to maintain the validity of the estimated rates of failure due to random hardware failures.
- Any limit on the lifetime of the subsystem which should not be exceeded in order to maintain the validity of the estimated rates of failure due to random hardware failure.
- Any periodic proof test / or maintenance required.
- Diagnostic coverage.
- Diagnostic test interval.
- Any additional information (for instance repair time) which is necessary to allow the derivation of the mean time to restoration (MTTR) following detection of a fault by the diagnostics.
- All information which is necessary to enable the derivation of the safe failure fraction (SFF) of the subsystem as applied in the E/E/PE safety-related system.
- The hardware fault tolerance of the subsystem.
- Any limits on the application of the subsystem which should be observed in order to avoid systematic failures.
- The highest safety integrity level (SIL) that can be claimed for a safety function which uses these subsystem on the base of:

- Measure and techniques used to prevent systematic failures being introduced during the design and implementation of the hardware and software of the subsystem,
- the design features which make the subsystem tolerant against systematic failures.
  Note: this is not required in the case of those subsystems which are considered to have been proven in use.

- Any information which is required to identify the hardware and software configuration of the subsystem in order to enable the configuration management hardware and software of the secondary system, to allow the management of the E/E/PE safety-related system in accordance with IEC 61508-1, 6.2.1.
- Documentary evidence that the subsystem has been validated.

IEC 61511-1, in section 1.2.4.4.7, defines the following requirements which the safety manual shall address:

- Use of diagnostics to perform safety functions.
- List of certified / verified safety libraries.
- Mandatory test and system shutdown logics.
- Use of watchdogs.
- Requirements for, and limitation of, tools and programming languages.
- Safety integrity level for which the device or system is suitable.

9.2 Example

As an example, it is possible to download G.M. International's ISM0071 Functional Safety Manual for its intrinsically safe isolated barriers D1000 Series suitable for SIL 2 and SIL 3 applications at the address:
http://www.gminternationalsrl.com/get.php?w=ism&id=ISM0071

Information presented in it is useful for proper use of the products, for design and maintenance engineers, system integrators and panel shops, as well as final users.
The functional safety manual does not substitute installation and maintenance manual, but is a complement to them, for those verification procedures that are actuated during proof tests.
It is also useful in the design phase for choosing the suitable interface for the specified SIL level.

Chapter 10 SIS design checklists

The use of checklists will not, in and of itself, lead to safer systems, just as performing an HAZOP (Hazard and Operability study) and not following the deriving recommendation will not lead to safer facilities.

Following the procedures outlined in the checklist, which are based on industry standards and cumulated knowledge (much of which was learned the hard way), should result in safer systems.
Checklist are an attempt to list as many procedures and common practices as possible in the hope that by following a systematic review of the overall design process, nothing will fall through the cracks of an organization and be forgotten.

The checklist is composed of various sections, each corresponding to different portions of the safety lifecycle as described in various standards.
Different sections of the checklist are intended for different groups involved with the overall system design, ranging from the user, contractor, vendor, and system integrator.

The checklist, therefore, does not dictate who has what responsibilities; it only summarizes items in the various lifecycle steps.
These checklists should not be considered final or complete; they leave ample space for additions and suggestions.

10.1 Management Requirements[1]

Item #	Item	Yes	No	N/A	Comments
1.1	Have persons or departments responsible for carrying out the phases of the lifecycles been identified?				
1.2	Have persons or departments responsible for carrying out the phases of the lifecycles been informed of their responsibilities?				
1.3	Are persons competent to perform he tasks assigned to them?				
1.4	Is personnel competency documented in terms of knowledge, experience, and training?				
1.5	Has a hazard-risk assessment been performed?				
1.6	Is a safety plan in place that defines the required activities?				
1.7	Are procedures in place to ensure prompt and satisfactory resolution of recommendations?				
1.8	Are procedures in place to audit compliance with requirements?				

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10.2 Safety Requirements Specification[2]

Item #	Item	Yes	No	N/A	Comments
2.1	Do the safety requirements originate from a systematic hazard assessment? If not, what are the requirements based on?				
2.2	Is there a clear and concise description of each safety related function to be implemented in the SIS?				
2.3	Have the safety state of the process been defined for each operating state of the plant? (Startup, normal operation, maintenance, etc.)?				
2.4	Are safety functions defined for each operating state of the plant?				
2.5	Are performance requirements (e.g. speed, accuracy, etc.) defined for each safety function?				
2.6	Has the required safety integrity level (SIL) been determined for each safety function?				
2.7	Are sensor inputs defined with regard to range, accuracy, noise limits, bandwidth etc.?				
2.8	Are output defined with regard to range, accuracy, update frequency, etc.?				
2.9	In the event of system failure, are sufficient information and means available for the operators to assume safe control?				
2.10	Is the operator interface defined in terms of data display, alarms, etc. ?				
2.11	Have local or application specific regulatory requirements been considered?				
2.12	Has the operation and implementation of resets been defined for each input and output?				
2.13	Have the operation of bypasses / overrides been defined for each input and output?				
2.14	Have process common cause considerations (e.g. corrosion, plugging, coating, etc) been considered?				

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10.3 Conceptual SIS Design[3]

Item #	Item	Yes	No	N/A	Comments
3.1	Are safety functions being handled by a completely separate system from the process control? If not, what is the justification?				
3.2	If multiple functions are being performed within the same logic solver, do the shared components meet the highest SIL requirements?				
3.3	Has the technology and level of redundancy been selected for each safety function? If so, what is it?				
3.4	Have manual test intervals been determined and justified for each safety functions?				
3.5	Has the performance of each safety function been analyzed and documented in a quantitative manner in order to see if it meets the safety integrity level (SIL)? If not, what is the justification for the system configuration?				
3.6	Are proven-in-use criteria established for non-certified equipments?				

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10.4 Detailed SIS Design[4]

Item #	Item	Yes	No	N/A	Comments
4.1	Are design documents under control of a formal revision and release program?				
4.2	Has the SIL of the final system been analyzed and documented in a quantitative manner? If not, what is the justification for the system configuration?				
4.3	Are suitable interfaces between field devices and the logic solver defined?				
4.4	Are suitable communication interfaces defined in terms of protocols and information to be exchanged?				
4.5	Are there provisions for future expansion?				
4.6	Are there provisions for incorporating changes as the design proceeds?				
4.7	Is the system "fail safe" in terms of:				
1	Loss of power?				
2	Loss of instruments air?				
3	Field cable faults?				
4.8	Can the action of a non-safety function interrupt or compromise any safety functions?				
4.9	Is the safe state of each system component defined?				
4.10	Has the impact of failure of each component in the system been considered, and the required action to be taken, defined?				
4.11	Is field I/O power separate from other circuits?				
4.12	Are I/O bypasses incorporated?				
4.13	When an input bypass is enabled, can the state of the sensor still be determined?				
4.14	Are there means for alarming a bypass after a pre-determine time interval?				
4.15	Does the system incorporate manual resetting to restart production? If not, what is the justification?				

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10.5 Power & Grounding[5]

Item #	Item	Yes	No	N/A	Comments
5.1	Are the power supplies direct current (DC)? If not, what is the justification?				
5.2	Is a redundant main power source available? If not, what is the justification?				
5.3	Has the impact of power failure been considered?				
5.4	Have the following power concerns been addressed?				
1	Voltage and current range, including in-rush current?				
2	Frequency range?				
3	Harmonics?				
4	Non linear loads?				
5	AC transfer time?				
6	Overload and short circuit protection?				
7	Lightning protection?				
8	Protection against transient spikes, surges, brownouts, and noise?				
9	Under and over voltage?				
10	Over voltage protections are redundant?				
5.5	Have the following grounding concerns been addressed?				
1	Corrosion protection?				
2	Cathodic protection?				
3	Electrostatic protection?				
4	Shield grounding?				
5	Test ground?				
6	Intrinsic Safety Zener barrier ground is separated from structural ground? Its value is less then 1Ω?				
7	Appropriate isolated communications techniques (e.g. communication transformers, fiber optics) between ground planes?				

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10.6 Field Devices[6]

Item #	Item	Yes	No	N/A	Comments
6.1	Are there valid failure rate, failure mode, and diagnostic coverage information for all devices?				
6.2	Have vendor provided a recommended functional safety manual with T-proof test interval and related procedures?				
6.3	Will means be available to periodically check the devices for dangerous undetected failures?				
6.4	Are circuits normally energized? If not, is the line monitoring circuit been incorporated?				
6.5	Does each device have its own dedicated wiring? If not, what is the justification?				
6.6	If smart sensors are being used, are they write-protected?				
6.7	Have minimum, as well as maximum, electrical loads been considered for field I/O circuits?				
6.8	Is feedback available to tell if the final element have moved to its commanded state?				
6.9	Have material (seals, etc.) been properly selected for the particular application?				
6.10	Does the user have good field experience with the devices in other applications?				
6.11	Are solenoid valves protected from plugging, dirt, insects, freezing, etc? What measures have been applied?				
6.12	Have the following areas been considered for final elements:?				
1	Operating and closing speeds?				
2	Shutoff differential pressure?				
3	Leakage?				
4	Fire resistant of body, actuator, and impulse line?				
6.13	Are safety critical field devices identified in some unique manner (e.g. color coding, labeling)?				

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10.7 Operator Interface[7]

Item #	Item	Yes	No	N/A	Comments
7.1	Has failure (loss) of the interface been considered?				
7.2	Are alternate means available to bring the process to a safe state?				
7.3	Are the following information shown on the interface:				
1	Where the process is in sequence?				
2	Indication that a SIF action has occurred?				
3	Indication that a SIF function is bypassed?				
4	Indication that a SIF component or subsystem has failed or is in a degraded state?				
5	Status of field devices?				
7.4	Is the update time appropriate for the application under emergency conditions?				
7.5	Have the operators been checked for color blindness?				
7.6	Is it possible to change SIS program logic from the operator interface?				
7.7	Do parameters that can be changed have security access protection?				

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10.8 Maintenance/Engineering Interface[8]

Item #	Item	Yes	No	N/A	Comments
8.1	Can failure of this interface adversely affect the SIS?				
8.2	Is there adequate access security? What methods are utilized?				
8.3	Is the maintenance/engineering interface used as the operator interface?				
8.4	Is the maintenance/engineering interface disconnected during normal system operation?				

10.9 Communications[8]

Item #	Item	Yes	No	N/A	Comments
9.1	Can communication failures have an adverse affect on the SIS?				
9.2	Are communication signals isolated from other energy sources?				
9.3	Has write protection been implemented so that external systems cannot corrupt SIS memory? If not, why?				
9.4	Are interfaces robust enough to withstand EMI/RFI And power disturbances?				

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10.10 Hardware Specifications[9]

Item #	Item	Yes	No	N/A	Comments
10.1	Has the physical operating environment been defined? and have suitable specifications been set for:				
1	Temperature range?				
2	Humidity?				
3	Vibration and shocks?				
4	Ingress of dust and/or water?				
5	Contaminating gases?				
6	Hazardous atmospheres?				
7	Power supply voltage tolerance?				
8	Power supply interruptions?				
9	Electrical interferences?				
10	Ionizing radiations?				
10.2	Are failure modes known for all components?				
10.3	Has the vendor supplied quantitative safe and dangerous failure rates, including assumptions and component data used?				
10.4	Has the vendor provided diagnostic coverage values for their system or components?				
10.5	Are logic system components (I/O modules, CPU, communication modules, etc.) all from the same vendor?				
10.6	Has the resulting action of restoring power to the system been considered?				
10.7	Are I/O modules protected from voltage spikes?				
10.8	If redundant devices or systems are being considered, have measures been taken to minimize potential common cause problems? If so, what are they?				

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10.11 Hardware Manufacture[10]

Item #	Item	Yes	No	N/A	Comments
11.1	Can the vendor provide evidence of an independent safety assessment of the hardware?				
11.2	Does the vendor maintain a formal revision of release control program?				
11.3	Are there visible indications of version number on the hardware?				
11.4	Does the vendor have specifications and procedures for the quality of materials, workmanship, and inspections?				
11.5	Are adequate precautions taken to prevent damage due to static discharge?				
11.6	Does the vendor have proof for the SIL level certification of component, or subsystem? What is the T-proof time interval specified in the report for the approved SIL level?				
1	1 yr?				
2	3 yr?				
3	5 yr?				
4	10 yr?				
5	Other?				
11.7	Does the vendor supply the component functional safety manual, with indication of all types of failure rates, safe detected, safe undetected, dangerous detected, dangerous undetected, SFF value, and PFDavg necessary to calculate the total SIF PFDavg?				
11.8	Does the vendor supply test procedures for the T-proof periodic testing of the component? If so, what is the effectiveness (diagnostic coverage factor) of each test?				

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10.12 SIF Components

Pos.	Item	Yes	No	N/A	Comments / Values
1	Are the component identification data complete? (Type, manufacturer, etc.)				
2	Do SIF functional and operative specifications correspond to requirements?				
3	Does manufacturer provide the safety manual?				
4	Is the subsystem certified or approved by an independent body according IEC 61508 and IEC 61511 requirements?				
5	Is the component A or B type according tables 2 and 3 of IEC 61508-2?				
6	Has the value of PFDavg been defined? If yes what is the value expressed per year?				
7	Is the defined PFDavg value suitable for the risk reduction factor required for the SIF?				
8	Is the TI interval for which the PFDavg has been calculated, of 1, 3, 5 or 10 years?				
a	State the PFDavg value for TI=1 year				
b	State the PFDavg value for TI=5 years				
c	State the PFDavg value for TI=10 years				
d	TI = other				
9	Is the defined fault tolerance value adequate?				
a	What is the fault tolerance of the component, (0, 1, 2 or unknown)?				
10	Is the calculated PFDavg value in compliance with the one set by the design?				
11	Is the % value of the SFF known? If yes, what is it?				
12	Is the MTBF value known? If yes, what is it?				
13	Is the sum of the safe detected failures (λsd) known? If yes, what is it (per year)?				
14	Is the sum of the safe undetected failures (λsu) known? If yes, what is it (per year)?				
15	Is the sum of the dangerous detected failures (λdd) known? If yes, what is it (per year)?				
16	Is the sum of the dangerous undetected failures (λdu) known? If yes, what is it(per year)?				
17	Is the SIL level for the component defined and adequate?				
18	What is the fault tolerance on demand (PFDavg) obtained for the SIL level value established for the component?				

19	Has the safe failure status been established in the SIF? If yes, what is it?				
20	Does the safety manual specify the procedures and the different tests to be performed in accordance with the TI interval set for the SIF? If yes, which is the periodic testing effectiveness assigned by the tester for each test? (See Section 5.4.3.1 at page 106)				
a	Test 1				
b	Test 2				
c	Test 3				
d	Test 4				
e	Test 5				
f	Test 6				
g	Test 7				
h	Test 8				
21	What is the new PFDavg value corrected by the periodic testing effectiveness as seen in line 20?				
22	Does the new PFDavg value corrected by the periodic testing effectiveness percentage, seen in line 20, confirm the SIL level assigned after the periodic proof test?				
23	Is the component used in an architecture different from 1oo1? If yes, which one?				
24	For this new architecture, has the PFDavg value been calculated in accordance with the TI interval chosen for the SIF? If yes, which one?				
25	Are the installation specifications defined and coherent?				
26	Is it possible to perform any change to the hardware and /or software?				
a	If yes, does any procedure exist in which the impact analysis is required, with the relative authorization, before installation?				
b	Has the impact analysis been approved by a competent person or body?				
27	Does any procedure or precaution for the decommissioning exist?				

Note:
Functional Safety Manual is required in order to fill-in this checklist.

10.13 Application Logic Requirements[11]

Item #	Item	Yes	No	N/A	Comments
12.1	Do all parties have a formal revision and release control program for application logic?				
12.2	Is the logic written in a clear and unambiguous manner that is understandable to all parties?				
12.3	Does the program include comments?				
12.4	Within the logic specification, is there a clear and concise statement of:				
1	Each safety-related function (SIF)?				
2	Information to be given to the operators?				
3	The required action of each operator command, including illegal or unexpected commands?				
4	The communication requirements between the SIS and other equipments?				
5	The initial states for all internal variables and external interfaces?				
6	The required action for out-of-range variables?				

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10.14 Embedded (Vendor) Software [12]

Item #	Item	Yes	No	N/A	Comments
13.1	Can the vendor provide evidence of an independent safety assessment of all embedded software?				
13.2	Has the software been used in similar applications for a significant period of time?				
13.3	Is the vendor software documented sufficiently for the user to understand its operation and how to implement the desired functionality?				
13.4	Are the results of abnormal math operation fully documented?				
13.5	Are there procedures for the control of software versions in use and the update of all similar systems?				
13.6	For spare which contain firmware, is there a procedure to insure all modules are compatible?				
13.7	Can software versions in use easily be checked?				
13.8	If errors are found in embedded software, are they reported to and corrected by the vendor, and incorporated into the SIS only after checking and testing the corrected code?				
13.9	Has the vendor made an impact analysis for software corrections or changes?				
13.10	Does the manufacturer provide competent technical support?				

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10.15 Software Coding[13]

Item #	Item	Yes	No	N/A	Comments
14.1	Are there standards or procedures for software coding?				
14.2	Are there procedures for documenting and correcting any deficiencies in the specification or design revealed during the coding phase?				
14.3	Are departure from or enhancements to the requirements of the design documented?				
14.4	Is a formal language or some other means taken to assure the program is both precise and unambiguous?				
14.5	Is there a procedure for generating and maintaining adequate documentation?				
14.6	Does the programming language encourage the use of small and manageable modules?				
14.7	Does the code include adequate comments?				
14.8	Are design reviews carried out during program development involving users, designers, and programmers?				
14.9	Does the software contain adequate error detection facilities associated with error containment, recovery, or safe shutdown?				
14.10	Are all functions testable?				
14.11	Is the final code checked against the requirements by persons other than those producing the code?				
14.12	Is a well-established compiler/assembler used?				
14.13	Is the compiler/assembler certified to recognized standards?				

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10.16 Factory Test[14]

Item #	Item	Yes	No	N/A	Comments
15.1	Are there procedures for testing the finished system?				
15.2	Are records maintained of test results?				
15.3	Are there procedures for documenting and correcting any deficiencies in the specification, design or programming revealed during testing?				
15.4	Is testing carried out by persons other than those producing the code?				
15.5	Is software tested in the target system rather than simulated?				
15.6	Is each control flow or logic path tested?				
15.7	Have arithmetic functions been tested with minimum and maximum values to ensure that no overflow conditions are reached?				
15.8	Are there tests to simulate exceptions as well as normal conditions?				
15.9	Have all of the following items been tested?				
1	Dependence on other systems/interfaces?				
2	Logic solver configuration?				
3	Operation of bypasses?				
4	Operation of resets?				
5	All functional logic?				

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10.17 Installation & Commissioning[15]

Item #	Item	Yes	No	N/A	Comments
16.1	Have personnel received appropriate training?				
16.2	Is there sufficient independence between those carrying out the work and those inspecting it?				
16.3	Was the material stocked with cure before installation?				
16.4	Are installation procedures for all devices sufficient in detail so has not to leave important interpretations or decisions to installation personnel?				
16.5	Has the SIS been inspected in order to reveal any damage caused during installation?				
16.6	Are items such as cabinets, junction boxes, and cables protected from:				
1	Steam leaks?				
2	Water leaks?				
3	Oil leaks?				
4	Heat sources?				
5	Mechanical damages?				
6	Corrosion (e.g. process fluid flowing from damaged sensors to junction boxes, the logic cabinet, or the control room?				
7	Combustible atmospheres?				
16.7	Are safety-related systems clearly identified to prevent inadvertent tampering?				
16.8	Has the proper operation of the following items been confirmed?				
1	Proper installation of equipments and wiring?				
2	Energy sources are operational?				
3	All field devices have been calibrated?				
4	All field devices are operational?				
5	Logic solver is operational?				
6	Communication with other systems?				
7	Operation and indication of bypasses?				
8	Operation of resets?				
9	Operation of manual shutdowns?				

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16.9	Is the documentation consistent with the actual installation?				
16.10	Is there documentation showing the allowing:				
1	Identification of the system been commissioned?				
2	Confirmation that commissioning has been successfully completed?				
3	The date the system was commissioned?				
5	Authorized signatures indicating the system was successfully commissioned?				

10.18 Operations & Maintenance[16]

Item #	Item	Yes	No	N/A	Comments
17.1	Have employees been adequately trained on the operating and maintenance procedures for the system?				
17.2	Are operating procedures adequately documented?				
17.3	Is there a user/operator/maintenance manual for the system?				
17.4	Does the manual describe:				
1	Limits of safe operation, and the implications of exceeding them?				
2	How the system takes the process to a safe state?				
3	The risk associated with system failures and the actions required for different failures?				
17.5	Are there means to limit access only to authorized personnel?				
17.6	Can all operational settings be readily inspected to ensure they are correct at all times?				
17.7	Are there means to limit the range of input trip settings?				
17.8	Have adequate means been established for bypassing safety functions?				
17.9	When functions are bypassed, are they clearly indicated?				
17.10	Have documented procedures been established to control the application and removal of bypasses?				
17.11	Have documented procedures been established to ensure the safety of the plant during SIS maintenance?				
17.12	Are maintenance procedures sufficient in detail so as not to leave important interpretations or decisions to maintenance personnel?				
17.13	Are maintenance activities and schedules defined for all portions of the system?				
17.14	Are procedures periodically reviewed?				
17.15	Are procedures in place to prevent unauthorized tampering?				

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17.16	Are there means to verify that repair carried out in a time consistent with that assumed in the safety assessment?				
17.17	Are maintenance and operational procedure in place to minimize the introduction of potential common cause problems?				
17.18	Is the documentation consistent with the actual maintenance and operating procedures?				

10.19 Testing[17]

Item #	Item	Yes	No	N/A	Comments
18.1	Are documented provisions and procedures in place to allow proof testing of all safety functions, including field devices?				
18.2	Are test procedures sufficient in detail so as not to leave important interpretations or decisions to maintenance personnel?				
18.3	Has the basics for the periodic test interval been documented?				
18.4	Are the following items been tested?				
1	Impulse lines?				
2	Sensing devices?				
3	Logics, computations, and/or sequences?				
4	Trip points?				
5	Alarm functions?				
6	Speed of response?				
7	Final elements?				
8	Manual trips?				
9	Diagnostics?				
18.5	Is there a fault reporting system?				
18.6	Are procedures in place to compare actual performance against the predicted or required performance?				
18.7	Are there documented procedures for correcting any deficiencies found?				
18.8	Is calibration of test equipments verified?				
18.9	Are test records maintained?				
18.10	Do test records show:				
1	Date of inspection/test?				
2	Name of person conducting inspection/test?				
3	Identification of device being inspected/tested?				
4	Results of inspection/test?				
18.11	Are testing procedures in place to minimize the introduction of potential common cause problems?				

[17] Excerpted with permission from *"Safety Instrumented Systems: Design, Analysis, and Justification, 2nd Edition,"*, Copyright 2006 © by ISA

10.20 Management of Changes[18]

Item #	Item	Yes	No	N/A	Comments
19.1	Are there approval procedures which consider the safety implications of all modifications, such as:				
1	Technical basis for the changes?				
2	Impact on safety and health?				
3	Impact on operating/maintenance procedures?				
4	Time required?				
5	Effect on response time?				
19.2	Are there procedures that define the level of review/approval required depending upon the nature of the change?				
19.3	Has the proposed change initiated a return to the appropriate phase of the lifecycle?				
19.4	Has the project documentation (e.g. operating, test, maintenance procedures, etc.) been altered to reflect the change?				
19.5	Has he complete system been tested after changes have been introduced, and the results documented?				
19.6	Are there documented procedures to verify that changes have been satisfactorily completed?				
19.7	Have all affected departments been apprised of the changes?				
19.8	Is access to the hardware and software limited to authorized and competent personnel?				
19.9	Is access to the project documentation limited to authorized and competent personnel?				
19.10	Are project documents subject to appropriate revision control?				
19.11	Have the consequences of incorporating new version of software been considered?				

[18] Excerpted with permission from "*Safety Instrumented Systems: Design, Analysis, and Justification, 2nd Edition,"*, Copyright 2006 © by ISA

10.21 Decommissioning[19]

Item #	Item	Yes	No	N/A	Comments
20.1	Have management of change procedures been followed for decommissioning activities?				
20.2	Has the impact on adjacent operating units and facilities been evaluated?				
20.3	Are there procedures to maintain the safety of the process during decommissioning?				
20.4	Are there procedures that define the level of authorization required for decommissioning?				

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Reference

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Examples are provided as simple illustrations of the topics discussed and, as such, are not intended as a guide to manage plant safety. The readers should use and apply only the guidance provided in the standards pertaining to their applications.

3rd Edition: Printed March 2010

SHORT FORM

INTRINSICALLY SAFE, SIL CERTIFIED INSTRUMENTATION FOR HAZARDOUS AREAS

GM INTERNATIONAL
TECHNOLOGY FOR SAFETY

COMPANY PROFILE

Headquarter offices in Villasanta (Milan) ITALY

GLISENTE LANDRINI

is the President and Managing Director of G.M. International and of its worldwide subsidiaries.

The company was founded in 1993, but the core Management experience remarkably exceeds over 30 years of qualified activity in Intrinsic Safety and industrial electronics.
In 1970 Mr. Landrini founded Elcon Instruments, which has been acknowledged as an international leader in the design and manufacturing of Intrinsic Safety interface products and systems.

Mr. Landrini started G.M. International to provide state of the art SIL rated products and services to support Intrinsically Safe applications in Oil & Gas, Petrochemicals and Pharmaceutical Industries.

G.M. International's products have been successfully installed in plants all over the world, including Europe, Russia, North America, Middle and Far East and China.

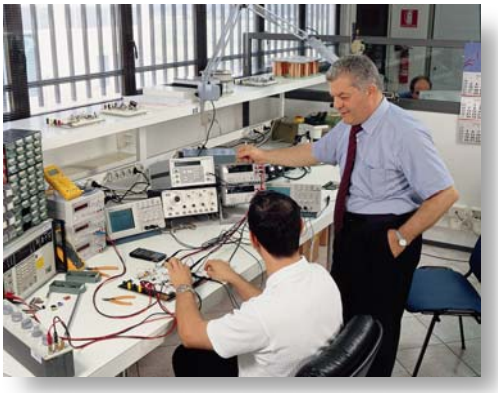
RESEARCH AND DEVELOPMENT

All products are designed, developed and manufactured internally.

G.M. International gives great value to R&D activities and strives to keep its production updated with the latest safety and quality standards. 20% of total employees are devoted to research and development of our products.

Tight relationships with customers worldwide combined with personal experience in the most various fields of application are key points for delivering products that meet requirements and needs of the market.

Continuous training and improvement of our staff's skills and capacities are important for enhancing the company's standard of efficiency.



COMPANY GOAL AND VALUES

Our **goals** are:

- To design and manufacturer Intrinsically Safe Instruments suitable to operate at Safety Integrity Level 3 (SIL 3) with Digital Control, Emergency Shutdowns and Fire & Gas Systems,
- To understand, manage and reduce risk,
- To prevent accidents,
- To stop unsafe operations,
- To minimize impact on environment and climate,
- To create a safe and healthy working environment,
- To improve HSE results,
- To succeed over time in a competitive environment.

For the achievement of such goals our **values** are:

- To identify opportunities and challenges,
- To be imaginative and stimulate new ideas,
- To be truthful and act with integrity,
- To work together and share experience,
- To strive for simplification and clarity, and focus on value-adding activities,
- To demonstrate social responsibility and contribute to sustainable development,
- To help others to succeed and contribute to a positive working environment.

MANUFACTURING FACILITIES

Quality in service is very important to achieve market penetration.

G.M. International considers service an integral part of Customer's requirements and satisfaction.
G.M. International's products satisfy customers' expectations and meet the specifications of international standards.

Safety, Performance, reliability and product documentation are the basic principles of product Quality.

G.M. International SMD products are manufactured internally, in our production facilities.
This allows high quality management and handling of relatively small batches, resulting in better delivery times.

Large quantity batches can also be handled for a production of up to 500 modules per day.

PCB Serigraphy

Assembly

Optical Inspection

Laser Engraving

Microprocessor Programming

Burn-In test

Conformal Coating

Testing

Final testing

APPROVALS AND CERTIFICATIONS

Intrinsically Safe products

G.M. International's products have been granted IS certificates from the most credited Notified bodies in the world. Certificates are available for ATEX (Europe), IECEX (International), Russian and Ukrainian standards, USA and Canada.
Certificates have been integrally scanned and are available for download from our website.

SIL Certifications according IEC 61508 and IEC 61511

G.M. International offers a wide range of products that have been proved to comply with the most severe quality and safety requirements.
IEC 61508 and IEC 61511 standards represent a milestone in the progress of industry in the achievement of supreme levels of safety through the entire instrumented system lifecycle.
The majority of our products are SIL certified; reports and analyses from TUV and EXIDA are available for download from our website.

Marine Type Approval

G.M. International offers Type Approval Certificates for its line of Intrinsically Safe Isolators D1000 Series and Power Supplies for use in Marine and Offshore applications.
Certificates have been released both by Korean Register of Shipping and Det Norske Veritas.

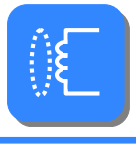
Company Quality System

G.M. International's Production Quality System is certified by Det Norske Veritas (Norway) to be compliant with ATEX 94/9/EC Directive and ISO 9001/2000.
This means our production facilities are periodically re-assessed throughout the whole manufacturing process, to ensure that the highest quality standards are met.

All certificates are freely downloadable from www.gmintsrl.com

	Field device	Model	Hazardous Area	Safe Area	Channels per unit	Supply	SIL level
ANALOG IN		**D1010S**	4-20 mA 0-20 mA 2/3-Wires Tx Smart compatible	4-20 mA 0-20 mA (source or sink) or 1-5 V 0-5 V	1	20-30 Vdc	SIL 3
		**D1010D**			2		SIL 3
		**D1010D**		Two duplicated outputs	2		SIL 3
		**D1010S-046**	4-20 mA 0-20 mA 2/3-Wires Tx Smart compatible Certified with lower safety parameters	4-20 mA 0-20 mA (source or sink) or 1-5 V 0-5 V	1	20-30 Vdc	-
		**D1010D-046**			2		-
		**D1012Q**	4-20 mA 2-Wires Tx	4-20 mA (source)	4	20-30 Vdc	-
		**D1014S**	4-20 mA 2-Wires Tx Hart compatible	4-20 mA (source or sink) or 1-5 V	1	10-30 Vdc	SIL 3
		**D1014D**			2		SIL 3
ANALOG OUT		**D1020S**	4-20 mA 0-20 mA Analog Signal to I/P Converters, Electrovalves, Actuators and Displays Smart compatible	4-20 mA 0-20 mA Bus powered signal from DCS, PLC or other control devices.	1	20-30 Vdc	SIL 2
		**D1020D**			2		SIL 2
		**D1021S**		plus line and load fault detection	1		SIL 2
FIRE & GAS DETECTOR		**D1022S**	1 to 40 mA Fire/Smoke Detector or Loop powered AI/AO isolator	1 to 40 mA to DCS, PLC or other control devices	1	Loop powered	-
		**D1022D**			2		-

D1000 - SELECTION TABLE

	Field device	Model	Hazardous Area	Safe Area	Channels per unit	Supply	SIL level
DIGITAL IN		**D1030S**	Voltage free Contact, Proximity Switch Line fault detection	1 SPDT (relay contact) +1 SPDT (alarm or duplicator) + LED (fault status)	1	20-30 Vdc	-
		**D1030D**		2 SPDT (relay contact) + LED (fault status)	2		-
		**D1130S**	Voltage free Contact, Proximity Switch Line fault detection	1 SPDT (relay contact) +1 SPDT (alarm or duplicator) + LED (fault status)	1	85-264 Vac	-
		**D1130D**		2 SPDT (relay contact) + LED (fault status)	2	100-350 Vdc	-
		**D1031D**	Voltage free Contact, Proximity Switch Line fault detection	2 Open Collectors +2 OC (alarm or duplicator) + LED (fault status)	2	10-30 Vdc	-
		**D1031Q**		4 Open Collectors + LED (fault status)	4		-
		**D1032D**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	2 SPST (relay contact) +2 SPST (alarm or duplicator) + LED (fault status)	2	20-30 Vdc	SIL 2
		**D1032Q**		4 SPST (relay contact) + LED (fault status)	4		SIL 2
		**D1033D**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	2 Open Collectors +2 OC (alarm or duplicator) + LED (fault status)	2	20-30 Vdc	SIL 2
		**D1033Q**		4 Open Collectors + LED (fault status)	4		SIL 2
		**D1034S**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	Transparent repeater of input status 0 to 8 mA range	1	10-30 Vdc	SIL 3
		**D1034D**			2		SIL 3
		**D1035S**	0-50 KHz Magnetic Pickup or Proximity Switch	Voltage free SPST optocoupled OC transistor	1	10-30 Vdc	-

	Field device	Model	Hazardous Area	Safe Area	Channels per unit	Supply	SIL level
DIGITAL OUT		**D1040Q**	Electrovalve, Audible Alarm or other devices	Voltage free Contact, Logic Level, Loop powered 24 Vdc from DCS, PLC or other control devices	4	21.5-30 Vdc	SIL 2 Bus powered or SIL 3 Loop powered
		**D1041Q**	LED		4		
		**D1042Q**	Electrovalve, Audible Alarm or other devices		4		
		**D1043Q**	Electrovalve, Audible Alarm or other devices		4		
		**D1044S**	1 SPDT (relay contact)	Voltage free Contact, Logic Level, from DCS, PLC or other control devices Bus powered	1	20-30 Vdc	-
		**D1044D**	2 SPDT (relay contact)		2		SIL 2
		**D1045Y**	Electrovalve, Audible Alarm or other devices	Voltage free Contact, Logic Level, Loop powered 24 Vdc from DCS, PLC or other control devices	2 alternate	21.5-30 Vdc	-
		**D1046Y**	Electrovalve, Audible Alarm or other devices		2 alternate		-
		**D1048S**	NE solenoid valve, other control devices. Line/Load fault detection.	Loop Powered control signal from safety PLC, DCS	1	20-30 Vdc	SIL 3
		**D1049S**	NE solenoid valve, other control devices. Line/Load fault detection.	Voltage free Contact, Logic Level, from DCS, PLC or other control devices. Bus powered	1	20-30 Vdc	SIL 3

D1000 - SELECTION TABLE

Field device	Model	Hazardous Area	Safe Area	Channels per unit	Supply	SIL level
SIGNAL CONVERTERS	D1052S	4-20 mA, 0-20 mA 1-5 V, 0-5 V, 2-10 V, 0-10 V from 3/4-Wires powered Tx or other instrument	4-20 mA, 0-20 mA (source) or 1-5 V, 0-5 V, 2-10 V, 0-10 V	1	10-30 Vdc	-
	D1052D			2		-
SIGNAL CONVERTER + TRIP AMPLIFIERS	D1053S	4-20 mA, 0-20 mA 1-5 V, 0-5 V, 2-10 V, 0-10 V	4-20 mA, 0-20 mA (source) or 1-5 V, 0-5 V, 2-10 V, 0-10 V 2 Independent set points via 2 SPST Relays	1	20-30 Vdc	SIL 2
	D1054S	4-20 mA, 0-20 mA 2/3-Wires Tx, Smart compatible		1	10-30 Vdc	SIL 2
	D1073S	Universal TC, 3/4-Wires RTD, Potentiometer, mV		1	20-30 Vdc	SIL 2
	D1060S	0-50 KHz Magnetic Pickup or Proximity Switch	mA (source) or V Out, Pulse repeater Output	1	10-30 Vdc	-
SERIAL CONVERT.	D1061S	RS-485, RS-422 up to 1.5 Mbit/s	RS-485, RS-422, RS-232	1	20-30 Vdc	-
VIBRATION INTERFACE	D1062S	Vibration Transducers, Accelerometers, 2/3-Wires sensors	Transparent input repeater	1	20-30 Vdc	SIL 2
LOAD CELLS ISOLATORS CONVERTERS	D1063S	Up to 4, 350 Ω, 6-Wires Load Cells in parallel.	Transparent input repeater.	1	20-30 Vdc	-
	D1064S		mA (source or sink) and V Output and MODBUS RTU	1		-
DIGITAL IN 3-WIRES SENSORS	D1080D	3-Wires sensors, Electro-optic, photo-cells and other devices	2 SPDT (relay contact)	2	20-30 Vdc	-
	D1180D			2	85-264 Vac 100-350 Vdc	-
	D1081D		2 Voltage free SPST optocoupled OC transistors	2	14-30 Vdc	-

Configurable via PPC1090 or PPC1092 via Software SWC1090

D1000 - SELECTION TABLE

	Field device	Model	Hazardous Area	Safe Area	Channels per unit	Supply	SIL level
TEMPERATURE CONVERTERS		**D1072S**	Universal TC, 3/4-Wires RTD, Potentiometer, mV	4-20 mA, 0-20 mA (source) or 1-5 V, 0-5 V, 2-10 V, 0-10 V	1	10-30 Vdc	SIL 2
		**D1072D**			2		-
		**D1072D**		Two duplicated outputs	2		-
		**D1010S-054**	-5 to +55 mV Thermocouple.	4-20 mA (source) Fast response time for temperature measurements in critical applications (i.e: gas turbines)	1	20-30 Vdc	SIL 3
		**D1010S-056**	-5 to +35 mV Thermocouple.		1		SIL 3
		**D1010S-057**	-5 to +10 mV Thermocouple.		1		SIL 3
SHUNT RESISTOR		**D1090Q**	Separately powered 4-20 mA, 0-20 mA	10 to 50 mV or 0 to 50 mV to D2010M, D2011M	4	-	-
		**D1094Q**	Separately powered 0-5 V, 0-10 V	0 to 20 mV or 0 to 40 mV to D2010M, D2011M	4	-	-
SAFETY RELAY OUTPUTS		**D1092S**	1 SPST for NE Load 1 SPST for ND Load	Loop Powered control signal from safety PLC, DCS to drive Ex 'd' valves or other devices	1	-	SIL 3
		**D1092D**	2 SPST for NE Load 2 SPST for ND Load		2		SIL 3
		**D1092S-069**	1 SPST NO Contact plus 1 SPST NC Contact		1		SIL 3
		**D1092D-069**	2 SPST NO Contacts plus 2 SPST NC Contacts		2		SIL 3
		**D1093S**	1 SPST for NE Load 1 SPST for ND Load Line/Load monitoring		1	20-30 Vdc	SIL 3

Configurable via PPC1090 or PPC1092 via Software SWC1090

D1000 - SELECTION TABLE

	Field device	Model	Hazardous Area	Safe Area	Channels per unit	Supply	SIL level
SURGE ARRESTORS		**D1097S**	2/3-Wires devices	30 V, 10 KA surge arrestor	1	-	-
		**D1097D**	Two 2/3-Wires devices or One 4-Wires device		2	-	-
POWER SUPPLIES		**PSD1000**	Installation in Safe Area or Zone 2 / Div. 2	24 V, 500 mA to power D1000 Series Modules	1	95-264 Vac 115-350 Vdc	-
		**PSD1001**	15 V, 20 mA 3-Wires Tx or other devices	24 Vdc	4	21.5-30 Vdc	SIL 2 Bus powered or SIL 3 Loop powered
		**PSD1001C**	13.5 V, 100 mA 3-Wires Tx or other devices	24 Vdc	1		
		**PSU1003**	5 V, 160 mA	PCB Mounting	1	via PSD1001C	-
		**PSD1004**		DIN-Rail mounting	1		-
		**PSD1206**	Installation in Safe Area or Zone 2 / Div. 2	24 V, 6 A	1	95-264 Vac	SIL 2 or SIL 3 redundant configuration
		**PSD1210**		24 V, 10 A	1	115-350 Vdc	
CONFIGURATION ACCESSORIES		**PPC1090**	Pocket Portable Configurator for D1000 Series Configurable Units. Supplied directly by the isolator, can be used in the field.				
		**PPC1092**	Serial adapter for connecting D1000 Series units to PC. Includes RS-232 Null-Modem cable and USB to Serial Adapter. Requires SWC1090 software to be installed on computer.				
		**SWC1090**	Configuration Software available for free on www.gmintsrl.com website. Modify module's parameters in an easy user-interface. Save to file, print report sheets and do live input variable monitoring.				

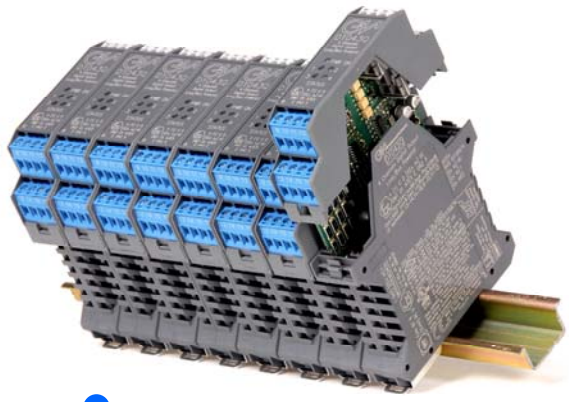
SERIES D1000 INTRINSICALLY SAFE ISOLATORS

Intrinsically Safe Galvanic Isolators SERIES D1000, for DIN Rail Mounting, provides the most simple and cost effective means of implementing Intrinsic Safety into Hazardous Area applications.

- Input and Output short circuit proof.
- High Performance and Reliability.
- Field Programmability.
- Three port isolation: Input/Output/Supply.
- High density (1, 2, 4 channels per unit).
- Operating Temperature limits: -20 to +60 Celsius.
- CE - EMC: according to 94/9/EC Atex Directive and to 89/336/CEE EMC Directive.
- EMC compatibility to EN61000-6-2 and EN61000-6-4.
- Worldwide Approvals and Certifications.
- Modules can be used with Custom Boards with suitable adapter cables for connection to DCS.

PLUG-IN TYPE TERMINAL BLOCKS

Standard on all models;
Gray color towards Safe Area and
Blue towards Hazardous Area.



PACKAGING DETAILS

Each module has **Aeration slots**; **Laser engraving** on both sides detailing schematic diagram, connections, tables and instructions; **LED**s for status and fault indication.

D1010

SIL 3 REPEATER POWER SUPPLY (AI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 - 2 Channels
- SMART Transmitters
- Active - Passive Inputs
- Sink - Source Output
- Output Signal 0/4 - 20 mA, linear 0 to 22 mA
- D1010D can be used for Signal Duplication
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1014

SIL 3 REPEATER POWER SUPPLY (AI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 - 2 Channels HART 2-wire passive TX
- 1 - 2 Sink - Source Outputs 4 - 20 mA, linear 2 to 22 mA
- Two fully independent SIL 3 channels with no common parts.
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1000

D1012

4 CHANNELS REPEATER POWER SUPPLY (AI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 4 Channels 2-wire passive transmitters
- 4 Source Outputs 4-20 mA, linear 1 to 21 mA
- 4 inputs / 4 Outputs or 2 Inputs / 2 Double Outputs (2 duplicators) or 1 Input / 4 Outputs (1 quadruplicator)
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1021

SIL 2 POWERED ISOLATING DRIVER FOR I/P, VALVE ACTUATORS (AO)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 Channel from SMART-HART valves
- Output Signal 4 - 20 mA, linear from 0 to 22 mA
- Local and Remote independent signaling for line Open and Short / Open Circuit
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

FULLY PLUG-IN

Plug-In Terminal Blocks avoid wiring mistakes and simplify module replacement. Plug-In Modules simplify and speed-up maintenance operations.

PACKAGING DETAILS

Front Panel and **Printed Circuit Board** are removable by applying pressure with a tool, without disconnecting power

D1020

SIL 2 POWERED ISOLATING DRIVER FOR I/P, VALVE ACTUATORS (AO)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 - 2 Channels from SMART-HART valves
- Output Signal 4 - 20 mA, linear from 0 to 22 mA
- Local independent signaling for line Open
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1022

LOOP POWERED FIRE/SMOKE DETECTOR INTERFACE (AO)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1-2 Channels
- Input Signal from Safe Area 1-40 mA (loop powered)
- Output Signal to Hazardous Area 1-40 mA
- Operating voltage 6-30 V (loop powered)
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1030

SWITCH/PROXIMITY DETECTOR REPEATER (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 - 2 Channels Relay Output SPDT
- Line fault detection
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1033

SIL 2 SWITCH/PROXIMITY DETECTOR REPEATER (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 2 - 4 Channels O.C. Transistor Output
- Line fault detection
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

RACK MOUNTING

19" rack mounting option D1000R

D1032Q SIL 2 QUAD CHANNEL

Switch / Proximity Detector Repeater

D1031

SWITCH/PROXIMITY DETECTOR REPEATER (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 2 - 4 Channels Transistor Outputs
- Line fault detection
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1034

SIL 3 SWITCH/PROXIMITY DETECTOR INTERFACE (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 - 2 Channels Input Impedance Repeater; transparent line fault detection
- Two fully independent SIL 3 channels with no common parts.
- Inputs from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1032

SIL 2 SWITCH/PROXIMITY DETECTOR REPEATER (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 2 - 4 Channels Relay Output SPST
- Input from Zone 0 / Div. 1
- Line fault detection
- Zone 2 / Div. 2 installation

D1035

FREQUENCY — PULSE ISOLATING REPEATER (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- Input Frequency 0 to 50 KHz
- Input from Proximity, Magnetic Pick-Up
- 1 channel Transistor Output
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1130

SWITCH/PROXIMITY DETECTOR REPEATER (DI)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- 1 - 2 Channels Relay Output SPDT
- Line fault detection
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation
- Power Supply 90 - 250 Vac

T3010S

4.5 digit LOOP POWERED INDICATOR

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- Large LCD Display, 20 mm high
- Less than 1 V drop, Supply 4 - 20 mA
- IP65 Enclosure with 2 separated chambers.
- Wall, Pipe-Post, or Panel mounting.
- Zone 0 IIC T5 / T6 or Div. 1 Installation
- Field configurable

D1130 AC DIGITAL INPUT

Switch / Proximity Detector Repeater

T3010S I.S. LOOP INDICATOR

2" pipe mounted complete unit with covers.

SAFETY INTEGRITY LEVELS

G.M. International offers a wide range of products that have been proved to comply with the most severe quality and safety requirements. IEC 61508 and IEC 61511 standards represent a milestone in the progress of industry in the achievement of supreme levels of safety through the entire instrumented system lifecycle.
The majority of our products are **SIL certified**; reports and analyses from TUV and EXIDA are available for download from our website.

SIL Safety Integrity Level	**PFDavg** Average probability of failure on demand per year (low demand)	**RRF** Risk Reduction Factor	**PFDavg** Average probability of failure on demand per hour (high demand)
SIL 4	≥ 10^{-5} and < 10^{-4}	100000 to 10000	≥ 10^{-9} and < 10^{-8}
SIL 3	≥ 10^{-4} and < 10^{-3}	10000 to 1000	≥ 10^{-8} and < 10^{-7}
SIL 2	≥ 10^{-3} and < 10^{-2}	1000 to 100	≥ 10^{-7} and < 10^{-6}
SIL 1	≥ 10^{-2} and < 10^{-1}	100 to 10	≥ 10^{-6} and < 10^{-5}

- Table for low and high demand modes of operation according **IEC 61508** and **IEC 61511**

DIGITAL OUTPUT MODELS

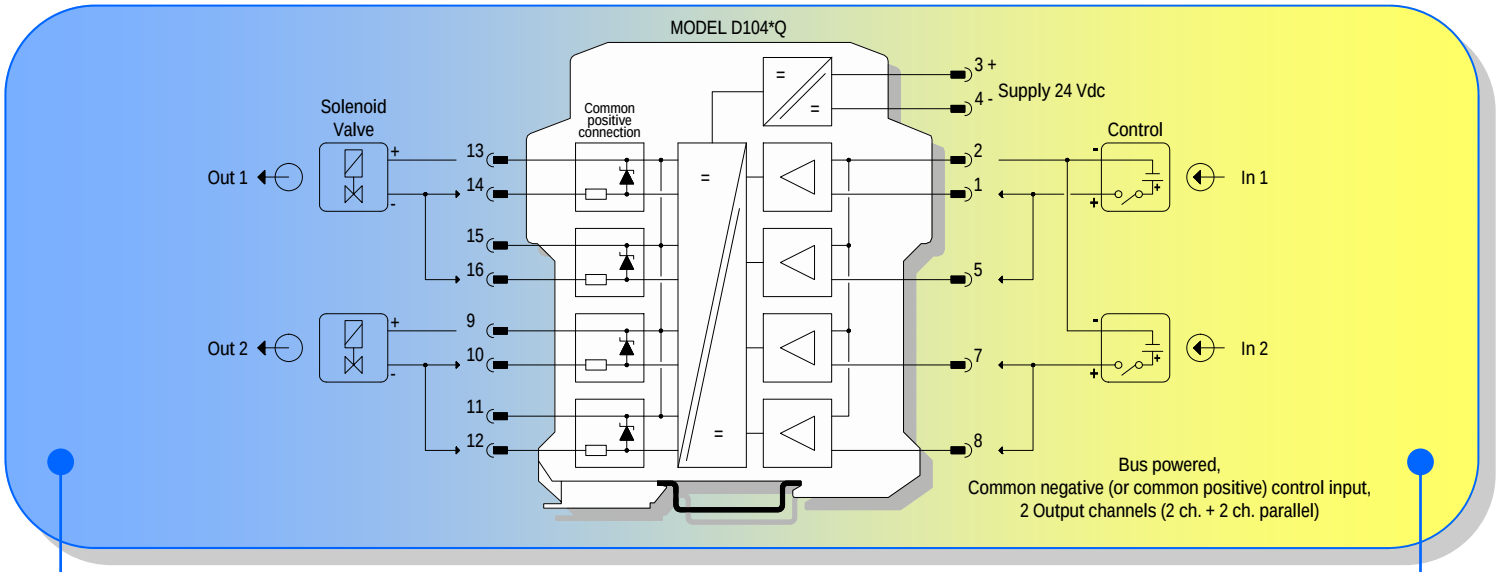
SIL 2 — SIL 3 for ND-NE LOADS
D1040Q, D1041Q, D1042Q, D1043Q, D1044D, D1045Y, D1046Y, D1047S, D1048S, D1049S SOLENOID DRIVERS (DO)

- II (1) G [Ex ia] IIC, II (1) D [Ex iaD], I (M2) [Ex ia] I, II 3G Ex nA IIC T4
- PLC, DCS, F&G, ESD applications with line and valve detection for NE or ND loads
- Loop/Bus Powered
- Output to Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1044

New SIL 2 DIGITAL RELAY OUTPUT

- Output to Zone 0 (Zone 20), Division 1, installation in Zone 2, Division 2.
- Voltage, contact, logic level input.
- Two SPDT Relay Output Signals.
- Three port isolation.
- Simplified installation using standard DIN Rail and plug-in terminal blocks.



Output channels can be **paralleled** if more power is required; 2 or 3 channels in parallel (depending on the model) are still suitable for Gas Group II C. Four basic models meet a large number of applications: it is possible to obtain **16 different combinations** of safety parameters and driving currents.

D1040 / D1041

SIL 3 - SIL 2 DIGITAL OUTPUT LOOP / BUS POWERED (DO)

- Output to Zone 0 (Zone 20), Division 1, installation in Zone 2, Division 2.
- Voltage input, contact, logic level, common positive or common negative, loop powered or bus powered.
- Flexible modular multiple output capability.
- Output short circuit proof and current limited.
- Three port isolation, Input/Output/Supply.
- D1041Q suitable for LED driving
- SIL 2 when Bus powered
- SIL 3 when Loop powered

D1042 / D1043

SIL 3 - SIL 2 DIGITAL OUTPUT LOOP / BUS POWERED (DO)

- Output to Zone 0 (Zone 20), Division 1, installation in Zone 2, Division 2.
- Voltage input, contact, logic level, common positive or common negative, loop powered or bus powered.
- Flexible modular multiple output capability.
- Output short circuit proof and current limited.
- Three port isolation, Input/Output/Supply.
- SIL 2 when Bus powered
- SIL 3 when Loop powered

D1045 / D1046

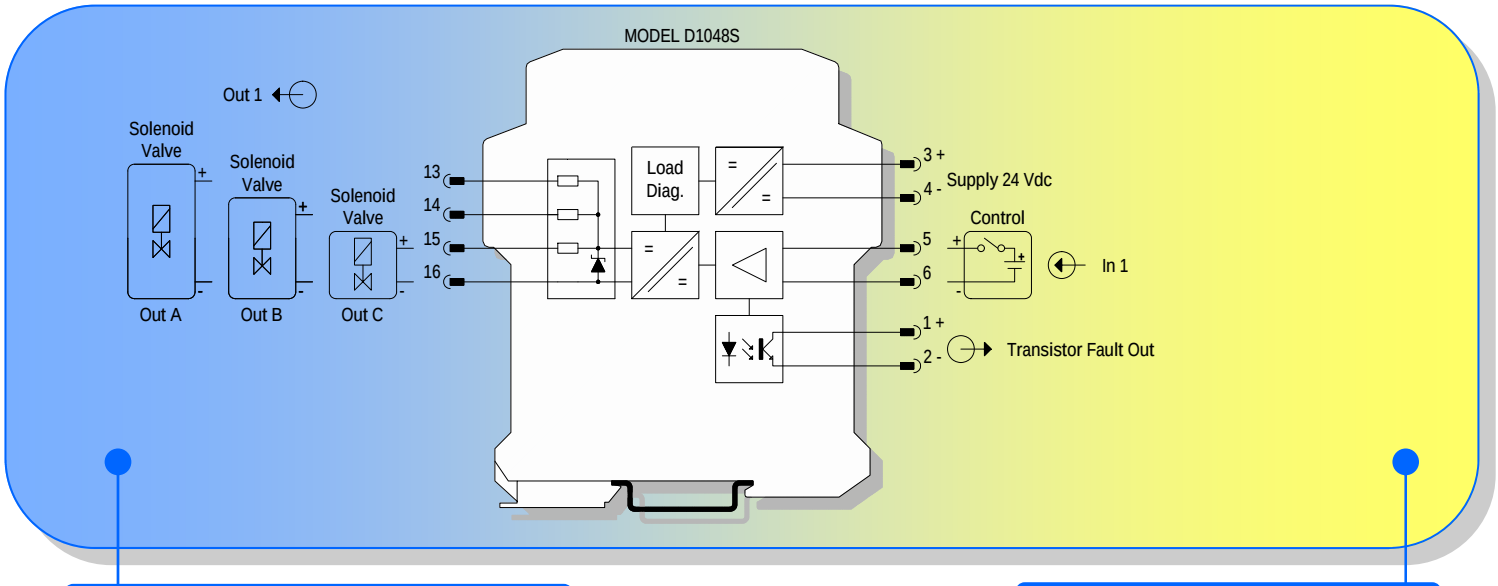
New **DIGITAL OUTPUT (DO) LOOP / BUS POWERED**

- Output to Zone 0 (Zone 20), Division 1, installation in Zone 2, Division 2.
- Voltage input with isolated commands, loop or bus powered.
- Suitable for driving 1 or 2 positions directional solenoid valves.
- Output short circuit proof and current limited.
- Three port isolation, Input/Output/Supply.

D1048

New **SIL 3 DIGITAL OUTPUT DRIVER LOOP POWERED FOR NE LOADS**

- SIL 3 for 10 years
- ESD, DCS, PLC application
- Output to Zone 0, Division 1, installation in Zone 2, Division 2.
- Two independent driving circuits.
- Loop powered for NE loads.
- Short and open circuit load diagnostic monitoring with LED and transistor output.
- Three port isolation, Input/Output/Supply.



HAZARDOUS AREA ZONE 0 / DIV. 1

SAFE AREA / ZONE 2, DIV. 2

Three basic output circuits are available, with different safety parameters, to interface the majority of solenoids on the market. The selection among the **three output characteristics** is obtained by connecting the final element to a different terminal block.

D1049

New **SIL 3 DIGITAL OUTPUT DRIVER BUS POWERED FOR NE LOADS**

- SIL 3 for 10 years.
- ESD, DCS, PLC application.
- Output to Zone 0 (Zone 20), Div. 1, installation in Zone 2, Division 2.
- Two independent driving circuits.
- Bus powered for NE loads.
- Short and open circuit load diagnostic monitoring with LED and transistor output.
- Output short circuit proof and current limited.

D1052

ANALOG INPUT OUTPUT SIGNAL CONDITIONER (SC)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- 1 - 2 Channels 0/4 - 20 mA, 0/1 - 5 V, 0/2 - 10 V, Input / Output
- Fully programmable
- D1052D can be used as Duplicator, Adder, Subtractor, High-Low signal Selector.
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1054

POWER SUPPLY REPEATER + DOUBLE TRIP AMPLIFIER (SC-TA)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- SMART Active - Passive Transmitters
- Input 0 /4 - 20 mA
- Output 0/4 - 20 mA, 0/1 - 5 V, 0/2 - 10 V
- 2 Independent Trip Amplifiers, SPST Relay
- Fully programmable (PPC1090 or PPC1092)
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

FACTORY ACCEPTANCE TESTS

G.M. International welcomes Factory Acceptance Tests on standard products or on completely assembled projects. Our facilities in Villasanta (Italy) are fully capable of handling projects of any size.

CABINET INSTALLATION

Instructions and suggestions on the use of our units in cabinets can be found on document ISM0075.

D1053

SIL 2 ANALOG SIGNAL CONVERTER + DOUBLE TRIP AMPLIFIER (SC-TA)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- 1 Channel 0/4 - 20 mA, 0/1 - 5 V, 0/2 - 10 V, Input / Output
- 2 Independent Trip Amplifiers, SPST Relay
- Fully programmable (PPC1090 or PPC1092)
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1060

FREQUENCY - PULSE (SC) ISOLATING REPEATER/CONVERTER

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- Input Frequency 0 to 50 KHz
- Input from Proximity, Magnetic Pick-Up
- One 0/4 - 20 mA, 0/1 - 5 V, 0/2 - 10 V Source Out
- 1 channel Transistor Output for Pulse repeater or Trip amplifier
- 1 channel Transistor Output for Trip Amplifier
- Fully programmable (PPC1090 or PPC1092)
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1000

D1061

RS-485 FIELDBUS ISOLATING REPEATER (SLC)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- RS-485/422 from Hazardous Area
- RS-485/422 / 232 to Safe Area
- Transmission Speed up to 1.5 Mbit/s
- Up to 31 Inputs / Outputs
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

RS-485
RS-422

D1064

New

LOAD CELL / STRAIN GAUGE BRIDGE ISOLATING CONVERTER

- II (1) G D [EEx ia] IIC; I (M2) [EEx ia]
- Up to four 350 Ohm load cells in parallel
- 0/4-20 mA, 0/1-5 V, 0/2-10 V Output
- RS-485 Modbus Output
- Software programmable
- Field automatic calibration
- Zone 2 / Div. 2 installation

HIGH DENSITY

Offshore and maritime applications, more than others, require that instrumentation occupies the least amount of space. D1000 Series modules can be packed up together for configurations of up to 180 channels per meter in case of Digital Output units and offer a great simplification in cabling and cost reduction.

D1062

New

SIL 2 VIBRATION TRANSDUCER INTERFACE (TC)

- II (1) G D [EEx ia] IIC or I (M2)
- - 0.5 to - 20 V Input, Output signal
- Interfaces all Bentley-Nevada, BK, Vibrometer sensors
- DC to 10 KHz within 0,1 dB
- 10 KHz to 20 KHz within 3 dB
- Zone 2 / Div. 2 Installation

D1063

STRAIN GAUGE BRIDGE SUPPLY AND ISOLATING REPEATER

- II (1) G D [EEx ia] IIC; I (M2) [EEx ia]
- Up to four 350 Ohm load cells in parallel
- 4 wire Supply 5 - 10 V
- mV Isolated Output
- Accuracy 0.003 %
- Eliminates the need of 6 channel Zener Barriers
- No need for expensive safety ground connections
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1000

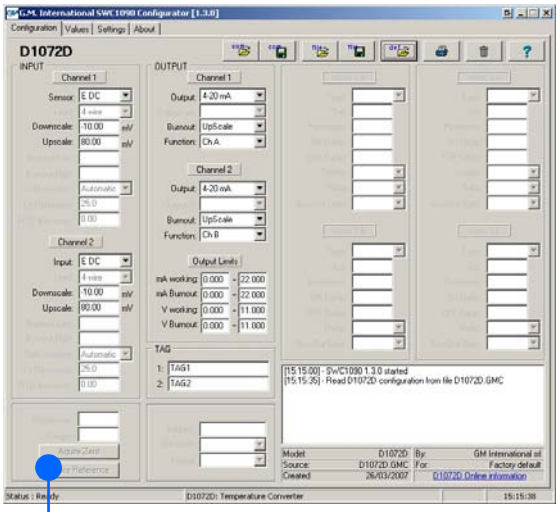
D1000 CONFIGURABILITY

The **SWC1090 software** is designed to provide a PC user interface to configure programmable D1000 modules.

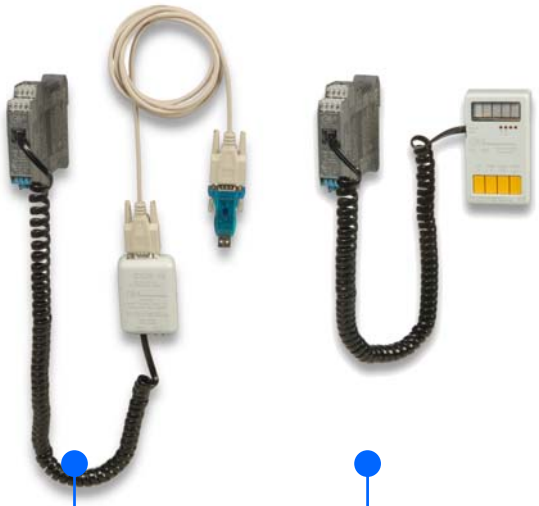
- Read and write configuration parameters to the units (via COM port);
- Store and restore data to and from local hard drive for backup or archive;
- Load factory default configurations;
- Monitor Input values via USB/COM port;
- Print a report sheet containing configuration parameters and additional information (see example on the right).
- SWC1090 software is downloadable free of charge.

D1000 Models can be configured via **SWC1090** PC Software by using the **PPC1092** adapter.
All parameters can be easily accessed, modified and stored as a backup on file for further use.

PPC1090 is a small and handy Pocket Portable Configurator suitable to program configuration parameters of D1000 series modules like.
The Configurator is powered by the unit and can be plugged in without disconnecting the module.



SWC1090 SOFTWARE



PPC1092

PPC1090

D1072

SIL 2 TEMPERATURE CONVERTER (TC)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- 1 - 2 Channels, 2-3-4 wire RTD, Pt100, Pt50,
- Ni100, Cu100, Cu53, Cu50, Cu46, TC Type A1, A2, A3, B, E, J, K, L, Lr, N, R, S, T, U
- 1 - 2 Outputs, 0/4 - 20 mA, 0/1 - 5 V, 0/2 - 10V
- Fully programmable (PPC1090 or PPC1092)
- D1072D can be used as Duplicator, Adder, Subtractor, High-Low signal Selector.
- Input from Zone 0 / Div. 1
- Installation in Zone 2 / Div. 2

D1073

SIL 2 TEMPERATURE CONVERTER + DOUBLE TRIP AMPLIFIER (TC-TA)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- 1 Channel, 2-3-4 wire RTD, Pt100, Pt50, Ni100, Cu100, Cu53, Cu50, Cu46, TC Type A1, A2, A3, B, E, J, K, L, Lr, N, R, S, T, U
- 1 Output, 0/4 - 20 mA, 0/1 - 5 V, 0/2 - 10V
- 2 Independent Trip Amplifiers, SPST Relay
- Fully programmable (PPC1090 or PPC1092)
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

D1000

SAFETY RELAYS

SIL 3 Safety Relays are used to drive high power solenoid valves for use in critical applications such as **ESD** (Emergency Shutdown) and **F&G** (Fire and Gas) systems.

Unlike the majority of similar products on the market, G.M. International D1000 safety relays offer the possibility to interface both NE (ESD) and ND (F&G) loads, covering almost 100% of possible applications.

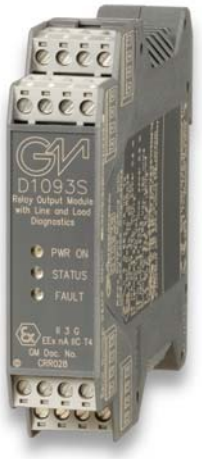
Moreover, model D1093S is the only safety relay available with inbuilt **diagnostic circuit** capable of detecting line and load breakages.

D1092-069

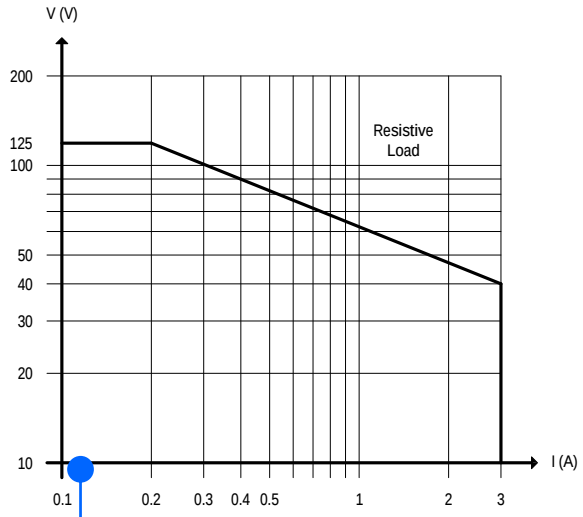
New SIL 3 RELAY OUTPUT MODULE (DO)

- 1 SPST NO contact and 1 SPST NC contact for NE Loads
- 1 or 2 fully independent channels
- SIL 3 for T proof = 20 yrs
- Zone 2 / Div. 2 installation
- TUV Certification for SIL
- High Reliability

D1092D



D1093S



DC Load Breaking capacity

D1092

New SIL 3 RELAY OUTPUT MODULE (DO)

- 1 or 2 fully Independent Channels
- 1 or 2 SPST for NE Loads and 1 or 2 SPST for ND Loads
- SIL 3 for T proof = 20 yrs
- Zone 2 / Div. 2 installation
- TUV Certification for SIL.
- High Reliability, SMD components.
- High Density, two channels per unit.
- Simplified installation using standard DIN Rail and plug-in terminal blocks.

D1093

New SIL 3 RELAY OUTPUT MODULE (DO)

- 1 SPST for NE Loads and 1 SPST for ND Loads
- SIL 3 for T proof = 10 yrs
- Line and Load open diagnostic in NE and ND conditions (requires 24 Vdc auxiliary supply)
- Zone 2 / Div. 2 installation
- TUV Certification for SIL.
- High Reliability, SMD components.
- High Density, two channels per unit.
- Simplified installation using standard DIN Rail and plug-in terminal blocks.

Relay

PSD1000

UNIVERSAL INPUT POWER SUPPLY FOR D1000 SERIES ISOLATORS (PS)

- Supply 90 - 265 Vac
- Output 24 Vdc, 500 mA
- 2 Units can be paralleled for Redundancy or additional power
- Remote indication for Power Failure
- Installation next to D1000 Series Modules, without Safety distance of 50 mm, because Supply and Outputs Terminal Blocks are on the same side
- Zone 2 / Div. 2 installation

PSD1001C

SIL 2 1 CHANNEL INTRINSICALLY SAFE POWER SUPPLY (PS)

- II (1) G D [EEx ia] IIB; I M2 [EEx ia]
- 1 Output 13.5 V - 100 mA or 10 V - 150 mA
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation

PSU1003 PCB MODULE

PSD1001 4 CHANNEL P.S.

PSD1001

SIL 2 4 CHANNELS INTRINSICALLY SAFE POWER SUPPLY (PS)

- II (1) G D [EEx ia] IIC; I M2 [EEx ia]
- 4 Independent Outputs 15 V, 20 mA
- Input from Zone 0 / Div. 1
- Zone 2 / Div. 2 installation
- Flexible modular multiple output capability.
- Output short circuit proof and current limited.
- High Reliability, SMD components.
- High Density, four channels per unit.
- Simplified installation using standard DIN Rail and plug-in terminal blocks.

PSD1004

INTRINSICALLY SAFE POWER SUPPLY (PS)

- II 1 G EEx ia IIB T4
- Output 5 Vdc, 160 mA
- Supplied by PSD1001C
- Zone 0 Installation
- 500 V input/output isolation

PSU1003

1 CHANNEL INTRINSICALLY SAFE POWER SUPPLY PCB MODULE (PS)

- II 1 G EEx ia IIB T4
- Output 5 Vdc, 160 mA, supplied by PSD1001C
- Zone 0 Installation
- Module for PCB Mounting
- 500 V input/output isolation
- Width 55 mm, Depth 30 mm, Height 15 mm

PSD1210 (PSD1206)

SIL 2 - SIL 3 NON/INCENDIVE POWER SUPPLY (PS)

- II 3 G EEx nA IIC T4
- Output: 24 V, 10 A (6 A), 250 W (150 W)
- Line and Load Regulation 0.2 %
- Supply 95 to 264 Vac
- Power Factor correction 0.95

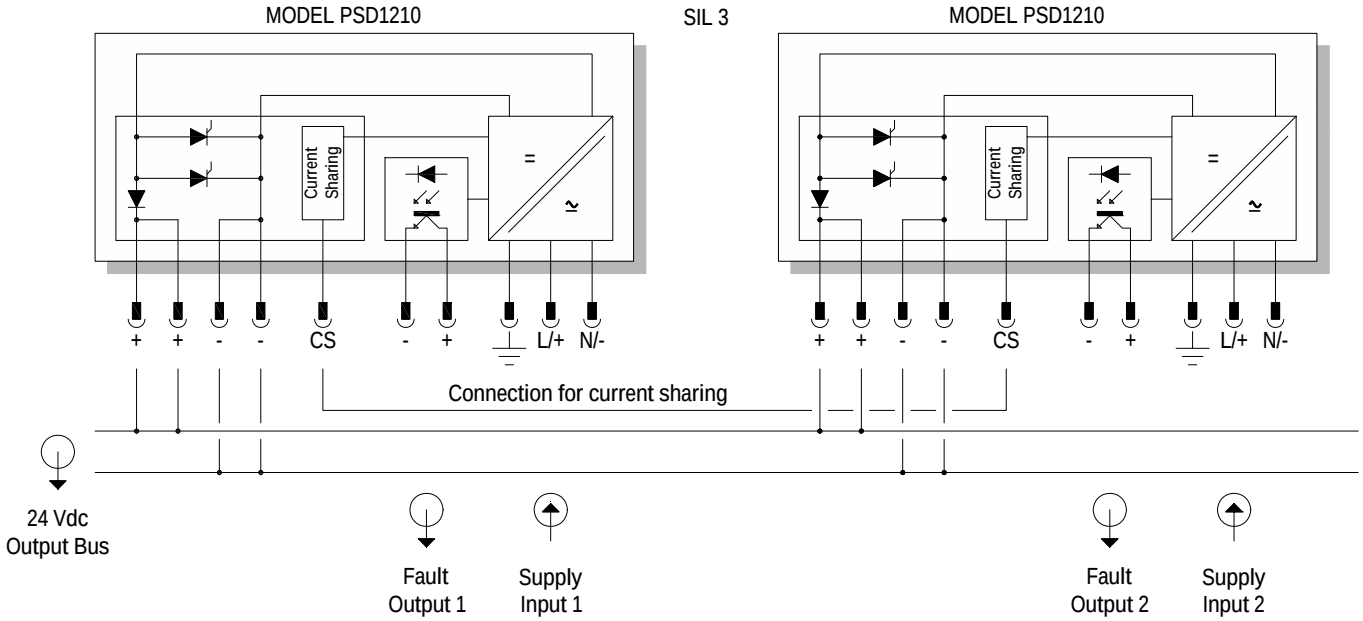
- Parallel operation for Redundancy with load sharing capability
- Redundant crowbars for overvoltage protection
- SPST O.C. transistor for remote alarm
- Zone 2 / Div. 2 installation
- External connections for T-proof testing

PSD1210 FRONT VIEW

PSD1210 REAR VIEW

FUNCTION DIAGRAM

PSD1200 units can be paralleled for redundancy operation to increase availability upgrading the system from SIL 2 to SIL 3 or to increase the output power. Internal power diodes for parallel operation prevent fault propagation in parallel connected supply systems and **load sharing** distributes current load equally to each power supply to increase reliability and reduce internal power dissipation.

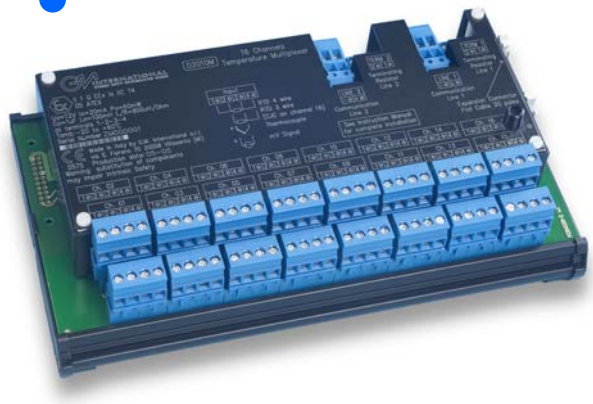


SERIES D2000M MULTIPLEXER

SYSTEM FEATURES

- High density, up to 256 Analog Inputs (TC, RTD, mV) and up to 128 digital Inputs (contact / proximity) in the same system (expandable up to 7936 inputs)
- Robust Isolation (± 200 V channel to channel), provides high immunity against interference and ground loops
- Intrinsically safe for installation in Zone 0, 1, 2
- Field units can be placed up to 5 km from Gateway
- High accuracy 18 bit A/D converter
- Redundant communication lines
- Programmable via PC (RS232) and Modbus (RS485)
- Repeats input contact via Relays or Transistor Output
- Reduces field wiring and installation costs
- Eliminates the need of PLC - DCS I/O cards.
- Field unit operating temperature: - 40 to + 60 Celsius.
- AISI 316 stainless steel enclosures are available for field units (Series GM2300).
- Gateway D2050M can be installed in Zone 1 / Div. 1 by using an explosion proof enclosure.

D2010M TEMPERATURE UNIT



D2050M GATEWAY UNIT

MODELS D2010M - D2011M

ANALOG / TEMPERATURE MULTIPLEXER UNIT

- II 1 G EEx ia IIC T4
- 16 Channels per Unit, each for 2-3-4 wire RTD, Pt100, Pt50, Ni 100, Cu100, Cu53, Cu50, Cu46, TC Type A1, A2, A3, B, E, J, K, L, Lr, N, R, S, T, U.
- Up to 16 Units per System
- 256 Channels are scanned in 1500 ms
- Redundant Communication with gateway D2050M
- PC Programmable via SWC2090 software
- Zone 0 / Div. 1 Installation
- Operating Temperature - 40 to + 60 ° Celsius

MODEL D2030M

SWITCH / PROXIMITY MULTIPLEXER UNIT

- II 1 G EEx ia IIC T4
- 32 Input Channels per Unit
- Up to 4 Units per System
- Input from Contact-Proximity Sensors
- 128 Channels are scanned in 50 ms
- Redundant Communication with D2050M Gateway
- PC Programmable via SWC2090 software
- Zone 0 / Div. 1 Installation
- Operating Temperature - 40 to + 60 ° Celsius

D2000M

MODEL D2050M

GATEWAY MULTIPLEXER UNIT

D2010M
D2030M

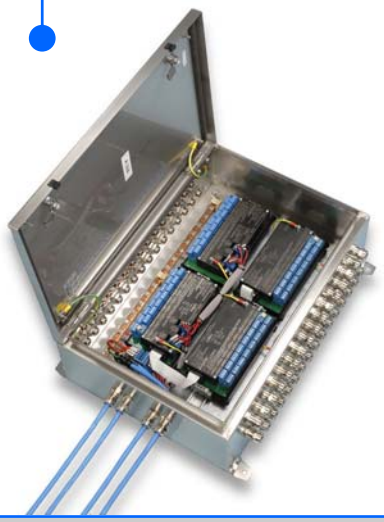
- II (1) G [EEx ia] IIC
- Supply 24 V - 350 mA
- Redundant MODBUS RTU - RS485 lines up to 115200 bauds
- 1 RS-232 line for configuration via PC
- Suitable to drive contact/proximity output repeaters
- Safe Area Installation or Zone 1 / Div. 1 when mounted in an explosion proof housing
- Operating Temperature - 20 to + 60 °Celsius

MODEL D2052M / D2053M

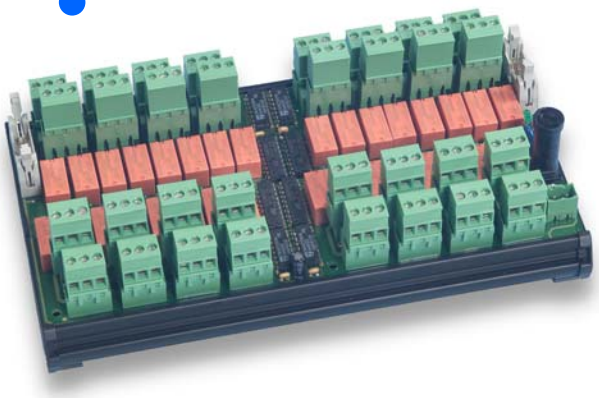
CONTACT / PROXIMITY OUTPUT REPEATER

- 32 Isolated Channels with SPDT Relay contacts (D2052M) or Open Collector Transistors (D2053M)
- 128 Channels are scanned in 50 ms
- Operating Temperature - 20 to + 60 ° Celsius
- Safe Area Installation or Zone 1 / Div. 1 when mounted in an explosion proof housing

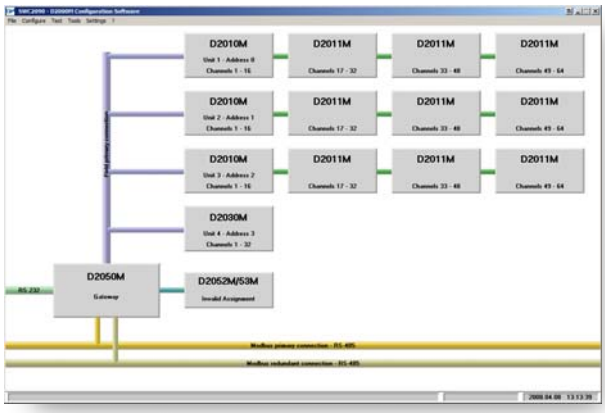
GM2320 FIELD ENCLOSURE



D2052M OUTPUT REPEATER



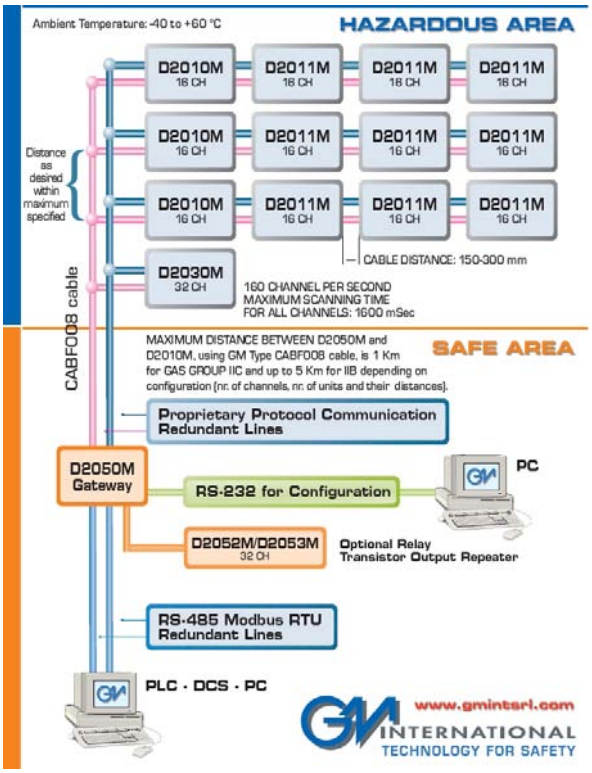
SWC2090 CONFIGURATOR



SOFTWARE CONFIGURATOR FOR D2000M

- Configure and monitor the entire system with your PC / Laptop via RS232 and/or RS485 connections
- Guided user interface
- Print complete report sheets
- Save configurations to file for backup
- Multilanguage

EXAMPLE OF ARCHITECTURE

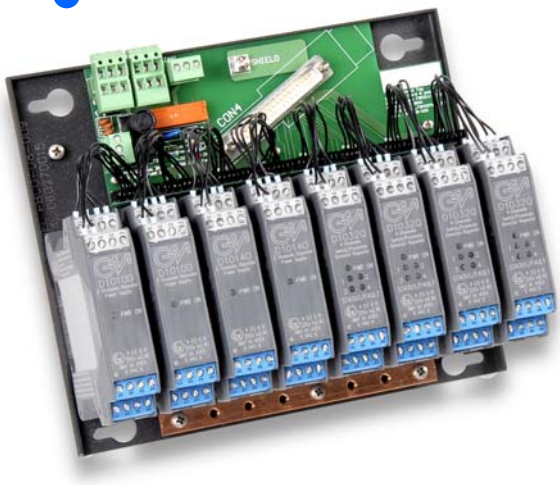


CONNECTOR OUTPUT CUSTOM PANELS

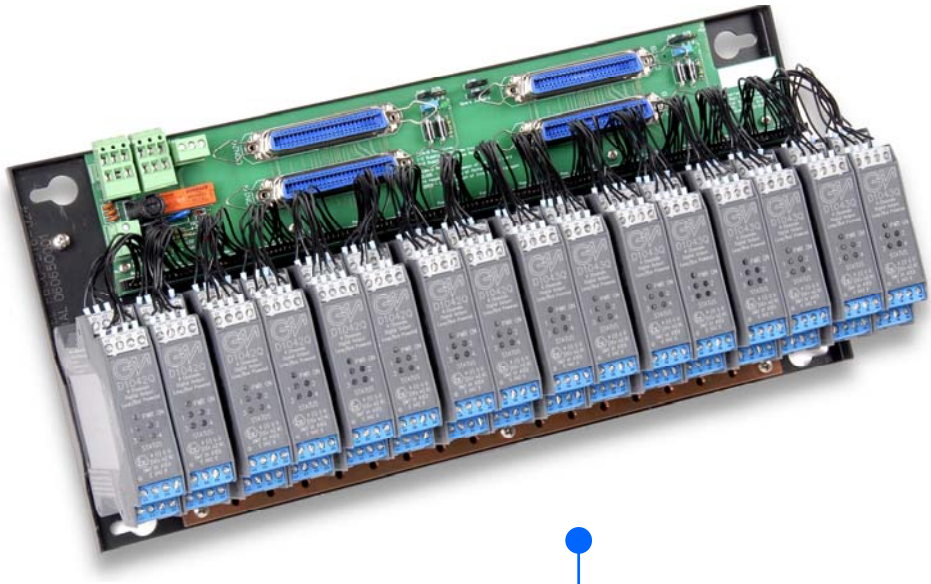
G.M. International offers many solutions for Customized Boards for an easy integration with instrumentation of manufacturers like **Invensys Foxboro**, **ABB**, **Triconex**, **Yokogawa**, **Honeywell** and many more.

New Board models are engineered on customer request for any system or application: contact us for details.
In the following page a selection of Customized PBCO Series Boards among our entire production.

8 MODULES - PBC0-D8



12 MODULES - PBC0-D12

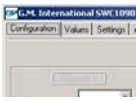


16 MODULES - PBC0-D16

CUSTOM BOARD MODELS

Code	Description	Ch.
	Boards with Output Connectors suitable for **Foxboro** FBM 200	
PBCO-D8-009	16 Ch. Board: 16 AI or 8 DI + 8 DO or 16 DI suitable for FBM 211, 241, 242, 207, single connector	16
PBCO-D8-010	8 Ch. Board: 8 AO or 8 AI or 4AO + 4AI suitable for FBM 237, 201, single or redundant connector	8
PBCO-D8-011	32 Ch. Board: 32 DI suitable for FBM 217 single connector	32
	Boards with Output Connectors suitable for **Triconex** TMR Version 9	
PBCO-D16-012	32 AI Ch. Board + Hart connector suitable for TMR 3704 E	32
PBCO-D16-013	32 DI Ch. Board suitable for TMR 3505 E	32
PBCO-D8-014	16 Ch. Board AO + Hart connector, suitable for TMR 3805E	16
PBCO-D16-015	32 DI Ch. Board suitable for TMR 3504 A, 3564	32
PBCO-D16-042	32 AI Ch. Board + Hart connector suitable for TMR 3700 A	32
PBCO-D16-043	32 DI Ch. Board suitable for TMR 3503 E	32
	Boards with Output connector suitable for **ABB**	
PBCO-D8-001	Analog Board for 6 Double Analog modules, suitable for 8 AI and 4 AO channels	12
PBCO-D8-002	Digital Board for 8 four channel Digital Input modules, suitable for 32 input channels	32
PBCO-D8-003	Relay Board for DO Signal customized for ABB System Six, + 8 Relays 24 Vdc driven by DCS	8
PBCO-D12-008	Analog Board for 12 Double Analog modules, suitable for 16 AI and 8 AO channels	24
PBCO-D04-038	4 Module / 8 Channels DI Board for ABB TC-200 System	8
PBCO-D04-039	4 Module / 4 Channels DO Board for ABB TC-200 System	4
PBCO-D04-040	4 Module / 8 Channels AI Board for ABB TC-200 System with Hart	8
PBCO-D01-041	1 Hart MUX Module / 32 Channels Board for ABB TC-200 System	32
	Boards with Output Connectors suitable for **Yokogawa** Centrum CS 3000 R3	
PBCO-D16-025	16+16 AI Ch. Board suitable for cards AAI 141 - 16+16 AI ch. each	32
PBCO-D16-026	16+16 AO Ch. Board suitable for card AAI 543 - 16 + 16 AO ch. each	32
PBCO-D16-027	32 or 64 DI Board suitable for card ADV 151 - 32/64 DI (use 16 dual/quad ch. modules)	32
PBCO-D16-028	32 DO Board suitable for card ADV 551- 32 DO each (use 16 dual ch. modules)	32
	Boards with Output Connectors suitable for **Honeywell**	
PBCO-D16-021	16 Modules Board for IOP, HLAI, CC, P/N 51304754-150	32
PBCO-D16-022	16 Modules Board for IOP, A/O, CC, P/N 51309152-175	32
PBCO-D16-023	16 Modules Board for IOP, DI, CC, P/N 51304485-150	32
PBCO-D16-024	16 Modules Board for IOP, DO, CC, P/N 513044485-150	32
	Boards with Output Connectors suitable for **Emerson** DeltaV	
PBCO-D8-033	16 AI + 16 AO or 32 DI + Hart connector suitable for DeltaV	32
	Boards with Output Connectors suitable for **Bailey** Infi 90	
PBCO-D16-029	15 AI, Simplex or Redundant Configuration	15
PBCO-D16-030	16 DI + 16 DO, Simplex or Redundant Configuration	32
PBCO-D16-031	16 DO, Simplex or Redundant Configuration	16
	Boards Standard **D1000** Series	
PBCO-D8-032	32 DI or 32 DO or 16AI or 16 AO + HART Connector with standard ELCO 56 Pin Output Conn.	32
PBCO-D16-035	16 AI or 16 AO with standard ELCON 56 Pin Output Connector	16
PBCO-D16-036	32 AI or 32 AO + HART Connector with 2 standard ELCO 56 Pin Output Connectors	32
PBCO-D16-037	32 AI or 32 AO + HART Multiplexer Ready with Terminal Block output	32
PBCO-D8-044	16 Ch (8 Modules) with Terminal Block output	16

D1000 SERIES ACCESSORIES

Image	Code	Description
	**MCHP065**	DIN-Rail Anchor for terminal block side of the Power Bus
	**MCHP139**	5 mm spacer for modules on DIN-Rail
	**MOR016**	DIN-Rail Stopper
	**MOR015**	Plug-in terminal block male, vertical out, for Power Bus
	**MOR017**	Plug-in terminal block male, horizontal out, for Power Bus
	**MOR022**	Plug-in terminal block female, horizontal out, for Power Bus
	**OPT1091**	Cold Junction Compensator
	**OPT1096**	Kit for Bus Mounting: 2 x MOR016, 1 x MOR017, 1 x MOR022, 2 x MCHP065
	**/B**	Power Bus Enclosure (see next page)
	**D1091S**	Common Bus Alarm Module with SPDT Relay Fault Output indication
	**PPC1090**	Pocket Portable Configurator with cables
	**PPC1092**	RS-232 Serial Adapter for Configuration via PC, includes USBADAPT and cables
	**USBADAPT**	USB to RS-232 Adapter for PC
	**SWC1090**	PC Software for Configuration (free of charge at www.gmintsrl.com)
	**D1000R**	19” Rack Unit, 3 units high, suitable for 16 modules

More information on www.gmintsrl.com

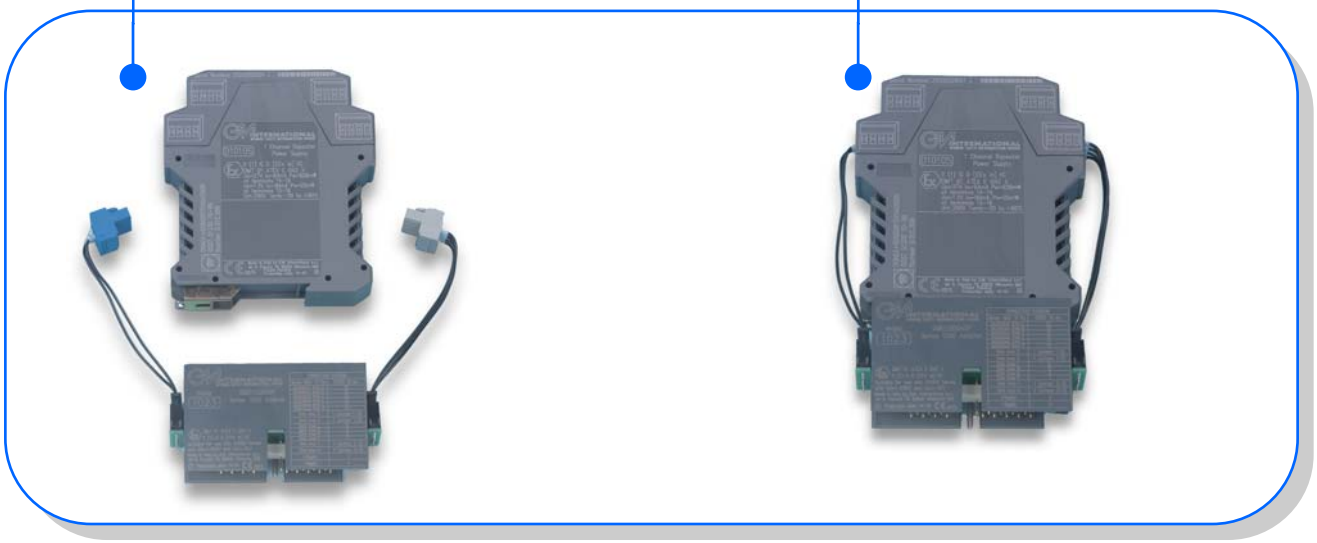
ELCON INSTRUMENTS ADAPTERS

G.M. International offers continuity in the service of Elcon Instruments 1000 series (no longer available from the manufacturer). ATEX, FM, FM-C Certifications.

- Interchangeability with Elcon 1000 Series modules.
- Possibility to replace Elcon modules without modifying any wiring or connections.
- Use of the same Elcon boards.
- Identification using the same Elcon part-number.

EIADP ELCON ADAPTER

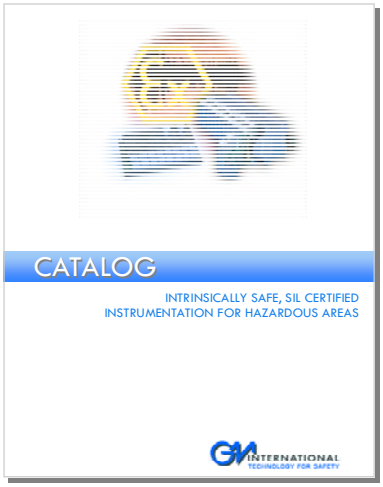
FULL INTERCHANGEABILITY



LIST OF ELCON ADAPTABLE MODELS

- **Analog Input, Power Supply Repeaters**
  1021, 1022, 1023, 1025, 1025G, 1026, 1026G, 1029, 1030
- **Analog Input, Power Supply Repeater and Trip Amplifier**
  1020, 1027
- **Analog Output, Powered Isolating Drivers for I/P**
  1031, 1032, 1033, 1034, 1037, 1038
- **Fire and Smoke Detectors Repeaters**
  1035, 1036, 1039, 1040
- **Analog Signal and Temperature Converters Fully Programmable**
  1061, 1062, 1065, 1066, 1071, 1072, 1073, 1074, 1090
- **Digital Input Switch/Proximity Repeater**
  1821, 1822, 1841, 1842
- **Digital Output Drivers for Solenoid Valves, LEDs, Horns**
  1861, 1862, 1871, 1872, 1873, 1874, 1881, 1882
- **Frequency to Analog Converter + Pulse Repeater**
  1891, 1893
- **Analog Signal and Temperature Trip Amplifiers Fully Programmable**
  1011, 1012, 1310, 1311, 1360, 1361, 1370, 1371

CATALOG

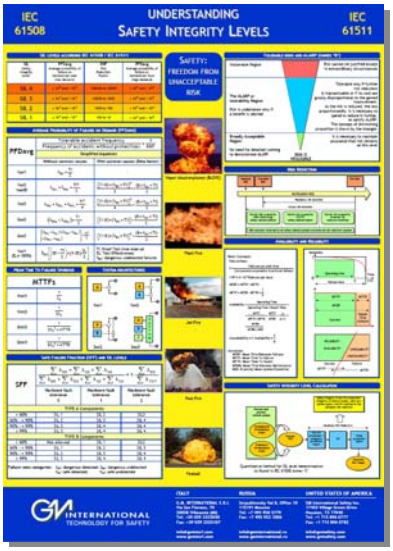


Company and products catalog

General catalog with information on product series, data sheets, full company profile.

Hard copy available free of charge upon request. File in electronic format can be downloaded from our website.

POSTERS



IS and SIL posters

A2 size (40x60cm) posters are available upon request free of charge on the following two arguments:

- **Understanding Safety Integrity Levels**
  Quick reference table on the major concepts of IEC 61508 and IEC61511 standards.
  Risk reduction, ALARP, Availability and Reliability formulae, SIL levels table, frequent acronyms, PFDavg simplified calculations formulae, system architectures, Safety Failure Fraction table and more.

- **Understanding Hazardous Locations**
  Quick reference table on the major concepts of Intrinsic Safety for both Europeans and North American standards.
  Marking, temperature codes, hazardous area classification, gas groups, enclosure ratings, reference standards and more.

INTERNET

www.gmintsrl.com

G.M. International offers a wide range of services and information through its online website.

Download
- Data Sheets
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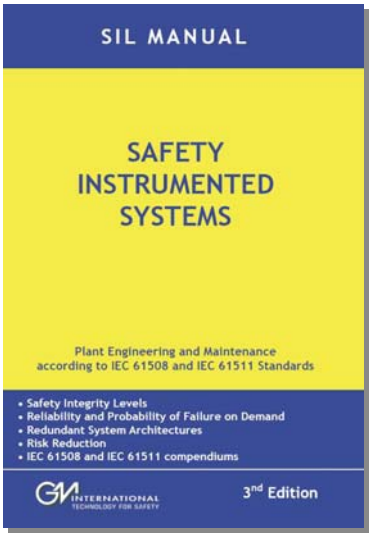
- Worldwide Exhibitions

Contacts
- Agents and Distributors
- Technical and Commercial contacts
- Quotation request form

Utilities
- Online tools for webmasters
- Mailing List

SIL MANUAL



Functional Safety Manual

IEC 61508 and IEC 61511 standards represent a milestone in the progress of industry in the achievement of supreme levels of safety through the entire instrumented system lifecycle.
The majority of our products are SIL 3 or SIL 2 certified.

The experience in safety and electronics acquired during the years has lead us to the writing of a comprehensive manual on IEC61508 and IEC 61511.

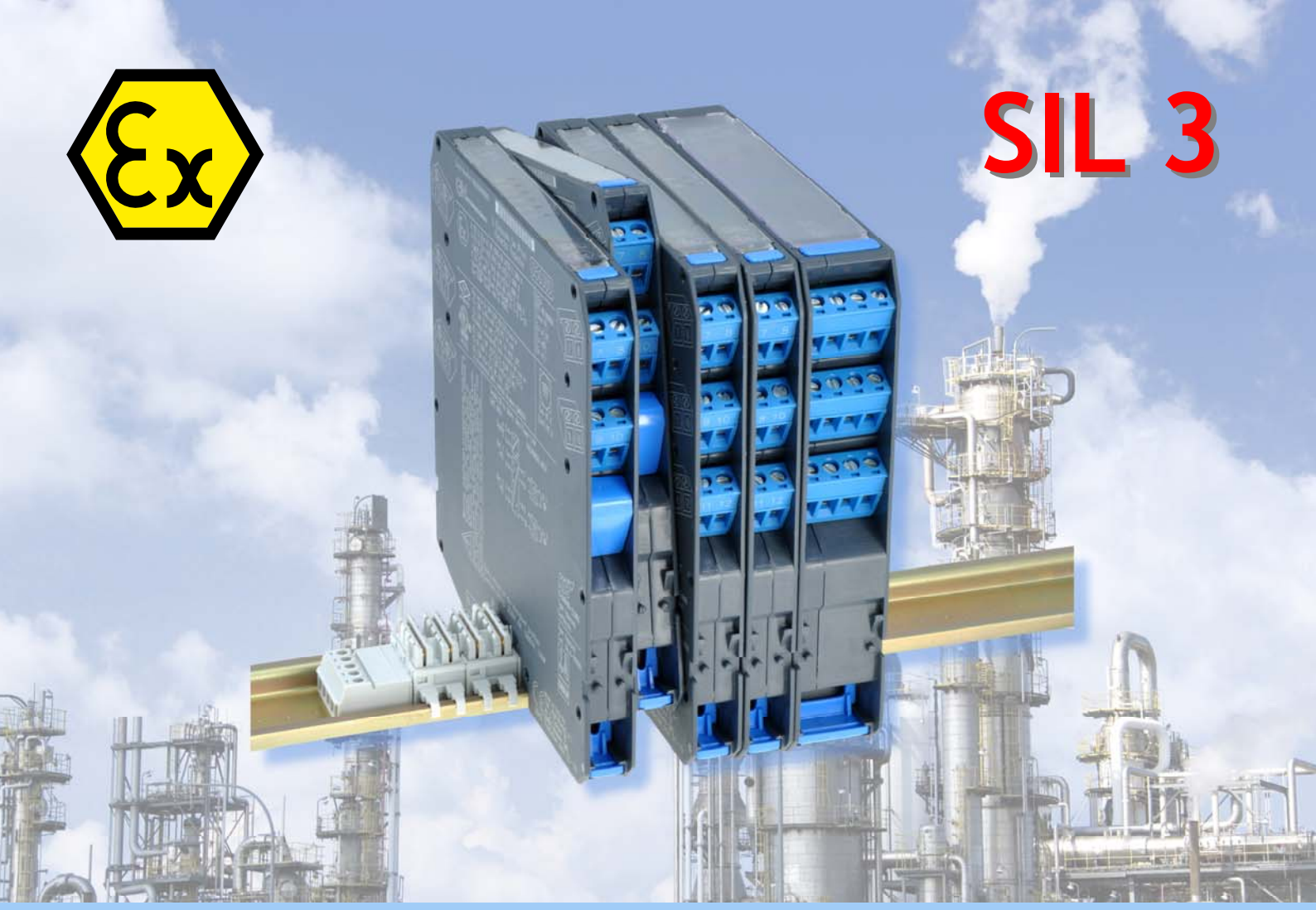
This effort has already proven to be a great benefit for engineers, maintenance personnel and whoever wishes to approach the concept of functional safety.

The manual is available on request in English, Spanish and Italian language.

GM INTERNATIONAL

TECHNOLOGY FOR SAFETY

SIL 3



D5000 - D5200

INTRINSICALLY SAFE ISOLATORS AND SAFETY RELAYS

DIN-RAIL, POWER BUS, TERMINATION BOARD MOUNTING

GM INTERNATIONAL
TECHNOLOGY FOR SAFETY

D5000 Series

SIL 3 Certified

Intrinsically Safe Isolators and Safety Relays

D5000 Modules provide the most simple and cost effective means of implementing Intrinsic Safety for Hazardous Areas / Locations applications.

A complete line of Isolators and Safety Relays.

High Integrity

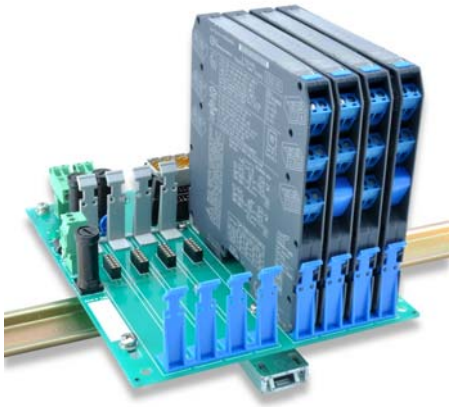
- SIL 3 according IEC 61508 - 61511
- Certified life duration: 20 years
- No electrolytic capacitors
- Three port galvanic isolation
- Safety Relay contacts rated for 4 A or 10 A

Enhanced Packing

- Space saving 12mm enclosure:
  160 channels into just 1m DIN-Rail
- Reduced power consumption
- Power Bus and DIN-Rail mounting
- All modules can be mounted on DIN-Rail, Power Bus and Termination Boards.
- Detachable transparent front panel

Advanced Features

- Short and open circuit detection reflected on PLC
- EMC compatibility for safety systems
- AI, AO, DI, DO, Temperature applications
- Signal converter, Encoders



GM INTERNATIONAL
TECHNOLOGY FOR SAFETY

www.gmintsrl.com

D5000 SERIES

CHARACTERISTICS

Universal mounting enclosure

All D5000 Modules can be mounted on **DIN-Rail**, **Power Bus** and **Termination Boards**.

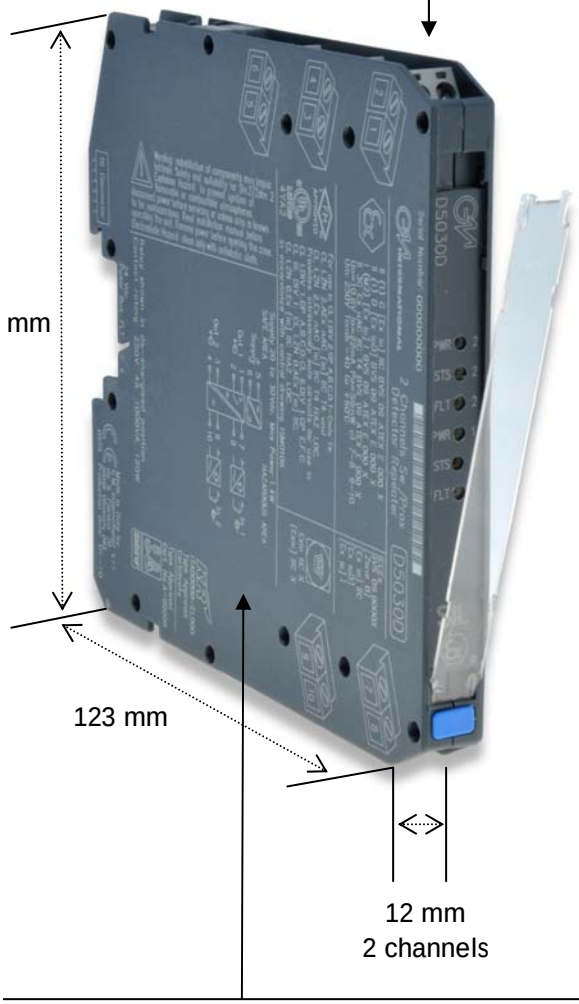
Termination Board connector

Power Bus connector

DIN-Rail lock

Guides for Termination board mounting

Safe Area Terminal blocks with engraved identification



Lexan detachable front cover

LEDs for power, status and fault indication are visible through the transparent cover

Modules are **SIL 3 certified**

Hazardous Area Terminal Blocks indicator

Laser engraving on entire enclosure and terminal blocks to provide accurate, safe and permanent marking of Intrinsic Safety parameters, schematic diagrams, connections and instructions.

D5000

D5000 - D5200 SERIES

HIGH INTEGRITY

INTRINSICALLY SAFE ISOLATORS & SAFETY RELAYS

High performance

- High signal transfer accuracy and repeatability.
- Advanced circuitry provides very low heat dissipation, ensuring modules run cool despite their high density and functionality.
- SMD manufacturing to maximize long, reliable life.
- Complete absence of electrolytic capacitors ensures minimum 20 years lifetime.

Wide functionality

- Wide range of digital and analog I/O.
- SIL 3 Safety Relay contacts rated for 4 A or 10 A for direct switching of high loads.
- Three port galvanic isolation to eliminate noise, ground loop problems and to provide Intrinsic Safety without a high integrity safety earth connection.
- Line fault alarm detects open or short circuit of field cables.
- Optional power bus DIN-Rail connector.
- Standard Termination Board, custom connectors for integration into customized Boards.
- EMC Compatibility to EN61000-6-2, EN61000-6-4, EN61326-1, EN61326-3-1 for safety system.

General features

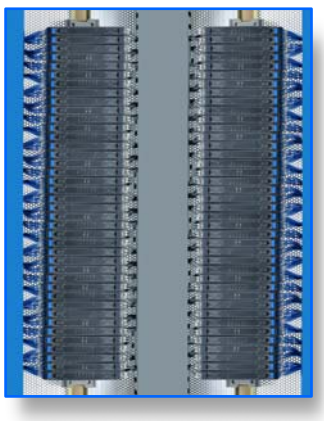
- More than 25 modules suitable for SIL 3 applications according to IEC 61508, IEC 61511.
- Independent power supply circuit for each channel.
- Double units are equivalent to two single units because of the absence of common circuitry.
- Single channel versions available if required, to provide single loop integrity on Emergency Shut Down and Fire & Gas applications.
- Configuration components are easily accessed by removing cover.
- DIP switch configurability for easy field setup.
- LED indication for power, signal status and line fault conditions.
- Modules accept DC power supply over a wide range for 24 Vdc (20-30 Vdc) applications.
- Wide operating temp. range: -40 to +60/+70 °C.
- Installation in Zone 2 / Division 2.
- Certified for Offshore and Marine applications.

High packing density

- 35 mm (Top Hat) DIN-Rail.
- Ultra slim 2 channels 12 mm wide DIN-Rail and Termination Board mounting modules.
- Power and fault on bus connectors.
- 6 mm per channel means 50% space reduction

Save up to 50% space

6 mm per channel + Ultra-low power consumption



Up to 160 I/O channels per 1m of DIN-Rail as shown in the configuration above.

APPROVALS AND CERTIFICATIONS

D5000 SERIES APPLIED FOR

Intrinsically Safe products

G.M. International
has obtained IS certificates from the most credited
Notified bodies in the world for its D1000 Series.
D5000 and D5200 Series will be applied for certification in 2010.

SIL Certifications according IEC 61508 and IEC 61511

G.M. International
offers a wide range of products that have been proved to comply
with the most severe quality and safety requirements.
IEC 61508 and IEC 61511 standards represent a milestone in the progress
of industry in the achievement of supreme levels of safety through
the entire instrumented system lifecycle.

Marine Type Approval

G.M. International
offers Type Approval Certificates for its line of Intrinsically Safe Isolators D1000 Series and
Power Supplies for use in Marine and Offshore applications.
Certificates have been released both by Korean Register of Shipping and Det Norske Veritas.
The D5000 and D5200 Series will be applied for soon.

Company Quality System

G.M. International's
Production Quality System is certified by Det Norske Veritas (Norway)
to be compliant with ATEX 94/9/EC Directive and ISO 9001/2008.
This means our production facilities are periodically re-assessed throughout the whole
manufacturing process, to ensure that the highest quality standards are met.

D5000 SERIES

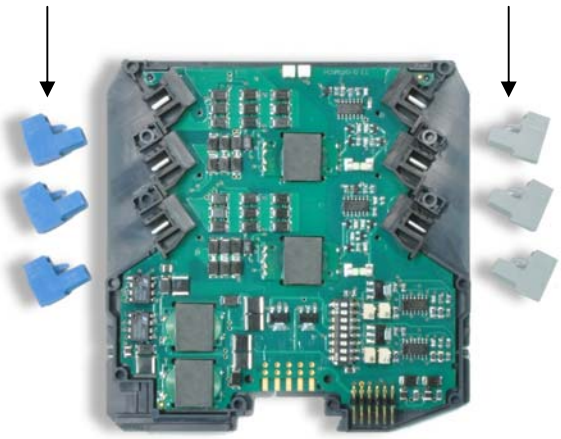
FEATURES

Enclosure Characteristics

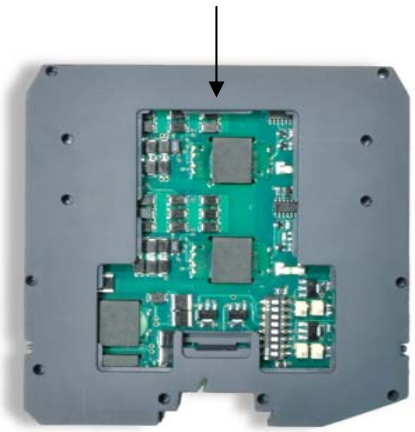
- High channel density result from innovative circuit design using advanced surface mount components.
- Plug-in screw terminal blocks to secure termination up to 2.5 mm^2.
- Configuration components are easily accessed by removing side cover.

Blue terminal blocks for Hazardous Area connections

Grey terminal blocks for Safe Area connections



Detachable cover for access to configuration component



Enhanced Power Bus mounting

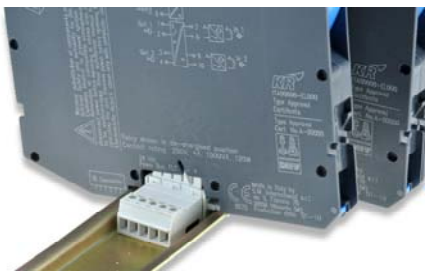
Power Supply Voltage 24 Vdc can be applied to the module, by connecting directly the voltage to the plug-in Terminal Block of each module, or via the Power Bus System.

The system consists of standard DIN-Rail modules mounted on standard DIN-Rail Bus connectors. The maximum allowed powering capacity is 8 A.

It is always possible to remove modules, without disconnecting the bus connector which remains attached to the DIN-Rail.

Cumulative Fault Alarm indication is provided on the Bus connection.
This signal is fed to a common unit (D5001S) which provides: 1 SPST Relay contact for common faults and 1 SPST Relay contact for power good (supply within operating range).
The D5002S is capable of operating also as redundant 4 A supply module for the system.

Bus plug-in connector



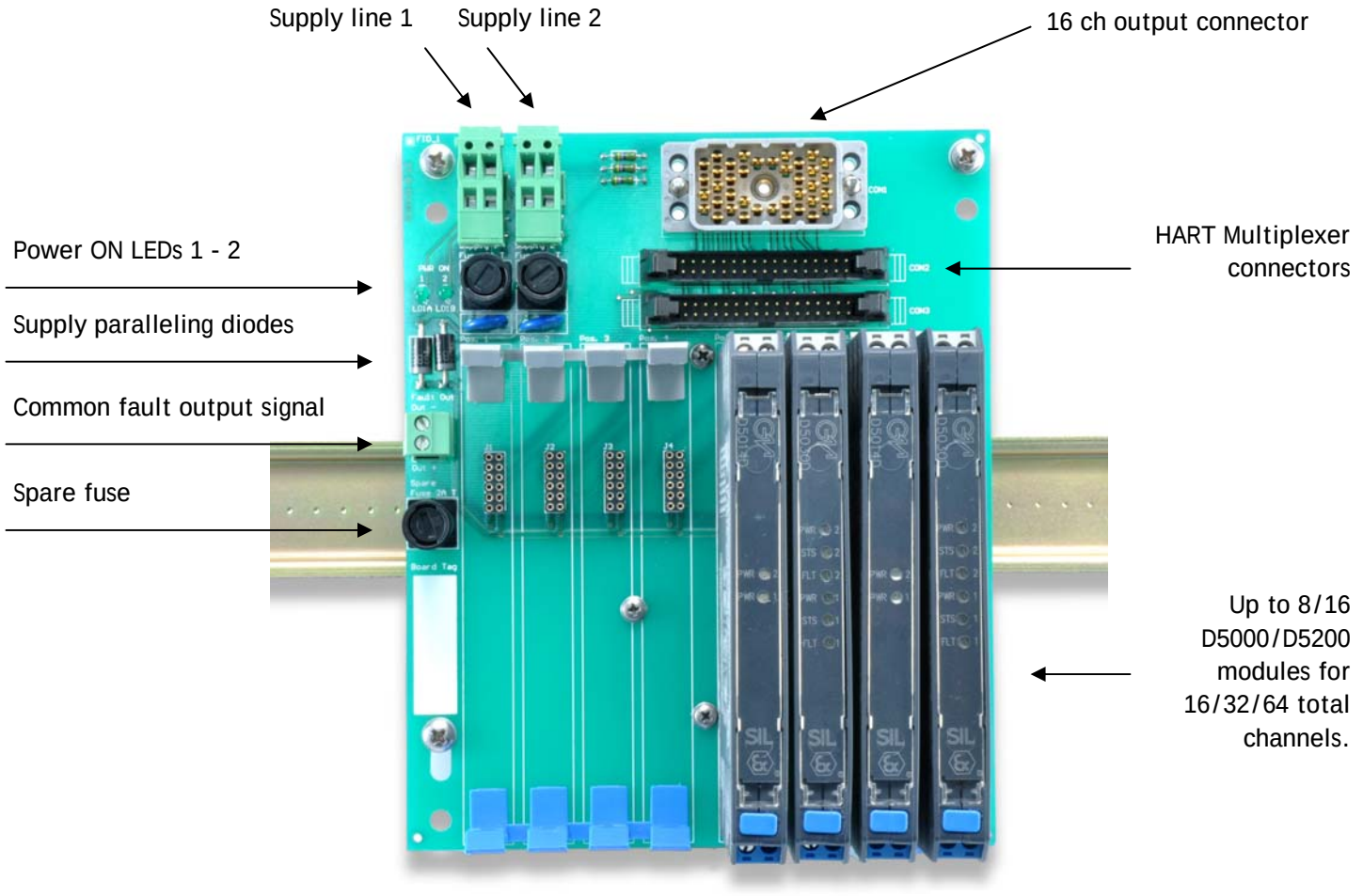
Bus connector terminal

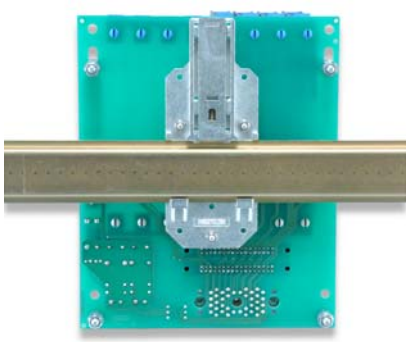
DIN-Rail stopper

D5000 SERIES TERMINATION BOARDS

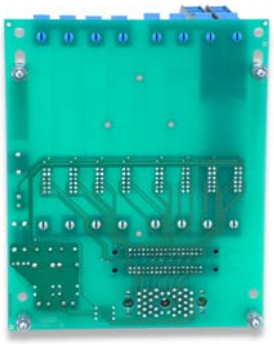
Characteristics

- Suitable to accept up to 8/16 D5000 or D5200 SIL 3 modules 12mm/22mm wide, which can be single or double channel.
- AI - AO - DI - Temperature: double channels.
- DO - Signal converter, Encoders, Safety Relay: single channel.
- 24 Vdc Power supply terminal blocks can be disconnected from the board without disconnecting the power to other boards connected in series.
- Boards are available with custom connectors for any system / PLC / DCS.
- Boards are available also for 8/16+2 modules:
  the extra 2 modules (D5001S) provide separated fault signal relay contacts
  for power supply fault and input/output lines open and short circuit detection.
  Two D5001S modules can be paralleled for 1oo2 redundancy, to increase availability on fault detection.





DIN-Rail mounting



Wall mounting

D5000 - D5200 Selection Table

	Field device	Model	Hazardous Area	Safe Area	Ch. per unit	Supply	SIL level
ANALOG IN		**D5011S**	4-20 mA 2-Wires Tx only Smart compatible	4-20 mA (source only)	1	20-30 Vdc	SIL 3
		**D5011D**			2		SIL 3
		**D5014S**	4-20 mA 2-Wires Active or Passive Tx Smart compatible	4-20 mA (source or sink)	1	20-30 Vdc	SIL 3
		**D5014D**			2		SIL 3
		**D5014D**		Two duplicated outputs	1		SIL 3
		**D5212Q**	4-20 mA 2-Wires Passive Tx	4-20 mA	4	20-30 Vdc	SIL 3
		**D5212Q**		Two duplicated outputs	2		SIL 3
		**D5212Q**		One Triplicated + One single outputs	2		SIL 3
		**D5212Q**		One Quadriplicated output	1		SIL 3
		**D5254S**	4-20 mA 2-Wires Tx Active or Passive Smart compatible	4-20 mA 2 Trip Amplifiers each whit 1 SPST (relay contact)	1	20-30 Vdc	SIL 2
ANALOG OUT		**D5020S**	4-20 mA Analog Signal to I/P Converters, Electrovalves, Actuators and Displays Smart compatible	4-20 mA Bus powered signal from DCS, PLC or other control devices. Two duplicated outputs.	1	20-30 Vdc	SIL 3
		**D5020D**			2		SIL 3

Configurable via PPC5092 with Software SWC5090

D5000 - D5200 Selection Table

	Field device	Model	Hazardous Area	Safe Area	Ch. per unit	Supply	SIL level
DIGITAL IN		**D5030S**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	1 SPDT (relay contact) + LED (fault status)	1	20-30 Vdc	SIL 3
		**D5030D**		1 SPST (relay contact) + 1 SPST (alarm or duplicator) + LED (fault status)	1		SIL 3
		**D5030D**		2 SPST (relay contact) + LED (fault status)	2		SIL 3
		**D5031S**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	1 Open Collector + LED (fault status)	1	20-30 Vdc	SIL 3
		**D5031D**		2 Open Collectors + LED (fault status)	2		SIL 3
		**D5231Q**	Voltage free Contact, Proximity Switch	4 Open Collectors + LED (fault status)	4		SIL 2
		**D5231E**		8 Open Collectors + LED (fault status)	8		SIL 2
		**D5032S**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	1 SPDT (relay contact) + LED (fault status)	1	20-30 Vdc	SIL 3
		**D5032D**		1 SPST (relay contact) + 1 SPST (alarm or duplicator) + LED (fault status)	1		SIL 3
		**D5032D**		2 SPST (relay contact) + LED (fault status)	2		SIL 3
		**D5034S**	Voltage free Contact, Proximity Switch Line fault detection Isolated inputs	Transparent repeater of input status 0 to 8 mA range	1	20-30 Vdc	SIL 3
		**D5034D**			2		SIL 3

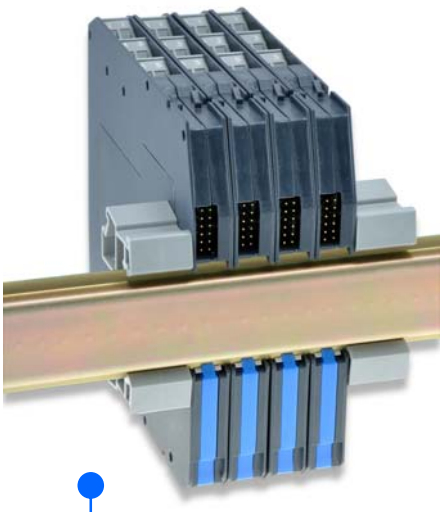
Continues at next page >>

D5000 - D5200 Selection Table

	Field device	Model	Hazardous Area	Safe Area	Ch. per unit	Supply	SIL level
DIGITAL OUTPUT DRIVER		**D5048S**	NE solenoid valve, other control devices. Line open/short fault detection reflected on PLC.	Loop Powered control signal from safety PLC, DCS	1	Loop + 20-30 Vdc	SIL 3
		D5049S		Bus Powered control signal from safety PLC, DCS	1	20-30 Vdc	SIL 3
		D5247S	F&G solenoid valve, other control devices. Line open/ short fault detection. High Availability (1oo2)	Loop Powered control signal from safety PLC, DCS	1	Loop + 20-30 Vdc	SIL 3
		D5280S	NE 12W 'Ex d' solenoid valve, other control devices. Line open/short fault detection.	Loop Powered control signal from safety PLC, DCS	1	Loop + 20-30 Vdc	SIL 3
		D5281S	F&G 12W 'Ex d' solenoid valve, other control devices. Line open/short fault detection. High Availability (1oo2)	Loop Powered control signal from safety PLC, DCS	1	Loop + 20-30 Vdc	SIL 3
SIGNAL CONV.		**D5060S**	0-50 KHz Magnetic Pickup or Proximity Switch	mA (source) or V Out, Pulse repeater Output	1	20-30 Vdc	SIL 2
ENCODER		**D5265S**	Intrinsically Safe Encoder	Transparent repeater	1	20-30 Vdc	

Configurable via PPC5092 with Software SWC5090

Side view



Rear view

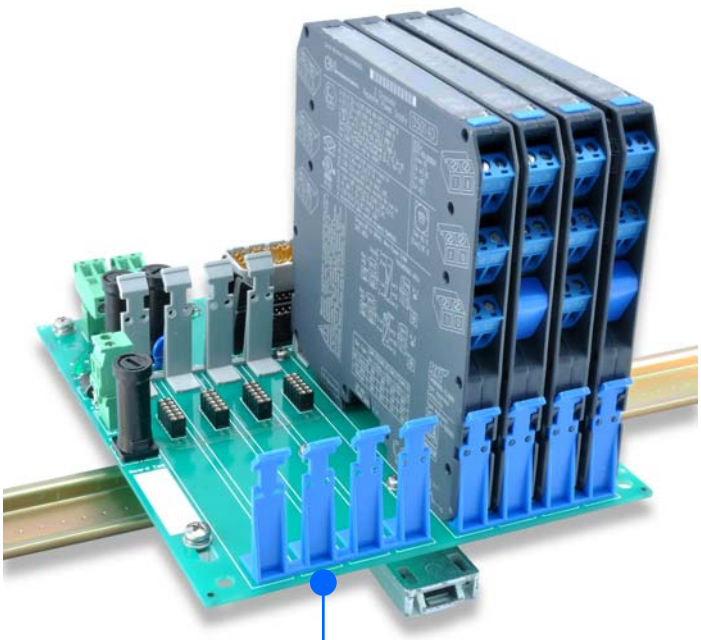
D5000 - D5200 Selection Table

TEMPERATURE CONVERTERS AND TRIP AMPLIFIERS

Field device	Model	Hazardous Area	Safe Area	Ch. per unit	Supply	SIL level
	D5072S	Universal TC, 3/4-Wires RTD, Potentiometer, mV	4-20 mA (source) 1 Independent set point via 1 Solid State Relay	1	20-30 Vdc	SIL 2
	D5072D	Universal TC, 3-Wires RTD, Potentiometer, mV	4-20 mA (source)	2	20-30 Vdc	SIL 2
	D5072D		4-20 mA (source) Duplicator	2		SIL 2
		2 inputs in 1oo2 Universal TC, 3-Wires RTD, Pot, mV	4-20 mA (source)	1	20-30 Vdc	SIL 3

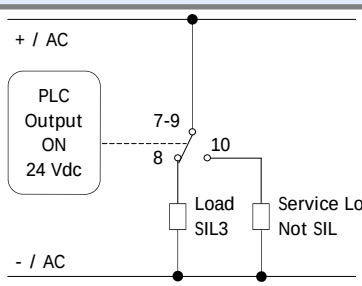
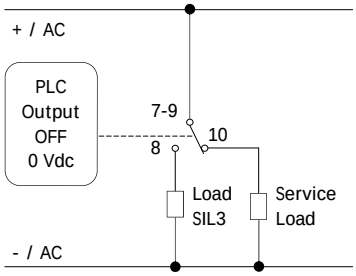
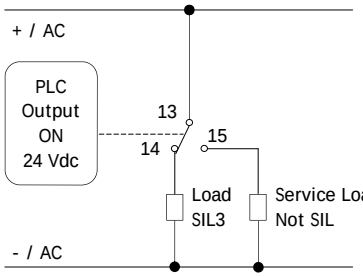
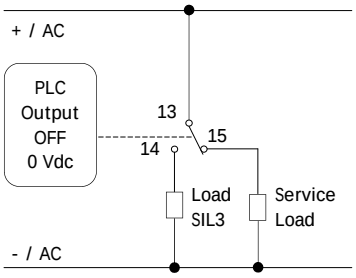
Configurable via PPC5092 with Software SWC5090

Continues >>



Custom Termination Board

SAFETY RELAYS

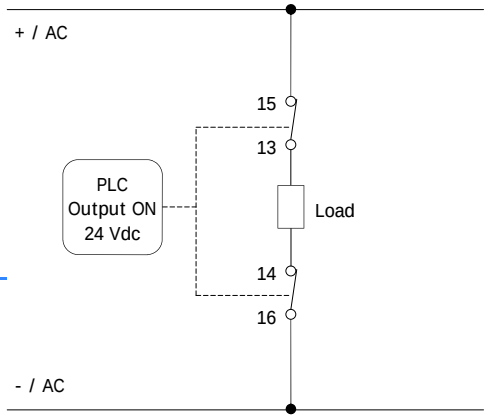
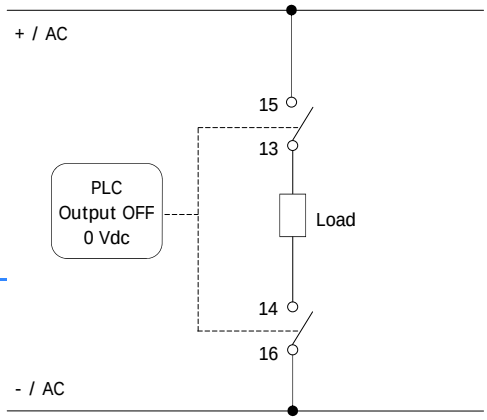
Field device	Model	Load Contacts	Connections	Rating	SIL level
	D5090S	4 A NE Load *Contacts 7-8:* *SIL 3 Function is met when contacts are in open state.*		250 Vdc 250 Vac	SIL 3
	D5091S	4 A ND Load *Contacts 7-8:* *SIL 3 Function is met when contacts are in closed state.*		250 Vdc 250 Vac	SIL 3
	D5290S	10 A NE Load *Contacts 13-14:* *SIL 3 Function is met when contacts are in open state.*		250 Vdc 250 Vac	SIL 3
	D5291S	10 A ND Load *Contacts 13-14:* *SIL 3 Function is met when contacts are in closed state.*		250 Vdc 250 Vac	SIL 3

D5090S

D5290S

D5000 - D5200 Selection Table

SAFETY RELAYS

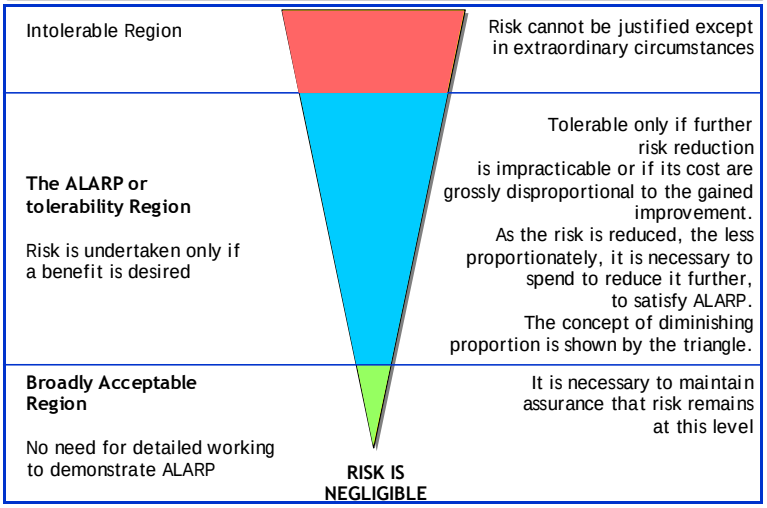
Field device	Model	Load Contacts	Connections	Rating	SIL level
	D5293S	10 A, NE Load + line and load diagnostic for open / short circuit programmable + earth leakage detection. 2 fault output contacts *Contacts 13-15 / 14-16: SIL 3 Function is met when contacts are in open state.*		250 Vdc 250 Vac	SIL 3
	D5294S	10 A, F & G Load + line and load diagnostic for open /short circuit programmable + earth leakage detection. 2 fault output contacts *Contacts 13-15 / 14-16: SIL 3 Function is met when contacts are in closed state.*		250 Vdc 250 Vac	SIL 3

D5090S-5091S-5290S-5291S

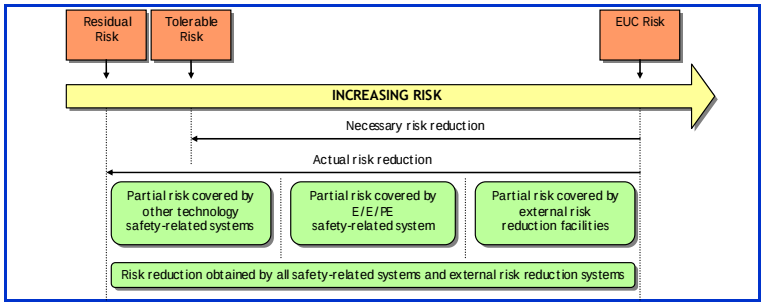
SIL Levels according IEC 61508 / IEC 61511

SIL Safety Integrity Level	PFDavg Average probability of failure on demand per year (low demand)	RRF Risk Reduction Factor	PFDavg Average probability of failure on demand per hour (high demand)
SIL 4	≥ 10^{-5} and < 10^{-4}	100000 to 10000	≥ 10^{-9} and < 10^{-8}
SIL 3	≥ 10^{-4} and < 10^{-3}	10000 to 1000	≥ 10^{-8} and < 10^{-7}
SIL 2	≥ 10^{-3} and < 10^{-2}	1000 to 100	≥ 10^{-7} and < 10^{-6}
SIL 1	≥ 10^{-2} and < 10^{-1}	100 to 10	≥ 10^{-6} and < 10^{-5}

Tolerable risks and ALARP (Annex 'B')



Risk Reduction



Average Probability of Failure on Demand (PFDavg)

$$\frac{\text{Tolerable accident frequency}}{\text{Frequency of accidents without protections}} = \frac{1}{RRF}$$

PFDavg	Simplified equations	
	Without common causes	With common causes (Beta factor)
1oo1	$\lambda_{DU} \times \frac{TI}{2}$	-
1oo2 1oo2D	$\lambda_{DU_1} \times \lambda_{DU_2} \times \frac{TI^2}{3}$	$\frac{\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^2}{3} + \frac{(\beta\times\lambda_{DU}\times TI)}{2}$
1oo3	$\lambda_{DU_1} \times \lambda_{DU_2} \times \lambda_{DU_3} \times \frac{TI^3}{4}$	$\frac{\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^3}{4} + \frac{(\beta\times\lambda_{DU}\times TI)}{2}$
2oo2	$\left(\lambda_{DU_1} + \lambda_{DU_2}\right) \times \frac{TI}{2}$	$\left[(1-\beta)\times(\lambda_{DU}\times TI)\right] + \frac{(\beta\times\lambda_{DU}\times TI)}{2}$
2oo3	$\left[\left(\lambda_{DU_1}\times\lambda_{DU_2}\right)+\left(\lambda_{DU_1}\times\lambda_{DU_3}\right)+\left(\lambda_{DU_2}\times\lambda_{DU_3}\right)\right] \times \frac{TI^2}{3}$	$\left[(1-\beta)\times(\lambda_{DU}\times TI)\right]^2 + \frac{(\beta\times\lambda_{DU}\times TI)}{2}$
1oo1 ($E_t \neq 100\%$)	$\lambda_{DU}\left[\left(Et\times\frac{TI}{2}\right)+(1-Et)\frac{SL}{2}\right]$	TI: Proof Test time interval Et: Test Effectiveness λ_{DU}: dangerous undetected failures

IEC 61508-61511

Facts and Formulae

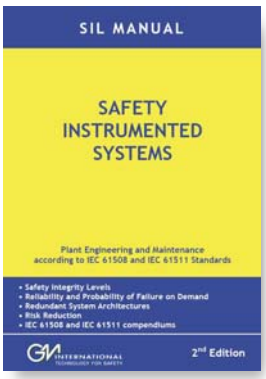
IEC 61508 and IEC 61511 standards represent a milestone in the progress of industry in the achievement of supreme levels of safety through the entire instrumented system lifecycle.

The benefits of these new standards include details and a greater effectiveness for what concerns:

- the definition of risk reduction and related requirements;
- system design and implementation;
- documentation management;
- safety assessment and validation;
- plant maintenance;
- cost management.

The majority of our products are SIL 3 or SIL 2 certified.

Safety Instrumented Systems



The experience in safety and electronics acquired during the years has lead us to the writing of a comprehensive manual on IEC61508 and IEC 61511.

This effort has already proven to be a great benefit for engineers, maintenance personnel and whoever wishes to approach the concept of functional safety.

The manual is available on request in English, Spanish and Italian language.

SAFETY:

FREEDOM FROM UNACCEPTABLE RISK

Boiling Liquid expanding Vapor Explosion (BLEVE)

Flash Fire

Jet Fire

Pool Fire

Fireball

AVAILABILITY AND RELIABILITY

Basic Concepts:

Failure Rate :

$$\lambda = \frac{\text{Failures per unit time}}{\text{Components exposed to functional failure}}$$

$1\ \text{FIT} = 1 \times 10^{-9}$ Failures per hour

$\text{MTBF} = \text{MTTF} + \text{MTTR}$ $\qquad \mu = \frac{1}{\text{MTTR}}$

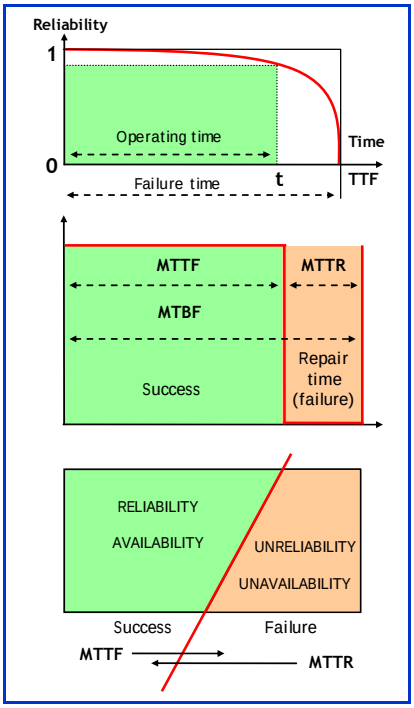
$\text{MTTF} = \text{MTBF} - \text{MTTR} = \frac{1}{\lambda}$ $\qquad \lambda = \frac{1}{\text{MTTF}}$

$$\text{Availability} = \frac{\text{Operating Time}}{\text{Operating Time} + \text{Repair Time}} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} = \frac{\text{MTTF}}{\text{MTBF}} = \frac{\mu}{\mu + \lambda} = \frac{\text{MTBM}}{\text{MTBM} + \text{MSD}}$$

$$\text{Unavailability} = 1 - \text{Availability} = \frac{\lambda}{\mu}$$

Acronyms:

MTBF: Mean Time Between Failures
MTTF: Mean Time To Failure
MTTR: Mean Time To Repair
MTBM: Mean Time Between Maintenance
MSD: Expected Mean System Downtime
λ: Failure rate
μ: Repair rate



SAFE FAILURE FRACTION (SFF) AND SIL LEVELS

$$\text{SFF} = \frac{\sum \lambda_{DD} + \sum \lambda_{SD} + \sum \lambda_{SU}}{\sum \lambda_{DD} + \sum \lambda_{DU} + \sum \lambda_{SD} + \sum \lambda_{SU}} = 1 - \frac{\sum \lambda_{DU}}{\sum \lambda_{TOT}}$$

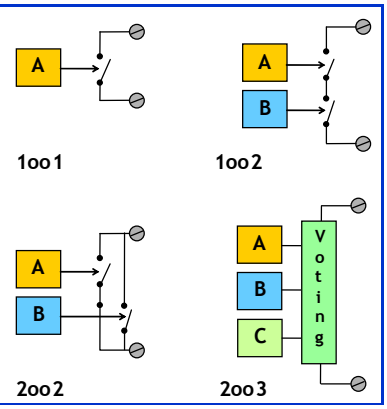
	Hardware fault tolerance 0	Hardware fault tolerance 1	Hardware fault tolerance 2
TYPE A Components			
< 60%	SIL 1	SIL 2	SIL3
60% - < 90%	SIL 2	SIL 3	SIL 4
90% - < 99%	SIL 3	SIL 4	SIL 4
> 99%	SIL 3	SIL 4	SIL 4
TYPE B Components			
< 60%	Not allowed	SIL 1	SIL2
60% - < 90%	SIL 1	SIL 2	SIL 3
90% - < 99%	SIL 2	SIL 3	SIL 4
> 99%	SIL 3	SIL 4	SIL 4

Failure rates categories: λ_{DD}: dangerous detected; λ_{DU}: dangerous undetected
λ_{SD}: safe detected; λ_{SU}: safe undetected

MEAN TIME TO FAILURE SPURIOUS

MTTFs	
1oo1	$\frac{1}{\lambda_S}$
1oo2	$\frac{1}{2\lambda_S}$
2oo2	$\frac{1}{2\lambda_S^2 \times \text{MTTR}}$
2oo3	$\frac{1}{6\lambda_S^2 \times \text{MTTR}}$

SYSTEM ARCHITECTURES



IEC 61508 and IEC 61511

are certainly the leading standards in terms of safety related equipment: the knowledge of their requirements and the ability to fulfill them are essential to both manufacturers and customers.

The benefits of these new standards include details and a greater effectiveness for what concerns:

- the definition of risk reduction and requirements;
- system design and implementation;
- documentation management;
- safety assessment and validation;
- plant maintenance;
- cost management.

G.M. International S.r.l.

is a manufacturer of SIL 2 and SIL 3 certified intrinsically safe instrumentation for use in hazardous areas such as, for example, oil & gas, petrochemical processes and the high demanding fields of DCS, F&G, BMS and ESD systems.

The experience in safety and electronics acquired during the years has lead to the writing of this manual, for the benefit of engineers, maintenance personnel and whoever wishes to approach the concept of functional safety.

Refer to www.gmintsrl.com for even more material, news, products and application notes.

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