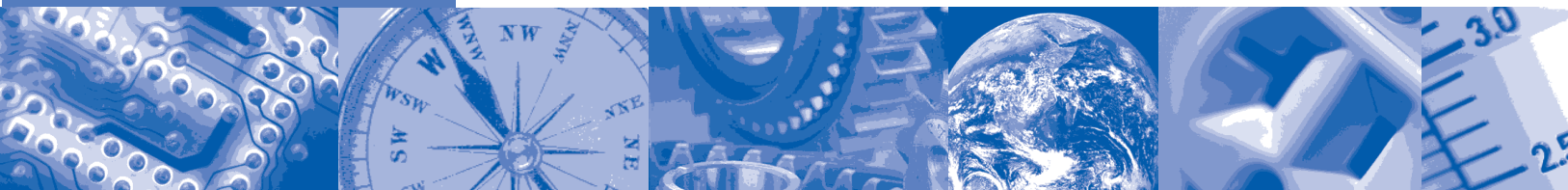


ISA-TR84.00.02-2002 - Part 1



Safety Instrumented Functions (SIF) -- Safety Integrity Level (SIL) Evaluation Techniques Part 1: Introduction



ISA—The Instrumentation,
Systems, and
Automation Society

Approved 17 June 2002

ISA-TR84.00.02-2002 – Part 1

Safety Instrumented Functions (SIF) — Safety Integrity Level (SIL) Evaluation Techniques Part 1:
Introduction

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Preface

This preface, as well as all footnotes and annexes, is included for information purposes and is not part of ISA-TR84.00.02-2002 – Part 1.

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Safety Instrumented Systems (SIS)

— Safety Integrity Level (SIL) Evaluation Techniques

Part 1: Introduction

Foreword

The information contained in ISA-TR84.00.02-2002 is provided for information only and is not part of the ANSI/ISA-84.01-1996 Standard ⁽¹⁾ requirements.

The purpose of ISA-TR84.00.02-2002 ⁽²⁾ is to provide the process industry with a description of various methodologies that can be used to evaluate the Safety Integrity Level (SIL) of Safety Instrumented Functions (SIF).

ANSI/ISA-84.01-1996 provides the minimum requirements for implementing a SIS given that a set of functional requirements have been defined and a SIL requirement has been established for each safety instrumented function. Additional information of an informative nature is provided in the Annexes to ANSI/ISA-84.01-1996 to assist the designer in applying the concepts necessary to achieve an acceptable design. However, Standards Project 84 (SP84) determined that it was appropriate to provide supplemental information that would assist the user in evaluating the capability of any given SIF design to achieve its required SIL. A secondary purpose of this document is to reinforce the concept of the performance based evaluation of SIF. The performance parameters that satisfactorily service the process industry are derived from the SIL and reliability evaluation of SIF, namely the probability of the SIF to fail to respond to a demand and the probability that the SIF creates a nuisance trip. Such evaluation addresses the design elements (hardware, software, redundancy, etc.) and the operational attributes (inspection/maintenance policy, frequency and quality of testing, etc.) of the SIF. The basis for the performance evaluation of the SIF is safety targets determined through hazard analysis and risk assessment ⁽⁶⁾ of the process. This document demonstrates methodologies for the SIL and reliability evaluation of SIF.

The document focuses on methodologies that can be used without promoting a single methodology. It provides information on the benefits of various methodologies as well as some of the drawbacks they may have.

THE METHODOLOGIES ARE DEMONSTRATED THROUGH EXAMPLES (SIS ARCHITECTURES) THAT REPRESENT POSSIBLE SYSTEM CONFIGURATIONS AND SHOULD NOT BE INTERPRETED AS RECOMMENDATIONS FOR SIS. THE USER IS CAUTIONED TO CLEARLY UNDERSTAND THE ASSUMPTIONS AND DATA ASSOCIATED WITH THE METHODOLOGIES IN THIS DOCUMENT BEFORE ATTEMPTING TO UTILIZE THE METHODS PRESENTED HEREIN.

The users of ISA-TR84.00.02-2002 include:

- Process Hazards Analysis teams that wish to develop understanding of different methodologies in determining SIL
- SIS designers who want a better understanding of how redundancy, diagnostic coverage, diversity, etc., fit into the development of a proper SIS architecture
- Logic solver and field device suppliers

- National and International standard bodies providing guidance in the use of reliability techniques for SIS architectures
- Reliability engineers (or any engineer performing this function) can use this information to develop better methods for determining SIL in the rapidly changing SIS field
- Parties who do not have a large installed base of operating equipment sufficient to establish appropriate statistical analysis for PFD_{avg} and $MTTF^{spurious}$ for SIS components
- Operations and maintenance personnel

ISA-TR84.00.02-2002 consists of the following parts, under the general title "Safety Instrumented Functions (SIF) — Safety Integrity Level (SIL) Evaluation Techniques."

Part 1: Introduction

Part 2: Determining the SIL of a SIF via Simplified Equations

Part 3: Determining the SIL of a SIF via Fault Tree Analysis

Part 4: Determining the SIL of a SIF via Markov Analysis

Part 5: Determining the PFD of Logic Solvers via Markov Analysis

Introduction

ANSI/ISA-84.01-1996 describes a safety lifecycle model for the implementation of risk reduction measures for the process industry (Clause 4). The standard then proceeds to provide specific guidance in the application of SIS, which may be one of the risk reduction methods used. The standard defines three levels of safety integrity (Safety Integrity Levels, SIL) that may be used to specify the capability that a safety instrumented function must achieve to accomplish the required risk reduction. ISA-TR84.00.02-2002 provides methodologies for evaluating SIF to determine if they achieve the specific SIL. This may be referred to as a probability of failure on demand (PFD) evaluation of the SIF.

ISA-TR84.00.02-2002 only addresses SIF operating in demand mode.

The evaluation approaches outlined in this document are performance-based approaches and do not provide specific results that can be used to select a specific architectural configuration for a given SIL.

THE READER IS CAUTIONED TO CLEARLY UNDERSTAND THE ASSUMPTIONS ASSOCIATED WITH THE METHODOLOGY AND EXAMPLES IN THIS DOCUMENT BEFORE DERIVING ANY CONCLUSIONS REGARDING THE EVALUATION OF ANY SPECIFIC SIF.

The evaluation processes described in this document take place before the SIS detailed design phase of the life cycle (see Figure I.1, Safety Lifecycle Model).

This document assumes that a SIS is required. It does not provide guidance in the determination of the need for a SIS. The user is referred to ANSI/ISA-84.01-1996 Annex A for methodologies that might be used in making this determination.

This document involves the evaluation of the whole SIF from the sensors through the logic solver to the final elements. Process industry experience shows that sensors and final elements are major contributors to loss of SIS integrity (high PFD). When evaluating the performance of sensors and final elements, issues such as component technology, installation, and maintenance should be considered.

Frequently multiple safety instrumented functions are included in a single logic solver. The logic solver should be carefully evaluated since a problem in the logic solver may adversely impact the performance of all of the safety instrumented functions (i.e., the logic solver could be the common cause failure that disables all of the SIFs.).

This principle (i.e., common cause) applies to any

- element of a SIS that is common to more than one safety instrumented function; and
- redundant element with one or more safety instrumented function.

Each element should be evaluated with respect to all the safety instrumented functions with which it is associated

- to ensure that it meets the integrity level required for each safety instrumented function;
- to understand the interactions of all the safety instrumented functions; and
- to understand the impact of failure of each component.

This document does not provide guidance in the determination of the specific SIL required (e.g., SIL 1, 2, and 3) for the SIS. The user is again referred to ANSI/ISA-84.01-1996 or to other references.

The primary focus of this document is on evaluation methodologies for assessing the capability of the SIS. The SIS lifecycle model is defined in ANSI/ISA-84.01-1996. Figure I.2 shows the boundaries of the SIS and how it relates to other systems.

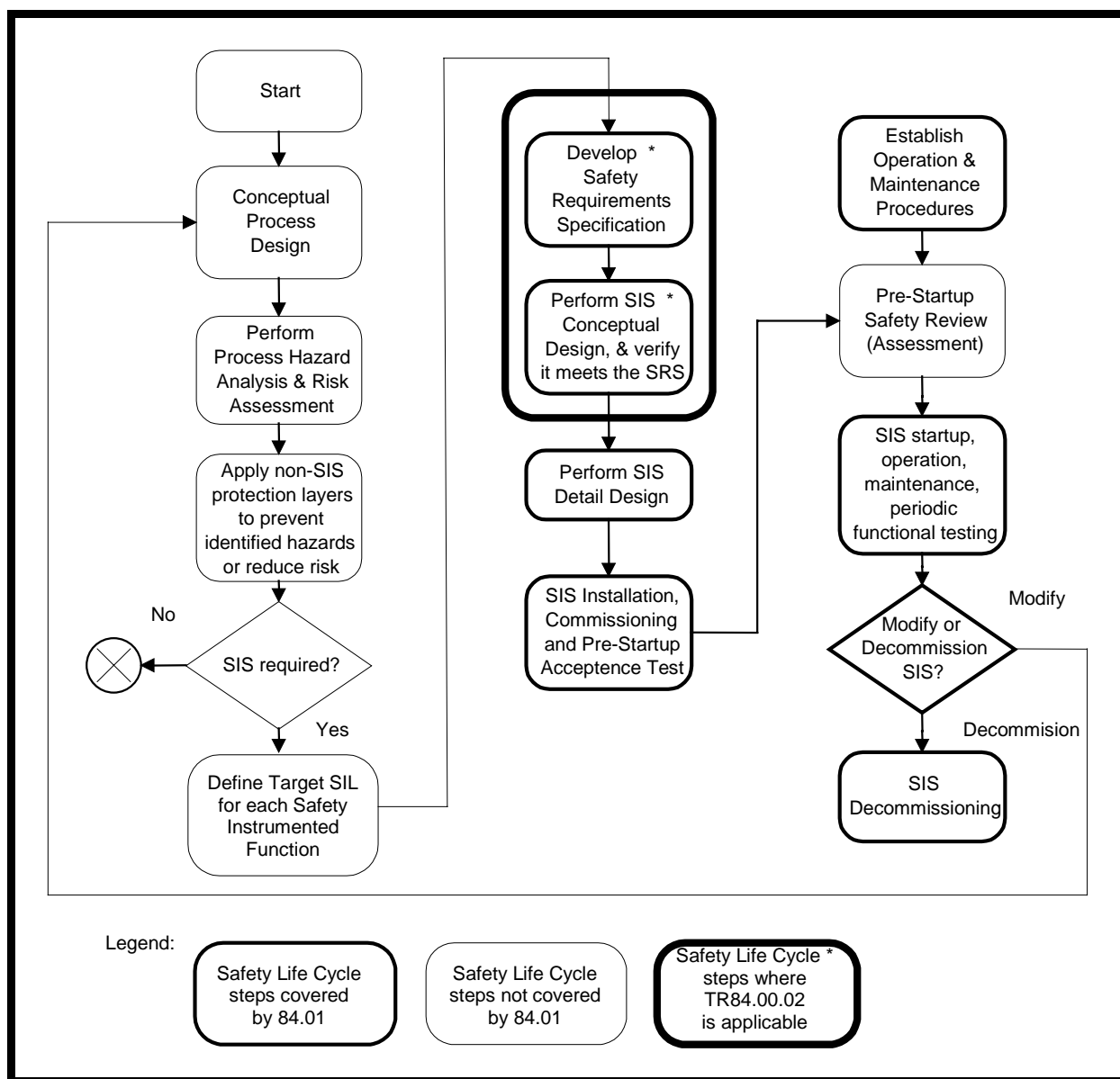


Figure I.1 — Safety lifecycle model

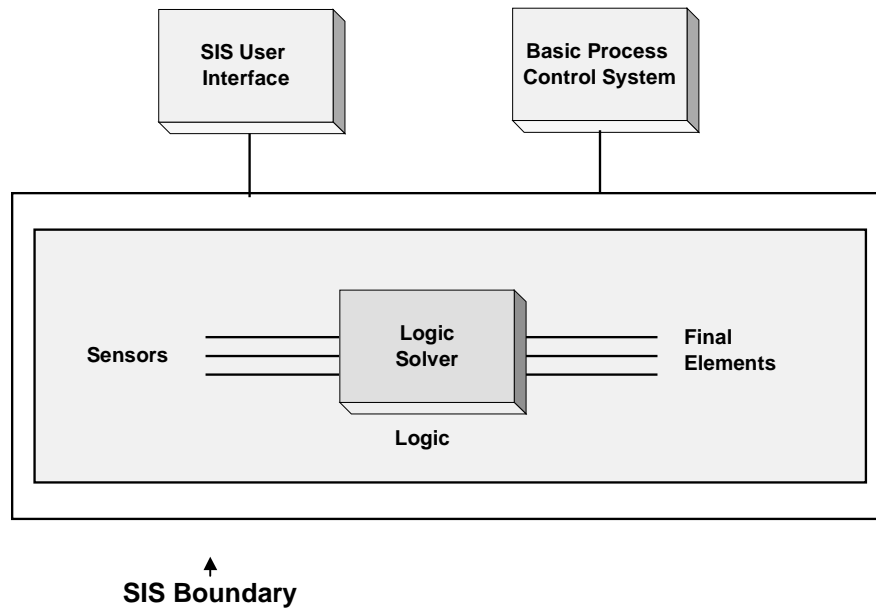


Figure I.2 — Definition of Safety Instrumented System (SIS)

The safety requirements specification addresses the design elements (hardware, software, redundancy, etc.) and the operational attributes (inspection/maintenance policy, frequency and quality of testing, etc.) of the SIS. These elements affect the PFD of each safety instrumented function.

The PFD of these systems can be determined using historical system performance data (e.g., statistical analysis). Where systems, subsystems, components, etc. have not been in use for a sufficiently long time and in large enough numbers to have a statistically significant population available for the evaluation of their performance solely based on actuarial data, a systematic evaluation of the performance of a system may be obtained through the use of PFD analysis techniques.

PFD analysis techniques employ systematic methodologies that decompose a complex system to its basic components. The performance and interactions of these basic components are merged into reliability models (such as simplified equations, fault trees, Markov models) to determine the overall system safety availability.

This document provides users with a number of PFD evaluation techniques that allow a user to determine if a SIF meets the required safety integrity level.

Safety integrity is defined as “The probability of a Safety Instrumented Function satisfactorily performing the required safety functions under all stated conditions within a stated period of time.” Safety integrity consists of two elements: 1) hardware safety integrity and 2) systematic safety integrity. Hardware safety integrity which is based upon random hardware failures can normally be estimated to a reasonable level of accuracy. ANSI/ISA-84.01-1996 addresses the hardware safety integrity by specifying target failure measures for each SIL. For SIF operating in the demand mode the target failure measure is PFD_{avg} (average probability of failure to perform its design function on demand). PFD_{avg} is also commonly referred to as the average probability of failure on demand. Systematic integrity is difficult to quantify due to the diversity of causes of failures; systematic failures may be introduced during the specification, design, implementation, operational and modification phase and may affect hardware as well as software. ANSI/ISA-84.01-1996 addresses systematic safety integrity by specifying procedures, techniques, measures, etc. that reduce systematic failures.

An acceptable safe failure rate is also normally specified for a SIF. The safe failure rate is commonly referred to as the false trip, nuisance trip, or spurious trip rate. The spurious trip rate is included in the evaluation of a SIF, since process start up and shutdown are frequently periods where chances of a hazardous event are high. Hence in many cases, the reduction of spurious trips will increase the safety of the process. The acceptable safe failure rate is typically expressed as the mean time to a spurious trip ($MTTF^{spurious}$).

NOTE In addition to the safety issue(s) associated with spurious trips the user of the SIS may also want the acceptable $MTTF^{spurious}$ to be increased to reduce the effect of spurious trips on the productivity of the process under control. This increase in the acceptable $MTTF^{spurious}$ can usually be justified because of the high cost associated with a spurious trip.

The objective of this technical report is to provide users with techniques for the evaluation of the hardware safety integrity of SIF (PFD_{avg}) and the determination of $MTTF^{spurious}$. Methods of modeling systematic failures are also presented so a quantitative analysis can be performed if the systematic failure rates are known.

ISA-TR84.00.02-2002 shows how to model complete SIF, which includes the sensors, the logic solver and final elements. To the extent possible the system analysis techniques allow these elements to be independently analyzed. This allows the safety system designer to select the proper system configuration to achieve the required safety integrity level.

ISA-TR84.00.02-2002 - Part 1 provides

- a detailed listing of the definition of all terms used in this document. These are consistent with the ANSI/ISA-84.01-1996, IEC 61508 and IEC 61511 standards.
- the background information on how to model all the elements or components of a SIF. It focuses on the hardware components, provides some component failure rate data that are used in the examples calculations and discusses other important parameters such as common cause failures and functional failures.
- a brief introduction to the methodologies that will be used in the examples shown in this document. They are Simplified equations ⁽³⁾, Fault Tree Analysis ⁽⁴⁾, and Markov Analysis ⁽⁵⁾.

ISA-TR84.00.02-2002 - Part 2 provides simplified equations for calculating the SIL values for Demand Mode Safety Instrumented Functions (SIF) installed in accordance with ANSI/ISA-84.01-1996, "Applications of Safety Instrumented Systems for the Process Industries." Part 2 should not be interpreted as the only evaluation technique that might be used. It does, however, provide the engineer(s) performing design for a SIS with an overall technique for assessing the capability of the designed SIF.

ISA-TR84.00.02-2002 - Part 3 provides fault tree analysis techniques for calculating the SIL for Demand Mode Safety Instrumented Functions (SIF) installed in accordance with ANSI/ISA-84.01-1996, "Applications of Safety Instrumented Systems for the Process Industries." Part 3 should not be interpreted as the only evaluation technique that might be used. It does, however, provide the engineer(s) performing design for a SIS with an overall technique for assessing the capability of the designed SIF.

ISA-TR84.00.02-2002 - Part 4 provides Markov analysis techniques for calculating the SIL values for Demand Mode Safety Instrumented Functions (SIF) installed in accordance with ANSI/ISA-84.01-1996, "Applications of Safety Instrumented Systems for the Process Industries." Part 4 should not be interpreted as the only evaluation technique that might be used. It does, however, provide the engineer(s) performing design for a SIS with an overall technique for assessing the capability of the designed SIF.

ISA-TR84.00.02-2002 - Part 5 addresses the logic solver only, using Markov Models for calculating the PFD of E/E/PE logic solvers because it allows the modeling of maintenance and repairs as a function of time, treats time as a model parameter, explicitly allows the treatment of diagnostic coverage, and models the systematic failures (i.e., operator failures, software failures, etc.) and common cause failures.

Figure I.3 illustrates the relationship of each part to all other parts.

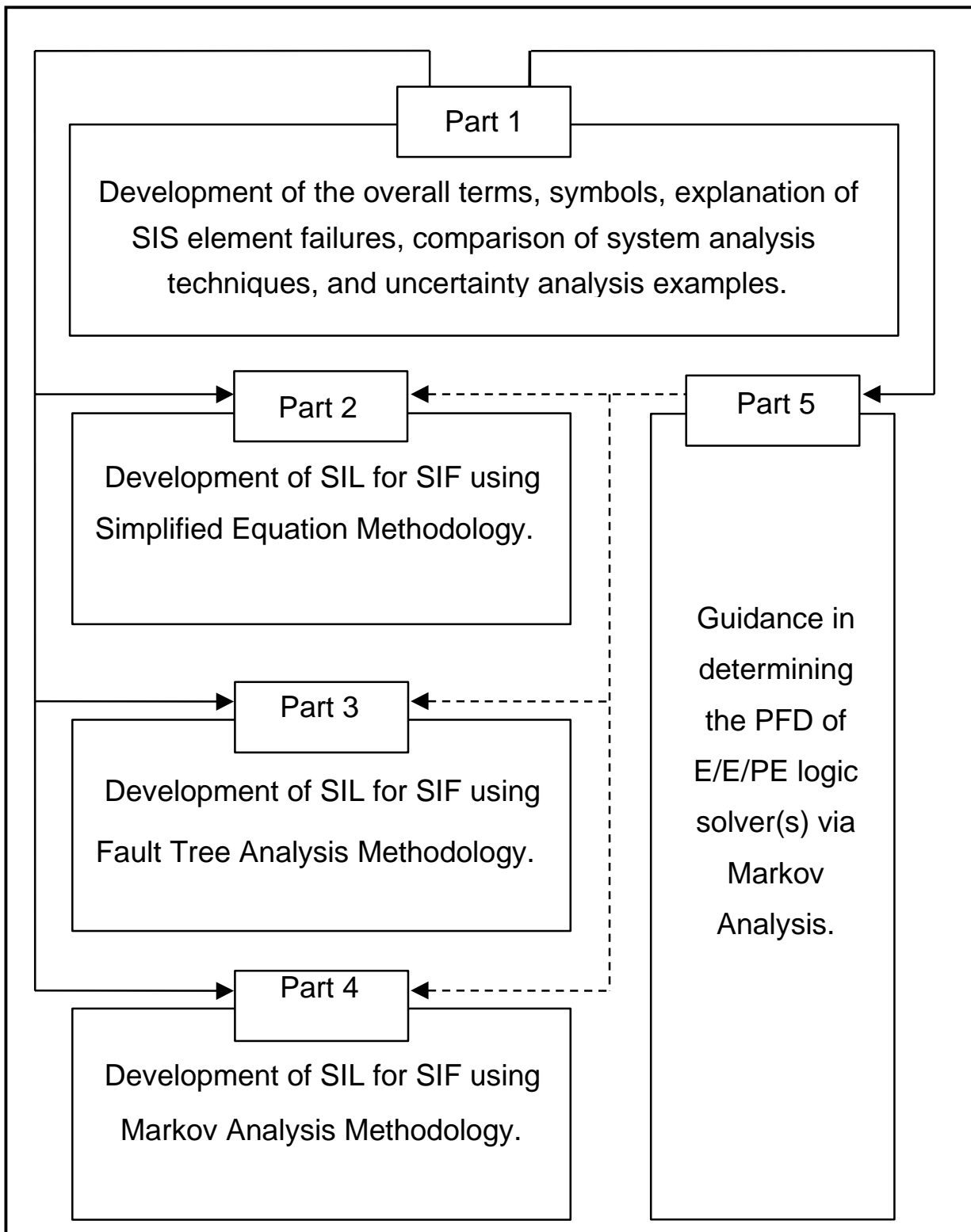


Figure I.3 — ISA-TR84.00.02-2002 Overall Framework

1 Scope

1.1 ISA-TR84.00.02-2002 - Part 1 is informative and does not contain any mandatory clauses. ISA-TR84.00.02-2002 is intended to be used only with a thorough understanding of ANSI/ISA-84.01-1996 (see Figure I.1). Prior to proceeding with use of ISA-TR84.00.02-2002 in a safety application, the Hazards and Risk Analysis must have been completed and the following information provided

- a) It is determined that a SIS is required.
- b) Each safety instrumented function to be carried out by the SIS(s) is defined.
- c) The SIL for each safety instrumented function is defined.

1.2 ISA-TR84.00.02-2002 - Part 1 provides

- a) guidance in Safety Integrity Level analysis;
- b) methods to implement Safety Instrumented Functions (SIF) to achieve a specified SIL;
- c) discussion of failure rates and failure modes (Annex D) of SIS and their components;
- d) discussion of diagnostic coverage, covert faults, common cause, systematic failures, redundancy of SIF;
- e) tool(s) for verification of SIL; and
- f) discussion of the effect of functional test interval.

1.3 The objective of ISA-TR84.00.02-2002 - Part 1 is to introduce the reader to the performance based approach for evaluating the reliability of SIF and to present system reliability methodologies that can be used to evaluate the system performance parameters, namely, the probability that the SIF fails to respond to a demand and the probability that the SIF creates a nuisance trip. ISA-TR84.00.02-2002 - Part 1 serves as an introduction for all other parts.

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3 Definitions of terms and symbols

3.1 Definition of terms

3.1.1 application program:
see "application software."

3.1.2 application software:
see "software."

3.1.3 architecture:
the arrangement of hardware and/or software elements in a system e.g., (1) arrangement of safety instrumented system (SIS) subsystems; (2) internal structure of a SIS subsystem; (3) arrangement of software programs; (4) voting.

3.1.4 availability:
see "safety availability."

3.1.5 Basic Process Control System (BPCS):
a system which responds to input signals from the process, its associated equipment, other programmable systems and/or an operator and generates output signals causing the process and its associated equipment to operate in the desired manner but which does not perform any safety instrumented functions with a claimed SIL ≥ 1 . Some examples include control of an exothermic reaction, anti-surge control of a compressor, and fuel/air controls in fired heaters. Also referred to as the Process Control System.

3.1.6 channel:

a channel is an element or a group of elements that independently perform(s) a function. The elements within a channel could include input/output(I/O) modules, logic system, sensors, and final elements. The term can be used to describe a complete system, or a portion of a system (for example, sensors or final elements).

NOTE A dual channel (i.e., a two channel) configuration is one with two channels that independently perform the same function.

3.1.7 common cause:

3.1.7.1. common cause fault:

a single fault that will cause failure in two or more channels of a multiple channel system. The single source may be either internal or external to the system.

3.1.7.2 common cause failure:

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 a system failure.

3.1.8 communication:

3.1.8.1 external communication:

data exchange between the SIS and a variety of systems or devices that are outside the SIS. These include shared operator interfaces, maintenance/engineering interfaces, data acquisition systems, host computers, etc.

3.1.8.2 internal communication:

data exchange between the various devices within a given SIS. These include bus backplane connections, the local or remote I/O bus, etc.

3.1.9 coverage:

see "diagnostic coverage."

3.1.10 overt:

see "undetected."

3.1.11 Cumulative Distribution Function (CDF):

the integral, from zero to infinity, of the failure rate distribution and takes values between zero and one.

3.1.12 dangerous failure:

a failure which has the potential to put the safety instrumented function in a hazardous or fail-to-function state.

NOTE Whether or not the potential is realised may depend on the channel architecture of the system; in systems with multiple channels to improve safety, a dangerous hardware failure is less likely to lead to the overall hazardous or fail-to-function state.

3.1.13 decommissioning:

the permanent removal of a complete SIS from active service.

3.1.14 de-energize to trip:

SIS circuits where the outputs and devices are energized under normal operation. Removal of the source of power (e.g., electricity, air) causes a trip action.

3.1.15 demand:

a condition or event that requires the SIS to take appropriate action to prevent a hazardous event from occurring or to mitigate the consequence of a hazardous event.

3.1.16 detected:

in relation to hardware and software, detected by the diagnostic tests, or through normal operation.

NOTE 1 For example, physical inspection and manual tests, or through normal operation.

NOTE 2 These adjectives are used in detected fault and detected failure.

NOTE 3 Synonyms include: revealed and overt.

3.1.17 diagnostic coverage:

the diagnostic coverage of a component or subsystem is the ratio of the detected failure rates to the total failure rates of the component or subsystem as detected by automatic diagnostic tests.

NOTE 1 Diagnostic coverage factor is synonymous with diagnostic coverage.

NOTE 2 The diagnostic coverage is used to compute the detected (λ_D) and undetected failure rates (λ_U) from the total failure rate (λ_T) as follows: $\lambda_D = DC \times \lambda_T$ and $\lambda_U = (1-DC) \times \lambda_T$

NOTE 3 Diagnostic coverage is applied to components or subsystems of a safety instrumented system. For example the diagnostic coverage is typically determined for a sensor, final element, or a logic solver.

NOTE 4 For safety applications the diagnostic coverage is typically applied to the safe and dangerous failures of a component or subsystem. For example the diagnostic coverage for the dangerous failures of a component or subsystem is $DC = \lambda_{DD}/\lambda_{DT}$, where λ_{DD} is the dangerous detected failure rates and λ_{DT} is the total dangerous failure rate.

3.1.18 diverse:

use of different technologies, equipment or design methods to perform a common function with the intent to minimize common cause faults.

3.1.19 Electrical (E)/ Electronic (E)/ Programmable Electronic Systems (PES) [E/E/PES]:

when used in this context, electrical refers to logic functions performed by electromechanical techniques, (e.g., electromechanical relay, motor driven timers, etc.), electronic refers to logic functions performed by electronic techniques, (e.g., solid state logic, solid state relay, etc.), and programmable electronic system refers to logic performed by programmable or configurable devices [e.g., Programmable Logic Controller (PLC), Single Loop Digital Controller (SLDC), etc.]. Field devices are not included in E/E/PES.

3.1.20 Electronic (/E):

see "E/E/PES."

3.1.21 embedded software:

see "software."

3.1.22 energize to trip:

SIS circuits where the outputs and devices are de-energized under normal operation. Application of power (e.g., electricity, air) causes a trip action.

3.1.23 Equipment Under Control (EUC):

equipment, machinery, operations or plant used for manufacturing, process, transportation, medical or other activities. In IEC 61511, the term "process" is used instead of Equipment Under Control to reflect process sector usage.

3.1.24 fail-to-danger:

the state of a SIF in which the SIF cannot respond to a demand. Fail-to-function is used in this document (see fail-to-function).

3.1.25 fail-to-function:

the state of a SIF during which the SIF cannot respond to a demand.

3.1.26 fail-safe:

the capability to go to a predetermined safe state in the event of a specific malfunction.

3.1.27 failure:

the termination of the ability of a functional unit to perform a required function.

NOTE 1 Performance of required functions necessarily excludes certain behaviour, and some functions may be specified in terms of behaviour to be avoided. The occurrence of such behaviour is a failure.

NOTE 2 Failures are either random or systematic.

3.1.28 failure rate:

the average rate at which a component could be expected to fail.

3.1.29 fault:

an abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function.

3.1.30 fault tolerance:

built-in capability of a system to provide continued correct execution of its assigned function in the presence of a limited number of hardware and software faults.

3.1.31 field devices:

equipment connected to the field side of the SIS logic solver I/O terminals. Such equipment includes field wiring, sensors, final control elements and those operator interface devices hard-wired to SIS logic solver I/O terminals.

3.1.32 final element:

the part of a safety instrumented system which implements the physical action necessary to achieve a safe state.

NOTE 1 Examples are valves, switch gear, motors including their auxiliary elements e.g., a solenoid valve and actuator if involved in the safety instrumented function.

NOTE 2 This definition is process sector specific only.

3.1.33 firmware:

special purpose memory units containing embedded software in protected memory required for the operation of programmable electronics.

3.1.34 functional safety:

the ability of a safety instrumented system or other means of risk reduction to carry out the actions necessary to achieve or to maintain a safe state for the process and its associated equipment.

NOTE 1 This term is not used in ANSI/ISA-84.01-1996. It is used in the IEC 61508 and IEC 61511 standards.

NOTE 2 This definition is from IEC 61511 and it deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.35 functional safety assessment:

an investigation, based on evidence, to judge the functional safety achieved by one or more protection layers.

NOTE 1 This term is not used in ANSI/ISA-84.01-1996. It is used in the IEC 61508 and IEC 61511 standards.

NOTE 2 This definition is from IEC 61511 and it deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.36 functional safety audit:

a systematic and independent examination to determine whether the procedures specific to the functional safety requirements comply with the planned arrangements, are implemented effectively and are suitable to achieve the specified objectives.

NOTE A functional safety audit may be carried out as part of a functional safety assessment.

3.1.37 functional testing:

periodic activity to verify that the devices associated with the SIS are operating per the Safety Requirements Specification. May also be called the proof testing or full function testing.

3.1.38 hardware configuration:

see “architecture.”

3.1.39 harm:

physical injury or damage to the health of people either directly, or indirectly as a result of damage to property or to the environment.

3.1.40 hazard:

potential source of harm.

NOTE The term includes danger to persons arising within a short time scale (for example, fire and explosion) and also those that have a long term effect on a person's health (for example, release of a toxic substance).

3.1.41 Hazard and Operability Study (HAZOP):

a systematic qualitative technique to identify process hazards and potential operating problems using a series of guide words to study process deviation. A HAZOP is used to examine every part of the process to discover that deviations from the intention of the design can occur and what their causes and consequences may be. This is done systematically by applying suitable guidewords. This is a systematic detailed review technique for both batch or continuous plants which can be applied to new or existing process to identify hazards.

3.1.42 input function:

a function which monitors the process and its associated equipment in order to provide input information for the logic solver

NOTE 1 An input function could be a manual function.

NOTE 2 This definition is process sector specific only.

3.1.43 input/output modules:

3.1.43.1 input module:

E/E/PES or subsystem that acts as the interface to external devices and converts input signals into signals that the E/E/PES can utilize.

3.1.43.2 output module:

E/E/PES or subsystem that acts as the interface to external devices and converts output signals into signals that can actuate field devices.

3.1.44 logic function:

a function which performs the transformations between input information (provided by one or more input functions) and output information (used by one or more output functions). Logic functions provide the transformation from one or more input functions to one or more output functions.

3.1.45 logic solver:

that portion of either a BPCS or SIS that performs one or more logic function(s).

NOTE 1 In ANSI/ISA-84.01-1996 and IEC 61511 the following logic systems are used:

- electrical logic systems for electro-mechanical technology;
- electronic logic systems for electronic technology;
- PE logic systems for programmable electronic systems.

NOTE 2 Examples are: electrical systems, electronic systems, programmable electronic systems, pneumatic systems, hydraulic systems, etc. Sensors and final elements are not part of the logic solver.

NOTE 3 This term deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.46 mean time to fail - spurious ($MTTF^{spurious}$):

the mean time to a failure of the SIS which results in a spurious or false trip of the process or equipment under control (EUC).

3.1.47 mean time to repair (MTTR):

the mean time to repair a module or element of the SIS. This mean time is measured from the time the failure occurs to the time the repair is completed and device returned to service (see $MTTR_{OT}$).

3.1.48 off-line:

process, to which the SIS is connected, is shutdown.

3.1.49 on-line:

process, to which the SIS is connected, is operating.

3.1.50 output function:

function which controls the process and its associated equipment according to final actuator information from the logic function.

NOTE This definition is process sector specific only.

3.1.51 overt:

see "detected."

3.1.52 preventive maintenance:

maintenance practice in which equipment is maintained on the basis of a fixed schedule, dictated by manufacturer's recommendation or by accumulated data from operating experience.

3.1.53 Probability of Failure on Demand (PFD):

a value that indicates the probability of a system failing to respond to a demand. The average probability of a system failing to respond to a demand in a specified time interval is referred to as PFD_{avg} . PFD equals 1 minus Safety Availability. It is also referred to as safety unavailability or fractional dead time.

3.1.54 Probability to Fail Safe (PFS):

a value that looks at all failures and indicates the probability of those failures that are in a safe mode.

3.1.55 process Industries:

refers to those industries with processes involved in, but not limited to, the production, generation, manufacture, and/or treatment of oil, gas, wood, metals, food, plastics petrochemicals, chemical, steam, electric power, pharmaceuticals and waste material(s). The various process industries together make up the process sector – a term used in IEC standards.

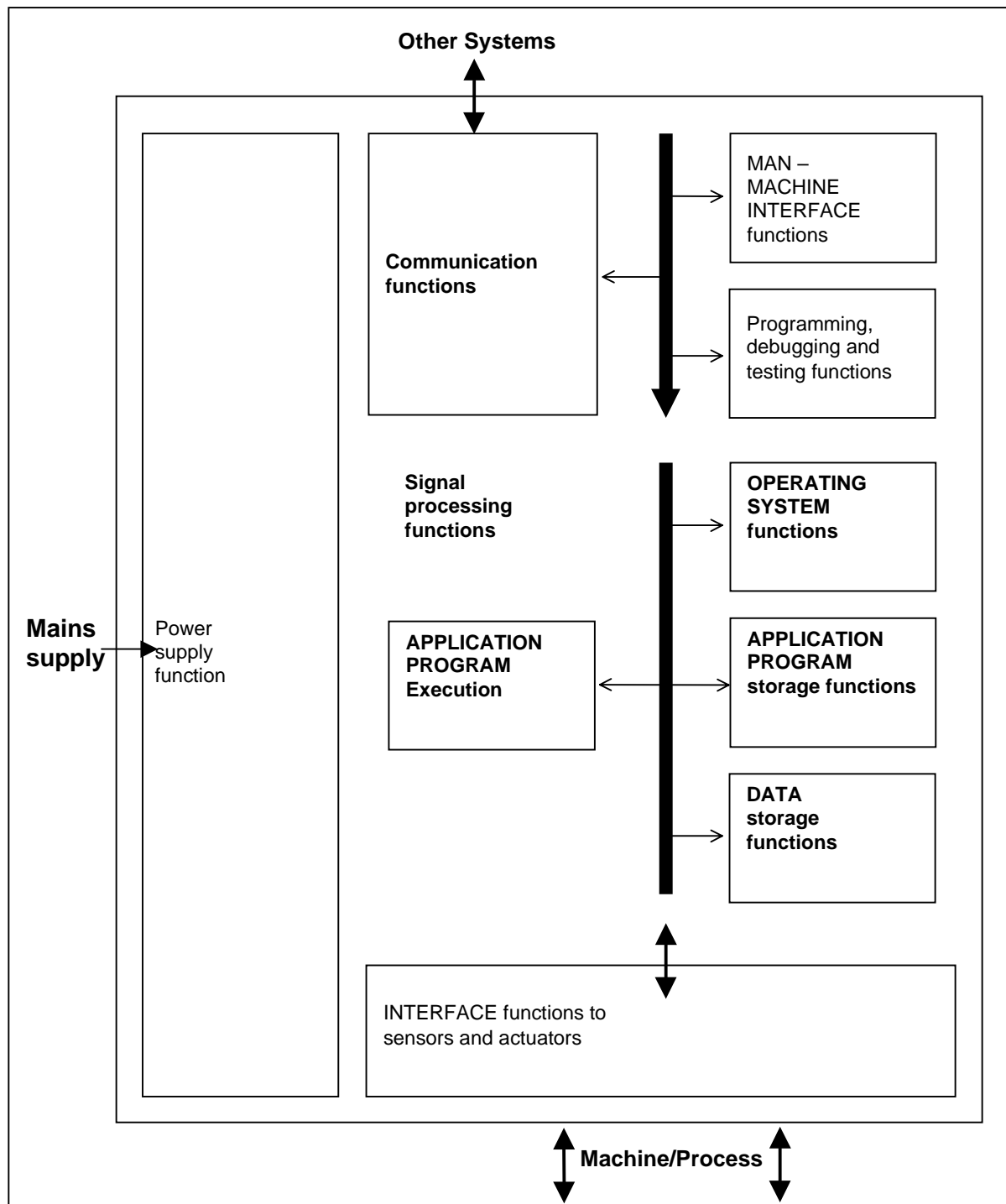
3.1.56 programmable electronics (PE):

electronic component or device forming part of a PES and based on computer technology. The term encompasses both hardware and software and input and output units.

NOTE 1 This term covers micro-electronic devices based on one or more central processing units (CPUs) together with associated memories, etc. Examples of process sector programmable electronics include:

- smart sensors;
- programmable electronic logic solvers including:
- programmable controllers;
- programmable logic controllers (PLC) (see figure 3.1);
- distributed control system (DCS);
- loop controllers; and
- smart final elements.

NOTE 2 This term differs from the definition in IEC 61508-4 to reflect differences in the process sector.



**Figure 3.1 – Structure and function of PLC system
(copied from IEC 61131)**

3.1.57 programmable electronic system (PES):

a system *for control, protection or monitoring* based on one or more programmable electronic devices, including all elements of the system such as power supplies, sensors and other input devices, data highways and other communication paths, actuators and other output devices (see Figure 3.2).

NOTE The structure of a PES is shown in Figure 3.2 (A). (B) illustrates the way in which a PES is represented with the programmable electronics shown as a unit distinct from sensors and actuators on the process and their interfaces but the programmable electronics could exist at several places in the PES. (C) illustrates a PES with two discrete units of programmable electronics. (D) illustrates a PES with dual programmable electronics (i.e., two channels) but with a single sensor and a single actuator. (E) illustrates a system based on non-programmable hardware.

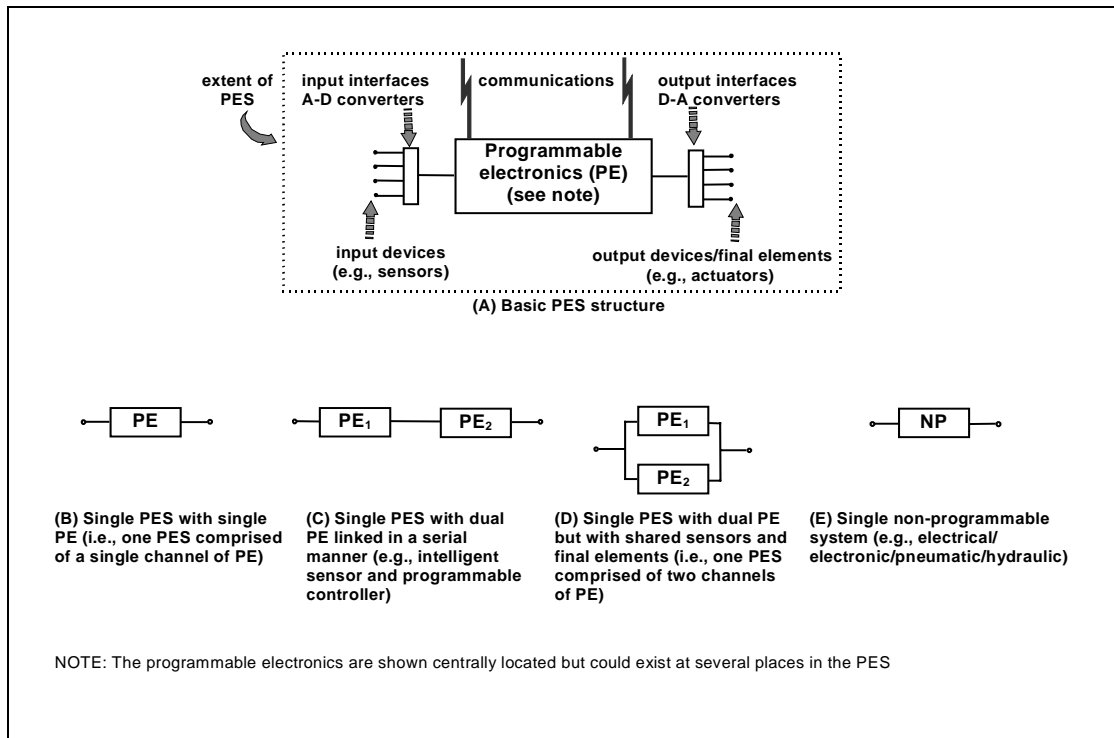


Figure 3.2 – Programmable electronic system (PES): structure and terminology

3.1.58 proof testing:
see “functional testing.”

3.1.59 protection layer:
any independent mechanism that reduces risk by control, prevention or mitigation.

NOTE 1 It could be a process engineering mechanism, such as the size of vessels containing hazardous chemicals; a mechanical engineering mechanism, such as a relief valve; a safety instrumented system; or an administrative procedure, such as an emergency plan against an imminent hazard. These responses may be automated or initiated by human actions.

NOTE 2 This term deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.60 qualitative methods:
methods of design and evaluation developed through experience or the application of good engineering judgement.

3.1.61 quantitative methods:
methods of design and evaluation based on numerical data and mathematical analysis.

3.1.62 random hardware failure:

failure occurring at random time, which results from one or more of the possible degradation mechanisms in the hardware.

NOTE 1 There are many degradation mechanisms occurring at different rates in different components and since manufacturing tolerances cause components to fail due to these mechanisms after different times in operation, failures of a total equipment comprising many components occur at predictable rates but at unpredictable (i.e., random) times.

NOTE 2 A major distinguishing feature between random hardware failures and systematic failures (see definition below), is that system failure rates (or other appropriate measures), arising from random hardware failures, can be predicted with reasonable accuracy but systematic failures, by their very nature, cannot be accurately predicted. That is, system failure rates arising from random hardware failures can be quantified with reasonable accuracy but those arising from systematic failures cannot be accurately statistically quantified because the events leading to them cannot easily be predicted.

3.1.63 redundancy:

use of multiple elements or systems to perform the same function. Redundancy can be implemented by identical elements (identical redundancy) or by diverse elements (diverse redundancy).

NOTE 1 Examples are the use of duplicate functional components and the addition of parity bits.

NOTE 2 Redundancy is used primarily to improve reliability or availability.

3.1.64 reliability:

probability that a system can perform a defined function under stated conditions for a given period of time.

3.1.65 reliability block diagram:

the reliability block diagram can be thought of as a flow diagram from the input of the system to the output of the system. Each element of the system is a block in the reliability block diagram and, the blocks are placed in relation to the SIS architecture to indicate that a path from the input to the output is broken if one (or more) of the elements fail.

3.1.66 risk:

the combination of the probability of occurrence of harm and the severity of that harm.

3.1.67 risk assessment:

process of making risk estimates and using the results to make decisions.

3.1.68 safe failure:

a failure which does not have the potential to put the safety instrumented function in a dangerous or fail-to-function state.

NOTE Other used names for safe failures are: nuisance failure, spurious failure, false trip failure or fail to safe failure.

3.1.69 safe failure fraction (SFF):

the fraction of the overall failure rate of a device that results in either a safe failure or a detected unsafe failure.

3.1.70 safety:

freedom from unacceptable risk.

3.1.71 safe state:

state of the process when safety is achieved.

NOTE 1 In going from a potentially hazardous condition to the final safe state the process may have to go through a number of intermediate safe-states. For some situations a safe state exists only so long as the process is continuously controlled. Such continuous control may be for a short or an indefinite period of time.

NOTE 2 This term deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.72 safety availability:

probability that a SIS is able to perform its designated safety service when the process is operating. The average Probability of Failure on Demand (PFD_{avg}) is the preferred term. (PFD equals 1 minus Safety Availability).

3.1.73 safety function:

a function to be implemented by a SIS, other technology safety-related system or external risk reduction facilities, which is intended to achieve or maintain a safe state for the process, in respect of a specific hazardous event.

NOTE This term deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.74 safety instrumented function (SIF):

an E/E/PE safety function with a specified safety integrity level which is necessary to achieve functional safety.

NOTE This definition is process sector specific only.

3.1.75 safety instrumented system (SIS):

implementation of one or more safety instrumented functions. A SIS is composed of any combination of sensor(s), logic solver(s), and final element(s) (e.g., see Figure 3.3) Other terms commonly used include Emergency Shutdown System (ESD, ESS), Safety Shutdown System (SSD), and Safety Interlock System.

NOTE SIS may or may not include software.

SIS architecture and safety instrumented function example with different devices shown.

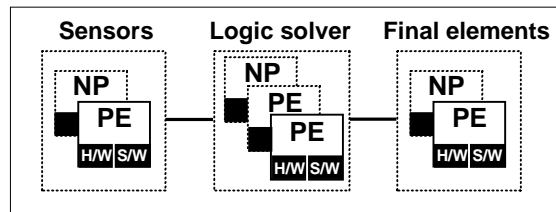


Figure 3.3 – Example SIS architecture

3.1.76 safety integrity:

the probability of a SIF satisfactorily performing the required safety functions under all stated conditions within a stated period of time.

NOTE 1 The higher the level of safety integrity of the safety instrumented function (SIF), the lower the probability that the SIF should fail to carry out the required safety instrumented functions.

NOTE 2 ANSI/ISA-84.01-1996 recognizes three levels of safety integrity for safety instrumented functions. IEC 61508 and IEC 61511 recognize four levels of safety integrity.

NOTE 3 In determining safety integrity, all causes of failures (both random hardware failures and systematic failures) which lead to an unsafe state should be included; for example, hardware failures, software induced failures and failures due to electrical interference. Some of these types of failure, in particular random hardware failures, may be quantified using such measures as the failure rate in the dangerous mode of failure or the probability of a safety instrumented function failing to operate on demand.

However, the safety integrity of a SIF also depends on many factors, which cannot be accurately quantified but can only be considered qualitatively.

NOTE Safety integrity comprises hardware safety integrity and systematic safety integrity.

3.1.77 safety integrity level (SIL):

discrete level (one out of four) for specifying the safety integrity requirements of the safety instrumented functions to be allocated to the safety instrumented systems. Safety integrity level 4 has the highest level of safety integrity; safety integrity level 1 has the lowest.

NOTE 1 ANSI/ISA-84.01-1996 recognizes only three Safety Integrity Levels. The above definition is used in this document to provide compatibility with IEC 61508 and IEC 61511.

NOTE 2 The target failure measures for the safety integrity levels are specified in Table 3.1.

NOTE 3 It is possible to use several lower safety integrity level systems to satisfy the need for a higher level function (e.g., using a SIL 2 and a SIL 1 system together to satisfy the need for a SIL 3 function). See IEC 61511-2 for guidance on how to apply this principle.

NOTE 4 This term differs from the definition in IEC 61508-4 to reflect differences in the process sector.

Table 3.1 — Safety integrity level (SIL) target ranges

Safety Integrity Level (SIL)	Target Range Probability of Failure on Demand Average (PFD _{avg})
1	10^{-1} to 10^{-2}
2	10^{-2} to 10^{-3}
3	10^{-3} to 10^{-4}
4	10^{-4} to 10^{-5}

3.1.78 safety lifecycle:

the necessary activities involved in the implementation of safety instrumented function(s), occurring during a period of time that starts at the concept phase of a project and finishes when all of the safety instrumented functions are no longer available for use.

NOTE The term “functional safety lifecycle” is strictly more accurate, but the adjective “functional” is not considered necessary in this case within the context of this technical report.

3.1.79 safety requirements specification:

the specification that contains all the requirements of the safety instrumented functions that have to be performed by the safety instrumented systems.

3.1.80 sensor:

a device or combination of devices, which measure the process condition (e.g., transmitters, transducers, process switches, position switches, etc.).

NOTE This definition is process sector specific only.

3.1.81 separation:

the use of multiple devices or systems to segregate control from safety instrumented functions. Separation can be implemented by identical elements (identical separation) or by diverse elements (diverse separation).

3.1.82 SIS components:

a constituent part of a SIS. Examples of SIS components are field devices, input modules, and logic solvers.

3.1.83 software:

an intellectual creation comprising the programs, procedures, data, rules and any associated documentation pertaining to the operation of a data processing system.

NOTE Software is independent of the medium on which it is recorded.

3.1.84 software languages in SIS subsystems:

3.1.84.1 fixed program language (FPL):

this type of language is represented by the many proprietary, dedicated-function systems which are available as standard process industry products.

The functional specification of the FPL should be documented either in the suppliers' data sheets, user manual or the like.

The user should be unable to alter the function of the product, but limited to adjust a few parameters (e.g., range of the pressure transmitter).

NOTE Typical example of systems with FPL: smart sensor (e.g., pressure transmitter), sequence of events controller, dedicated smart alarm box, small data logging systems.

3.1.84.2 limited variability language (LVL):

this type of language is a more flexible language which provides the user with some capability for adjusting it to his own specific requirements. The safety instrumented functions are configured by the use of an application-related language and the specialist skills of a computer programmer are not required.

The documentation of the LVL should consist of a comprehensive specification which defines the basic functional components and the method of configuring them into an application program. In addition an engineering tool and a library of application specific functions should be given together with a user manual.

The user should be able to configure/program the required application functions according to the functional requirement specification.

NOTE 1 Typical examples of LVL are ladder logic, function block diagram and sequential function chart.

NOTE 2 Typical example of a system using LVL is a standard programmable logic controller (PLC) performing burner management.

3.1.84.3 full variability language (FVL):

this type of language is general-purpose computer-based, equipped with an operating system which usually provides system resource allocation and a real-time multi-programming environment. The language is tailored for a specific application by computer specialists, using high level languages.

The FVL application will often be unique for a specific application. As a result most of the specification will be special-to-project.

NOTE 1 Typical example of a system using FVL is a personal computer which performs supervisory control or process modeling.

NOTE 2 In the process sector FVL is found in embedded software and rarely in application software.

NOTE 3 FVL examples include: ADA, C, Pascal.

NOTE 4 This definition is process sector specific only.

3.1.85 software program types:

3.1.85.1 application software:

software specific to the user application in that it is the SIS functional description programmed in the PES to meet the overall Safety Requirement Specifications. In general, it contains logic sequences, permissives, limits, expressions, etc., that control the appropriate input, output, calculations, decisions necessary to meet the safety instrumented functional requirements. See fixed and limited variability software language.

3.1.85.2 system software:

software that is part of the system supplied by the manufacturer and is not accessible for modification by the end user. Embedded software is also referred to as firmware or system software.

3.1.85.3 utility software:

software tools for the creation, modification, and documentation of application programs. These software tools are not required for the operation of the SIS.

NOTE This definition is process sector specific only.

3.1.86 software lifecycle:

the activities occurring during a period of time that starts when software is conceived and ends when the software is permanently disused.

NOTE 1 A software lifecycle typically includes a requirements phase, development phase, test phase, integration phase, installation phase and modification phase.

NOTE 2 Software cannot be maintained; rather, it is modified.

3.1.87 spurious trip:

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

3.1.88 Spurious Trip Rate (STR):

the expected rate (number of trips per unit time) at which a trip of the SIF can occur for reasons not associated with a problem in the process that the SIF is designed to protect (e.g., the trip resulted due to a hardware fault, software fault, electrical fault, transient, ground plane interference⁽¹²⁾, etc.). Other terms used include nuisance trip rate and false shutdown rate.

3.1.89 systematic failure:

failure related in a deterministic way to a certain cause, which can only be eliminated by a modification of the design or of the manufacturing process, operational procedures, documentation or other relevant factors.

NOTE 1 Corrective maintenance without modification should usually not eliminate the failure cause.

NOTE 2 A systematic failure can be induced by simulating the failure cause.

NOTE 3 Example causes of systematic failures include human error in:

- the safety requirements specification;
- the design, manufacture, installation and operation of the hardware;
- the design, implementation, etc. of the software.

3.1.90 Test Interval (TI):

time between functional tests. Test interval is the amount of time that lapses between functional tests performed on the SIS or a component of the SIS to validate its operation.

3.1.91 undetected:

in relation to hardware and software, not found by the diagnostic tests or during normal operation.

NOTE 1 For example, physical inspection and manual tests, or through normal operation.

NOTE 2 These adjectives are used in undetected fault and undetected failure.

NOTE 3 Synonyms include: unrevealed and covert.

NOTE 4 This term deviates from the definition in IEC 61508-4 to reflect differences in the process sector.

3.1.92 utility software:

see “software.”

3.1.93 verification:

process of confirming for certain steps of the Safety Life Cycle that the objectives are met.

3.1.94 voting system:

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

3.1.95 watchdog:

a combination of diagnostics and an output device (typically a switch) for monitoring the correct operation of the programmable electronic (PE) device and taking action upon detection of an incorrect operation.

NOTE 1 The watchdog confirms that the software system is operating correctly by the regular resetting of an external device (e.g., hardware electronic watchdog timer) by an output device controlled by the software.

NOTE 2 The watchdog can be used to de-energize a group of safety outputs when dangerous failures are detected in order to put the process into a safe state. The watchdog is used to increase the on-line diagnostic coverage of the PE logic solver.

NOTE 3 This definition is process sector specific only.

3.2 Definition of symbols

NOTE Symbols specific to the analysis of the logic solver portion are included in ISA-TR84.00.02-2002 - Part 5.

β is the fraction of single module or circuit failures that result in the failure of an additional module or circuit. Hence two modules or circuits performing the same function fail. This parameter is used to model common cause failures that are related to hardware failures.

β_D is the fraction of a single module or circuit failures that result in the failure of an additional module or circuit taking diagnostic coverage into account.

C	is the diagnostic coverage factor. It is the fraction of failures that are detected by on-line diagnostics.
C^D	is the fraction of dangerous failures that are detected by on-line diagnostics.
C^S	is the fraction of safe failures that are detected by on-line diagnostics.
C^D_A	is the fraction of dangerous final element failures that are detected by on-line diagnostics.
C^D_S	is the fraction of dangerous sensor failures that are detected by on-line diagnostics.
C^S_A	is the fraction of safe final element failures that are detected by on-line diagnostics.
C^S_S	is the fraction of safe sensor failures that are detected by on-line diagnostics.
C^D_{IC}	is the fraction of dangerous input circuit failures that are detected by on-line diagnostics.
C^D_{IP}	is the fraction of dangerous input processor failures that are detected by on-line diagnostics.
C^D_{MP}	is the fraction of dangerous main processor failures that are detected by on-line diagnostics.
C^D_{OC}	is the fraction of dangerous output circuit failures that are detected by on-line diagnostics.
C^D_{OP}	is the fraction of dangerous output processor failures that are detected by on-line diagnostics.
C^D_{PS}	is the fraction of dangerous power supply failures that are detected by on-line diagnostics.
C^S_{IC}	is the fraction of safe input circuit failures that are detected by on-line diagnostics.
C^S_{IP}	is the fraction of safe input processor failures that are detected by on-line diagnostics.
C^S_{MP}	is the fraction of safe main processor failures that are detected by on-line diagnostics.
C^S_{OC}	is the fraction of safe output circuit failures that are detected by on-line diagnostics.

C_{OP}^S	is the fraction of safe output processor failures that are detected by on-line diagnostics.
C_{PS}^S	is the fraction of safe power supply failures that are detected by on-line diagnostics.
f_{ICO}	is the average number of output modules affected by the failure of an input circuit on an input module (typically $f_{ICO} = f_{IPO}/n_{IC}$).
f_{IPO}	is the average number of output modules affected by the failure of the input processor on an input module (typically $f_{IPO} = m/n$).
f_{OCI}	is the average number of output circuits on output modules affected by the failure of an input module (typically $f_{OCI} = f_{OPI}/n_{OC}$).
f_{OPI}	is the average number of output processors on output modules affected by the failure of an input module (typically $f_{OPI} = 1/f_{IPO}$).
k	is the number of watchdog circuit devices in one channel or leg of a PES.
l	is the number of power supplies in one channel or leg of an E/E/PES.
m	is the number of output modules in one channel or leg of an E/E/PES.
$MTTF^D$	is the mean time to the occurrence of a dangerous event. Dimension (Time)
$MTTF^{spurious}$	is the mean time to the occurrence of a spurious trip. This is also referred to as the mean time to the occurrence of a safe system failure. Dimension (Time)
$MTTR_{OT}$	is the mean time to repair failures that are detected through on-line tests. Dimension (Time)
$MTTR_{PT}$	is the mean time to repair failures that are detected through periodic testing off-line. This time is essentially equal to one half the time between the periodic off-line tests ($TI/2$) (see $MTTR_{OT}$). Dimension (Time)
n	is the number of input modules in one channel or leg of an E/E/PES.
n_{IC}	is the number of input circuits on an input module.

n_{OC}	is the number of output circuits on an output module.
P	is probability vector.
PFD	is the probability of failure on demand (See definition in Clause 3.1). Dimensionless
PFD_A	is the average probability of the final elements failing to respond to a process demand. (PFD_{Ai} is used to indicate PFD_A for a final element configuration).
PFD_L	is the average probability of the logic solver failing to respond to a process demand.
PFD_S	is the average probability of the sensor failing to respond to a process demand.
PFD_{PS}	is the average probability of the power supply failing to respond to a process demand.
PFD_{avg}	is the average probability of the SIF failing to respond to a process demand. It is commonly referred to as the average probability of failure on demand. It is also referred to as average safety unavailability or average fractional dead time. Dimensionless
PFD_{SIS}	See PFD_{avg} .
PFS	Probability to Fail Safe.
p_n	is conditional probability.
P_{xm}	is the probability density function of input parameter X_m .
P_y	is the probability density function of output y .
q	is the number of time steps.
S	is the value of β (for undetected failures).
S_D	is the value of β_D (for detected failures).
SFF	is the safe failure fraction.

STR_A	is the safe failure rate for all final elements. (STR_{Ai} is used to indicate STR_A for a final element configuration).
STR_L	is the safe failure rate for all logic solvers.
STR_S	is the safe failure rate for all sensors.
STR_{PS}	is the safe failure rate for all power supplies.
STR_{SIS}	is the safe failure rate for the SIS.
S_y	is the statistical sensitivity of output y.
T	is the Transition Matrix.
TI	is the time interval between periodic off-line testing of the system or an element of the system. Dimension (Time)
X	is the number of successful fault simulation tests.
X_m	is an input parameter used in the Monte Carlo Process.
X_{PE}	is the scoring factor for programmable electronics from Table A.1 that provides credit for automatic diagnostics that are in operation.
X_{SA}	is the scoring factor for sensors and actuators from Table A.1 that provides credit for automatic diagnostics that are in operation.
Y_{PE}	is the scoring factor for sensors and actuators from Table A.1 that provides credit for automatic diagnostics that are in operation.
Y_{SA}	is the scoring factor for sensors and actuators from Table A.1 that corresponds to those measures whose contribution will not be improved by the use of automatic diagnostics.
v	is the rate of external system shocks.
λ	is used to denote the failure rate of a module or a portion of a module [normally expressed in failures per million (10^{-6}) hours].

- λ^C is used to denote the common cause failure rate for a module or portion of a module.
- λ^D is used to denote the dangerous failure rate for a module or portion of a module. These failures can result in a dangerous condition.
- λ^N is the normal mode failure rate.
- λ^S is used to denote the safe or false trip failure rate for a module or portion of a module. These failures typically result in a safe shutdown or false trip.
- λ^{DD} is the dangerous (e.g., fail in a direction that would defeat the purpose of the SIS) detected failure rate for a module or portion of a module. Detected dangerous failures are failures that can be detected by on-line tests. λ^{DD} is computed by multiplying the dangerous failure rate for a module (λ^D) by the diagnostic coverage for dangerous failures (C^D).
- λ^{DU} is used to denote the dangerous undetected (covert) failure rate for a module or portion of a module. Dangerous undetected failures are failures that cannot be detected by on-line tests. λ^{DU} is computed by multiplying the dangerous failure rate for a module (λ^D) by one minus the diagnostic coverage for dangerous failures ($1-C^D$).
- λ^{SD} is the safe detected failure rate for a module or portion of a module. λ^{SD} is equal to $\lambda^S \cdot C^S$.
- λ^{SU} is the safe undetected failure rate for a module or portion of a module. λ^{SU} is equal to $\lambda^S \cdot (1-C^S)$.
- λ^{DDC} is the dangerous detected common cause failure rate.
- λ^{DDN} is the dangerous detected normal mode failure rate.
- λ^{DUC} is the dangerous undetected common cause failure rate.
- λ^{DUN} is the dangerous undetected normal mode failure rate.
- λ^{SDC} is the safe detected common cause failure rate.
- λ^{SDN} is the safe detected normal mode failure rate.

λ^{SUC}	is the safe undetected common cause failure rate.
λ^{SUN}	is the safe undetected normal mode failure rate.
λ_A	is the failure rate for a final element or other output field device.
λ_I	is the failure rate for an input module ($\lambda_I = \lambda_{IP} + n_{IC} \lambda_{IC}$).
λ_D	is the failure rate of a device ($\lambda_D = \lambda^D + \lambda^S$).
λ_I	is the failure rate for an input module ($\lambda_I = \lambda_{IP} + n_{IC} \lambda_{IC}$).
λ_L	is the failure rate for the logic solver.
λ_O	is the failure rate for an output module ($\lambda_O = \lambda_{OP} + n_{OC} \lambda_{OC}$).
λ_P	is the failure rate for physical failures.
λ_S	is the failure rate for a sensor or other input field device.
λ_{IC}	is the failure rate for each individual input circuit on the input module.
λ_{IP}	is the failure rate for the input processor and associated circuitry (portion of input module that is common to all inputs).
λ_{IV}	is the failure rate for the input voter.
λ_{MP}	is the failure rate for the main processor.
λ_{OC}	is the failure rate for each individual output circuit on the output module.
λ_{OP}	is the failure rate for the output processor and associated circuitry (portion of the output module that is common to all output points).

λ_{PS}	is the failure rate for a power supply.
λ_A^D	is the dangerous failure rate for a final element or other output field device.
λ_F^D	is the systematic failure rate that results in a dangerous state of the system. This is used to model systematic failures that affect the operation of all legs of a SIS configuration. Examples include SIS design errors, software implementation errors, wiring errors, human interaction errors, etc.
λ_I^D	is the dangerous failure rate for an input module.
λ_L^D	is the dangerous failure rate for the logic solver.
λ_O^D	is the dangerous failure rate for an output module.
λ_S^D	is the dangerous failure rate for a sensor or other input field device.
λ_A^S	is the safe failure rate for a final element or other output field device.
λ_F^S	is the systematic failure rate that results in a safe state of the system. This is used to model systematic failures that affect the operation of all legs of a SIS configuration, where the cause cannot be related directly to hardware failures. Examples include SIS design errors, software implementation errors, wiring errors, human interaction errors, etc.
λ_I^S	is the safe failure rate for an input module.
λ_L^S	is the safe failure rate for the logic solver.
λ_O^S	is the safe failure rate for an output module.
λ_S^S	is the safe failure rate for a sensor or other input field device.
λ_{FA}^D	is the systematic failure rate that results in a dangerous state of a final element.
λ_{FS}^D	is the systematic failure rate that results in a dangerous state of a sensor.

λ_{IC}^D is the dangerous failure rate for each individual input circuit.

λ_{IP}^D is the dangerous failure rate for the input processor and associated circuitry.

λ_{IV}^D is the dangerous failure rate for the input voter.

λ_{MP}^D is the dangerous failure rate for the main processor.

λ_{OC}^D is the dangerous failure rate for each individual output circuit.

λ_{OP}^D is the dangerous failure rate for the output processor and associated circuitry.

λ_{PS}^D is the dangerous failure rate for a power supply.

λ_{FA}^S is the systematic failure rate that results in a safe state of a final element.

λ_{FS}^S is the systematic failure rate that results in a safe state of a sensor.

λ_{IC}^S is the safe failure rate for each individual input circuit.

λ_{IP}^S is the safe failure rate for the input processor and associated circuitry.

λ_{IV}^S is the safe failure rate for the input voter.

λ_{MP}^S is the safe failure rate for the main processor.

λ_{OC}^S is the safe failure rate for each individual output circuit.

λ_{OP}^S is the safe failure rate for the output processor and associated circuitry.

λ_{PS}^S is the safe failure rate for a power supply.

λ_{LEG}^D is the dangerous failure rate for each individual leg or channel.

λ_{TOTAL}^D is the total dangerous failure rate of the system.

λ_{TOTAL}^S is the total safe failure rate of the system.

λ_{LEG}^{DD} is the dangerous detected failure rate for each individual leg or channel.

λ_{LEG}^{DU} is the dangerous undetected failure rate for each individual leg or channel.

μ_A^D is the effective repair rate for the dangerous failures of the final element.

μ_S^D is the effective repair rate for the dangerous failures of the sensor.

μ_A^S is the effective repair rate for the safe failures of the final element.

μ_S^S is the effective repair rate for the safe failures of the sensor.

μ_{IC}^D is the effective repair rate for the dangerous failures of an individual input circuit.

μ_{IP}^D is the effective repair rate for the dangerous failures of the input processor and associated circuitry.

μ_{MP}^D is the effective repair rate for the dangerous failures of the main processor.

μ_{OC}^D is the effective repair rate for the dangerous failures of an individual output circuit.

μ_{OP}^D is the effective repair rate for the dangerous failures of the output processor and associated circuitry.

μ_{PS}^D is the effective repair rate for the dangerous failures of the power supply.

μ_{OT} is used to denote the repair rate for failures that are detected through on-line tests ($\mu_{OT}=1/MTTR_{OT}$).

μ_{IC}^S is the effective repair rate for the safe failures of an individual input circuit.

μ_{IP}^S is the effective repair rate for the safe failures of the input processor and associated circuitry.

μ_{MP}^S is the effective repair rate for the safe failures of the main processor.

μ_{OC}^S is the effective repair rate for the safe failures of an individual output circuit.

μ_{OP}^S is the effective repair rate for the safe failures of the output processor and associated circuitry.

μ_{PS}^S is the effective repair rate for the safe failures of the power supply.

4 Probability of failure on demand (PFD)

The Probability of Failure on Demand is the measure of safety integrity for the SIF. It is the probability that the safety instrumented function will fail in a manner which will render it incapable of performing its intended safety function. As such, the SIF will be unable to respond to a demand and no safety action (e.g. shutdown) will be initiated. PFD is usually expressed as PFD_{avg} , which is the average value over the functional test interval and is used to define the limits of the three Safety Integrity Levels (SILs), as given in ANSI/ISA-ISA-84.01-1996 (Table 4.1), or four SILs, as given in IEC 61508 and IEC 61511.

To satisfy the requirements of a given SIL, the PFD_{avg} should be less than the upper limit as provided in ANSI/ISA-84.01-1996.

Given the above, we can state that in general:

$$PFD = f(\text{failure rate, repair rate, test interval, common cause, etc.})$$

The specific functionality (f) is an attribute of the system architecture selected for the SIS (E/E/PES and field devices).

The functional test interval is that period of time over which the SIF must operate within the PFD limits of the specified SIL. It could be equal to a "mission time" and should be as long as possible to reduce the possibility of human error associated with frequent functional testing of the SIS.

The dangerous undetected failure rate is strongly impacted by the diagnostic coverage factor of the system (for random hardware failures). Comprehensive internal diagnostics dramatically improves the diagnostic coverage factor; thereby, reducing the possibility of a dangerous undetected failure, and consequently minimizing the PFD.

It is important to recognize that the SIF configuration, including the number and quality of field devices, has a major impact on the PFD for the SIF. If one assumes a single input with a $MTTF^{DU}$ of 30 years, a single output with a $MTTF^{DU}$ of 50 years, and a logic solver with a $MTTF^{DU}$ of 100 years, about 85% of the SIF PFD will fall in the field devices and about 15% in the logic solver. On the other hand, using redundant inputs and outputs with similar $MTTF^{DU}$, configured for high safety availability and with the same logic solver, the PFD for the field devices may account for only 30% and the logic solver may account for 70% of the SIF PFD. The distribution of SIF PFD will change as the number and type of system elements and the configuration vary. Therefore, enhancing the PFD of the logic solver (E/E/PES) of the SIF without corresponding enhancement of the field devices may not be effective in improving the SIF SIL. Making a change to improve one

portion of the system (e.g., adding a redundant PES) may not have significant impact on the overall SIF. Thus, the overall SIF must be evaluated.

5 Modeling of SIF element failures

The objective of this section is to define the terminology and symbols for the different types of SIF element failures to be used by the safety integrity evaluation techniques that are discussed in the following sections. The SIF elements include input field devices (e.g., sensors), logic solvers, and output field devices (e.g., valves). Electrical (E), electronic (E), and programmable electronic (PE) technology elements are modeled for the logic solver functions.

The modeling of the system includes all possible types of failures. Failures can be grouped into 2 major categories:

- a) Physical Failures ⁽⁶⁾
 - 1) Independent failures
 - 2) Common cause failures
- b) Systematic Failures ^(11,15)

NOTE Systematic failures may be separated into independent and common cause failures. Systematic failures may impact single and/or multiple system elements, simultaneously.

Since systematic failures are in addition to the physical failures, they are shown in the models of the overall system architecture, as an additional failure rate.

5.1 Physical failures

A failure is classified as physical when some physical stress (or combination of stressors) exceeds the capability of the installed components (e.g. associated susceptibility).

5.2 Hardware common cause failures

Hardware common cause failures must be modeled differently since multiple failures occur simultaneously. Common cause failures are the direct result of a shared root cause. An example is radio frequency interference that causes simultaneous failure of multiple modules.

Common cause susceptibility is an important characteristic in the safety rating of a SIF. The Beta model (Annex A) partitions the failure rate into those failures due to stress events high enough to fail multiple units if they are exposed to the same stress. Annex A discusses a technique to evaluate the β factor and proposes a methodology to apply it to the reliability models.

5.3 Systematic failures

Systematic failures occur when the physical hardware is operating but unable to perform the specified function due to errors of omission or errors of commission.

In the models, the systematic failures are separated into safe failures and dangerous failures. It is assumed that a systematic safe failure, $\lambda_{F,S}^S$, will have the potential to result in a spurious trip. In a similar manner, a systematic dangerous failure, $\lambda_{F,D}^D$ will have the potential to result in a fail-to-function state of the SIF. The estimation of the systematic failure rate must consider many possible causes. A partial list of causes is as follows:

a) SIF design errors

These errors include errors in the safety logic specification, incorrect selections of sensors and final elements, and errors in the design of the interface between the **E/E/PES** and sensors and actuators. Failure due to errors of this type will likely fail an entire redundant architecture.

b) Hardware implementation errors

These errors include errors in the installation, setup (calibration, initialization, set-point settings), and start-up of SIS components which are not detected and resolved during functional testing of SIS. Examples of such errors are

- 1) wiring/tubing errors;
- 2) inadequate electrical/pneumatic power supply;
- 3) improper or blocked-in connections to the process (impulse lines); and
- 4) installation of wrong sensor or final control component.

c) Software errors

These errors include errors in vendor written and user written embedded, application, and utility software. The vendor software typically includes the operating system, I/O routines, diagnostics, application oriented functions and programming languages. User written software errors include errors in the application program, diagnostics, and user interface routines (display systems, etc.).

d) Human interaction errors

These errors include errors in the operation of the man machine interface to the SIF, errors during periodic testing of the SIF and during the repair of failed modules in the SIF.

e) Hardware design errors

These errors include errors in the manufacturer's design or construction of selected SIF components which prevent proper functionality and failure of component to meet specified conditions. Examples of such errors are failure of a component to

- 1) meet specified process conditions (pressure, temperature, etc.);
- 2) function properly in the installed environment (atmospheric temperature/humidity, vibration, etc.); and
- 3) the wrong selection of type or rating for components.

f) Modification errors

These errors occur when altering any or all of the five categories mentioned in this clause (i.e., SIF design, hardware implementation, software, human interaction, hardware design). These errors have three common characteristics:

- 1) They may occur during maintenance activities.
- 2) They may be subtle.

- 3) They may impact an adjacent area.

Examples of such errors are:

- 1) Inability to replace a component with an identical component (e.g. due to discontinued support) and the replacement component does not fully function with adjacent components.
- 2) Modification reduces the load on the power source, thus raising the voltage level and causing problems with other existing non-modified components.

5.4 Partitioning of SIF element failures

Since the object of safety integrity evaluation techniques is to calculate the PFD_{avg} and $MTTF^{spurious}$, all SIF element failures are partitioned into “Safe” failures and “Dangerous” failures. All failures that have the potential to cause the **SIF** to shut down the process without a process demand present are categorized as “Safe.” All failures that have the potential to cause the **SIF** to fail to respond to a process demand are categorized as “Dangerous.”

Dangerous failure rates are denoted by a superscript “D.” Safe (spurious trip) failure rates are denoted by a superscript “S.” Hence for a device, the dangerous and safe failure rates are λ^D and λ^S . All failures detected on-line while the **SIS** is operating are classified as detected (overt) failures. Those failures not detected on-line are classified as undetected (covert) failures. As a result of this additional partitioning, every element failure rate can be split into four mutually exclusive failure rates:

- a) Safe/ Detected - SD
- b) Safe/ Undetected - SU
- c) Dangerous/ Detected - DD
- d) Dangerous/ Undetected - DU

These four categories are shown in Figure 5.1 below.

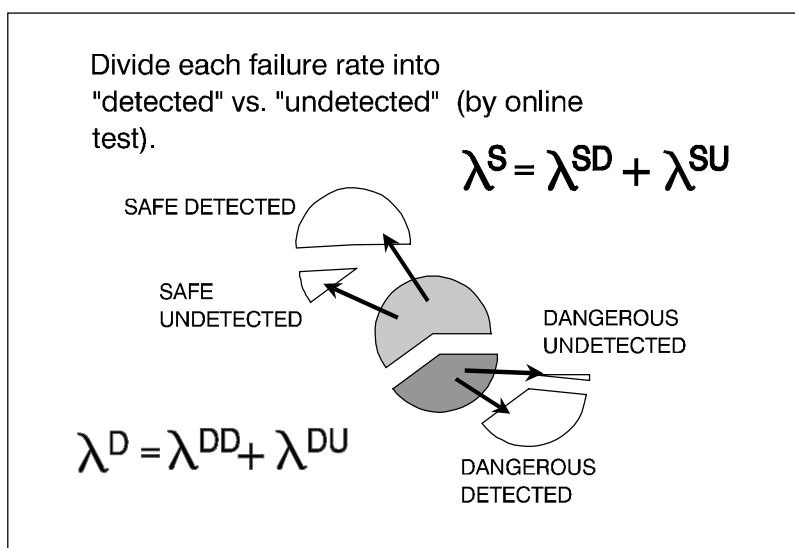


Figure 5.1 — Safe and dangerous-detected and undetected failure rate diagram

The superscript SD, SU, DD, and DU are used on the element failure rate to denote the category of failure. The four failure rates are denoted as follows:

- 1) λ^{SD} - safe detected failure rate.
- 2) λ^{SU} - safe undetected failure rate.
- 3) λ^{DD} - dangerous detected failure rate.
- 4) λ^{DU} - dangerous undetected failure rate.

The detected and undetected failure rates are computed by determining the diagnostic coverage factor for each element of the system. Normally the diagnostic coverage for dangerous failures is lower than the diagnostic coverage for safe failures since dangerous failures cause the state of the element to remain unchanged. Safe failures result in a change of state of the element and hence are easier to diagnose. Hence, a different diagnostic coverage factor for safe and dangerous failures is assumed. As in the case of failure rates, a superscript "D" is used on the diagnostic coverage factor "C" to denote the diagnostic coverage for dangerous failures. In a similar manner, a superscript "S" is used on the diagnostic coverage factor "C" to denote the diagnostic coverage for safe failures. The diagnostic coverage factors for dangerous and safe failures are C^D and C^S . Refer to Annex E for guidance in determining the split ratio. The four failure rates for an element are computed as follows:

$$\lambda^{SD} = \lambda^S \cdot C^S$$

$$\lambda^{SU} = \lambda^S \cdot (1 - C^S)$$

$$\lambda^{DD} = \lambda^D \cdot C^D$$

$$\lambda^{DU} = \lambda^D \cdot (1 - C^D)$$

In the Beta model, the Beta factor (see ISA-TR84.00.02-2002 - Part 1, Annex A) is used to partition the failure rates into independent (i.e., random) versus common cause.

NOTE There are other common cause models available. The Beta model was chosen because it is simple and sufficient to model configurations covered by this document.

Figure 5.2 shows the four primary failure rate categories.

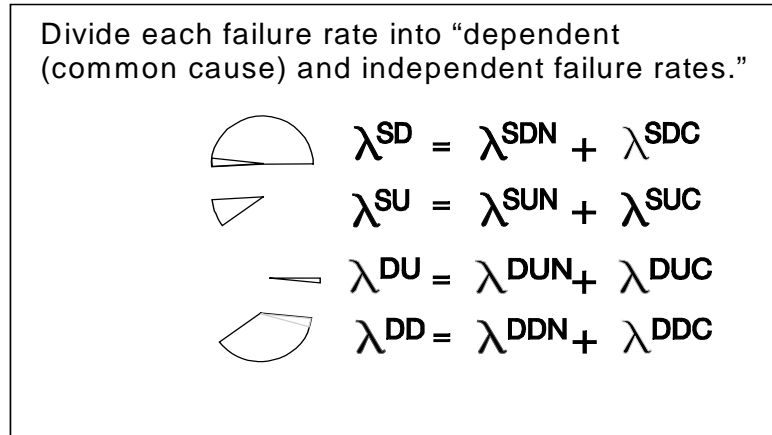


Figure 5.2 — Failure rate categories

The four primary failure rates categories are divided into eight, as follows:

$$\lambda^{SD} = \lambda^{SDN} + \lambda^{SDC} \quad \text{where} \quad \lambda^{SDC} = \beta \lambda^{SD} \quad \text{and}$$

$$\lambda^{SDN} = (1 - \beta) \lambda^{SD}$$

$$\lambda^{SU} = \lambda^{SUN} + \lambda^{SUC} \quad \text{where} \quad \lambda^{SUC} = \beta \lambda^{SU} \quad \text{and}$$

$$\lambda^{SUN} = (1 - \beta) \lambda^{SU}$$

$$\lambda^{DD} = \lambda^{DDN} + \lambda^{DDC} \quad \text{where} \quad \lambda^{DDC} = \beta \lambda^{DD} \quad \text{and}$$

$$\lambda^{DDN} = (1 - \beta) \lambda^{DD}$$

$$\lambda^{DU} = \lambda^{DUN} + \lambda^{DUC} \quad \text{where} \quad \lambda^{DUC} = \beta \lambda^{DU} \quad \text{and}$$

$$\lambda^{DUN} = (1 - \beta) \lambda^{DU}$$

5.5 Modeling of field devices

5.5.1 Modeling of sensors (input field devices)

A large variety of input devices are available for use in safety applications, however, most of these devices interface to the SIF logic solver through analog input boards, digital input boards and serial communication links.

The overall failure rate of a sensor is given by λ_s , where the **S** subscript indicates a sensor.

The sensor failure rate must be split into four mutually exclusive failure rates:

- a) Safe/Detected - λ_s^{SD}
- b) Safe/Undetected - λ_s^{SU}
- c) Dangerous/Detected - λ_s^{DD}
- d) Dangerous/Undetected - λ_s^{DU}

These failure rates are computed using the safe and dangerous failure rates (λ_s^S and λ_s^D) and the sensor diagnostic coverage factors (C_s^S and C_s^D).

The equations used to compute the four failure rates are as follows:

$$\lambda_s^{SD} = \lambda_s^S \cdot C_s^S$$

$$\lambda_s^{SU} = \lambda_s^S \cdot (1 - C_s^S)$$

$$\lambda_s^{DD} = \lambda_s^D \cdot C_s^D$$

$$\lambda_s^{DU} = \lambda_s^D \cdot (1 - C_s^D)$$

In many cases, the sensor diagnostic coverage factors are low, and hence the undetected failure rates are large. This requires off-line functional testing of the sensors at frequent intervals, and/or redundant sensors to achieve the desired safety integrity level.

5.5.2 Modeling of final elements (output field devices)

A large variety of output devices are available for use in safety applications, however, most of these devices interface to the SIF logic solver through analog output boards, digital output boards and serial communication links.

The overall failure rate of a final element or output device is given by λ_A . The **A** subscript indicates a final element.

As with the sensors, the final element failure rate must be split into four mutually exclusive failure rates:

- a) Safe/Detected - λ_A^{SD}
- b) Safe/Undetected - λ_A^{SU}
- c) Dangerous/Detected - λ_A^{DD}
- d) Dangerous/Undetected - λ_A^{DU}

These failure rates are computed using the following equations:

$$\lambda_A^{SD} = \lambda_A^S \cdot C_A^S$$

$$\lambda_A^{SU} = \lambda_A^S \cdot (1 - C_A^S)$$

$$\lambda_A^{DD} = \lambda_A^D \cdot C_A^D$$

$$\lambda_A^{DU} = \lambda_A^D \cdot (1 - C_A^D)$$

In many cases, the final element diagnostic coverage factor is typically low, and hence, the undetected failure rates are large. This requires functional testing of the final elements at frequent intervals, and/or redundant final elements to achieve the desired safety integrity level.

5.6 Modeling of elements in PES arithmetic/logic solvers

Programmable electronic systems (**PESs**) can vary significantly in architecture. **Three typical architectures for a single PES are:**

- a) Small single board **PES** with integral I/O (Figure 5.3)
- b) Multiboard **PES** with main processor module and processor based I/O modules (Figure 5.4)
- c) Multiboard **PES** with main processor module, and I/O chassis with I/O processor module and non intelligent I/O modules (Figure 5.5)

Since there are many different kinds of I/O modules (i.e., digital inputs, digital outputs, analog inputs, etc.) and different ways of connecting them to the main processor, the **PES** is broken into blocks. The blocks used in the basic architectural model must be carefully chosen so that interactions between modules in the **PES** can be described. For example, the failure of a main processor affects the operation of all I/O modules, while the failure of an I/O processor may only affect those I/O circuits attached to it.

An examination of the PES architecture in Figure 5.2 shows that the I/O modules can be modeled using individual input and output circuits that connect field devices to the main processor. However, Figures 5.3 and 5.4 contain PES architectures with I/O processors that process the data from the input and output circuits which are connected to the field devices. As a result of these differences the I/O is modeled using input processors, individual input circuits, output processors and individual output circuits. Hence the overall failure rate of an input module, λ_I , is as follows:

$$\lambda_I = \lambda_{IP} + n_{IC} \lambda_{IC}$$

where λ_{IP} is the failure rate of the input processor, n_{IC} is the number of input circuits per input processor, and λ_{IC} is the failure rate of the individual input circuits.

In a similar manner the failure rate of an output module, λ_o , is as follows:

$$\lambda_o = \lambda_{OP} + n_{OC}\lambda_{OC}$$

where λ_{OP} is the failure rate of the output processor, **n_{OC}** is the number of output circuits per output processor, and λ_{OC} is the failure rate of the individual output circuits.

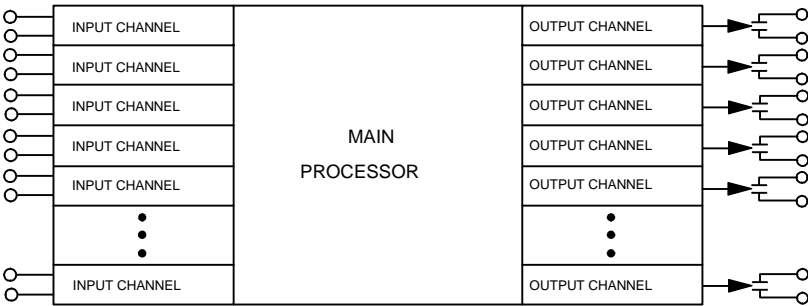


Figure 5.3 — Single board PES architecture

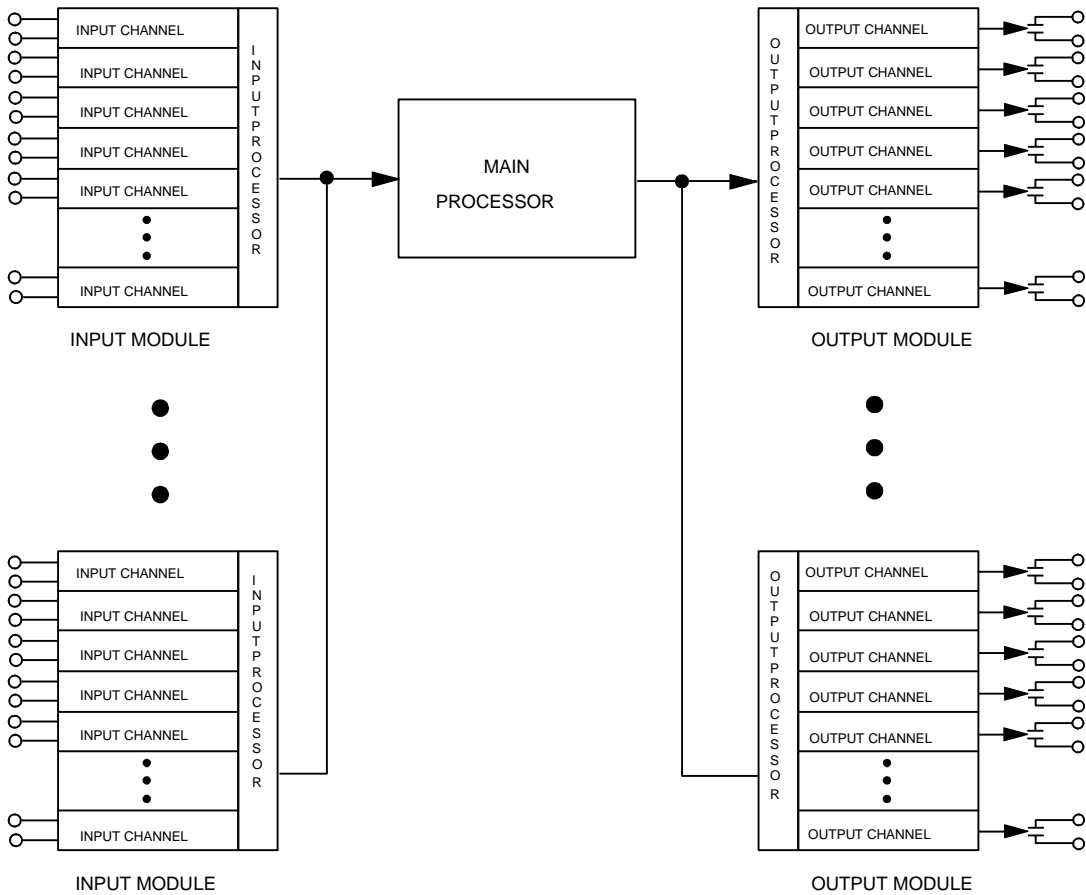


Figure 5.4 — PES architecture with processor-based I/O modules

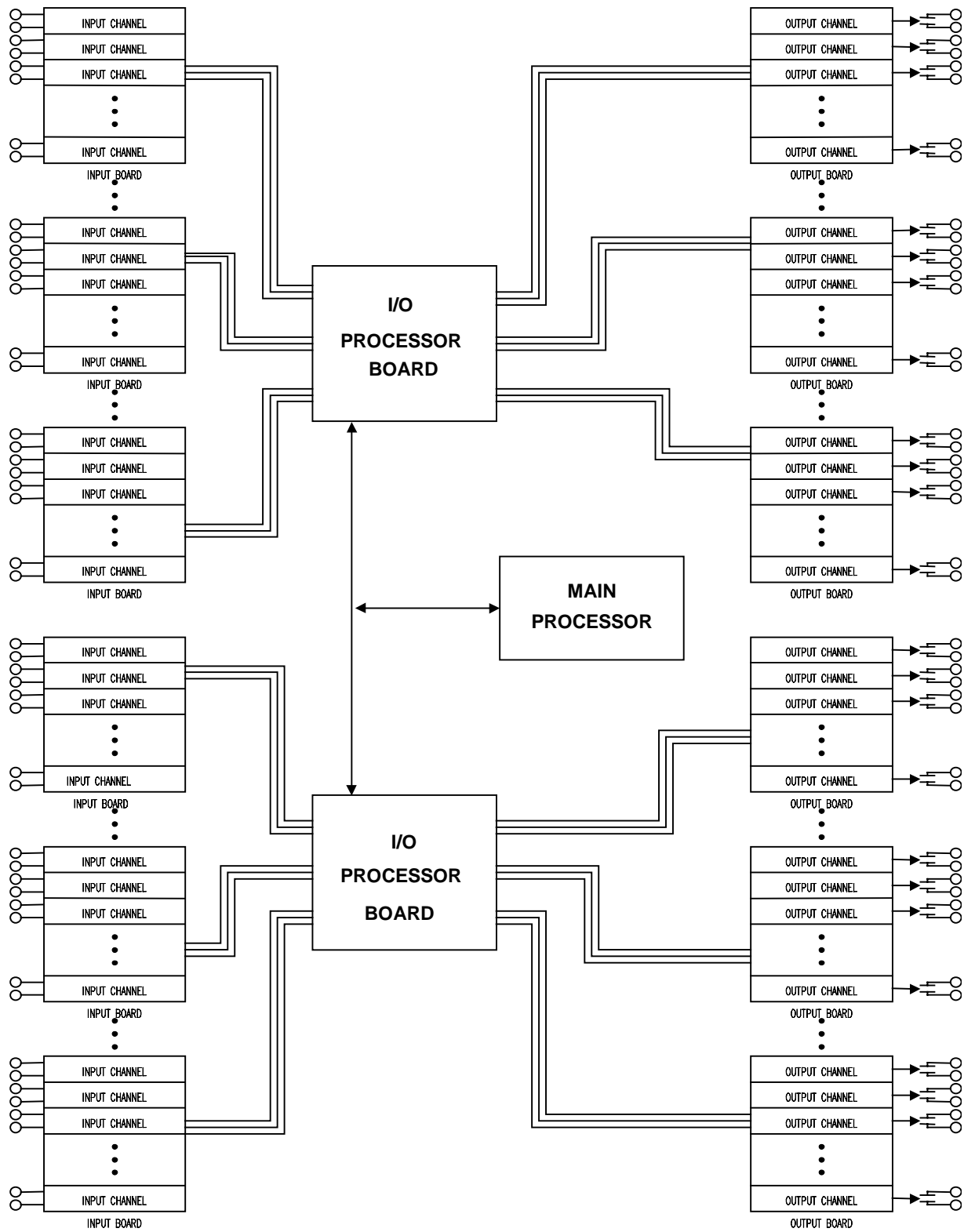


Figure 5.5 — PES architecture with I/O processor boards & I/O boards

If the **PES** is a single board with integral I/O, λ_{IP} and λ_{OP} are set to zero, and n_{IC} and n_{OC} are the total number of input and output circuits on the single board. If the **PES** is like the system illustrated in Figure 5.5, n_{IC} and n_{OC} are the total number of input and output circuits serviced by a single I/O processor.

The rest of the modules that make up the **PES** are not split into sections like the I/O modules. Hence, the elements used in the models and their respective failure rates are as follows:

- a) Main Processor - λ_{MP}
- b) Input Processor - λ_{IP}
- c) Individual Input Circuit - λ_{IC}
- d) Output Processor - λ_{OP}
- e) Individual Output Circuit - λ_{OC}
- f) Power Supplies - λ_{PS}

These PES element failure rates can be partitioned into “Safe/ Detected” failures, “Safe/ Undetected” failures, “Dangerous/ Detected” failures, and “Dangerous/ Undetected” failures. Using the same notation as in Section 4.4, the failure rates for the main processor are as follows:

- a) λ_{MP}^{SD} - main processor safe detected failure rate.
- b) λ_{MP}^{SU} - main processor safe undetected failure rate.
- c) λ_{MP}^{DD} - main processor dangerous detected failure rate.
- d) λ_{MP}^{DU} - main processor dangerous undetected failure rate.

5.7 System modeling

System modeling of any fault tolerant E/E/PES architecture can be done using simplified equations, fault tree analysis, Markov analysis or other technique using the failure rate categories described above. This failure rate classification depends on an accurate and detailed Failure Modes, Effects and Diagnostic Analysis (FMEA). When it is impractical to do this level of analysis, simplifying assumptions can be made, however, it is important that these assumptions be conservative. If failure modes are not known, it must be assumed that all failures are dangerous. If diagnostic coverage capability is not known, it must be assumed that no failures are detected. If beta factors (common cause) are not known, a value of 10% is conservative (see Annex A).

5.8 Failure rate data for commonly used field instrumentation

In order to predict the $MTTF^{spurious}$ and PFD_{avg} of a SIS, one must have failure rate data of the different components, such as the sensor, logic solver, and final elements. Failure rate data may come from a variety of different sources, such as public databases, user compiled maintenance records, vendor compiled field returns, reliability⁽¹³⁻¹⁸⁾ calculations or operating experience.

THE NUMBERS IN TABLE 5.1 WERE COMPILED FROM USER DATA AND ARE IN NO WAY ENDORSED BY ISA. THEY DO NOT REFLECT THE VARIABILITY OF FAILURE RATES DUE TO THE SEVERITY OF DIFFERENT PROCESSES, THE DIFFERENT FAILURE MODES OF THE ACTUAL

DEVICES, NOR HOW THE DATA WAS ACTUALLY COLLECTED BY EACH COMPANY. THE USER IS CAUTIONED IN THEIR USE AND SHOULD TRY TO COMPILE THEIR OWN DATA.

Reliability practitioners usually work with failure rates expressed as failures per million hours. Failure rates may be inverted and expressed as mean time to failure (MTTF) and may be expressed in years. Note that MTTF and component life are not the same.

Table 5.1 — MTTF^D and MTTF^{spurious} values (expressed in years) for common field instrumentation

	Company A		Company B		Company C		Company D		Company E	
	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}
Sensors										
Flow Switch			20-30	10-15	10	5	7	8	25	
Pressure Switch			20-30	10-15	35	15	16	20	35	20
Level Switch			20-30	10-15	25	5-10	80	60	30	60
Temp. Switch			20-30	10-15	15	5	10	20	10	12
Pressure Transmitter (service < 1500 psig)	100	100	40-60	20-30	50	25	60	60	55	55
Pressure Transmitter (service ≥ 1500 psig)	100	100	40-60	20-30			60	60	55	55
Level Transmitter	50	50	40-60	20-30	30	15	25	25	35	15
Flow Transmitter										
Orifice Meter	75	75	30-50	15-25	40	20	20	2	35	15
Mag Meter			40-50	20-25	100	25	150	150		
Coriolis Meter			40-60	20-30	40	15	76.1			
Vortex Shedding			40-60	20-30	50	10				
Temp. Transmitter	75	75	40-60	20-30	40	20	160	100	65	50
Flame Detector	10,000	1	15-30	5-15						
Thermo couple			60-80	30-40	40	20	20	10	100	20
RTD (Resistance Temp. Detect.)			60-80	30-40	30	15				
Vibration Proximitior	20	20	40-60	20-30	10	5				
Combustible Gas Detector									2.8	
Final Elements	(See Next Page)									

Table 5.1 — MTTF^D and MTTF^{spurious} values (expressed in years) for common field instrumentation

	Company A		Company B		Company C		Company D		Company E	
	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}	MTTF ^D	MTTF ^{spur}
Final Elements										
Air Operate Gate Valve	50	50	30-50	15-25	50	25	40	40	40	40
Air Operate Globe Valve	50	50	40-60	20-30	60	25	40	40	40	40
Air Operate Ball Valve	50	50	40-60	20-30	50	25	40	120	40	40
Solenoid (DTT)	100	10	25-35	12-15	50	25	100	15	125	
Solenoid (ETT)	30	100								
Motor Starter			1000-1500							
Hydraulic Operated Ball Valve							25	80		
Motor Operated Ball Valve							15	135	30	
Electro-Mechanical Relay			1500-2500				70	40		
Annunciator							4	10		
Current Switch			25-35							
Sensors	(See Previous Page)									

5.9 Statistical data analysis methods

This clause outlines three statistical analysis methods that are useful in analyzing the performance of a SIF, i.e., the PFD and PFS, taking into account the uncertainties associated with the model and the data. The methods are statistical Uncertainty (clause 5.9.1), Sensitivity (clause 5.9.2), and Correlation Analysis (clause 5.9.3).

For any reliability technique, the PFD and the PFS are based on a reliability model of the SIF application and reliability data for parameters like the failure rates and the repair rates of the different elements.

Any model is just an approximation of the real world. It is impossible to model every single aspect of real life; therefore, assumptions need to be made to simplify the modeling effort whenever a model is created. There is uncertainty associated with each model that is created. The failure and repair rate data used in reliability models are uncertain, for many reasons. The background of the data may be unclear; good data might be unavailable; no data may be available because equipment might be new. In such cases, using a single or point value for the failure and repair rates might give very misleading results. Of course, how good (or how bad) the model is, and how good (or how bad) the failure and repair rate data used in that model is, affects the usefulness of the PFD and PFS values calculated by the model.

The theory behind the methods is not explained. In order to understand the theory and implement the different methods, the reader is referred to the references as presented in the different sections. These techniques are based on statistics, which means that the results are based on simulating a significant number of SIF^(24, 25, 27). These simulations are usually done by specialized software (Annex C) applications. ISA-TR84.00.02-2002 - Part 2 and ISA-TR84.00.02-2002 – Part 3 do not use these techniques, although in principle, it is possible to do so. ISA-TR84.00.02-2002 - Part 4 uses uncertainty and sensitivity analysis. ISA-TR84.00.02-2002 - Part 5 uses all three methods.

5.9.1 Uncertainty analysis

Uncertainty analysis is a method that a) takes the uncertainty associated with the input parameters (i.e., failure rates, repair rates) to a reliability model, b) propagates this uncertainty through the model, and c) creates a range of values for the outputs^(22, 23). A range of values (e.g., minimum through maximum likely values), instead of a single value, is used for failure and repair rates. This range can be based, for example, on such factors as: the manufacturing quality, the specific application, the environment of the component, the size of the sample used to determine the failure rate, or other factors. Using a range of values as input means that a range of values is created for the output, i.e., the PFD or PFS. When uncertainty analysis is applied the results are often presented as in Figure 5.6.

The result of the uncertainty analysis is a number of values for the PFD and PFS. The plots represent three levels of confidence in the results: the so-called 10th, 50th and 90th percentiles⁽²⁶⁾. In practice it is possible to represent any level of confidence (e.g. 5th, 95th and so on). The reader should interpret the graphs as follows: Given this input data and reliability model,

10% of the cases the PFD value would be below the 10th percentile line;

50% of the cases the PFD value would be below the 50th percentile line; and,

90% of the cases the PFD value would be below the 90th percentile line.

The use of these uncertainty graphs is based on good engineering judgment. In the case of Figure 5.6, it would be worth investigating the cause of the wide range of PFD values (it covers all three SIL levels) as seen in the graph on the right. The following two statistical techniques provide the tools to do this investigation. They are very useful during the architecture design of SIF. The reader is cautioned however that the following discussions are only brief overviews of these tools. Before attempting to apply these tools, the reader should refer to the references cited in each section.

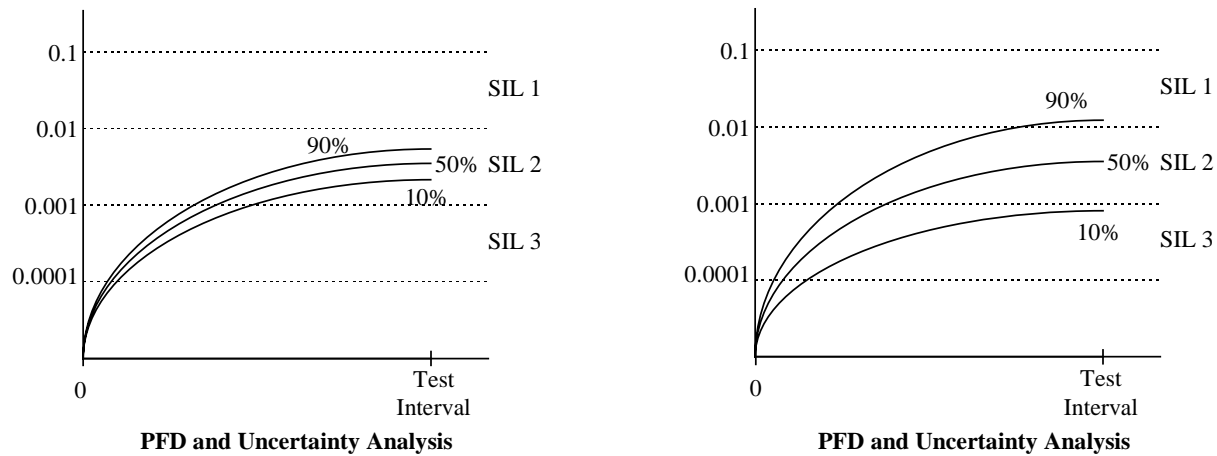


Figure 5.6 — Two examples of uncertainty plots

5.9.2 Statistical sensitivity analysis

Statistical sensitivity analysis is a method which quantifies the effect of the uncertainty associated with an input parameter (e.g., the failure and repair rates) to the uncertainty associated with the output parameter (e.g., the PFD or PFS) ⁽²⁸⁾. In other words, for example, if there is a range of input values for the failure rate of a valve, then the statistical sensitivity analysis would show how this range propagates through the reliability model and how much influence it has on the range of PFD, as presented in Figure 5.6.

The results of a statistical sensitivity analysis are presented in a Pareto plot as in Figure 5.7. The reader should interpret the graph as follows. The horizontal axis gives a range for the statistical sensitivity, which can vary between zero and two ^(29, 30). Zero means that the output is not sensitive to the input while two means that the output is very sensitive to the input. On the vertical axis the input parameters are listed in order of their statistical sensitivity (most sensitive highest, and least sensitive lowest). In this case the PFD value is most sensitive to the failure rate of the valve. That is, the variation in the specified values of valve failure rate cause more variation in the PFD value than variation in any other input parameter.

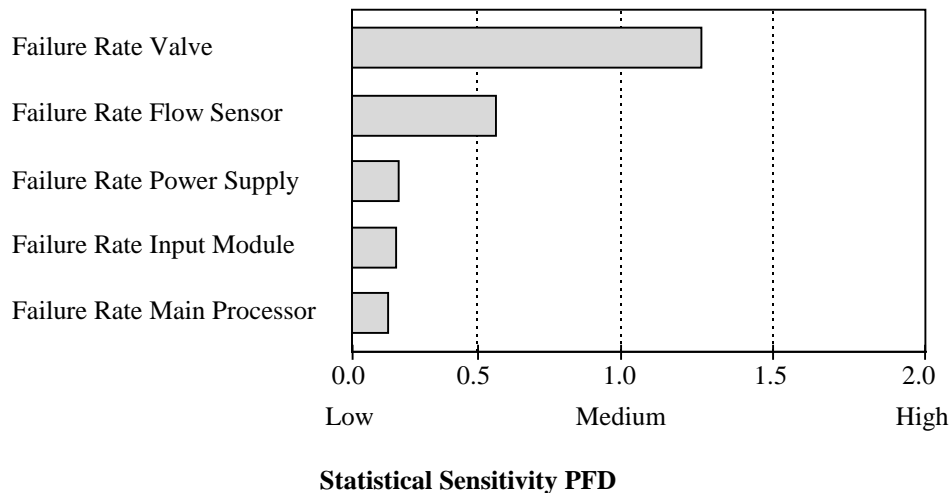


Figure 5.7 — Example plot statistical sensitivity results

How can the reader use this kind of information while examining a SIF architecture? Suppose that reliability data is collected for all the input parameters of the reliability model. It turns out that there is not enough data available for the valve and input module failure rates. A conservative approach is to apply a wide range of data based on experience and carry out the uncertainty and sensitivity analysis. The results of the Uncertainty Analysis are presented in the right graph of Figure 5.6. From the sensitivity plot the conclusion can be drawn that the PFD of the SIF is robust against failures of the input module. Even though a wide range of failure data is used, the range of the PFD values is not influenced much by the input module. On the other hand, the output is much influenced by the failure data of the valve. The PFD is very sensitive to valve failures. The next step can be a) to get better failure data for the valve and see how that affects the PFD values or b) to change the SIF architecture and make the design more robust against valve failures.

5.9.3 Statistical correlation analysis

When a certain input parameter has a high sensitivity factor and the cause for this high factor is unknown, then there are two possibilities:

- The architecture design or set-up (represented by the reliability model) is the cause of this high sensitivity of the input parameter.
- The spread between the Minimum and Maximum failure rate is very wide and caused the high sensitivity of the input parameter.

A statistical correlation analysis helps to answer the question: Is it the architecture design or the range of data for a particular input parameter that causes the variation in output?

A typical correlation result is presented in Figure 5.8. The correlation coefficient can vary between -1 and +1; it indicates the degree or strength of the linear relation between the input parameter, e.g., a failure rate, and the output, e.g., the PFD⁽³¹⁾. A value of +1 indicates a strong positive correlation meaning that the output (PFD) increases as the input parameter (failure rate) increases. A value of -1 indicates a strong negative correlation meaning that the output decreases as the input parameter increases. A value of zero means that the input parameter has no linear effect on the output. Thus if the correlation is strong (negative or positive) then it is more likely that the architecture design is the dominant factor. If the correlation is zero the range in input parameters is more likely to be the dominant factor.

The particular advantage in applying the sensitivity and correlation analysis will be the ability to use less accurate input data. Experienced technicians know that accurate single value failure and repair rate data are seldom available for all the elements in a SIF. If this is the case, then it is necessary to generate the best guess of the expected minimum and maximum range of values. When, after the sensitivity and correlation analysis, this estimation proves to be important in the results (PFD or PFS), then either the failure rate estimation range has to be very closely examined, adjusted, and justified, or else the SIF configuration has to be examined.

Three remedies can be considered (stand-alone or in combination):

- a) Change the SIF architecture to meet the objectives.
- b) Attempt to acquire more accurate and justifiable input data.
- c) Choose alternative sensor, logic solver or final element types (with different failure and repair rate data).

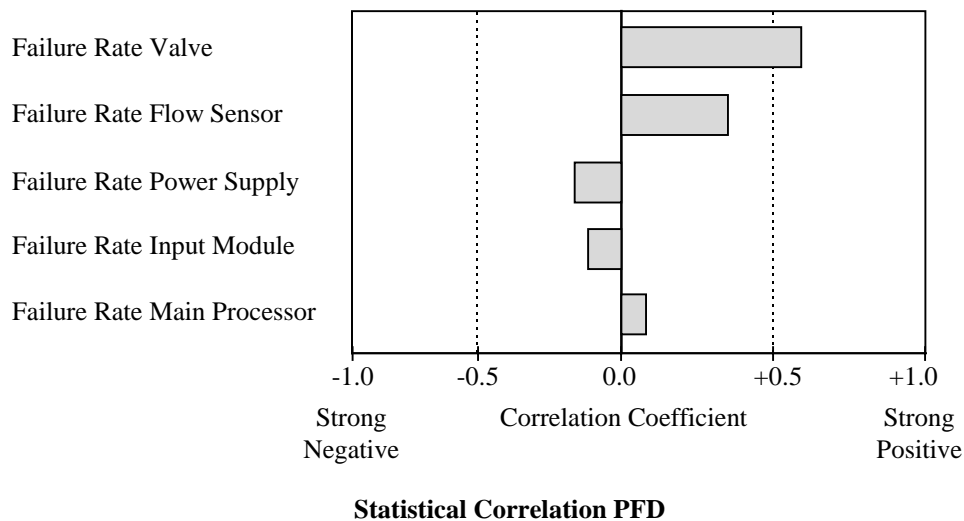


Figure 5.8 — Example statistical correlation results

6 Comparison of system analysis techniques

The modeling techniques discussed in ISA-TR84.00.02-2002 to evaluate the PFD_{avg} and the $MTTF^{spurious}$ for Safety Instrumented Functions are simplified equations (Part 2), fault tree analysis (Part 3), Markov Analysis (Part 4), and for logic solvers only, Markov Analysis (Part 5). To use any of these techniques requires a thorough understanding of the modeling technique being used. The presentation of the techniques provided in ISA-TR84.00.02-2002 does not illustrate their full capability. Table 6.1 is included to help guide users as to which method may be most appropriate for their particular application.

Table 6.1 — Comparison of system analysis techniques presented in ISA-TR84.00.02-2002 - Parts 2, 3, 4 and 5

		Simplified Equations	Fault Tree Analysis	Markov Analysis
	Typical Systems Modeled	Simple SIF	SIF with complex relationships	SIF with complex relationships, time dependent requirements, or PE logic solvers
Attributes of Analysis Techniques	Handles different repair times for redundant elements	Not shown	Yes	Yes
	Handles diverse technology for redundant elements	Not shown	Yes	Yes
	Handles sequence dependent failures	No	Difficult	Yes
	Quantification technique	Simple math	Simple math or Boolean Algebra	Matrix algebra
	Provides graphics that allow easy visualization of failure paths	Practical for simple SIF	Yes	More difficult
NOTE A more detailed discussion on the three techniques is provided in Reference 11.				

Table 6.2 summarizes the calculation results for PFD_{avg} and $MTTF^{spurious}$ for the SIF Base Case example problems presented in Parts 2, 3, and 4.

For the Base Case PFD_{avg} , all three methods give essentially the same value (Figure 6.1).

For the Base Case $MTTF^{spurious}$, all three methods give similar values (Figure 6.2).

Table 6.2 — Summary of SIF base case example problems presented in ISA-TR84.00.02-2002 - Parts 2, 3, and 4

	Case	PFD_{avg}	$MTTF^{spurious}$
Part 2 Simplified Equations	Clause 6	8.3 E-3	1.0 yr
	Base Case		
Part 3 Fault Tree Analysis	Clause 7	7.4 E-03	1.5 yr
	Base Case		
	Average Before Logic (ABL)		
	Clause 7	8.3 E-3	1.5 yr
	Base Case		
	Average After Logic (AAL)		
Part 4 Markov Model	Clause 14 and 15	8.3 E-3	1.7 yr
	Base Case		

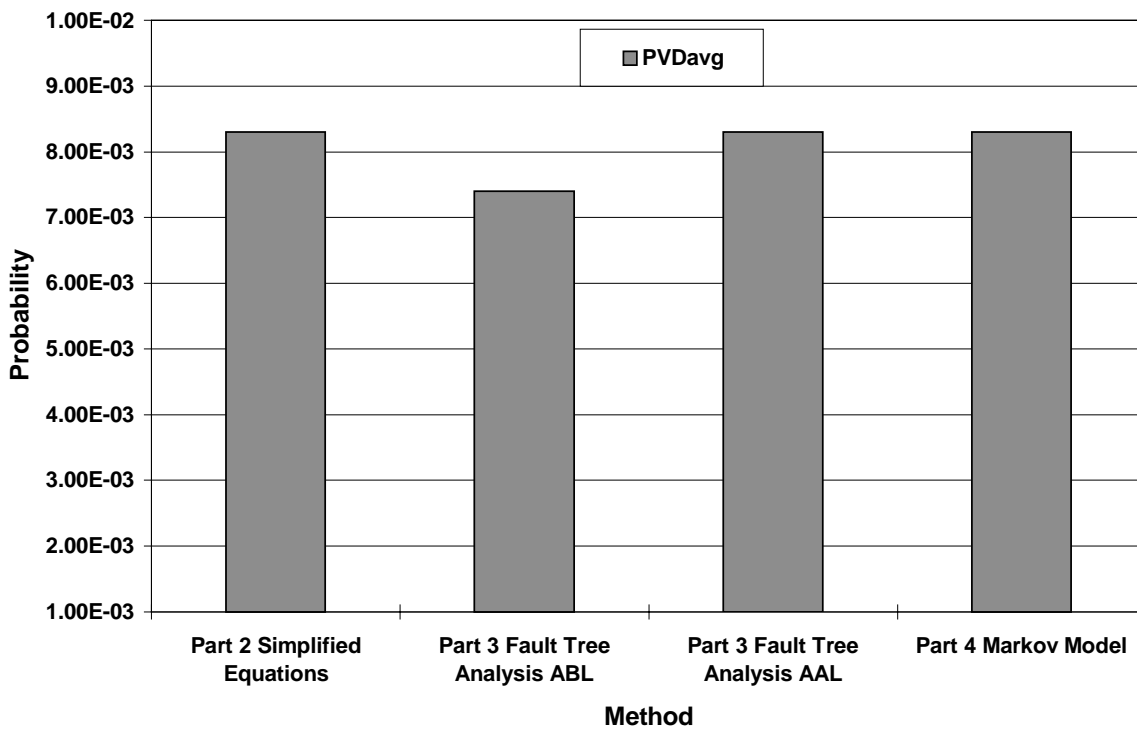


Figure 6.1 — PFD_{avg} for SIS base case example problems presented in ISA-TR84.00.02-2002 - Parts 2, 3, and 4

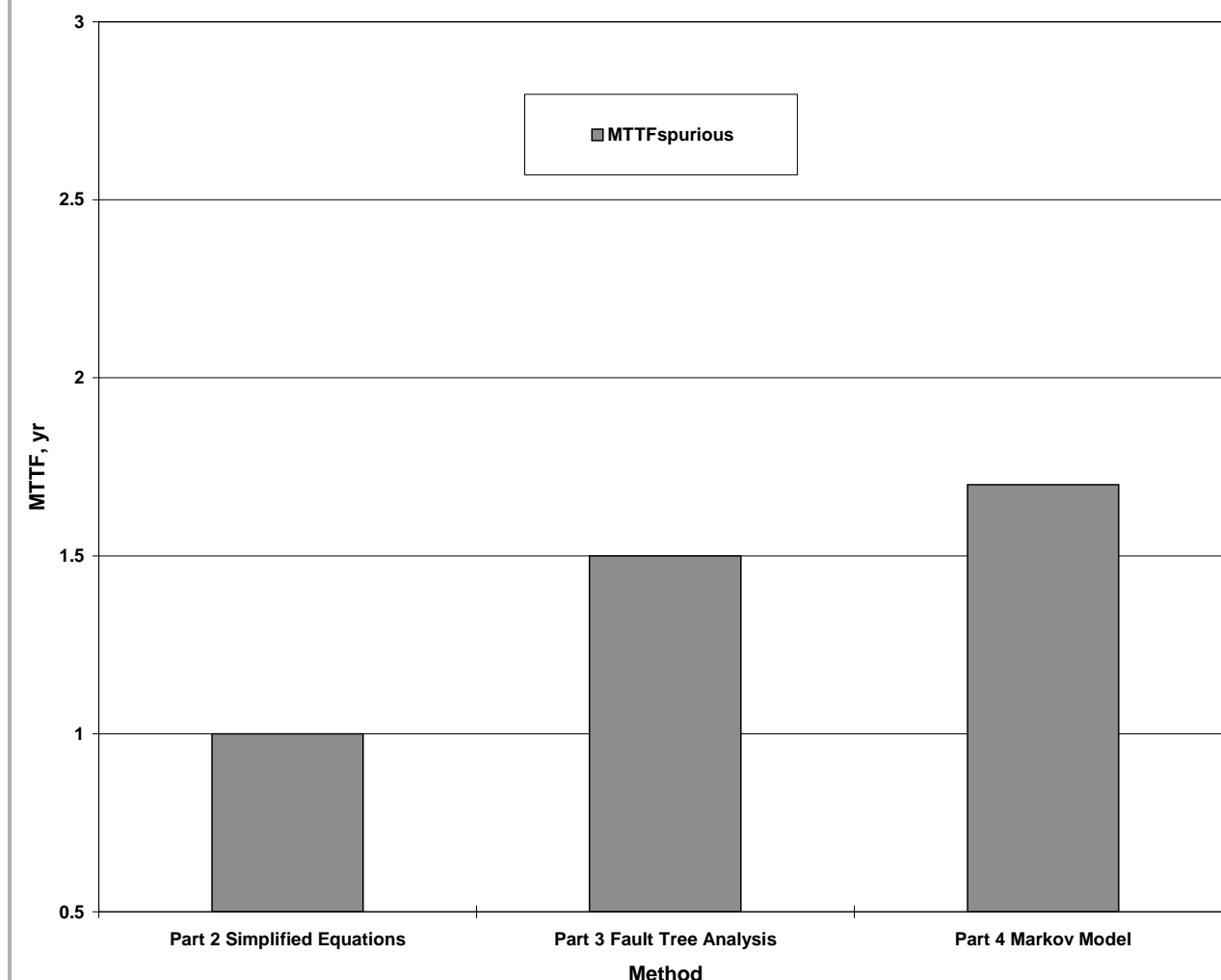


Figure 6.2 — MTTF^{spurious} for SIS base case example problems presented in ISA-TR84.00.02-2002 - Parts 2, 3, and 4

All three methods give similar results for this SIF Base Case example based on the configuration and assumptions used in the Base Case. For a different SIF configuration with different assumptions, the methods may give different values and one method may be more appropriate as suggested in Table 6.1.

Additional examples are given in ISA-TR84.00.02-2002 - Parts 3 and 4 to illustrate features of the calculation methods.

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Annex A (informative) — Methodology for quantifying the effect of hardware-related common cause failures in Safety Instrumented Functions

NOTE The source of this document is IEC 61508, Part 6, Annex A. It has been modified to harmonize with ISA-TR84.00.02-2002.

A.1 Introduction

Technical Report 84.00.02 incorporates a number of measures that deal with systematic failures. However, no matter how well these measures are applied, there will be a residual probability of systematic failures occurring. Although this will not have a significant effect on the reliability calculations for single-channel systems, the potential for failures which may affect more than one channel in a multi-channel system, i.e., common cause failures, will result in substantial errors when reliability calculations are applied to multi-channel systems.

This informative annex describes a methodology which will allow common cause failures to be taken into account in the safety assessment of a multi-channel SIS. The use of the methodology will give a more accurate estimation of the integrity of such a system than if the potential for common cause failures were ignored. Alternative methodologies may be preferred in some cases, for example, where a more accurate β -factor can be proven as a result of the availability of data on Common cause failures.

A.2 Brief overview

The failures of a system are considered to arise from two causes:

- a) Random hardware failures, and
- b) Systematic failures

The former are assumed to occur randomly in time for any component and will result in a failure of one or more channels within a system of which the component forms part. There is a finite probability that independent Random Hardware Failures could occur in all channels of a multi-channel system such that all of the channels were simultaneously in a failed state.

Common cause failures may result from a systematic fault (e.g., a design or specification error) or an external stress leading to an early random hardware failure (e.g., an excessive temperature, which accelerates the life of the components or takes them outside their specified environment) or, possibly, a combination of both. Because common cause failures affect more than one channel in a multi-channel system, the probability of common cause failures is likely to be the dominant factor in determining the overall probability of a failure of a multi-channel system and this **must** be taken into account if a realistic estimate of the SIL of the combined system is to be obtained.

Programmable electronic systems may provide the ability to carry out diagnostic functions during their on-line operation. These can be employed in a number of ways, for example:

- a) a single channel PES can continuously be checking its internal operation together with the functionality of the input and output devices. A diagnostic coverage in the region of 99% is often achievable⁽¹⁹⁾. If 99% of internal faults are revealed before they can result in a failure, the rate of single-channel faults which can ultimately contribute to common cause failures will be significantly reduced.
- b) In addition to self-testing, each channel in a PES can monitor the outputs of other channels in multi-channel PES (or each PES can monitor another PES in a multi-PES). Therefore, if a failure occurs in

one channel, this can be detected and an appropriate action initiated by the non-failed channel(s) which is executing the cross-monitoring test.

As a result of the above:

- a) PE-based systems may have the potential to incorporate defenses against common cause failures.
- b) A different β -factor may be applicable to PES-based systems when compared to other technologies. Therefore, β -factor estimates based on historical data may be invalid. (None of the identified models used for estimating the rate of common cause failures allow for the effect of automatic cross-monitoring and none of the identified models have the ability to house so many safety instrumented functions in one logic solver.)
- c) Common cause failures that are distributed in time may be revealed by the automatic diagnostics before they affect all channels, such failures may not be recognized/reported as being common cause failures.

Following are three avenues that can be taken to reduce the rate at which common cause failures are likely to manifest themselves:

- a) 1) Reduce the number of overall systematic failures. (This will reduce the areas of the ellipses in Figure A.1 leading to a reduction in the area of overlap.)
- b) 2) Maximize the independence and diversity of the channels. (This will reduce the amount of overlap between the ellipses in Figure A.1 while maintaining their area.)
- c) Reveal the initial failure before a second channel has been affected, i.e., use automatic diagnostics.

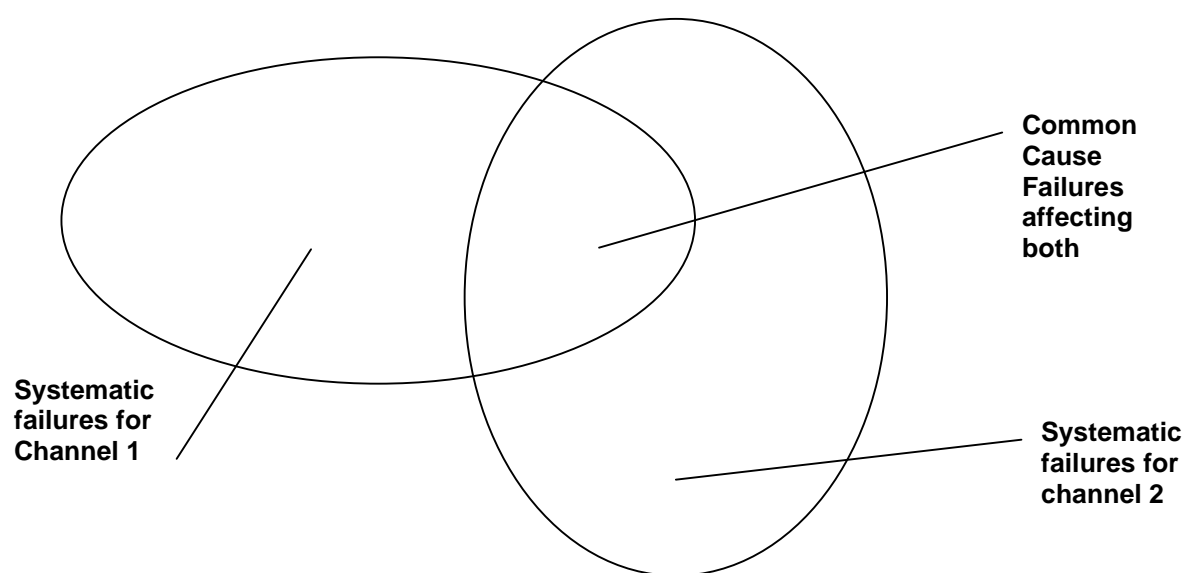


Figure A.1 — Relationship of CCF to the systematic failures of individual channels

The methodology to be described is based on these avenues and has a three-pronged approach:

- a) Apply the techniques described in ANSI/ISA-84.01-1996 to reduce the overall rate of systematic failures to a level commensurate with the random hardware failure rate.
- b) Quantify those factors that can be quantified, i.e., take into account the rate of random hardware failures.
- c) Derive, by what is considered at the present time to be the best practicable means, a factor relating the rate of common cause failures of the hardware to the rate of random hardware failures. The methodology described in this annex relates to the derivation of this factor.

Most methodologies for estimating the probability of common cause failures attempt to make their predictions from the probability of random hardware failure. Clearly, the justification for any direct relationship between these probabilities is tenuous, nevertheless, such a correlation has been found in practice and probably results from second-order effects. For example, the higher the random hardware failure rate of a system:

- a) the higher will be the amount of maintenance required of the system. The probability of a systematic fault being introduced during maintenance will depend on the number of times maintenance is carried out and, subsequently, so will the rate of common cause failures. This will lead to a relationship between the probability of random hardware failures and the probability of common cause failures. For example:
 - 1) A repair, followed by testing and, possibly, recalibration will be required each time a random hardware failure occurs.
 - 2) For a given SIL, a system with a higher probability of random hardware failure will require proof tests to be carried out more frequently, leading to additional human interference.
- b) the more complex will be the system. The probability of random hardware failure will depend on the number of components, and, hence, the complexity of a system. A complex system will be less easily understood, so will be more prone to the introduction of systematic faults. In addition, the complexity will make it difficult to identify the faults, by either analysis or test, and could lead to parts of the logic of a system not being exercised except in infrequent circumstances. Again, this will lead to a relationship between the probability of random hardware failures and the probability of common cause failures.

Despite the limitations of the current models, it is believed that they represent the best way forward at the present time for providing an estimate of the probability of common cause failure of a multi-channel system. The methodology described in this annex uses an approach similar to the well-established β -factor model as the third part of the three-pronged approach already described.

There are two difficulties faced when using the β -factor model on a PES:

- a) What value should be chosen for β ? Many sources (e.g., Reference 19) suggest ranges within which the value of β is likely to occur, however, no actual value is given, the user being left to make a subjective choice. To overcome this problem, the methodology is based on the system originally described in Reference 20 and recently refined in Reference 21.
- b) The β -factor model does not take into account the sophisticated diagnostic capabilities of modern PES, which can be used to identify a non-simultaneous common cause failure before it has had sufficient time to manifest itself fully. To overcome this deficiency, the approach described in References 20 and 21 have been modified to reflect the effect of diagnostics in the estimation of the likely value of β .

The diagnostic testing functions running within a PES are continuously comparing the operation of the PES with predefined states. These states can be predefined in software or in hardware (e.g., by a watchdog circuit).

A.3 Scope of the methodology

The scope of the methodology is limited to common cause failures within the hardware. The reasons for this include:

- a) the β -factor model relates the probability of common cause failure to the random hardware failure rate. The probability of common cause failures which involve the system as a whole will depend on the complexity of the system (possibly dominated by the user software) and not on the hardware alone. Clearly, any calculations based on the rate of random hardware failures cannot take into account the complexity of the software.
- b) reporting of common cause failures will generally be limited to hardware failures - the area of most concern to the manufacturers of the hardware.
- c) it is not considered practicable to model common cause failures (for example, software failures).
- d) the measures described in the SRS and software design in ANSI/ISA-84.01-1996 are intended to reduce the rate of software-related common cause failures to an acceptable level for the target SIL.

Therefore, the estimate of the probability of common cause failures derived by this methodology relates to only those failures associated with the hardware. It should NOT be assumed that the methodology can be used to obtain an overall failure rate which takes the probability of software-related failures into account.

A.4 Points taken into account in the methodology

Because the sensors, (programmable) electronics and actuators will be subject to, for example, different environmental conditions and diagnostics with varying levels of capability, the methodology must be applied to each of these subsystems separately. For example, the logic systems are more likely to be in a controlled environment, whereas the sensors may be mounted outside on pipework that is exposed to the elements.

Programmable electronics channels have the potential for carrying out sophisticated diagnostic functions. These can

- a) have a high fault coverage within the channels;
- b) monitor additional redundancy channels;
- c) have a high repetition rate; and
- d) in an increasing number of cases, also monitor sensors and/or actuators.

A large fraction of common cause failures do not occur concurrently in all of the affected channels. Therefore, if the repetition frequency of the diagnostic checks is sufficiently high, a large fraction of common cause failures can be revealed and, hence, avoided before they affect all available channels.

Not all features of a multi-channel system, that will have a bearing on its immunity to common cause failures, will be affected by diagnostics. However, those features relating to diversity or independence will be made more effective. Any feature which is likely to increase the time between channel failures in a non-simultaneous common cause failure (or reduce the fraction of simultaneous common cause failures)

will increase the probability of the automatic diagnostics identifying the failure and putting the plant into a safe state. Therefore, the features relating to immunity to common cause failures have been divided into those whose effect is thought would be increased by the use of automatic diagnostics and those whose effect would not. This leads to the two columns X and Y, respectively in Table A.1.

Although the probability of common cause failures for “N” channels which will affect all “N” channels is likely to be slightly lower than the probability of affecting “N-1” channels, in order to simplify the methodology, it is assumed that the rate is independent of the number of affected channels, i.e., it is assumed that, if a common cause failure occurs, it will affect all channels.

There is no known data on hardware-related common cause failures available for the calibration of the methodology. Therefore, the tables associated with this β methodology have been based on engineering judgement.

Diagnostic routines are sometimes not regarded as having a direct safety role so may not receive the same level of quality assurance as the routines providing the main control functions. The methodology was developed on the presumption that the diagnostics have an integrity commensurate with the target SIL. Therefore, any software-based diagnostic routines should be developed using techniques appropriate to the target SIL.

A.5 Using β to calculate the failure rate of a system

Consider the effect of common cause failures on a multi-channel system with automatic diagnostics running within each of its channels.

Using the β -factor model, the rate of dangerous common cause failures is

$$(Eq. A.1) \quad \lambda_{LEG}^D(\beta)$$

Here, λ_{LEG}^D is the rate of dangerous random hardware failures for each individual leg or channel and β is the β -factor in the absence of diagnostics, i.e., the fraction of single-channel failures that will affect both channels.

We shall assume that Common cause failures affect all channels, and, such that the span of time between the first and all channels being affected is small compared to the time interval between Common cause failures.

Suppose that there are diagnostics running in each channel, a fraction C of the failures will be detected and revealed by the diagnostics. Therefore, we can divide the failures into two: those that lie outside the coverage of the diagnostics (and so can never be detected) and those that lie within the coverage (so would eventually be detected by the diagnostics).

The overall failure rate due to Common Cause dangerous failures is then given by

$$\lambda_{LEG}^{DU}(\beta) + \lambda_{LEG}^{DD}(\beta_D).$$

λ_{LEG}^{DU} is the covert failure rate of a single channel, i.e., the rate of failures which lie outside the coverage of the diagnostics. Clearly, any reduction in the β -factor resulting from the repetition rate of the diagnostics cannot affect this fraction of the failures.

λ_{LEG}^{DD} is the overt failure rate of a single channel, i.e., the rate of failures of a single channel that lie within the coverage of the diagnostics. Here, if the repetition rate of the diagnostics is high, a fraction of the failures will be revealed leading to a reduction in the value of β , i.e., β_D .

β is obtained from Table A.4, using a score, $S = X + Y$ (see Section A.6).

β_D is obtained from Table A.4, using a score, $S_D = X(Z + 1) + Y$.

A.6 Using the tables to estimate β

β should be calculated for the sensors, the programmable electronics and the actuators separately.

In order to minimize the probability of occurrence of common cause failures, one must first establish which measures will lead to an efficient defense against their occurrence. The implementation of the appropriate measures in the system will lead to a reduction in the value of β used in estimating the failure rate due to common cause failures.

In order to take the contribution of each of these measures into account, the methodology uses tables which list the measures and contain an associated value representing the contribution of each. Because sensors and actuators must be treated differently to the programmable electronics, separate columns are used in Table A.1 for scoring the programmable electronics and the sensors or actuators.

Extensive diagnostics may be incorporated into programmable electronic systems which allow the detection of non-simultaneous common cause failures. To allow for these to be taken into account in the estimation of β , two sets of values are incorporated into the tables. One of these sets of values, in the column labeled Y, corresponds to those measures whose contribution will not be improved by the use of automatic diagnostics. The other, in the column labeled X, is thought to lead to an improvement when automatic diagnostics are in operation.

The user of Table A.1 must ascertain which measures apply to the system in question and sum the corresponding values shown in each of columns X_{PE} & Y_{PE} , for the programmable electronics, or X_{SA} and Y_{SA} , for the sensors or actuators, the sums being referred to as X and Y, respectively.

Tables A.1 and A.2 may be used to determine a factor from the frequency and coverage of the diagnostics, Z, taking into account the important note below Table A.2. The score S is then calculated using the following equations, as appropriate (see previous section):

$S = X + Y$ to obtain the value of β (for undetected failures), and

$S_D = X(1 + Z) + Y$ to obtain the value of β_D (for detected failures).

Here S or S_D is a score which is used in Table A.4 to determine the appropriate β -factor.

Table A.1 — Scoring programmable electronics or sensors/actuators

Item	X _{PE}	Y _{PE}	X _{SA}	Y _{SA}
Separation/segregation:				
Are all signal cables for the channels routed separately at all positions?	1.5	1.5	1.0	2.0
Are the PE channels on separate printed-circuit boards?	3.0	1.0		
Are the PE channels in separate cabinets?	2.5	0.5		
If the sensors/actuators have dedicated control electronics, is the electronics for each channel on separate printed-circuit boards?			2.5	1.5
If the sensors/actuators have dedicated control electronics, is the electronics for each channel indoors and in separate cabinets?			2.5	0.5
Diversity/Redundancy:				
Do the channels employ different electrical technologies? e.g., one electronic or PE and the other relay	7.0			
Do the channels employ different electronic technologies? e.g., one electronic, the other PE	5.0			
Do the devices employ different physical principles for the sensing elements e.g., pressure and temperature, vane anemometer and Doppler transducer, etc.			7.5	
Do the devices employ different electrical principles/designs e.g., digital and analogue, different manufacturer (not rebadged) or different technology			5.5	
Do the channels employ enhanced redundancy: e.g., MooN N>M+2	2.0	0.5	2.0	0.5
Do the channels employ enhanced redundancy: e.g., MooN N=M+2	1.0	0.5	1.0	0.5
Is partial diversity used, e.g. hardware watchdog same technology	2.0	1.0		
Is partial diversity used, e.g. hardware watchdog other technology	3.0	1.5		
Were the channels designed by different designers with no communication between them during the design process?	1.0	1.0		
Are separate test methods and people used for each channel during commissioning?	1.0	0.5	1.0	1.0
Is maintenance on each channel carried out by different people at different times?	2.5		2.5	
Complexity/design/application/maturity/experience:				
Does cross-connection between channels preclude the exchange of any information other than that used for diagnostic or voting purposes?	0.5	0.5	0.5	0.5
Is the design based on techniques used in equipment that has been used successfully in the field for > 5 years?	0.5	1.0	1.0	1.0
Is there more than 5 years experience with the same hardware used in similar environments?	1.0	1.5	1.5	1.5
Is the system simple, e.g. no more than 10 inputs or outputs per channel?		1.0		
Are inputs and outputs protected from potential levels of over-voltage and over-current?	1.5	0.5	1.5	0.5
Are all devices/components conservatively rated? (e.g., by a factor of 2 or more)	2.0		2.0	
Table A.1 continued on next page				

Continued from Table A.1 on previous page				
Assessment/analysis and feedback of data:				
Have the results of the FMEA or FTA been examined to establish sources of CCF and have identified sources of CCF been eliminated by design?		3.0		3.0
Were CCFs addressed in design reviews with the results fed back into the design? (Documentary evidence of the design review process is required.)		3.0		3.0
Are all field failures fully analyzed with feedback into the design? (Documentary evidence of the procedure is required.)	0.5	3.5	0.5	3.5
Procedures/ human interface:	X _{PE}	Y _{PE}	X _{SA}	Y _{SA}
Is there a written system of work which will ensure that all component failures (or degradations) are identified, the root causes established and other similar items are inspected for similar potential causes of failure?		1.5	0.5	1.5
Are procedures in place to ensure that: maintenance (including adjustment or calibration) of any part of the independent channels is staggered, and, in addition to the manual checks carried out following maintenance, the automatic diagnostic checks are allowed to run satisfactorily between the completion of maintenance on one channel and the start of maintenance on another?	1.5	0.5	2.0	1.0
Do the documented maintenance procedures specify that all parts of redundant systems (e.g., cables, etc.), intended to be independent of each other, must not be relocated?	0.5	0.5	0.5	0.50
Is all maintenance of printed-circuit boards, etc. carried out off-site at a qualified repair center and have all the repaired items gone through a full pre-installation testing?	0.5	1.0	0.5	1.5
Do the system have low diagnostics coverage (60% to 90%) and report failures to the level of a field-replaceable module?	0.5			
Do the system have medium diagnostics coverage (90% to 99%) and report failures to the level of a field-replaceable module?	1.5	1.0		
Do the system have high diagnostics coverage (>99%) and report failures to the level of a field-replaceable module?	2.5	1.5		
Do the system diagnostics report failures to the level of a field-replaceable module?			1.0	1.0
Competence/ training/ safety culture:				
Have designers been trained (with training record) to understand the causes and consequences of Common cause failures	2.0	3.0	2.0	3.0
Have maintainers been trained (with training record) to understand the causes and consequences of Common cause failures	0.5	4.5	0.5	4.5
Environmental control:				
Is personnel access limited (e.g. locked cabinets, inaccessible position)?	0.5	2.5	0.5	2.5
Will the system be operating within the range of temperature, humidity, corrosion, dust, vibration, etc., over which it has been tested, without the use of external environmental control?	3.0	1.0	3.0	1.0
Are all signal and power cables separate at all positions?	2.0	1.0	2.0	1.0
Environmental testing:				
Has a system been tested for immunity to all relevant environmental influences (e.g. EMC, temperature, vibration, shock, humidity) to an appropriate level as defined in recognized standards?	10.0	10.0	10.0	10.0

NOTE See applicable notes after Table A.3.

Table A.2 — Level of diagnostics: Programmable electronics

Level of coverage of the automatic diagnostics	Value of Z to be used when the automatic diagnostic tests are repeated at intervals of:		
	Less than 1 minute	Between 1 and 5 mins	Greater than 5 minutes
> 99%	2.0	1.0	0
> 90%	1.5	0.5	0
> 60%	1.0	0	0

NOTE Diagnostic tests are effective against common cause failures only if an automatic shut-down, initiated by the diagnostics on the detection of a fault, can be assured before a non-simultaneous common cause failure would prevent a safe shut-down being implemented. If a safe shut-down is not initiated after a first fault then the following requirements will apply:

- The diagnostics shall determine the locality of the fault and be capable of localizing the fault.
- The diagnostic tests shall continue to be capable of placing the process in the safe state after the detection of any subsequent faults.

Only if the above criteria apply, can a non-zero value be used for Z.

See applicable notes after Table A.3.

Table A.3 — Level of diagnostics: Sensors or actuators

Level of coverage of the automatic diagnostics	Value of Z to be used when the automatic diagnostic tests are repeated at intervals of:			
	Less than 2 hours	Between 2 hours & 2 days	Between 2 days & 1 week	Greater than 1 week
> 99%	2.0	1.5	1.0	0
> 90%	1.5	1.0	0.5	0
> 60%	1.0	0.5	0	0

Notes to Tables A.1, A.2 & A.3

NOTE 1 If sensors or actuators are PE-based, they should be treated as PE if they are enclosed within the same building (or vehicle) as the PE that is used as the logic solver, and as sensors/actuators, if they are not.

NOTE 2 When using Table A.1, take account of the scores for all items that apply - the scoring has been designed to allow for items which are not mutually exclusive. For example, a system with PE channels in separate racks is entitled to both the score for "Are the PE channels in separate cabinets" and that for "Are the PE channels on separate printed-circuit boards."

NOTE 3 For a non-zero value of Z to be used, it must be ensured that the equipment under control is put into a safe state before a non-simultaneous Common cause failure can affect the all channels. The time taken to assure this safe state must be less than the claimed repetition time of the automatic diagnostics. A non-zero value for Z can be used only if:

- the system initiates an automatic shut-down on the identification of a fault, or,

- the system continues to run on a reduced number of channels and, following a fault, automatic shut-down will be assured immediately that the number of operating channels, that are capable of ensuring a safe shut-down, reduces to one, or,
- a formal system of work is in place to ensure that the cause of any revealed fault will be fully investigated within the claimed period between the automatic diagnostic tests and:
 - if the fault has the potential for leading to a common cause failure, the plant will be immediately shut-down, or,
 - the faulty channel will be repaired within the claimed period between the automatic diagnostic tests.

NOTE 4 The operation of the system on the identification of a fault must be taken into account. For example, a simple 2oo3 system must be shutdown (or be repaired) within the times quoted in Tables A.2 or A.3, following the identification of a single failure. If this is not done, a failure of a second channel could result in the two failed channels outvoting the remaining (good) channel. A system which automatically reconfigures itself to 1oo2 voting when one channel fails, and which will automatically shutdown on the occurrence of a second failure, has an increased probability of revealing the fault in the second channel and so a non-zero value for Z may be claimed.

NOTE 5 In the process industries, it is unlikely to be feasible to shutdown the EUC when a fault is detected within the repetition period for the automatic diagnostics as specified in Table A.2. This methodology should not be interpreted as a requirement for process plants to be shutdown when such faults are detected. However, if a shutdown is not implemented, no reduction in the β -factor can be gained by the use of automatic diagnostics for the programmable electronics. In some industries, a shutdown may be feasible within the specified time. In these cases, a non-zero value of Z may be used.

NOTE 6 Where diagnostics are carried out in a modular way, the repetition time used in Tables A.2 or A.3 is the time between the successive completions of the full set of diagnostic modules. The diagnostic coverage is the total coverage provided by all of the modules.

Table A.4 — Calculation of β or β_D

	Corresponding value of β or β_D for the:	
Score (S or S_D)	PES	Sensors or actuators
120 or above	0.5%	1%
70 to 120	1%	2%
45 to 70	2%	5%
Less than 45	5%	10%
<p>NOTE The maximum levels of β_D shown in this table are lower than would normally be used, reflecting the use of the techniques described elsewhere in this technical report for the reduction in the probability of systematic failures as a whole, and of Common cause failures as a result of this.</p> <p>Values of β_D lower than 0.5% for the PES and 1% for the sensors would be difficult to justify.</p>		

A.7 Examples of the use of the methodology

In order to demonstrate the effect of using the methodology, some simple examples (Table A.5) have been worked through for the Programmable Electronics. These are:

Example 1: A diverse system with good diagnostics

Example 2: A diverse system with poor diagnostics

Example 3: A redundancy system with good diagnostics

Example 4: A redundancy system with poor diagnostics

For categories not relating to diagnostics nor diversity, half the maximum score for a category was used; this being the same for each of the examples. It should be noted that when Table A.1 is used in practice, no such subdivision of scores is allowed.

Table A.5 — Examples

Category		Example 1	Example 2	Example 3	Example 4
Separation/segregation	X	3.50	3.50	3.50	3.50
	Y	1.50	1.50	1.50	1.50
Diversity/redundancy	X	14.50	14.50	2.00	2.00
	Y	3.00	3.00	1.00	1.00
Complexity/design/.....	X	2.75	2.75	2.75	2.75
	Y	2.25	2.25	2.25	2.25
Assessment/analysis....	X	0.25	0.25	0.25	0.25
	Y	4.75	4.75	4.75	4.75
Procedures/human interface	X	3.50	3.50	3.50	3.50
	Y	3.00	3.00	3.00	3.00
Competence/training/...	X	1.25	1.25	1.25	1.25
	Y	3.75	3.75	3.75	3.75
Environmental control	X	2.75	2.75	2.75	2.75
	Y	2.25	2.25	2.25	2.25
Environmental test	X	7.50	7.50	7.50	7.50
	Y	7.50	7.50	7.50	7.50
Level of diagnostics	Z	2.00	0.00	2.00	0.00
Total X		32.25	32.25	19.75	19.75
Total Y		24.25	24.25	22.25	22.25
Score S		56.5	56.5	42	42
β		2%	2%	5%	5%
Score S_D		121	56.5	81.5	42
β_D		0.5%	2%	1%	5%

Annex B (informative) — Fault simulation test procedure

B.1 Objective

Fault simulation testing is a verification method to determine the safety integrity and diagnostic coverage of the SIS by purposely introducing faults that simulate those that could occur in an on-line SIS, under specified environmental conditions.

B.2 Scope

This test procedure applies to SIS elements in the process industries.

Simulate only single faults unless this fault is covert, in which case a second fault may be simulated.

Perform fault simulation testing of the SIS elements by independent third parties.

Determine the fault simulation test success/failure criteria based on the failure mode of the SIS, and the ability of the SIS to correctly detect, diagnose and annunciate the fault.

Estimate the diagnostic coverage of the SIS from the test results.

B.3 Qualification of test personnel

“Qualified personnel” performing the fault simulation test are those persons who have previously performed a fault simulation test program, or have served as an apprentice to a qualified person for two previous fault simulation test programs.

B.4 Fault models

Each fault included in the test should simulate a potential real-world fault in an on-line SIS. A fault model is to be developed for each type of component used in the SIS. The fault model is determined by identifying the failure modes and mechanisms for each type of component. Some examples of fault models are found in Table B.1.

Table B.1 — Fault model examples

Component	Failure Mode	Fault Mechanism
Resistor	Open	
	Short	
	Drift	
Capacitor	Open	
	Short	
	Leakage	
Relay	Open Contact	
	Shorted Contact	
	High Contact Resistance	
	Open Coil	
	Closed Coil	
Connectors	Open	Corrosion
	Short	Misalignment
Integrated Circuits	Open of pins	
	Short of pins	
	Stuck at "0" of all pins	
	Stuck at "1" of all pins	
	Directed shorts between pins	
	Functional failures	

B.5 Fault simulation tests

B.5.1 Required faults

The following fault simulations are required to be performed in each fault simulation test program:

a) Data lines

Fault several data lines of each and every data bus in the SIS.

b) Address lines

Several address lines of each and every address bus in the SIS shall be faulted. Every address line used for memory-mapped input/output, or to decode external logic, shall be faulted.

c) Control lines

Fault every control line of each and every control bus. Fault each CPU interrupt.

d) Error detection circuitry (e.g. parity)

Fault each error detection circuit in such a way as to attempt to disable error detection. If this condition is not covered, then introduce a second fault simulating an error.

e) Watchdog circuit

Fault each watchdog circuit (internal or external to the SIS) in such a way as to attempt to disable the time-out function.

f) Selection logic

Fault any logic which selects or decodes among a number of channels in such a way as to attempt to select the wrong channel.

g) Memory

Simulate several single bit memory errors for each memory device type. Utilize a photographic flash for SIS which use EPROM's to simulate a temporary change in memory contents.

e) Power fail Detection

Vary the input and output of power supplies to ensure that the SIS operates properly both inside and outside the specified voltage limits.

f) Bus arbitration logic

Fault the bus arbitration logic in such a way as to attempt to allow simultaneous access to the bus, and to allow no access to the bus.

g) Communications misaddressing

Fault serial or parallel type communications in such a way as to attempt to select more than one subsystem.

h) Input/output voting logic

Fault each and every independent channel of a typical voting scheme for each type of input and output.

B.5.2 Randomly selected faults

Select additional faults at random so that the total number of tests allows a statistically significant determination of the diagnostic coverage.

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Annex C (informative) — SIL quantification of SIS – Advisory software packages

C.1 Advisory software

Advisory software packages may be used to assist in the types of calculation presented in this technical report. Some of the advantages, disadvantages, and cautions associated with these packages are presented below.

C.2 Advantages

C.2.1 Advisory software packages generally speed the quantification and presentation of specific cases of interest. This capability allows comparison of a number of test cases to illustrate the relative effect of varying individual input parameters (functional test interval, redundancy, etc).

C.2.2 These packages make the more complex calculations less prone to random calculation errors than hand calculations. In addition, the most complex techniques are not very practical without some type of computer assistance.

C.2.3 The packages are often easy to use.

C.3 Disadvantages

C.3.1 The user must make some effort to understand the modeling technique, assumptions, and limitations used in the package. The relevant information may not be readily apparent to the user or well documented by the supplier. Without this understanding, the user may be confused by the results obtained.

C.3.2 These packages may not have been verified for accuracy by the supplier or by a third party.

C.4 Cautions

C.4.1 Some of the advisory software packages are so easy to use and contain enough hidden assumptions that a user with insufficient skill may calculate an incorrect SIL for a SIS. The user must be aware that the ease of use does not dictate the skill required to perform these calculations.

C.4.2 The user must be aware of and assume the responsibility for the sufficiency and applicability of the modeling technique, the assumptions, the limitations, and the supplier validation activities before using one of these software packages for calculation of the SIL of a SIS.

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Annex D (informative) — Failure mode effect, hazard and criticality analysis

D.1 Introduction

The Failure Mode Effect, Hazard and Criticality Analysis (FMEHCRA) is a widely used and effective safety analysis technique. The standard reference for this method is US MIL-STD-1629 [MIL1629] which describes the Failure Mode and Effect Analysis (FMEA).

Engineers have always performed a FMEA type of analysis on their design and manufacturing processes, but the first formal applications of the FMEHCRA can be found in the mid-1960 in the American aerospace industry. The FMEHCRA consists of three different analysis techniques.

- 1) Failure Mode and Effect Analysis
- 2) Fault Hazard Analysis
- 3) Criticality analysis

FMEHCRA is a bottom up technique that is used qualitative, quantitative or as a combination of both and is very effective in identifying critical failures of the system in consideration. Very often the FMEHCRA technique is adjusted to the company strategy or ideas about this technique.

A FMEHCRA can be described as a systematic way

- to identify and evaluate the different failure modes and effects of the system in consideration.
- to determine the actions to be taken which could eliminate or reduce the chance of the different failure modes occurring.
- to document the system in consideration.

As part of the safety analysis process, the FMEA technique is used for two purposes. At the system level a FMEA is used to document system behavior under failure conditions. A variation of the FMEA technique is recommended at the electronic module level to establish diagnostic capability and failure rates for each failure mode.

A FMEDA (Failure Mode Effect and Diagnostic Analysis) is a FMEA variation. It combines standard FMEA techniques with extensions to identify on-line diagnostic techniques. It is a technique recommended to generate failure rates for each important category (safe detected, safe undetected, dangerous detected, dangerous undetected) in the safety models.

D.2 Failure mode and effect analysis

The information needed for a FMEA is typically stored in a worksheet, see Table D.1. The first nine columns of the worksheet represent the Failure Mode and Effect Analysis. The following will explain the different columns of the worksheet.

Column 1 Name

This column describes the name of the component in consideration (definition of module/component).

Column 2 Code

This column describes the code number or reference of the component.

Column 3 Function

This column describes the function of the component. This is important for anybody who writes or reads the document to understand the way in which the system works. It is an easy way to get a good understanding of how the different components work and how eventually the system works.

Column 4 Failure mode

This column describes the failure modes of the component. For example, leakage, fail open or close for valves, fracture, wear out, etc.

Column 5 Cause

This column describes the cause of the failure mode of column four. For example, aging, overload, misuse, etc.

Column 6 Failure effect on function level

This column describes the effect of the failure on function level of the component.

Column 7 Failure effect on next sub level; Criticality

This column describes the effect of the failure one level higher than in column six. Depending on the complexity of the system it is possible to consider more levels. This gives a good insight in how the system works.

Column 8 Failure rate λ

In this column the failure rate of the current failure mode is given, usually in failures per unit time. If no failure rates are available it is possible to use the information of standards or databases.

Column 9 Remarks / action

This column is reserved for any comment that is of importance. For example the action to be taken to prevent a failure mode like this, change the design, condition monitoring, better education of employees, etc.

D.3 Failure mode effect and diagnostic analysis

The following additional columns are added to a FMEA to analyze the diagnostic capability of the equipment.

Column 10 Detectability

This column is an extension to the standard for the purpose of identifying that this component failure is detectable by on-line diagnostics. The number must be in the range of 0 to 1. A number between 0 and 1 may be entered to indicate the probability of detection.

NOTE Whenever a component failure mode is claimed detectable, this may be verified with a fault simulation test in some cases (see Annex B). The component failure mode is simulated on actual E/E/PES equipment and the diagnostic capability of the E/E/PES is verified.

Column 11 Diagnostic

This column is an extension to the standard used to identify the diagnostic used to detect the failure.

Column 12 Failure Mode Number

This column is used to numerically identify failure mode. A "1" is entered for safe failure modes. A "0" is entered for dangerous failure modes. The number is used in spreadsheets to calculate the various failure categories.

Column 13 Safe Detected Failure Rate

This column contains the calculated failure rate of safe detected failures. It is obtained by multiplying the failure rate (Column 8) by the failure mode number (Column 12) and the detectability (Column 10).

Column 14 Safe Undetected Failure Rate

This column contains the calculated failure rate of safe undetected failures. It is obtained by multiplying the failure rate (Column 8) by the failure mode number (Column 12) and one minus the detectability (Column 10).

Column 15 Dangerous Detected Failure Rate

This column contains the calculated failure rate of dangerous detected failures. It is obtained by multiplying the failure rate (Column 8) by one minus the failure mode number (Column 12) and the detectability (Column 10).

Column 16 Dangerous Undetected Failure Rate

This column contains the calculated failure rate of dangerous undetected failures. It is obtained by multiplying the failure rate (Column 8) by one minus the failure mode number (Column 12) and one minus the detectability (Column 10).

FMEDA Example

Table D.1 is an example of a FMEDA applied to an input circuit for a PES.

Table D.1 — Example FMEDA table

Failure Modes and Effects Analysis					Failures/billion hours = 10^9 failures / hour										
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Name	Code	Function	Mode	Cause	Effect	Criticality	λ	Remarks	Det.	Diagnostics	Mod	SD	SU	DD	DU
R1-10K	4555-10	Input	short		Threshold shift	Safe	0.125		0		1	0	0.125	0	0
		Threshold	open		open circuit	Safe	0.5		0.95	loose input pulse	1	0.475	0.025	0	0
R2-100K	4555-100	Min. I	short		short circuit	Safe	0.125		0.95	loose input pulse	1	0.11875	0.00625	0	0
			open		Threshold shift	Safe	0.5		0		1	0	0.5	0	0
D1	4200-7	Drop volts	short	surge	overvoltage	Safe	2		0.95	loose input pulse	1	1.9	0.1	0	0
			open		open circuit	Safe	5		0.95	loose input pulse	1	4.75	0.25	0	0
D2	4200-7	Drop volts	short	surge	overvoltage	Safe	2		0.95	loose input pulse	1	1.9	0.1	0	0
			open		open circuit	Safe	5		0.95	loose input pulse	1	4.75	0.25	0	0
OC1	4805-25	Isolate	led dim	wear	no light	Safe	28		0.95	comp. mismatch	1	26.6	1.4	0	0
			tran. short	ss	read logic 1	Dangerous	10		0.95	comp. mismatch	0	0	0	9.5	0.5
			tran. open		read logic 0	Safe	6		0.95	comp. mismatch	1	5.7	0.3	0	0
OC2	4805-25	Isolate	led dim	wear	no light	Safe	28		0.95	comp. mismatch	1	26.6	1.4	0	0
			short	ss	read logic 1	Dangerous	10		0.95	comp. mismatch	0	0	0	9.5	0.5
			open		read logic 0	Safe	6		0.95	comp. mismatch	1	5.7	0.3	0	0
R3-100K	4555-100	Filter	short		loose filter	Safe	0.125		0		1	0	0.125	0	0
			open		input float high	Dangerous	0.5		0.95	comp. mismatch	0	0	0	0.475	0.025
R4-10K	4555-10		short		read logic 0	Safe	0.125		0.95	comp. mismatch	1	0.11875	0.00625	0	0
			open		read logic 1	Dangerous	0.5		0.95	comp. mismatch	0	0	0	0.475	0.025
R5-100K	4555-100	Filter	short		loose filter	Safe	0.125		0		1	0	0.125	0	0
			open		input float high	Dangerous	0.5		0.95	comp. mismatch	0	0	0	0.475	0.025
R6-10K	4555-10		short		read logic 0	Safe	0.125		0.95	comp. mismatch	1	0.11875	0.00625	0	0
			open		read logic 1	Dangerous	0.5		0.95	comp. mismatch	0	0	0	0.475	0.025
C1	4350-32	Filter	short	cd	read logic 0	Safe	2		0.95	comp. mismatch	1	1.9	0.1	0	0
			open		loose filter	Safe	0.5		0		1	0	0.5	0	0
C2	4350-32	Filter	short	cd	read logic 0	Safe	2		0.95	comp. mismatch	1	1.9	0.1	0	0
			open		loose filter	Safe	0.5		0		1	0	0.5	0	0
IC1	4017BT	Buffer	short		cross talk	Dangerous	5		0.95			0	0	4.75	0.25
			open		read logic 0	Safe	5		0.95			0	0	4.75	0.25
Total							120.8					82.5	6.2	30.4	1.6
Total Failure Rate							121			Safe Coverage		93.0%			
Total Safe Failure Rate							88.8			Dangerous Coverage		95.0%			
Total Dangerous Failure Rate							32.0								
Safe Detected Failure Rate							82.5								
Safe Undetected Failure Rate							6.2								
Dangerous Detected Failure Rate							30.4								
Dangerous Undetected Failure Rate							1.6								

D.4 Conclusions FMEHCrA analysis

The FMEHCrA is a bottom-up procedure, starting from failures at component or subsystem level and evaluating their consequences on system level. The primary objectives of the analysis are to document system operation at the system level and to determine failure modes and coverage factors at the module level. Some remarks on the FMEHCrA analysis:

- Omission of important failure modes is always possible (for example omission of possible human failure causes) and leads to a totally unreliable FMEHCrA.
- The FMEHCrA approach is recommended primarily as a qualitative method at the system level. The FMEHCrA cannot give an accurate quantification of the safety of a system, but only a comparison of the effects of different failure modes within one system or a comparison between systems. More important it can lead to misleading results due to the human selection and interpretation of failure modes and their consequences.
- The FMEHCrA technique is poor at identifying combinations of failures that cause critical problems. Each component is reviewed individually, combinations are not addressed.
- Common cause failures are not taken into account, Operational and maintenance failures are likely to be missed unless the team of reviewers is skilled in human reliability analysis
- The technique can best be used to find that small failures that may not seem important at first but that eventually, can lead to critical system failures.

- The outputs of the FMEHCrA and FMEDA can be very well used as input values for extended techniques like Markov, FTA and RBD to make an accurate qualitative analysis on system level.

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Annex E (informative) — Common cause failures and systematic failure checklist

This includes a checklist of common cause failure and systematic failure events that may be modeled during SIS evaluation using the techniques described in ISA-TR84.00.02-2002 - Parts 2, 3, 4, and 5.

Note that common cause failures and systematic failures can be due to a single failure event or to a combination of systematic failure, common cause failure, poor design practices, and/or poor operation/maintenance practices.

These common cause failures and systematic failures can include, but are not limited to, the following:

- Component
- Specification
 - Manufacture
 - Calibration
 - Wear-out susceptibility
 - Test degradation
 - Maintenance degradation
 - Aging
 - Data sharing
 - Application software error
 - Embedded software error
- Plant Personnel
 - Installation
 - Operation, e.g., incorrect procedures or procedures not followed
 - Maintenance, e.g., incorrect procedures or procedures not followed
 - Management of change
 - Improper bypassing
- Environmental Stress
 - Vibration
 - Uninhibited monomer
 - Solids, e.g., plugging and erosion

- RFI/ESD
- Temperature
- Freezing, icing, failed heat tracing
- Humidity
- Corrosion
- Flood susceptibility
- Seismic susceptibility

This list is not an exhaustive catalogue of the potential common cause failures and systematic failures. Rather, it is a partial list of common cause failures and systematic failures that have been observed by industry and that have played a critical part in the PFD or real systems ^(11, 34, 35).

Some specific examples of common cause failures and systematic failures are as follows:

- Process chemistry disables safety function of final element (valve plugs or valve corroded);
- Valve leaks due to corrosion AND this leak is not detected by mechanical integrity inspection;
- Solenoid valve fails due to incorrect installation AND this is not detected by testing;
- Solenoid vent port is plugged by dirt daubers or plugged by insulation AND is not detected by testing;
- User application logic errors;
- Poor communication of the safety requirements specification (SRS) to SIS designer and installer;
- Transmitter calibrated incorrectly (wrong specification, bad calibration standard, technician makes a mistake);
- Wrong specification device (transmitter, solenoid valve, shutdown valve, etc.) installed.

NOTE Dirt daubers – other common names: mud dauber or mud wasp; there are three types (scientific names):

Organ pipe mud dauber (*Trypoxylon politum*),

Blue mud dauber (*Chalybion californicum*), and

Black and white mud dauber (*Sceliphron caementarium*).

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