Determining the SIL level of a Safety Instrumented Function (SIF)

INTERNATIONAL
TECHNOLOGY FOR SAFETY

TECHNOLOGY FOR SAFETY

STANDARD DEFINITIONS

For safety instrumented system there are two important standards when it comes to functional safety:

- **IEC 61508** Title: Standard for Functional Safety of Electrical / Electronic/ Programmable Electronic Safety-Related System

IEC 61508 was conceived to define and harmonize a method to reduce risks for human beings and/or reduce valuable loss for all industrial and non industrial environments.

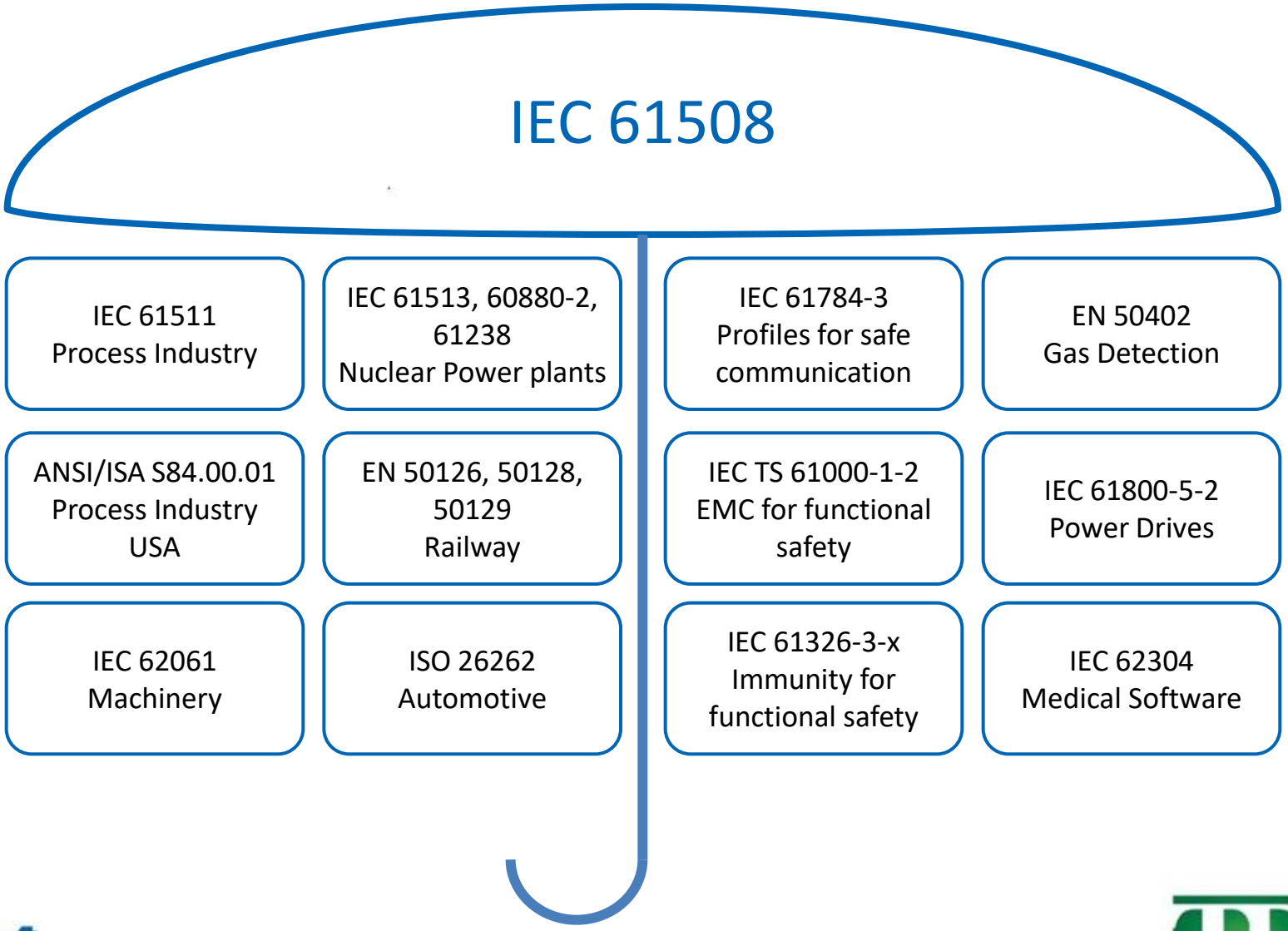
- **IEC 61511** Title: Safety Instrumented Systems for the Process Industry

IEC 61511 was developed as a Process Sector implementation of IEC 61508

Following the above standard is the minimum necessary condition to obtain plant safety. However this, alone, does not guarantee that the process will be safe.

NOT implementing these safety standards will certainly lead to an UNSAFE process.

UMBRELLA STANDARD



APPLICATION AREA IEC 61508 AND IEC 61511

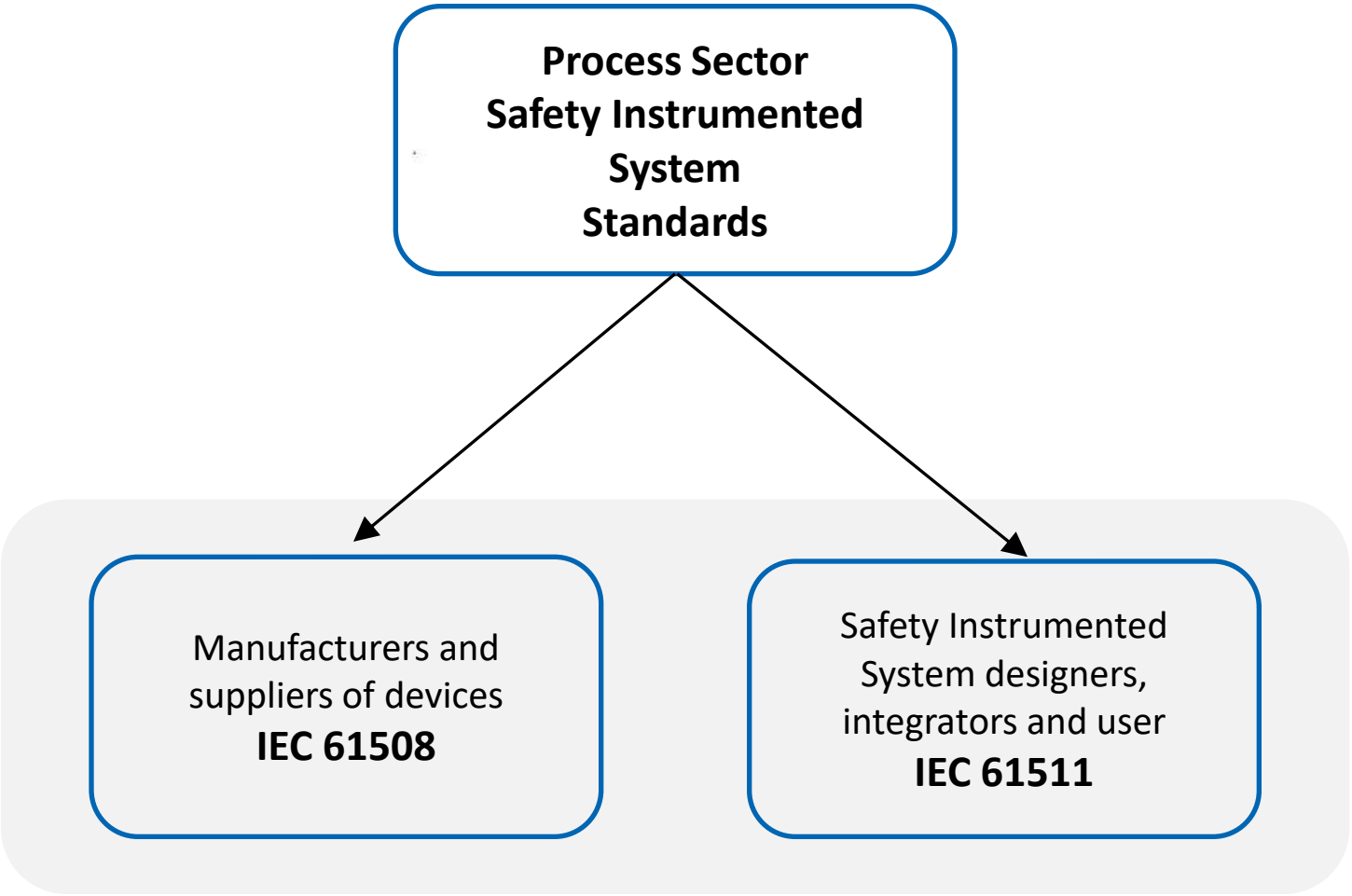
IEC 61508 typical applications are:

- Programmable Electronic Systems (PES)
- Safety Instrumented Systems (SIS)
- Emergency Shutdown Systems (ESD)
- High Integrity Pressure Protection Systems (HIPPS)
- Burner Management Systems (BMS)
- Fire & Gas Systems (F&G)
- High Speed Over Protection Systems
- Train Emergency Brake Systems

IEC 61511 applies to safety instrumented systems:

- Instruments (E/E/PE or not)
- Logic Solver (E/E/PE or not)
- Actuators (E/E/PE or not)

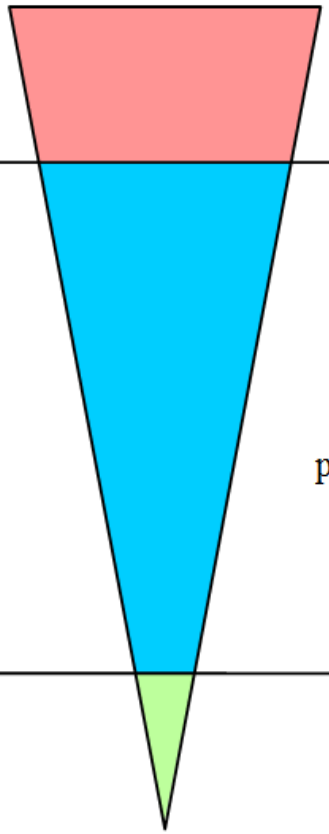
IEC 61508 VERSUS IEC 61511



WHAT IS SAFETY?

“Freedom from unacceptable risks”

A.L.A.R.P.



Intolerable Region
(Red Zone)

Risk cannot be justified except in extraordinary circumstances

Tolerable only if further risk reduction is impracticable or if its cost are grossly disproportional to the gained improvement.

The ALARP or tolerability Region
(Blue Zone)

As the risk is reduced, the less proportionately, it is necessary to spend to reduce it further, to satisfy ALARP. The concept of diminishing proportion is shown by the triangle.

Risk is undertaken only if a benefit is desired

Broadly Acceptable Region
(Green Zone)

It is necessary to maintain assurance that risk remains at this level

No need for detailed working to demonstrate ALARP

NEGLIGIBLE RISK

Figure 67, Risk and ALARP zone

TOLERABLE RISK

How governments think about us:

Country	Maximum risk to the public
UK	1×10^{-4}
Hong Kong	1×10^{-5}
Netherlands	1×10^{-6}
Australia	1×10^{-6}
Germany	0

RISK REDUCTION

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

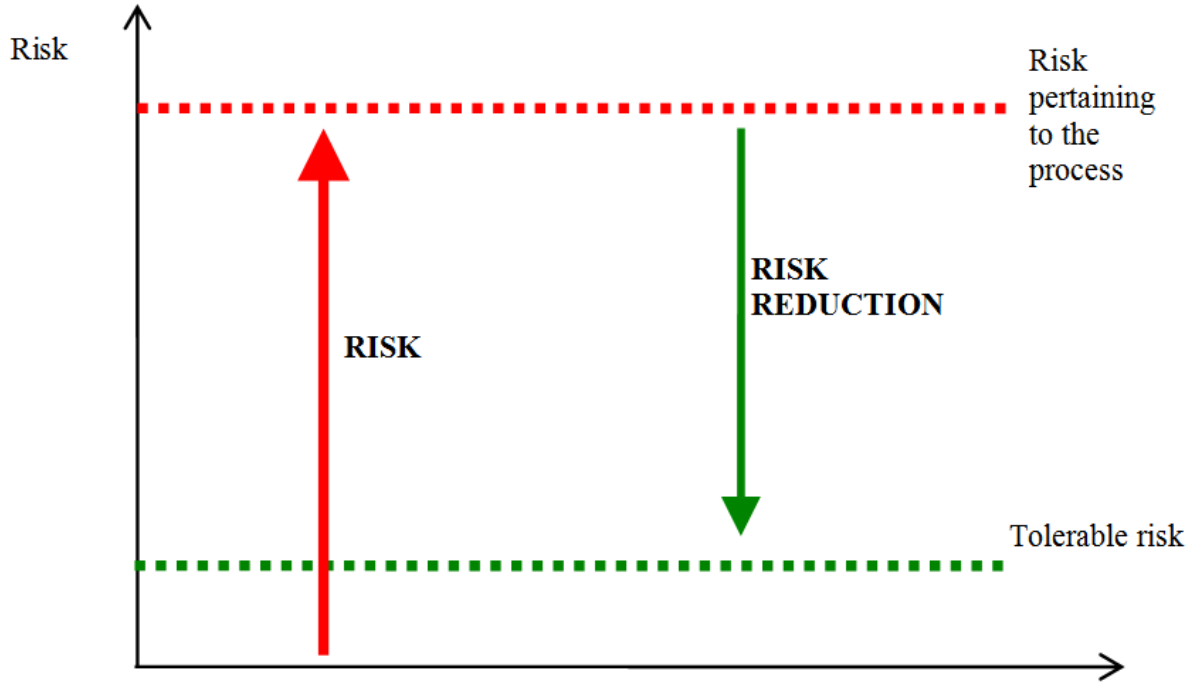


Figure 65, Basic concept of risk reduction

RISK REDUCTION FACTOR

- Nr. of accidents per year without protections: 10
- Nr. of tolerable accidents: 1 per 100 years
- 10 x 100 / 1 = 1000 = RRF
  (Risk Reduction Factor)
- 1 / 1000 = 0.001 = PFDavg per year
  (Average Probability of Failure on Demand)
- This means to obtain a SIF safety unavailability of 1/1000 in one year (about 10 hours).

BENEFITS VS. COSTS IN THE ALARP BLUE ZONE

$$\frac{\text{Benefits}}{\text{Costs}} = \frac{F_{NO\,SIS} \times EV_{NO\,SIS} - F_{SIS} \times EV_{SIS}}{COST_{SIS} + COST_{NT}}$$

Where:

- B-C ratio: The ratio of benefits to costs
- $F_{NO\text{-}SIS}$: Frequency of the unwanted event without a SIS.
- $EV_{NO\text{-}SIS}$: Total expected value of loss of the event without a SIS.
- F_{SIS} : Frequency of the unwanted event with a SIS.
- EV_{SIS} : Total expected value of loss of the event with a SIS.
- $COST_{SIS}$: Total lifecycle cost of the SIS (annualized).
- $COST_{NT}$: Cost incurred due to nuisance trip (annualized)

Example:

A SIS is being installed to prevent a fire that will cost the company $1,000,000.
The frequency prior to application of SIS has been calculated in one every 10 years.
After SIS installation the expected frequency is one every 1000 years, and its annualized cost is approximately $66.000.
Cost for nuisance trip is negligible, being F&G normally de-energized.
What is the benefit-to-cost ratio for the F&G project?
The Benefits/Costs relation will be:

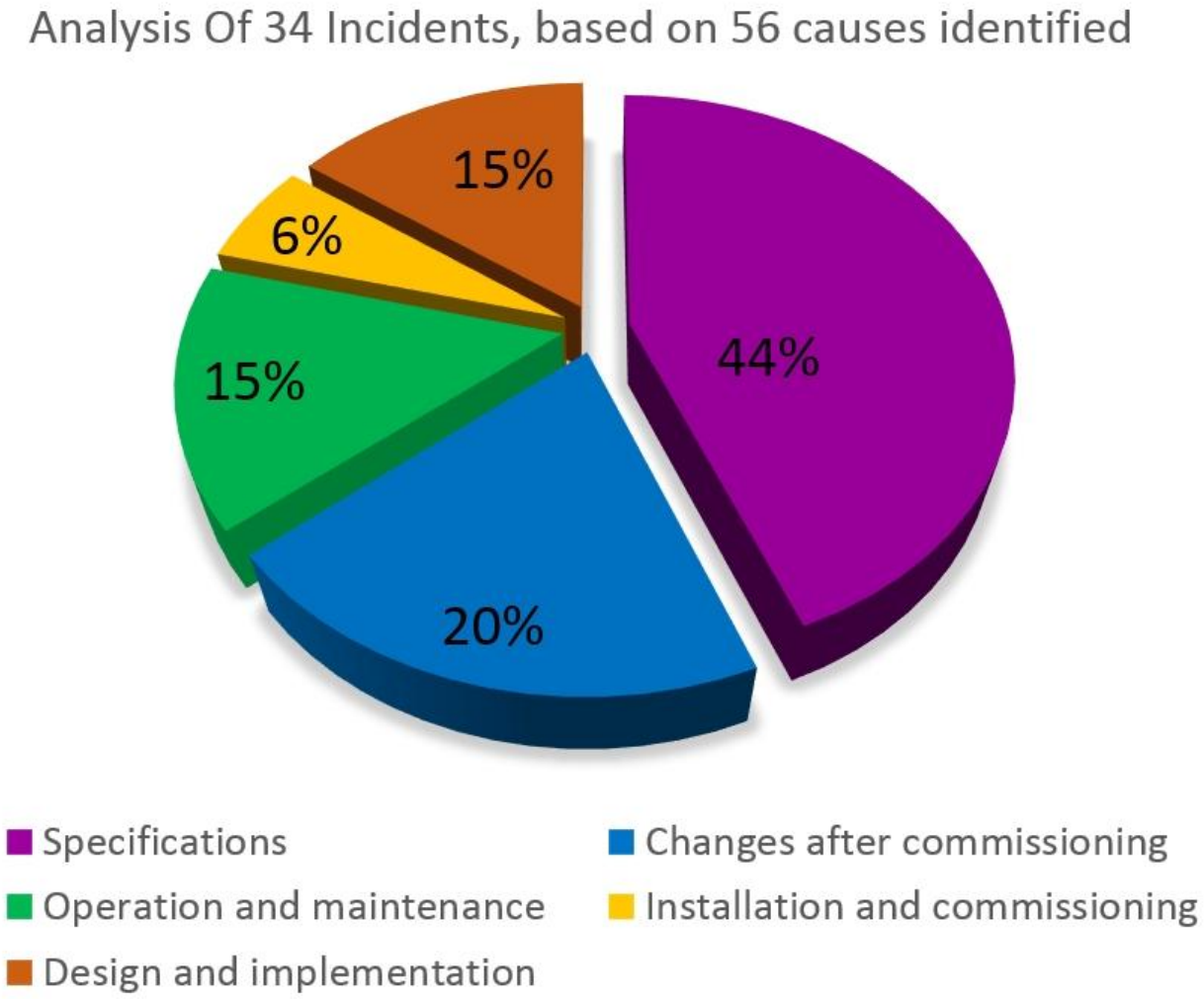
$$\text{Benefits} = \left(\frac{1}{10} \times 1000000\right) - \left(\frac{1}{1000} \times 1000000\right) = 99000$$

$$\text{Costs} = (66000 + 0) = 66000$$

$$\frac{\text{Benefits}}{\text{Costs}} = \frac{99000}{66000} = 1.5$$

A benefit-to-cost ratio of 1.5 means that for every $1 of investment the plant owner can expect $1.5 in return.

FREQUENCY OF FAILURES

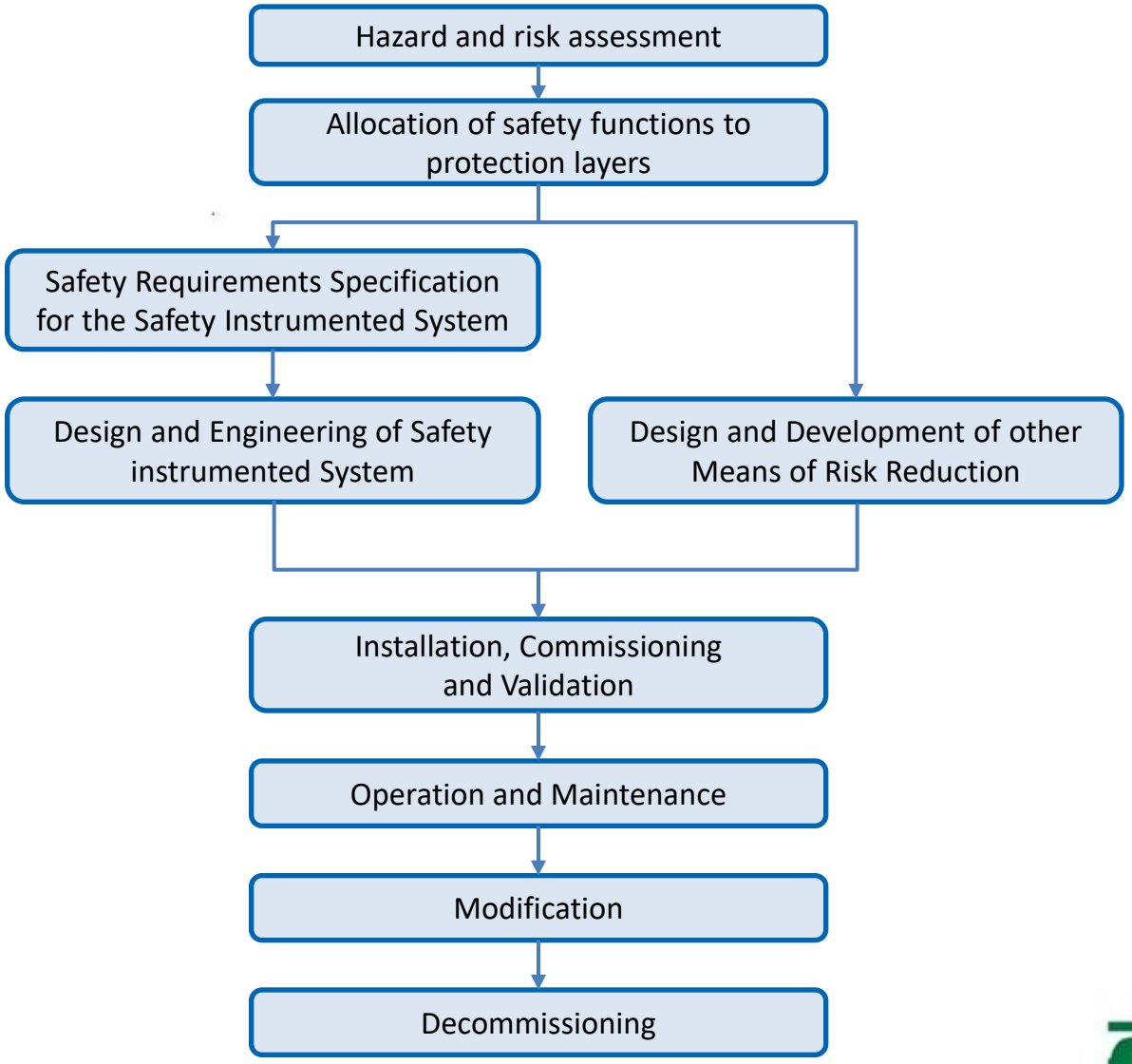


Out of control: Why control systems go wrong and how to prevent failure?
(2nd edition, source: © Health & Safety Executive HSE – UK)

IEC 61511 LIFECYCLE CONCEPT

Functional Safety Management and Assessment

Lifecycle Structure and Planning

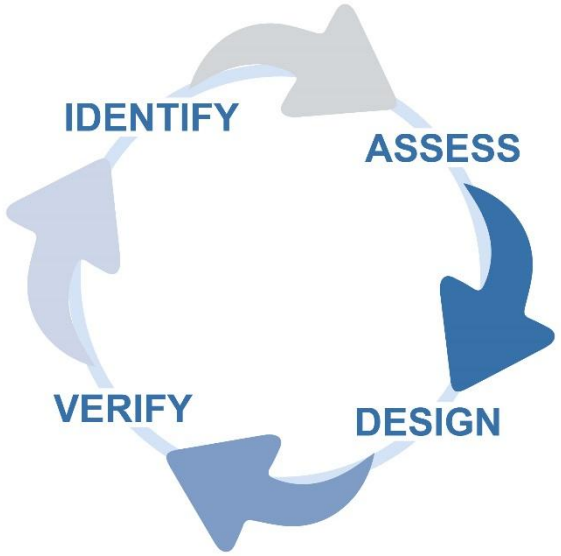


Verification

Safety Lifecycle (IEC 61511)

"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."

It is a closed loop / continuous Process; it has no end.



LIFECYCLE AREAS

SLC can be categorized into three broad areas:

1. **Analysis**: which focuses on identifying hazards and hazardous events, the likelihood these hazardous events will occur, potential consequences, and the availability of a layer of protection, as well as the need for any SISs and the allocated SIL.
2. **Realization**: which focuses on design and fabrication of the SIS.
3. **Operation**: which covers startup, operation, maintenance, modification and eventual decommissioning of the SIS.

These phases encompass the entire life-cycle process of the safety system from concept through decommissioning.

HAZARD & OPERABILITY ANALYSIS (HAZOP)

HAZOP:

- Is a structured and critical examination of a process.
- Is a brainstorming technique.
- All possible deviations from the design intent are examined.
- The consequences of the undesirable effects are examined.

Dev	Cause	Consequence	Safeguards	Recommendations
1.0	**More pressure**			
1.1	Column steam reboiler pressure control fails, causing excessive heat input	Column overpressure and potential mechanical failure of the vessel and release of its contents	Pressure relief valve, operator intervention to high-pressure alarms, mechanical design of vessel	Install SIF to stop reboiler steam flow upon high column pressure
1.2	Steam reboiler tube leak causes high-pressure steam to enter vessel	Column overpressure and potential mechanical failure of the vessel and release of its contents	Pressure relief valve, operator intervention to high-pressure alarms	See item 1.1
2.0	**Less flow**			
2.1	Low flow through bottoms pump causes pump failure and subsequent seal failure	Pump seal fails and releases flammable material	Low outlet flow Pump Shutdown SIS	Existing safeguards adequate

Debutanizer Column Node: Reboiler Section

LAYERS OF PROTECTION ANALYSIS (LOPA)

LOPA:

- It helps determine the frequency of occurrence of the hazardous event
- It is a modified version of event tree analysis
- It helps establish the frequency of a hazardous event leading to an accident
- It takes into account only protection layers
- Can be used qualitatively as well as quantitatively

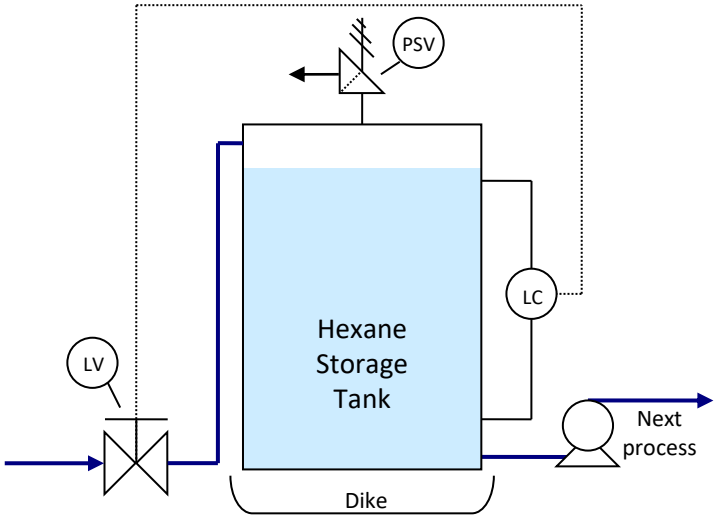


Figure 72, Sample Process for LOPA Example

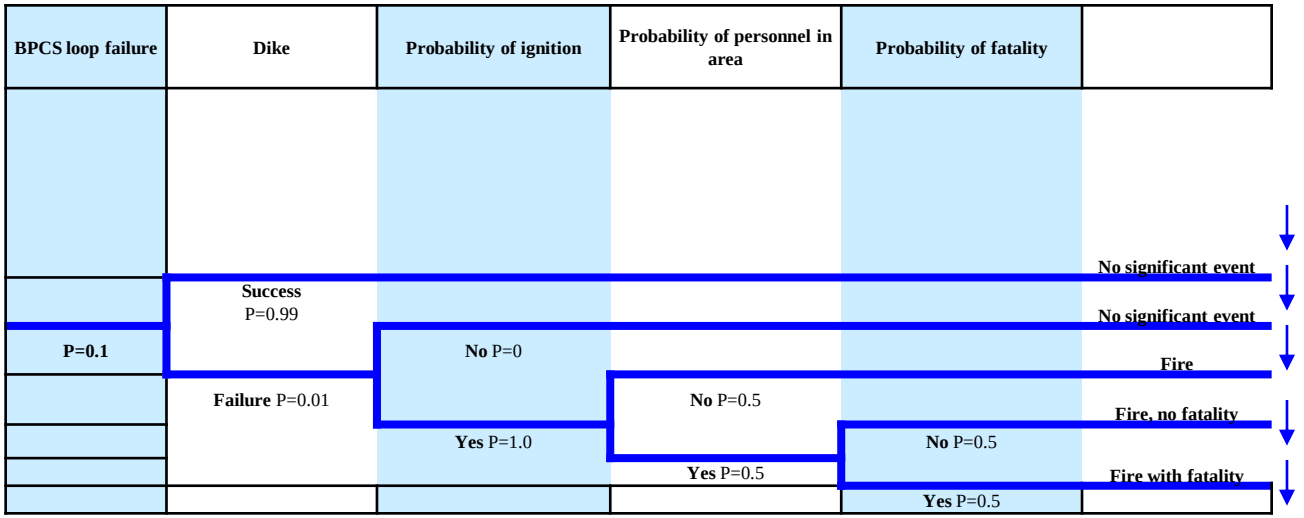


Figure 73, Event tree for LOPA example

RISK REDUCTION WITH PROTECTION LAYERS

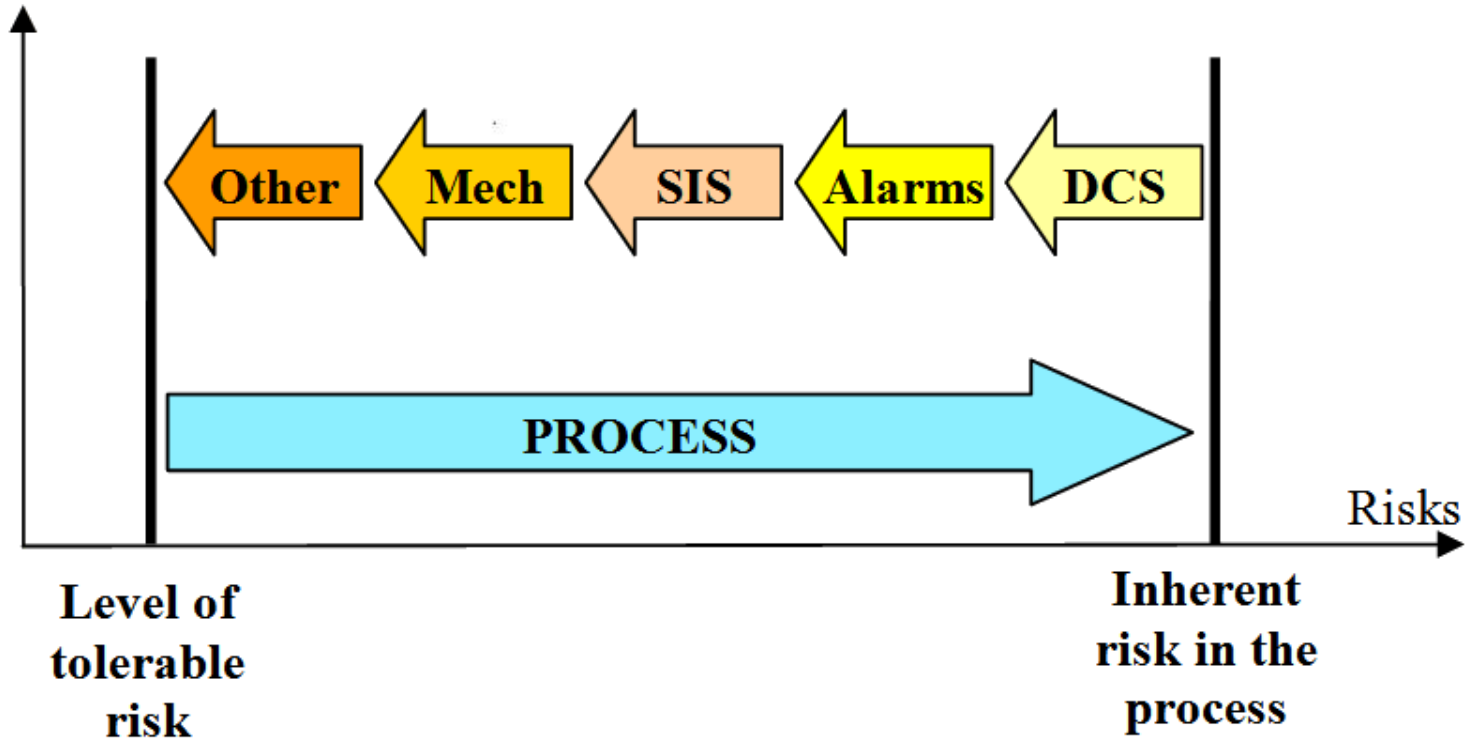
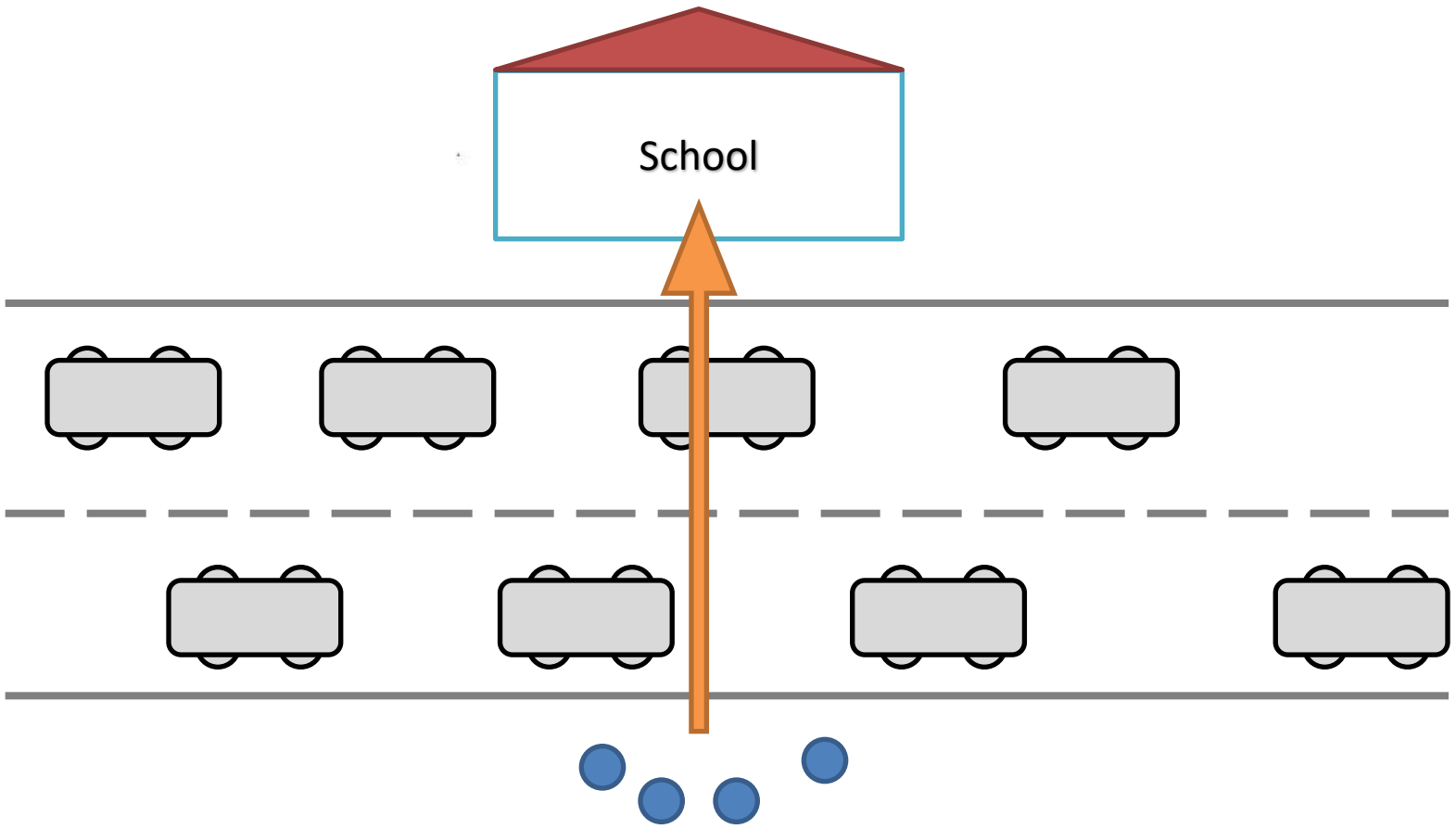
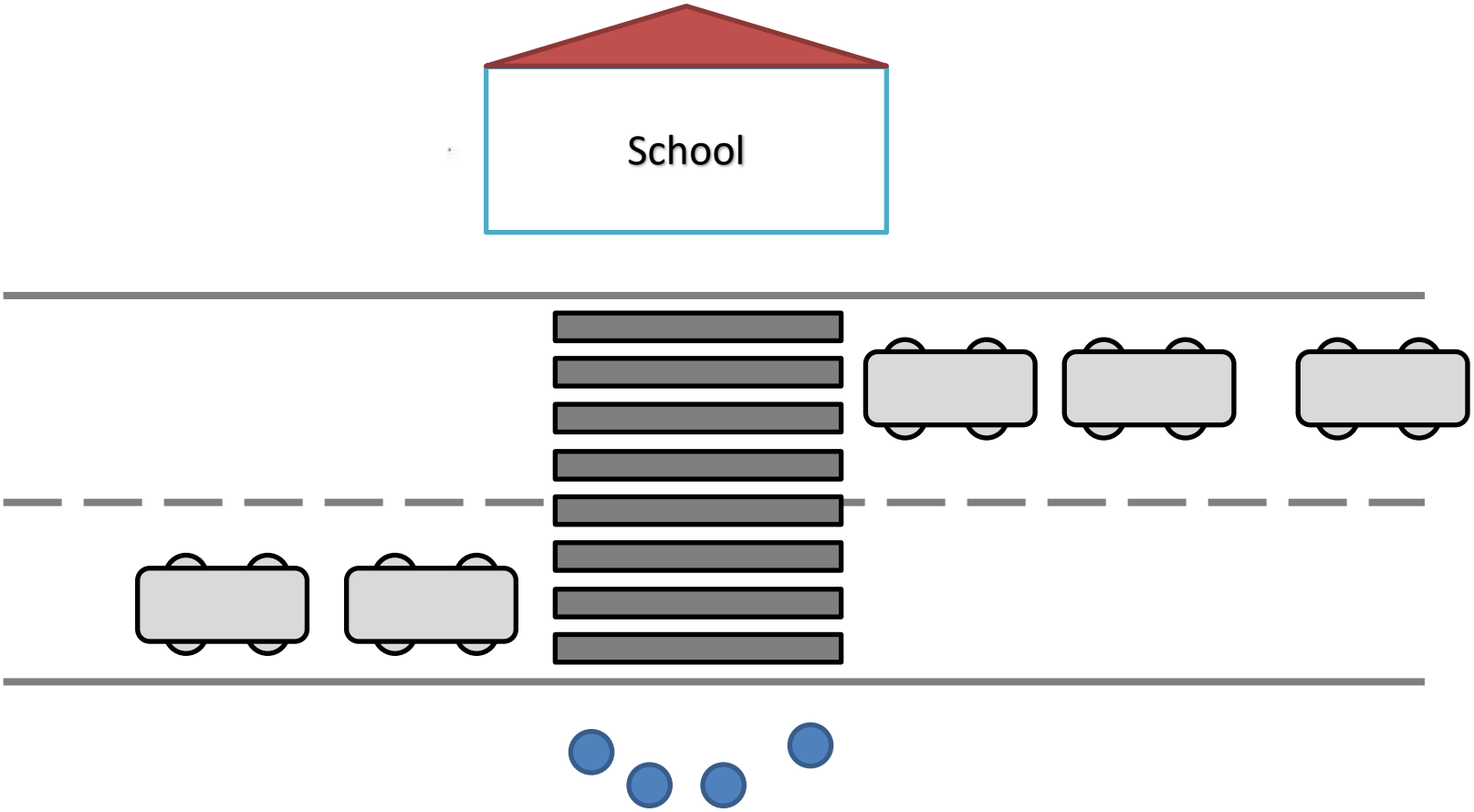
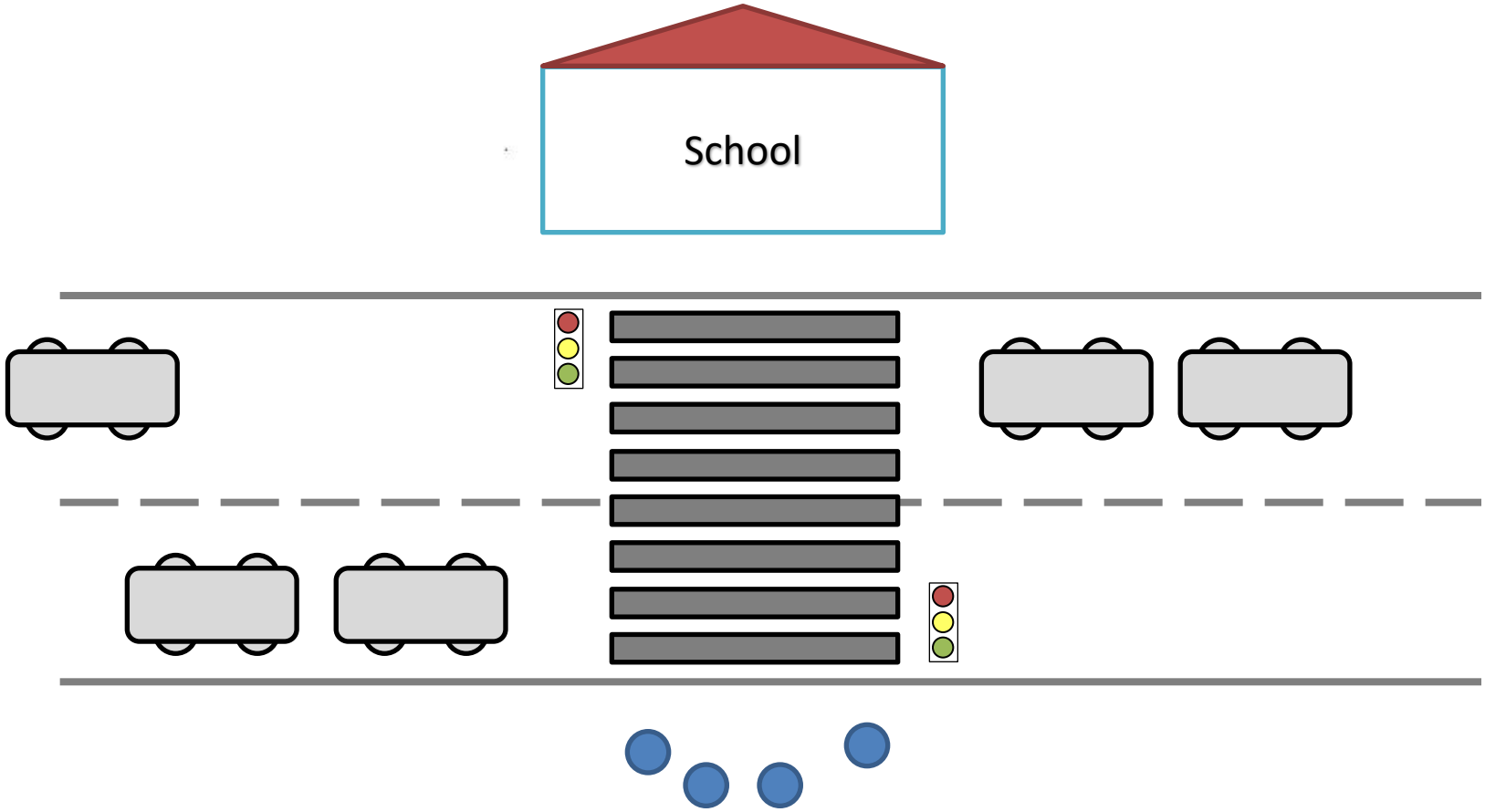
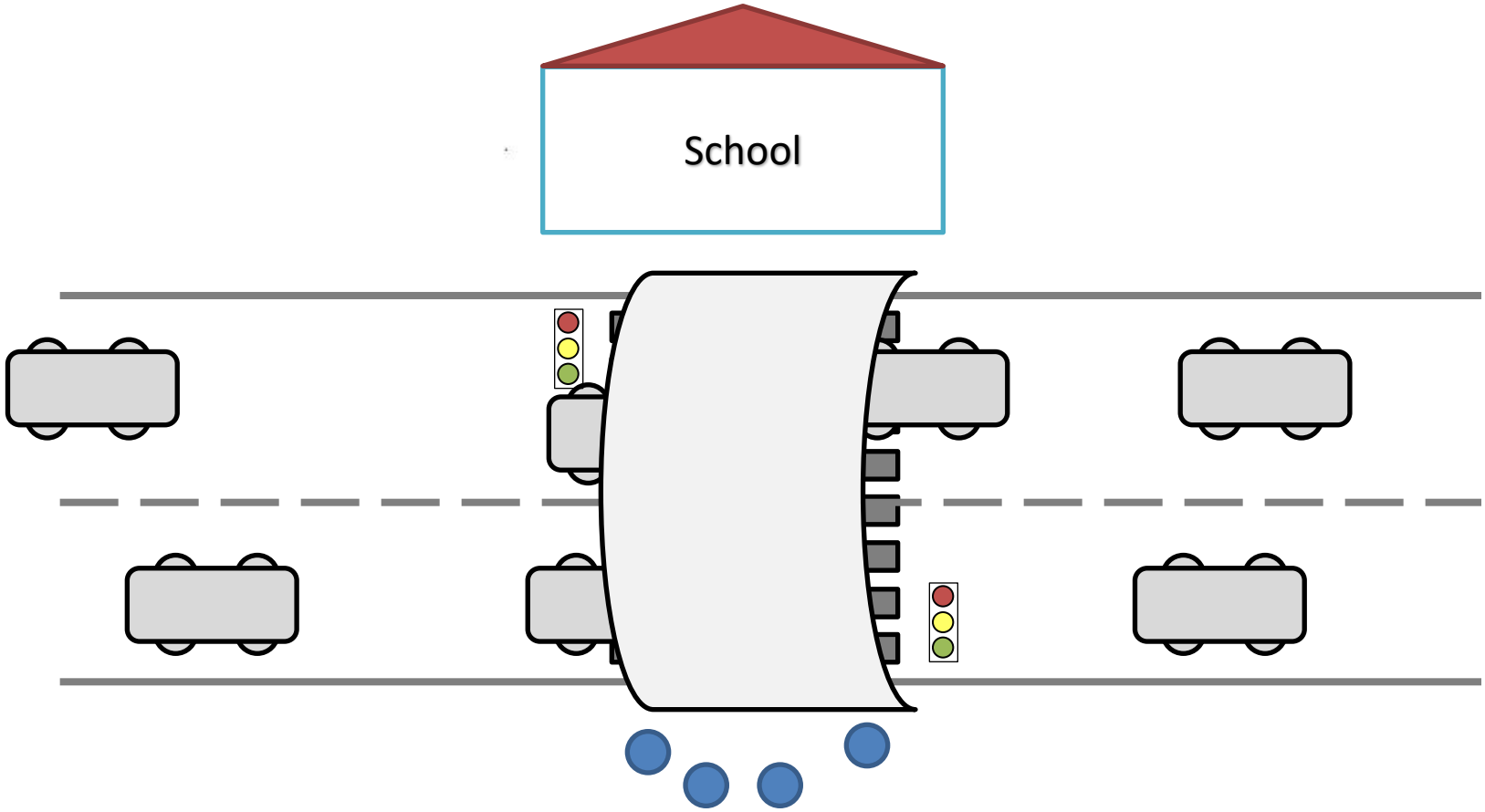


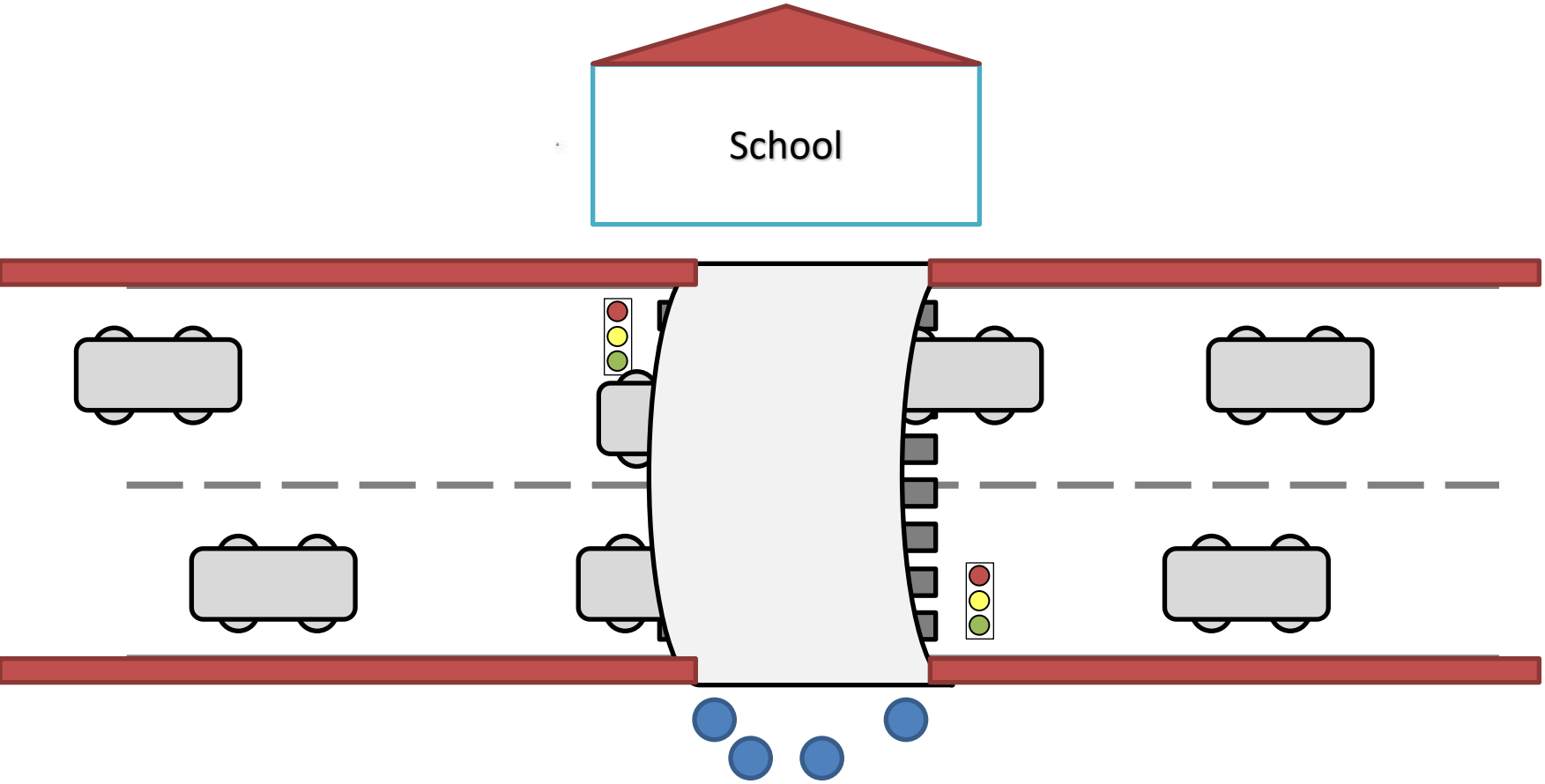
Figure 4, Risk reduction with several prevention layers



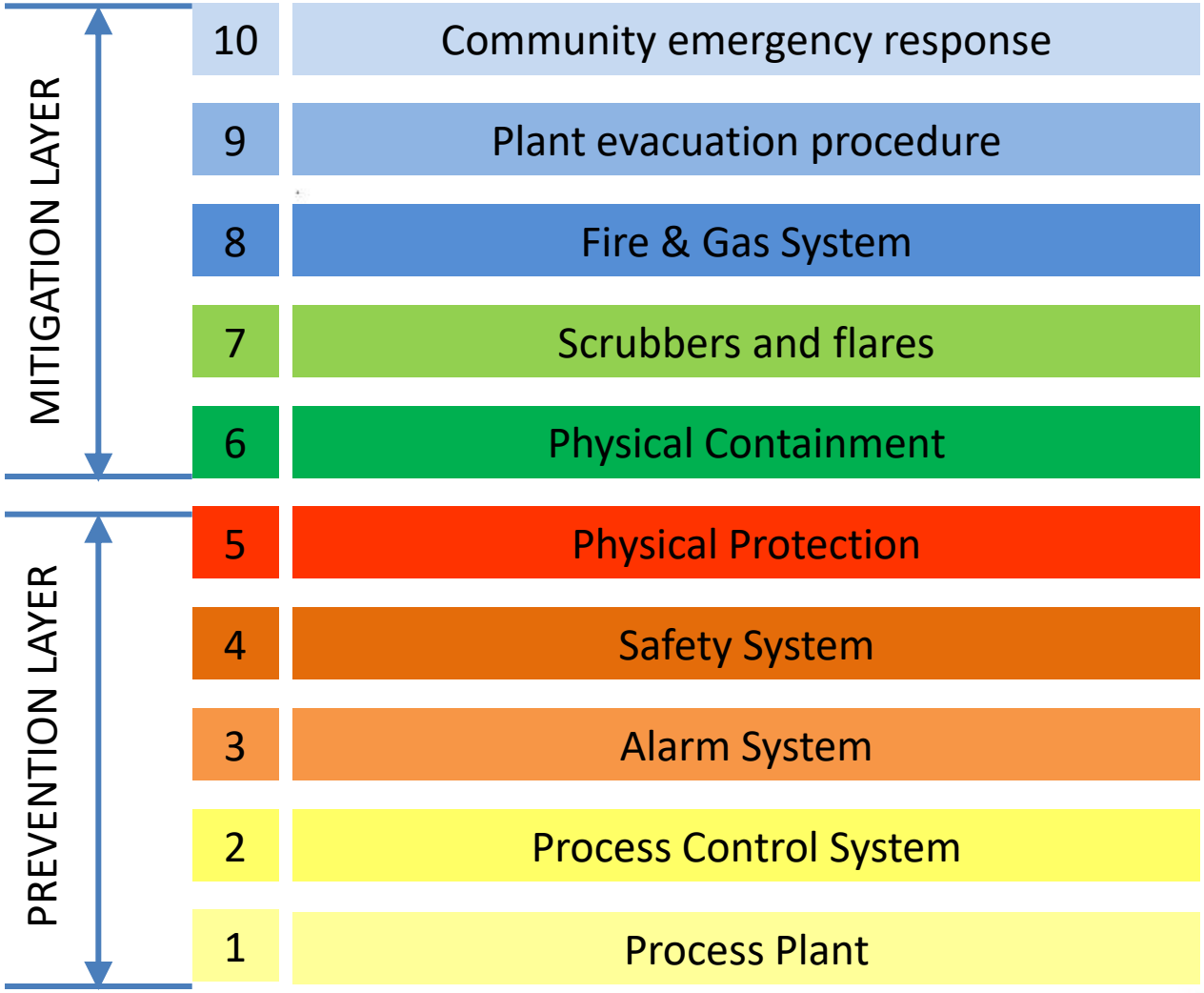








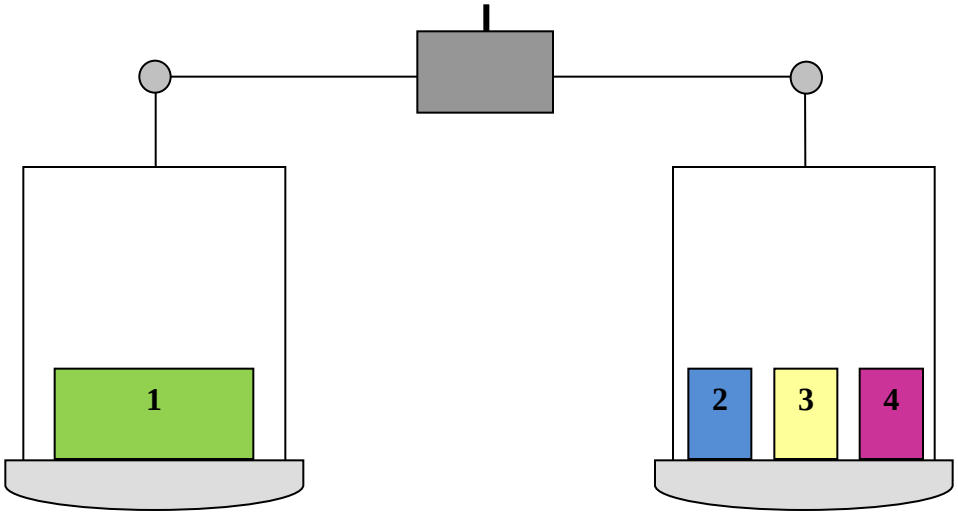
LAYERS OF PROTECTION



RISK PROTECTION BALANCE

The Risk Must be balanced by the Protection Layers

(Optimal Safety Balance)



RISK

1. Plant, Process and Environment

PREVENTION

2. DCS

3. SIS / ESD

4. Physical Protections

SAFETY INTEGRITY LEVELS IEC 61508

SIL Safety Integrity Level	**PFDavg** Average probability of failure on demand per year (low demand)	**(1-PFDavg)** Safety availability	**RRF** Risk Reduction Factor	**PFDavg** Average probability of failure on demand per hour (high demand)
SIL 4	**$\geq 10^{-5}$ to $< 10^{-4}$**	**99.99 to 99.999 %**	**100000 to 10000**	**$\geq 10^{-9}$ to $< 10^{-8}$**
SIL 3	**$\geq 10^{-4}$ to $< 10^{-3}$**	**99.9 to 99.99 %**	**10000 to 1000**	**$\geq 10^{-8}$ to $< 10^{-7}$**
SIL 2	**$\geq 10^{-3}$ to $< 10^{-2}$**	**99 to 99.9 %**	**1000 to 100**	**$\geq 10^{-7}$ to $< 10^{-6}$**
SIL 1	**$\geq 10^{-2}$ to $< 10^{-1}$**	**90 to 99 %**	**100 to 10**	**$\geq 10^{-6}$ to $< 10^{-5}$**

Table 26, Risk reduction factor, as function of SIL levels and Availability

MTBF

MTTF is an indication of the average successful operating time of a device (system) before a failure in any mode.

- MTBF: Mean Time Between Failures
- MTBF = MTTF + MTTR
- MTTF = MTBF - MTTR
- MTTR: Mean Time To Repair

- Since (MTBF >> MTTR)

  MTBF ≠ MTTF

  (very close in values)

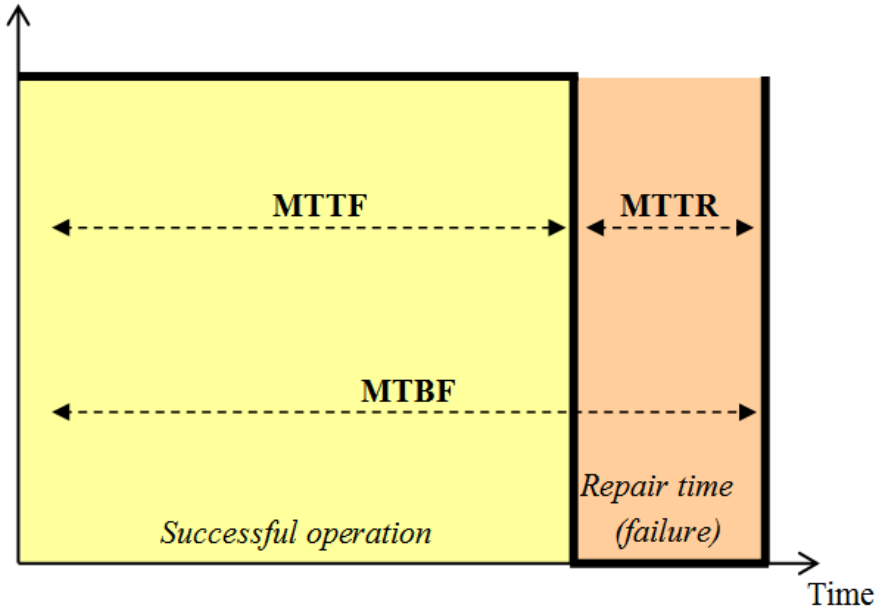


Figure 17, Schematic representation of MTTF, MTTR, MTBF

AVAILABILITY

Availability time (hrs)	Repair time (Hrs)	Availability (%)
1000	10	99
10000	10	99,9
100000	10	99,99
1000000	10	99,999

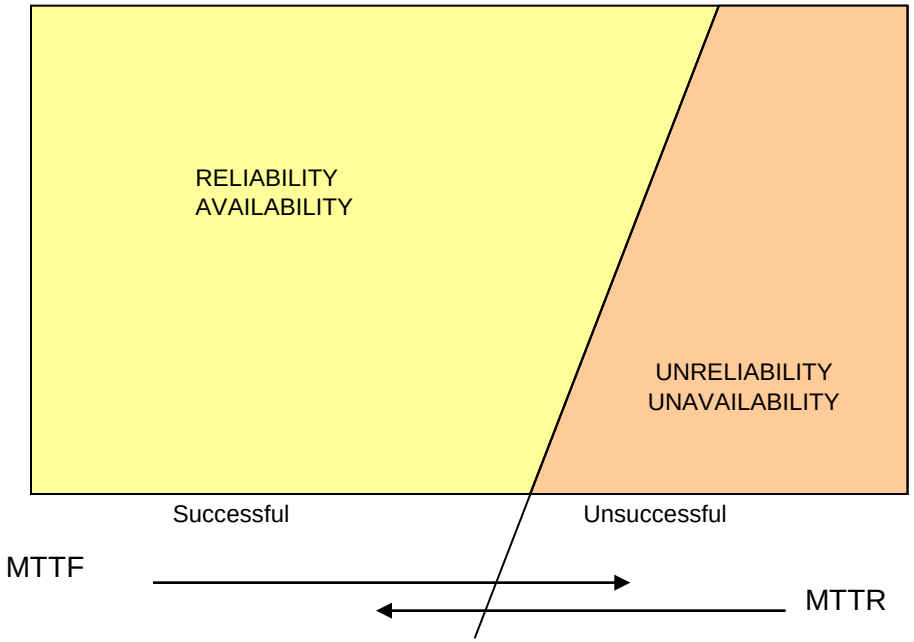
What does an availability of 99,99% for a specific component or system really stand for?
That the component or system could stop working one time ..

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

MTBF AND FAILURE RATE

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

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



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

MTBF AND FAILURE RATE

Relation between MTBF and Failure Rate λ

$$\lambda = \frac{\text{Failure per unit time}}{\text{Quantity Exposed}} = \frac{1}{\text{MTBF}}$$

$$\text{MTBF} = \frac{1}{\lambda} = \frac{\text{Quantity Exposed}}{\text{Failure per unit time}}$$

MTBF - EXAMPLE

- Instantaneous failure rate is commonly used as measure of reliability.
- Eg. 300 Isolators have been operating for 10 years. 3 failures have occurred. The average failure rate of the isolators is:

$$\lambda = \frac{\textit{Failure per unit time}}{\textit{Quantity Exposed}} = \frac{3}{300*10*8760} =$$

= 0.0000000115 per hour = 0.001 per year
= 11,5 FIT (Failure per billion hours) =
= 11,5 probabilities of failure in one billion hours.
= 0.001 probability of failure per year

- MTBF = 1 / λ = 1000 years (for constant failure rate)

FIT

Failure In Time is the number of failures per one billion device hours.

1 FIT =
= 1 Failure in 10^9 hours
= 10^{-9} Failures per hour

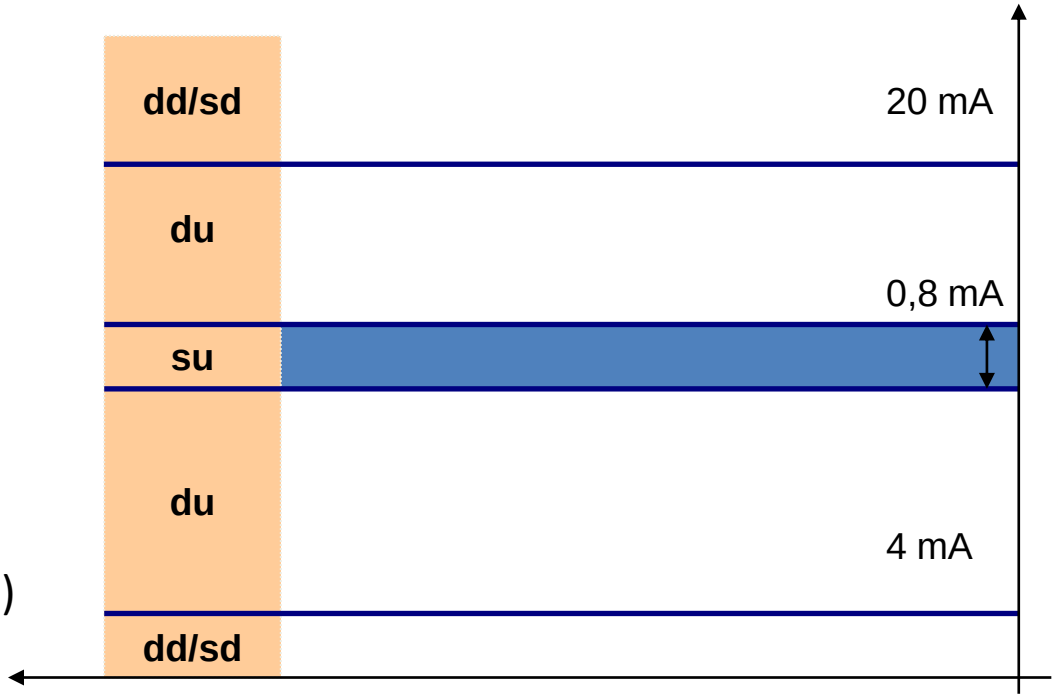
FAILURE RATE CATEGORIES

$\lambda_{tot} = \lambda_{safe} + \lambda_{dangerous}$
$\lambda_{s} = \lambda_{sd} + \lambda_{su}$
$\lambda_{d} = \lambda_{dd} + \lambda_{du}$
$\lambda_{tot} = \lambda_{sd} + \lambda_{su} + \lambda_{dd} + \lambda_{du}$

Where:

- sd = Safe detected
- su = Safe undetected
- dd = Dangerous detected
- **du = Dangerous undetected**

$\lambda_{tot} = \lambda_{safe} + \lambda_{dangerous}$
(MTBF = MTBFs + MTBFd)
λ_{safe}: spurious trip (nuisance trip)
$\lambda_{dangerous}$: safety trip



Example for a 4-20 mA signal

EXAMPLE OF FMEDA ANALYSIS

Failure

Modes

Effects

Diagnostic

Analysis

ID	Component type	λ (FIT)	% of failure rate	Simulated failure type	Effect on output signal	λ_{SD} (FIT)	λ_{SU} (FIT)	λ_{DD} (FIT)	λ_{DU} (FIT)
C1A	Cond. MC 10 nF 50V 10 % x 7R 0805 SMD	31.8	80 20	Open Short	SD SU	25.4	6.36		
C2A	Cond. MC 10 nF 50V 10 % x 7R 0805 SMD	31.8	80 20	Open Short	DU SU		6.36		15.4
C12A	Cond. MC 10 nF 50V 10 % x 7R 0805 SMD	28.6	80 20	Open Short	DD SU		5.72	22.8	
R48A	Res.TF392KR 1/8 W 1% 100 ppm 0805 SMD	9.6	20 40 15 25	Open Short 0,5 x R 2 x R	SU SD SD SD	3.88 1.46 2.43	1.94		
R52A	Res. TF 1 KR 1/8 W 1% 100 ppm 0805 SMD	9.6	50 50	Open Short	DU DD SU SU		1.46 2.43	3.88	1.94
T1A	Tras. EF16 1p/1s 45/95s Vds 90 V Ids 300 mA 2.8/12.6 mH		50 50	Open Short	SD DD	8.9		8.9	
TR5A	Trans. 2N7002 Nmos Vds 60V Ids 300 mA Rds 0,5R SOT23 SMD	25	50 50	Open Short	SD SU	12.5	12.5		
TR7A	Trans. 2N7002 Nmos Vds 60V Ids 300 mA Rds 0,5R SOT23 SMD	25	50 50	Open Short	DU DD			12.5	7.5
IC3A	Integ. TLC272 Ampl. Operaz. S08 SMD	2.7	40 40 20	Open Short Unstable	SD SU DU		1.08 1.08		15.4 0.054
IC4A	Integ. TLC272 Ampl. Operaz. S08 SMD	2.7	40 40 20	Open Short Unstable	SU SD DU	1.08	1.08		0.054
					Total Failure Rates	**55.65**	**40.01**	**48.16**	**24.95**

D5014 SIL 3 ANALYSIS

D5014 module

Repeater Power Supply

Failure rate tables:

Failure category	Failure rates (FIT)
λ_{dd} = Total Dangerous Detected failures	146.72
λ_{du} = Total Dangerous Undetected failures	14.97
λ_{sd} = Total Safe Detected failures	0.00
λ_{su} = Total Safe Undetected failures	0.00
$\lambda_{tot\ safe}$ = Total Failure Rate (Safety Function) = $\lambda_{dd} + \lambda_{du} + \lambda_{sd} + \lambda_{su}$	**161.69**
MTBF (safety function, single channel) = (1 / $\lambda_{tot\ safe}$) + MTTR (8 hours)	**706 years**
$\lambda_{no\ effect}$ = "No Effect" failures	205.11
$\lambda_{not\ part}$ = "Not Part" failures	4.80
$\lambda_{tot\ device}$ = Total Failure Rate (Device) = $\lambda_{tot\ safe} + \lambda_{no\ effect} + \lambda_{not\ part}$	371.60
MTBF (device, single channel) = (1 / $\lambda_{tot\ device}$) + MTTR (8 hours)	**307 years**

Failure rate category	λ_{sd}	λ_{su}	λ_{dd}	λ_{du}	SFF	DC_S	DC_d
Rates	0.00 FIT	0.00 FIT	146.72 FIT	14.97 FIT	90.74%	0%	90.74%

PFDavg vs T[Proof] table, with determination of SIL supposing module contributes 10% of entire safety function:

T[Proof] = 1 year	T[Proof] = 14 years
PFDavg = 6.69E-05 Valid for **SIL 3**	PFDavg = 9.37E-04 Valid for **SIL 2**

PFDavg vs T[Proof] table, with determination of SIL supposing module contributes 20% of entire safety function:

T[Proof] = 2 years	T[Proof] = 20 years
PFDavg = 1,34E-04 Valid for **SIL 3**	PFDavg = 1,34E-03 Valid for **SIL 2**

GM INTERNATIONAL TECHNOLOGY FOR SAFETY

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SAFE FAILURE FRACTION (SFF)

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

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

$$\frac{\lambda tot - \lambda du}{\lambda tot} = SFF$$

- **Type A** components are described as simple devices with well-known failure modes and a solid history of operation.

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

Table 23, SFF (Safe Failure Fraction) for A type components

- **Type B** devices are complex components with potentially unknown failure modes, e.g. microprocessors, ASICs, etc.

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

Table 24, SFF (Safe Failure Fraction) for B type components

SYSTEMATIC FAILURES

Definition:

- A hidden fault in design or implementation
  - Software as well as hardware
  - Design specification
  - User manuals
  - Procedures, etc
- Can occur in any lifecycle phase

IEC 61508:2010 Ed. 2 approach:

- Measures to avoid failures.

SYSTEMATIC FAILURES

Italia

SUMMARY TABLE
T-IS-236198-03

	ITEM NAME	REPORT CODE	FINAL RESULTS			
			T_{Proof}	Configuration	Allowed SIL	Allowed Systematic SIL
1	D1093S	R-IS-236198-15 Rev.1	14 years	NE loads	SIL 3*	SIL 3
			20 years	NE loads	SIL 2*	
			20 years	NE loads	SIL 3**	
			9 years	ND loads	SIL 3*	
			20 years	ND loads	SIL 2*	
			19 years	ND loads	SIL 3**	
			20 years	ND loads	SIL 2**	

(*)Considering the products not contribute more than 10% of total SIF dangerous failure
(**)Considering the products not contribute more than 20% of total SIF dangerous failure

T-IS-236198-03
NOTE: The present table is integral part of the Document: C-IS-236198-03
Date: June, 06th 2014

INTERNATIONAL TECHNOLOGY FOR SAFETY

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SYSTEMATIC FAILURES

Italia

SUMMARY TABLE
T-IS-204399-01

	ITEM NAME	REPORT CODE	FINAL RESULTS					
			System type	PFH [h^{-1}]	PFD_{avg}	T_{Proof}	Configuration	Allowed SIL
1.	HiC2025ES HiD2025ES KCD2-STC-Ex1.ES(.SP) KFD2-STC4-Ex1.ES	R-IS-204399-02-Rev.1	Type A	0,99 E-8	9,44 E-5	1 year	Input from active or passive Ex and Output as current source or current sink or voltage source.	SIL3*
					1,32 E-4	2 years		SIL3**
					2,45 E-4	5 years		SIL3**
					4,32 E-4	10 years		SIL3**

Safe Detected Failure λ_{SD}	Safe Undetected Failure λ_{SU}	Dangerous Detected Failure λ_{DD}	Dangerous Undetected Failure λ_{DU}	Safe Failure Fraction SFF
0,00 FIT	301.64 FIT	220,00 FIT	9.87 FIT	98,47 %

(*)Considering the products not contribute more than 10% of total SIF dangerous failure.
(**)Considering the products contribute more than 10% of total SIF dangerous failure.

T-IS-204399-01
NOTE: The present table is integral part of the Document: C-IS-204399-01-Rev.1
Date: March, 28th 2012

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TECHNOLOGY FOR SAFETY

SYSTEM ARCHITECTURES

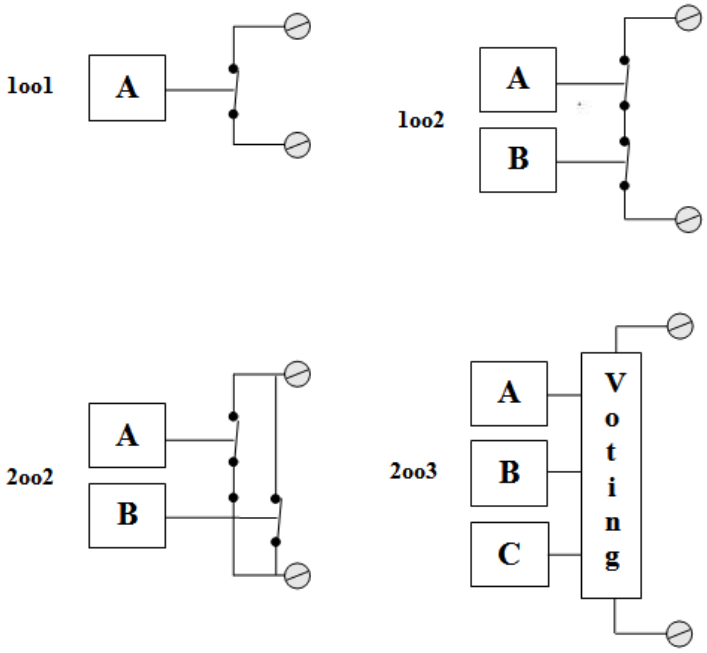


Figure 43, Schematic diagrams of some system architectures

Architecture	Probability of safe failure per year	$MTTF_S$ (yrs)	Probability of dangerous failure per year	$MTTF_D$ (yrs)
1oo1	0,0400	25	0,0200	50
1oo2	0,0800	12,5	0,0004	2500
2oo2	0,0016	625	0,0400	25
2oo3	0,0048	208	0,0012	833

Table 7, The impact of redundancy

PFDavg SIMPLIFIED EQUATIONS

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

Table 2, Simplified equations for PFDavg calculation

COMMON FAULT / BETA FACTOR

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

For redundant subsystems using electronic components, the value of **β** ranges from 1% to 10 %.

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

Example:

λdu = 0.01 / yr; TI = 1 yr; β = 0.05

For 1oo2 the equation is:

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

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

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

CONSIDERATION ON β FACTOR

Comparisons using different values of β factor:

[PFDavg] 1oo1 = 0.005 / yr	[RRF] 1oo1 = 200
[PFDavg] 1oo2 = 0.00003 / yr (no β factor)	[RRF] 1oo2 = 33.333 = 200 x **166.6**
[PFDavg] 1oo2 = 0.000082 / yr (with 1% β factor)	[RRF] 1oo2 = 12.195 = 200 x **61**
[PFDavg] 1oo2 = 0.00028 / yr (with 5% β factor)	[RRF] 1oo2 = 3571 = 200 x **17.8**
[PFDavg] 1oo2 = 0.000527 / yr (with 10% β factor)	[RRF] 1oo2 = 1897 = 200 x **9.48**

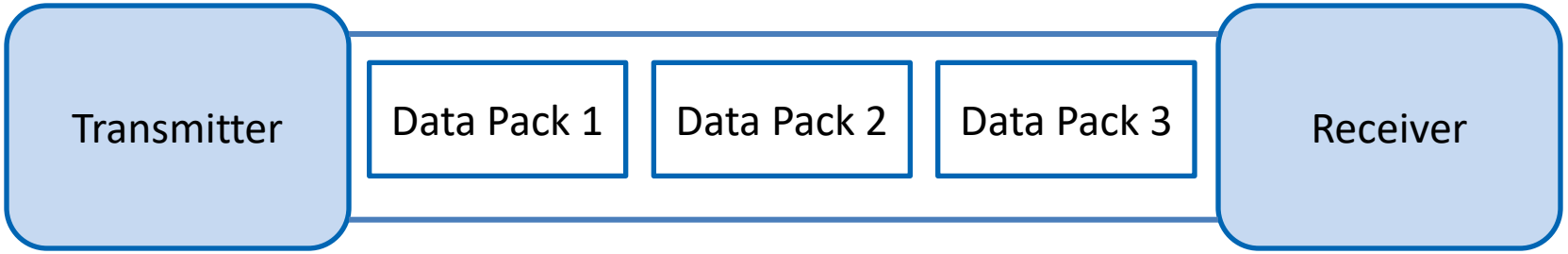
Considerations:

- The value 0.00003 is 166.6 times lower than 0.005.
- The value 0.000082 is 61 times lower than 0.005.
- The value 0.00028 is 17.8 times lower than 0.005.
- The value 0.000527 is 9.48 times lower than 0.005.
- Without β factor the PFDavg, of 1oo2 architecture, is 166.6 times better than PFDavg value of 1oo1 architecture.
- With 1% β factor the PFDavg, of 1oo2 architecture, is 61 times better than PFDavg value of 1oo1 architecture.
- With 5% β factor the PFDavg, of 1oo2 architecture, is 17.8 times better than PFDavg value of 1oo1 architecture.
- With 10% β factor the PFDavg, of 1oo2 architecture, is 9.48 time better than PFDavg value of 1oo1 architecture.

EXAMPLES - REDUNDANCY

Redundant equipment:

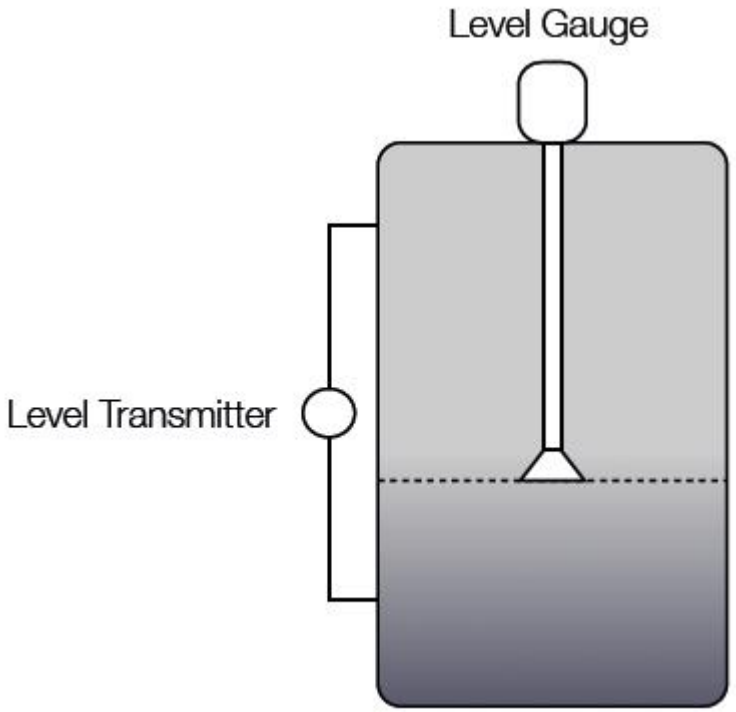
Single bus with triple communication messaging:



EXAMPLES - DIVERSITY

Diverse design solution

Diverse equipment:



PFDavg 1oo1 CALCULATION

Equation for 1oo1 loop

$$PFDavg\ (T1) = \lambda dd * RT + \lambda du * T1/2$$

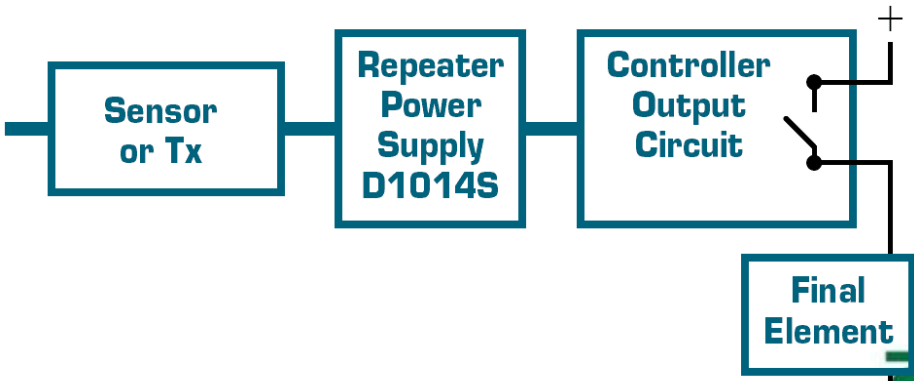
Where:

RT = repair time in hours (conventionally 8 hours)

T1 = T proof test, time between circuit functional tests (1-5-10 years)

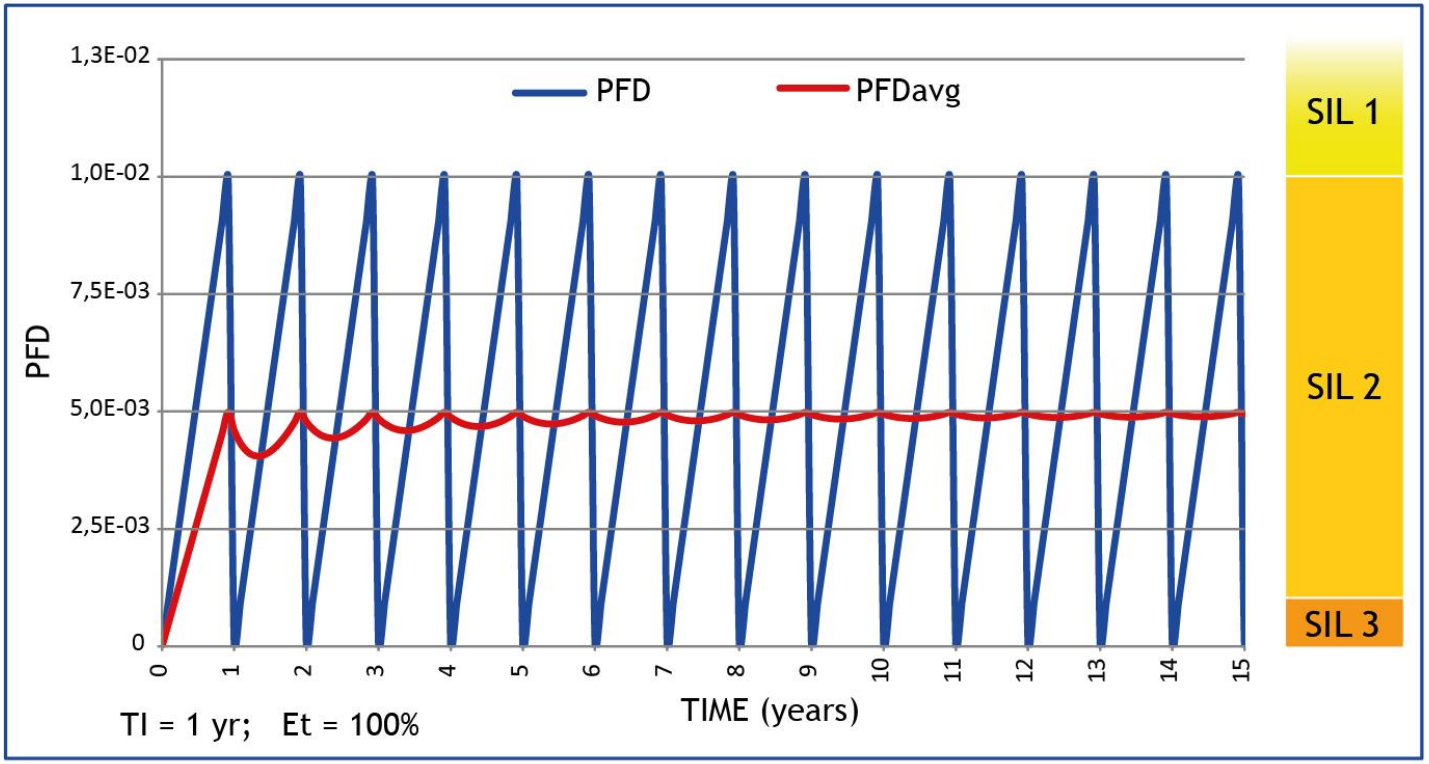
λ_{dd} = failure rate for detected dangerous failures

λ_{du} = failure rate for undetected dangerous failures



PFD VERSUS T-PROOF TIME INTERVAL (TI)

PFD degrades in time.
The probability of failure of any equipment (therefore the PFD of a SIF) increases with time (linearly for constant failure rate).

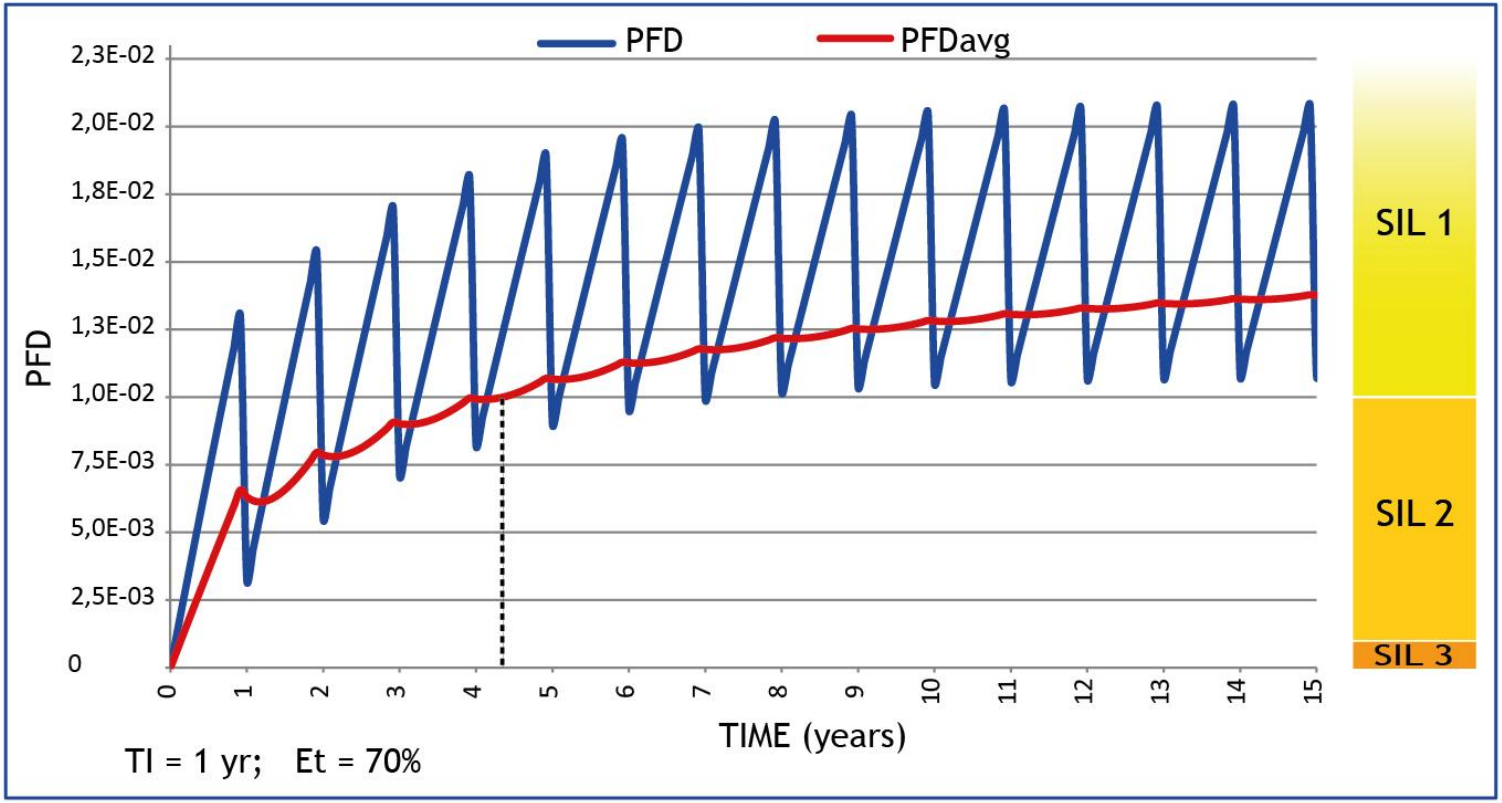


HOW PFD CHANGES IN TIME

- Since PFD increases with time, its value can be kept under control by actuating maintenance proof tests at certain time intervals.
- A periodic test at T-proof interval (as specified by the manufacturer), is capable of identifying any non directly detectable failure mechanisms in the equipment (dangerous undetected failures);
- The grade of the test effectiveness affects the value to which the PFDavg is set afterwards.

HOW PFD CHANGES IN TIME

When effectiveness is 100% the equipment can be considered “as new”, when < 00%, then SIL changes during the life of equipment.



PERIODIC TEST FOR D5014 – 50%

The Proof test 1 consists of the following steps:

Steps	Action
1	Bypass the safety-related PLC or take other appropriate action to avoid a false trip.
2	By HART command or other technique, set the transmitter connected to the input of the repeater in order to go to high alarm current and verify that the output current of the repeater reaches that value. This tests for compliance voltage problems such as a low loop power supply voltage or increased wiring resistance.
3	By HART command or other technique, set the transmitter connected to the input of the repeater in order to go to low alarm current and verify that the output current of the repeater reaches that value. This tests for possible quiescent current related failures.
4	Restore the loop to full operation.
5	Remove the bypass from the safety-related PLC or restore normal operation.

This test will reveal approximately 50 % of possible Dangerous Undetected failures in the repeater.

PERIODIC TEST FOR D5014 – 99%

The Proof test 2 consists of the following steps:

Steps	Action
1	Bypass the safety-related PLC or take other appropriate action to avoid a false trip.
2	Perform step 2 and 3 of the **Proof Test 1**.
3	Perform a two-point calibration (i.e. down scale as 4 mA and full scale as 20 mA) of the transmitter connected to the input of the repeater. Then set the transmitter to impose some input current values of 4-20 mA range and verify that the correspondent output current values of repeater are within the specified accuracy. This proof requires that the transmitter has already been tested without the repeater and it works correctly according to its performance.
4	Restore the loop to full operation.
5	Remove the bypass from the safety-related PLC or restore normal operation.

This test will reveal approximately 99 % of possible Dangerous Undetected failures in the repeater.

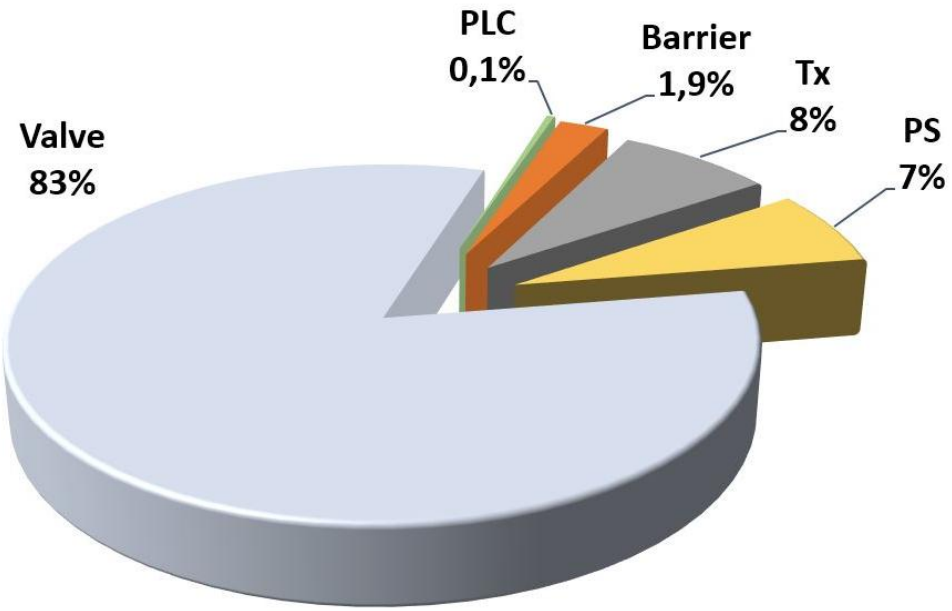
PFDavg “WEIGHT” IN SIF

Each subsystem’s PFDavg has a percentage value in relation to the total.

Component manufacturers list, in their functional safety manual, the value of PFDavg obtained by authorized certification bodies like TUV, EXIDA, FM, etc.

These bodies apply a conventional “weighing” of the PFDavg of the component in consequence of the importance that it has in the entire loop, as reported in the following Table:

Subsystem	PFDavg 1oo1 (%)
Transmitter	8%
Barrier	1.9%
PLC	0.1%
Valve	83%
Power Supply	7%
Total (SIF)	100%



LEVEL OF INDEPENDENCE – IEC 61508

Independence applies to assessment and audits, not V&V activities, according to IEC 61508

Minimum Level of Independence	Safety Integrity Level			
	1	2	3	4
Independent person	X	X^1	Y	Y
Independent department	-	X^2	X^1	Y
Independent organization	-	-	X^2	X

- = not necessary

Y = not sufficient

X = sufficient

X^1 = If X^2 applies then X1 should be read as NR

X^2 = Applies if less previous experience, more complexity, novelty of design, newer technology, etc.

FS Engineer Course
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Certify your Functional Safety competency!

ABOUT THE COURSE

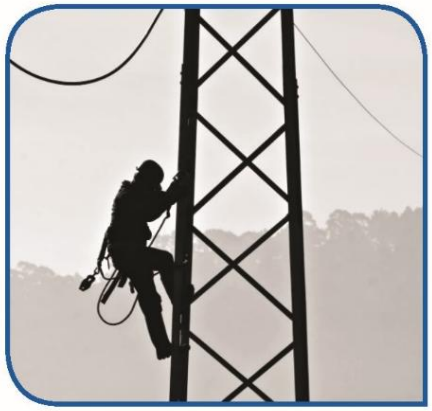
G.M. International is a course promoter of the TÜV Rheinland Functional Safety Program for Safety Instrumented Systems (SIS) trainings.
The course focuses on functional safety aspects for the process, oil & gas, and chemical industries according to IEC 61508 and IEC 61511.

FSE TÜV COURSE

COURSE OBJECTIVES

The main objective is to provide all engineers involved in safety instrumented systems with elementary and necessary knowledge about functional safety, based on the leading international functional safety standards IEC 61508 and IEC 61511.
A second objective is to give anybody attending the course the opportunity to have his or her functional safety competency confirmed by the TÜV Rheinland upon successfully passing the exam.

TÜVRheinland®
Precisely Right.



WHY SHOULD YOU ATTEND

IEC 61508 ed2.0, released in April 2010, clearly indicates as a 'Normative' requirement, that anybody involved in safety lifecycle activities shall be competent to carry out the activities for which they are accountable.
Take advantage of this course, examination and certification to prove your clients, peers and management, your competency in the field of Functional Safety.
Success in the final examination certifies your functional safety knowledge on your personal name, adding a great value to your professional career and image.

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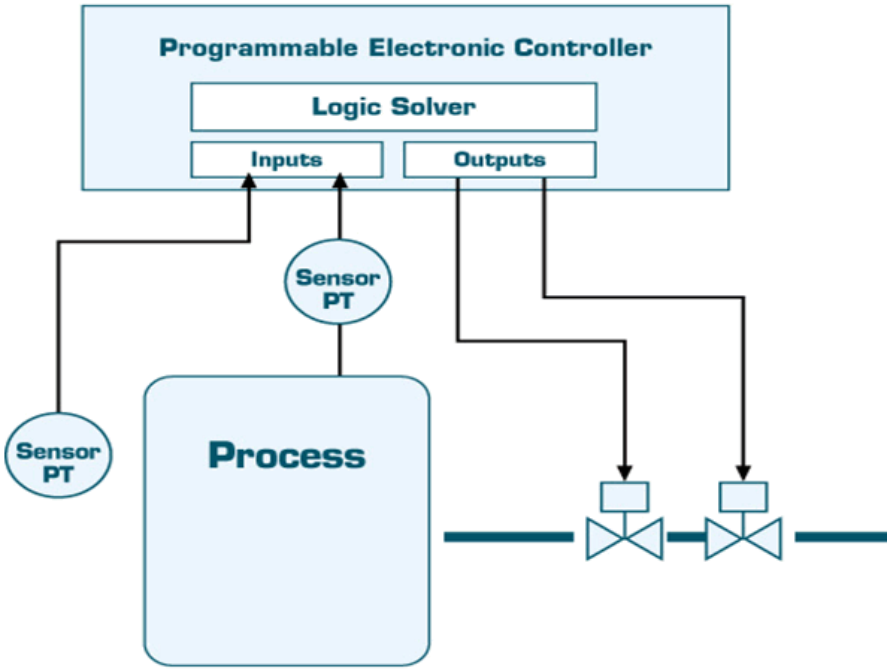
TECHNOLOGY FOR SAFETY

SAFETY INSTRUMENTED SYSTEMS (SIS)

- A simple SIS, with one logic solver, is a safety function as shown in the picture.
- A SIS is made up of multiple SIFs: one for each potentially dangerous condition.
- Its objective is to collect and analyzes data information from sensors to determine if a dangerous condition occurs, and consequently to start a shutdown sequence to bring the process to a safe state.
- A potentially dangerous condition is called "demand“.

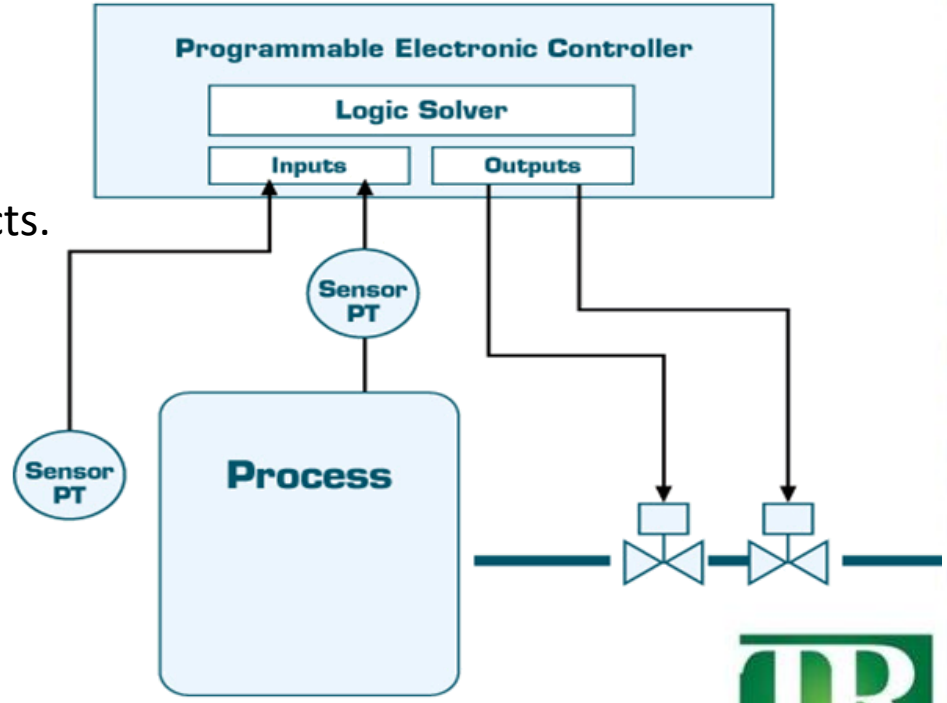


SAFETY INSTRUMENTED SYSTEMS (SIS)

- The majority of SIS are based on the concept of de-energizing to trip.
  In normal working conditions input and output are energized
  (F&G systems are the opposite)

- For each SIF, the required Risk Reduction Factor (RRF) is determined.

- IEC 61508 and IEC 61511,
  - recognized Standards,
  - cover in detail these safety aspects.



PFDavg 1oo1 CALCULATION

Equation for 1oo1 loop

$$PFDavg\ (T1) = \lambda dd * RT + \lambda du * T1/2$$

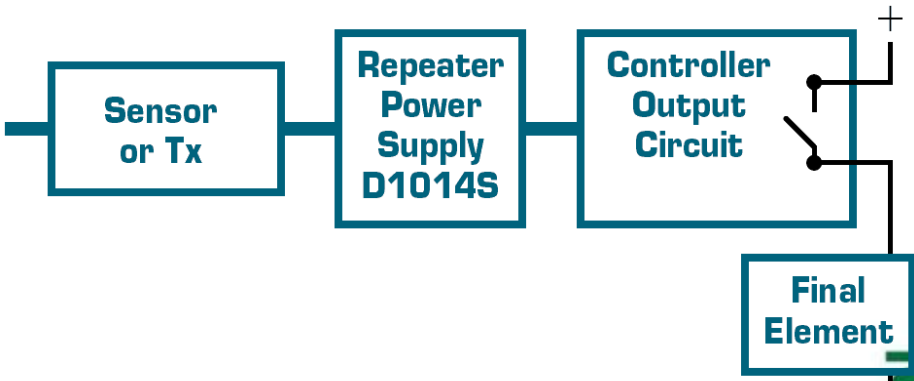
Where:

RT = repair time in hours (conventionally 8 hours)

T1 = T proof test, time between circuit functional tests (1-5-10 years)

λ_{dd} = failure rate for detected dangerous failures

λ_{du} = failure rate for undetected dangerous failures



LOOP PFDavg CALCULATION

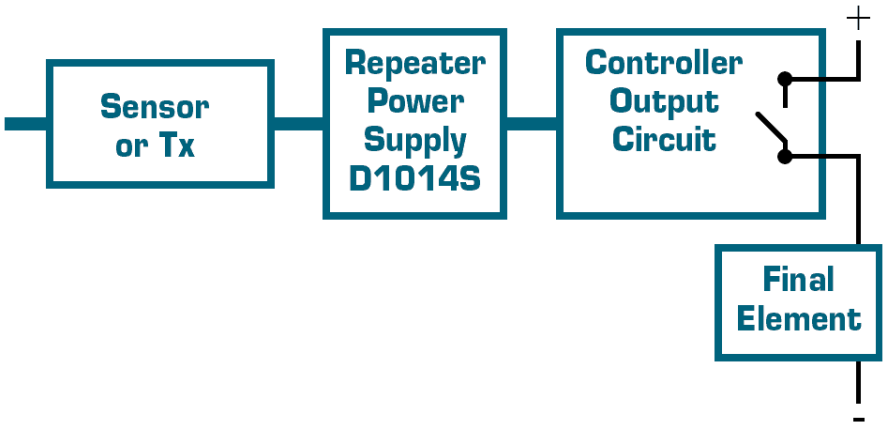
$$PFDavg\ (T1) = \lambda dd * RT + \lambda du * T1/2$$

If T1 = 1 year then

$$PFDavg = \lambda dd * 8 + \lambda du * 4380$$

but being $\lambda_{dd} * 8$ far smaller than $\lambda_{du} * 4380$

$$PFDavg = \lambda du * T1/2$$

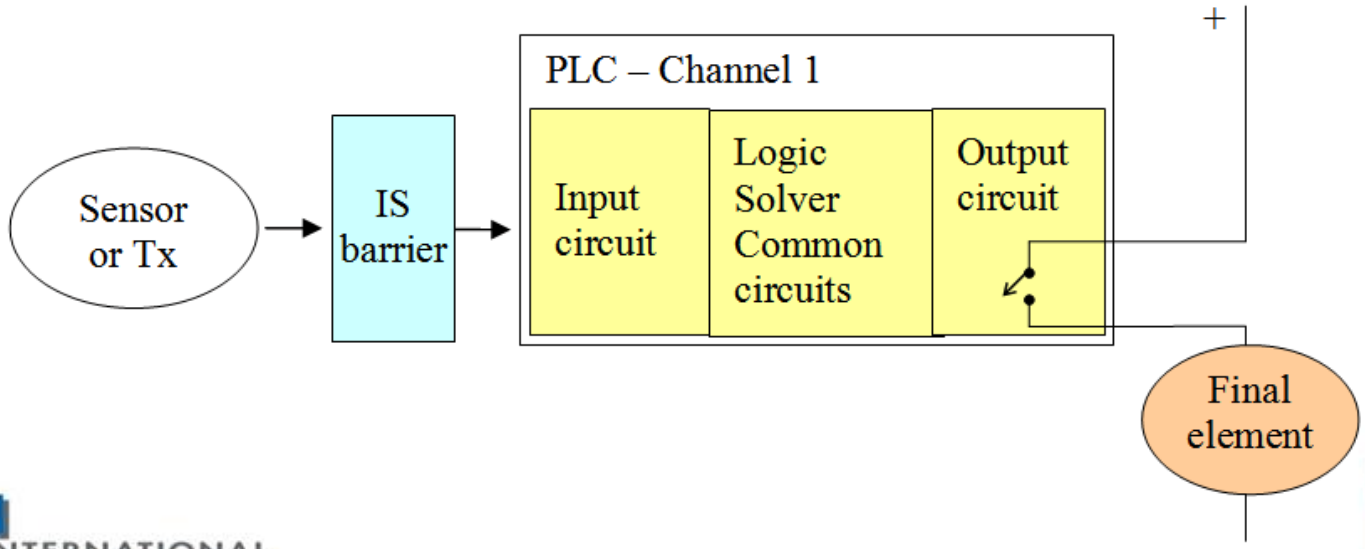


SIF EXAMPLE

Calculate values of MTBF, PFDavg, RRF
for a possible SIL level of the following SIF.

These values are given by the manufacturers:

TX:	MTBF = 102 yrs;	λDU = 0,00080 / yr;	λDD = 0,0010 / yr;	λS = 0,00800 / yr
Barrier:	MTBF = 314 yrs;	λDU = 0,00019 / yr;	λDD = 0,0014 / yr;	λS = 0,00159 / yr
PLC:	MTBF = 685 yrs;	λDU = 0,00001 / yr;	λDD = 0,0001 / yr;	λS = 0,00135 / yr
Supply:	MTBF = 167 yrs;	λDU = 0,00070 / yr;	λDD = 0,0000 / yr;	λS = 0,00530 / yr
Valve:	MTBF = 12 yrs;	λDU = 0,02183 / yr;	λDD = 0,0200 / yr;	λS = 0,00400 / yr



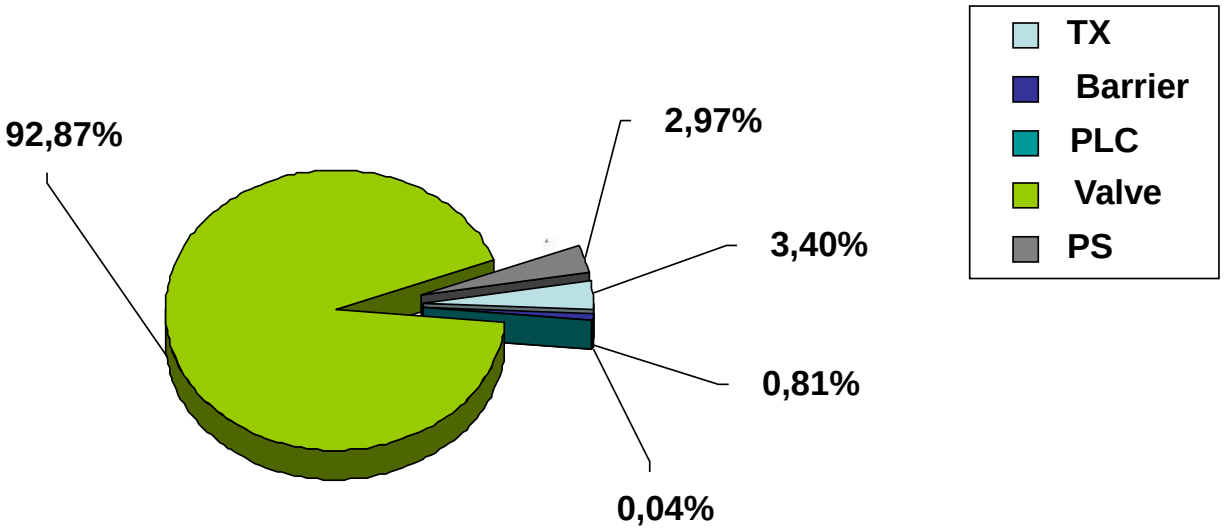
SUMMARY TABLE FOR SIL 1

Sub-system	MTBF (yr)	λ / yr = 1/MTBF	MTBFs= 1/ λ_S (yr)	λ_S / yr	λ_{DD} / yr	λ_{DU} / yr	PFDavg 1oo1 = $\lambda_{DU}/2$	% of total PFDavg	RRF = 1/PFDavg	SFF	SIL Level
Tx	102	0.00980	125	0.00800	0.0010	0.00080	0.000400	3.40 %	2500	91.8 %	SIL 3
Barrier D1014S	314	0.00318	629	0.00159	0.0014	0.00019	0.000095	0.81 %	10526	94.0 %	SIL 3
PLC	685	0.00146	741	0.00135	0.0001	0.00001	0.000005	0.04 %	200000	99.3 %	SIL 3
Valve	12	0.08333	24	0.04150	0.0200	0.02183	0.010915	92.87 %	92	73.8 %	SIL 2
Power Supply	167	0.00600	189	0.00530	0.0000	0.00070	0.000350	2.97 %	2857	88.3 %	SIL2
Total (SIF)	**10**	**0.10377**	**17**	**0.05774**	**0.0225**	**0.02353**	**0.011765**	**100 %**	**85**	-	**SIL 1**

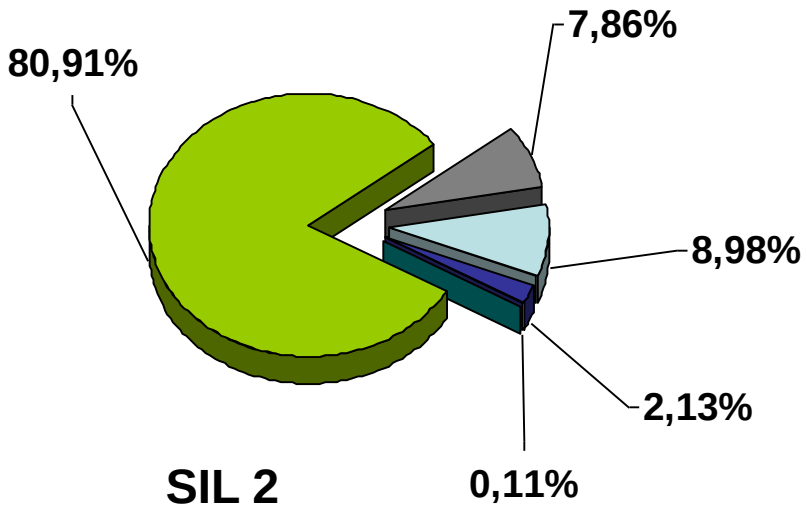
SUMMARY TABLE FOR SIL 2

Sub-system	MTBF (yr)	λ = 1/MTBF per yr	MTBFs= 1/ λ_S (yr)	λ_S / yr	λ_{DD} / yr	λ_{DU} / yr	PFDavg 1oo1 = $\lambda_{DU}/2$	% of total PFDavg	RRF = 1/PFDavg	SFF	SIL Level
Tx	102	0.00980	125	0.00800	0.0010	0.00080	0.000400	8.98 %	2500	91.8 %	SIL 3
Barrier D1014S	314	0.00318	629	0.00159	0.0014	0.00019	0.000095	2.13 %	10526	94.0 %	SIL 3
PLC	685	0.00146	741	0.00135	0.0001	0.00001	0.000005	0.11 %	200000	99.3 %	SIL 3
Valve 4 Months TProof	36	0.02750	73	0.01370	0.0066	0.00720	0.003602	80.91 %	278	73.8 %	SIL 2
Power Supply	167	0.00600	189	0.00530	0.0000	0.00070	0.000350	7.86 %	2857	88.3 %	SIL 2
Total (SIF)	**21**	**0.04794**	**33**	**0.02994**	**0.00910**	**0.00890**	**0.004452**	**100 %**	**225**	-	**SIL 2**

SIFs PFDavg CONFRONTATION

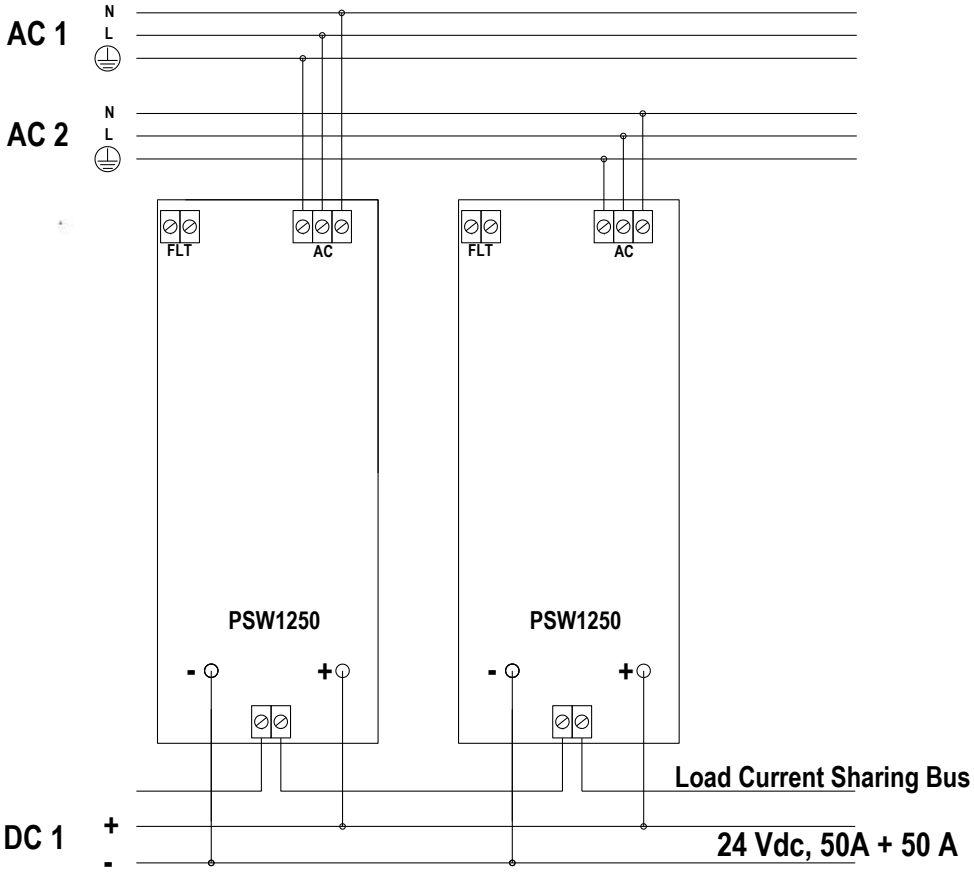


SIL 1



SIL 2

POWER SUPPLY CONSIDERATIONS



PSW1250, dual AC supply, 1 redundant 50 A Output + 1 redundant 50 A Output.
two modules connected in parallel to provide full redundancy on AC lines (AC1 and AC2) and one 50 A redundant output.

POWER SUPPLY CONSIDERATIONS

Safe state for a 24 VDC Power Supply is an output voltage within the range of 20-30 VDC.

Dangerous state is an output voltage below 20 VDC or greater than 30 VDC, because with voltage below 20 VDC the instrumentation could work out of specifications, while voltage greater than 30 VDC (f.e. 50 VDC) may destroy all the instrumentation supplied.

SIL Certification warrants the user that PFDavg is suitable for the SIL level specified (f.e. SIL 2), the multiple overvoltage protections has a very low failure rate, and the possibility to increase SIL level with one or two redundancy.

Typically SIL level for NE of a single power supply is SIL 2 and SIL 3 with one redundancy, while for ND applications the supply is SIL 1 and SIL 2 with one redundancy. For SIL 3 applications a second redundancy is required.

T-PROOF TABLE FOR SIL 2 SIF

Since the SIF has a safety integrity level SIL 2 the periodic proof tests can be performed according to the following table:

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

2ND SIF EXAMPLE

Calculate values of MTBF, PFDavg, RRF
for a possible SIL level of the following SIF.

These values are given by the manufacturers:

TX:	MTBF = 102 yrs;	λDU = 0,00080 / yr;	λDD = 0,0010 / yr;	λS = 0,00800 / yr
Barrier:	MTBF = 314 yrs;	λDU = 0,00019 / yr;	λDD = 0,0014 / yr;	λS = 0,00159 / yr
PLC:	MTBF = 685 yrs;	λDU = 0,00001 / yr;	λDD = 0,0001 / yr;	λS = 0,00135 / yr
Supply:	MTBF = 167 yrs;	λDU = 0,00070 / yr;	λDD = 0,0000 / yr;	λS = 0,00530 / yr
Valve:	MTBF = 12 yrs;	λDU = 0,02183 / yr;	λDD = 0,0200 / yr;	λS = 0,00400 / yr

Considering the same data used in the 1oo2 architecture as in the first example but introducing a β factor of 5% (0.05) on redundant sub-systems.

TABLE 1oo2

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

SUMMARY TABLE 1oo2

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

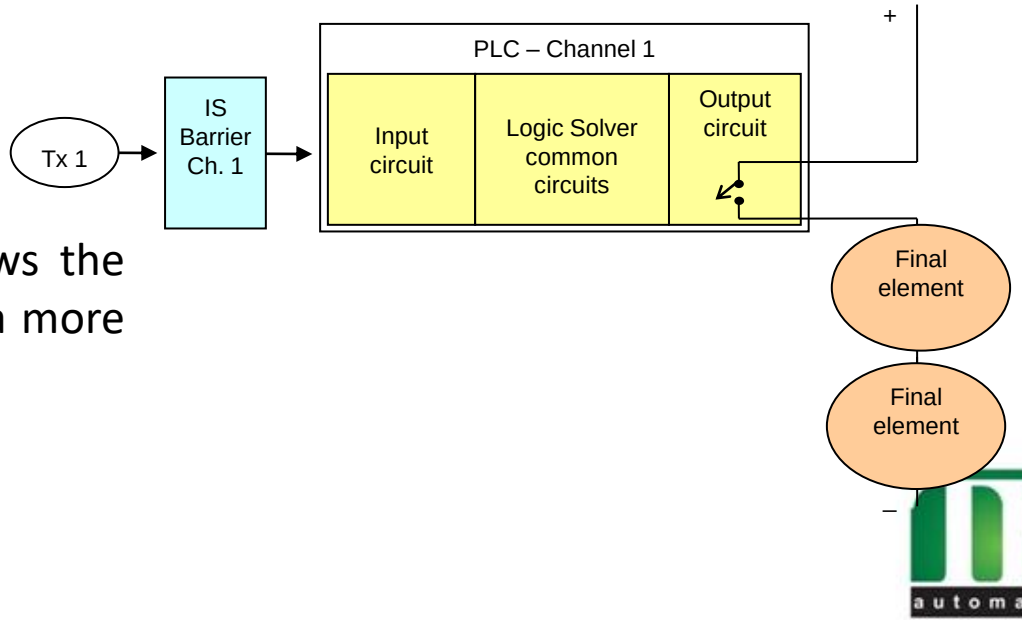
Note 2:
Using such system configuration, the risk reduction factor is highly increased. If a SIL 2 level is required instead of SIL 3, it would be possible to extend the T-proof test time interval (TI).

Table 10a shows how the 1oo2 SIF would change for TI = 3, 5 &10 years.

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

TABLE 1oo2 ONLY FINAL ELEMENT

Subsystem	PFDavg 1oo1	RRF 1oo1	MTBFs 1oo1		PFDavg 1oo2 (Valve Only)	RRF	MTBFs	SFF	SIL Level
Tx	0.000400	2500	125		0.000400	2500	125	91.8 %	SIL 2
Barrier D1014D	0.000095	10526	629		0.000095	10526	629	94.0 %	SIL 3
PLC	0.000005	200000	741		0.000005	200000	741	99.3 %	SIL 3
Valve 1 yr T-proof	0.010915	92	24		0.00068768	1454	12	73.8 %	SIL 3
Power Supply	0.000350	2857	189		0.000350	2857	189	88.3 %	SIL 2
Total (SIF)	**0.011765**	**85**	**17**		**0.00153268**	**652**	**10**	**-**	**SIL 2**



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

CONSIDERATION 1oo2 ONLY FINAL ELEMENT

- Adding a redundant valve; Supposing a β factor of 5%, the RFF is =1454.
- The PFDavg value is now 1/1454 = 0.00068 and for a test proof time interval or 1 year (SIL 3).
- The SIL value of the total SIF becomes 0.0015 with RRF = 652.

Considerations:

Adjusting the T-proof time and the redundancy of final element it is possible to obtain a better SIL level of the SIF, and even to advance it to SIL 3.

SUMMARY TABLE 1oo2 FINAL ELEMENT

Note 1:

The Table highlights advantages of 1oo2 system architecture of the final element.

Safety integrity level of the SIF has moved from SIL 1 to a good SIL 2 maintaining the same T-proof test time interval of 1 year.

Table 10b shows how the 1oo2 Final Element SIF would change for TI = 3, 5 & 10 years.

System	PFDavg 1oo2	RRF	Max SIL Level
$1oo2\|_{TI=1}$	0.00153268	**652**	**SIL 2**
$1oo2\|_{TI=3}$	0.00459804	**217**	**SIL 2**
$1oo2\|_{TI=5}$	0.0076634	**130**	**SIL 2**
$1oo2\|_{TI=10}$	0. 0153268	**65**	**SIL 1**

IEC 61511 SOFTWARE

IEC 61511:

- Does not differentiate between SIL 1, 2 or 3 software
- Lists requirements which are suitable for up to SIL 3
- Does not allow SIL 4 software but refers in that case back to IEC 61508

1oo1:

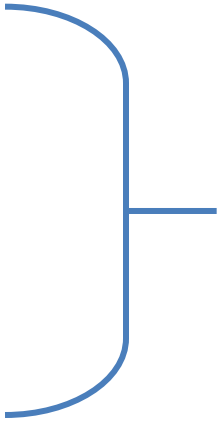
Hardware	Software
SIL 2	SIL 2

HFT 1 = 1oo2:

Hardware	Software
SIL 2	SIL 2

+

Hardware	Software
SIL 2	SIL 2



Hardware	Software
SIL 3	SIL 2

TRUE OR FALSE?

SIL rating does not change in time.

FALSE!

SIL integrity levels depend on the probability of failure which increases with time.

TRUE OR FALSE?

Safety Manual must be provided by the instrument manufacturer.

TRUE!

Safety Manual is an integral document to the SIL rating of any component. It defines the assumption behind the certification and the conditions of the SIL rating as well as provide proper maintenance information.

TRUE OR FALSE?

Two products both claiming SIL 2 offer the same level of safety.

FALSE!

1) PFDavg or RRF value of a SIL level ranges in a factor of 10.
Example: SIL 2 means from RRF = 100 to 1000.
2) SIL ratings are time related.
Example: SIL 2 rating for 10 yrs differs from SIL 2 for 1 yr.

TRUE OR FALSE?

Periodic test is required to maintain the SIL Level.

TRUE!

Since some failures are undetected in operating conditions (dangerous undetected failures) Tests are required to restore the SIF in “as-new” condition (effectiveness 100%)

Periodic Tests are essential for maintaining the SIL level.

TRUE OR FALSE?

T-Proof Time Interval are specified by the Plant Maintenance Personnel.

FALSE!

It is specified in the Hardware Specification and is decided by the manufacture and verified by the certification agency.

TRUE OR FALSE?

Component Type (A & B) are defined by the customer (User)..

FALSE!

The component class is defined by the Manufacturer.

TRUE OR FALSE?

Shorter T-proof time intervals improve SIL ratings.

TRUE!

Reducing time intervals between T-proof tests decreases the probability of failure (PFDavg) in time.

Example: SIL 1 for 1 yr may become SIL 2 for 3 months.

TRUE OR FALSE?

PFDavg value of the SIF is equal to the highest of all the SIF components

FALSE!

The PFDavg value of the safety function (SIF) is the SUM of PFDavg values of all its components (subsystems).

TRUE OR FALSE?

SFF % and PFD figures both must match the SIF SIL Requirement .

TRUE!

The SFF value of each of the SIF component must be within the table A or B requirement to claim a given SIL level.

The SIF total PFD must also match that of the required RRF

TRUE OR FALSE?

It is possible to make software changes without an Impact Analysis

FALSE!

Safety Impact Analysis must be performed for any hardware or software change in the plant!

TRUE OR FALSE?

SIL 3 equipment can be useful in SIL 2 functions.

TRUE!

Using a higher SIL level than necessary allows to reduce frequency of T-proof tests and has a lower incidence on the total PFDavg of the SIF.

Example: SIL 3 for 1 yr could become SIL 2 for 10 yrs.

TRUE OR FALSE?

Maintenance must be considered in the design phase.

TRUE!

A safety function under maintenance is unavailable therefore the length of the repair time must be considered.
The improvement obtained applying redundant architectures is temporarily lost.

TRUE OR FALSE?

All failures have the same effect on safety.

FALSE!

Failures can be SAFE or DANGEROUS.
The first lead to a spurious trip which does not harm, but induces a stopping of production.

The second instead will render the safety function unavailable.

MTBF includes time for repair.

TRUE!

MTBF = MTTF + MTTR.
For most applications, MTTR is negligible therefore
MTBF ≈ MTTF.
However in high demand applications,
even a few hours of unavailability are critical
and should be taken into account.

All redundant system architectures improve safety.

FALSE!

Redundant Architectures have different effects on SAFE and DANGEROUS failure rates.

Example: 1oo2 improves dangerous failure rates but worsens safe failure rates. 2oo2 is the opposite

TRUE OR FALSE?

Safety Manual Provides for T-Proof test procedure but not the test effectiveness percentage.

FALSE!

Test Effectiveness (TE) must be specified along with the T-proof procedure and must be used in calculating recurring SIL level

SIL level and relating RRF are defined by HSE (Health Safety Executive)

TRUE!

A team composed of Management, Plant, Process, Instrument, Maintenance, Quality Engineers is responsible for determining RRF factor for each SIF

TRUE OR FALSE?

HSE Engineers have the responsibility to maintain the SIL level during plant life time

FALSE!

Maintenance Engineer are responsible to maintain the SIL level as mandated by initial calculations.

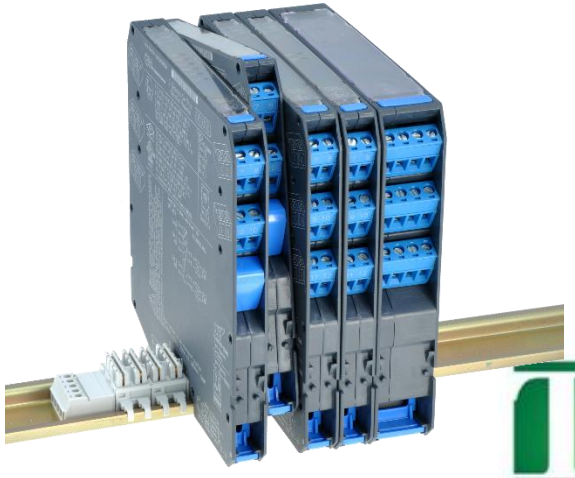
For SIL 2 SIFs their work must be reviewed by a separate department. For SIL 3 or 4 SIFs by an external agency.

STRATEGIES FOR MAINTAINING SAFETY IN A SIS

Considerations:

- The SIL level of an equipment alone gives a partial, and incomplete, picture of the prospecting solution for a given SIF application.

- Information concerning:
  - Safe and Dangerous Failure Rates,
  - PFDavg Values for 1-3-5-10 years continuous operation,
  - T-proof Time Intervals,
  - Test proof Procedures & their percentage of effectiveness to reveal the dangerous undetected failures, shall be provided in the Safety Manual of the equipment.



STRATEGIES FOR MAINTAINING SAFETY IN A SIS

- A scheduled maintenance plan of the system is mandatory for each component of a SIF chain to restore the initial level of PFD and therefore its SIL rating.

- Maintenance, in the form of periodic tests at T-proof time interval, normally requires a bypass for the equipment under test, and often implies some critical operations, therefore the time interval should be the longest possible and the proof procedure should be safe, effective, and as quick as possible.

STRATEGIES FOR MAINTAINING SAFETY IN A SIS

When selecting safety-related components:

- Select equipments with lowest PFDavg and highest T-proof time interval, for the same SIL level.
- Consider also Time To repair for the T-proof test (choose the lowest time to repair).
- Take note of the percentage of effectiveness of the proof test and recalculate the PFDavg value to verify if this value is still valid for the requested SIL level.
- Choose a higher SIL level than required, if possible, to benefit for longer T-proof intervals and to reduce maintenance costs.

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