Achieving Compliance in Hardware Fault Tolerance

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Abstract

The functional safety standards ISA S84/IEC 61511 (1st Edition, 2003) and IEC 61508 both set out requirements for 'hardware fault tolerance' or 'architectural constraints'.

The method specified in the 1st Edition of IEC 61511 for assessing hardware fault tolerance has often proven to be impracticable for SIL 3 in the process sector. Many users in the process sector have not been able to comply fully with the requirements.

Further confusion has been created because there are many SIL certificates in circulation that are undeniably incorrect and misleading.

This paper describes common problems and misunderstandings in assessing hardware fault tolerance.

The 2010 edition of IEC 61508 brought in a new and much simpler and more practicable method for assessing hardware fault tolerance. The method is called Route 2_H.

This paper explains how Route 2_H overcomes the problems with the earlier methods.

The 2nd Edition of IEC 61511 released in 2016 is based on Route 2_H.

Why do we need Hardware Fault Tolerance?

The standards impose '**architectural constraints**' to compensate for the uncertainty in the failure rates and the assumptions made in the design.

IEC 61508 and IEC 61511 both set architectural constraints according the required integrity level.

The architectural constraints are characterised by '**hardware fault tolerance**', (HFT), the ability to perform a required function in the presence of a fault.

> '*Hardware fault tolerance is the ability of a component or subsystem to continue to be able to undertake the required safety instrumented function in the presence of one or more dangerous faults in hardware. A hardware fault tolerance of 1 means that there are, for example, two devices and the architecture is such that the dangerous failure of one of the two components or subsystems does not prevent the safety action from occurring.*'

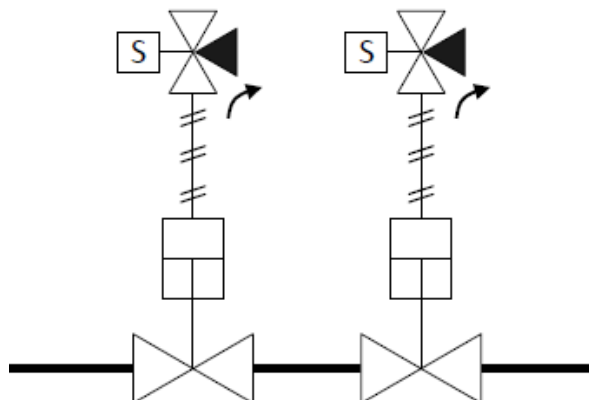IEC 61511 explains that hardware fault tolerance is necessary:

> '*to alleviate potential shortcomings in SIF design that may result due to the number of assumptions made in the design of the SIF, along with uncertainty in the failure rate of components or subsystems used in various process applications.*'

The simple calculation of probability of failure is not enough. If we don't have sufficient confidence in the failure rate data the calculated probability may be unrealistically optimistic.

We need to have a certain minimum level of fault tolerance in addition to showing that the calculated probability of failure is low enough to meet the SIL target. Exactly what level of fault tolerance we need depends on:
- The level of confidence we have in the failure rate data,
- The dominant failure behaviour (safe or dangerous)
- Whether we can detect and respond to failures.

Fault tolerance may be achieved by using redundant elements in a fault tolerant circuit architecture, for instance 2 valves in series:

The IEC 61511-1 method for HFT can only be used for relatively simple architectures. The IEC 61508-2 methods can be applied to assess hardware fault tolerance requirements for complex architectures.

What was the problem in Ed. 1?

IEC 61511 Ed 1 set requirements for HFT in Sub-clause 11.4.

Table 6 specifies the level of HFT for sensors and final elements. The level of HFT required increases with SIL.

The basic table shows the requirement provided that the dominant failure mode is to the safe state, or dangerous failures are detected:

SIL	Minimum HFT
SIL 1	0
SIL 2	1
SIL 3	2

If the dominant failure is to dangerous state, and if we don't have effective diagnostics we need to increase the HFT:

SIL	Dominant failure to a dangerous state	Dominant failure to a safe state
SIL 1	1	0
SIL 2	2	1
SIL 3	3	2

Actuated shutdown valves generally have dominant failure to a dangerous state. They tend to jam or stick in an open position. They tend to leak. These failure modes are not only dangerous, they are also undetected.

The basic requirement is 4 valves in series to achieve SIL 3!
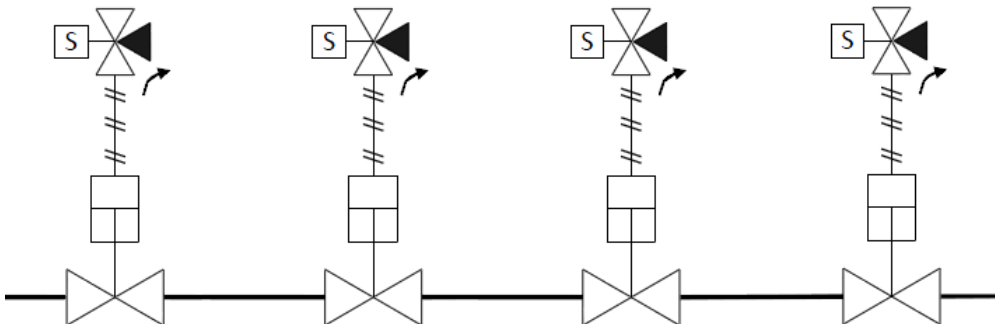
The standard allows us to reduce the HFT requirement if we can demonstrate 'limited adjustment' and 'prior use' (with extensive evidence):

SIL	Prior use, limited adjustment, dominant failure to a dangerous state	Prior use, limited adjustment, dominant failure to a safe state
SIL 1	0	0
SIL 2	1	0
SIL 3	2	1

The bare minimum requirement for SIL 3 is therefore to have 3 valves in series:
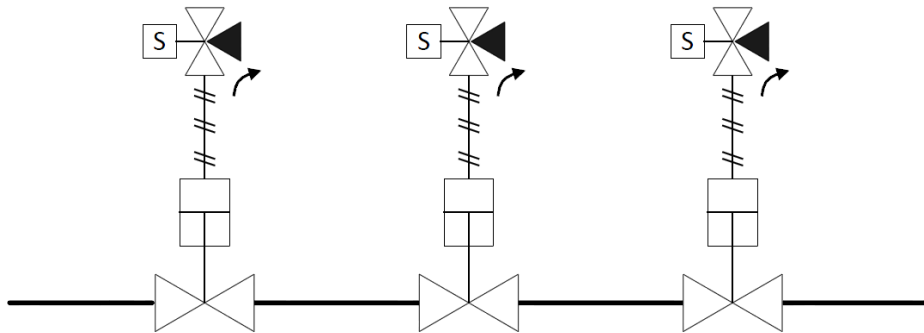
This is simply NOT practicable. Installing 3 valves rather than 2 increases capital cost as well as maintenance costs and it reduces reliability.

An alternative approach: IEC 61508 Route 1$_H$

IEC 61508 Route 1$_H$ is allowed as an alternative to IEC 61511 to determine the HFT required.

Route 1$_H$ distinguishes between simple 'Type A' devices and complex 'Type B' devices.

'Type A' devices have:
- Well defined failure modes
- Deterministic behaviour
- Sufficient dependable failure rate data

Other devices are classified as 'Type B'. These devices with complex behavior and failure modes, typically devices containing software.

Route 1$_H$ requires comprehensive data and documentation for every element and rigorous quality management and configuration management. Safety manuals must be provided for every element to demonstrate compliance to IEC 61508.

The requirements for 'Type A' are similar in intent to those for 'limited adjustment' and 'prior use' in IEC 61511.

Route 1_H applies the concept of Safe Failure Fraction (SFF). This is another way of assessing whether the dominant failure is to the safe state. The maximum SIL that can be claimed depends on the HFT.

The results are very similar to those of the IEC 61511-1 Ed. 1 method.

The following table shows that maximum SIL that can be claimed for Type A elements under Route 1_H, depending on the HFT and SFF:

Safe Failure Fraction of the element	Hardware Fault Tolerance		
	0	1	2
SFF < 60%	SIL 1	SIL 2	SIL 3
60% ≤ SFF < 90%	SIL 2	SIL 3	SIL 4
90% ≤ SFF < 99%	SIL 3	SIL 4	SIL 4
SFF ≥ 99%	SIL 3	SIL 3	SIL 4

If the SFF < 60% then the dominant failure mode is not to the safe state and to claim SIL 3 we still need HFT 2, requiring 3 valves in series:
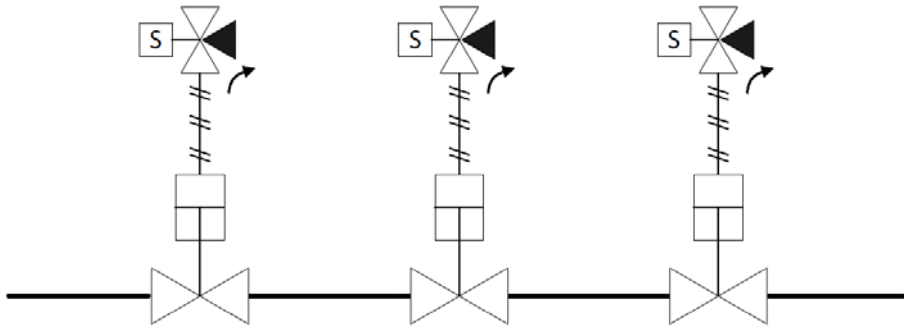
To claim SIL 3 with only 2 valves we need to prove that **SFF ≥ 60%:**
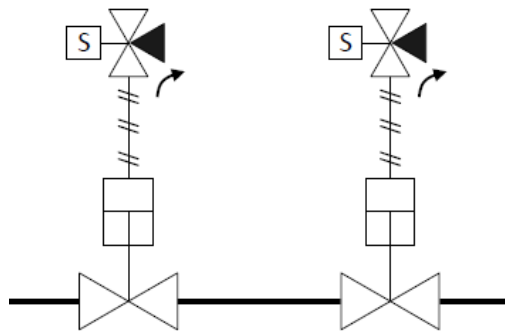
Common errors in trying to show compliance

The total failure rate is the sum of failure rates for 'safe' failures, those causing a trip (λ_S), plus the rate of 'dangerous' failures detected by on-line diagnostics (λ_{DD}) and rate of 'dangerous' failures that remain undetected (λ_{DU}):

$$\Sigma\lambda = \Sigma\lambda_S + \Sigma\lambda_{DD} + \Sigma\lambda_{DU}$$

The SFF is the proportion of failures that are either 'safe' (λ_S) or are 'dangerous' but detected by on-line diagnostics (λ_{DD}):

$$SFF = (\Sigma\lambda_S + \Sigma\lambda_{DD})/ \Sigma\lambda$$

Understandably, equipment suppliers and designers have been creative in trying to prove that SFF ≥ 60%.

Error No. 1: No-effect Failures

The first trick is to add in irrelevant 'no-effect' failures as if they were 'safe'. For example, a typical valve and actuator assembly will have:

$\lambda_S \approx 0.5 \times 10^{-6}$ failures per hour

$\lambda_D \approx 1 \times 10^{-6}$ failures per hour,

and no diagnostic functions, so

$\lambda_{DD} = 0$

SFF ≈ 0.5 / 1.5 ≈ 33%

'No-effect' failures have absolutely no effect on the safety function. A typical 'no-effect' failure might be a faulty position switch on the actuator.

Adding in the no-effect failures increases the SFF:

$\lambda_S \approx 0.5 \times 10^{-6}$ failures per hour

$\lambda_{NE} \approx 1 \times 10^{-6}$ failures per hour,

$\lambda_D \approx 1 \times 10^{-6}$ failures per hour,

$\lambda_{DD} = 0$

SFF ≈ 1.5 / 2.5 ≈ 60%

The formula for SFF given in IEC 61508 has never allowed the inclusion of 'no-effect' failures. The 2010 revision IEC 61508 Ed. 2 added specific clarification that 'no-effect' failures must be excluded from SFF.

Beware that there are many certificates in circulation that are invalid because they take credit for 'no-effect' failures.

This example certificate is no longer valid and has been withdrawn:

Certificate of Conformity No.: 28711185   TÜVRheinland

Manufacturer: Cameron Italy S.r.l.
CAM Engineered Valves Voghera
Via Italo Betto, 11
I-27058 Voghera (PV)

Specifications: IEC 61508-1÷7:2010

Product: Side-Entry Trunnion Mounted Ball Valves

RESULT:

As per the TÜV Rheinland Italia Report No. FS 28711185 Rev. 0 we declare that the product meets the below requirements:

IEC 61508: 2010, part 1 to 7

Functional Safety of electrical/electronic/programmable electronic safety related systems;

Type A, Low Demand Mode, HFT=0, Systematic Capability=3

Safety Action	λ_D [1/h]	λ_{NE} [1/h]	SFF
Close / Open	2,86E-08	1,13E-06	> 90 %
Close with Tight Shut Off	8,41E-08	8,92E-07	> 90 %

For detailed results: see TÜV Rheinland Italia Report No. FS 28711185 Rev. 0.

As per these values, the aforementioned product can be used up to SIL 3 as a "single device".

Any certificate taking credit for 'no-effect' failures is invalid.

Beware that some of the commercial software packages commonly used for SIL calculations take credit for 'no-effect' failures (also called 'residual' failures) if the 'IEC 61508-2000' method is selected.

The 3rd edition of the SERH 'Safety Equipment Reliability Handbook' published by *exida* in 2007 takes credit for called 'residual' failures in the calculation of SFF. Users should recalculate the SFF excluding the 'residual' failures.

Error No. 2: Partial Stroke Testing

The following example certificate takes credit for partial stroke testing in the calculation of SFF:

Certificate of Conformity No.: 28711191 Rev. 1

TÜVRheinland®

Manufacturer: Cameron Italy S.r.l. – Ledeen Facility
Via Gandini, 4
I-27058 Voghera (PV)

Specifications: IEC 61508-1÷7:2010

Product: Pneumatic Actuator

RESULT:

As per the TÜV Rheinland Italia Report No. FS 28711191 Rev. 1 we declare that the product meets the below requirements:

IEC 61508: 2010, part 1 to 7

Functional Safety of electrical/electronic/programmable electronic safety related systems;

Type A, Low Demand Mode, HFT=0, Systematic Capability=3

Series	λ_D [1/h]	SFF
LIN…DA	3,19E-08	> 90 %
LIN…SR (FTC)	2,22E-08	> 90 %
LIN…SR (FTO)	1,97E-08	> 90 %
VA/GS/SY/HT/MT…DA GS/SY…P-A GS/SY…P-S	3,80E-08	> 90 %
GS/SY/HT/MT…SR GS/SY…P-A-SR… GS/SY…P-S-SR…	2,78E-08	> 90 %
VA…SR	2,46E-08	> 90 %

For detailed results: see TÜV Rheinland Italia Report No. FS 28711191 Rev. 1.

As per these values, the aforementioned product can be used up to SIL 3 as a "single device".

Partial stroke testing *can* be claimed as a diagnostic if it is sufficiently frequent.

IEC 61508-2 §7.4.4.1 defines the requirements for the frequency of diagnostic functions.

In low demand mode

> '*credit shall only be taken for the diagnostics if the sum of the diagnostic test interval and the time to perform the repair of a detected failure is less than the MTTR used in the calculation to determine the achieved safety integrity for that safety function.*'

The diagnostic interval must be included in the MTTR that is used in calculating probability of failure:

Mean Time to Restoration (MTTR)							
Fault detection time	**Mean Repair Time (MRT)**						
	Administrative delays (work orders, permits)	Technical delays, materials identification	Logistical delays, materials procurement	Active repair time			Reinstatement delay
				Fault localisation	Fault correction	Testing	

If the MTTR is extended to periods measured in months it will lead to a significant increase in the probability of failure of the safety function.

The same requirement applies to high demand mode and continuous mode functions that have HFT > 0.

In high demand mode and continuous mode functions with HFT = 0 then either:

- The diagnostic interval + time for safety action response must be less than the process safety time OR

- The diagnostic test rate must be at least 100 times more frequent than the demand rate.

Automatic weekly or daily testing *might* be sufficiently frequent for low demand applications in the process sector but it is usually impractical.

6-monthly testing cannot be classed as a diagnostic and does not contribute to improving SFF.

TÜV Rheinland has published a statement clarifying how these certificates should be interpreted:

TÜVRheinland®
Precisely Right.

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2014-08-13

Failure Modes and SFF of final elements esp. valves, Revision 2

To whom it may concern

For the certification of final elements, especially valves, according to the requirements of Functional Safety standard IEC 61508:2010 for a certain SIL the safety parameter Safe Failure Fraction (SFF) is a crucial factor.

As the SFF is the ratio of safe plus dangerous detected failures to all failures it is necessary to have sufficient of the safe and dangerous detected failure, depending on the required SIL.

Regarding to the more precise definition of IEC 61508:2010 for safe failures, it is obvious that a final element - especially a valve - does not have sufficient safe failures (or even has no safe failures) in order to achieve a SIL higher than 1. Therefore a diagnostic measure has to be applied to the final element to increase the dangerous detected failures and the SFF.

The following requirements apply to diagnostic measures:

- A diagnostic measure has to be an <u>automatic online</u> testing
- The test frequency shall be at least 10 times higher than the demand rate
- A partial stroke test normally can reach max. up to DC = 70 %
- The Proof Test is <u>no</u> diagnostic measure and can therefore not be used to increase the SFF

An alternative approach for the determination of the required Hardware Fault Tolerance using an alternative definition of the SFF is defined in EN 161:2011/A3:2013. This approach is based on an FMEA and takes into account fault exclusions, which are treated as equal with detected faults. During the cause of the FMEA these fault exclusions have to be justified and proven. The method defined in EN 161:2011/A3:2013 requires a Hardware Fault Tolerance of at least HFT = 1 for SIL 3 systems. It has to be declared in the certificate, if this alternative approach was used for the estimation of SFF.

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51105 Köln

Best regards from Cologne

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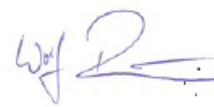Stephan Schmitt

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Dr.-Ing. Thorsten Gantevoort

i. V.

Dipl.-Ing. Wolf Rückwart

Error No. 3: Assuming prior use without evidence

IEC 61511-1 §11.5.3 stipulates rigorous documentary requirements to support claims for 'prior use'.

The requirements are onerous and difficult to achieve in practice. Most users find it easier to demonstrate compliance to IEC 61508-2 and/or IEC 61508-3 but sourcing independently certified components.

Error No. 4: Assuming compliance to IEC 61508

IEC 61508-2 §7.4.9.6 requires that suppliers must provide a safety manual for each item that is claimed to be in compliance with the IEC 61508 series. Annex D describes very detailed requirements for what should be included in a safety manual.

Compliance cannot be claimed unless the safety manuals are provided. The information required in the manuals is similar to what is required to support claims of 'prior use'.

The solution: IEC 61508 Route 2_H

IEC 61508 Route 1_H and IEC 61511 are based on using failure rates with a confidence level of at least 70%.

This effectively means that there is a 70% chance that the actual average failure rate of a device is less than the assumed failure rate that will be used in the calculations.

The purpose of HFT is to compensate for uncertainty in the failure rate data and assumptions. If we can reduce the uncertainty we can reduce the HFT.

Route 2_H is based on confidence level being increased from 70% to 90%.

A confidence level of 90% indicates that there is only a 10% chance that the true average failure rate is higher than the estimated failure rate.

There is no need to consider SFF for Type A elements.

The requirement for Type B elements is simply that

> *'All type B elements used in Route 2_H shall have, as a minimum, a diagnostic coverage of not less than 60 %.'*

The requirement for Route 2_H is very simple. If the failure rate is estimated with a confidence level of 90% then HFT of 1 is sufficient for SIL 3, and HFT of 0 is acceptable for SIL 2.

To take advantage of Route 2_H, we need to understand how to determine confidence levels in failure rates.

By definition, events that are truly random occur at a fixed rate.

If only one or two failures have been recorded the measured failure rate (number of failures divided by total time in service) will not be an accurate representation of the true average failure rate of the population.

The degree of confidence in the measurement of that failure rate is essentially a matter of how many failures have been recorded. As more failures are recorded the width of the confidence interval is reduced.

For failures occurring randomly in any given population of devices the failure rate can be estimated with any desired level of confidence by applying a chi-squared distribution.

Given 'n' measured failures occurring in a time period 'T' with a population of 'm' devices, the true average failure rate 'λ' may be estimated in Microsoft Excel for any required confidence level 'a' by using the function CHISQ.INV(a,2*n+2)/(2*T*m)). (The CHISQ.INV function returns the inverse of the left-tailed probability of the chi-squared distribution.)

The ratios of $\lambda_{90\%}$ to $\lambda_{70\%}$ of $\lambda_{90\%}$ to λ_{AVG} depend only on the number of failures recorded. These ratios do not depend on either the failure rate or on the population size.

As more failures are recorded the band of uncertainty is reduced and the values $\lambda_{90\%}$ and $\lambda_{70\%}$ converge closer to the true average λ_{AVG}.
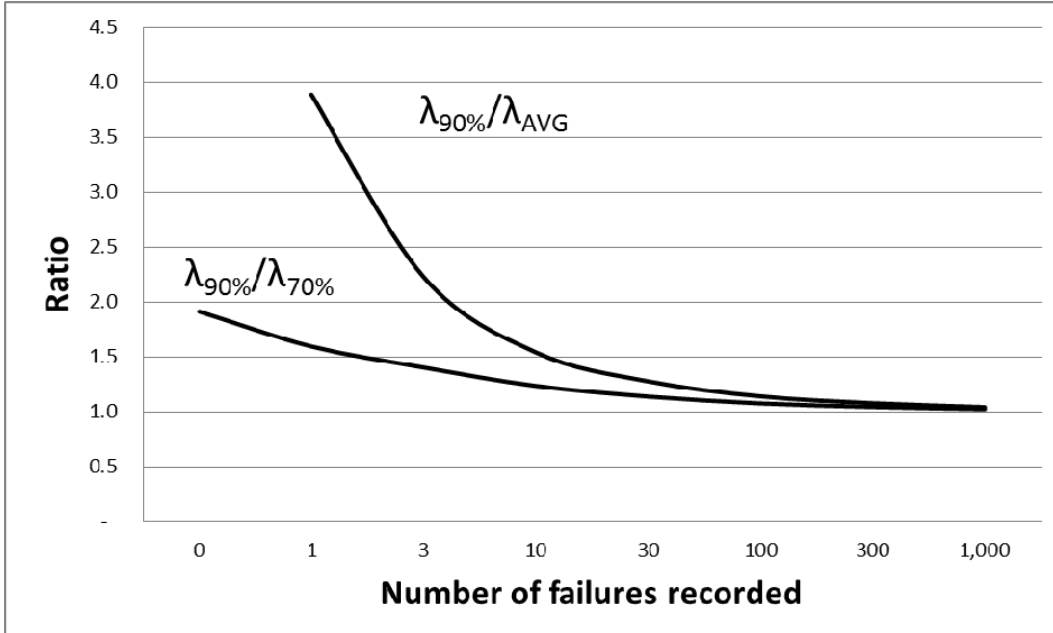
The dependability of failure rate measurements also depends on the quality of the records of failures and time in service. IEC 61508 Route 2_H requires the application of data collection standards such as IEC 60300-1 or ISO 14224. IEC 61511 Ed. 2 also refers users to these standards.

Reference should also be made to IEC 60605-6:2007 for guidance on tests to determine whether failure rates are genuinely constant.

Finding data

Two dependable sources: OREDA and *exida* SERH

The OREDA 'Offshore Reliability Handbook' published by SINTEF gives the standard deviations and the means for average failure rates of components commonly applied in the hydrocarbons industry.

OREDA is based on extensive field experience, though in limited applications. It presents average failure rates recorded across a variety of users, and it shows that the average failure rates can vary over at least an order of magnitude between different applications.

The SERH 'Safety Equipment Reliability Handbook' is published by exida.

The failure rates in *exida* SERH are calculated using FMEDA, but are based on extensive datasets for individual component parts.

The results are broadly consistent, though OREDA includes some 'site specific' failures and OREDA failure rates may be twice as high as corresponding *exida* rates.

Differing treatment of systematic failures

One of the reasons for the differences between sources is in how the decision is made whether to include or exclude failures from the datasets.

Failures of non-electronic components such as valves are always 'systematic' but can be treated as 'quasi-random'.

The standards require that systematic failures should be avoided or controlled through the application of appropriate techniques and measures. However many systematic failures cannot be eliminated easily. The intention of the standards is that these 'quasi random' failures should be included in the probability of failure calculations.

Judgement is needed in deciding which failures to exclude.

Confidence levels

The confidence level in *exida* SERH is stated as 70%.

OREDA shows full details of the spread of failure rates recorded by many different users, including an overall mean and the standard deviation.

The term 'confidence level' cannot be applied when comparing average failure rates reported by different sources in different applications. Instead, OREDA attempts to merge similar several similar samples into a multi-sample. A 'Gamma' distribution is applied to estimate 'uncertainty intervals' based on a mean and a standard deviation of items in the multi-sample. OREDA presents

upper and lower decile failure rates as well as the mean and standard deviation.

The upper decile of the distribution corresponds to a failure rate that is higher than 90% of the mean failure rates reported by each of the various users who have contributed data.

The diagram below shows a simple normal distribution as an illustration. In practice the distributions are skewed.
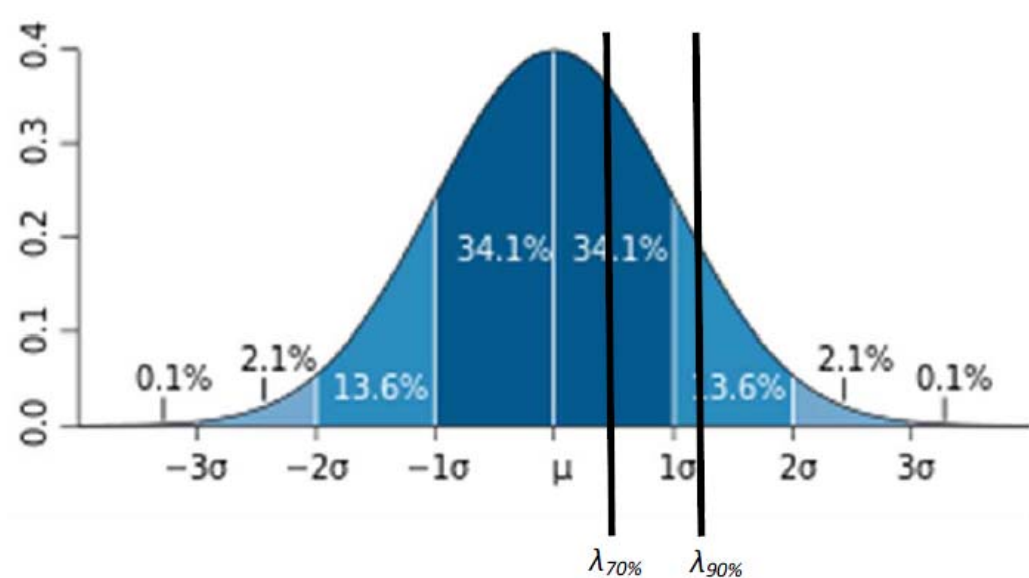
It may be inferred that 70% of reported mean failure rates are lower than a rate that is approximately 0.8 standard deviation below the upper decile.

Typically failure rates are distributed over one or two orders of magnitude.

According to OREDA, the following failure rates are typical for actuated ball valves:

$\lambda_{50\%} \approx 2.3$ per 10^6 hours
$\sigma \quad \approx 2.7$ per 10^6 hours
$\lambda_{70\%} \approx 3.6$ per 10^6 hours
$\lambda_{90\%} \approx 5.8$ per 10^6 hours

$\lambda_{90\%} / \lambda_{70\%} \approx 1.6$

This value of 1.6 for the ratio of $\lambda_{90\%} / \lambda_{70\%}$ is typical for OREDA data.

Less dependable: Studies based on vendor returns

Many SIL certificates have been published that show failure rates up to **50 x lower** than those in SERH or OREDA **and** claiming 90% confidence level.

The example certificates shown above have:

$\lambda \approx 3 \times 10^{-8}$ per hour for a ball valve
$\lambda \approx 3 \times 10^{-8}$ per hour for a pneumatic actuator
$\Sigma\lambda \approx 6 \times 10^{-8}$ per hour for the assembly

For similar equipment, SERH has
$$\lambda \approx 1.4 \times 10^{-6} \text{ per hour}$$

OREDA has
$$\lambda \approx 3.6 \times 10^{-6} \text{ per hour.}$$

Note that uncertainty intervals are related to the spread of data across many users, while the confidence level is related to the number of failures in a given dataset.

The confidence level in a single dataset does not guarantee the validity or applicability of the measured failure rate in a wider context.

Failures per hour
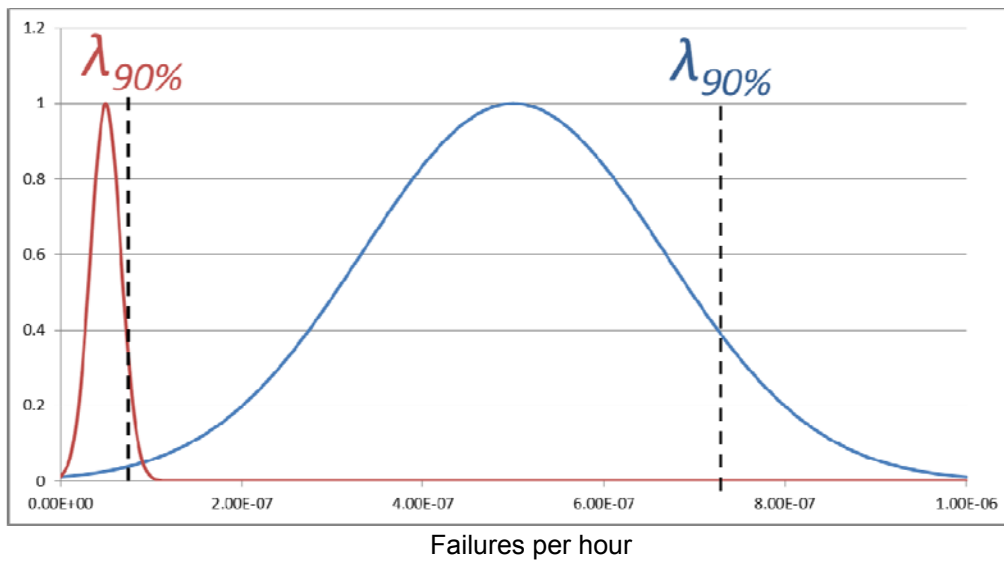
Studies based on vendor returns may inadvertently exclude many failures that were not reported to the vendor. They may also exclude failures considered to be 'systematic' or 'outside the design envelope'.

Low failure rates from restricted datasets may be unrealistically optimistic.

Most dependable: The user's own data

The difficulty is that a large volume of operating experience is required in order to record enough failures to estimate a failure rate close to the true average. It may need the equivalent of decades of experience with a sizeable population of devices.

Analysis of failure causes is just as important as failure rates. Common systematic causes must be controlled.

IEC 61511 Edition 2 – released in 2016

The 2nd Edition of IEC 61511-1 specifies HFT requirements based on Route 2_H.

HFT of 1 is sufficient for SIL 3.

SIL	Minimum required HFT
SIL 1	0
SIL 2 (low demand mode)	0
SIL 2 (high demand/continuous mode)	1
SIL 3	1
SIL 4	2

The standard excludes the requirement for 90% confidence level, but it does require evidence to demonstrate the dependability of the failure rate data. It recommends the application of IEC 60300-1 or ISO 14224.

Conclusions

The HFT methods in IEC 61511 Ed. 1 and IEC 61508 Route 1_H do not work well in practice for the process sector. These methods require 3 valves in series (1 out of 3) to achieve SIL 3.

IEC 61508 Route 2_H is based on confidence level increased to 90%. It is much simpler and easier to apply. It allows SIL 3 to be achieved with only 2 valves as final elements.

IEC 61511 Ed. 2 is based on Route 2_H, but it does not state an explicit requirement for 90% confidence levels. Instead it requires the reliability data to be credible, traceable, documented and justified, and based on similar devices used in a similar environment.

OREDA and *exida* SERH provide failure rate data that are widely accepted as being credible and dependable. These references provide enough information to allow us to infer failure rates with at least a 90% likelihood of being representative of the mean failure rates that can be achieved in operation. That is not the same as a 90% confidence level.

There are many certificates in circulation that claim failure rates that are much lower than the rates published by OREDA and *exida*.

Users should collect their own data. Requirements for collection of evidence are onerous. A large volume of evidence is required. User should compare their failure rates with those in OREDA and SERH.

Failure rates from different sources should always be compared and assessed for plausibility. For Route 2_H a conservative approach should be taken, the complete spread of failure rates should be taken into account.

Published failure rates for valves all include systematic failures. All valve failures are essentially systematic in nature and can be avoided or controlled to some extent. In evaluating failure rates the effectiveness of the planned operation and maintenance should be considered. Particular attention should be given to identifying and controlling common cause failures as these will almost always dominate in the calculated probability of failure.

There are some certificates in circulation that take credit for 'no effect' failures or for partial stroke testing in determining SFF. These certificates must be interpreted with caution. It is not valid to claim SFF > 60% for valves by:
- Taking credit for 'no effect' failures
- Taking credit for infrequent partial stroke testing as a diagnostic

Certificates on their own are not sufficient as evidence of compliance to IEC 61508-2 and IEC 61508-3. Detailed safety manuals must be provided in accordance with IEC 61508-2 Annex D.

References

IEC 61511-1 2003 (Ed.1) and 2016 (Ed.2) 'Functional safety—Safety instrumented systems for the process industry sector
Part 1: Framework, definitions, systems, hardware and software requirements'

IEC 61508-2 2010 'Functional safety of electrical/electronic/programmable electronic safety-related systems
Part 2: Requirements for electrical/electronic/programmable electronic safety-related systems'

IEC 60300-1:2014 'Dependability management Part 1: Guidance for management and application'

ISO 14224:2006 'Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment'

IEC 60605-6:2007 'Equipment reliability testing Part 6: Tests for the validity and estimation of the constant failure rate and constant failure intensity'

SINTEF 2009, 'OREDA Offshore Reliability Handbook' 5th Edition
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exida.com L.L.C. 2007, 'Safety Equipment Reliability Handbook' 3rd Edition
Volume 3 – Final Elements

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http://www.exida.com/images/uploads/Field_Failure_Rates-good_bad_and_ugly_Feb_2012.pdf