Proof Testing… A key performance indicator for designers and end users of Safety Instrumented Systems

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Proof Testing is a key performance indicator with respect to the achievement of functional safety and the paper sets out a structured approach to the development of Proof Test Procedures for Safety Instrumented Functions (SIFs) within the process sector and guides the reader through a five stage process to ensure the development of robust Proof Test Procedures. This requires addressing both the technical requirements and the competence requirements of those having responsibilities for Proof Testing.

This staged approach has been established based on two decades of operational experience by the principal author, within top tier COMAH establishments within the UK, and subsequent consultancy work within multiple industry sectors.

The five stage process consists of:

Stage 1: Specification of the Proof Test Procedures;

Stage 2: Verification of the proposed Proof Test Procedures;

Stage 3: Modification to the Proposed Proof Test Procedures;

Stage 4: Competence of those managing and undertaking the Proof Test Procedures;

Stage 5: Review of the Proof Test Procedures to assess the their effectiveness.

Current good practice in the process sector, with respect to functional safety, is to achieve compliance with IEC 61511 [1] and IEC 61508 [2]. The approach adopted by HSE is to benchmark the functional safety achieved, including Proof Testing, against requirements in IEC 61511 [1] and IEC 61508 [2].

The paper covers the operational challenges to optimise Proof Testing with minimum business interruption. In the context of dangerous random hardware failures, the paper will cover:

Imperfect Proof Testing versus Perfect Proof Testing and optimisation of overhaul periods;

Modification of Proof Tests with underpinning justification and the implications of inappropriate modifications;

The impact on facility resources when an overly conservative approach is taken to the Proof Test interval.

Introduction

Current good practice in the process sector, with respect to functional safety, is to achieve compliance with IEC 61511 [1]. The approach adopted by UK Health & Safety Executive (HSE) is to benchmark the functional safety achieved, including Proof Testing, against requirements in IEC 61511 [1]. This is present within the COMAH Competent Authority - Inspection of Electrical, Control and Instrumentation Systems at COMAH Establishments - Operational Delivery Guide.

IEC 61511 [1] defines the following regarding a Proof Test:

'Periodic test performed to detect dangerous hidden failures in a SIS so that, if necessary, a repair can restore the system to an 'as new' condition or as close as practical to this condition' [IEC61511-1:2016, Corrigendum / 3.2.56 [1]]

Proof Testing and Reliability Modelling

The overall framework for achieving compliance to IEC 61511 [1], with respect to the technical requirements of the design, is indicated in Figure 1. Proof Testing is a key parameter relating to the quantification of dangerous random hardware failures in respect of maintaining the Target Failure Measure for the specific SIF. The usually optimum Target Failure Measures, with respect to the SIF operating in Low Demand Mode, are specified in Table 1. For a SIF operating in Low Demand Mode the Target Failure Measure is the Probability of Failure on demand (PFDavg). The calculation of this Target Failure Measure based on dangerous random hardware failures will then allow the maximum Safety Integrity Level (SIL) for the specified SIF to be determined from Table 1.

Note: IEC 61511-1:2016, Corrigendum [1], incorporates the concept of Demand Mode (encompassing Low Demand Mode and High Demand Mode) and indicates that the required SIL can be based on PFDavg or the Average frequency of dangerous failures per hour. However, it is also stated in IEC 61511-1:2016, Corrigendum/ 3.2.39.1 [1], Note 2; that in High Demand Mode it will normally be appropriate to use the Continuous Mode criteria (which is the Average frequency of dangerous failures per hour). Simply put, for SIL determination purposes, when the SIF is operating Low Demand Mode it is normally appropriate to use PFDavg as the Target Failure Measure and when in High Demand Mode it is appropriate to use the Average frequency of dangerous failures per hour as the Target Failure Measure.

Figure 1 - The IEC 61511 [1] design framework

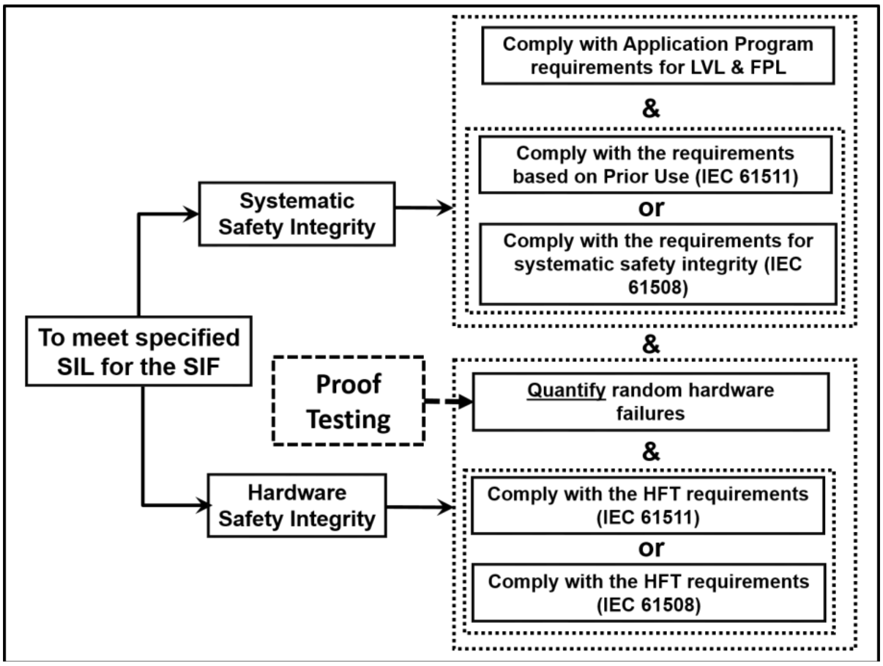


Table 1 Safety integrity levels – target failure measures for a safety function operating in a low demand mode

Safety Integrity Level (SIL)	Average probability of a dangerous failure on demand of the safety function (PFD_{avg})	Risk Reduction Factor (RRF)
4	10^{-5} to < 10^{-4}	>10,000 - 100,000
3	10^{-4} to < 10^{-3}	>1,000 - 10,000
2	10^{-3} to < 10^{-2}	>100 -1,000
1	10^{-2} to < 10^{-1}	>10 -100

PFD is the numerical value that describes the probability that the safety function will fail to operate when required. The following formula is used to determine the PFDavg for a safety function comprising a single element.

The PFD of a single channel element is:

$$PFD = 1 - e^{-\lambda_{DU} T_p} \quad (1)$$

where λdu is the dangerous undetected failure rate per hour and Tp is the proof test frequency.

If λduTp (x) is small (<0.1), then

$$1 - e^{-x} \approx x \quad (2)$$

Thus

$$PFD = \lambda_{DU} T_p \quad (3)$$

The following formula is used to determine the PFDavg, as it is assumed that, on average, a fault will occur at the mid-point of the test interval, so that the time taken to detect a fault is equal to half the test interval, Tp/2:

$$PFD_{avg} = \lambda_{DU} T_p / 2 \quad (4)$$

It can be seen from this equation that the proof test interval Tp has an effect on the achieved PFDavg without physically replacing any equipment. This is due to the fact that there is a reduced time period in which a fault can develop prior to being detected by a proof test.

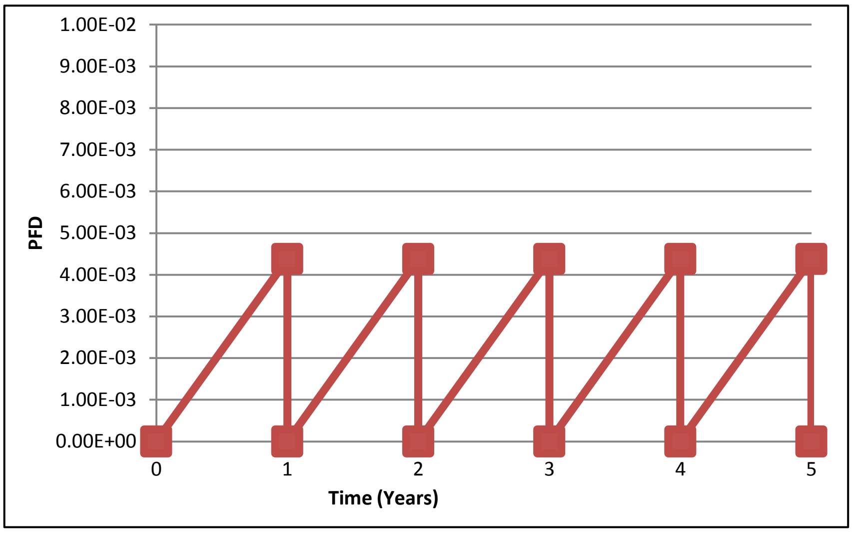
With a Safety Instrumented Function(SIF) with a total system λdu of 1.6E-06 per hour installed with all components installed as single devices (1 out of 1 voting arrangement), the results from the movement of the Proof Test interval between 1 and 10 years' frequency is demonstrated within Table 2.

Table 2 - Effect on PFDavg with change in Proof Test Interval Tp

T_p (years)	PFD_{avg}	SIL band
1	7.0E-03	2
2	1.4E-02	1
3	2.1E-02	1
4	2.8E-02	1
5	3.5E-02	1
6	4.2E-02	1
7	4.9E-02	1
8	5.6E-02	1
9	6.3E-02	1
10	7.0E-02	1

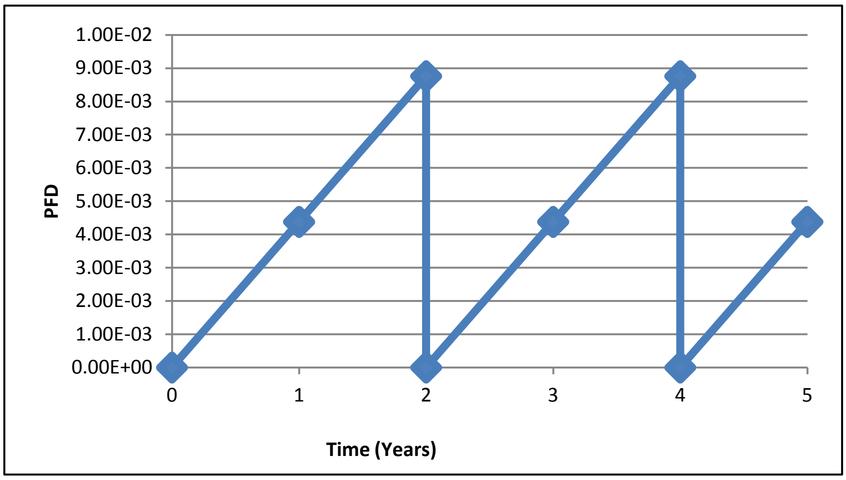
The concept of Proof Testing is illustrated in Figure 2 Once the Proof Test is completed then the PFDavg returns to zero meaning that the SIF has been returned to its as designed status. This is based upon the fact that the Safety Instrumented System (SIS), with respect to the specified SIF, has been restored to the 'as new' condition after completion of the Proof Test. During this test all of the unrevealed dangerous failures have been removed. This is defined as the Perfect Proof Test.

Figure 2 - Effect of proof testing on PFDavg



If the frequency is changed to every other year (once per two years), as illustrated in Figure 3, it can be seen that the PFDavg doubles. Therefore, the probability that the SIF will fail increases.

Figure 3 - Effect on PFDavg by doubling the proof test interval



Imperfect Proof Testing

The previous section assumed that a Perfect Proof Test was achievable, that the Proof Test detected 100% of the dangerous unrevealed failures. In practice this is often difficult to achieve.

The dangerous failures that are not detected at each Proof Test will continue to be present and increase their PFD based upon the exponential equation seen earlier:

$$PFD = 1 - e^{-\lambda_{DU} T_p} \qquad (5)$$

Therefore, given enough time the PFDavg will exceed the target which is necessary to maintain the required risk reduction within your overall system for the hazard being protected against. The concept which defines the effectiveness of a proof test is referred to as Proof Test Coverage (PTC). The amount of PTC which can be claimed depends upon how many of the unrevealed dangerous failures can be detected by the proof test and is expressed as a percentage e.g. 90%. The percentage being representative of the percentage of failures which are revealed by the test.

Table 3 demonstrates the effect of different PTC based on a component λdu of 1.0E-07 per hour and an annual proof test interval.

Table 3 - Effect of <100% PTC on PFDavg

Year	PTC / Corresponding PFDavg					
	100%	90%	80%	70%	60%	50%
1	4.38E-04	4.38E-04	4.38E-04	4.38E-04	4.38E-04	4.38E-04
5	4.38E-04	6.13E-04	7.88E-04	9.64E-04	1.14E-03	1.31E-03
10	4.38E-04	8.32E-04	1.23E-03	1.62E-03	2.01E-03	2.41E-03

The reasons for imperfect tests are varied but include considerations such as:

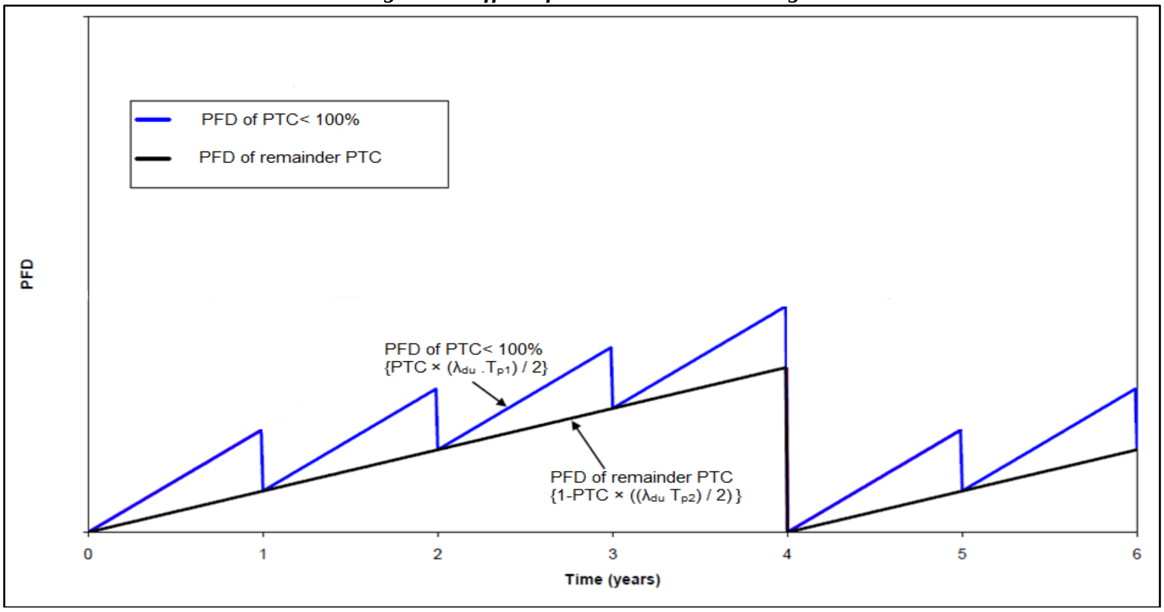
- Not testing the system under normal operating process conditions;
- Not testing impulse lines for blockages;
- Failure to check valves close fully and to the required shut off class.

Some manufacturers' safety manuals help in this area by providing guidance on the testing of their equipment and the PTC which can be achieved utilising this test method.

The PTC can be estimated by the means of Failure Mode and Effects Analysis (FMEA) in conjunction with engineering judgement based on sound evidence.

Figure 4 illustrates the effect of testing with less than 100% PTC.

Figure 4 - Effect of <100% PTC on PFDavg



The generalised formula, for an imperfect proof test, including PTC for undetected failures of a component can be shown to be (with 1oo1 voting arrangements):

$$\mathrm{PFDavg} = \mathrm{PTC} \times \frac{(\lambda\mathrm{du\ Tp1})}{2} + (1 - \mathrm{PTC}) \times \frac{(\lambda\mathrm{du\ Tp2})}{2} \qquad (6)$$

Where PTC is expressed as value between 0 and 1 (0=0%, 1=100%) and Tp1 and Tp2 are the proof test intervals of the imperfect test (Tp1) and the perfect test (Tp2).

Proof Testing Procedures

The Key Stages of the Procedures

The procedures which are required for the maintenance of the SIFs need to be developed, recorded and completed adequately in order that an audit trail can be maintained to demonstrate that the SIFs have been tested in compliance with the frequencies determined in section 2. This chapter will detail the different aspects of the proof test procedures and documentation.

There are five key Stages in the development and implementation of Proof Test Procedures:

Stage 1: Development of Proposed Proof Test Procedures for the specified SIFs;

Stage 2: Verification of the proposed Proof Test Procedures;

Stage 3: Modification to the Proposed Proof Test Procedures;

Stage 4: Ensuring that those undertaking the Proof Test Procedures are competent.

Stage 5: Reviewing and amending the proof test procedure when in use.

Stage 1 involves the creation of a proof test procedure based upon the system design and the site information. At this point the proof test is treated as a proposal. The proof test procedure needs to be developed in a systematic way utilising the FMEA, Manufacturers' manuals and engineering experience to ensure that all of the unrevealed failures have been addressed adequately in line with the PTC assumptions utilised within the random hardware reliability calculations.

Stage 2 can now be undertaken which is to verify that the basis on which the Proof Test Procedures were developed can be implemented in practice and that the underlying assumptions on which the Proof Test Procedures were developed are valid.

This verification process will require that for each SIF, the Proposed Proof Test Procedure for that SIF be undertaken in accordance with the requirements specified in the Proposed Proof Test Procedures. The Proof Tests carried out as part of the verification process should be undertaken by a senior, competent person, who has sufficient theoretical knowledge and practical experience of proof testing relevant to the specific application.

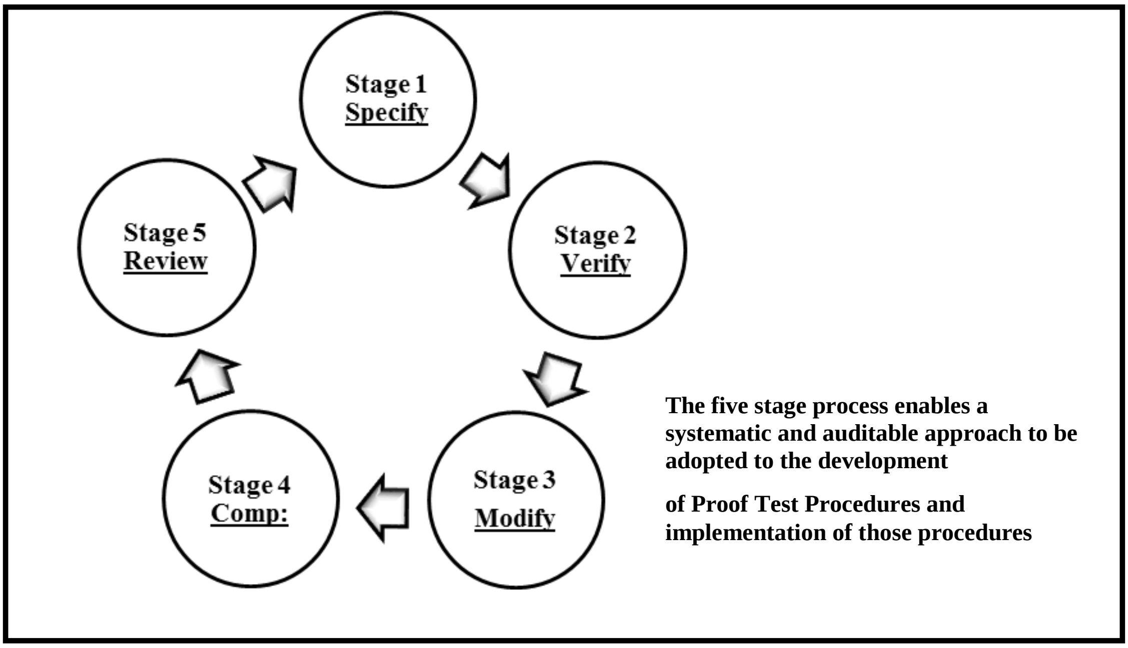
Stage 3 - If the Proof Test for the specified SIF cannot be carried out in accordance with the proposed Proof Test Procedure, a review of the procedure needs to be undertaken. Such a review may necessitate modifications to the procedure in order to ensure that they can be implemented in practice. Any modifications to the Proposed Proof Test Procedures should only be undertaken by persons competent on the development of Proof Test Procedures relevant to the specific application. Once a new proposal is present then the verification activity in Stage 2 should be repeated.

Stage 4 is to ensure that personnel undertaking the Proof Tests in accordance with the Proof Test Procedures are competent in both the theoretical and practical aspects of implementing the Proof Test Procedures on the specified equipment. Because of the importance of Proof Testing in maintaining functional safety, it is strongly recommended that those carrying out the Proof Testing Procedures should be subject to a formal competence assessment.

The Final Stage (Stage 5) is the phase in which the Proof Test procedure is reviewed and amended during use. This maybe as a result of the modification to the equipment utilised within the SIF or that there is a suggestion of a better way to test the function, usually from the maintenance personnel. This stage is likely to be over many years and therefore it is recommended to have a formal process in place, or audit program, to confirm the proof test procedures are correct periodically.

Figure 5 shows the cycle of the five phases to the proof test procedure development. There may be instances where stages are completed out of order, such as Stage 3 back to Stage 2 once a modification has been conducted to verify the success of the change.

Figure 5 - Proof Test Procedure Development Cycle



Practical Considerations

The procedures need to be clear and understandable for the individuals who are being asked to perform the Proof Tests. They must include:

- A level of detail suitable to the competence of the personnel involved;
- A language which the individuals will understand;
- Have clear guidance as to what is acceptable to pass the test.

The proof test procedure must cover:

- Details of the equipment to be tested;
- The expected functionality of the equipment being tested, including expected executive action (e.g. Close valve V-1234);
- The activation point(s) of the equipment including the tolerance in order to determine whether the test has been successful;
- The expected time for the function to respond;
- A record of the physical condition of the installation, including:
    - Equipment is correctly labelled;
    - Housing and cabling in an acceptable condition with no signs of damage or excessive wear;
    - Glands in good order and no sign of weather ingress;
    - Ancillaries in good condition and secure;
    - Loop drawing accurate including hazardous area requirements.
- A record of the required test equipment to conduct the test;
- Any special requirements to complete the test (e.g. Equipment shutdown, Access Platforms, Restricted zones required etc.);
- Methodology to perform the test fully, including:

- Manipulation of input devices to simulate abnormal conditions;
- Observation of output devices correct operation;
- Test of all voting configurations installed within the SIF.
- Tests to confirm fail-safe actions upon loss of signal / ancillary supplies.

The considerations within this section are of equal importance when any reviews and modifications are being considered as well as the initial specification.

Results from the Proof Testing

The recording of the proof test completion is as important as defining the test adequately. This allows the operator to demonstrate that the test has been conducted to the methodology prescribed, by competent personnel and that the function has been verified as to being able to provide the necessary functionality to reduce the hazard as required within the risk analysis for the asset.

The following items should be recorded in a manner that facilitates effective review. For example, the following information should be recorded:

- Names of the individuals conducting the test;
- Date of test completed;
- Test equipment used and its unique reference;
- Record of the results of the test (as found / as left);
- Indication of the success of the test (Pass / Fail);
- Actions taken to restore the function upon failure;
- Re-test results where applicable;
- Discovered faults and whether the function would have worked when called upon.

Reviewing the Proof Testing results

The Review of the Proof Testing results is an important aspect of the functional safety lifecycle. This forms part of the validation processes detailed in IEC 61511-1:2016, Corrigendum clause 15.2.4 [1].

The review should be conducted by an individual representing the operating company with appropriate authority to implement remedial action in the case that the proof test demonstrates a deviation from the required response.

When undertaking a Proof Test, the undertaking of a visual inspection of the equipment is an important aspect and should consider the requirements specified in IEC 61511-1 2016, Corrigendum clause 16.3.2 [1]. The visual inspection confirms that equipment in use within the SIF is in good order and that physical installation considerations won’t render the SIF inoperable.

The results should be reviewed for the following aspects:

- Pass result (within defined tolerances)
    - Is there any drift being observed test on test, if so is this acceptable for the equipment;
    - Has any deterioration been observed in the system response time;
    - Is the installation in good order?
- Failed result (outside of defined tolerances)
    - Cause of failure – external influences (steam leaks, impact etc.);
    - Would have the failure resulted in the SIF not operating in the event of a demand?
        - Was there human intervention rendering the function inoperable? (isolated from the process stream, wires disconnected, incorrect setup)
        - Was the equipment unresponsive to the simulated process?
    - Would the failure have resulted in the operation of the function at an incorrect setting?
        - Would the SIF have activated late?
        - Would the SIF have activated early?

Once a series of tests have been conducted there will be a series of data points which can be analysed to evaluate the achieved hardware reliability and will allow an analysis which can be done to verify the validity of the data utilised within the hardware reliability calculations is conservative.

The results of the review may show that the data utilised in the calculations is incorrect and may need to be revised. Generally, however the data would only be changed should the data observed be worse than the data utilised. Sufficient data is required to obtain a statistically representative sample. Meaning that there is a sufficient population of the same device operating for many operating years within the same operating conditions, prior to any change being made to the utilised data.

Many methods exist for the establishment of the achieved reliability of the equipment. The basic method is to evaluate the operating time of devices and the number of observed failures. If there are more than 10 failures, then a simple calculation can be used to determine the observed failure rate as shown below. If fewer than 10 failures have been observed, then a statistical method needs to be employed such as Chi squared methodology.

$$\boldsymbol{\lambda = k/T} \qquad (7)$$

Where T = Number of unit operating years

k = Number of observed failures

The following example shows how the equation can be utilised:

- Population 750 devices (in same conditions);
- Period Evaluated 10 years (7500 operating years = 6.57E07 operating hours). [T]
- Number of failures (Safe and Dangerous) observed = 52 [k]
- Number Safe failures = 38
- Number Dangerous failures = 14
- Therefore, using the equation $\lambda = k/T$
  - Total Failure rate λ = 52/ 6.57E07 = 7.914E-07 per hour, Of which:
    - Dangerous failure rate λd = 14/ 6.57E07 = 2.131E-07 per hour
    - Safe failure rate λs = 38/ 6.57E07 = 5.784E-07 per hour

Equipment for use in Proof Testing

The accuracy of proof testing is determined by the quality and accuracy of the equipment used to conduct the proof test.

All equipment utilised in proof testing shall itself be tested and calibrated with traceability to the relevant national standard such as United Kingdom Accreditation Service (UKAS) or National Association of Testing Authorities - Australia (NATA).

The test equipment shall be subject to regular calibration and inspections to ensure its accuracy.

Following a calibration of test equipment should there be an error / fault be found with the test instrument then the plant equipment which has been tested by this device needs to be rechecked to ensure that the plant equipment is operating correctly. The amount of equipment to be rechecked is subject to which tests have been conducted by the test equipment in question until the last successful test on the equipment.

Competence

The subject of competence is relevant through the full functional safety lifecycle, with regard to proof testing then the following competencies need to be ensured.

Competence: Proof Test Procedure Development

The personnel charged with development of the proof test procedure need to be competent in the concepts of functional safety and have the understanding of the purpose of the SIF in which the proof test is being written.

The person needs to be competent in basic instrumentation engineering and the best practices of testing such devices, understanding the implications on the test methodology in relation to PTC. The person should be fully conversant with the devices utilised in the SIF for the test method being developed.

Competence: Proof Test Completion

The personnel charged with the completion of the proof test activities must be qualified instrumentation / electrical tradespersons in order to understand the equipment being tested and the correct method of doing so.

The personnel must be trained in the hazards associated with the specific facility to ensure their own safety when conducting the tests.

The personnel should have an understanding and training in functional safety and the purpose of the SIF under test in order that the tests are conducted to ensure that the results are recorded correctly.

Competence: Proof Test Review

The personnel charged with the review of the proof test results must be proficient in data analysis and be in sufficient authority to effect changes required due to the results of the proof tests.

The competence of data analysis and functional safety appreciation is a must for this role.

Proof testing categories

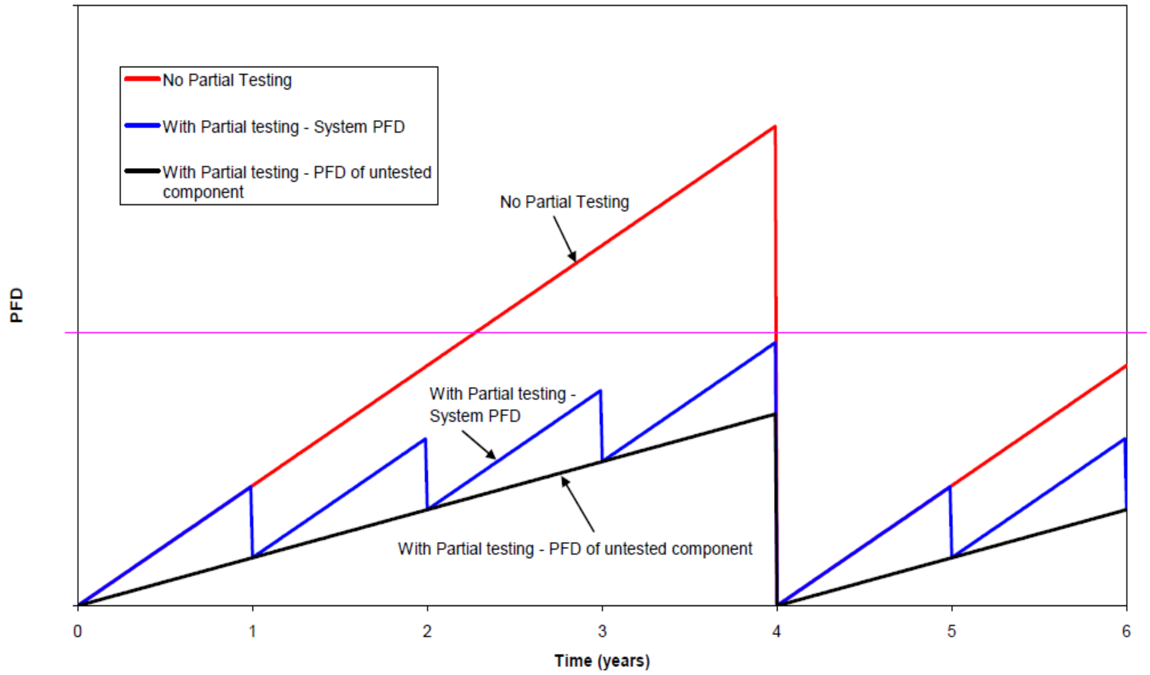
Partial testing

Partial testing is the term used for tests which do not reveal all possible failure modes and are therefore tests with PTC <100%.

A partial test example is partial stroke checking of a valve, this would involve closing / opening a valve from its fully open / close position by a small percentage between 10 and 20%. This test would likely be credited of a PTC of < 100%.

The failure modes of the equipment, for example a valve arrangement, must be analysed to see if Partial Stroke Testing would detect the failure. Figure 6 taken from HSE guidance OG-00054 Appendix 3 [3] shows the effect on the PFDavg when partial testing is implemented.

Figure 6 - Effect of Partial testing on PFDavg



Functional testing

Functional testing is the term utilised for a test which demonstrates that upon a condition being present within the monitored system that the required actions are effected e.g. valves close or drives stop.

These tests don't confirm the full functionality of the system. For instance:

- the settings at which the sensor activates;
- whether tight shut-off by the valve is achieved; OR
- that all voting arrangements operate correctly.

Online Proof testing

Online proof testing is when the test is completed with the highest PTC possible for an in-situ test. Cautions need to be made if the proof test is intending on utilising the process medium for the conducting of the test, you may need to implement additional risk reduction measures to ensure that the hazard being protected against is not realised. The test can utilise calibration equipment to conduct the test, with the correct PTC assumed. This is the preferred option for conducting Proof Tests.

The Proof Test should confirm:

- Actual test points in which the sensors are activated;
- Voting arrangements;
- Full final element operation;
- Response time of the system;
- Tight shut-off by the valve (if facilities available).

The evaluation of the facilities and methodology will allow the establishment of the PTC as defined within the random hardware reliability calculations.

Off-line Proof tests

In the event of the online proof tests being an imperfect test, then the testing of the latent (remaining) failures needs to be addressed. Usually this involves removing the equipment from the process lines / equipment and conducting an off-line test (overhaul) of the devices. The overhaul tests should be designed to restore to equipment to the 'as new' condition.

There have been discussions with regards to when equipment used in SIFs needs to be replaced. The standard doesn't require the replacement of equipment but the returning of the equipment to the as new condition as defined in IEC61511-1:2016, Corrigendum / 3.2.56 [1].

The frequency of the overhaul is sometimes referred to as the 'mission time' of the SIF. Some software products allow you to manipulate the overhaul frequency to extend periods between the proof test interval (on-line test).

Dependent upon the financial value of the equipment, and other operational parameters, some site operators choose to keep a spare device and swap the equipment with the spare device rather than removing the device and conducting an overhaul / service of the device at the time (longer period with equipment not in service).

Irrespective of the strategy being utilised it is important to remember that the device removed need to be tested in the 'as found' condition to establish whether it would have provided the protection required, prior to undertaking any remedial action. Upon completion of the work, commissioning and validation of the function needs to be conducted to confirm that the equipment has been restored as per the SRS.

The test results (as found / as left) should be recorded and reviewed in line with all of the other types of test, even if the equipment is being scrapped.

Business Impact of Proof Testing

The importance of correctly specifying the proof test intervals within the reliability modelling are not only related to the protection which your SIF provides.

If the frequency is incorrect, being too often, then you will be impacting the viability of your business. Testing of the SIFs does not produce any goods / materials. Quite often the testing of your SIFs impacts the production rates.

The costs associated with each test include:

- Production losses
- Labour costs
- Cost of calibration materials / test equipment (including re-calibrations)
- Transport costs

By optimising your installed equipment and proof test intervals the costs can be fewer and the chance of introducing errors to your system are less.

It can be clearly seen within an example:

A test takes 5 hours and requires the unit to be shutdown and de-contaminated therefore 8 hrs production losses. The test requires a pressure calibrator.

- Production losses
  - £17k/hr = 136k
- Labour costs
  - 2 people at £50/hr = £500 (10 man hours)
- Cost of calibration materials / test equipment (including re-calibrations):
  - £3.5k per pressure calibrator + £300 annual calibration (annualised (5-year life) is £700/yr + £300 = £1000/yr)
- Transport costs
  - £50 per day = £50

The resultant losses per test for this single SIF are approximately £137.55k

In this example it can be seen that the costs are dominated by the loss of production, should the tests have the ability to be conducted with insignificant production interruption then it may be more practical to have more frequent tests.

Conclusions

1. The paper has indicated that Proof Testing the SIFs is of the utmost importance in maintaining the design Target Failure Measure for the SIF and thereby the Target Risk.

2. The procedures need to be precisely specified, reviewed and updated as appropriate to the system under test.

3. The results of the Proof Tests should be fed back, via the analysis of the results, into the random hardware reliability calculations. Hopefully this will only be confirming that the expected failure rates are being observed, but may necessitate a reappraisal of the original data used and to a change of the devices used to implement the SIF.

4. Perfect and Imperfect Proof Testing presents a challenge in itself. Can you "hand on heart" state that your Proof Test are perfect in detecting all of the dangerous failures within your system?

5. The whole process is flawed if those tasked with the Proof Testing are not competent to perform the Proof Tests in an effective manner. From specifying the procedures through to execution and reviewing the Proof Tests it is important that all persons having responsibilities for Proof Testing are competent to undertake their specific tasks.

6. Ineffective Proof Testing may lead to an increase in the Hazardous Event Frequency (i.e. the frequency of the incident on site arising) which will not only impact the organisations legal compliance by not meeting the Target Risk but could also have significant financial implications on business operations and reputational damage.

7. The PFDavg of the SIFs should be reviewed and optimised to minimise the impact to the business, it may be worth more capital investment in the design state to minimise the longer term operational costs.

References

[1] IEC 61511-1, Functional safety – Safety instrumented systems for the process industry sector. Edition 2, 2016, Corrigendum edition.

[2] IEC 61508, Functional Safety of Electrical/ Electronic/ Programmable Electronic Safety Related Systems. Edition 2, 2010.

[3] HSE guidance OG-00054, Proof Testing of Safety Instrumented Systems in the Onshore Chemical / Specialist Industry Appendix 3 http://www.hse.gov.uk/foi/internalops/og/og-00054-appendix3.pdf