Failure Modes, Effects and Diagnostic Analysis

Project:
One Series Safety Switch

Company:
United Electric Controls
Watertown, MA
USA

Contract Number: Q21/01-054
Report No.: UE 21/01-054 R001
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Management Summary

This report summarizes the results of the hardware assessment in the form of a Failure Modes, Effects, and Diagnostic Analysis (FMEDA) of the One Series Safety Switch, hardware and software revision per Section 2.5.1. A Failure Modes, Effects, and Diagnostic Analysis is one of the steps to be taken to achieve functional safety certification per IEC 61508 of a device. From the FMEDA failure rates are determined. The FMEDA that is described in this report concerns only the hardware of the One Series Safety Switch. For full functional safety certification purposes, all requirements of IEC 61508 must be considered.

The One Series Safety Switch is a smart pressure or temperature switch. It provides a relay output as well as an I Am Working (IAW) contact output. The One Series is powered by the main output loop.

Table 1 gives an overview of the different versions that were considered in the FMEDA of the One Series Safety Switch.

Table 1 Version Overview

Pressure DC IAW	Pressure input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 24VDC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Pressure AC IAW	Pressure input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 120V AC or DC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Pressure AC IAW High Power	Pressure input; the high power de-energize-to-trip relay output provides the safety variable to the final element. The unit is powered by 120V AC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Temperature DC IAW	Temperature input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 24VDC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Temperature AC IAW	Temperature input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 120V AC or DC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Temperature AC IAW High Power	Temperature input; the high power de-energize-to-trip relay output provides the safety variable to the final element. The unit is powered by 120V AC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.

The One Series Safety Switch is classified as a Type B[1] element according to IEC 61508, having a hardware fault tolerance of 0.

[1] Type B element: “Complex” element (using micro controllers or programmable logic); for details see 7.4.4.1.3 of IEC 61508-2, ed2, 2010.

The failure rate data used for this analysis meet the *exida* criteria for Route 2_H (see Section 5.2). Therefore, the One Series Safety Switch meets the hardware architectural constraints for up to SIL 2 at HFT=0 (or SIL 3 @ HFT=1) when the listed failure rates are used.

Based on the assumptions listed in 4.3, the failure rates for the One Series Safety Switch are listed in section 4.5.

These failure rates are valid for the useful lifetime of the product, see Appendix A.

The failure rates listed in this report are based on over 400 billion unit operating hours of process industry field failure data. The failure rate predictions reflect realistic failures and include site specific failures due to human events for the specified Site Safety Index (SSI), see section 4.2.2.

A user of the One Series Safety Switch can utilize these failure rates in a probabilistic model of a safety instrumented function (SIF) to determine suitability in part for safety instrumented system (SIS) usage in a particular safety integrity level (SIL).

Table of Contents

1 Purpose and Scope

This document shall describe the results of the hardware assessment in the form of the Failure Modes, Effects and Diagnostic Analysis carried out on the One Series Safety Switch. From this, failure rates for each failure mode/category, useful life, and proof test coverage are determined.

The information in this report can be used to evaluate whether an element meets the average Probability of Failure on Demand (PFD_{AVG}) requirements and if applicable, the architectural constraints / minimum hardware fault tolerance requirements per IEC 61508 / IEC 61511.

A FMEDA is part of the effort needed to achieve full certification per IEC 61508 or other relevant functional safety standard.

2 Project Management

2.1 *exida*

exida is one of the world's leading accredited Certification Bodies and knowledge companies specializing in automation system safety, availability, and cybersecurity with over 500 person years of cumulative experience in functional safety, alarm management, and cybersecurity. Founded by several of the world's top reliability and safety experts from manufacturers, operators, and assessment organizations, *exida* is a global corporation with offices around the world. *exida* offers training, coaching, project oriented consulting services, safety engineering tools, detailed product assurance and ANSI accredited functional safety and cybersecurity certification. *exida* maintains a comprehensive failure rate and failure mode database on electronic and mechanical equipment and a comprehensive database on solutions to meet safety standards such as IEC 61508.

2.2 Roles of the parties involved

United Electric Controls	Manufacturer of the One Series Safety Switch
exida	Performed the hardware assessment

United Electric Controls contracted *exida* in January 2021 with the hardware assessment of the above-mentioned device.

2.3 Standards and literature used

The services delivered by *exida* were performed based on the following standards / literature.

[N1]	IEC 61508-2: ed2, 2010	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems
[N2]	Electrical Component Reliability Handbook, 4th Edition, 2017	*exida* LLC, Electrical Component Reliability Handbook, Fourth Edition, 2017
[N3]	Mechanical Component Reliability Handbook, 4th Edition, 2017	*exida* LLC, Electrical & Mechanical Component Reliability Handbook, Fourth Edition, 2017
[N4]	Goble, W.M. 2010	Control Systems Safety Evaluation and Reliability, 3rd edition, ISA, ISBN 97B-1-934394-80-9. Reference on FMEDA methods
[N5]	IEC 60654-1:1993-02, second edition	Industrial-process measurement and control equipment – Operating conditions – Part 1: Climatic condition
[N6]	O'Brien, C. & Bredemeyer, L., 2009	*exida* LLC., Final Elements & the IEC 61508 and IEC Functional Safety Standards, 2009, ISBN 978-1-9934977-01-9

[N7]	Scaling the Three Barriers, Recorded Web Seminar, June 2013,	Scaling the Three Barriers, Recorded Web Seminar, June 2013, http://www.exida.com/Webinars/Recordings/SIF-Verification-Scaling-the-Three-Barriers
[N8]	Meeting Architecture Constraints in SIF Design, Recorded Web Seminar, March 2013	http://www.exida.com/Webinars/Recordings/Meeting-Architecture-Constraints-in-SIF-Design
[N9]	Random versus Systematic – Issues and Solutions, September 2016	Goble, W.M., Bukowski, J.V., and Stewart, L.L., Random versus Systematic – Issues and Solutions, exida White Paper, PA: Sellersville, www.exida.com/resources/whitepapers, September 2016.
[N10]	Assessing Safety Culture via the Site Safety Index^{TM}, April 2016	Bukowski, J.V. and Chastain-Knight, D., Assessing Safety Culture via the Site Safety Index^{TM}, Proceedings of the AIChE 12th Global Congress on Process Safety, GCPS2016, TX: Houston, April 2016.
[N11]	Quantifying the Impacts of Human Factors on Functional Safety, April 2016	Bukowski, J.V. and Stewart, L.L., Quantifying the Impacts of Human Factors on Functional Safety, Proceedings of the 12th Global Congress on Process Safety, AIChE 2016 Spring Meeting, NY: New York, April 2016.
[N12]	Criteria for the Application of IEC 61508:2010 Route 2H, December 2016	Criteria for the Application of IEC 61508:2010 Route 2H, exida White Paper, PA: Sellersville, www.exida.com, December 2016.
[N13]	Using a Failure Modes, Effects and Diagnostic Analysis (FMEDA) to Measure Diagnostic Coverage in Programmable Electronic Systems, November 1999	Goble, W.M. and Brombacher, A.C., Using a Failure Modes, Effects and Diagnostic Analysis (FMEDA) to Measure Diagnostic Coverage in Programmable Electronic Systems, Reliability Engineering and System Safety, Vol. 66, No. 2, November 1999.
[N14]	FMEDA – Accurate Product Failure Metrics, June 2015	Grebe, J. and Goble W.M., FMEDA – Accurate Product Failure Metrics, www.exida.com, June 2015.

2.4 *exida* tools used

[T1]	V2.1.0.30307	*exida* FMEDAx Tool

2.5 Reference documents

2.5.1 Documentation provided by United Electric Controls

[D1]	Doc #624-694, Rev F, 2019-01-10	Schematic Drawing, One Series 2 Wire Switch
[D2]	Doc #6247-708, Rev G, 2019-01-10	Schematic Drawing, One Series 2 Wire Switch, Model 2: 1XSWHL/1XSWHH
[D3]	Doc # 6247-709, Rev B, 2016-05-05	Schematic Drawing, One Series 2 Wire Switch, Model 2: 1XSWHL/1XSWHH Relay Board
[D4]	Doc # SR#133036.D3.2, 2014-06-27	Circuit description
[D5]	Doc # SR133037.D3.2, 2016-06-08	Circuit description
[D6]	One Series Fault Codes.docx	Fault Codes
[D7]	RE_ One Series FMEDA - Soft Errors.msg, 2021-06-23	Soft error handling

2.5.2 Documentation generated by *exida*

[R1]	1XSWHL Pressure 2021-06-24.nefm	Failure Modes, Effects, and Diagnostic Analysis – One Series Safety Switch
[R2]	1XSWHL Temperature 2021-06-24.nefm	Failure Modes, Effects, and Diagnostic Analysis – One Series Safety Switch
[R3]	2 Wire Switch Pressure 2021-06-24.nefm	Failure Modes, Effects, and Diagnostic Analysis – One Series Safety Switch
[R4]	2 Wire Switch Temperature 2021-06-24.nefm	Failure Modes, Effects, and Diagnostic Analysis–One Series Safety Switch
[R5]	1XSWHH Relay Board 2022-03-01.nefm	Failure Modes, Effects, and Diagnostic Analysis–One Series Safety Switch
[R6]	One Series High Power Summary 2022-03-01.xlsx	Failure Modes, Effects, and Diagnostic Analysis–One Series Safety Switch – High Power Summary

3 Product Description

The One Series Safety Switch is a smart pressure or temperature switch. It provides a relay output as well as an I Am Working (IAW) contact output. The One Series Safety Switch is powered by the main output loop.

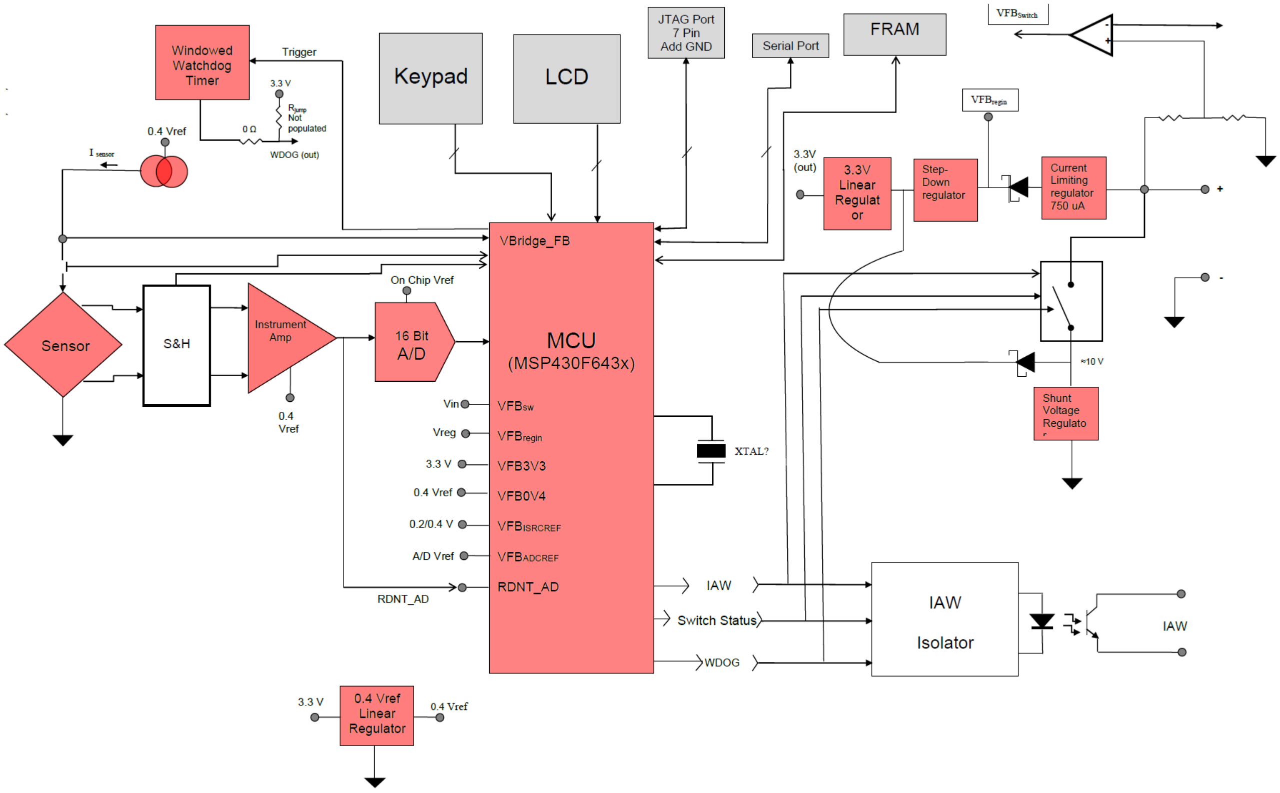


Figure 1 One Series Safety Switch, Parts included in the FMEDA

Table 2 gives an overview of the different versions that were considered in the FMEDA of the One Series Safety Switch.

Table 2 Version Overview

Pressure DC IAW	Pressure input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 24VDC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Pressure AC IAW	Pressure input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 120V AC or DC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Pressure AC IAW High Power	Pressure input; the high power de-energize-to-trip relay output provides the safety variable to the final element. The unit is powered by 120V AC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Temperature DC IAW	Temperature input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 24VDC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Temperature AC IAW	Temperature input; the de-energize-to-trip relay output provides the safety variable to a logic solver or directly to the final element. The unit is powered by 120V AC or DC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.
Temperature AC IAW High Power	Temperature input; the high power de-energize-to-trip relay output provides the safety variable to the final element. The unit is powered by 120V AC nominal from the output loop. The I Am Working (IAW) output provides the status of the One Series.

The One Series Safety Switch is classified as a Type B[2] element according to IEC 61508, having a hardware fault tolerance of 0.

[2] Type B element: “Complex” element (using micro controllers or programmable logic); for details see 7.4.4.1.3 of IEC 61508-2, ed2, 2010.

4 Failure Modes, Effects, and Diagnostic Analysis

The Failure Modes, Effects, and Diagnostic Analysis was performed based on the documentation in section 2.5.1 and is documented in [R1] to [R4].

4.1 Failure categories description

In order to judge the failure behavior of the One Series Safety Switch, the following definitions for the failure of the device were considered.

Fail-Safe State
State where output is de-energized.

Fail Safe
Failure that causes the device to go to the defined fail-safe state without a demand from the process.

Fail Detected
Failure that causes the output signal to go to the predefined alarm state (IAW open).

Fail Dangerous
Failure that prevents the output from transitioning to its fail-safe state.

Fail Dangerous Undetected
Failure that is dangerous and that is not being diagnosed by automatic diagnostics.

Fail Dangerous Detected
Failure that is dangerous but is detected by automatic diagnostics.

No Effect
Failure of a component that is part of the safety function but that has no effect on the safety function.

Annunciation Detected
Failure that does not directly impact safety but does impact the ability to detect a future fault (such as a fault in a diagnostic circuit) and that is detected by internal diagnostics. A Fail Annunciation Detected failure leads to a false diagnostic alarm.

Annunciation Undetected
Failure that does not directly impact safety but does impact the ability to detect a future fault (such as a fault in a diagnostic circuit) and that is not detected by internal diagnostics.

The failure categories listed above expand on the categories listed in IEC 61508 in order to provide a complete set of data needed for design optimization.

Depending on the application, a Fail High or a Fail Low failure can either be safe or dangerous and may be detected or undetected depending on the programming of the logic solver. Consequently, during a Safety Integrity Level (SIL) verification assessment the Fail High and Fail Low failure categories need to be classified as safe or dangerous, detected or undetected.

The Annunciation failures are provided for those who wish to do reliability modeling more detailed than required by IEC61508. It is assumed that the probability model will correctly account for the Annunciation failures.

4.2 Methodology – FMEDA, failure rates

4.2.1 FMEDA

A FMEDA (Failure Mode Effect and Diagnostic Analysis) is a failure rate prediction technique based on a study of design strength versus operational profile stress. It combines design FMEA techniques with extensions to identify automatic diagnostic techniques and the failure modes relevant to safety instrumented system design. It is a technique recommended to generate failure rates for each failure mode category [N13, N14].

4.2.2 Failure rates

The accuracy of any FMEDA analysis depends upon the component reliability data as input to the process. Component data from consumer, transportation, military or telephone applications could generate failure rate data unsuitable for the process industries. The component data used by *exida* in this FMEDA is from the Electrical and Mechanical Component Reliability Handbooks [N3] which were derived using over 400 billion unit operational hours of process industry field failure data from multiple sources and failure data formulas from international standards. The component failure rates are provided for each applicable operational profile and application, see Appendix C. The *exida* profile chosen for this FMEDA was 2 as this was judged to be the best fit for the product and application information submitted by United Electric Controls. It is expected that the actual number of field failures will be less than the number predicted by these failure rates.

Early life failures (infant mortality) are not included in the failure rate prediction as it is assumed that some level of commission testing is done. End of life failures are not included in the failure rate prediction as useful life is specified.

The failure rates are predicted for a Site Safety Index of SSI=2 [N10, N11] as this level of operation is common in the process industries. Failure rate predictions for other SSI levels are included in the exSILentia® tool from exida.

The user of these numbers is responsible for determining the failure rate applicability to any particular environment. *exida* Environmental Profiles listing expected stress levels can be found in Appendix C. Some industrial plant sites have high levels of stress. Under those conditions the failure rate data is adjusted to a higher value to account for the specific conditions of the plant. exida has detailed models available to make customized failure rate predictions. Contact exida.

Accurate plant specific data may be used to check validity of this failure rate data. If a user has data collected from a good proof test reporting system such as *exida* SILStat^{TM} that indicates higher failure rates, the higher numbers shall be used.

4.3 Assumptions

The following assumptions have been made during the Failure Modes, Effects, and Diagnostic Analysis of the One Series Safety Switch.

- The worst-case assumption of a series system is made. Therefore, only a single component failure will fail the entire One Series Safety Switch and propagation of failures is not relevant.
- Failure rates are constant for the useful life period.

- Any product component that cannot influence the safety function (feedback immune) is excluded. All components that are part of the safety function including those needed for normal operation are included in the analysis.
- The stress levels are specified in the *exida* Profile used for the analysis are limited by the manufacturer's published ratings.
- Practical fault insertion tests have been used when applicable to demonstrate the correctness of the FMEDA results.
- The application program in the logic solver is constructed in such a way that IAW state is detected regardless of the effect, safe or dangerous, on the safety function.
- Materials are compatible with process conditions.
- The device is installed and operated per manufacturer's instructions.
- Soft Error Rates (SER) were considered for relative neutron flux of 4.5 corresponding to 1,600 meters above sea level.
- External power supply failure rates are not included.
- Worst-case internal fault detection time is 10 minutes.

4.4 Application specific restrictions

The following application specific restrictions are applicable to the One Series Safety Switch and have been considered during the Failure Modes, Effects, and Diagnostic Analysis of the One Series Safety Switch. These restrictions shall be included in the safety manual for the One Series Safety Switch.

- The I Am Working (IAW) output must be connected and monitored.

4.5 Results

Using reliability data extracted from the *exida* Electrical and Mechanical Component Reliability Handbook the following failure rates resulted from the One Series Safety Switch FMEDA.

Table 3 through Table 8 list the failure rates for the One Series Safety Switch with a Site Safety Index (SSI) of 2 (good site maintenance practices). See Appendix E for an explanation of SSI and the failure rates for SSI of 4 (ideal maintenance practices).

Table 3 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 (Pressure DC IAW)

Failure Category	Failure Rate (FIT)
Fail Safe Detected	239
Fail Safe Undetected	41
Fail Dangerous Detected	266
Fail Dangerous Undetected	33
No Effect	203
Annunciation Detected	66
Annunciation Undetected	25

Table 4 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 (Pressure AC IAW)

Failure Category	Failure Rate (FIT)
Fail Safe Detected	243
Fail Safe Undetected	110
Fail Dangerous Detected	290
Fail Dangerous Undetected	44
No Effect	211
Annunciation Detected	90
Annunciation Undetected	30

Table 5 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 (Pressure AC IAW High Power)

Failure Category	Failure Rate (FIT)
Fail Safe Detected	312
Fail Safe Undetected	129
Fail Dangerous Detected	290
Fail Dangerous Undetected	53
No Effect	218
Annunciation Detected	90
Annunciation Undetected	30

Table 6 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 (Temperature DC IAW)

Failure Category	Failure Rate (FIT)
Fail Safe Detected	256
Fail Safe Undetected	53
Fail Dangerous Detected	268
Fail Dangerous Undetected	22
No Effect	203
Annunciation Detected	66
Annunciation Undetected	25

Table 7 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 (Temperature AC IAW)

Failure Category	Failure Rate (FIT)
Fail Safe Detected	260
Fail Safe Undetected	123
Fail Dangerous Detected	291
Fail Dangerous Undetected	33
No Effect	211
Annunciation Detected	90
Annunciation Undetected	30

Table 8 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 (Temperature AC IAW High Power)

Failure Category	Failure Rate (FIT)
Fail Safe Detected	328
Fail Safe Undetected	142
Fail Dangerous Detected	291
Fail Dangerous Undetected	42
No Effect	218
Annunciation Detected	90
Annunciation Undetected	30

Table 9 lists the failure rates for the One Series Safety Switch according to IEC 61508.

Table 9 Failure rates with Good Maintenance Assumptions in FIT @ SSI=2 according to IEC 61508

Application/Device/Configuration	λ_{SD}	λ_{SU}[3]	λ_{DD}	λ_{DU}	#
Pressure DC IAW	305	41	266	33	228
Pressure AC IAW	333	110	290	44	241
Pressure AC IAW High Power	392	129	290	53	248
Temperature DC IAW	322	53	268	22	228
Temperature AC IAW	350	123	291	33	241
Temperature AC IAW High Power	418	142	291	42	248

Where:

λ_{SD} = Fail Safe Detected

λ_{SU} = Fail Safe Undetected

λ_{DD} = Fail Dangerous Detected

λ_{DU} = Fail Dangerous Undetected

# = No Effect Failures

These failure rates are valid for the useful lifetime of the product, see Appendix A.

According to IEC 61508-2 the architectural constraints of an element must be determined. This can be done by following the 1_H approach according to 7.4.4.2 of IEC 61508-2 or the 2_H approach according to 7.4.4.3 of IEC 61508-2, or the approach according to IEC 61511:2016 which is based on 2_H (see Section 5.2).

The 1_H approach involves calculating the Safe Failure Fraction for the entire element.

The 2_H approach involves assessment of the reliability data for the entire element according to 7.4.4.3.3 of IEC 61508-2.

The failure rate data used for this analysis meet the *exida* criteria for Route 2_H which is more stringent than IEC 61508-2. Therefore, the One Series Safety Switch meets the hardware architectural constraints for up to SIL 2 at HFT=0 (or SIL 3 @ HFT=1) when the listed failure rates are used.

The architectural constraint type for the One Series Safety Switch is B. The hardware fault tolerance of the device is 0. The SIS designer is responsible for meeting other requirements of applicable standards for any given SIL.

Table 14 lists the failure rates for the One Series Safety Switch according to IEC 61508 with a Site Safety Index (SSI) of 4 (perfect site maintenance practices). This data should not be used for SIL verification and is provided only for comparison with other analysis than has assumed perfect maintenance. See Appendix E for an explanation of SSI.

[3] It is important to realize that the No Effect failures are no longer included in the Safe Undetected failure category according to IEC 61508, ed2, 2010.

5 Using the FMEDA Results

The following section(s) describe how to apply the results of the FMEDA.

5.1 PFD$_{avg}$ calculation One Series Safety Switch

Using the failure rate data displayed in section 4.5, and the failure rate data for the associated element devices, an average the Probability of Failure on Demand (PFD$_{avg}$) calculation can be performed for the element.

Probability of Failure on Demand (PFD$_{avg}$) calculation uses several parameters, many of which are determined by the particular application and the operational policies of each site. Some parameters are product specific and the responsibility of the manufacturer. Those manufacturer specific parameters are given in this third-party report.

Probability of Failure on Demand (PFD$_{avg}$) calculation is the responsibility of the owner/operator of a process and is often delegated to the SIF designer. Product manufacturers can only provide a PFD$_{avg}$ by making many assumptions about the application and operational policies of a site. Therefore, use of these numbers requires complete knowledge of the assumptions and a match with the actual application and site.

Probability of Failure on Demand (PFD$_{avg}$) calculation is best accomplished with *exida's* exSILentia tool. See Appendix D for a complete description of how to determine the Safety Integrity Level for an element. The mission time used for the calculation depends on the PFD$_{avg}$ target and the useful life of the product. The failure rates and the proof test coverage for the element are required to perform the PFD$_{avg}$ calculation. The proof test coverage for the suggested proof test are listed in Table 11.

5.2 *exida* Route 2$_H$ Criteria

IEC 61508, ed2, 2010 describes the Route 2$_H$ alternative to Route 1$_H$ architectural constraints. The standard states:

> "based on data collected in accordance with published standards (e.g., IEC 60300-3-2: or ISO 14224); and, be evaluated according to
>
> - the amount of field feedback; and
> - the exercise of **expert judgment**; and when needed
> - the undertaking of specific tests,
>
> in order to estimate the average and the uncertainty level (e.g., the 90% confidence interval or the probability distribution) of each reliability parameter (e.g., failure rate) used in the calculations."

exida has interpreted this to mean not just a simple 90% confidence level in the uncertainty analysis, but a high confidence level in the entire data collection process. As IEC 61508, ed2, 2010 does not give detailed criteria for Route 2$_H$, *exida* has established the following:

1. field unit operational hours of 100,000,000 per each component; and

2. a device and all its components have been installed in the field for one year or more; and

3. operational hours are counted only when the data collection process has been audited for correctness and completeness; and

4. failure definitions, especially "random" vs. "systematic" [N9] are checked by *exida*; and

5. every component used in an FMEDA meets the above criteria.

This set of requirements is chosen to assure high integrity failure data suitable for safety integrity verification [N12].

6 Terms and Definitions

Automatic Diagnostics	Tests performed online internally by the device or, if specified, externally by another device without manual intervention.
DC	Diagnostic Coverage
exida criteria	A conservative approach to arriving at failure rates suitable for use in hardware evaluations utilizing the 2_H Route in IEC 61508-2.
Fault tolerance	Ability of a functional unit to continue to perform a required function in the presence of faults or errors (IEC 61508-4, 3.6.3).
FIT	Failure in Time ($1x10^{-9}$ failures per hour)
FMEDA	Failure Mode Effect and Diagnostic Analysis
HFT	Hardware Fault Tolerance
PFD_{avg}	Average Probability of Failure on Demand
SFF	Safe Failure Fraction, summarizes the fraction of failures which lead to a safe state plus the fraction of failures which will be detected by automatic diagnostic measures and lead to a defined safety action.
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIS	Safety Instrumented System – Implementation of one or more Safety Instrumented Functions. A SIS is composed of any combination of sensor(s), logic solver(s), and final element(s).
Type A element	“Non-Complex” element (using discrete components); for details see 7.4.4.1.2 of IEC 61508-2
Type B element	“Complex” element (using complex components such as micro controllers or programmable logic); for details see 7.4.4.1.3 of IEC 61508-2

7 Status of the Document

7.1 Liability

exida prepares FMEDA reports based on methods advocated in International standards. Failure rates are obtained from a collection of industrial databases. *exida* accepts no liability whatsoever for the use of these numbers or for the correctness of the standards on which the general calculation methods are based.

Due to future potential changes in the standards, product design changes, best available information and best practices, the current FMEDA results presented in this report may not be fully consistent with results that would be presented for the identical model number product at some future time. As a leader in the functional safety market place, *exida* is actively involved in evolving best practices prior to official release of updated standards so that our reports effectively anticipate any known changes. In addition, most changes are anticipated to be incremental in nature and results reported within the previous three-year period should be sufficient for current usage without significant question.

Most products also tend to undergo incremental changes over time. If an *exida* FMEDA has not been updated within the last three years, contact the product vendor to verify the current validity of the results.

7.2 Version History

Contract Number	Report Number	Revision Notes
Q21/01-054	UE 21/01-054 R001 V2 R1	Added high power models, 2022-03-01
Q21/01-054	UE 21/01-054 R001 V1 R1	Initial Release
Q21/01-054	UE 21/01-054 R001 V0 R1	Initial draft

Reviewer: Chris O’Brien, exida, 2021-06-30

Status: Released, 2021-06-25

7.3 Future enhancements

At request of client.

7.4 Release signatures

Rudolf P. Chalupa

Rudolf P. Chalupa, Senior Safety Engineer

Chris O’Brien, CFSE, Partner

Appendix A Lifetime of Critical Components

According to section 7.4.9.5 of IEC 61508-2, a useful lifetime, based on experience, should be determined and used to replace equipment before the end of useful life.

Although a constant failure rate is assumed by the exida FMEDA prediction method (see section 4.2.2) this only applies provided that the useful lifetime[4] of components is not exceeded. Beyond their useful lifetime, the result of the probabilistic calculation method is likely optimistic, as the probability of failure significantly increases with time. The useful lifetime is highly dependent on the subsystem itself and its operating conditions.

It is the responsibility of the end user to maintain and operate the One Series Safety Switch per manufacturer’s instructions. Furthermore, regular inspection should show that all components are clean and free from damage.

The useful is predicted to be 50 years.

When plant experience indicates a shorter useful lifetime than indicated in this appendix, the number based on plant experience should be used.

[4] Useful lifetime is a reliability engineering term that describes the operational time interval where the failure rate of a device is relatively constant. It is not a term which covers product obsolescence, warranty, or other commercial issues.

Appendix B Proof Tests to Reveal Dangerous Undetected Faults

According to section 7.4.5.2 f) of IEC 61508-2 proof tests shall be undertaken to reveal dangerous faults which are undetected by automatic diagnostic tests. This means that it is necessary to specify how dangerous undetected faults which have been noted during the Failure Modes, Effects, and Diagnostic Analysis can be detected during proof testing.

B.1 Suggested Proof Test

The suggested proof test for the One Series Safety Switch is described in Table 10. Refer to the table in B.2 for the Proof Test Coverages

The suggested proof test consists of checking the IAW output, and a calibration check, see Table 10.

Table 10 Suggested Proof Test

Step	Action
1.	Bypass the safety function and take appropriate action to avoid a false trip.
2.	Remove power to the unit (disconnect switch output) to clear any soft errors. Check that the IAW output is open
3.	Restore power to the switch. Check that the IAW output is closed.
4.	Set the input variable to one side of the threshold and ensure the output is correct.
5.	Set the input to the other side of the threshold and ensure the output is correct.
6.	Remove the bypass and otherwise restore normal operation.

B.2 Proof Test Coverage

The Proof Test Coverage for the various product configurations is given in Table 11.

Table 11 Proof Test Coverage –One Series Safety Switch

Device	λ_{DU}PT (FIT)	Proof Test Coverage
Pressure DC IAW	6	82%
Pressure AC IAW	10	77%
Pressure AC IAW High Power	17	69%
Temperature DC IAW	6	74%
Temperature AC IAW	10	69%
Temperature AC IAW High Power	16	61%

Appendix C *exida* Environmental Profiles

Table 12 *exida* Environmental Profiles

***exida* Profile**	1	2	3	4	5	6
Description (Electrical)	Cabinet mounted/ Climate Controlled	Low Power Field Mounted no self-heating	General Field Mounted self-heating	Subsea	Offshore	N/A
Description (Mechanical)	Cabinet mounted/ Climate Controlled	General Field Mounted	General Field Mounted	Subsea	Offshore	Process Wetted
IEC 60654-1 Profile	B2	C3 also applicable for D1	C3 also applicable for D1	N/A	C3 also applicable for D1	N/A
Average Ambient Temperature	30 C	25 C	25 C	5 C	25 C	25 C
Average Internal Temperature	60 C	30 C	45 C	5 C	45 C	Process Fluid Temp.
Daily Temperature Excursion (pk-pk)	5 C	25 C	25 C	0 C	25 C	N/A
Seasonal Temperature Excursion **(winter average vs. summer average)**	5 C	40 C	40 C	2 C	40 C	N/A
Exposed to Elements / Weather Conditions	No	Yes	Yes	Yes	Yes	Yes
Humidity[5]	0-95% Non-Condensing	0-100% Condensing	0-100% Condensing	0-100% Condensing	0-100% Condensing	N/A
Shock[6]	10 g	15 g	15 g	15 g	15 g	N/A
Vibration[7]	2 g	3 g	3 g	3 g	3 g	N/A
Chemical Corrosion[8]	G2	G3	G3	G3	G3	Compatible Material
Surge[9]						
Line-Line	0.5 kV	0.5 kV	0.5 kV	0.5 kV	0.5 kV	N/A
Line-Ground	1 kV	1 kV	1 kV	1 kV	1 kV	
EMI Susceptibility[10]						
80 MHz to 1.4 GHz	10 V/m	10 V/m	10 V/m	10 V/m	10 V/m	N/A
1.4 GHz to 2.0 GHz	3 V/m	3 V/m	3 V/m	3 V/m	3 V/m	
2.0Ghz to 2.7 GHz	1 V/m	1 V/m	1 V/m	1 V/m	1 V/m	
ESD (Air)[11]	6 kV	6 kV	6 kV	6 kV	6 kV	N/A

[5] Humidity rating per IEC 60068-2-3
[6] Shock rating per IEC 60068-2-27
[7] Vibration rating per IEC 60068-2-6
[8] Chemical Corrosion rating per ISA 71.04
[9] Surge rating per IEC 61000-4-5
[10] EMI Susceptibility rating per IEC 61000-4-3
[11] ESD (Air) rating per IEC 61000-4-2

Appendix D Determining Safety Integrity Level

The information in this appendix is intended to provide the method of determining the Safety Integrity Level (SIL) of a Safety Instrumented Function (SIF). **The numbers used in the examples are not for the product described in this report.**

Three things must be checked when verifying that a given Safety Instrumented Function (SIF) design meets a Safety Integrity Level (SIL) [N4] and [N7].

These are:

A. Systematic Capability or Prior Use Justification for each device meets the SIL level of the SIF;

B. Architecture Constraints (minimum redundancy requirements) are met; and

C. a PFD_{avg} calculation result is within the range of numbers given for the SIL level.

A. Systematic Capability (SC) is defined in IEC61508:2010. The SC rating is a measure of design quality based upon the methods and techniques used to design and development a product. All devices in a SIF must have a SC rating equal or greater than the SIL level of the SIF. For example, a SIF is designed to meet SIL 3 with three pressure transmitters in a 2oo3 voting scheme. The transmitters have an SC2 rating. The design does not meet SIL 3. Alternatively, IEC 61511 allows the end user to perform a "Prior Use" justification. The end user evaluates the equipment to a given SIL level, documents the evaluation and takes responsibility for the justification.

B. Architecture constraints require certain minimum levels of redundancy. Different tables show different levels of redundancy for each SIL level. A table is chosen and redundancy is incorporated into the design [N8].

C. Probability of Failure on Demand (PFD_{avg}) calculation uses several parameters, many of which are determined by the particular application and the operational policies of each site. Some parameters are product specific and the responsibility of the manufacturer. Those manufacturer specific parameters are given in this third-party report.

A Probability of Failure on Demand (PFD_{avg}) calculation must be done based on a number of variables including:

1. Failure rates of each product in the design including failure modes and any diagnostic coverage from automatic diagnostics (an attribute of the product given by this FMEDA report);
2. Redundancy of devices including common cause failures (an attribute of the SIF design);
3. Proof Test Intervals (assignable by end user practices);
4. Mean Time to Restore (an attribute of end user practices);
5. Proof Test Effectiveness; (an attribute of the proof test method used by the end user with an example given by this report);
6. Mission Time (an attribute of end user practices);
7. Proof Testing with process online or shutdown (an attribute of end user practices);
8. Proof Test Duration (an attribute of end user practices); and
9. Operational/Maintenance Capability (an attribute of end user practices).

The product manufacturer is responsible for the first variable. Most manufacturers use the *exida* FMEDA technique which is based on over 400 billion hours of field failure data in the process industries to predict these failure rates as seen in this report. A system designer chooses the second variable. All other variables are the responsibility of the end user site. The exSILentia® SILVer^{TM} software considers all these variables and provides an effective means to calculate PFD_{avg} for any given set of variables.

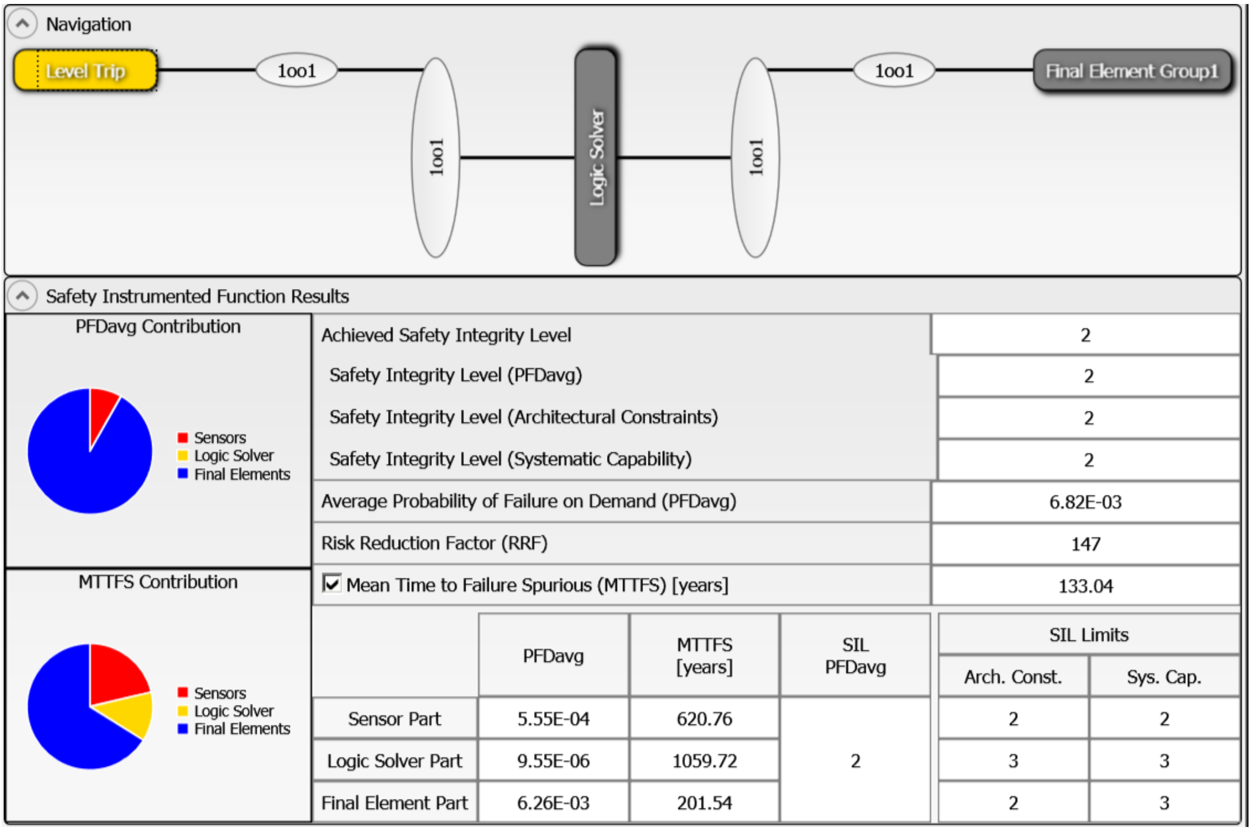
Simplified equations often account for only for first three variables. The equations published in IEC 61508-6, Annex B.3.2 [N1] cover only the first four variables. IEC61508-6 is only an informative portion of the standard and as such gives only concepts, examples and guidance based on the idealistic assumptions stated. These assumptions often result in optimistic PFD_{avg} calculations and have indicated SIL levels higher than reality. Therefore, idealistic equations should not be used for actual SIF design verification.

All the variables listed above are important. As an example, consider a high-level protection SIF. The proposed design has a single SIL 3 certified level transmitter, a SIL 3 certified safety logic solver, and a single remote actuated valve consisting of a certified solenoid valve, certified scotch yoke actuator and a certified ball valve. Note that the numbers chosen are only an example and not the product described in this report.

Using exSILentia with the following variables selected to represent results from simplified equations:

- Mission Time = 5 years
- Proof Test Interval = 1 year for the sensor and final element, 5 years for the logic solver
- Proof Test Coverage = 100% (ideal and unrealistic but commonly assumed)
- Proof Test done with process offline

This results in a PFD_{avg} of 6.82E-03 which meets SIL 2 with a risk reduction factor of 147. The subsystem PFD_{avg} contributions are Sensor PFD_{avg} = 5.55E-04, Logic Solver PFD_{avg} = 9.55E-06, and Final Element PFD_{avg} = 6.26E-03. See Figure 2.



Achieved Safety Integrity Level	2
Safety Integrity Level (PFDavg)	2
Safety Integrity Level (Architectural Constraints)	2
Safety Integrity Level (Systematic Capability)	2
Average Probability of Failure on Demand (PFDavg)	6.82E-03
Risk Reduction Factor (RRF)	147
☑ Mean Time to Failure Spurious (MTTFS) [years]	133.04

	PFDavg	MTTFS [years]	SIL PFDavg	SIL Limits	
				Arch. Const.	Sys. Cap.
Sensor Part	5.55E-04	620.76	2	2	2
Logic Solver Part	9.55E-06	1059.72		3	3
Final Element Part	6.26E-03	201.54		2	3

Figure 2: exSILentia results for idealistic variables.

If the Proof Test Interval for the sensor and final element is increased in one year increments, the results are shown in Figure 3.

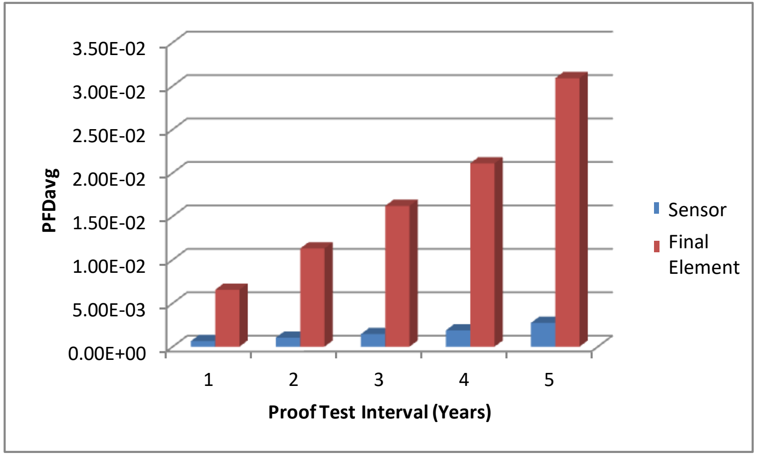
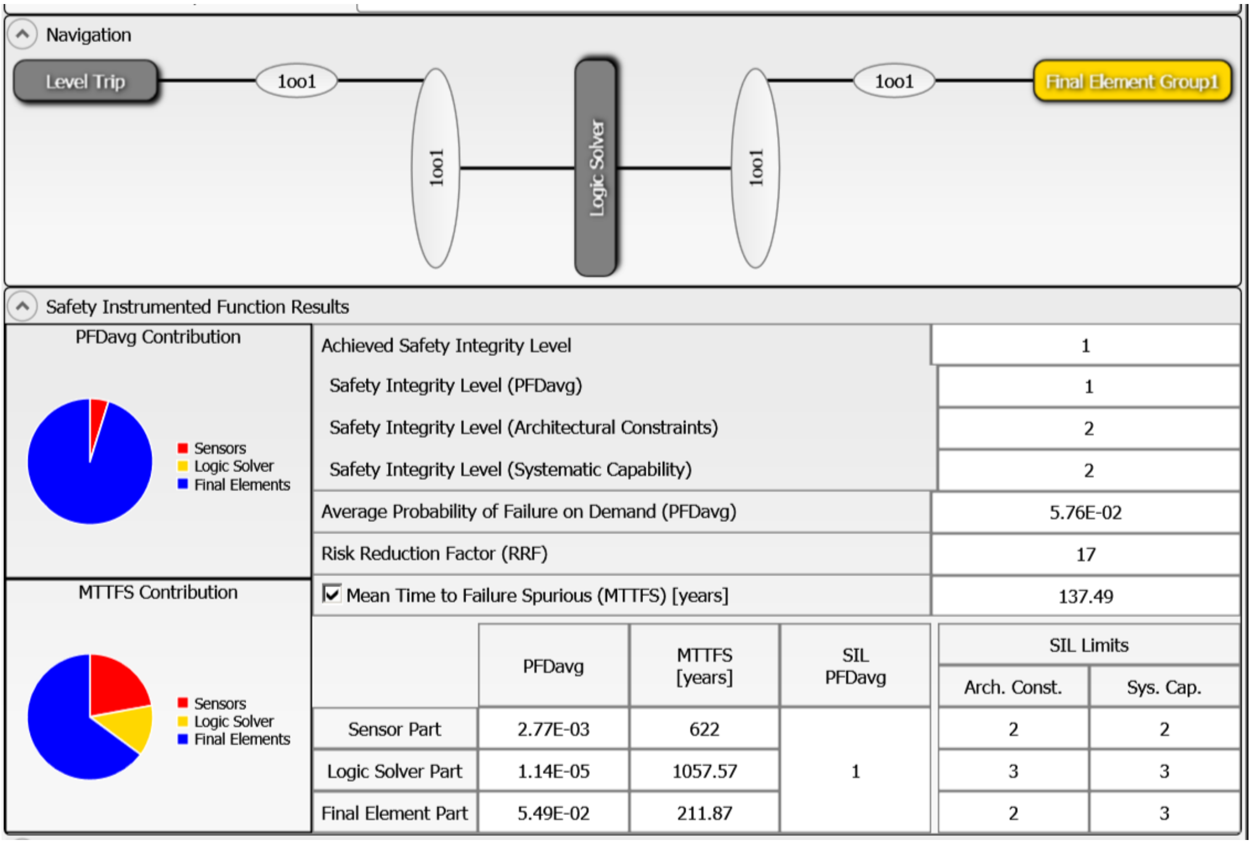


Figure 3 PFD$_{avg}$ versus Proof Test Interval.

If a set of realistic variables for the same SIF are entered into the exSILentia software including:

- Mission Time = 25 years
- Proof Test Interval = 1 year for the sensor and final element, 5 years for the logic solver
- Proof Test Coverage = 90% for the sensor and 70% for the final element
- Proof Test Duration = 2 hours with process online.
- MTTR = 48 hours
- Maintenance Capability = Medium for sensor and final element, Good for logic solver

with all other variables remaining the same, the PFD$_{avg}$ for the SIF equals 5.76E-02 which barely meets SIL 1 with a risk reduction factor 17. The subsystem PFD$_{avg}$ contributions are Sensor PFD$_{avg}$ = 2.77E-03, Logic Solver PFD$_{avg}$ = 1.14E-05, and Final Element PFD$_{avg}$ = 5.49E-02 (Figure 4).



Achieved Safety Integrity Level	1
Safety Integrity Level (PFDavg)	1
Safety Integrity Level (Architectural Constraints)	2
Safety Integrity Level (Systematic Capability)	2
Average Probability of Failure on Demand (PFDavg)	5.76E-02
Risk Reduction Factor (RRF)	17
☑ Mean Time to Failure Spurious (MTTFS) [years]	137.49

	PFDavg	MTTFS [years]	SIL PFDavg	SIL Limits	
				Arch. Const.	Sys. Cap.
Sensor Part	2.77E-03	622	1	2	2
Logic Solver Part	1.14E-05	1057.57		3	3
Final Element Part	5.49E-02	211.87		2	3

Figure 4: exSILentia results with realistic variables

It is clear that PFD_{avg} results can change an entire SIL level or more when all critical variables are not used.

Appendix E Site Safety Index

Numerous field failure studies have shown that the failure rate for a specific device (same Manufacturer and Model number) will vary from site to site. The Site Safety Index (SSI) was created to account for these failure rates differences as well as other variables. The information in this appendix is intended to provide an overview of the Site Safety Index (SSI) model used by *exida* to compensate for site variables including device failure rates.

E.1 Site Safety Index Profiles

The SSI is a number from 0 – 4 which is an indication of the level of site activities and practices that contribute to the safety performance of SIF's on the site. Table 13 details the interpretation of each SSI level. Note that the levels mirror the levels of SIL assignment and that SSI 4 implies that all requirements of IEC 61508 and IEC 61511 are met at the site and therefore there is no degradation in safety performance due to any end-user activities or practices, i.e., that the product inherent safety performance is achieved.

Several factors have been identified thus far which impact the Site Safety Index (SSI). These include the quality of:

Commission Test
Safety Validation Test
Proof Test Procedures
Proof Test Documentation
Failure Diagnostic and Repair Procedures
Device Useful Life Tracking and Replacement Process
SIS Modification Procedures
SIS Decommissioning Procedures
and others

Table 13 *exida* Site Safety Index Profiles

Level	Description
SSI 4	Perfect - Repairs are always correctly performed, Testing is always done correctly and on schedule, equipment is always replaced before end of useful life, equipment is always selected according to the specified environmental limits and process compatible materials. Electrical power supplies are clean of transients and isolated, pneumatic supplies and hydraulic fluids are always kept clean, etc. Note: This level is generally considered not possible but retained in the model for comparison purposes.
SSI 3	Almost perfect - Repairs are correctly performed, Testing is done correctly and on schedule, equipment is normally selected based on the specified environmental limits and a good analysis of the process chemistry and compatible materials. Electrical power supplies are normally clean of transients and isolated, pneumatic supplies and hydraulic fluids are mostly kept clean, etc. Equipment is replaced before end of useful life, etc.
SSI 2	Good - Repairs are usually correctly performed, Testing is done correctly and mostly on schedule, most equipment is replaced before end of useful life, etc.
SSI 1	Medium – Many repairs are correctly performed, Testing is done and mostly on schedule, some equipment is replaced before end of useful life, etc.
SSI 0	None - Repairs are not always done, Testing is not done, equipment is not replaced until failure, etc.

E.2 Site Safety Index Failure Rates – One Series Safety Switch

Failure rates of each individual device in the SIF are increased or decreased by a specific multiplier which is determined by the SSI value and the device itself. It is known that final elements are more likely to be negatively impacted by less than ideal end-user practices than are sensors or logic solvers. By increasing or decreasing device failure rates on an individual device basis, it is possible to more accurately account for the effects of site practices on safety performance.

Table 14 lists the failure rates for the One Series Safety Switch according to IEC 61508 with a Site Safety Index (SSI) of 4 (ideal maintenance practices).

Table 14 Failure rates for Static Applications with Ideal Maintenance Assumption in FIT (SSI=4)

Application/Device/Configuration	λ_{SD}	λ_{SU}	λ_{DD}	λ_{DU}	#
Pressure DC IAW	275	37	239	30	205
Pressure AC IAW	300	99	261	40	217
Pressure AC IAW High Power	353	116	261	48	223
Temperature DC IAW	290	48	241	20	205
Temperature AC IAW	315	111	262	30	217
Temperature AC IAW High Power	376	128	262	38	223