



Failure Modes, Effects and Diagnostic Analysis

Project:

644 Temperature Transmitter
with option code QT
Device Label SW REV 1.1.X

Customer:

Rosemount Inc.
Chanhassen, MN
USA

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Management summary

This report summarizes the results of the Failure Modes, Effects, and Diagnostic Analysis (FMEDA) of the 644 Temperature Transmitter with Hardware revision 1, schematic revision AC and Device Label SW REV 1.1.X. 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 and Safe Failure Fraction are determined. The FMEDA that is described in this report concerns only the hardware of the 644 Temperature Transmitter, electronic and mechanical. For full functional safety certification purposes all requirements of IEC 61508 must be considered.

The 644 Temperature Transmitter is a two wire, 4 – 20 mA smart device. For safety instrumented systems usage it is assumed that the 4 – 20 mA output is used as the primary safety variable. This analysis includes the optional T1 transient protector. The transmitter can be equipped with or without display.

The 644 Temperature Transmitter is classified as a Type B¹ device according to IEC61508, having a hardware fault tolerance of 0.

The 644 Temperature Transmitter together with a temperature-sensing element becomes a temperature sensor assembly. When using the results of this FMEDA in a SIL verification assessment, the failure rates and failure modes of the temperature sensing element must be considered. This is discussed in detail in Section 5.1 and Appendix B. Failure rates for the 644 Temperature Assembly when using thermocouples in a low stress environment are listed in Table 1. The dual sensing element mode assumes PV is S1, S2 or first good and drift alert is set to alarm.

Table 1 Failure rates 644 Temperature Assembly with T/C

Failure category	Failure rate (in FITs)			
	Single T/C mode		Dual T/C mode Drift Alert = Alarm	
Fail High (detected by the logic solver)	31		31	
Fail Low (detected by the logic solver)	426		440	
	Fail detected (int. diag.)*	398	412	
	Fail low (inherently)	28	28	
Fail Dangerous Undetected	44		39	
No Effect	124		128	
Annunciation Undetected	12		12	
Safe Failure Fraction	91.3%		92.4%	

* These failures follow the setting of the Alarm switch and result in either a High or Low output of the transmitter. It is assumed that upon the detection of a failure the output will be sent downscale, therefore all detected failures are listed as a sub-category of the Fail Low failure category. If the Alarm switch is set to High, these failures would need to be added to the Fail High failure category.

¹ Type B component: “Complex” component (using micro controllers or programmable logic); for details see 7.4.3.1.3 of IEC 61508-2.



Failure rates for the 644 Temperature Assembly when using RTDs in a low stress environment are listed in Table 1. The dual sensing element mode assumes PV is S1, S2 or first good and drift alert is set to alarm.

Table 2 Failure rates 644 Temperature Assembly using RTDs

Failure category	Failure rate (in FITs)	
	Single 4-wire RTD mode	Dual 3-wire RTD mode, Drift Alert = Alarm
Fail High (detected by the logic solver)	31	31
Fail Low (detected by the logic solver)	330	347
Fail detected (int. diag.)*	302	319
Fail low (inherently)	28	28
Fail Dangerous Undetected	36	31
No Effect	119	123
Annunciation Undetected	12	12
Safe Failure Fraction	90.9%	92.5%

* These failures follow the setting of the Alarm switch and result in either a High or Low output of the transmitter. It is assumed that upon the detection of a failure the output will be sent downscale, therefore all detected failures are listed as a sub-category of the Fail Low failure category. If the Alarm switch is set to High, these failures would need to be added to the Fail High failure category.

The failure rates are valid for the useful lifetime of the transmitter, see Appendix A.

A user of the 644 Temperature Transmitter 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). A full table of failure rates is presented in section 4.5 along with all assumptions.



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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 644 Temperature Transmitter. From this, failure rates, Safe Failure Fraction (SFF) and example PFD_{AVG} values may be calculated.

The information in this report can be used to evaluate whether a sensor subsystem 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.

An FMEDA is part of 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 and availability with over 300 years of cumulative experience in functional safety. Founded by several of the world's top reliability and safety experts from assessment organizations and manufacturers, *exida* is a global company with offices around the world. *exida* offers training, coaching, project oriented system consulting services, safety lifecycle engineering tools, detailed product assurance, cyber-security and functional safety certification, and a collection of on-line safety and reliability resources. *exida* maintains a comprehensive failure rate and failure mode database on process equipment.

2.2 Roles of the parties involved

Rosemount Inc. Manufacturer of the 644 Temperature Transmitter

exida Performed the hardware assessment

Rosemount Inc. contracted *exida* in February 2012 with the hardware assessment of the above mentioned device.

2.3 Standards / 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 & Mechanical Component Reliability Handbook, 2nd Edition, 2008	<i>exida</i> LLC, Electrical & Mechanical Component Reliability Handbook, Second Edition, 2008, ISBN 978-0-9727234-6-6
[N3]	EMCR Handbook, 2011 Update	<i>exida</i> LLC, Electrical & Mechanical Component Reliability Handbook, 2011 Update
[N4]	Safety Equipment Reliability Handbook, 3rd Edition, 2007	<i>exida</i> LLC, Safety Equipment Reliability Handbook, Third Edition, 2007, ISBN 978-0-9727234-9-7
[N5]	Goble, W.M. 1998	Control Systems Safety Evaluation and Reliability, ISA, ISBN 1-55617-636-8. Reference on FMEDA methods
[N6]	IEC 60654-1:1993-02, second edition	Industrial-process measurement and control equipment – Operating conditions – Part 1: Climatic condition

2.4 Reference documents

2.4.1 Documentation provided by the customer

[D1]	00644-7401, Rev AB, 10/13/11	Terminal Cap Assembly 644
[D2]	00644-6411, Rev AF, 7/27/11	Module Assembly 664R
[D3]	00644-7100, Rev AC, 5 Mar 2012	Schematic, 644 Electronics Board Headmount
[D4]	00644-7110, Rev 01, 5/3//11	Schematic, 644 Hart and Fieldbus Transient Protector, T1 Option
[D5]	Fault Injection List 644T_27Mar2012_results.xls, 28 Mar 2012	644 Fault Injection Test Results
[D6]	Fault_Injection_Test_Details.doc, 28 Mar 2012	644 Fault Injection Test Result Details
[D7]	644 Next Generation Transmitter Safety Integrity Requirements Specification Revision: A.4, 2 Nov 2011	644 Safety Integrity Requirements Specification
[D8]	644NG Diagnostic Design.doc	644 Diagnostics Design, attached to 27 Oct 2011 e-mail from Corey Wolf (Rosemount)
[D9]	00644-7600, Rev AB, 11 Oct 2011	Temperature Transmitter Hub Assembly 644, includes hardware revision history
[D10]	644_vdd.htm	software release notes/version description document, shows released software drawing number
[D11]	00644-7300, Rev AA, 9 Apr 2012	644 HART Software Revision Drawing, associates software release drawing (dash #) with NE-53 software revision

2.4.2 Documentation generated by exida

[R1]	644NG TT and sensing devices Rev AB.xls	Failure rate calculations Summary, 644 Temperature Transmitter, April 2012
[R2]	644NG Temp Transmitter part 1 of 3 Rev AB.xls	Failure rate calculations, 644 Temperature Transmitter, April 2012
[R3]	644NG Temp Transmitter part 2 of 3 Rev AB.xls	Failure rate calculations, 644 Temperature Transmitter, April 2012
[R4]	644NG Temp Transmitter Common Portion of part 3 of 3 Rev AB.xls	Failure rate calculations Common Portion, 644 Temperature Transmitter, April 2012



[R5]	644NG Temp Transmitter TC Portion of Rev AB.xls	Failure rate calculations T/C Portion, 644 Temperature Transmitter, April 2012
[R6]	644NG Temp Transmitter Dual TC Portion of Rev AB.xls	Failure rate calculations Dual T/C, 644 Temperature Transmitter, April 2012
[R7]	644NG Temp Transmitter 3 Wire RTD Portion of Rev AB.xls	Failure rate calculations 3 Wire RTD, 644 Temperature Transmitter, April 2012
[R8]	644NG Temp Transmitter Dual 3 Wire RTD Portion of Rev AB.xls	Failure rate calculations Dual 3 Wire RTD, 644 Temperature Transmitter, April 2012
[R9]	ROS 11-02-058 R001 V1 R1 644 FMEDA	FMEDA report, 644 Temperature Transmitter, 15 May 2012



3 Product Description

This report documents the results of the Failure Modes, Effects and Diagnostics Analysis performed for the 644 Temperature Transmitter with Hardware version 1 and Device Label SW REV 1.1.X. The 644 Temperature Transmitter is a two wire, 4 – 20 mA smart device. For safety instrumented systems usage it is assumed that the 4 – 20 mA output is used as the primary safety variable. The transmitter can be equipped with or without display.

The 644 Temperature Transmitter is classified as a Type B² device according to IEC61508, having a hardware fault tolerance of 0. Combined with one or two temperature sensing elements, the 644 transmitter becomes a temperature sensor assembly. The temperature sensing elements that can be connected to the 644 Temperature Transmitter are:

- 2-, 3-, and 4-wire RTD
- Thermocouple
- Millivolt input (–10 to 100mV)
- 2-, 3-, and 4-wire Ohm input (0 to 2000Ω)

The FMEDA has been performed for different input sensing element configurations of the 644 transmitter, i.e. 3-wire RTD, 4-wire RTD, and thermocouple. Estimates have been made of the temperature sensing element failure rates given the ability of the 644 transmitter to detect several failure modes of the temperature sensing element.

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 Diagnostics Analysis

The Failure Modes, Effects, and Diagnostic Analysis was performed based on the documentation received from Rosemount Inc. and is documented in [R1] through [R8]. When the effect of a certain failure mode could not be analyzed theoretically, the failure modes were introduced on component level and the effects of these failure modes were examined on a system level [D5] and [D6].

4.1 Description of the failure categories

In order to judge the failure behavior of the 644 Temperature Transmitter, the following definitions for the failure of the product were considered.

Fail-Safe State	State where the process reaches a safe situation. Depending on the application the fail-safe state is defined as the output going to fail low or fail high.
Fail Safe	Failure that causes the transmitter to go to the defined fail-safe state without a demand from the process. Safe failures are divided into safe detected (SD) and safe undetected (SU) failures.
Fail Dangerous	Failure that deviates the measured input state or the actual output by more than 2% of span and that leaves the output within active scale.
Fail Dangerous Undetected	Failure that is dangerous and that is not being diagnosed by internal diagnostics.
Fail Dangerous Detected	Failure that is dangerous but is detected by internal diagnostics (These failures may be converted to the selected fail-safe state).
Fail High	Failure that causes the output signal to go to the maximum output current (> 20.9 mA, output saturate high) or high alarm (>21 mA)
Fail Low	Failure that causes the output signal to go to the minimum output current (< 3.7 mA, output saturate low) or low alarm (3.5, 3.75 mA)
Fail No Effect	Failure of a component that is part of the safety function but that has no effect on the safety function.
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 which are only safe and dangerous, both detected and undetected. In IEC 61508, Edition 2010, the No Effect failures cannot contribute to the failure rate of the safety function. Therefore they are not used for the Safe Failure Fraction calculation needed when Route 2H failure data is not available.

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. Otherwise the Annunciation Undetected failures have to be classified as Dangerous Undetected failures according to IEC 61508 (worst-case assumption).



4.2 Methodology – FMEDA, Failure rates

4.2.1 FMEDA

A Failure Modes and Effects Analysis (FMEA) is a systematic way to identify and evaluate the effects of different component failure modes, to determine what could eliminate or reduce the chance of failure, and to document the system in consideration.

An FMEDA (Failure Mode Effect and Diagnostic Analysis) is an FMEA extension. It combines standard FMEA techniques with the extension to identify online diagnostics techniques and the failure modes relevant to safety instrumented system design. It is a technique recommended to generate failure rates for each important category (safe detected, safe undetected, dangerous detected, dangerous undetected, fail high, fail low) in the safety models. The format for the FMEDA is an extension of the standard FMEA format from MIL STD 1629A, Failure Modes and Effects Analysis.

4.2.2 Failure rates

The failure rate data used by *exida* in this FMEDA is from the Electrical and Mechanical Component Reliability Handbook [N2] which was derived using over ten billion unit operational hours of field failure data from multiple sources and failure data from various databases. The rates were chosen in a way that is appropriate for safety integrity level verification calculations. The rates were chosen to match exida Profile 2, see Appendix E. It is expected that the actual number of field failures due to random events will be less than the number predicted by these failure rates.

For hardware assessment according to IEC 61508 only random equipment failures are of interest. It is assumed that the equipment has been properly selected for the application and is adequately commissioned such that early life failures (infant mortality) may be excluded from the analysis.

Failures caused by external events however should be considered as random failures. Examples of such failures are loss of power, physical abuse, or problems due to intermittent instrument air quality.

The assumption is also made that the equipment is maintained per the requirements of IEC 61508 or IEC 61511 and therefore a preventative maintenance program is in place to replace equipment before the end of its “useful life”. The user of these numbers is responsible for determining their applicability to any particular environment. Accurate plant specific data may be used for this purpose. If a user has data collected from a good proof test reporting system such as exida SILStat™ that indicates higher failure rates, the higher numbers shall be used. 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.

4.3 Assumptions

The following assumptions have been made during the Failure Modes, Effects, and Diagnostic Analysis of the 644 Temperature Transmitter with 4..20 mA output.

- Only a single component failure will fail the entire product
- Failure rates are constant, wear out mechanisms are not included.
- Propagation of failures is not relevant.

- All components that are not part of the safety function and cannot influence the safety function (feedback immune) are excluded.
- The HART protocol is only used for setup, calibration, and diagnostics purposes, not for safety critical operation.
- The application program in the logic solver is constructed in such a way that Fail High and Fail Low failures are detected regardless of the effect, safe or dangerous, on the safety function.
- The stress levels are average for an industrial environment and can be compared to the *exida* Profile 2 with temperature limits within the manufacturer's rating. Other environmental characteristics are assumed to be within manufacturer's rating.
- External power supply failure rates are not included.
- The device is installed per manufacturer's instructions.
- Worst-case internal fault detection time is <1 hour.

4.4 Behavior of the safety logic solver

Depending on the application, the following scenarios are possible:

- Low Trip: the safety function will go to the predefined fail-safe state when the process value below a predefined low set value. A current < 3.75mA (Fail Low) is below the specified trip-point.
- High Trip: the safety function will go to the predefined fail-safe state when the process value exceeds a predefined high set value. A current > 21mA (Fail High) is above the specified trip-point.

The Fail Low and Fail High failures can either be detected or undetected by a connected logic solver. The PLC Detection Behavior in Table 3 represents the under-range and over-range detection capability of the connected logic solver.

Table 3 Application example

Application	PLC Detection Behavior	λ_{low}	λ_{high}
Low trip	< 4mA	= λ_{sd}	= λ_{du}
Low trip	> 20mA	= λ_{su}	= λ_{dd}
Low trip	< 4mA and > 20mA	= λ_{sd}	= λ_{dd}
Low trip	-	= λ_{su}	= λ_{du}
High trip	< 4mA	= λ_{dd}	= λ_{su}
High trip	> 20mA	= λ_{du}	= λ_{sd}
High trip	< 4mA and > 20mA	= λ_{dd}	= λ_{sd}
High trip	-	= λ_{du}	= λ_{su}

In this analysis it is assumed that the logic solver is able to detect under-range and over-range currents, therefore the yellow highlighted behavior is assumed.

4.5 Results

Using reliability data extracted from the *exida* Electrical and Mechanical Component Reliability Handbook the following failure rates resulted from the 644 Temperature Transmitter FMEDA.

Table 4 Failure rates 644 Temperature Transmitter (T/C configuration)

Failure category	Failure rate (in FITs)			
	Single T/C mode		Dual T/C mode	
Fail High (detected by the logic solver)	31		31	
Fail Low (detected by the logic solver)	331		340	
Fail detected (int. diag.) ³	303		312	
Fail low (inherently)	28		28	
Fail Dangerous Undetected	39		39	
No Effect	124		128	
Annunciation Undetected	12		12	

Table 5 Failure rates 644 Temperature Transmitter (RTD configuration)

Failure category	Failure rate (in FITs)			
	Single RTD mode		Dual RTD mode (3-wire RTD)	
Fail High (detected by the logic solver)	31		31	
Fail Low (detected by the logic solver)	286		299	
Fail detected (int. diag.) ³	258		271	
Fail low (inherently)	28		28	
Fail Dangerous Undetected	30		31	
No Effect	119		123	
Annunciation Undetected	12		12	

According to IEC 61508 [N1], the Safe Failure Fraction (SFF) of the 644 Temperature Transmitter should be calculated. The SFF is the fraction of the overall failure rate of a device that results in either a safe fault or a diagnosed unsafe fault. As both the Fail High and Fail Low failure categories are assumed to be detected by the logic solver (regardless of the fact if their effect is safe or dangerous), the Safe Failure Fraction can be calculated independently of the 644 Temperature Transmitter application.

³ These failures follow the setting of the Alarm switch and result in either a High or Low output of the transmitter. It is assumed that upon the detection of a failure the output will be sent downscale, therefore all detected failures are listed as a sub-category of the Fail Low failure category. If the Alarm switch is set to High Alarm, these failures would need to be added to the Fail High failure category.

This is reflected in the following formula for SFF:

$$\text{SFF} = 1 - \lambda_{du} / \lambda_{total}$$

Note that according to IEC61508:2010 definition the No Effect and Annunciation Undetected failures are not included in the total failure rate and therefore are not part of the Safe Failure Fraction calculation.

Table 6 Safe Failure Fraction of 644 Temperature Transmitter

644 Temperature Transmitter	SFF
644, Single T/C mode	90.4%
644, Dual T/C mode	90.5%
644, Single RTD mode	91.3%
644, Dual RTD mode	91.5%

The architectural constraint type for 644 Temperature Transmitter is B. The SFF and required SIL determine the level of hardware fault tolerance that is required per requirements of IEC 61508 [N1] or IEC 61511. The SIS designer is responsible for meeting other requirements of applicable standards for any given SIL as well.

5 Using the FMEDA results

5.1 Temperature sensing elements

The 644 Temperature Transmitter together with a temperature-sensing element becomes a temperature sensor. When using the results of this FMEDA in a SIL verification assessment, the failure rates and failure modes of the temperature sensing element must be considered. Typical failure rates for thermocouples and RTDs are listed in Table 7.

Table 7 Typical failure rates thermocouples and RTDs

Temperature Sensing Element	Failure rate (in FITs)
Thermocouple low stress environment	100
Thermocouple high stress environment	2,000
RTD, 4 wire low stress environment	50
RTD, 4 wire high stress environment	1,000

The following sections give examples on how to combine the temperature-sensing element failure rates and the transmitter failures. The examples given are for PV (Process Value) set to represent Sensor 1 or Sensor 2 when using a single sensor, either T/C or RTD. More information on how to combine temperature-sensing element failure rates and transmitter failure rates for other configurations, including the use of dual sensing-elements is given in Appendix B.

5.1.1 644 Temperature Transmitter with single thermocouple

The failure mode distributions for thermocouples vary in published literature but there is strong agreement that open circuit or “burn-out” failure is the dominant failure mode. While some estimates put this failure mode at 99%+, a more conservative failure rate distribution suitable for SIS applications is shown in Table 8 when close-coupled thermocouples are used with the transmitter. The drift failure mode is primarily due to T/C aging. The 644 Temperature Transmitter will detect a T/C burnout failure and drive its output to the specified failure state.

Table 8 Typical failure mode distributions for thermocouples

Thermocouple Failure Modes	Percentage
Open Circuit (Burn-out)	95%
Wire Short (Temperature measurement in error)	4%
Drift (Temperature measurement in error)	1%

A complete temperature sensor assembly consisting of 644 Temperature Transmitter and a closely coupled thermocouple supplied with the 644 Temperature Transmitter can be modeled by considering a series subsystem where failure occurs if there is a failure in either component. For such a system, failure rates are added. Assuming that the 644 Temperature Transmitter is programmed to drive its output low on detected failure, the failure rate contribution for the thermocouple in a low stress environment is:

- $\lambda^L = (100) * (0.95) = 95 \text{ FITs}$

- $\lambda^{DU} = (100) * (0.05) = 5 \text{ FITs}$

When these failure rates are added to the failure rates of the 644 Temperature Transmitter, single T/C mode (see Table 4), the total for the temperature sensor subsystem is:

- $\lambda^L = 95 + 331 = 426 \text{ FITs}$
- $\lambda^H = 31 \text{ FITs}$
- $\lambda^{DU} = 5 + 39 = 44 \text{ FITs}$

These numbers could be used in safety instrumented function SIL verification calculations for this set of assumptions. For these circumstances, the Safe Failure Fraction of this temperature sensor subsystem is 91.3%.

5.1.2 644 Temperature Transmitter with RTD

The failure mode distribution for an RTD also depends on application with the key variables being stress level, RTD wire length and RTD type (3-wire or 4-wire). The key stress variables are high vibration and frequent temperature cycling as these are known to cause cracks in the substrate leading to broken lead connection welds. Failure rate distributions are shown in Table 9. The 644 Temperature Transmitter will detect open circuit and short circuit RTD failures and drive its output to the specified failure state.

Table 9 Typical failure mode distributions for 3-Wire and 4-Wire RTDs in a Low Stress environment or using a cushioned sensor construction

RTD Failure Modes – Close coupled element	Percentage	
	3-wire RTD	4-wire RTD
Open Circuit	79%	83%
Short Circuit	3%	5%
Drift (Temperature measurement in error)	18%	12%

A complete temperature sensor assembly consisting of 644 Temperature Transmitter and a closely coupled, cushioned 4-wire RTD supplied with the 644 Temperature Transmitter can be modeled by considering a series subsystem where failure occurs if either component fails. For such a system, failure rates are added. Assuming that the 644 Temperature Transmitter is programmed to drive the output low on detected failure, the failure rate contribution for the 4-wire RTD in a low stress environment is:

- $\lambda^L = (50) * (0.83 + 0.05) = 44 \text{ FITs}$
- $\lambda^{DU} = (50) * (0.12) = 6 \text{ FITs}$

When these failure rates are added to the failure rate of the 644 Temperature Transmitter, single RTD mode (see Table 5), the total for the temperature sensor subsystem is:

- $\lambda^L = 44 + 286 = 330 \text{ FITs}$
- $\lambda^H = 31 \text{ FITs}$
- $\lambda^{DU} = 6 + 30 = 36 \text{ FITs}$



These numbers could be used in safety instrumented function SIL verification calculations for this set of assumptions. The Safe Failure Fraction for this temperature subsystem, given the assumptions, is 90.9%.

5.2 Converting failure rates to IEC 61508 format

The failure rates that are derived from the FMEDA for the 644 Temperature Transmitter are in a format different from the IEC 61508 format. This section will explain how the failure rates can be converted into the IEC 61508 format.

First of all, depending on the application, the high and low failure rates of the 644 Temperature Transmitter must be classified as either safe or dangerous. Assume an application where a safety action needs to be performed if the temperature drops below a certain level. The 644 Temperature Transmitter will therefore be configured with a low trip level. A low failure of the transmitter will cause the transmitter output to go through the low trip level. Consequently the transmitter will indicate that the safety action needs to be performed. Therefore a low failure can be classified as a safe failure for this application. A high failure on the other hand will cause the transmitter output to move away from the trip level and therefore not cause a trip. The failure will prevent the transmitter from indicating that the safety action needs to be performed and is therefore classified as a dangerous failure for this application.

Assuming that the logic solver can detect both over-range and under-range, a low failure can be classified as a safe detected failure and a high failure can be classified as a dangerous detected failure. For this application, assuming 644 Temperature Transmitter with single RTD, the following would then be the case:

$$\lambda^H = \lambda^{DD} = 31 \text{ FITs}$$

$$\lambda^L = \lambda^{SD} = 330 \text{ FITs}$$

$$\lambda^{DU} = 36 \text{ FITs}$$

In a similar way the high and low failure rates can be classified as respectively safe detected and dangerous detected in case the application has a high trip level. The failure rates as displayed above are the same failure rates as stored in the exida equipment database that is part of the online SIL verification tool, SILver.

No Effect failures and Annunciation Undetected failures are not classified as Safe Undetected failures according to IEC 61508:2010.

$$\lambda^{SU} = 0 \text{ FITs}$$

Note that the dangerous undetected failures will of course remain dangerous undetected.

Table 10 shows the failure rates according to IEC 61508 for this application, assuming 644 Temperature Transmitter with single RTD.

Table 10: Failure rates according to IEC 61508 – 644 with single RTD

Failure Categories	λ^{SD}	λ^{SU}	λ^{DD}	λ^{DU}	SFF
Low trip	330 FIT	0 FIT	31 FIT	36 FIT	90.9%
High trip	31 FIT	0 FIT	330 FIT	36 FIT	90.9%

5.3 PFD_{AVG} calculation 644 Temperature Transmitter

An average Probability of Failure on Demand (PFD_{AVG}) calculation is performed for a single (1oo1) 644 Temperature Transmitter with single 4-wire RTD. The failure rate data used in this calculation is displayed in section 5.1.2. It is assumed that the transmitter output is send low upon detection of failure and the safety function has a low trip point.

The resulting PFD_{AVG} values for a variety of proof test intervals are displayed in Figure 1. As shown in the figure the PFD_{AVG} value for a single 644 Temperature Transmitter with single 4-wire RTD, with a proof test interval of 1 year equals 2.17E-04.

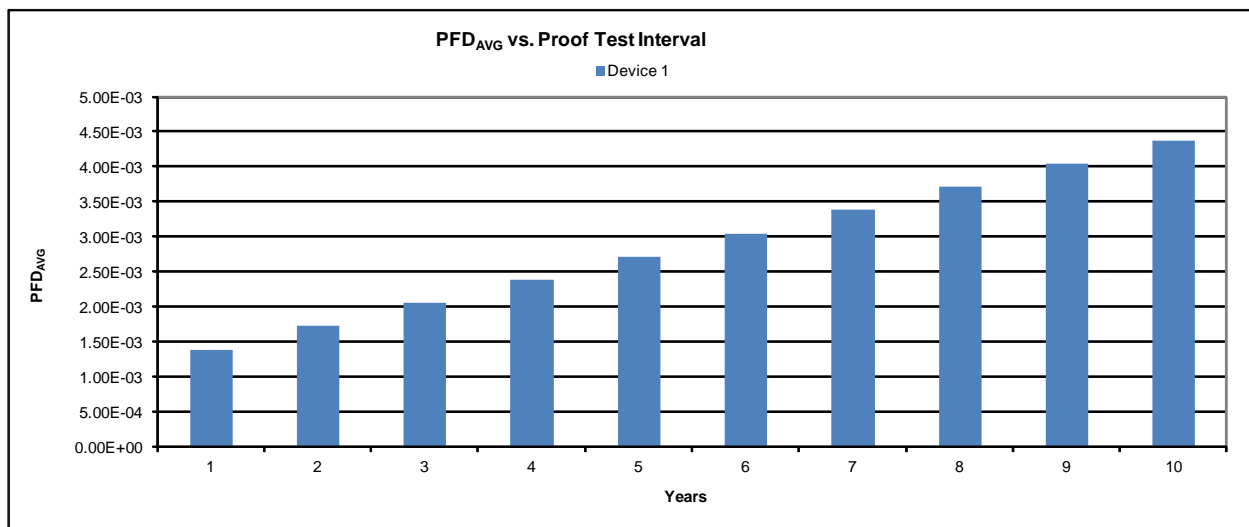


Figure 1: PFD_{AVG} 644 Temperature Transmitter with single RTD

For SIL 2 applications, the PFD_{AVG} value for the safety function needs to be $< 10^{-2}$. This means that for a SIL 2 application, the PFD_{AVG} for a 1-year Proof Test Interval of the 644 Temperature Transmitter with single 4-wire RTD is equal to 2.2% of the range. These results must be considered in combination with PFD_{AVG} values of other devices of a Safety Instrumented Function (SIF) in order to determine suitability for a specific Safety Integrity Level (SIL).



6 Terms and Definitions

FIT	Failure In Time (1×10^{-9} failures per hour)
FMEDA	Failure Mode Effect and Diagnostic Analysis
HART	Highway Addressable Remote Transducer
HFT	Hardware Fault Tolerance
Low demand mode	Mode, where the frequency of demands for operation made on a safety-related system is no greater than one per year and no greater than twice the proof test frequency.
PFD_{AVG}	Average Probability of Failure on Demand
SFF	Safe Failure Fraction summarizes the fraction of failures, which lead to a safe state and the fraction of failures which will be detected by 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 component	“Non-Complex” component (using discrete elements); for details see 7.4.3.1.2 of IEC 61508-2
Type B component	“Complex” component (using micro controllers or programmable logic); for details see 7.4.3.1.3 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, 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 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 and the exact results are critical to the SIL verification you may wish to contact the product vendor to verify the current validity of the results.

7.2 Releases

Version: V1

Revision: R1

Version History: V1, R1: updated with comments in 27 April 2012 e-mail, released to Rosemount; 15 May 2012

V0, R1: Initial version; 20 April 2012

Author: Griff Francis

Review: V0, R1: Todd Larson, Rosemount

V0, R1: William Goble, *exida*

Release status: Released

7.3 Future Enhancements

At request of client.



7.4 Release Signatures

Griff Francis

Griff Francis, Senior Safety Engineer

William M. Goble

Dr. William M. Goble, Principal 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 assumed.

Although a constant failure rate is assumed by the probabilistic estimation method (see section 4.2.2) this only applies provided that the useful lifetime⁴ of components is not exceeded. Beyond their useful lifetime the result of the probabilistic calculation method is therefore meaningless, as the probability of failure significantly increases with time. The useful lifetime is highly dependent on the subsystem itself and its operating conditions.

This assumption of a constant failure rate is based on the bathtub curve. Therefore it is obvious that the PFD_{AVG} calculation is only valid for components that have this constant domain and that the validity of the calculation is limited to the useful lifetime of each component.

Table 11 shows which components are contributing to the dangerous undetected failure rate and therefore to the PFD_{AVG} calculation and what their estimated useful lifetime is.

Table 11: Useful lifetime of electrolytic capacitors contributing to λ^{DU}

Type	Useful life at 40°C
Capacitor (electrolytic) - Tantalum electrolytic, solid electrolyte	Approx. 500,000 hours

As there are no aluminium electrolytic capacitors used, the limiting factors with regard to the useful lifetime of the system are the Tantalum electrolytic capacitors. The Tantalum electrolytic capacitors have an estimated useful lifetime of about 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: Failure rates for various transmitter modes

This Appendix discusses in more detail how to combine the 644 Temperature Transmitter failure rates with sensing element failure rates and how to take credit for diagnostics provided by the transmitter on the sensing element (Drift Alert = Alarm).

Table 12 644 Temperature Transmitter modes

S1 Type	S2 Type	Suspend Non-PV Faults	Drift Alert ⁵	Primary Variable (PV)	Calculation
T/C, 3 Wire RTD, 4 wire RTD	Disabled	X	N/A	S1	1
Disabled	T/C, 3 Wire RTD	X	N/A	S2	1
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Disable	S1	1
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Alarm	S1	2
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Disable	S1	1
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Alarm	S1	2*
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Disable	S2	1
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Alarm	S2	2
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Disable	S2	1
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Alarm	S2	2
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Disable	Differential	3
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Alarm	Differential	3
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Disable	Differential	3
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Alarm	Differential	3
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Disable	Average	3
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Alarm	Average	4
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Disable	Average	3*
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Alarm	Average	4*
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Disable	First Good	1
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Disable	Alarm	First Good	2
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Disable	First Good	1*
T/C, 3 Wire RTD	T/C, 3 Wire RTD	Enable	Alarm	First Good	2

* These modes represent “Hot back-up”. Using the calculation method as described will result in accurate numbers for PFD_{AVG}, but will overestimate the false trip rate. (The sensing elements are configured as a 2oo2 voting and will not alarm on a single sensor failure).

Calculation 1

Single Sensor configured, PV = S1 or PV = S2 or,

Dual Sensors configured, PV = S1, PV = S2 or PV = First Good and Drift Alert = disabled

⁵ For purposes of safety validation, Drift Alert = Warning is considered the same as Drift Alert = disabled



Modeled as a series subsystem where failure occurs if either sensing element or transmitter fails. For such a system, failure rates are added. Use single mode failure rates for the 644 Temperature Transmitter and add sensing element failure rates (single element). This has been described in detail in sections 5.1.1 and 5.1.2.

Calculation 2

Dual Sensors configured, PV = S1 or PV = S2 or PV = First Good, and Drift Alert = alarm

Modeled as a series subsystem where failure occurs if either component fails. For such a system, failure rates are added. Use dual mode failure rates for the 644 Temperature Transmitter and add sensing element failure rates (single element). The sensing element failure rates should reflect the additional coverage on the drift failures (99%) provided by the Drift Alert.

Example: 644 with dual 3-wire RTDs

Table 13 Typical failure mode distributions for 3-wire RTDs, Low Stress environment / cushioned sensor

RTD Failure Modes – Close coupled element	Percentage
Open Circuit	79%
Short Circuit	3%
Drift (Temperature measurement in error)	18%

Assuming that the 644 Temperature Transmitter is programmed to drive the output low on detected failure, the failure rate contribution for the 3-wire RTD in a low stress environment is:

- $\lambda^L = (48) * (0.79 + 0.03 + 0.99 \cdot 0.18) = 47.9 \text{ FITs}$
- $\lambda^{DU} = (48) * (0.01 \cdot 0.18) = 0.1 \text{ FITs}$

When these failure rates are added to the failure rate of the 644 Temperature Transmitter, single RTD mode (see Table 5, second column), the total for the temperature sensor subsystem is:

- $\lambda^L = 47.9 + 286 = 333.9 \text{ FITs}$
- $\lambda^H = 31 \text{ FITs}$
- $\lambda^{DU} = 0.1 + 30 = 30.1 \text{ FITs}$

Calculation 3

Dual Sensors configured, PV = Average or PV = Differential mode, Drift Alert = disabled

Both sensing elements need to function. Use single mode failure rates for the 644 Temperature Transmitter (single mode failure rates are selected because Drift Alert = disabled) and add failure rates for both sensing elements.

Example: 644 with dual 3-wire RTDs

Assuming that the 644 Temperature Transmitter is programmed to drive the output low on detected failure, the failure rate contribution for the 3-wire RTD in a low stress environment is:

- $\lambda^L = 2 * ((48) * (0.79 + 0.03)) = 79 \text{ FITs}$
- $\lambda^{DU} = 2 * ((48) * (0.18)) = 17 \text{ FITs}$



When these failure rates are added to the failure rate of the 644 Temperature Transmitter, single RTD mode (see Table 5, first column), the total for the temperature sensor subsystem is:

- $\lambda^L = 79 + 299 = 378$ FITs
- $\lambda^H = 31$ FITs
- $\lambda^{DU} = 17 + 31 = 48$ FITs

Calculation 4

Dual Sensors configured, PV = Average and Drift Alert = alarm

To obtain the overall failure rates of the sensor assembly, use the dual mode failure rates for the 644 Temperature Transmitter and add failure rates for both sensing elements. The sensing element failure rates should be adjusted to reflect the additional coverage on the drift failures (99%) provided by the Drift Alert.

Example: 644 with dual 3-wire RTDs

Assuming that the 644 Temperature Transmitter is programmed to drive the output low on detected failure, the failure rate contribution for the 3-wire RTD in a low stress environment is:

- $\lambda^L = 2 * ((48 * (0.79 + 0.03 + 0.99 \cdot 0.18))) = 95.8$ FITs
- $\lambda^{DU} = 2 * ((48 * (0.01 \cdot 0.18))) = 0.2$ FITs

When these failure rates are added to the failure rate of the 644 Temperature Transmitter, dual RTD mode (see Table 5, second column), the total for the temperature sensor subsystem is:

- $\lambda^L = 95.8 + 299 = 394.8$ FITs
- $\lambda^H = 31$ FITs
- $\lambda^{DU} = 0.2 + 31 = 31.2$ FITs

Appendix C: Proof tests to reveal dangerous undetected faults

According to section 7.4.3.2.2 f) of IEC 61508-2 proof tests shall be undertaken to reveal dangerous faults which are undetected by diagnostic tests. This means that it is necessary to specify how dangerous undetected faults which have been noted during the FMEDA can be detected during proof testing.

C.1 Proof test 1

Proof test 1 consists of an analog output Loop Test, as described in Table 14. This test will detect approximately 63% of possible DU failures in the transmitter and approximately 90% of the simple sensing element DU failures. This means a Proof Test Coverage of 67% for the overall sensor assembly, assuming a single 4-wire RTD is used.

Table 14 Steps for Proof Test 1

Step	Action
1	Bypass the safety PLC or take other appropriate action to avoid a false trip
2	Send a HART command to the transmitter to go to the high alarm current output and verify that the analog current reaches that value. This tests for compliance voltage problems such as a low loop power supply voltage or increased wiring resistance. This also tests for other possible failures.
3	Send a HART command to the transmitter to go to the low alarm current output and verify that the analog current reaches that value. This tests for possible quiescent current related failures
4	Use the HART communicator to view detailed device status to ensure no alarms or warnings are present in the transmitter
5	Perform reasonability check on the sensor value(s) versus an independent estimate (i.e. from direct monitoring of BPCS value) to show current reading is good
6	Restore the loop to full operation
7	Remove the bypass from the safety PLC or otherwise restore normal operation

C.1 Proof test 2

The alternative proof test consists of the following steps, as described in Table 15. This test will detect approximately 96% of possible DU failures in the transmitter and approximately 99% of the simple sensing element DU failures. This results in a Proof Test Coverage of 96% for the overall sensor assembly, assuming a single 4-wire RTD is used.

Table 15 Steps for Proof Test 2

Step	Action
1	Bypass the safety PLC or take other appropriate action to avoid a false trip
2	Perform Proof Test 1
3	Verify the measurement for two temperature points for Sensor 1. Verify the measurement for two temperature points for Sensor 2, if second sensor is present.
4	Perform reasonability check of the housing temperature
5	Restore the loop to full operation
6	Remove the bypass from the safety PLC or otherwise restore normal operation



Appendix D: Common Cause for redundant transmitter configurations

A method for estimating the beta factor is provided in IEC 61508, part 6. This portion of the standard is only informative and other techniques may be used to estimate the beta factor. Based on the approach presented in IEC 61508 a series of questions are answered. Based on the total points scored for these questions, the beta factor number is determined from IEC61508-6 Table D.4.

Example – 2oo3 Temperature Transmitters

A design is being evaluated where three Rosemount 644 Temperature Transmitters are chosen. The transmitters are connected to a logic solver programmed to detect over-range and under-range currents as a diagnostic alarm. The process is not shutdown when an alarm occurs on one transmitter. The logic solver has a two out of three (2oo3) function block that votes to trip when two of the three transmitters indicate the need for a trip. Following the questions from the sensor portion of Table D.1 of IEC 61508, Part 6, the following results are obtained.

Table 16 Example version of Table D.1, Part 6 IEC 61508

Item	X _{SF}	Y _{SF}	Example	Score
Are all signal cables for the channels routed separately at all positions?	1.0	2.0	Not guaranteed	0.0
If the sensors/final elements have dedicated control electronics, is the electronics for each channel on separate printed-circuit boards?	2.5	1.5	Transmitters are separate	4.0
If the sensors/final elements have dedicated control electronics, is the electronics for each channel indoors and in separate cabinets?	2.5	0.5	Transmitters are in different housings	3.0
Do the devices employ different physical principles for the sensing elements for example, pressure and temperature, vane anemometer and Doppler transducer, etc.?	7.5		No – transmitters are identical	0.0
Do the devices employ different electrical principles/designs for example, digital and analogue, different manufacturer (not re-badged) or different technology?	5.5		No – transmitters are identical	0.0
Do the channels employ enhanced redundancy with MooN architecture, where $N > M + 2$?	2.0	0.5	No – 2oo3	0.0
Do the channels employ enhanced redundancy with MooN architecture, where $N = M + 2$?	1.0	0.5	No – 2oo3	0.0
Are separate test methods and people used for each channel during commissioning?	1.0	1.0	No - impractical	0.0
Is maintenance on each channel carried out by different people at different times?	2.5		No - impractical	0.0
Does cross-connection between channels preclude the exchange of any information other than that used for diagnostic testing or voting purposes?	0.5	0.5	No cross channel information between transmitters	1.0
Is the design based on techniques used in equipment that has been used successfully in the field for > 5 years?	1.0	1.0	644 based on well proven design	2.0
Is there more than 5 years experience with the same hardware used in similar environments?	1.5	1.5	Extensive experience in process control	3.0



Item	X _{SF}	Y _{SF}	Example	Score
Are inputs and outputs protected from potential levels of over-voltage and over-current?	1.5	0.5	Transient voltage and current protection provided	2.0
Are all devices/components conservatively rated? (for example, by a factor of 2 or more)	2.0		Design has conservative rating factors proven by field reliability	2.0
Have the results of the failure modes and effects analysis or fault tree analysis been examined to establish sources of common cause failure and have predetermined sources of common cause failure been eliminated by design?		3.0	FMEDA done by third party – exida. No common cause issues	3.0
Were common cause failures considered in design reviews with the results fed back into the design? (Documentary evidence of the design review activity is required.)		3.0	Design review is part of the development process. Results are always fed back into the design	3.0
Are all field failures fully analyzed with feedback into the design? (Documentary evidence of the procedure is required.)	0.5	3.5	Field failure feedback procedure reviewed by third party – exida. Results are fed back into the design.	4.0
Is there a written system of work which will ensure that all component failures (or degradations) are detected, the root causes established and other similar items are inspected for similar potential causes of failure?	0.5	1.5	Proof test procedures are provided but they cannot insure root cause failure analysis.	0.0
Are procedures in place to ensure that: maintenance (including adjustment or calibration) of any part of the independent channels is staggered, and, in addition to the manual checks carried out following maintenance, the diagnostic tests are allowed to run satisfactorily between the completion of maintenance on one channel and the start of maintenance on another?	2.0	1.0	Procedures are not sufficient to ensure staggered maintenance.	0.0
Do the documented maintenance procedures specify that all parts of redundant systems (for example, cables, etc.), intended to be independent of each other, must not be relocated?	0.5	0.5	MOC procedures require review of proposed changes, but relocation may inadvertently be done.	0.0
Is all maintenance of printed-circuit boards, etc. carried out off-site at a qualified repair centre and have all the repaired items gone through a full pre-installation testing?	0.5	1.5	Repair is done by returning product to the factory, therefore this requirement is met.	2.0
Do the system diagnostic tests report failures to the level of a field-replaceable module?	1.0	1.0	Logic solver is programmed to detect current out of range and report the specific transmitter.	2.0



Item	X _{SF}	Y _{SF}	Example	Score
Have designers been trained (with training documentation) to understand the causes and consequences of common cause failures	2.0	3.0	Control system designers have not been trained.	0.0
Have maintainers been trained (with training documentation) to understand the causes and consequences of common cause failures	0.5	4.5	Maintenance personnel have not been trained.	0.0
Is personnel access limited (for example locked cabinets, inaccessible position)?	0.5	2.5	A tool is required to open the transmitter therefore this requirement is met.	3.0
Is the system likely to operate always within the range of temperature, humidity, corrosion, dust, vibration, etc., over which it has been tested, without the use of external environmental control?	3.0	1.0	Environmental conditions are checked at installation.	4.0
Are all signal and power cables separate at all positions?	2.0	1.0	No	0.0
Has a system been tested for immunity to all relevant environmental influences (for example EMC, temperature, vibration, shock, humidity) to an appropriate level as specified in recognized standards?	10.0	10.0	Rosemount has complete testing of all environmental stress variables and run-in during production testing.	20.0
Totals	23	37	S=X+Y	58

A score of 58 results in a beta factor of 5%. If the owner-operator of the plant would institute common cause training and more detailed maintenance procedures specifically oriented toward common cause defense, a score of greater than 70 could be obtained. Then the beta factor would be 2%.

Note that the diagnostic coverage for the transmitter is not being considered. Additional points can be obtained when diagnostics are taken into account. However this assumes that a shutdown occurs whenever any diagnostic alarm occurs. In the process industries this could even create dangerous conditions. Therefore the practice of automatic shutdown on a diagnostic fault is rarely implemented. IEC 61508, Part 6 has a specific note addressing this issue. The note states:

“NOTE 5 In the process industries, it is unlikely to be feasible to shut down the EUC when a fault is detected within the diagnostic test interval as described in table D.2. This methodology should not be interpreted as a requirement for process plants to be shut down when such faults are detected. However, if a shut down is not implemented, no reduction in the b-factor can be gained by the use of diagnostic tests for the programmable electronics. In some industries, a shut down may be feasible within the described time. In these cases, a non-zero value of Z may be used.”

In this example, automatic shutdown on diagnostic fault was not implemented so no credit for diagnostics was taken.



Appendix E: exida Environmental Profiles

Table 17 *exida* Environmental Profiles

EXIDA ENVIRONMENTAL PROFILE		GENERAL DESCRIPTION	PROFILE PER IEC 60654-1	AMBIENT TEMPERATURE [°C]		TEMP CYCLE [°C / 365 DAYS]
				AVERAGE (EXTERNAL)	MEAN (INSIDE BOX)	
1	Cabinet Mounted Equipment	Cabinet mounted equipment typically has significant temperature rise due to power dissipation but is subjected to only minimal daily temperature swings	B2	30	60	5
2	Low Power /Mechanical Field Products	Mechanical / low power electrical (two-wire) field products have minimal self heating and are subjected to daily temperature swings	C3	25	30	25
3	General Field Equipment	General (four-wire) field products may have moderate self heating and are subjected to daily temperature swings. Non-process wetted components of valves and actuators.	C3	25	45	25
4	Unprotected Mechanical Field Products	Unprotected mechanical field products with minimal self heating, are subject to daily temperature swings and rain or condensation.	D1	25	30	35
4	Process Wetted Parts	Typically valve and sensor parts that are process wetted	Per Manufacturer's Specifications			