Failure Modes, Effects and Diagnostic Analysis

Project:

Direct-acting solenoid valves
2/2 way 6013-*-***, 2/2 way 6027-*-*** and 3/2 way 6014-*-***,
Pilot-operated solenoid valves
2/2 way 0290-*-*** and 2/2 way 5404-*-***,
3/2 way 6518-*-***, 3/2 way and 5/2 way 6519-*-***,
3/2 way and 4/2 way 5470-*-***

Customer:

Bürkert Werke GmbH & Co. KG
Ingelfingen
Germany

Contract No.: Buerkert 19/07-048

Report No.: Buerkert 12/10-097-C R001

Version V4, Revision R1, March 2020

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Management summary

This report summarizes the results of the hardware assessment carried out on the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-***. Table 1 gives an overview of the different versions that belong to the considered solenoid valves.

The mechanical assessment consists of a Failure Modes, Effects and Diagnostics Analysis (FMEDA). A FMEDA is one of the steps taken to achieve functional safety assessment of a device per IEC 61508. From the FMEDA, failure rates are determined and consequently the Safe Failure Fraction (SFF) is calculated for the device. For full assessment purposes all requirements of IEC 61508 must be considered.

Table 1: Version overview

6013-A-*[1]**	2/2 way threaded port G 1/8" – G 3/8" general purpose compact solenoid valve; when de-energized, normally closed
6014-C-* **	3/2 way threaded port G 1/8" – G 1/4" general purpose compact solenoid valve; when de-energized, outlet A pressure relieved (normally closed)
6014-D-* **	3/2 way threaded port G 1/8" – G 1/4" general purpose compact solenoid valve; when de-energized, outlet B pressurized (normally open)
6518-C-* **	3/2 way solenoid valve; pilot-operated; DN 8 and 9; flow rate: 1300 l/min; G 1/4 port connection; when de-energized, port 2 exhausted
6518-D-* **	3/2 way solenoid valve; pilot-operated; DN 8 and 9; flow rate: 1300 l/min; G 1/4 port connection; when de-energized, port 2 pressurized
6519-H-* **	5/2 way solenoid valve; pilot-operated; DN 8; flow rate: 1300 l/min; G 1/4 port connection; when de-energized, port 2 pressurized, port 4 exhausted
6519-W-* **	5/2 way solenoid valve; pilot-operated; DN 9; flow rate: 1300 l/min; G 1/4 port connection; when de-energized, port 2 pressurized, port 4 exhausted
6519-W-* **	3/2 way and 5/2 way solenoid valve; pilot-operated; DN 6; flow rate: 900 l/min; NAMUR flange interface
5470-G-* **	4/2 multi-way valve; servo-assisted; DN 4; flow rate: 300 l/min; G 1/8 ø 6 mm port connections
290-A-* **	2/2 way valve; Servo-assisted diaphragm valve, DN50, flow rate: 266 l/min; G1¼ port connections
5404-A-* **	2/2 way valve; Servo-assisted piston valve, DN32/40, flow rate: 600 l/min; G 2 port connections
6027-A-* **	2/2 way valve; Direct-acting plunger valve, AC19 DN13, flow rate: 66 l/min; G 1/2 port connections

For safety applications only the described valve functions have been considered. All other possible valve functions are not covered by this report.

Bürkert Werke GmbH & Co. KG and *exida* together did a quantitative analysis of the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-*** to calculate the failure rates using Profile 2 [2] of *exida*'s component database (see [N2]) for the different mechanical components.

The solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-

[1] *** stands for the different certifications carried out on the considered solenoid valves.

[2] See appendix 3 for detailed definitions.

*** and 6027-*-*** are considered to be Type A[3] elements with a hardware fault tolerance of 0 and can be classified as 2_H devices when the listed failure rates are used. **When 2_H data is used for all of the devices in an element, then the element meets the hardware architectural constraints up to SIL 2 at HFT=0 for low demand mode applications or SIL 2 / SIL3 at HFT=1 for high and low demand mode applications.** If Route 2_H is not applicable for the entire element, the architectural constraints will need to be evaluated per Route 1_H.

The following table shows how the above stated requirements are fulfilled under worst-case assumptions.

[3] Type A element: "Non-complex" element (all failure modes are well defined); for details see 7.4.4.1.2 of IEC 61508-2.

Table 2: Summary – IEC 61508:2010 failure rates

	λ_{safe}	$\lambda_{dangerous}$	**PL** [4] **(calculated according ISO 13849-1:2015, Table 2)**
6013-A-* **	62 FIT	70 FIT	e
6014-C-* **	62 FIT	70 FIT	e
6014-D-* **	62 FIT	77 FIT	e
6518-C-* **	62 FIT	277 FIT	d
6518-D-* **	62 FIT	287 FIT	d
6519-H-* **	62 FIT	425 FIT	d
6519-W-* (3/2 way)**	62 FIT	411 FIT	d
6519-W-* (5/2 way)**	62 FIT	421 FIT	d
5470-G-* **	55 FIT	231 FIT	d
290-A-* **	52 FIT	87 FIT	e
5404-A-* **	87 FIT	66 FIT	e
6027-A-* **	40 FIT	54 FIT	e

The failure rates are valid for the useful life of the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-*** (see Appendix 2).

[4] The Performance Level (PL) is not based on B_{10d} values or any cyclic tests but is based on $\lambda_{dangerous}$.

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Table of Contents

1 Purpose and Scope

This document shall describe the results of the mechanical assessment carried out on the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-***

The FMEDA builds the basis for an evaluation whether the described solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-*** meet the average Probability of Failure on Demand (PFD_{AVG}) requirements and the architectural constraints / minimum hardware fault tolerance requirements per IEC 61508. It **does not** consider any calculations necessary for proving intrinsic safety.

2 Project management

2.1 *exida*

exida is one of the world's leading product certification 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 consulting services, internet-based safety engineering tools, detailed product assurance and certification analysis 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

Bürkert Werke GmbH & Co. KG	Manufacturer of the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-***.
exida	Performed the hardware assessment.

Bürkert Werke GmbH & Co. KG contracted *exida* in February 2013 with the update of the FMEDA of the above mentioned devices.

2.3 Standards / Literature used

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

[N1]	IEC 61508-2:2010	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems, 2nd edition
[N2]	Mechanical Component Reliability Handbook, 4th Edition, 2016	*exida* LLC, Electrical & Mechanical Component Reliability Handbook, Fourth Edition, 2016 (pending publication, not publicly available at the time of this report)

2.4 Reference documents

2.4.1 Documentation provided by the customer

[D1]	DS6013-Standard-EU-EN.pdf	Data sheet 6013-*-***
[D2]	DS6014-Standard-EU-EN.pdf	Data sheet 6014-*-***
[D3]	DS6518-Standard-EU-EN.pdf	Data sheet 6518-*-*** and 6519-*-***
[D4]	DS0290-Standard-EU-EN.pdf	Data sheet 0290-*-***
[D5]	DS5404-Standard-EU-EN.pdf	Data sheet 5404-*-***
[D6]	DS6027-2-way-Comp.-EU-EN.pdf	Data sheet 6027-*-***
[D7]	US_6519_NAMUR.pdf	Data sheet 6519-*-*** NAMUR
[D8]	DS5470-Single-EU-EN.pdf	Data sheet 5470-*-***
[D9]	6013-BG01.pdf	Diagram "2/2–Wege–Ventil" 6013 BG01 index G of 22.08.02
[D10]	6013 Id. Nr. 142 301.pdf	Parts list 6013 material no. 142 301

[D11]	6014-BG01.pdf	Diagram “3/2–Wege–Ventil” 6014 BG01 index G of 07.03.05
[D12]	6014 NC Id. Nr. 126 403.pdf	Parts list 6014 NC material no. 126 403
[D13]	6014 NO Id. Nr. 460 624.pdf	Parts list 6014 NO material no. 460 624
[D14]	6518-BG01.pdf	Diagram “3/2–Wege–Pneumatikventil” 6518 BG01 index C of 14.08.01
[D15]	6518 NC Id. Nr. 139 442.pdf	Parts list 6518 NC material no. 139 442
[D16]	6518 NO Id. Nr. 132 462.pdf	Parts list 6518 NO material no. 132 462
[D17]	6519-BG01.pdf	Diagram “5/2–Wege–Pneumatikventil” 6519 BG01 index C of 14.08.01
[D18]	6519-BG03.pdf	Diagram “3/2– u. 5/2– Pneumatikventil NAMUR Flanschanschluss” 6519 BG03 index C of 11.09.03
[D19]	6519-BM03.pdf	Diagram “3/2– und 5/2–Wege Pneumatikventil NAMUR Flanschanschluss” 6519 BM03 index C of 24.03.98
[D20]	6519 Id. Nr. 456 978.pdf	Parts list 6519 material no. 456 978
[D21]	0475-BG01.pdf	Diagram “5/2–Wege–Pneumatikventil” 0475 BG01 index B of 15.05.95
[D22]	0475-BG02.pdf	Diagram “3/2–Wege–Pneumatikventil WWC” 0475 BG02 index C of 23.01.96
[D23]	0475-BG03.pdf	Diagram “3/2–Wege–Pneumatikventil WWD” 0475 BG02 index B of 15.05.95
[D24]	0475-BM04-BG08.pdf	Diagram “3/2– und 5/2–Wege–Pneumatikventil NAMUR Flanschanschluss” 0475 BM04 of 18.09.95
[D25]	V013-BG01.pdf	Diagram “Armatur kpl.” V013 BG01 index G of 11.05.99
[D26]	V014-BG01.pdf	Diagram “Armatur kpl.” V014 BG01 index E of 11.05.99
[D27]	Zeichnung G1 668 446.pdf	Diagram “Armatur” G1 668 446 of 14.06.05
[D28]	5470 Id. Nr. 458352.pdf	Parts list 5470 material no. 458 352
[D29]	SIL 2 valves 12.01.06.doc	Overview of available certificates for the considered valves
[D30]	MOM_Buerkert_exida_2013-10-09.pdf	Minutes of Meeting, Version 2.0 of 10.09.2013
[D31]	Typ_0290_SK04.pdf	Diagarm 0290 Doc. ID: 9000470622; DN32/40; Aug. 2019
[D32]	Typ_0290_Stückliste.pdf	Partlist 0290; Doc. ID: 9000471455; Aug. 2019
[D33]	Typ_5404_SK04.PDF	Diagram 5404; Doc. ID: 9000469479; Jul. 2019
[D34]	Typ_5404_Stückliste.pdf	Partlist 5404; Doc. ID: 9000469492; Jul. 2019
[D35]	Typ_6027_SK04.PDF	Diagram 6027; Doc ID. 9000470114; Jul. 2019
[D36]	Typ_6027_Stückliste.pdf	Partlist 6027; Doc. ID: 9000470117; Jul. 2019

The list above only means that the referenced documents were provided as basis for the FMEDA but it does not mean that *exida* checked the correctness and completeness of these documents.

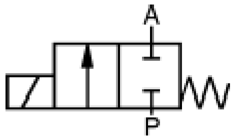
2.4.2 Documentation generated by *exida.com*

[R1]	FMEDA_V8_6013NC_V2R0.efm of 03.04.13
[R2]	FMEDA_V8_6014NC_V2R0.efm of 08.04.13
[R3]	FMEDA_V8_6014NO_V2R0.efm of 08.04.13
[R4]	FMEDA_V8_6518NC_V2R0.efm of 08.04.13
[R5]	FMEDA_V8_6518NO_V2R0.efm of 08.04.13
[R6]	FMEDA_V8_6519H_V2R0.efm of 08.04.13
[R7]	FMEDA_V8_6519W3-2_V2R0.efm of 19.04.13
[R8]	FMEDA_V8_6519W5-2_V2R0.efm of 19.04.13
[R9]	FMEDA_V8_5470G_V2R0.efm of 25.04.13
[R10]	FMEDA_V9_0290A_V1R0.xlsx of 05.02.2020
[R11]	FMEDA_V9_5404A_V1R0.xlsx of 05.02.2020
[R12]	FMEDA_V9_6027A_V1R0.xlsx of 05.02.2020
[R13]	2H Nachweis_R001.zip of 05.03.2020

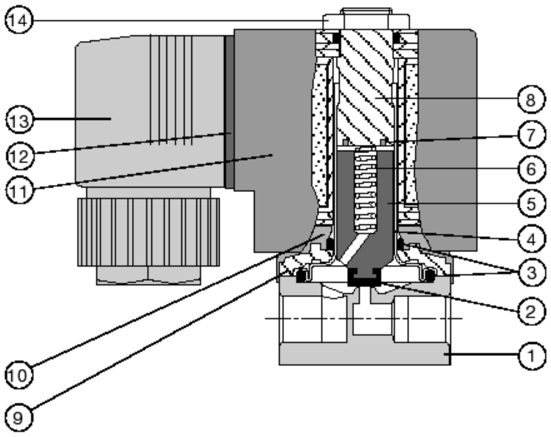
3 Description of the analyzed module

The solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***,0290-*-***, 5404-*-*** and 6027-*-***, are considered to be Type A elements with a hardware fault tolerance of 0.

3.1 2/2 way solenoid valve 6013-*-***

Circuit function	Symbol
A: 2/2-way valve, normally closed	

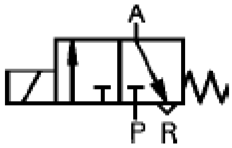
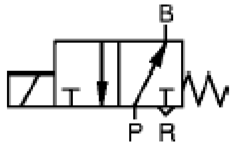
The direct-acting 2/2 way solenoid valves 6013-*-*** are based on a modular concept comprising three basic elements: Valve body, pushover coil and standard cable plug. The valve assembly consists of a body to which the armature guide tube containing the plunger, seals and springs is attached. The coil is pushed over the guide tube and thus isolated from the medium. The medium is only in contact with the valve internals and body.



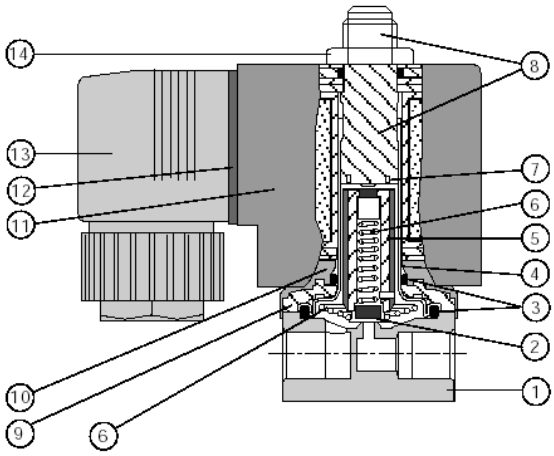
1	Valve body:	Brass, SS 1.4305 (G1/8") SS 1.4401 (G1/4")
2	Plunger-seal:	FPM (Viton)
3	O-rings:	FPM (Viton)
4	Armature guide tube:	1.4303
5	Plunger:	1.4105
6	Spring:	1.4310
7	Shading ring:	Cu (brass version) Ag (stainless steel version)
8	Stopper:	1.4105
9	Flange:	Zn3 gl cC (surface)
10	Bonnet:	Durethan BKV30H
11	Coil:	PA (Polyamide)
12	Flat seal:	NBR
13	Cable plug:	PA (Polyamide)
14	Locknut:	9SMnPb28K (surface Zn5glcA)

Figure 1: Assembly drawing

3.2 3/2 way solenoid valve 6014-*-***

Circuit function	Symbol
C: 3/2-way valve, when de-energized, outlet A pressure relieved	
D: 3/2-way valve, when de-energized, outlet B pressurized	

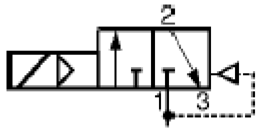
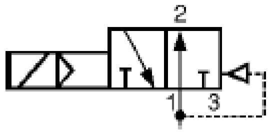
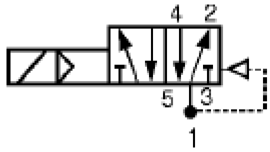
The direct-acting 3/2 way solenoid valve 6014-*-*** are based on a modular concept comprising three basic elements: Valve body, pushover coil and standard cable plug. The valve assembly consists of a body to which the armature guide tube containing the plunger, seals and springs is attached. The coil is pushed over the guide tube and thus isolated from the medium. The medium is only in contact with the valve internals and body.



1	Valve body:	Brass, S.Steel 1.4305 (G1/8") S.Steel 1.4401 (G1/4")
2	Plunger-seal:	FPM (Viton)
3	O-rings:	FPM (Viton)
4	Armature guide tube:	1.4303
5	Plunger:	1.4105
6	Spring:	1.4310
7	Shading ring:	Cu (brass version) Ag (stainless steel version)
8	Stopper:	1.4105
9	Flange:	Zn3 gl cC (surface)
10	Bonnet:	Durethan BKV30H
11	Coil:	PA (Polyamide)
12	Flat seal:	NBR
13	Cable plug:	PA (Polyamide)
14	Locknut:	9SMnPb28K (surface Zn5glcA)

Figure 2: Assembly drawing

3.3 3/2 way solenoid valve 6518-*-*** and 5/2 way solenoid valve 6519-*-***

Circuit function	Symbol
C: 3/2-way valve, in de-energized position port 2 exhausted	
D: 3/2-way valve, in de-energized position port 2 pressurized	
H: 5/2-way valve, in de-energized position port 2 pressurized, port 4 exhausted	

The pilot-operated 3/2 way solenoid valve 6518-*-*** and 5/2 way solenoid valve 6519-*-*** feature are high switch reliability diaphragm driven seat valves. A compact solenoid valve type 6014 with push-over coil is used as pilot. Types 6518 and 6519 can be used as single valves or as serial blocks.

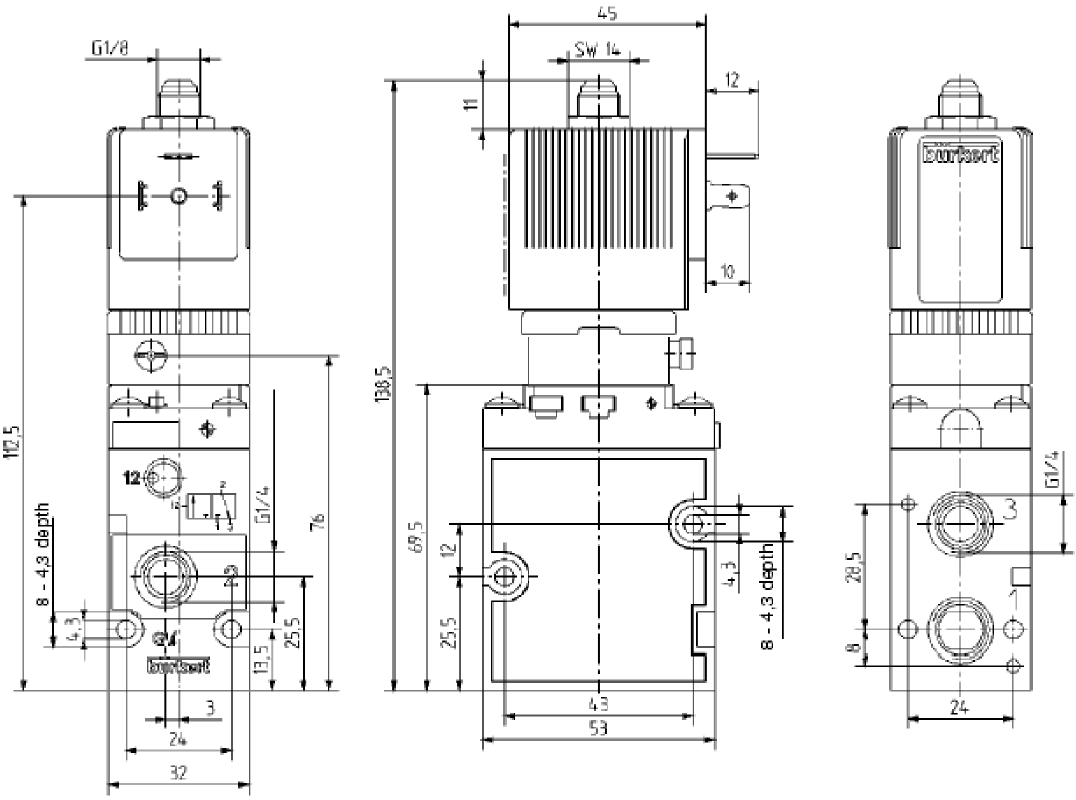


Figure 3: Assembly drawing 3/2 way solenoid valve 6518-*-*

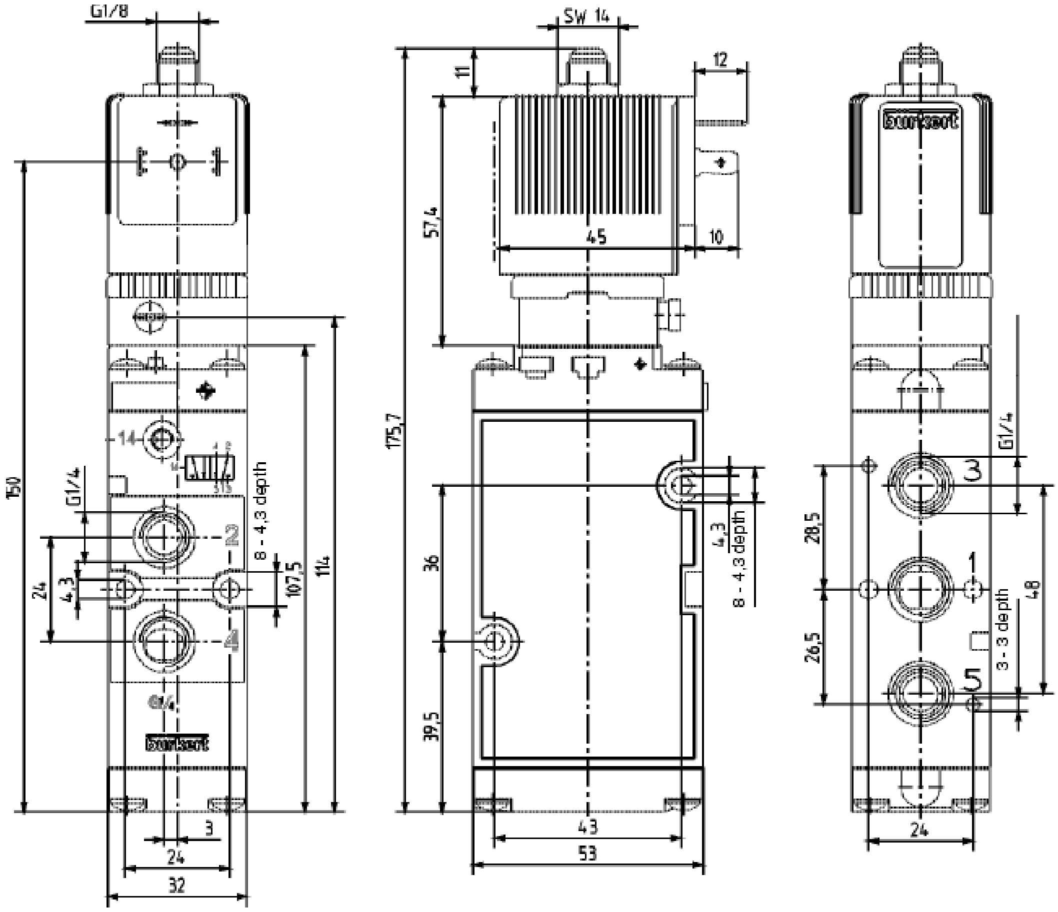


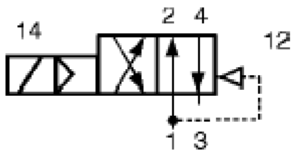
Figure 4: Assembly drawing 5/2 way solenoid valve 6519-H-***

The Type 6519 NAMUR valve can be operated as a 5/2–way or 3/2–way valve through the various mounting positions of the changeover plate on the side.

The NAMUR flange interface allows easy assembly on different pneumatic actuators on the spot.

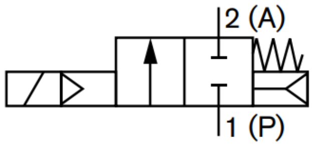
Figure 5: Type 6519 NAMUR EEx m

3.4 4/2 way solenoid valve 5470-G-***

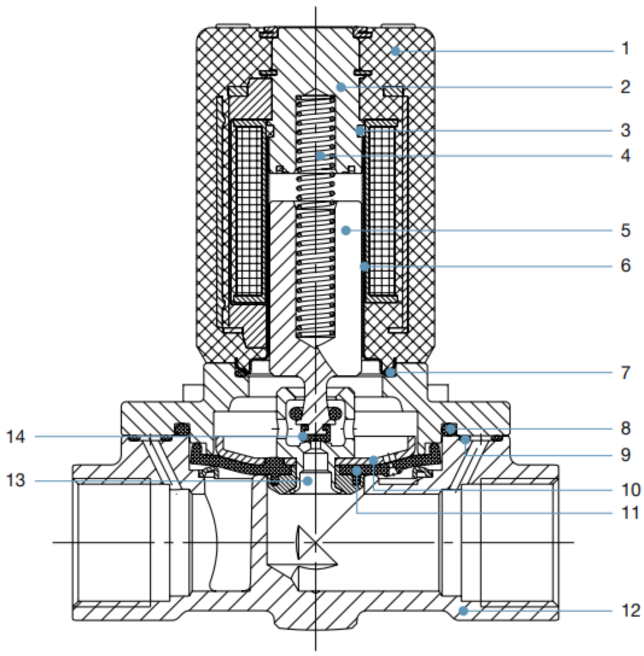
Circuit function	**Symbol**
G: 4/2-way valve, when de-energized, pressure inlet port 1 connected to outlet port 2, outlet port 4 exhausted	

The solenoid valve 5470-*-***includes high switch reliable diaphragm seat valves as 3/2 and 4/2 way version. The valve consists of three modules, valve body with servo-diaphragm, plungers and seat seals as well as numerous connection possibilities for the ports.

3.5 2/2 way Servo-assisted diaphragm valve 0290-A-***

Circuit function	Symbol
A: 2/2-way valve, Servo-assisted, normally closed	

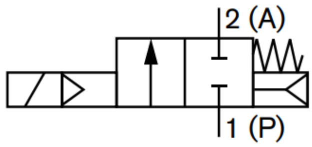
The 0290-*-*** valve is a servo-assisted solenoid valve of the S.EV series. The valve opens without differential pressure. The opening process is supported by the fixed coupling of the diaphragm to the plunger. In the process, the integrated 'soft-kick' function opens in a manner that is gentle on the material. Various diaphragm material combinations are available depending on the application. The range of housings is rounded off by stainless steel versions. The solenoid coils are encapsulated with a chemically resistant epoxy. 'Kick and drop' electronics are molded into all DC versions for reduced electrical power consumption.



No.	Element	Material
1	Coil	Epoxide
2	Stopper	1.4105 or 1.4113
3	Shading ring (AC variant only)	Brass variant: Copper Stainless steel variant: Silver
4	Spring	1.4310
5	Magnetic core	1.4105 or 1.4113
6	Core guide tube	1.4303
7	O-ring	NBR, FKM, EPDM
8	O-ring	NBR, FKM, EPDM
9	O-ring	NBR, FKM, EPDM
10	Diaphragm plate	Brass variant: CuZn37 Stainless steel variant: 1.4401
11	Diaphragm	NBR, FKM, EPDM
12	Body	Brass or stainless steel 1.4581
13	Pilot valve seat	Brass variant: MS Stainless steel variant: 1.4401
14	Seat seal	NBR, FKM, EPDM

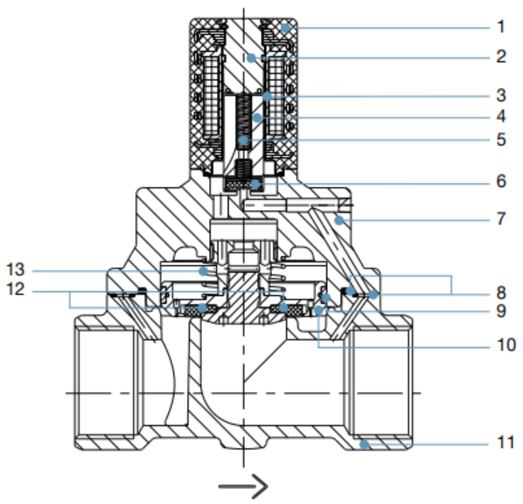
Figure 6: Type 0290 assembly drawing

3.6 2/2 way Servo-assisted piston valve 5404-A-***

Circuit function	Symbol
A: 2/2-way valve, Servo-assisted, normally closed	

The 5404-*-*** valve is a servo-assisted piston valve available in NC and NO versions. A minimum differential pressure is required for the valve switching function. The solenoid coils are molded with high-quality epoxy resin.

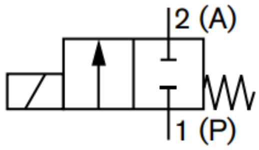
DN32, Circuit function A



No.	Element	Material
1	Coil	Epoxy
2	Stopper	1.4105 Stainless steel
3	Armature guide tube	1.4303 Stainless steel
4	Plunger	1.4105 Stainless steel
5	Spring	1.4310 Stainless steel
6	Plunger seal	FKM
7	Cover	Brass
8	O-Rings	FKM
9	Piston rings	PTFE
10	Piston	Brass
11	Valve body	Brass
12	Piston seal	PTFE
13	Spring	1.4310 Stainless steel

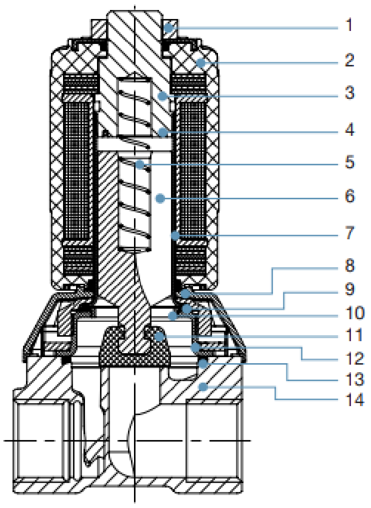
Figure 7: Type 5405 assembly drawing

3.7 2/2 way direct-acting plunger valve 6027-A-***

Circuit function	Symbol
A: 2/2-way valve, direct-acting, normally closed	

Valve 6027-*-*** is a direct-acting plunger valve. The stopper and plunger guide tube are welded together to enhance pressure resistance and leak-tightness. Various seal material combinations are available depending on the application. The coils are molded with chemically resistant epoxy. An optional sliding ring bearing increases the service life with dry gases. Special seal technology is used for high-pressure applications

Version DN13 standard



No.	Element	Material
1	Locknut	DIN 176 thick-film passivated or stainless steel
2	Coil	Epoxy
3	Stopper	Stainless steel 1.4113
4	Shading ring	Copper (brass body) Silver (stainless steel body)
5	Spring	Stainless steel 1.4310
6	Core	Stainless steel 1.4113
7	Guide tube	Stainless steel 1.4303
8	Hood	PA6
9	Seal	FKM, EPDM
10	Support ring	PPS Fortron
11	Core seal	FKM, EPDM, NBR
12	Cover	DN10…DN25 stainless steel 1.4301
13	Seal	FKM, EPDM
14	Housing	Brass, stainless steel 1.4408

Figure 8: Type 6027 assembly drawing

4 Failure Modes, Effects, and Diagnostic Analysis

The Failure Modes, Effects, and Diagnostic Analysis was done together with Bürkert Werke GmbH & Co. KG and is documented in [R1] to [R9].

4.1 Description of the failure categories

In order to judge the failure behavior of the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-*** and 5470-*-***, the following definitions for the failure of the products were considered.

Fail-Safe State

6013-A-***

The fail-safe state is defined as the output being closed without electrically operated (circuit function A).

6014-C-*,**

The fail-safe state is defined as the output being closed without electrically operated (circuit function C).

6014-D-***

The fail-safe state is defined as the output being open without electrically operated (circuit function D).

6518-C-***

The fail-safe state is defined as the output being closed without electrically operated (circuit function C).

6518-D-***

The fail-safe state is defined as the output being open without electrically operated (circuit function D).

6519-H-***

The fail-safe state is defined as port 2 being pressurized (1 -> 2), port 4 being exhausted (4 -> 5) and port 3 being closed without electrically operated (circuit function H).

6519-W-* (3/2 way – C)**

The fail-safe state is defined as circuit function W (3/2 C) where port 2 and 4 are exhausted (2,4 -> 5) and port 3 is blocked without being electrically operated.

6519-W-* (5/2 way – H)**

The fail-safe state is defined as circuit function W (5/2 H) where port 2 is pressurized (1 -> 2), port 4 is exhausted (4 -> 5) and port 3 is closed without being electrically operated.

5470-G-***

The fail-safe state is defined as circuit function G where port 2 is pressurized (1 -> 2) and port 4 is exhausted (4 -> 3) without being electrically operated.

0290-A-***

The fail-safe state is defined as the output being closed without electrically operated (circuit function A).

5404-A-***

The fail-safe state is defined as the output being closed without electrically operated (circuit function A).

6027-A-***

The fail-safe state is defined as the output being closed without electrically operated (circuit function A).

Safe	A safe failure (S) is defined as a failure that plays a part in implementing the safety function that: a) results in the spurious operation of the safety function to put the EUC (or part thereof) into a safe state or maintain a safe state; or, b) increases the probability of the spurious operation of the safety function to put the EUC (or part thereof) into a safe state or maintain a safe state.
Dangerous	A dangerous failure (D) is defined as a failure that plays a part in implementing the safety function that: a) prevents a safety function from operating when required (demand mode) or causes a safety function to fail (continuous mode) such that the EUC is put into a hazardous or potentially hazardous state; or, b) decreases the probability that the safety function operates correctly when required.
Dangerous Undetected	Failure that is dangerous and that is not being diagnosed by internal or external diagnostics (DU).
Dangerous Detected	Failure that is dangerous but is detected by internal or external diagnostics (DD). These failures may be converted to the selected fail-safe state.
No effect	Failure mode of a component that plays a part in implementing the safety function but is neither a safe failure nor a dangerous failure.
No part	Component that plays no part in implementing the safety function but is part of the circuit diagram and is listed for completeness.

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.

A FMEDA (Failure Modes, Effects, and Diagnostic Analysis) is a FMEA extension. It combines standard FMEA techniques with 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) 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 a proprietary mechanical component failure rate database derived using 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 operating stress conditions typical of an industrial field environment similar to profile 2 of *exida*'s component database (see [N2]). 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". Corrosion, erosion, coil burnout etc. are considered age related (late life) or systematic failures, provided that materials and technologies applied are indeed suitable for the application, in all modes of operation.

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.

4.2.3 Assumptions

The following assumptions have been made during the Failure Modes, Effects, and Diagnostic Analysis of the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-***.

- Failure rates are constant, wear out mechanisms are not included.
- Propagation of failures is not relevant.
- Sufficient tests are performed prior to shipment to verify the absence of vendor and/or manufacturing defects that prevent proper operation of specified functionality to product specifications or cause operation different from the design analyzed.
- Materials are compatible with process conditions and process fluids.
- The Mean Time To Restoration (MTTR) after a safe failure is 24 hours.
- All devices are operated in the low demand mode of operation.
- External power supply failure rates are not included.
- Practical fault insertion tests can demonstrate the correctness of the failure effects assumed during the FMEDAs.
- Clean medium is applied to the valve.
- The valves are installed per the manufacturer's instructions.
- Only the described versions and circuit functions are used for safety applications.
- Manual override must not be used for safety applications.
- Clean and dry operating air is used per ANSI/ISA-7.0.01-1996 Quality Standard for Instrument Air.

5 Results

λ_{total} consists of the sum of all component failure rates. This means:

$\lambda_{total} = \lambda_{SD} + \lambda_{SU} + \lambda_{DD} + \lambda_{DU}$

$SFF = 1 – \lambda_{DU} / \lambda_{total}$

$MTBF = MTTF + MTTR = (1 / (\lambda_{total} + \lambda_{no\ part} + \lambda_{no\ effect})) + 24\ h$

According to IEC 61508 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.

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.

This assessment supports the 2_H approach.

The failure rate data used for this analysis meets the *exida* criteria for Route 2_H, see Section 6.2. Therefore, the direct-acting solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-*** can be classified as 2_H devices when the listed failure rates are used. **When 2_H data is used for all of the devices in an element, then the element meets the hardware architectural constraints up to SIL 2 at HFT=0 for low demand mode applications or SIL 2 / SIL3 at HFT=1 for high and low demand mode applications.** If Route 2_H is not applicable for the entire element, the architectural constraints will need to be evaluated per Route 1_H.

As the solenoid valves 6013-*-***, 6014-*-***, 6518-*-***, 6519-*-***, 5470-*-***, 0290-*-***, 5404-*-*** and 6027-*-*** are only one part of an element, the architectural constraints should be determined for the entire final element.

5.1 Air quality failures

The product failure rates that are displayed in this section are failure rates that reflect the situation where the device is used with clean filtered air. Additionally, contamination from poor control air quality may affect the function or air flow in the device. For applications where these assumptions do not apply, the user must estimate the failure rates due to contaminated air and add this failure rate to the product failure rates.

5.2 2/2 way 6013-A-*** solenoid valve

The FMEDA carried out on the 2/2 way 6013-A-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 3: Summary for 6013-A-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**70**

No effect	102
No part	56

Total failure rate of the safety function (λ_{Total})	**132**

MTBF	**395 Years**

5.3 3/2 way 6014-C-*** solenoid valve

The FMEDA carried out on the 3/2 way 6014-C-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 4: Summary 6014-C-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**70**

No effect	102
No part	157

Total failure rate of the safety function (λ_{Total})	**132**

MTBF	**293 Years**

5.4 3/2 way 6014-D-*** solenoid valve

The FMEDA carried out on the 3/2 way 6014-D-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 5: Summary 6014-D-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**77**

No effect	90
No part	156

Total failure rate of the safety function (λ_{Total})	**139**
MTBF	**299 Years**

5.5 3/2 way 6518-C-*** solenoid valve

The FMEDA carried out on the 3/2 way 6518-C-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 6: Summary 6518-C-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**277**

No effect	640
No part	143

Total failure rate of the safety function (λ_{Total})	**339**

MTBF	**102 Years**

5.6 3/2 way 6518-D-*** solenoid valve

The FMEDA carried out on the 3/2 way 6518-D-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 7: Summary 6518-D-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**287**

No effect	673
No part	134

Total failure rate of the safety function (λ_{Total})	**349**

MTBF	**99 Years**

5.7 5/2 way 6519-H-*** solenoid valve

The FMEDA carried out on the 5/2 way 6519-H-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 8: Summary 6519-H-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**425**

No effect	953
No part	134

Total failure rate of the safety function (λ_{Total})	**487**

MTBF	**73 Years**

5.8 NAMUR 6519-W-*** (3/2 way – C) solenoid valve

The FMEDA carried out on the NAMUR 6519-W-*** (3/2 way – C) solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 9: Summary NAMUR 6519-W-* (3/2 way – C) solenoid valve- IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**411**

No effect	879
No part	133

Total failure rate of the safety function (λ_{Total})	**473**

MTBF	**77 Years**

5.9 NAMUR 6519-W-*** (5/2 way – H) solenoid valve

The FMEDA carried out on the NAMUR 6519-W-*** (5/2 way – H) solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 10: Summary NAMUR 6519-W-* (5/2 way – H) solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**62**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**421**

No effect	859
No part	133

Total failure rate of the safety function (λ_{Total})	**483**

MTBF	**77 Years**

5.10 4/2 way 5470-G-*** solenoid valve

The FMEDA carried out on the 4/2 way 5470-G-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 11: Summary 5470-G-* solenoid valve - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**55**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**231**

No effect	724
No part	3

Total failure rate of the safety function (λ_{Total})	**286**

MTBF	**113 Years**

5.11 2/2 way Servo-assisted diaphragm valve 0290-A-***

The FMEDA carried out on the 2/2 way 0290-A-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 12: Summary Servo-assisted diaphragm valve 0290-A-* - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**52**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**87**
No effect / No part	83
Total failure rate of the safety function (λ_{Total})	**139**
MTBF	**517 Years**

5.12 2/2 way Servo-assisted piston valve 5404-A-***

The FMEDA carried out on the 2/2 way 5404-A-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 13: Summary Servo-assisted piston valve 5404-A-* - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**87**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**66**

No effect / No Part	183

Total failure rate of the safety function (λ_{Total})	**153**

MTBF	**341 Years**

5.13 2/2 way direct-acting plunger valve 6027-A-***

The FMEDA carried out on the 2/2 way 6027-A-*** solenoid valve leads under the assumptions described in sections 4.2.3 and 5 to the following failure rates:

Table 14: Summary direct-acting plunger valve 6027-A-* - IEC 61508:2010 failure rates**

Failure category	Failure rate [FIT]
Fail Safe Detected (λ_{SD})	**0**
Fail Safe Undetected (λ_{SU})	**40**
Fail Dangerous Detected (λ_{DD})	**0**
Fail Dangerous Undetected (λ_{DU})	**54**
No effect / No Part	210
Total failure rate of the safety function (λ_{Total})	**94**
MTBF	**381 Years**

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6 Using the FMEDA results

It is the responsibility of the Safety Instrumented Function designer to do calculations for the entire SIF. *exida* recommends the accurate Markov based exSILentia tool for this purpose.

The following section describes how to apply the results of the FMEDA.

6.1 Example PFD_{AVG} calculation

The following 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).

An average Probability of Failure on Demand (PFD_{AVG}) calculation is performed for a single (1oo1) 5/2 way 6519-H-*** solenoid valve with *exida's* exSILentia tool. The failure rate data used in this calculation are displayed in section 5.7 (worst-case results). A mission time of 10 years has been assumed, a Mean Time To Restoration of 24 hours and a maintenance capability of 100%. Table 15 lists the results for different proof test interval considering a proof test coverage of 99% (see Appendix 1).

Table 15: PFD_{AVG} values

T[Proof] = 1 year	T[Proof] = 2 years	T[Proof] = 5 years
PFD_{AVG} = 2.02E-03	PFD_{AVG} = 3.86E-03	PFD_{AVG} = 9.34E-03

For SIL1 the overall PFD_{AVG} shall be better than 1.00E-01. As the 5/2 way 6519-H-*** solenoid valve is contributing to the entire safety function it should only consume a certain percentage of the allowed range. Assuming 10% of this range as a reasonable budget it should be better than or equal to 1.00E-02. The calculated PFD_{AVG} values are within the allowed range for SIL 1 according to table 2 of IEC 61508-1 and do fulfill the assumption to not claim more than 10% of the allowed range, i.e. to be better than or equal to 1.00E-02 for a proof test interval of 1 year.

The resulting PFD_{AVG} graph generated from the exSILentia tool for a proof test of 1 year is displayed in Figure 9.

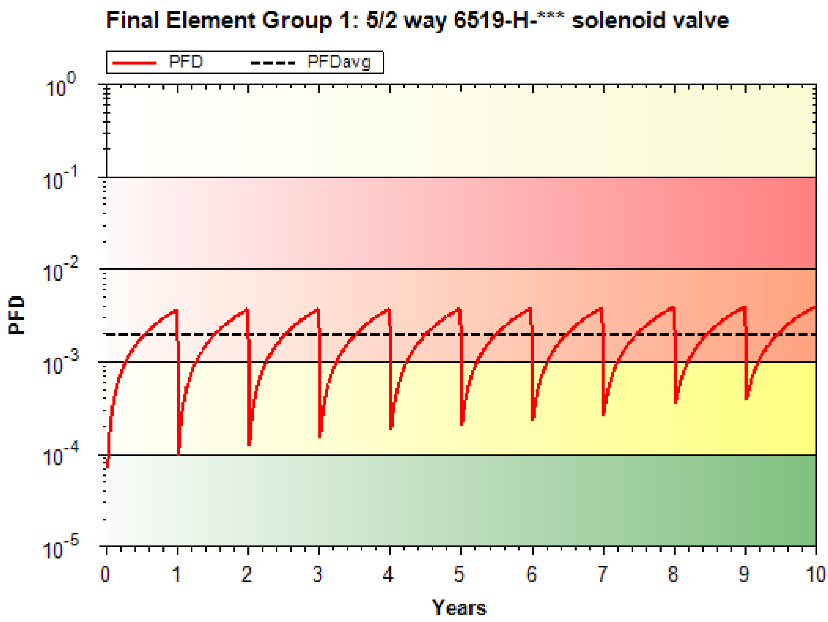


Figure 9: PFD_{AVG} value with proof test interval of 1 year

6.2 *exida* Route 2_H Criteria

IEC 61508:2010 2nd edition 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 undertake 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 61508:2010 2nd edition 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 of 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" versus "systematic" are checked by *exida*; and
5. every component used in an FMEDA meets the above criteria.

This set of requirements

7 Terms and Definitions

FIT	Failure In Time (1x10^{-9} failures per hour)
FMEDA	Failure Modes, Effects, and Diagnostic Analysis
HFT	Hardware Fault Tolerance
Low demand mode	Mode, where the demand interval for operation made on a safety-related system is greater than twice the proof test interval.
MTTR	Mean Time To Restoration
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
Type A element	"Non-complex" element (all failure modes are well defined); for details see 7.4.4.1.2 of IEC 61508-2
T[Proof]	Proof Test Interval

8 Status of the document

8.1 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.

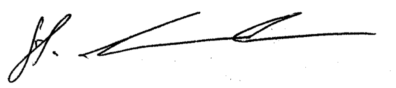
Most products also tend to undergo incremental changes over time. If an *exida* FMEDA has not been updated within the last three years and the exact results are critical to the SIL verification you may wish to contact the product vendor to verify the current validity of the results.

8.2 Releases

Version History:	V4R1:	Added valves 0290-*-***, 5404-*-***, 6027-*-***; Assessment changed from route 1H to route 2H; March 2020
	V3R2:	Additional valve added, November 22, 2013
	V3R1:	Editorial changes; May 2, 2013
	V3R0:	Updated according to IEC 61508:2010 2nd edition; May 2, 2013
	V2, R1.0:	Additional valves added; January 30, 2006
	V1, R1.0:	Released version; December 9, 2005
	V0, R2.0:	Internal review comments incorporated; December 5, 2005
	V0, R1.0:	Initial version; November 11, 2005
Authors:	Philipp Hanzik	
Review:	V0, R1.0:	Rachel Amkreutz (*exida*); December 1, 2005
	V0, R2.0:	Otto Walch (Bürkert); December 9, 2005
Release status:	Released to Bürkert Werke GmbH & Co. KG	

8.3 Release Signatures

Philipp Hanzik, Safety Engineer



Dipl.-Ing. (Univ.) Stephan Aschenbrenner, Partner, CEO

Appendix 1: Possibilities to reveal dangerous undetected faults during the proof test

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 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.

Appendix 1 shall be considered when writing the safety manual as it contains important safety related information.

The proof test consists of a full stroke of the solenoid, as described in Table 15.

Table 16 Steps for proof test

Step	Action
1	Bypass the safety function and take appropriate action to avoid a false trip.
2	Send a signal to the solenoid to perform a full stroke and verify that this is achieved.
3	Inspect the solenoid for any visible damage or contamination.
4	Remove the bypass and otherwise restore normal operation.

It is assumed that this proof test will detect 99% of possible “du” failures in the device.

Appendix 2: Impact of lifetime of critical components on the failure rate

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 4.2.3) this only applies provided that the useful lifetime of components is not exceeded. Beyond their useful lifetime, the result of the probabilistic calculation method is meaningless, as the probability of failure significantly increases with time. The useful lifetime is highly dependent on the component itself and its operating conditions – temperature in particular (for example, electrolyte capacitors can be very sensitive).

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

It is assumed that early failures are detected to a huge percentage during the installation period and therefore the assumption of a constant failure rate during the useful lifetime is valid.

Based on general field failure data, a useful life period of approximately 10 to 15 years or longer is expected for the valves.

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

Major factors influencing useful life are the air quality, ambient temperature and the air circulation around the solenoid.

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

If the assessed solenoid valves are used with clean air in an ambient with air circulation (draft air) and an ambient temperature average of 40ºC, then a lifetime of 10 years is expected.

Appendix 3: *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]						
80MHz to 1.4 GHz	10V /m	10V /m	10V /m	10V /m	10V /m	N/A
1.4 GHz to 2.0 GHz	3V/m	3V/m	3V/m	3V/m	3V/m	
2.0Ghz to 2.7 GHz	1V/m	1V/m	1V/m	1V/m	1V/m	
ESD (Air)[11]	6kV	6kV	6kV	6kV	6kV	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 6100-4-3
[11] ESD (Air) rating per IEC 61000-4-2