Functional safety:
Safety-relevant temperature measurement per IEC 61508

Introduction

Under certain conditions, electrical thermometers can be used in a safety-related system in accordance with IEC 61508. The version of the electrical thermometer as resistance thermometer or thermocouple as well as the technical features of the used temperature transmitter have to be taken into account for the evaluation of the safety-related system.

This technical information describes the basics of functional safety in accordance with IEC 61508 and offers advice on the safety-related design of a temperature measuring point.

Need for risk reduction

Due to rising expectations of society on the safety of technical plants, the risks presented from technical systems have been ever more reduced over time. Guidelines and standards have been created to help every plant operator to operate his or her plant to the highest levels of safety. Conducting accident analyses and risk assessments is the basis for this. The aim is to reduce the risk presented by a technical system to an acceptable risk in line with society´s values by means of safety measures.

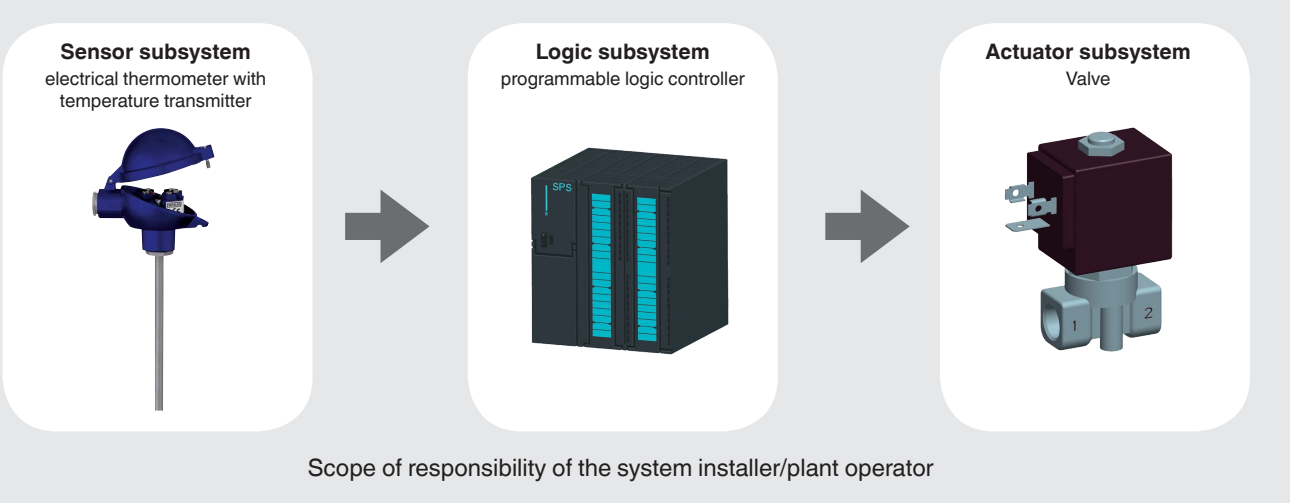
To prevent a failure to danger in a plant, electrical/electronic/programmable electronic systems (E/E/PE systems) are employed. The totality of all required safety functions which serve towards maintaining the safe state of a plant is referred to as a safety instrumented system SIS or safety-related system.

An example of such a safety system is a temperature monitoring system that, when the temperature limits are exceeded, reliably shuts down the power supply of a plant, placing it in the safe state and thus preventing a hazardous event.

Architecture of a safety-related system

An electrical/electronic/programmable electronic system basically consists of the elements of sensor, controller and actuator. In this case one refers to a single-channel architecture of the safety system (1oo1 system). The architecture describes the specific configuration of hardware and software elements in a system. A 1oo1 system indicates that the system is made up of one channel, which must operate safely so that the safety function can be performed (1 out of 1). For safety systems with multi-channel architecture, hardware or software elements are implemented with redundancy (see “Redundant systems”).

Example of a single-channel architecture for a safety instrumented system



An electrical thermometer with models T32.1S temperature transmitter (head mounting version) and T32.3S (rail mounting version) can be used by the plant operator as a sensor subsystem of a safety instrumented system.

Temperature transmitter, model T32.xS

Legislative basis

The IEC 61508 series of standards “Functional safety of electrical/electronic/programmable electronic safety-related systems” is referred to as a fundamental safety standard. It describes the measures for the prevention and containment of failures in instruments and plants and can be used irrespective of the industry sector.

IEC 61508 should be used in particular when
- the safety function is implemented through an E/E/PE system
- a failure of the safety instrumented system will lead to a hazard to people and the environment
- no application-specific standard exists for the design of safety systems

IEC 61508 represents the state of the art with respect to the design of safety instrumented systems. With the design of safety systems, the best available technology, and thus IEC 61508, absolutely must be followed.

For planners, contractors and operators of the safety system, there are also application-specific standards. These are, for example, IEC 61511 “Functional safety - safety instrumented systems for the process industry sector” for the process industry and EN 62061 “Safety of machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems” for machine building.

An electrical thermometer can be used in a safety instrumented system in accordance with the IEC 61508 standard when the thermometer is used in conjunction with a temperature transmitter certified for safety-relevant applications. The model T32.xS temperature transmitter from WIKA has been developed with reference to IEC 61508 for use in the process industry and certified by TÜV Rheinland for this application.

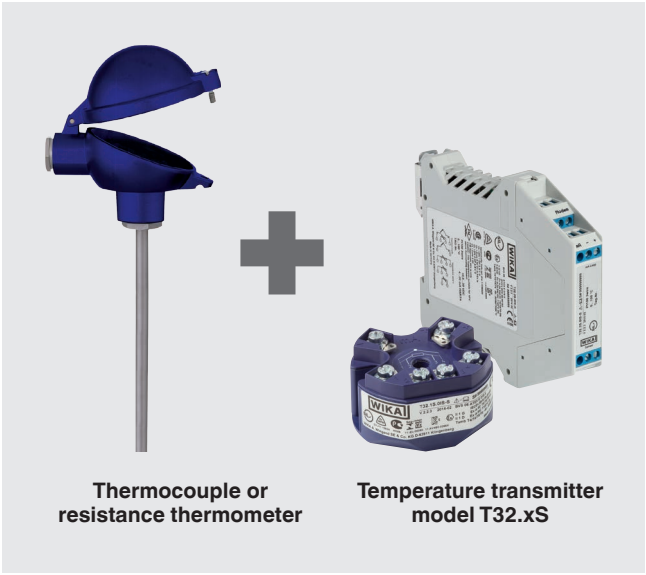
An electrical thermometer without a temperature transmitter, for example a resistance thermometer or a thermocouple, is not covered by IEC 61508, since (for example) a measuring resistor is a simple electrical component that cannot perform any self-diagnostics nor detect errors.

For electrical thermometers without a temperature transmitter certified to IEC 61508, only failure rates can be specified. This is because it always depends on the operator's evaluation instrument as to what failure types can be detected and safely recognised in the electrical thermometer.

With the certification of the model T32.xS temperature transmitter, the temperature transmitter has been considered in connection with an electrical thermometer. In the safety manual “Information on functional safety for temperature transmitter model T32.xS”, safety-relevant characteristic values for the temperature transmitter, the connected temperature sensors and the entire assembly are specified.

For the evaluation, the sensor subsystem is divided into the elements “electrical thermometer (temperature sensor)” and “temperature transmitter”. The temperature sensors are classified as type A components (elementary component) and the temperature transmitter as type B components (complex component).

Sensor subsystem consisting of temperature transmitter and temperature sensor



Thermocouple or resistance thermometer | **Temperature transmitter model T32.xS**

Evaluation of safety-related systems

The probability that a safety function on demand is carried out (i.e. when a system fault occurs) is defined by the safety integrity. To obtain a measure of the requirements for safety integrity, these are divided into four Safety Integrity Levels (SIL). If SIL 4 is achieved, the probability that the safety function is executed is at its maximum, and thus the maximum possible risk reduction is ensured.

Levels of safety integrity

The term “SIL” is thus an important parameter of the safety system, but is often used as a synonym for “Functional Safety”.

The safety integrity level always refers to the entire safety system. An element has no SIL, but may still be suitable for a SIL application. For example, the model T32.xS temperature transmitter alone does not form a safety-related system. The operator is responsible for defining and maintaining the required safety integrity level as well as the entire safety system and the individual elements!

WIKA, as a manufacturer of electrical thermometers, supports the user in this. On the one hand, by confirming that the requirements of IEC 61508 have been met, such as during the development of the T32.xS. On the other hand, the operator can be provided with the appropriate safety-related characteristic data for the plant design and the evaluation of the safety function.

Requirements on a safety system

In order to design a temperature measuring point which is optimised for a safety-related system, the following aspects must be considered:

- The safe state of the plant and the safety function of each element must be defined by the plant operator.
- The required safety integrity level must be determined by the operator of the safety system through a risk assessment, e.g. with risk graphs.
- The thermometer's operating conditions (process medium, environmental influences) should be sufficiently specified so that the temperature measuring point can be designed optimally in cooperation with WIKA.
- The instructions in the WIKA documentation about the thermometer used must be observed.
- Ensure that wetted parts are suitable for the measuring medium.

Fundamental for optimal safety at the temperature measuring point is the correct design of the electrical thermometer, corresponding to the requirements of the process. The next step is the selection of a temperature transmitter suitable for safety systems, that detects as many fault types as possible of the electrical thermometer and of the transmitter itself.

Determination of the maximum achievable safety integrity level with the example of the temperature transmitter model T32.xS

To determine the safety integrity level of a safety-related system, both the requirements for systematic safety integrity and the hardware safety integrity must be determined.

Systematic safety integrity

To fulfil the requirements for systematic safety integrity, systematic failures must be taken into account. Systematic failures are design faults, manufacturing faults or operating faults. To reduce these, IEC 61508 specifies safety measures that must be maintained throughout the full service life (product lifecycle) of a technical system. The safety life cycle of safety systems begins with the conception and ends with the decommissioning. As part of the safety management during the development of the T32.xS, systematic failures were prevented, for example, by means of validation and verification activities as well as planning and thorough documentation. Thus the software of model T32.xS even fulfils the criteria for SIL 3 concerning safety integrity.

Hardware safety integrity

Random faults

To evaluate the hardware safety integrity, random faults must be observed. These are caused by random changes of a component's behaviour, e. g. open circuit, short circuit or random change in value of a capacitor in an electrical circuit. Random faults cannot be avoided. Only the probability of the occurrence of such a fault can be calculated. The failure rate is given in the unit FIT (Failures in Time).

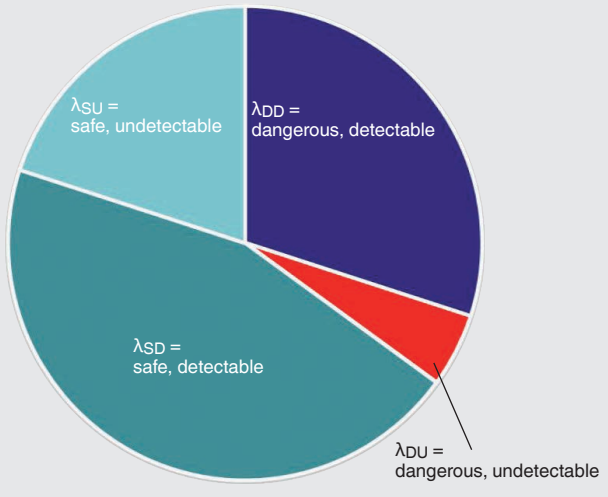
It is defined as: $1\ FIT = 10^{-9}\ \frac{1}{h}$

The totality of all failures in a time interval at a constant rate of failure is referred to as the base failure rate λ_B. The base failure rate is composed of hazardous faults λ_D = dangerous, and non-hazardous faults λ_S = safe, that have an impact on the safety function.

$$\lambda = \lambda_S + \lambda_D$$

Depending on whether a fault, for example, can be detected through a diagnostic function of the electronics in the safety system or remains undetected, the hazardous and non-hazardous faults are further divided.

Sub-division of failure rates



Failure types in an electrical thermometer

The following failures can occur in an electrical thermometer:
- Open circuit - the measuring circuit is interrupted
- Short circuit - two connecting cables are connected unintentionally
- Drift due to changes in the resistor material or drift in the thermoelectric voltage
- Change in the lead resistance, e.g. through temperature changes

Depending on the fault detection functions of the temperature transmitter used, the type of failure (λ_{SD}, λ_{SU}, λ_{DD}, λ_{DU}) for different faults in the electrical thermometer must be defined.

Table 1: Fault detection through the temperature transmitter model T32.xS

Possible failure cases in electrical thermometers	Resistance thermometer, 2-wire connection	Resistance thermometer, 3-wire connection	Resistance thermometer, 4-wire connection	Thermo-couple
Open circuit	λ_{DD}	λ_{DD}	λ_{DD}	λ_{DD}
Short circuit	λ_{DD}	λ_{DD}	λ_{DD}	**λ_{DU}**
Drift	**λ_{DU}**	**λ_{DU}**	**λ_{DU}**	**λ_{DU}**
Change in the lead resistance	**λ_{DU}**	λ_{DD} [1)]	λ_{DD}	λ_{DD}

1) A change of the lead resistance in a 3-wire connection can only be detected based on the understanding that the connecting cables between the measuring resistor and transmitter are the same length and have the same conductor cross-section.

In the literature, the failure rates for thermocouples and resistance thermometers are given in different applications and configurations. The failure rates are based on the “worst case” of a thermometer failure and serve as guidance for the design of safety instrumented systems. The failure rates should be used taking into account the operating conditions and the connecting cable between the measuring point and the transmitter. They are differentiated in accordance with the vibration requirements at the site of operation (low stress/ high stress) and on the type of connection between the measuring point and temperature transmitter (close-coupled/ extension wire) (see “Definitions and abbreviations”).

Table 2: Failure rates for thermocouples without temperature transmitter [2)]

Type of fault	Close coupled		Extension wire	
	Low stress	High stress	Low stress	High stress
Open circuit	95 FIT	1,900 FIT	900 FIT	18,000 FIT
Short circuit	4 FIT	80 FIT	50 FIT	1,000 FIT
Drift	1 FIT	20 FIT	50 FIT	1,000 FIT

2) The stated failure rates are based on calculations by WIKA using key basic data from exida.com L.L.C. (see page 12 “Literature and sources”, “Exida”)

Table 3: Failure rates for resistance thermometers with 4-wire connection without temperature transmitter [2)]

Type of fault	Close coupled		Extension wire	
	Low stress	High stress	Low stress	High stress
Open circuit	42 FIT	830 FIT	410 FIT	8,200 FIT
Short circuit	3 FIT	50 FIT	20 FIT	400 FIT
Drift	6 FIT	120 FIT	70 FIT	1,400 FIT

Table 4: Failure rates for resistance thermometers with 2- or 3-wire connection without temperature transmitter [2)]

Type of fault	Close coupled		Extension wire	
	Low stress	High stress	Low stress	High stress
Open circuit	38 FIT	758 FIT	371 FIT	7,410 FIT
Short circuit	1 FIT	29 FIT	10 FIT	190 FIT
Drift	9 FIT	173 FIT	95 FIT	1,900 FIT

2) The stated failure rates are based on calculations by WIKA using key basic data from exida.com L.L.C. (see page 12 “Literature and sources”, “Exida”)

Limitation of the safety integrity level of an element

The maximum achievable SIL of an element of the safety system is limited by the following factors:

- Proportion of safe failures of a hardware element (Safe Failure Fraction, SFF)
- Hardware Fault Tolerance (HFT)
  The hardware fault tolerance represents a measure of the degree of redundancy of the safety system. With a hardware fault tolerance of N, N+1 is the minimum number of errors that could lead to the loss of a safety function. A safety instrumented system with single-channel architecture has a hardware fault tolerance of 0.
- Complexity of the components (type A and B components)
  - Type A components are primary components whose failure performance is fully defined and whose malfunction is identified. Type A components are, for example, resistance temperature sensors and thermocouples.
  - For complex type B components, the failure performance of at least one component is not defined, or not fully defined. A type B component is, for example, an electronic circuit containing a microprocessor. The T32.xS temperature transmitter is defined as a type B component (see table 5).

In order to calculate the SFF value of resistance temperature sensors and thermocouples which are connected to the T32.xS temperature transmitter, the failure rates of the temperature sensors should be subdivided into the categories (λ_S, λ_{DD}, λ_{DU}), taking into account the diagnostic function of the transmitter. Consequently, the SFF value can be calculated according to the following formula:

$$SFF = \frac{\lambda_{DD} + \lambda_S}{\lambda_{DU} + \lambda_{DD} + \lambda_S}$$

Thus temperature sensors defined as type A components in a single-channel architecture (HFT = 0) should be used in safety instrumented systems up to SIL 2, and an SFF ≥ 60 % is maintained in accordance with table 5. For the same application, for the T32.xS temperature transmitter as type B components, an SFF ≥ 90 % is required.

Table 5: Maximum safety integrity level of a component dependent on the hardware fault tolerance, the complexity of the components and the safe failure fraction

SFF	Hardware fault tolerance					
	0		1		2	
	Type A	Type B	Type A	Type B	Type A	Type B
< 60 %	SIL 1	not allowed	SIL 2	SIL 1	SIL 3	SIL 2
60 … < 90 %	SIL 2	SIL 1	SIL 3	SIL 2	SIL 4	SIL 3
90 … < 99 %	SIL 3	SIL 2	SIL 4	SIL 3	SIL 4	SIL 4
≥ 99 %	SIL 3	SIL 3	SIL 4	SIL 4	SIL 4	SIL 4

Only if the SFF value of both the temperature transmitter and also the temperature sensor meet the specified limit are these elements permissible for safety instrumented systems with the corresponding SIL. In addition, the PFD value of the entire safety function must satisfy the requirements of table 6.

Limitation of the SIL of the entire safety system

The IEC 61508 standard specifies values that limit the safety integrity level of the entire safety system. Depending on how often the safety system is required, two characteristic values are differentiated:

- **PFH** (probability of dangerous failure per hour

Average frequency of a dangerous failure of the safety function for an operating mode with high or continuous demand rates (high demand). These modes are particularly relevant for machine building.

- **PFD_{avg}** (probability of failure on demand)

Average probability of dangerous failure on demand of a safety function for an operating mode with low demand rate (low demand).

T_{proof} indicates the interval of the repeat testing. After this interval, through a suitable test (proof test), the system is brought to an almost "as new" state within the stipulated service life. With this test, dangerous, undetectable faults can also be detected. For an electrical thermometer, it is ensured by regular calibration that the measured value still lies within the required accuracy. With this, an unacceptably high drift is also excluded.

With a proof test interval of one year (T_{proof} = 8,760 h) the following PFD_{avg} values result for a resistance thermometer with 4-wire connection and a model T32.xS temperature transmitter connected:
- Ambient condition: low stress
- Connection between measuring point and transmitter: close coupled
- Failure rate λ_{DU} = 16 FIT [3)]

$$PFD_{avg} = 0{,}5 * \lambda_{DU} * T_{proof}$$
$$= 0{,}5 * 16\ FIT * 8760\ h = 7{,}15 * 10^{-5}$$

Thus this combination, with respect to the requirements on the PFD_{avg} value, is suitable for safety systems with increased safety integrity level to SIL 2, however, due to the single-channel structure (see "Limitation of the safety integrity level of an element") and the SFF, it is limited to SIL 2.

The formula described above is derived from IEC 61508. It is assumed that the time period of 8 hours, which is required for the renovation of the system is negligibly small in comparison with the proof test interval of 8,760 h.

The PFD_{avg} value conforms almost linearly to the proof test interval, T_{proof}. The shorter the proof test interval, the better the PFD_{avg} value achievable. Likewise, the proof test interval can be increased if the PFD_{avg} value of the entire system is lower than the permissible limit value. If the proof test interval is shortened to 0.5 years, the PFD_{avg} value is halved, and if it is extended to 2 years, it is doubled.

The smaller the PFD_{avg} or PFH value, the greater the achievable SIL of the entire system. In table 6 the PFD_{avg} or PFH characteristic values are assigned a safety integrity level.

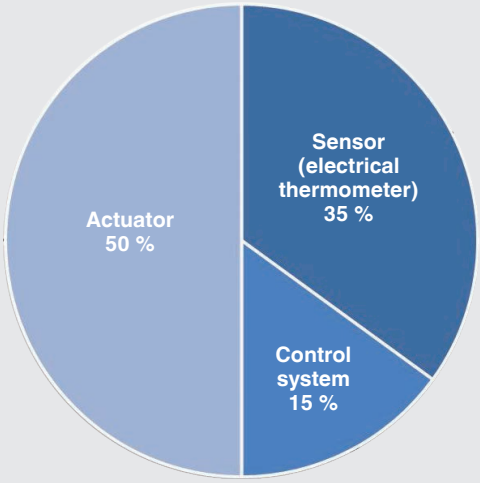
Table 6: Limitation of the SIL of the safety system by PFD_{avg} and PFH values

Safety Integrity Level (SIL)	Average probability of a dangerous failure on demand of a safety function (PFDavg)	Average frequency of a dangerous failure per hour (PFH)
4	≥ 10^{-5} to < 10^{-4}	≥ 10^{-9} to < 10-8 h^{-1}
3	≥ 10^{-4} to < 10^{-3}	≥ 10^{-8} to < 10^{-7} h^{-1}
2	≥ 10^{-3} to < 10^{-2}	≥ 10^{-7} to < 10^{-6} h^{-1}
1	≥ 10^{-2} to < 10^{-1}	≥ 10^{-6} to < 10^{-5} h^{-1}

3) see page 12 "Literature and sources" and page 18-20 in the safety manual "Information on functional safety for temperature transmitter model T32.xS"

For the operator of the system, it is always the PFD_{avg} value of the entire safety system and not the value of a single element that is relevant. For evaluation, the following distribution of the PFD_{avg} values for the safety system has been established as a guideline:

Distribution of sensor, controller, actuator in the total PFD value of the SIS



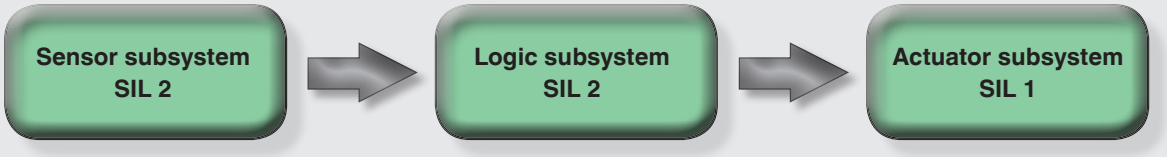
A different distribution of the components can be specified by the plant operator.

If the sensor uses less than 35 % of the maximum allowable PFD_{avg} value of the safety system, such as for an electrical thermometer with a model T32.xS temperature transmitter, then the operator can use a controller and an actuator with correspondingly poorer PFD_{avg} values.

Structural limitations

Structural characteristics of the safety instrumented system may limit the maximum achievable SIL. In a single-channel architecture, the maximum SIL is determined by the weakest link. In the safety system illustrated, the “sensor” and “logic” subsystems are suitable for SIL 2, while the “actuator” subsystem is only suitable for SIL 1. The entire safety system can therefore only achieve a maximum of SIL 1.

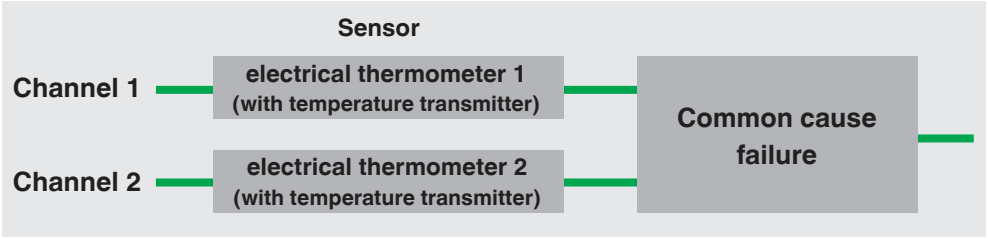
Components of a safety-related system



Redundant systems

If two electrical thermometers with model T32.xS temperature transmitter are assembled in parallel, common cause failures must be considered. Common cause failures can occur, for example, when environmental conditions or EMC interferences influence several channels simultaneously. These faults affect all channels of a redundant system at the same time.

Reliability block diagram: electrical thermometer in redundant configuration



The electrical thermometers from the previous figure represent, in this case, a two-channel architecture (1oo2) system. Such a structure is referred to as MooN system. A MooN system (M out of N) consists of N independent channels, of which M channels must function safely in order that the entire system can perform the safety function.

The occurrence of common cause failures is less likely if the two electrical thermometers with temperature transmitters used are as diverse as possible with respect to construction, measuring principle and software. Thus, for example, a resistance thermometer can be used for one channel and a thermocouple may be used for the other channel. For measuring, one thermowell can be used for the resistance thermometer and another for the thermocouple, or a single thermowell can be used for both. When using a single thermowell, the common cause failures are correspondingly more likely. A higher diversity is additionally achieved when the temperature transmitters used are from different manufacturers and differ in their construction as well as their software.

In particular, the WIKA model T32.xS temperature transmitter has the advantage that it can be used in homogeneous redundant systems up to SIL 3. This means that an electrical thermometer with a model T32.xS temperature transmitter is connected in parallel with a second thermometer with a structurally identical transmitter. In a single-channel architecture, the transmitter is suitable up to SIL 2. Due to the complete development and certification of the model T32.xS temperature transmitter to all elements of the IEC 61508 standard (Full-Assessment Development), the transmitter is also suitable in a homogeneous redundant assembly for SIL 3 applications. Even during the development, the measures for fault avoidance in the software have been designed for use in SIL 3 applications. Thus, the model T32.xS temperature transmitter differs from operationally proven instruments that are only suitable for SIL applications on the basis of earlier use.

Operationally proven field instruments in a two-channel architecture achieve, as a maximum, the SIL of the individual instrument. Unlike the model T32.xS temperature transmitter, systematic faults in these instruments are not prevented or reduced in the first place, e.g. during the development of the instrument.

To account for the effect of common cause failure, a “β factor” is needed to calculate the PFD value of redundant systems. The β factor refers to the proportion of undetected common cause failures. In accordance with IEC 61508-6 and taking into account that the period of 8 h, which is needed for the renovation of the system, is negligibly small compared to the proof test interval of 8,760 h, the PFD value for a 1oo2 structure is calculated using the following simplified formula:

$$PFD_{1oo2} = \frac{\lambda_{DU}^2 * T_{proof}^2}{3} + 0{,}5 * \lambda_{DU} * T_{proof} * \beta$$

To determine the β factor, measures must first be defined that reduce the occurrence of common cause failures. Through engineering assessment it must be defined, in cooperation with WIKA, the extent to which each measure reduces the occurrence of common cause failures.

Summary of recommendations

For the best possible design of a temperature measuring point for safety-related applications, the requirements in the chapter “Requirements for a safety system” must be followed.

Furthermore, in safety applications, it is recommended that the model T32.xS temperature transmitter (head-mounted or rail-mounted version) is used in conjunction with a resistance thermometer in 4-wire connection or with a thermocouple. Through the extensive diagnostic features of the T32.xS and the benefits of a 4-wire connection, a high safety in the temperature measurement is guaranteed.

To protect the measuring insert from the process medium and to enable a quick and easy calibration of the electrical thermometer, protective thermometer fittings with exchangeable measuring inserts should be used. It is important to pay particular attention to the proper design of the thermowell in accordance with the requirements of the process.

Literature and sources

1.) IEC 61508:2010:
Functional safety of safety-related electrical/electronic/programmable electronic systems
Beuth Verlag GmbH, 10772 Berlin

2.) Exida:
Safety Equipment Reliability Handbook - 3rd Edition, 2012, exida.com L.L.C.

3.) WIKA Alexander Wiegand SE & Co. KG:
Safety manual “Information on functional safety for temperature transmitter model T32.xS” (from firmware revision 2.2.3)

Abbreviations and definitions

Abbreviation	Definition
Close coupled	The temperature transmitter is located in the connection head of the electrical thermometer (head-mounted).
DC	Diagnostic coverage
Extension wire	The temperature transmitter is located outside of the connection head of the electrical thermometer, and is located, for example, in a cabinet distant from the measuring point (remote-mounted).
FIT	Failures in time
HFT	Hardware Fault Tolerance
High Stress	Applications with vibration (≥ 67 % of the maximum vibration resistance of the electrical thermometer)
Low stress	Low vibration (< 67 % of the maximum vibration resistance of the electrical thermometer)
PFD_{avg}	Average probability of a dangerous failure on demand of the safety function
PFH	Average frequency of a dangerous failure of the safety function
RTD	“**R**esistance **t**emperature **d**etector”; resistance thermometer
SFF	Safe Failure Fraction of a hardware element
SIS	Safety Instrumented System
TC	**T**hermo**c**ouple
TR	“**T**emperature **R**esistance”; resistance thermometer

Impact of the re-evaluation of the temperature transmitter model T32.xS (from firmware revision 2.2.3) on the safety-relevant characteristic values

Within the scope of the re-evaluation, no safety-related changes were carried out on the temperature transmitter. The diagnostic coverage of the transmitter remains unchanged. Only the new assessment approach led to a change in the safety-relevant characteristic values.

New edition of the IEC 61508 standard
Since the initial assessment of the model T32.xS temperature transmitter, the base standard for functional safety, IEC 61508 "Functional Safety of Electrical/Electronic/ Programmable Electronic Safety-related Systems" has been updated to the revision IEC 61508:2010. From firmware revision 2.2.3, the T32.xS will be evaluated against this edition of the standard.

Updated failure rates
In this context, the FMEDA (Failure Modes, Effects and Diagnostic Analysis) was also repeated with current component failure rates. The calculations were based on component failure rates in accordance with SN29500. For the temperature resistance sensors and thermocouples connected to the temperature transmitter, the failure rates determined by exida.com LLC were used.

Elemental analysis of the "sensor" subsystem
With the introduction of the term "element" into IEC 61508-4:2010 Section 3.4.5, the interconnection of the temperature transmitter and electrical thermometer as a "sensor" subsystem was considered and evaluated as follows:

Element 1	**Element 2**
Electrical thermometer without transmitter (thermocouple or resistance thermometer) Type A / SFF ≥ 60 % for HFT = 0 and SIL 2	Model T32.xS temperature transmitter (without thermocouple or resistance thermometer) Type B / SFF ≥ 90 % for HFT = 0 and SIL 2

This separate consideration affects the assessment of the SFF value. For example, the required SIL 2 SFF value for thermocouples or resistance thermometers drops to 60 %.

Application-specific failure rates
With the re-evaluation of the T32.xS the failure rates are defined specifically for the application, depending on the vibration levels at the point of installation of the electrical thermometer and dependent on the connection of the thermometer to the transmitter. Furthermore, failure rates for the "stand alone" temperature transmitter are calculated for different configurations.

Rather improved failure rates
The failure rates of the T32.xS transmitter with connected thermocouple or resistance sensor have shown a trend of improvement. In particular, for the conditions of "low stress, close coupled", the failure rate for hazardous, non-detectable failures has decreased.

Effects on the PFD_{avg} value
Especially for the application condition "low stress, close coupled", the PFD_{avg} value has improved. This allows the user, if required, to use logic or actuating subsystems with correspondingly larger PFD_{avg} values in the safety instrumented system or to extend the proof testing interval.

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