Technical information

Functional safety:
Safety-relevant temperature measurement per EN 61508

Introduction

Under certain conditions, electrical thermometers can be used in a safety-related system in accordance with EN 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 fundamentals of functional safety in accordance with EN 61508 and gives tips on the safety design for 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.

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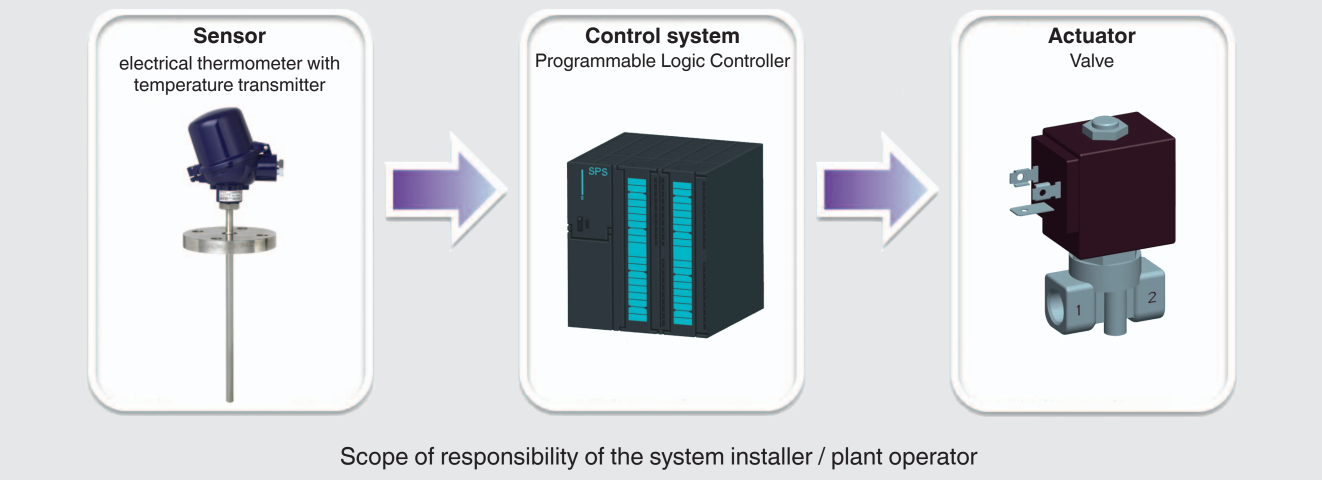
Architecture of a safety-related system

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 (1 out of 1) consists of a channel that has to work safely so that the safety function can be performed. 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


Sensor
electrical thermometer with temperature transmitter
Control system
Programmable Logic Controller
SPS
Actuator
Valve
1
2
Scope of responsibility of the system installer / plant operator

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

Temperature transmitter, model T32.xS

Legislative basis

The EN 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 devices and plants and can be used irrespective of the industry sector.

EN 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

EN 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 EN 61508, absolutely must be followed.

For planners, contractors and operators of the safety system, there are also application-specific standards. These are, for example, EN 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 EN 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 EN 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 EN 61508, since (for example) a measuring resistor is a simple electrical component that cannot perform any self-diagnostics nor detect errors.

Fig. left: Electrical thermometer with transmitter
Fig. right: Electrical thermometer without transmitter

With the certification of the model T32.xS temperature transmitter, the entire assembly with electrical thermometer and temperature transmitter has been considered. In the Safety Manual “Information on functional safety for temperature transmitter model T32.xS”, safety-relevant characteristics for the entire assembly are specified. For electrical thermometers without a temperature transmitter certified to EN 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.

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

SIL1
SIL2
SIL3
SIL4
niedrig
Sicherheitsintegrität
hoch

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, it may only be suitable for a SIL application. For example, the model T32.xS temperature transmitter alone does not form a safety instrumented 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 EN 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 characteristics 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 model T32.xS temperature transmitter

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, EN 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. Within the scope of the safety management, during the development of the T32.xS, systematic errors have been prevented, for example by validation and verification activities as well as through planning and careful documentation. As a result, the software of the model T32.xS temperature transmitter meets the criteria for SIL 3 with reference to the systematic 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).

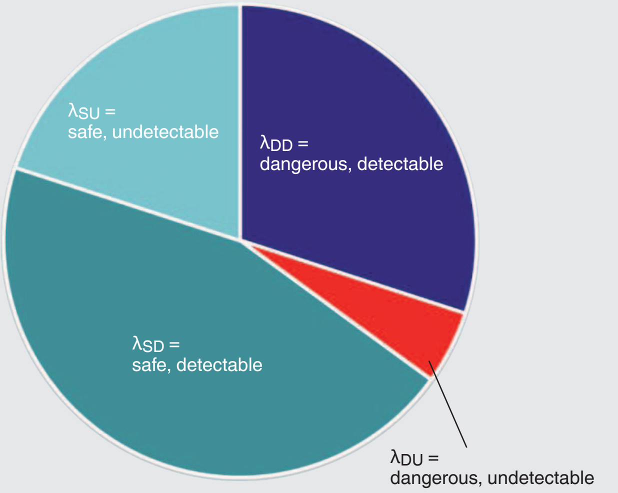
It is defined as: $1\ FIT = 10^{-9}\ \frac{1}{h}$

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 resistance 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 model T32.xS temperature transmitter

Possible failure cases in electrical thermometers	Resistance thermometer, 2-wire connection	Resistance thermometer, 3-wire connection	Resistance thermometer, 4-wire connection	Thermo-couple
Cable 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 leads between the measuring resistance 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.

For thermocouples and resistance thermometers, generally accepted failure rates, based around experience in operation, are stated as follows in the literature (Exida). The failure rates 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	Low stress	High stress
Cable circuit	4,750 FIT	19,000 FIT
Short circuit	0 FIT	0 FIT
Drift	250 FIT	1,000 FIT

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
Cable circuit	1,400 FIT	7,200 FIT	1,400 FIT	5,600 FIT
Short circuit	580 FIT	720 FIT	580 FIT	2,320 FIT
Drift	20 FIT	80 FIT	20 FIT	80 FIT

[2] see page 12 "Literature and sources", "Exida"

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
Cable circuit	1,000 FIT	4,800 FIT	800 FIT	3,200 FIT
Short circuit	600 FIT	800 FIT	600 FIT	2,400 FIT
Drift	400 FIT	1,600 FIT	600 FIT	2,400 FIT

2) see page 12 “Literature and sources”, “Exida”

Internal statistical analyses shows that the failure rate for WIKA resistance thermometers with 3-wire connection at different operating conditions are significantly lower than comparable data in literature. Taking into account the diagnostic functions of the model T32.xS temperature transmitter, the following failure rates are given:

Specific failure rates for WIKA resistance thermometers with 3-wire connection

λ_{du} = 15 FIT
λ_{dd} = 1,985 FIT

Specifically for the model T32.xS temperature transmitter in combination with WIKA model TR or TC thermometers, the following safety-relevant characteristics result. These are determined for the conditions “low stress/close coupled”. Depending on the individually selected proof test interval (T_{proof}), the corresponding characteristic values of the safety system result.

Table 5: Safety-relevant characteristics for an electrical thermometer (models TR and TC) with model T32.xS temperature transmitter, T_{proof} = 1 year

Electrical thermometer	SFF	PFD_{avg}	λ_{du}	λ_{dd}	$\lambda_{su} + \lambda_{sd}$
TR with T32.xS with 2-wire connection	81.2 %	1.815×10^{-3}	414 FIT	1,657 FIT	118 FIT
TR with T32.xS with 3-wire connection	98.6 %	1.316×10^{-4}	30 FIT	2,037 FIT	118 FIT
TR with T32.xS with 4-wire connection	98.6 %	1.482×10^{-4}	34 FIT	2,037 FIT	119 FIT
TC with T32.xS with internal cold-junction compensation	94.9 %	1.162×10^{-3}	265 FIT	4,807 FIT	116 FIT
TC with T32.xS with external cold-junction compensation	90.7 %	2.910×10^{-3}	664 FIT	6,407 FIT	118 FIT
2 x TR with T32.xS with 2-wire connection	98.8 %	2.495×10^{-4}	57 FIT	4,017 FIT	119 FIT
2 x TC with T32.xS with internal cold-junction compensation	95.3 %	2.262×10^{-3}	516 FIT	9,557 FIT	117 FIT

Table 6: Safety-relevant characteristics of an electrical thermometer (models TR and TC) with model T32.xS temperature transmitter, T_{proof} = 0.5 year

Electrical thermometer	SFF	PFD_{avg}	λ_{du}	λ_{dd}	$\lambda_{su} + \lambda_{sd}$
TR with T32.xS with 2-wire connection	81.2 %	9.075×10^{-4}	414 FIT	1,657 FIT	118 FIT
TR with T32.xS with 3-wire connection	98.6 %	6.580×10^{-4}	30 FIT	2,037 FIT	118 FIT
TR with T32.xS with 4-wire connection	98.6 %	7.410×10^{-5}	34 FIT	2,037 FIT	119 FIT
TC with T32.xS with internal cold-junction compensation	94.9 %	5.810×10^{-4}	265 FIT	4,807 FIT	116 FIT
TC with T32.xS with external cold-junction compensation	90.7 %	1.455×10^{-3}	664 FIT	6,407 FIT	118 FIT
2 x TR with T32.xS with 2-wire connection	98.8 %	1.248×10^{-4}	57 FIT	4,017 FIT	119 FIT
2 x TC with T32.xS with internal cold-junction compensation	95.3 %	1.131×10^{-3}	516 FIT	9,557 FIT	117 FIT

■ 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, resistances.
  - 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 electrical thermometer with temperature transmitter is defined as a type B component.

The safe failure fraction is calculated from the failure rates as follows:

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

The maximum SIL is determined using table 7.

Table 7: Maximum safety integrity level of a component dependent on the hardware fault tolerance, the complexity 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

The SFF value of an electrical thermometer is dependent on the diagnostics functions of the temperature transmitter used. Depending on the hardware fault tolerance and the complexity of a component, the SFF value must meet a defined limit, with which the required SIL can be achieved. If this condition is fulfilled, an element is suitable for this SIL. For the design of a safety-related system, the PFD value of the entire safety function must satisfy the requirements in accordance with table 8.

Limitation of the SIL of the entire safety system

The EN 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). The model T32.xS temperature transmitter is designed for this operating mode, which is mainly used in the process industry.

- T_{proof} indicates the interval of the repeat testing. After this interval, through a suitable test (proof test), the system is brought to an "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} = 34 FIT (see table 5)

$$PFD_{avg} = 0{,}5 * \ \lambda_{DU(Thermometer)} * T_{proof} = 0{,}5 * 34\ FIT * 8760\ h = 1{,}49 * 10^{-4}$$

Thus this combination, with respect to the requirements on the PFD$_{avg}$ value, is suitable for safety systems to SIL 3, 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 (see "Structural limitations").

The formula described above is derived from EN 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.

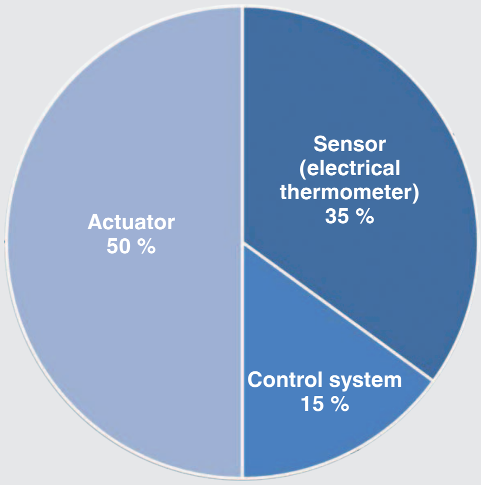
The smaller the PFD$_{avg}$ or PFH value, the greater the achievable SIL of the overall system. In table 8 the PFD$_{avg}$ or PFH characteristic values are assigned a safety integrity level.

Table 8: 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 (PFD$_{avg}$)	Average frequency of a dangerous failure per hour (PFH)
4	$\geq 10^{-5}$ to $< 10^{-4}$	$\geq 10^{-9}$ to $< 10^{-8}$ h^{-1}
3	$\geq 10^{-4}$ to $< 10^{-3}$	$\geq 10^{-8}$ to $< 10^{-7}$ h^{-1}
2	$\geq 10^{-3}$ to $< 10^{-2}$	$\geq 10^{-7}$ to $< 10^{-6}$ h^{-1}
1	$\geq 10^{-2}$ to $< 10^{-1}$	$\geq 10^{-6}$ to $< 10^{-5}$ h^{-1}

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

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



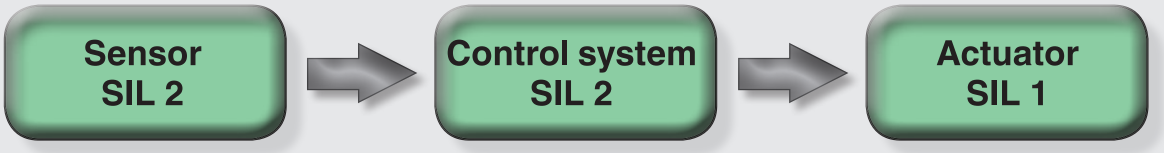
A different distribution of the components can be specified by the plant operator.

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 illustrated safety system, the sensor and controller are suitable for SIL 2, the actuator is only suitable for SIL 1. The overall safety system can therefore only reach a maximum of SIL 1.

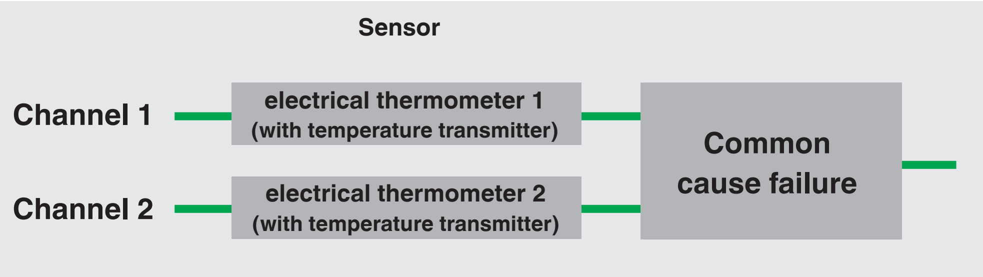
Components of a safety-related system



Redundant systems

If two electrical thermometers with model T32.xS 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 overall system can perform the safety function.

The occurrence of common cause failures is less likely if the two electrical thermometers are used as diversely as possible with the temperature transmitter, 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, a thermowell each can be used for the resistance thermometer and 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 further 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 EN 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 in use devices” that are only suitable for SIL applications on the basis of earlier use. Operationally “proven in use devices” in a two-channel architecture achieve, as a maximum, the SIL of the individual device. Unlike the model T32.xS temperature transmitter, systematic faults in these devices are not prevented or reduced in the first place during the development of the device.

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 EN 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:

$$PFD_{1oo2} = \frac{\lambda^2_{DU(Thermometer)} * T^2_{proof}}{3} + 0{,}5 * \lambda_{DU(Thermometer)} * T_{proof} * \beta$$

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 four-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.

Definitions and abbreviations

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
Low stress	Applications without vibration
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

Literature and sources

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

2.) Exida:
Safety Equipment Reliability Handbook 2003, exida.com L.L.C.

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

The specifications given in this document represent the state of engineering at the time of publishing.
We reserve the right to make modifications to the specifications and materials.

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