# Annex D

# Study of ‘ Used Safety Devices’

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# 1. SCOPE OF THE DOCUMENT– LIMITS OF THE STUDIES

## 1.1 SCOPE OF THE DOCUMENT

The SAFEC project (contract SMT4-CT98-2255) has the overall objective to produce a harmonised system for subdivision of safety devices which are used in potentially explosive atmospheres (see references [1] to [8]), together with a methodology for selecting the appropriate subdivision of safety device for any particular application (see reference [9]).

This report describes the work associated with Task 4 of the SAFEC project whose objective is to study used safety devices identified in task 3, and assess them with regard to their use in flammable atmospheres. This report will deal with the following aspects :

[1] Safety requirements of IEC 61508 standards.

[2] Risk analysis – hazardous event definition.

[3] Safety level assessment procedure.

[4] Application of safety integrity level assessment procedure.

[5] Conclusions.

## 1.2 LIMITS OF THE STUDY

The ATEX Directive covers the following :

[1] Equipment.

[2] Protective systems.

[3] Components.

[4] Safety, controlling or regulating devices.

It is the safety, controlling or regulating devices which are the concern of this project. These will be parts of equipment or protective systems but, unlike components, **they have an autonomous safety function.**

Only safety devices are studied. Studies that assess the explosion risk resulting from a failure of the safety device and from the presence of an explosive atmosphere are the subject of previous tasks 1 and 2.

# 2. SAFETY REQUIREMENTS OF IEC 61508 STANDARD

IEC 61508 standard (see reference [10]) consists of the following parts, under the general title " Functional safety of electrical/ electronic/programmable electronic safety-related systems " :

- Part 1: General requirements
- Part 2: Requirements for electrical/electronic/programmable electronic safety-related systems
- Part 3: Software requirements
- Part 4: Definitions and abbreviations
- Part 5: Examples of methods for the determination of safety integrity levels
- Part 6: Guidelines on the application of IEC 61508-2 and IEC 61508-3
- Part 7: Overview of techniques and measures

This International Standard sets out a generic approach for all safety lifecycle activities for systems comprised of electrical and/or electronic and/or programmable electronic components (electrical/electronic/ programmable electronic systems (E/E/PESs)) that are used to perform safety functions.

Systems intended to fulfil safety functions must meet the following main requirements, in order to be graded in accordance with the safety integrity levels of the IEC 61508 standard (see reference [10]). The main requirements are :

[1] System development cycle requirements around a safety life cycle and in terms of related documentation (part 1 and 2 of reference [10]).

**[2] Qualitative and quantitative technical requirements in the presence of faults (parts 1 and 2 of reference [10]).**

[3] Technical requirements in relation to software design and validation (part 3 of reference [10]).

**Only the validation of the qualitative and quantitative technical requirements in the presence of faults, will be studied in the following for the types of devices identified below.**

## 2.1 SAFETY SYSTEM GRADING - CLASSIFICATION

IEC 61508 requirements are graded according to 6 classes from " a, SIL 1 to SIL 4, b " in which " a " corresponds to " no specific safety requirements ".

These requirements are linked to defect behaviour qualitative requirements and quantitative requirements in terms of fault accumulation and probability of safety function loss.

Safety systems defined in the IEC 61508 standard are graded according to 2 safety related system types :

- Safety related control systems, systems ensuring a check of the monitored parameter (e.g. : motor or relay output) that may enter a dangerous state if the control system fails. **ONLY THESE SAFETY DEVICES ARE UNDER THE SCOPE OF THE SAFEC PROJECT**
- Safety related protection systems, systems designed to react when the checked element is subject to certain conditions, liable to be dangerous. These safety systems operate in order to reduce the risk or prevent hazardous events.

### 2.2 ARCHITECTURAL CONSTRAINTS ON HARDWARE SAFETY INTEGRITY

In the context of hardware safety integrity, the highest safety integrity level that can be claimed for a safety function is limited by the hardware fault tolerance and safe failure fraction of the subsystems that carry out that safety function. The following tables specify the highest safety integrity level that can be claimed for a safety function which uses a subsystem taking into account the hardware fault tolerance and safe failure fraction (see  annex C of IEC 61508 standard, part 2).

The requirements of these tables shall be applied to each subsystem carrying out a safety function and hence every part of the E/E/PE safety related system. With respect to these requirements,

- a hardware fault tolerance of “ N ” means that “ N+1 ” faults could cause a loss of the safety function. In determining the hardware fault tolerance, no account shall be taken of other measures that may control the effects of faults such as diagnostics, and
- where one fault directly leads to the occurrence of one or more subsequent faults, these are considered as a single fault.

A subsystem can be regarded as **type A** if, for the components required to achieve the safety function, the failure modes of all constituent components are well defined; the behaviour of the subsystem under fault conditions can be completely determined; there is sufficient dependable failure data from field experience to show that the claimed rates of failure for detected and undetected dangerous failures are met.

A subsystem shall be regarded as **type B,** if for the components required to achieve the safety function, the failure mode of at least one constituent component is not well defined; or the behaviour of the subsystem under fault conditions cannot be completely determined; or there is insufficient dependable failure data from field experience to support claims for rates of failure for detected and undetected dangerous failures.

The architectural constraints of either the following tables shall apply to each subsystem carrying out a safety function, so that the hardware fault tolerance requirements shall be achieved for the whole of the E/E/PE safety-related system.

Following tables will be applicable to E/E/PE safety-related systems comprising both type A and type B subsystems.

| **Safe failure fraction** | **Hardware fault tolerance** (see note 2) | | |
|---|---|---|---|
| | **0** | **1** | **2** |
| < 60 % | SIL1 | SIL2 | SIL3 |
| 60 % - < 90 % | SIL2 | SIL3 | SIL4 |
| 90 % - < 99 % | SIL3 | SIL4 | SIL4 |
| $\geq$ 99 % | SIL3 | SIL4 | SIL4 |

**Table 1 : Hardware safety integrity : architectural constraints on type A safety-related subsystems**

| **Safe failure fraction** | **Hardware fault tolerance** (see note 2) | | |
|---|---|---|---|
| | **0** | **1** | **2** |
| < 60 % | not allowed | SIL1 | SIL2 |
| 60 % - < 90 % | SIL1 | SIL2 | SIL3 |
| 90 % - < 99 % | SIL2 | SIL3 | SIL4 |
| $\geq$ 99 % | SIL3 | SIL4 | SIL4 |

**Table 2 : Hardware safety integrity : architectural constraints on type B safety-related subsystems**

## 2.3 Quantitative requirements of IEC 61508

Quantitative requirements of the IEC 61508 international standard are established in terms of probability for the safety system to no longer ensure the safety function for which it was designed.

The standard sets goals according to the safety system's operation :

- operation mode on request,
- continuous operation mode.

The “ on request ” operation refers to the use of safety systems for which the frequency of demands is lower than the periodic test frequency. The IEC 61508 standard's quantitative requirements are as follows :

| **Safety integrity level (SIL)** | **“ On request ” operation mode (dangerous failure probability per year)** |
|---|---|
| SIL 4 | $\geq 10^{-5}$ to $< 10^{-4}$ |
| SIL 3 | $\geq 10^{-4}$ to $< 10^{-3}$ |
| SIL 2 | $\geq 10^{-3}$ to $< 10^{-2}$ |
| SIL 1 | $\geq 10^{-2}$ to $< 10^{-1}$ |

**Table 3 : Quantitative requirements of IEC 61508**

## 2.4 Comments on IEC 61508 and SIL levels

In IEC 61508 part 1 chapter 7.6.2.10, it is written that *“ an architecture that is comprised of only a single E/E/PE safety related system of safety integrity level 4 shall be permetted only if :*

*There has been an explicit demonstration, by a combination of appropriate analytical methods and testing, of the safety integrity failure measure ;*

*Or, there has been extensive operating experience of the components used as part of the E/E/PE safety-related system (...), and the is sufficient harware failure data obtained for components used as part of the E/E/PE safety-related system (...).*

In general, in process industries, when a safey integrity level of SIL 4 is required for a safety function, the risk reduction is provided by the three following devices :

- other technology safety-related systems **AND**
- E/E/PE safety-related system **AND**
- external risk reduction facilities.

When a risk reduction can be provided only with a E/E/PE safety-related system (also called Safety Instrumented System SIS), engineers decide to change the design because the risk level is too high.

In addition, the highest safety level claim for safety devices such as safety PLC according to IEC 61508 is SIL 3.

## 2.5 Differences between hardware fault tolerance of IEC 61508 and of ATEX standards

The requirements of hardware fault tolerance of IEC 61508 are defined to their consequence regarding the loss of the safety function. The IEC 61508 requirements regarding fault tolerance and SIL calculations give some construction principles (see chapter 2.2 and 2.3). Those requirements are a measurement of the effectiveness of a safety-related device.

The requirements of hardware fault tolerance of ATEX standards are defined to their consequence regarding the explosion hazard. The ATEX standards requirements regarding fault tolerance are construction principles that have to be applied to the electrical apparatus in order to guarrante that the consequence of the failure will not be a spark or an over heating.

## 2.6 Differences between IEC 61508 safety - reliabilty and of ATEX standards infaillible components

According to EN 50020 and EN 50028 (see references [7] and [8]), if some construction principles are met (for example if the component is working lower than the 2/3 of its maximum characteristics, …), then the component is considered as infaillible.

According to IEC 61508, the safety-level of a safety-device is a part of the reliability of this device (see Figure 2  : Failure distribution according to their effect). In reliability standards and databases (such as CNET (see reference [12]), MIL HDBK 217, …), used for the calculation of the Safety Integrity Level of E/E/PE safety-related system, the concept of infaillible component is not considered.

## 3. RISK ANALYSIS – HAZARDOUS EVENT DEFINITION

The following types of failures or faults must be considered to grade the safety systems or components with respect to ATEX and IEC 61508 standard requirements :

- Failures that are “ without consequence ” on the safety function and that may cause either the ignition or non-ignition of the explosive atmosphere. The ATEX standards cover these types of failures or faults.

- Failures whose consequence on the safety function is a “ loss of safety function ” and that can cause either the ignition or the non-ignition of the explosive atmosphere. The ATEX standards cover these types of failures or faults. In addition, in the event of safety function loss, the consequence is indirect and requires an external initiating action. Consequences may be :

    - Either an explosion in the event of contact between an explosive atmosphere and the system due to a failure of the safety device. As an example, one can mention the case of a temperature or pressure probe that would have failed to fulfil its function and whose failure prevents the safety function. Such a safety device could correspond to what the IEC 61508 standard refers to as the “ safety related control systems ”.

    - Or another consequence, or another hazard depending on the safety system's application and use. As an example, one can mention the case of a level detector (petrol or LPG (Liquid Petroleum Gas) storage tank filling) that may result in tank overflowing. Those type of safety device could correspond to what the IEC 61508 standard refers to as “ safety related protection systems ”. Those devices are not in the scope of this study.

Various failure cases and related consequences are presented below :

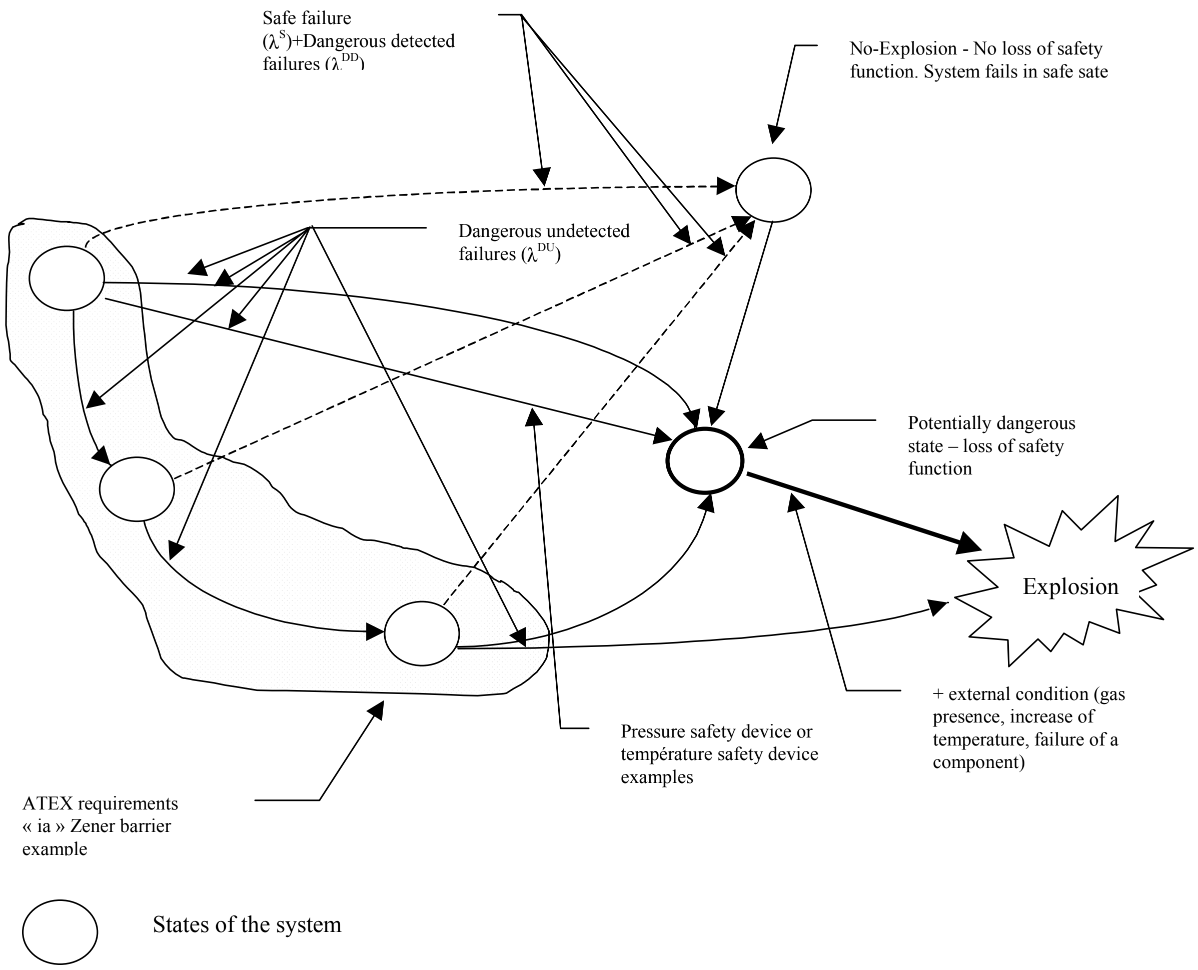

Safe failure
($\lambda^{S}$)+Dangerous detected
failures ($\lambda^{DD}$)
No-Explosion - No loss of safety function. System fails in safe sate
Dangerous undetected failures ($\lambda^{DU}$)
Potentially dangerous state – loss of safety function
Explosion
+ external condition (gas presence, increase of temperature, failure of a component)
Pressure safety device or température safety device examples
ATEX requirements « ia » Zener barrier example
States of the system

**Figure 1 : Safety device failure effects**

# 4. SAFETY LEVEL ASSESSEMENT PROCEDURE

The system's safety integrity level is assessed in accordance with the following procedure that breaks down the assessment into the five following stages with logical links :

- 1st stage : functional analysis,
- 2nd stage : failure rate prediction
- 3rd stage : failure modes, effects and criticality analysis,
- 4th stage : modelling of the system's various states,
- 5th stage : system safety integrity level assessment.

This procedure is defined in reference [11], which is confidential.

## 4.1 ASSUMPTIONS

This assessment does not take into account :

- common mode failures,
- systematic errors,
- connection failures,
- errors linked to cabling,
- human errors.

## 4.2 FIRST STAGE : FUNCTIONAL ANALYSIS

The purpose of the functional analysis is to identify the functions to be fulfilled by the system. It is also intended to explain the system's operation by establishing a link between the hardware and software functions. This stage is the assessment's input point. It is sufficiently accurate to identify failures with an impact on the system's safety.

Several functional analysis procedures may be used to explain the operation of automatic systems :

- functional block diagram procedure,
- SADT procedure,
- SA_RT procedure,
- etc.

## 4.3 SECOND STAGE : FAILURE RATE PREDICTION

### 4.3.1 Purpose

The purpose of the failure rate prediction is not to assess the system's reliability. Calculations are only conducted for the components with a risk in relation to safety, in order to quantify the dangerous failure rate. To that end, a calculation makes it possible to assess an equivalent failure rate of the system. This calculation comprises : component failure rates, component stress, climatic environment, component quality, etc.

The failure rate prediction allows us to quantify the FMECA (**F**ailure **M**odes **E**ffects and **C**riticality **A**nalysis - See 3rd stage) and to identify the contribution of the various failure modes to the system's unsafe situation.

### 4.3.2 Calculation assumptions

Failure rate calculations are grounded on databases that supply a basic failure rate for each type of component. This basic failure rate is modulated according to corrective factors according to the environment and component.

The databases (for information) are :

- MIL HDBK 217 (Military Handbook);
- CNET,
- etc.

The database used by INERIS for the failure rate calculations is the CNET RDF 93 rev. 2/95 database (see reference [12]). Calculations are conducted with the RAM Commander version 6.1 software. The selected calculation assumptions are as follows :

- temperature or pressure measurement device environment : GM; + 40 °C (fixed on a track, motor, …),
- power supply shut off device environment : GF; + 40 °C,
- temperature or pressure measurement device component quality : “ non-CECC ” or equivalent; stress rate inferior or equal to 50%; CMS machine assembly,
- power supply shut off device component quality : “ CECC ” or equivalent; stress rate inferior or equal to 50%; assembly on card “ components to be punched ” manual assembly.

### 4.3.3 Experience of returns

There is experience of returns to the company manufacturing the low level detection system. These systems are mainly installed to detect petroleum product levels in tankers.

By comparing the number of devices returned to the manufacturer with the pool of installed devices and by assuming :

- a balanced distribution between detected failures and undetected failures,
- a reliability according to the constant failure rate exponential law.

We obtain a failure rate grounded on the returns experience “ sixfold ” lower than the predicted failure rate. This can be explained by :

- certain devices are probably being stored for availability reasons,
- failing devices are probably not systematically returned in the event of fault (guarantee period expired, …).

In the following safety integrity level calculations, the selected value is that of the predicted reliability.

In addition, this “ sixfold ” ratio between the predicted values and measured values is less than the order of magnitude range of failure rates within a safety integrity level as defined by the IEC 61508 standard.

## 4.4 THIRD STAGE : FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)

After identifying the components fulfilling the functions (hardware and software), identified by the functional analysis, the failure modes and their effects on the system's operation must be analysed in the scope of this study. Certain standards formalise this type of study (MIL STD 1629, …), others give values to distribute the components' failure modes (CNET, manufacturer data, …).

The purpose of this stage is to analyse the failures to identify “ dangerous ” failure modes, and to quantify the probability of failure occurrence.

The **F**ailure **M**odes **E**ffects and **C**riticality **A**nalysis (FMECA) is conducted at electronic component detail level for the safety device. The purpose of this analysis is :

- to identify the “ dangerous ” failure modes to assess the “ dangerous ” failure rates leading to the hazardous event, while assessing a coverage rate for the various tests;
- to identify the possible preventive maintenance provisions to be integrated to guarantee a safety integrity level in compliance with the defined goals.

Failures are classified in 4 classes :

- dangerous detected failures whose effects are on safety and availability ($\lambda^{DD}$),
- dangerous un-detected failures whose effects are only on safety ($\lambda^{DU}$),
- non-dangerous detected failures whose effects are only on availability ($\lambda^{SD}$),
- non-dangerous and undetected failures whose effects are only on availability ($\lambda^{SU}$).

($\lambda^{DU}$ = $\lambda$ **D**angerous, **U**ndetected ; $\lambda^{S}$ = $\lambda$ **S**afe).

$\lambda^{S}$ = Safe failure : i.e. a failure that results in system fallback (safe situation for safety),

$\lambda^{DU}$ = Unsafe failure : failure whose consequence leads to a dangerous state from the standpoint of safety.

The following diagram give further details of this notion of distribution of failures according to their effect.

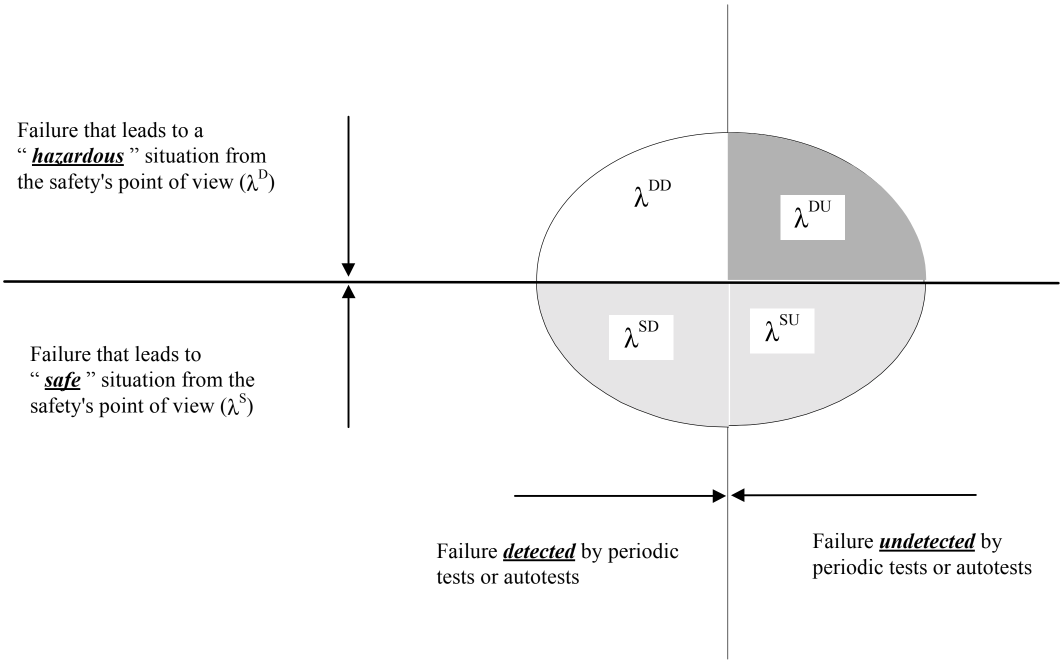

Failure that leads to a
" hazardous " situation from
the safety's point of view (λ^D)
λ^DD
λ^DU
λ^SD
λ^SU
Failure that leads to
" safe " situation from the
safety's point of view (λ^S)
Failure detected by periodic
tests or autotests
Failure undetected by
periodic tests or autotests

**Figure 2 : Failure distribution according to their effect**

References [12] and [13] state the failure mode distribution for various components.

## 4.5 FOURTH STAGE : MODELLING OF THE SYSTEM'S VARIOUS STATES

There are three system types according to the various encountered systems :

[1] Failsafe systems

[2] Non-redundant systems

[3] Redundant systems

The system's dangerous failure probability calculation is different according to the various types of system.

### 4.5.1 Failsafe systems

Failsafe systems are systems in which the failure modes of all components of the system lead to a “ safe state ” in relation to safety. For these systems, there is no use in calculating the dangerous failure probability as the $\lambda^{DU}$ dangerous failure rate does not exist

### 4.5.2 Non-redundant systems

Non-redundant systems are “ simple ” systems in which the safety function can be lost in the event of failure. Two states are possible : safe state or dangerous state. The calculation of the dangerous failure probability for the systems comes down to a specific reliability calculation depending on the dangerous failure rate ($\lambda^{DU}$ - identified in FMECA) and with the same duration as the preventive maintenance operations.

### 4.5.3 Redundant systems

In the event of redundant systems, the safety function can be lost due to combinations of failures depending on the logic implemented within the safety system. There are several safety integrity level quantitative assessment procedures for such systems. The main drawback of the more traditional procedures such as the analysis by fault tree system, or the analysis by reliability block diagram, is that they do not always take into account the time aspect, test periodicity, coverage levels, as well as the repair rate.

The various failure and operating states can be modelled with MARKOV graphs, by integrating the time aspect of the preventive maintenance tests, the autotests as well as the coverage rate, as the electronic systems are subject to a failure law of exponential form with a constant failure rate.

### *4.5.3.1* Influence of testability on safety

For safety purposes, the state of the resources must be known on a permanent basis to see if hidden (or dormant or latent) failures liable to mask the safety function exist. These dormant failures are only detected during periodic tests voluntarily conducted by the user.

A test policy is useless for failsafe systems as each failure leads to a “ safe ” position in relation to safety.

On the contrary, for systems that are neither failsafe nor autotestable and on which dangerous failures exist, a test policy to detect the “ dangerous failures ” (with a risk for safety) is required.

These tests must be conducted according to a periodicity grounded on the characteristics of the various elements constituting the system. Dangerous failures can be detected in two ways :

- Either by the test and autotests system of the safety system for detectable failures ($\lambda^{DD}$),
- Or during verification operations for non-detectable failures ($\lambda^{DU}$).

The PLC's reliability level is not increased by testability. It just makes it possible to ensure that resources are still available : to read the inputs and control the outputs, on the one hand, and to make sure that the processing modules are still functional, on the other hand. Only dangerous failure detection comes into play. It is possible to detect and switch to safe position in the event of failure, thanks to this test, and therefore to better guarantee safety. The following diagram shows the impact of testability on safety, and the impact of a state changeover test policy conducted every 24 hours or every 6 months on safety.

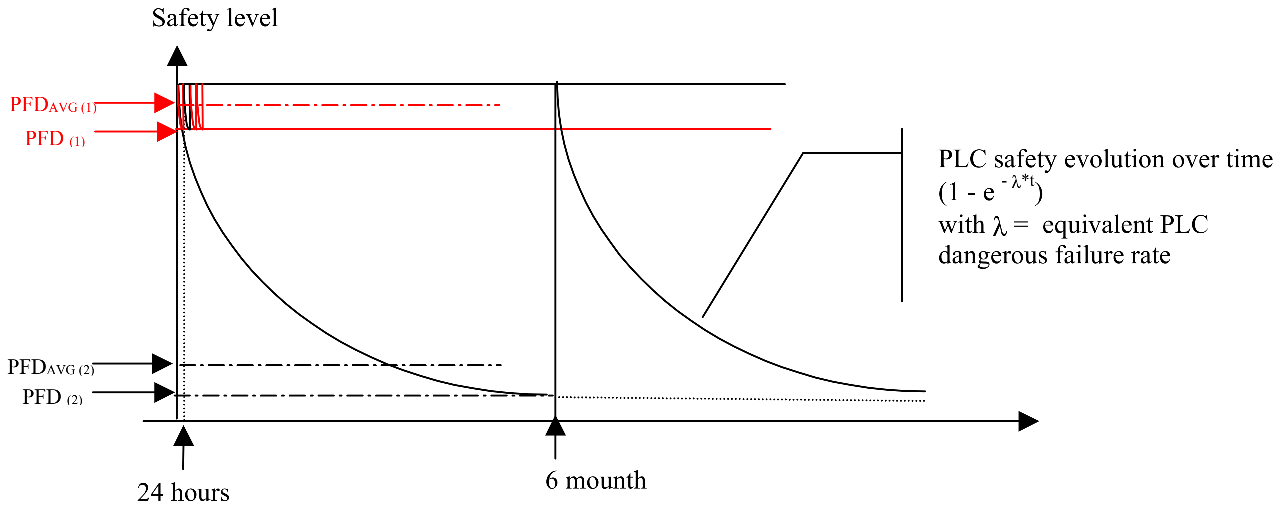


**Figure 3 : Testability impact on safety**

On this figure is shown that PFD is the probability of failure and $\mathrm{PFD}_{\mathrm{AVG}}$ is the average probability of failure which is aproximately the half of PFD (see PFD $_{(1)}$) for safety systems with short period state changeover test, and the third of PFD (see PFD $_{(2)}$) for safety systems with long period state changeover test. This difference is due, for electronic systems, to a constant failure rate ($\lambda$) and to the reliability calculation with the exponential law.

### *4.5.3.2 Graph establishment*

References [10] and [14] stipulate the procedure and various stages of system modelling. State graphs are represented below for each safety function. Modelling is achieved with " states " that the system is liable to enter. There are 3 states in most cases :

**State 2** represented as follows ② :

This state corresponds to the modelling of redundancy. In this state, all implemented resources are present and operate in a nominal manner.

**State 1** represented as follows : ①

This state corresponds to the modelling of redundancy downgraded by the dangerous failure of a hardware element on one of two channels. In this state, all implemented resources are not present. It is an undetected dangerous failure state. Safety is still guaranteed.

**State 0** represented as follows ⓪ :

This state corresponds to the modelling of the loss of redundancy due to the dangerous failure of several hardware elements from the channels. In this state, safety is no longer guaranteed and in the event that the safety function is called upon, the system will not go to safe position.

The " P " probability of being in " 0 " state is designated by PFD(t) in the IEC 61508 standard. The meanning of PFD(t) value is the value defined in the previous paragraph.

### *4.5.3.3* Assumptions

MARKOV graph modelling for the studied systems by INERIS was grounded on the following assumptions :

[1] failure rates ($\lambda$) and repair rates ($\mu$) are assumed constant to make it possible to model and calculate the safety level with MARKOV graphs.

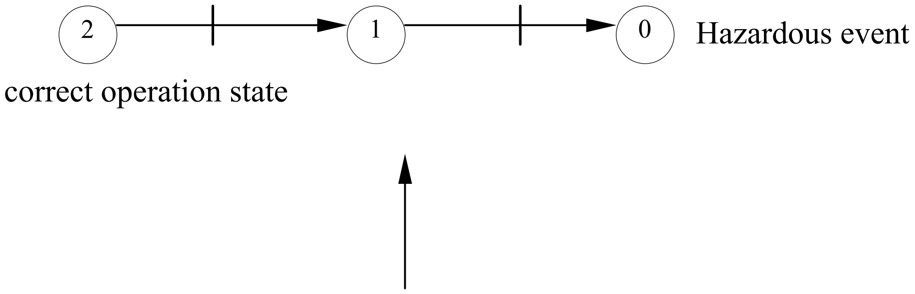
[2] The mission time (TI) corresponds to the intervals between the OFF LINE periodic test times. All test rates concerning the aptitude to detect state changeovers ($\mu_{\mathrm{PTi}}$) are stated for each arc of each graph.

[3] Inputs and outputs do not go to the safe state if the power supply is cut off.

[4] The common failure modes, and the systematic errors are assumed equal to those defined in reference [14]. $\lambda^D$ common mode failures or faults have the specificity of affecting all lines at the same time. The selected values are those defined in the same document.

### 4.5.4 System modelling example

Two active redundancy systems are modelled as follows



It is possible to be in an intermediate state in which safety is still guaranteed with active redundancy.

**Figure 4 : Redundant system state modelling**

This graph is equivalent to the following graph :

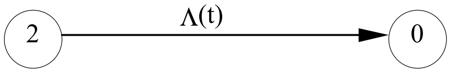


**Figure 5 : Redundant system state reduced modelling**

The " P " probability of being in a " 0 " state therefore depends on a failure rate that in turn depends on time T : P = Λ(t) x T.

This example shows that the more time T increases and the more the probability of being at " 0 " state increases.

## 4.6 FIFTH STAGE : SAFETY INTEGRITY LEVEL ASSESSMENT

The system's various states were modelled with the fourth stage. This stage consists of resolving the mathematical calculation and comparing the level achieved by the system with the classifications of the IEC 61508 standard.

The dangerous failure probability calculation (PFD) is a function of a system failure rate (function variable over time) and of a duration, in most cases. Therefore, the safety integrity level calculation is a specific reliability calculation in which safety is equal : either to the reliability during a time equal to that of the auto-test's overall time, or to that of the preventive maintenance intervals.

# 5. APPLICATION OF SAFETY INTEGRITY LEVEL ASSESSEMENT PROCEDURE

## 5.1 CASE STUDY OF DIODE SAFETY BARRIER

### 5.1.1 Description and functional analysis

Diode safety barriers are assemblies incorporating shunt diodes or diode chains (including zener diodes) protected by fuses or resistors or a combination of these.

The diodes, zener diodes in the example of figure 6, limit the voltage applied to an intrinsically safe circuit and a following infallible current limiting resistor limits the current which can flow into the circuit. These assemblies are intended for use as interfaces between intrinsically safe circuits and non-intrinsically safe circuits.

The diode safety barrier is manufactured as an individual apparatus rather than a part of a larger apparatus and, as it contains both intrinsically safe circuits and non-intrinsically safe circuits, the barrier is an associated apparatus and shall be :

- either protected by an alternative type of protection listed in EN 50014 [1] for use in the appropriate explosive gas atmosphere,
- or situated outside the explosible atmosphere.

Besides, the barrier shall comply with requirements of EN 50020 [7] which specify in particular for safety devices that the assembly must contain :

- three diodes or three diode chains for category “ ia ” (safe with two faults),
- two diodes or two diode chains for category “ ib ” (safe with one fault).

The choice of category “ ia ” for an intrinsically safe apparatus allows the use of such an electrical apparatus in hazardous areas where explosive gas atmosphere is present continuously or for long periods.

The choice of category “ ib ” for an intrinsically safe apparatus allows the use of such an electrical apparatus in hazardous areas where explosive gas atmosphere is likely to occur in normal operation.

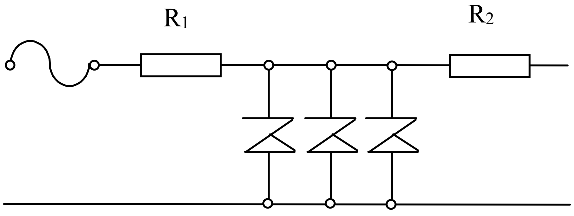


**Figure 6 : zener barrier**

### 5.1.2 Failure rate prediction

Results of the calculation for a low power (1.5 W) Zener diode give a failure rate of $\lambda = 2.4*10^{-9}$/hr grounded on assumptions defined in paragraph 4.3.

### 5.1.3 FMECA

#### *5.1.3.1 ATEX classification*

According to ATEX requirements this failure mode is impossible because :

- According to EN 50020, during normal operation, a component can't fail if it works under the 2/3 of its maximum characteristics. This component is considered as an unfaillible component.
- According to EN 50020 if a zener diode fails to short-circuit during the transient period, the fuse can blow if the maximum current is over 1.7 of the nominal current of the fuse. In this case the maximum power dissipated by the diode is lower than its maximum power characteristics, and the safety function of the safety barrier is guarranted. If the maximum current is lower than 1.7 nominal current, then the power dissipated in the diode is lower than its maximum power characteristics.
- During worst functionning (maximum input voltage up to 250 Volts applied to the barrier inputs), the fuse will blow in a very short time (usually lower than 1 milli-second) and the consequence of this worst functionning is a " safe state ", so the safety barrier has to be changed, and there is no hazard. In addition, during the short time of the blowing of the fuse, the functionning power rate of the components (Zener diodes and resistors) complies with the 2/3 rules of their maximum characteristics. So the Zener diode have a low probability to get a short circuit because of the worst functionning of the associated electrical circuit connected to the barrier inputs.

#### *5.1.3.2 IEC 61508 / CNET classification*

According to reliability of the CNET standard (see reference [12]) and of other reliabiity standards, a component has several *failures modes* which not take into account the working conditions of the component. Only the failure rate take into account the working conditions of the component.

The CNET's database gives the following failure mode for a low power Zener diode (1.5 W) :

- 10% for voltage drifts
- 20% for open circuit and
- 70% for short-circuit.

##### *5.1.3.2.1 Safe state*

The loss of the safety function leading to a safe position regarding safety is achieved if one of the three diodes is short-circuited.

#### *5.1.3.2.2 Dangerous state*

The hazardous event in relation to the explosion would be the loss of intrinsic safety characteristics i.e. the following failure mode : " open circuit on the 3 diodes ".

Safety level assessment

#### ***5.1.3.3 Dangerous state***

Modelling by MARKOV graph is not required for this type of system, and the safety level calculation (3 diodes in open circuit) comes down to a specific reliability calculation in which the probability of event occurrence is equal to *Q(t)* = 1 - *R(t)* with :

- $\theta = \frac{1}{\lambda} * \sum_{i=1}^{3} \frac{1}{i}$
- then $\theta = \frac{1}{\lambda} * \left[ 1 + \frac{1}{2} + \frac{1}{3} \right] = \theta = \frac{11}{6 * \lambda} = \frac{1}{\lambda_{EQ}}$ for the loss of 3 diodes in open circuit (C.O.)
- hence $\lambda_{EQ} = \frac{6 * \lambda}{11}$ and
- $R(t) = e^{-(\lambda_{EQ}) * t}$

With a failure distribution assumption of 20% for the open system failure mode and 70% for the short-circuit failure mode, and a failure rate for a low power Zener diode (1.5 W) of $\lambda = 2.4*10^{-9}$/hr, we obtain a $\lambda^{DU}$ of $4.8*10^{-10}$/hr for one diode, a $\lambda_{EQ}$ for the 3 diodes of $2.6*10^{-10}$/hr.

The results of the calculations for the dangerous state (loss of intrinsic safety characteristics) are :

- Probability for the dangerous state for one year duration without tests :
  $1 - R(t) = 1 - e^{-(\lambda_{EQ}) * t}$ = **$2.28*10^{-6}$**.
- Probability for the dangerous state for ten years duration without tests :
  $1 - R(t) = e^{-(\lambda_{EQ}) * t}$ = **$2.28*10^{-5}$**

### 5.2 These are the " worst cases " assumptions for the SIL calculations

#### ***5.2.1.1 Safe state***

The consequence of the failure of one of the three diodes in " short circuit " is a safe state because the fuse will blow in a very short time (usualy lower than 1 milli-second) and during this blowing the functionning rate of the component (zener diodes and resistors) complies with the 2/3 rules of their maximum characteristics.

With the same failure distribution assumptions and failure rate, the probability of this event is $Q(t) = 1 - R(t)$ with :

- $R(t) = e^{-[\sum \lambda i] * t}$

- and $R(t) = e^{-(3*\lambda i)*t}$
- Probability of safety function loss leading to a safe state for one year duration :
  $1 - R(t) = e^{-(3*\lambda i)*t} = 4.4*10^{-5}$
- Probability of safety function loss leading to a safe state for ten years duration :
  $1 - R(t) = e^{-(3*\lambda i)*t} = 4.4*10^{-4}$

### 5.2.2 IEC 61508 quality requirement observance examination

For the safe states, there is no need to check the Zener barrier because this unit will be replace by a new one to keep the well functionning of the safety-function.

The Zener diode safety barrier is a device for which 20% of failures lead to the hazardous event. This architecture can tolerate two failures and has a failsafe fraction of 80%.

This Zener diode safety barrier reachs the SIL 4 level qualitative and quantitative requirements for a one year period (and for a period of 10 years) without periodic test for a safety related protection system.

In theory, the Zener diode safety barrier reachs the SIL 4 qualitative and quantitative requirements for a period of 43 years. After this period, the Zener diode safety barrier reachs the SIL 3 quantitative requirements. This result must not be taken into account because the calculations basis are not valid after a period of ten years for electronic components (after this period, the failure rate is not constant).

## 5.3 CASE STUDY OF SAFETY LEVEL DETECTION SAFETY DEVICE

**A system already " ia " intrinsic safety certified formed the subject of an assessment by INERIS in accordance with requirements of standard IEC 61508.**

### 5.3.1 Functional analysis

We represent the case of a safety low level detection system installed in a tank containing liquid or liquefied hydrocarbons. The system is constituted of one detector connected to a processing unit to detect a low level in order to shut off the electric power.

### 5.3.2 Failure rate prediction

Grounded on assumptions mentioned in paragraph 4.3, the calculation results give a failure rate of $\lambda = 4*10^{-6}$/h for the detector, and of $\lambda = 1.1*10^{-6}$/h for the processing unit.

### 5.3.3 FMECA

The hazardous event in relation to safety for the safety level detection system is the loss of low level detection. The system's dangerous failure rate was calculated grounded on the detailed FMECAs. Results are as follows :

- A dangerous failure rate of $2*10^{-6}$/h for the detector i.e. an FSF of 49%
- A dangerous failure rate of $1.5*10^{-7}$/h for the processing unit, i.e. an FSF of 85%
- i.e. for the full system, an FSF under 60%

### 5.3.4 Safety level assessment

MARKOV graph modelling is not required, and the safety level calculation comes down to a specific reliability calculation in which the probability of occurrence of this event is $Q(t) = 1 - R(t) = 1 - (e^{-\lambda_d * t} * e^{-\lambda_{pu} * t})$.

By assuming a dangerous failure rate for the detector of $2*10^{-6}$/h and $1.5*10^{-7}$/h for the processing unit, we obtain the following values for a year :

| Safety function loss of low level detection of $1.7*10^{-2}$ |
|---|

### 5.3.5 IEC 61508 requirement observance examination

If a processing unit design in simple chain tolerance to " 0 " failures is selected and if the following values are selected for the overall safety level detection system : a failsafe fraction (FSF) inferior to 60% and a PFD of $1.7*10^{-2}$, the safety level detection system can be graded as safety related control system, and is compliant with the SIL 1 level qualitative and quantitative requirements for a one year term and for operation on demand.

## 5.4 CASE STUDY OF PRESSURE AND TEMPERATURE SAFETY DEVICES

### 5.4.1 Functional analysis

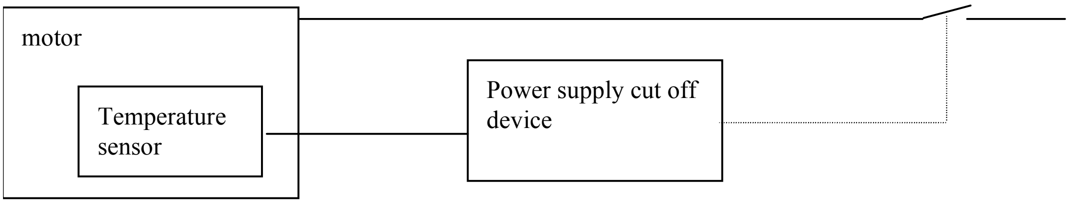


**Figure 7 : Motor protection device**

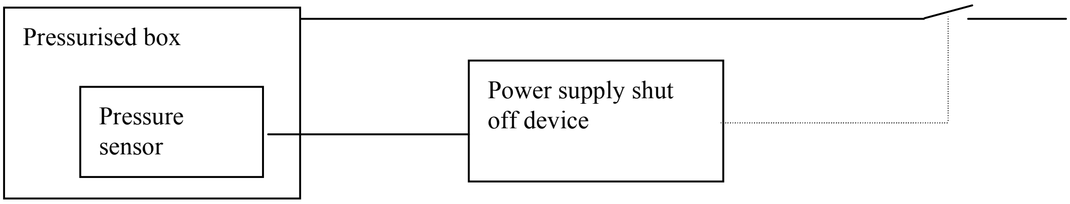


**Figure 8 : Pressurised box protection device**

### 5.4.2 Failure rate prediction

With the assumptions defined in paragraph 4.3, the results of the calculations give the following failure rate :

- Temperature sensor $\lambda = 5*10^{-9}$/h and
- Power supply shut off device $\lambda = 1.1*10^{-6}$/h

### 5.4.3 FMECA

Both architectures are similar. The safety function loss leads to an explosion risk under explosive atmosphere in both cases. The safety function loss occurs in the event of pressure sensor or power supply shut off device dangerous failure for the first architecture. The safety function loss occurs in the event of temperature sensor **or** power supply shut off device dangerous failure for the second architecture.

The detailed FMECAs at component level were conducted on a low level detection system in the event of LPG storage (see the values of chapter 5.3) in simple chain. Assuming a similar architecture for the power supply shut off device, the dangerous failure rate is $1.5*10^{-7}$/hr i.e. an FSF of 85%.

### 5.4.4 Safety level assessment

If a power supply shut off device design in simple chain based on discrete electronics is selected, the MARKOV graph modelling is not required, and the safety level calculation comes down to a specific reliability calculation in which the probability of occurrence of this event is equal to $Q(t) = 1 - R(t)$ with $R(t) = e^{-[\sum \lambda i]*t}$

By assuming a failure rate of $5*10^{-9}$/hr for the temperature sensor, a dangerous failure distribution of 100%, and a dangerous failure rate for the power supply shut off device of $1,5*10^{-7}$/hr, we obtain the following values for a year :

Safety function loss leading to an explosion risk $R(t) = e^{-(\sum \lambda_i)*t}$ = $1.35*10^{-3}$

### 5.4.5 IEC 61508 requirement observance examination

If the power supply shut off device design in simple chain tolerance to “ 0 ” failure, a failsafe fraction of 85% and a PFD of $1.35*10^{-3}$ are selected, the device must meet the SIL 2 level quality and quantity requirements for operation on demand for a year and for a safety related protection system.

# 6. CONCLUSIONS

## 6.1 MAIN DIFFERENCES BETWEEN ATEX STANDARDS AND IEC 61508

There are differences between hardware fault tolerance of IEC 61508 and of ATEX standards. The requirements of hardware fault tolerance of IEC 61508 are defined to their consequence regarding the loss of the safety function. Those requirements are a measurement of the effectiveness of a safety-related device.

The requirements of hardware fault tolerance of ATEX standards are defined to their consequence regarding the explosion hazard.

According to some ATEX standards, if some construction principles are met, then the component is considered as infaillible. In IEC 61508 and reliability standards and databases the concept of infaillible component is not considered.

## 6.2 CLASSIFICATION OF ATEX SAFETY DEVICES ACCORDING TO IEC 61508

IEC 61508 standard requirements (see reference [10]) are :

- System development cycle requirements around a safety life cycle and in terms of related documentation (Part 1).
- Qualitative and quantitative technical requirements in presence of faults (Parts 1 and 2).
- Technical requirements in relation to software design and validation (Part 3).

INERIS only checked the qualitative and quantitative technical requirements in the presence of faults which were taken into account. The system's overall safety validation by functional safety tests, behaviour tests on defect and tests related to sizing and compliance with the environmental parameters were not conducted by INERIS. Similarly, INERIS did not check whether the requirements of the system's development cycle around a safety life cycle was taken into account and did not check the related documentation.

There are two types of failures according to the consequences for safety, in accordance with the qualitative and quantitative technical requirements in the presence of faults, set out in the IEC 61508 standard. These failures are :

- Safe failures, i.e; failures whose consequences lead to system fallback (safe situation in relation to safety),
- Dangerous failures, i.e. failures resulting in a dangerous state in relation to safety.

In accordance with the ATEX standards, failures are graded according to their effect in relation to the ignition of explosive atmospheres. These types of failures or faults correspond to the loss of safety function as defined in the IEC 61508 standard.

**Ours conclusions concerning the safety devices' grading used in applications liable to form an explosive atmosphere are as follows :**

- Safety devices must meet the requirements of applicable standards (see reference documents [1] to [9]).
- The only purpose of grading safety devices in accordance with the IEC 61508 standard requirement is to assess their capacity to guarantee the safety function for which they were designed during the time.
- Devices can be graded in accordance with the ATEX standard requirements and to those of the IEC 61508 standard if the effect of dangerous failures and safe failures as defined in the IEC 61508 standard correspond to the failures as defined in the ATEX standard, and that the failures can lead to the ignition of explosive atmospheres.

There are two main types of configurations :

- Configurations in which the undetected dangerous failure of a safety device does not directly lead to an explosion (e.g. case of a temperature measurement device and of an electric motor power supply shut off device in the event of overheating). In this case, the probability of explosion occurrence is subject to : motor overheating AND failure of the safety devices AND presence of an explosive atmosphere. This type of situation could correspond to what the IEC 61508 standard refers to as the " **safety related protection systems** ". These are the devices under the scope of the SAFEC project.
- Configurations in which an undetected dangerous failure of the safety device does not lead to an explosion but to another hazard (case of the level detection system). This case could correspond to what the IEC 61508 standard refers to as the " **safety related control systems** ". These devices are not under the scope of the SAFEC project because their use is under the knowledge and under the responsability of the end user. (A level detection system would fall into the first category if it was used as part of a submersible pump, such that ignition could occur if the level dropped below the level of the pump).

These conclusions only encompass safety devices used in applications under explosive atmospheres studied in paragraph 4 of this document, and with an autonomous safety function.

These conclusions are only valid if preventive maintenance is conducted. The purpose of these preventive maintenance operations is to detect, when it's possible, component failures leading to a dangerous state.

## 7. REFERENCES

[1] EN 50014 Electrical apparatus for potentially explosive atmospheres. General requirements[1].

[2] EN 50015 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode "o" oil immersion[2].

[3] EN 50016 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode : pressurised apparatus "p"[3].

[4] EN 50017 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode : powder filling "q"[4].

[5] EN 50018 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode : flameproof enclosure "d"[5].

[6] EN 50019 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode : increased safety "e"[6].

[7] EN 50020 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode : intrinsic safety "i"[7].

[8] EN 50028 Electrical apparatus for potentially explosive atmospheres. Specific requirements for the protective mode : encapsulation "m"[8].

[9] Reports on task 1 and 2 of the SAFEC project

[10] CEI 61508 - version FDIS of 1998-07-31
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