STUDIES ON THE EXPLOSION PROTECTION IN HAZARDOUS AREA BASED ON INTRINSICALLY SAFE METHOD EXI ACCORDING TO IEC60079-14

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechatronics Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDIES ON THE EXPLOSION PROTECTION IN HAZARDOUS AREA BASED ON INTRINSICALLY SAFE METHOD EXI ACCORDING TO IEC60079-14"** was prepared by **LESLIE CHAM YEONG LIE** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechatronics Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Explosion protection is indispensable in the industry operating in an atmosphere filled with combustible substances. Intrinsic safety (Ex i) is one of the explosion protection methods which can restrict the energy entering the hazardous area and limit the energy reserved in the field devices. Furthermore, it is mostly applied in the control and instrumentation system. The project aims to examine the conformity of various Ex i systems as per IEC 60079-14. The objectives are to verify the compliance of the apparatuses and carry out the analysis on the intrinsic safety loop verification. Additionally, the emphasis is put on the verification regarding the validity of the Ex i systems that implement temperature sensing and the controlling of the solenoid valve. Throughout the project, the experiment and site visit are not implemented. The specifications of the apparatuses and the configuration of the Ex i systems are obtained from the datasheets of the companies specializing in explosion protection such as Eaton MTL, Pepperl+Fuchs and Phoenix Contact. Based on the parameters and certification of conformity shown in the datasheets, the compliance of apparatuses and intrinsic safety loop can be examined. In this project, the conformity of four Ex i systems has been validated in terms of the compliance of the apparatuses and the intrinsic safety loop verification. The ways to implement the validation regarding the compliances of various apparatuses including temperature transducer, digital display, temperature sensors, solenoid valves and intrinsic safety barriers have been demonstrated. Furthermore, the proper way to utilize the energy curves in the verification of the safety parameters is covered. Apart from that, the intrinsic safety loop verification of several Ex i system configurations is executed. In addition, the flowcharts and equations are presented to interpret the intrinsic safety loop verification more understandably. In short, the conformity of all of the four Ex i systems is proven and the detailed steps of the verification are shown, thus providing clearer guidelines on the implementation of Ex i method as per IEC 60079-14.

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LIST OF SYMBOLS / ABBREVIATIONS

C_c	cable capacitance, F
C_i	maximum internal capacitance of field device, F
C_o	maximum allowed capacitance of Ex i barrier, F
I_i	maximum input current for field device, A
I_O	maximum output current of Ex i barrier, A
L_c	cable inductance, H
L_i	maximum internal inductance of field device, H
L_o	maximum allowed inductance of Ex i barrier, H
P_i	maximum input power for field device, W
P_o	maximum output power of Ex i barrier, W
R_{th}	surface Temperature Rise, °C/ W
T	maximum surface temperature, °C
T_{amb}	ambient temperature, °C
U_i	maximum input voltage for field device, V
U_O	maximum output voltage of Ex i barrier, V

ATEX	atmosphere explosible
EPL	equipment protection level
Ex d	flameproof
Ex e	increased safety
Ex i	intrinsic safety
Ex m	encapsulation
Ex p	pressurization
Ex q	powder filled
IEC	International Electrotechnical Commission
IECEx	international certification scheme operated by the IEC

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

In some industries such as petrochemical industries and flour milling industries, flammable substances such as gases and dust will form explosive atmospheres. As a result, explosion protection methods have to be carried out to prevent the explosion and assure safety. The International Electrotechnical Commission (IEC) has established a series of guidelines and standards, known as IEC 60079. The purpose of the standards is to assure the conformity of electrical equipment and to regulate the use of electrical equipment in explosive atmospheres. Under the standards, the explosion protection methods such as intrinsic safety, pressurization, flame proof and so on are introduced (IEC-IECEx, 2022). Intrinsic safety (or Ex i) is one of the most widely applied protection methods in industries operating under an explosive atmosphere. Furthermore, intrinsic safety is mostly used method to provide explosion protection in the control and instrumentation system. By applying intrinsic safety techniques, the energy is bound within a safe level that is lower than the ignition point and does not result in an explosion (MTL Instruments, n.d). In this report, intrinsic safety is studied in accordance with IEC 60079-14 standard.

1.2 Importance of the Study

Among the explosion protection methods, intrinsic safety is the only method that can be applied in the most hazardous area (Zone 0). Also, the restriction of energy due to the nature of Ex i can ensure the safety of the maintenance work. Through the implementation of the Ex i technique, the maintenance can be executed without switching off the electrical apparatus and therefore the operation of the industries will not be affected (Sackett, 2018). Aside from that, the Ex i system can allow more than one fault condition depending on the level of protection. For instance, if the protection level of the Ex i system is higher, it can withstand more fault conditions (Mirza, 2015).

Referring to IEC 60079-14, it provides sufficient guidelines to carry out the Ex i method. However, it will be easier to perform the Ex i method if there is a case study or several case studies to refer to. Since a few case studies will be carried out throughout this report, the study may provide a better understanding of the guidelines to implement Ex i method, especially in the compliance of the apparatuses installed in the intrinsic safety circuit system and the intrinsic safety loop verification.

1.3 Problem Statement

Ex i method is applied in the hazardous area to prevent the explosion. In the condition that the Ex i method is not carried out properly, the safety of the hazardous area in the industries cannot be assured. The explosion may be present due to the improper Ex i implementation. Therefore, the studies on the Ex i safety loop verification and installation of Ex i circuit are carried out. The factors leading to failures in implementing the Ex i are due to:

- The non-compliance of the apparatuses installed in the intrinsic safety circuit system.
- The misconception in the analysis regarding the intrinsic safety loop verification.

1.4 Aim and Objectives

In this project, the major aim is to verify the validity of Ex i systems in terms of compliance of each apparatus and intrinsic safety loop verification according to IEC 60079-14. Specifically, the objectives of this project are as follows:

- To verify the compliance of the apparatuses installed in intrinsic safety circuit systems.
- To carry out analysis on the intrinsic safety loop verification and calculation.

1.5 Scope and Limitation of the Study

First and foremost, the compliance of the apparatuses including associated apparatuses, certified field devices and simple apparatuses is one of the scopes of the study. Apart from that, the emphasis of the study is put on the verification of the intrinsic safety loop by taking the current, voltage, power, inductance and capacitance of associated apparatuses and field devices into consideration. Moreover, the maximum allowable cable length is computed to comply with the intrinsic safety loop verification.

The limitation of the study is that the practical experiment is not implemented. Hence, the actual parameter of the electrical apparatus and the cable cannot be verified. For instance, some parameters such as capacitance and inductance of the cables may slightly differ from the actual value. Besides that, the construction of the Ex i circuit system and site visit are not carried out. Therefore, in the analysis of intrinsic safety, the parameters of the electrical equipment are obtained from the marking label.

1.6 Contribution of the Study

In this project, four Ex i systems have been validated. The ways to verify the compliances for various kinds of apparatuses installed in Ex i system have been covered. For instance, the specifications obtained from the IECEx marking including equipment group, temperature class, equipment protection level and type of protection are interpreted by showing examples. Furthermore, the way to verify the specifications based on the environment of the hazardous area is shown throughout the verification of the Ex i systems.

Besides that, this project has covered the intrinsic safety loop verification of several Ex i system configurations. To interpret the guidelines stated in IEC 60079-14 more understandably, the flowcharts and equations to carry out the intrinsic safety loop verification are provided in this project.

In short, this project provides a clearer and more understandable guidelines for the execution of Ex i method in accordance with IEC 60079-14.

1.7 Outline of the Report

There are five chapters in this report.

In chapter 1, the background, problem statements, goals, scopes, limitations and contributions of the study are presented.

Regarding chapter 2, the literature review can be separated into two parts. Concerning the first part of the literature review, the emphasis is put on the foundation knowledge of explosion protection. Besides that, intrinsic safety protection is focused on in the second part.

In chapter 3, the methodology to carry out the case studies is covered. In addition, the planning for this project is presented. Besides that, the problems encountered and solutions are covered.

In chapter 4, four Ex i systems are verified in terms of compliance of each apparatus and intrinsic safety loop verification. Also, the common mistakes regarding the installation are discussed.

In chapter 5, the conclusions are firstly presented. After that, recommendations for future work are provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this section, the literature review is firstly focused on the foundation knowledge of explosion protection such as the explosion, hazardous area, apparatus marking and several types of explosion protection techniques. After that, the emphasis is put on intrinsic safety protection. For instance, the configuration of the intrinsic safety circuit system, safety barrier, intrinsic safety loop calculation, requirement of wiring and earthing are the main topics that are covered.

2.2 Explosion

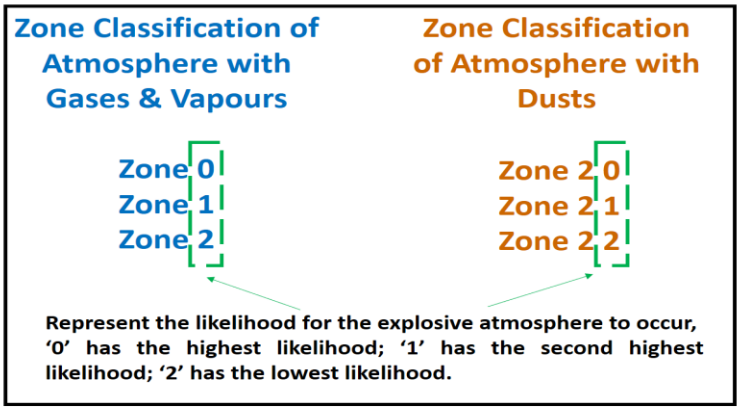
In the event of an explosion, an enormous quantity of energy is emitted in a very short period. The factors leading to the explosion are the same as fire. Therefore, a study on the fire triangle consisting of three elements is required. For instance, the three elements are the oxidizer, flammable material and ignition source. Concerning the avoidance of fire as well as an explosion, the three elements cannot occur together at the same time. Once they present together, it results in fire or even leads to an explosion in a worse scenario (Blazquez and Thorn, 2010).

Besides that, the oxidizer generally refers to oxygen. If the percentage of oxygen in the air is higher, it can intensify the explosion and make the condition worse. Moreover, the flammable material is the element being oxidized acutely during the explosion. The flammable material can be any state of matter, it can be a solid, liquid or gas. In addition, ignition sources refer to events or substances having the ability to contribute extra energy to ignite the explosion. Furthermore, if there is a lack of one of the components, the explosion is not going to happen (Engel, 2020). For instance, in the condition that the ignition source is eliminated, only the oxidizer and flammable material are present, the explosion is not going to occur.

2.3 Explosive Atmosphere and Zone Classification

In certain industries, the atmosphere is usually filled with material that is easy to be burned and combusted. Furthermore, the concentration of combustible substances in the air is relatively high. Such an atmosphere is known as an explosive atmosphere (LCM Systems Ltd., 2020). Generally, in such an atmosphere, the oxidizer or oxygen always occurs. If there is an element or event that contributes to the source of ignition, the explosion will happen.

Apart from that, the hazardous zone can be categorized based on the chances of the occurrence of an explosive atmosphere. Concerning the atmosphere filled with gas, it is classified as Zone 0, 1 and 2 (Lisi, Milazzo and Maschio, 2010). Besides that, it is categorized as Zone 20, 21 and 22 for the atmosphere filled with dust. As shown in Figure 2.1, the digit (‘0’, ‘1’ and ‘2’) indicates the chances for the explosive atmosphere to occur and such chances are getting less from ‘0’ to ‘2’ (LCM Systems Ltd., 2020).



Represent the likelihood for the explosive atmosphere to occur, ‘0’ has the highest likelihood; ‘1’ has the second highest likelihood; ‘2’ has the lowest likelihood.

Figure 2.1: Zone Naming (LCM Systems Ltd., 2020).

In addition, Figure 2.2 illustrates the possibility for the explosive atmosphere to occur and provides its presence hours on an annual basis. In Zone 0 and Zone 20, the duration of the presence of the explosive atmosphere exceeds 1000 hours per year. For Zone 1 and Zone 21, the duration of the presence of such an atmosphere ranges from 10 to 1000 hours per year. Furthermore, its presence duration in Zone 2 and Zone 22 is less than 10 hours per year.

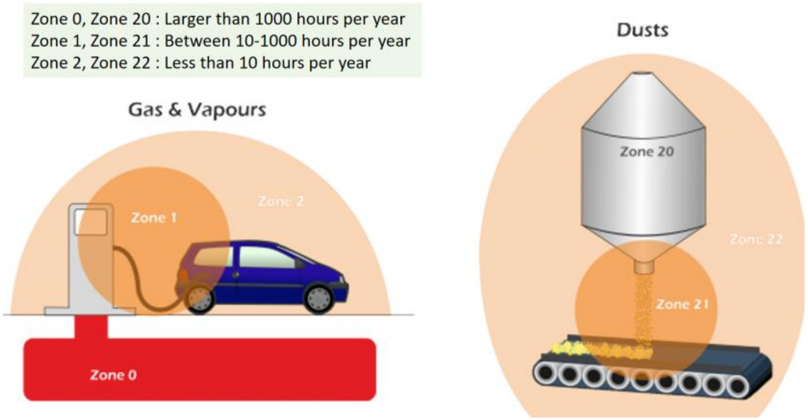


Figure 2.2: Zone Classification (LCM Systems Ltd., 2020).

In a nutshell, the aim to classify the zone is to assure that the equipment applied or installed in the hazardous environment fulfils the protection requirement. For instance, if the equipment which is only certified for Zone 2 is installed in Zone 1, the equipment will become the factor leading to the industrial incident. Such a case should not happen since it does not comply with the safety regulations and guidelines. As a result, zone classification provides a good guideline for the industry to choose the right equipment (UK HSE, 2004).

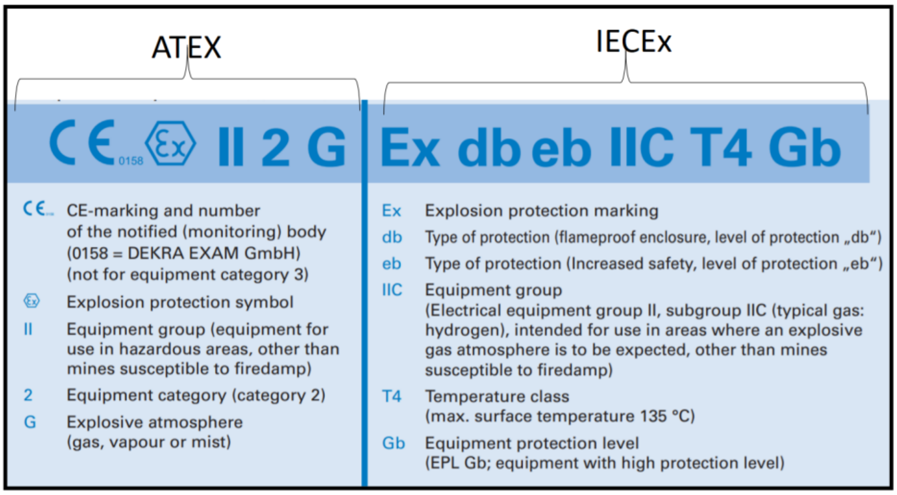
2.4 Electrical Equipment Mark in Hazardous Area

First and foremost, IECEx is a scheme implemented by IEC. It is to deal with the certification of conformity for the electrical equipment utilized in the explosive atmosphere (R&M Electrical Group LTD, n.d.).

To perform case studies, the basic knowledge of the IECEx marking of the electrical equipment utilized in the potentially explosive area is required. Moreover, such electrical equipment is also known as Ex equipment. The overview on the marking of Ex equipment is presented in the first subsection. Furthermore, there are four more subsections which to further discuss the ‘equipment group’, ‘temperature class’, ‘equipment protection level’ and ‘type of protection’.

2.4.1 Overview

Typically, every piece of equipment installed in hazardous areas is certified by ATEX and IECEx. ATEX is the standard that abides by the law and is mainly applied in Europe whereas IECEx is used globally (MIBEX, 2020). In this section, Figure 2.3 which is the example of the Ex apparatus mark will be taken as a reference to carry out the overview. Referring to the figure, the Ex equipment mark is reviewed starting from ‘CE-marking’ to ‘equipment protection level’.



CE	CE-marking and number of the notified (monitoring) body (0158 = DEKRA EXAM GmbH) (not for equipment category 3)
Ex	Explosion protection symbol
II	Equipment group (equipment for use in hazardous areas, other than mines susceptible to firedamp)
2	Equipment category (category 2)
G	Explosive atmosphere (gas, vapour or mist)

Ex	Explosion protection marking
db	Type of protection (flameproof enclosure, level of protection „db“)
eb	Type of protection (Increased safety, level of protection „eb“)
IIC	Equipment group (Electrical equipment group II, subgroup IIC (typical gas: hydrogen), intended for use in areas where an explosive gas atmosphere is to be expected, other than mines susceptible to firedamp)
T4	Temperature class (max. surface temperature 135 °C)
Gb	Equipment protection level (EPL Gb; equipment with high protection level)

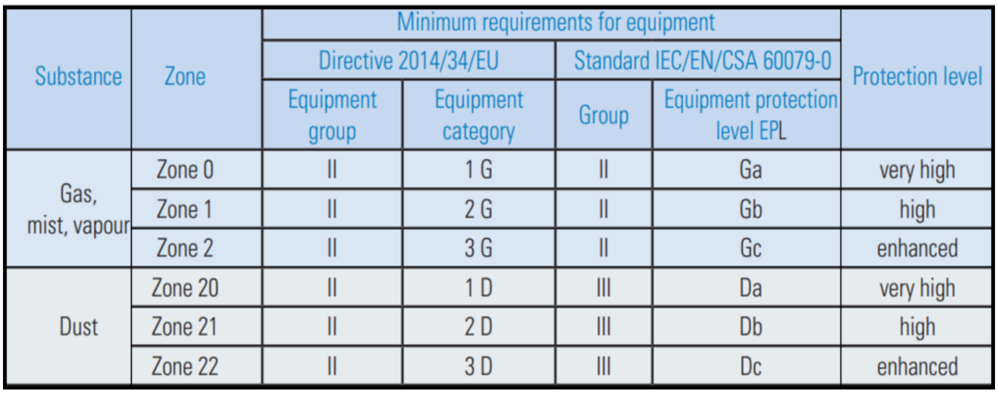
Figure 2.3: Ex Equipment Mark (Eaton, 2017).

First and foremost, under ATEX, the ‘CE-marking’ is followed by four digits which represent the code number of the notified body. The duty of the notified body is to perform the testing for the purpose of quality assurance. The ATEX ‘explosion protection symbol’ is to indicate the equipment is under explosion protection. For the ‘equipment group’ under ATEX, ‘I’ is for the mining industry while ‘II’ is for the other industries. Besides that, for ‘explosive atmosphere’, ‘G’ stands for gas and ‘D’ stands for dust (Eaton, 2017).

Apart from ATEX, the ‘Ex’ under IECEx shows that the explosion protection is applied. For ‘type of protection', there are several protections under IECEx. In addition, the ‘equipment group’ is to indicate the type of atmosphere in which the equipment can be applied. Besides that, ‘temperature class’ is to show the maximum surface temperature. The ‘equipment protection level’ is to indicate the protection level. For instance, ‘Ga’ has the highest protection in an atmosphere with flammable gases (Eaton, 2017).

Table 2.1 provides a clear concept of the relationship among the specifications of Ex marking.

Table 2.1: Summary of Ex Marking (Eaton, 2017).



Substance	Zone	Minimum requirements for equipment				Protection level
		Directive 2014/34/EU		Standard IEC/EN/CSA 60079-0		
		Equipment group	Equipment category	Group	Equipment protection level EPL	
Gas, mist, vapour	Zone 0	II	1 G	II	Ga	very high
	Zone 1	II	2 G	II	Gb	high
	Zone 2	II	3 G	II	Gc	enhanced
Dust	Zone 20	II	1 D	III	Da	very high
	Zone 21	II	2 D	III	Db	high
	Zone 22	II	3 D	III	Dc	enhanced

2.4.2 Equipment Group

Table 2.2 shows the classification of gases and the corresponding minimum ignition energy. For the gas atmosphere, the IIC group requires the least energy to be self-ignited (Coetzee, 2016). In other words, it can be said that such a gas group is the most hazardous group.

Table 2.2: Classification of Gases (Coetzee, 2016).

Gas Group	**Representative Gas**	**Minimum Ignition Energy**
IIA	Propane	180 µJ and Higher
IIB	Ethylene	60 µJ – 180 µJ
IIC	Hydrogen	20 µJ – 60 µJ

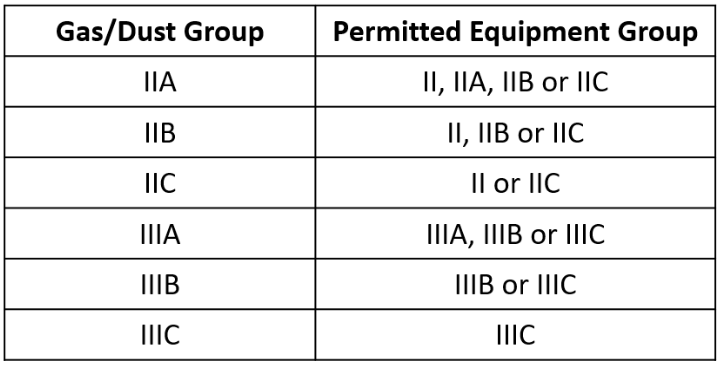
Furthermore, the same concept applies to the dust group. Table 2.3 shows the classification of dust. Regarding the dust group, the IIIC group is the most hazardous while the IIIA group is the group having the least risk.

Table 2.3: Classification of Dusts (Coetzee, 2016).

Dust Group	**Description**
IIIA	Combustible flying’s
IIIB	Non-conductive dust
IIIC	Conductive dust

As per IEC 60079-14 Clause 5.5, the guidelines regarding the permitted equipment group based on different gas and dust groups are provided. Table 2.4 shows the equipment group that can be applied according to different groups of gases and dusts. For instance, when the gas group is IIC, only the apparatus with the equipment group marked as II or IIC can be applied (IEC, 2013).

Table 2.4: Permitted Equipment Group (IEC, 2013).



Gas/Dust Group	Permitted Equipment Group
IIA	II, IIA, IIB or IIC
IIB	II, IIB or IIC
IIC	II or IIC
IIIA	IIIA, IIIB or IIIC
IIIB	IIIB or IIIC
IIIC	IIIC

In short, when verifying the compliance of apparatuses installed in the hazardous area, the equipment group marked on the apparatus has to be checked according to the surrounding gas or dust groups.

2.4.3 Temperature Class

First and foremost, the temperature class of the Ex apparatus can provide information regarding the maximum surface temperature (Eaton Electric Limited, n.d.). The temperature class is utilized to verify whether the installation of the Ex apparatus is compatible with the auto-ignition temperature of the surrounding gases.

Furthermore, Table 2.5 shows the temperature class and the maximum surface temperature of the Ex apparatus.

Table 2.5: Temperature Class and Maximum Surface Temperature of Apparatus (Coetzee, 2016).

Temperature Class	Maximum Surface Temperature of Electrical Apparatus (°C)
T1	450
T2	300
T3	200
T4	135
T5	100
T6	85

Referring to Table 2.5, if the temperature class marked on the apparatus is T2, its maximum surface temperature will be 300 °C. For instance, the apparatus having a maximum surface temperature of 150 °C is classified under the temperature class of T3 since its maximum surface temperature is higher than 135 °C but lower than 200 °C.

As per IEC 60079-14 Clause 5.6.2, the range of the applicable temperature classes based on the auto-ignition temperature of gases is provided. Additionally, it is shown in Table 2.6.

Table 2.6: Applicable Temperature Classes Based on the Auto-ignition Temperature of Gases (IEC, 2013).

Auto-ignition Temperature of Gases (°C)	Applicable Temperature Classes
> 450	T1-T6
> 300; ≤ 450	T2-T6
> 200; ≤ 300	T3-T6
> 135; ≤ 200	T4-T6
> 100; ≤ 135	T5-T6
> 85; ≤ 100	T6

According to Table 2.6, if the auto-ignition temperature of gas exceeds 450 °C, the temperature class marked on the Ex equipment can range from T1 to T6. In the condition that the auto-ignition temperature of the gas is larger than 85 °C but less than 100 °C, only the temperature class of T6 is allowed.

Furthermore, Figure 2.4 shows the applicable temperature class depending on the auto-ignition temperature of some gases. For example, in the surrounding atmosphere filled with diethyl ether which has the auto-ignition temperature of 175 °C, the equipment marked with temperature class of T3 is applied. In this case, its surface can reach a temperature up to 200 °C, resulting in the self-ignition of the carbon disulphide.

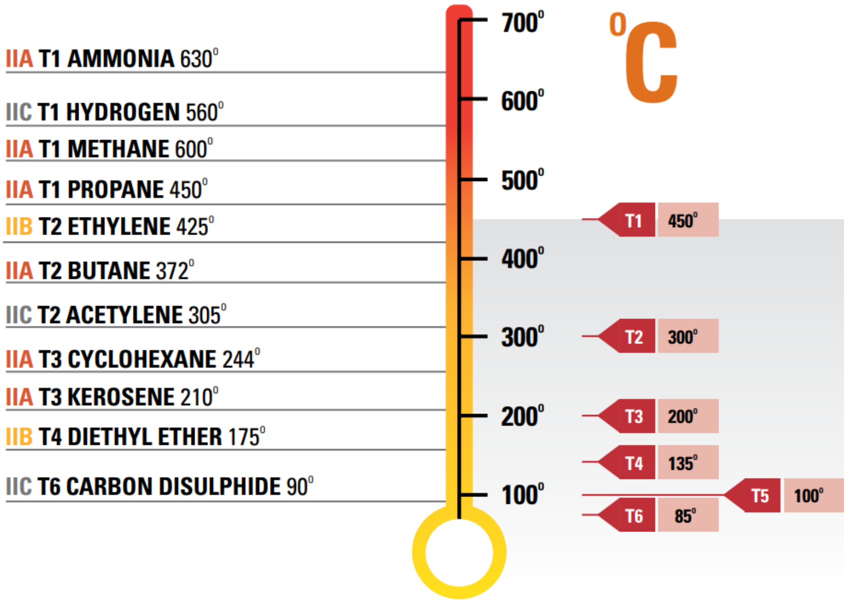


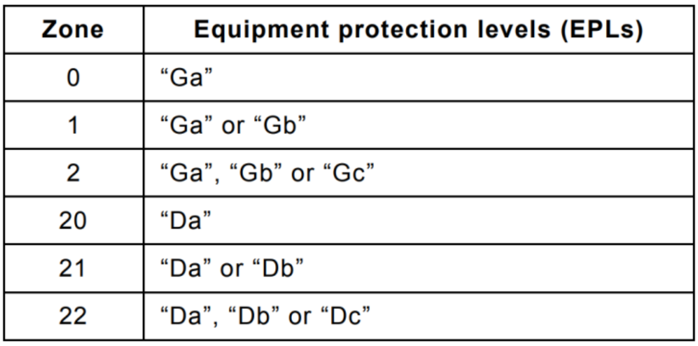
Figure 2.4: Applicable Temperature Class (Eaton Electric Limited, n.d.).

As a result, the temperature class marked on the apparatus has to be checked according to the surrounding gas or dust groups. This is to ensure that the maximum surface temperature does not exceed the auto-ignition temperature of the surrounding gases.

2.4.4 Equipment Protection Level

As per IEC 60079-14 Clause 5.3, the permitted equipment protection level based on the zone classification is provided. In addition, it is shown in Table 2.7.

Table 2.7: Permitted Equipment Protection Level According to Zone Classification (IEC, 2013).



Zone	Equipment protection levels (EPLs)
0	“Ga”
1	“Ga” or “Gb”
2	“Ga”, “Gb” or “Gc”
20	“Da”
21	“Da” or “Db”
22	“Da”, “Db” or “Dc”

Referring to Table 2.7, if the hazardous area is classified as Zone 0, only the equipment protection level of ‘Ga’ is applicable. In short, the equipment protection level is determined based on the zone classification.

2.4.5 Type of Protection

The applicable type of protection method based on the equipment protection level is stated as per IEC 60079-14 Clause 5.4. Additionally, it is shown in Table 2.8.

Table 2.8: Applicable Type of Explosion Protection Method Based on Equipment Protection Level (IEC, 2013).

Equipment Protection Level	Method of Protection	Ex Code
Ga	Intrinsic Safety	Ex ia
Gb	Explosion-proof	Ex db
	Increased Safety	Ex eb
	Intrinsic Safety	Ex ib
Gc	Intrinsic Safety	Ex ic
	Increased Safety	Ex ec

As per Table 2.8, intrinsic safety has three subdivisions, namely ‘ia’, ‘ib’ and ‘ic’. Among the subdivisions of the Ex i, ‘ia’ is the only method that is compatible with the equipment protection level of ‘Ga’. In short, the type of protection method is determined according to the equipment protection level.

2.5 Explosion Protection Method

In this section, several types of explosion protection (or Ex protection) techniques are introduced. Generally, they can be classified into two categories, namely prevention and containment. Figure 2.5 shows the classification of the explosion protection method.

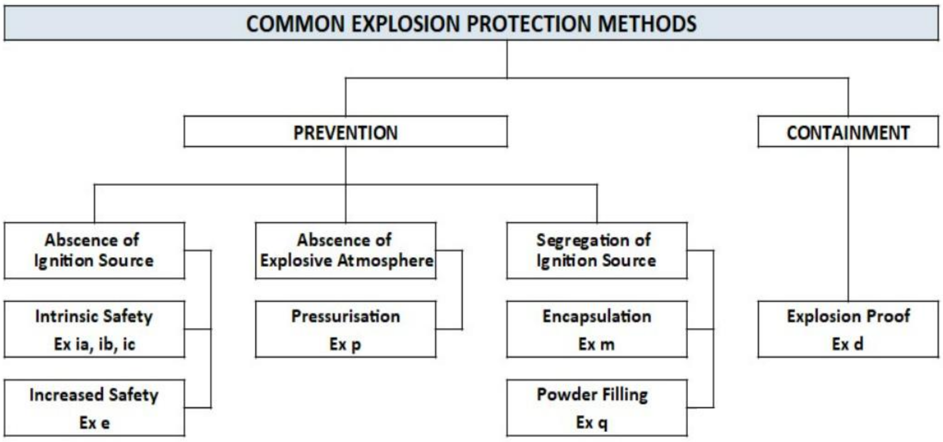


Figure 2.5: Explosion Protection (Control and Instrumentation, 2021).

Based on Figure 2.5, apart from explosion proof, the other explosion methods are implemented on the basis of eliminating flammable materials or preventing the occurrence of the additional energy leading to an explosion. As a result, the explosion prevention method is executed through the removal of any elements in the fire triangle.

2.5.1 Pressurization

Pressurization (Ex p) is a way to prevent the electrical apparatus from being exposed to combustible materials in a hazardous area. In some events such as short circuits, the equipment may be the source contributing to the additional energy. For instance, such energy might lead to an explosion. As a result, Ex p is utilised to implement the separation between them (SOURCE IEx, n.d.). In addition, Figure 2.6 shows a scenario of applying Ex p.

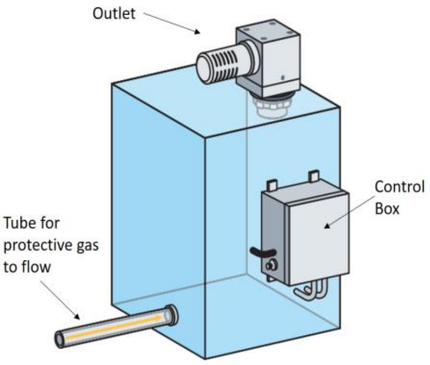


Figure 2.6: Pressurization (Pepperl+Fuchs, n.d.).

Based on Figure 2.6, in the condition that an electrical apparatus is located inside a protective casing, the mixture of inert gas and air is pressurized and inserted into the protective casing through the tube with a small cross-sectional area. The concept behind this operation is to make the pressure inside the protective casing to be larger than the pressure of the surrounding air filled with combustible gas. As a result, the combustible gas cannot flow into the protective casing due to the pressure difference. In addition, the control box is to monitor the decrease or increase of the pressure inside the protective casing. Through the feedback provided by the control box, the pressure difference between the surrounding and the space inside the protective casing can be maintained. As long as the pressure difference is maintained, the apparatus will not be exposed to combustible materials (Pepperl+Fuchs, n.d.). Last but not least, the main advantage of Ex p is that it can come up with a relatively large safe area using a relatively low cost.

2.5.2 Encapsulation

The concept of encapsulation (Ex m) is to implement the usage of a protective casing for electrical apparatus. Typically, such apparatus encapsulated by the protective casing may cause ignition leading to an explosion. As a result, such a protective casing is treated as a barrier in order to implement the segregation between the apparatus having the chance to cause ignition and the surrounding environment filled with combustible substances. Following Ex m guidelines, the material of such protective casing can be thermoplastic, resin or elastomer. Such protective casing is normally applied for relay and solenoid (SOURCE IEx, n.d.). In addition, Figure 2.7 illustrates the concept of encapsulation.

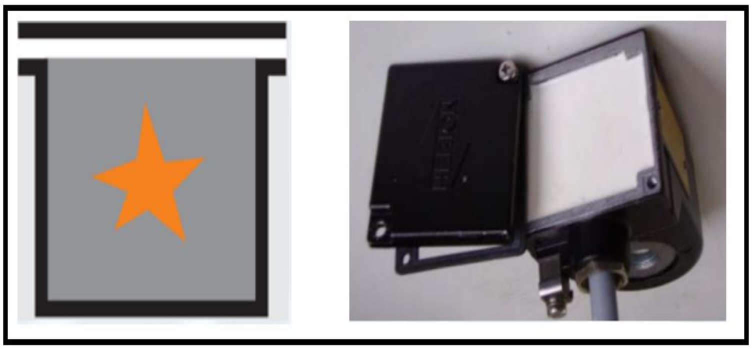


Figure 2.7: Encapsulation (Neleman, 2018).

2.5.3 Powder Filled

The nature of powder filled (Ex q) is to isolate the electrical apparatus from the combustible gas using filling material within an enclosure. Following guidelines under Ex q, such filling material can be quartz sand or glass beads. To avoid the loss of such material, the enclosure has to be designed well. Furthermore, there must be no pore remains unfilled within the enclosure (SOURCE IEx, n.d.). In addition, Figure 2.8 illustrates the concept of powder filled method.

Figure 2.8: Powder Filled (SOURCE IEx, n.d.).

2.5.4 Flameproof

Based on the nature of flameproof (Ex p), its main concern is not segregation or prevention. Its concept is to minimize the damages by restricting the explosion from spreading when such an event occurs. The main advantage of Ex d is that it accepts a wide range of electrical equipment including that equipment can cause sparking effects. In addition, Figure 2.9 shows the concept of flameproof.

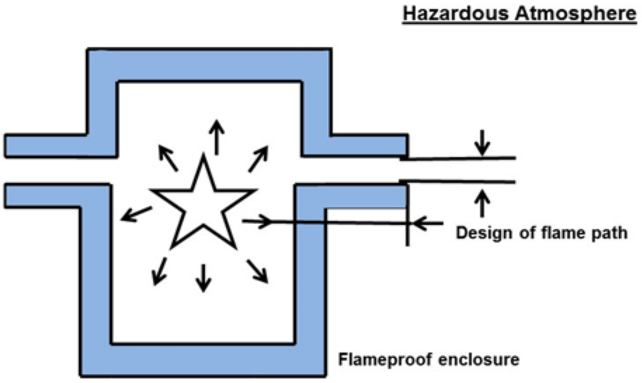


Figure 2.9: Flameproof (Desuki, 2013).

First and foremost, one of the concerns regarding flameproof is the flame path. In the condition that the explosion occurs, there will have an enormous amount of energy being produced inside the enclosure. If there is no appropriate mechanism to deal with such energy, it may ignite the explosion in the outbound area of the enclosure. In this case, the explosion may spread. Typically, such energy is released through the gas. Therefore, the length and the cross-sectional area of the flame path should be planned properly to reduce the temperature of the gas to a safe level. (Desuki, 2013).

Apart from the flame path, the other concern is the enclosure. Undoubtedly, the pressure inside the enclosure is extremely high during an explosion. As a result, it must have the appropriate mechanical properties to deal with such conditions. Besides that, in the condition that the explosion occurs inside the enclosure, its surface temperature must be maintained at a level that is unable to cause an explosion (Krause, Bewersdorff and Markus, 2017).

2.5.5 Increased Safety

The concept of increased safety (Ex e) is to implement the prevention against explosion. In addition, it provides guidelines for enclosures. Obeying guidelines under Ex e, the apparatus having the nature of suddenly introducing an enormous amount of energy is not allowed. For instance, under the concept of Ex e, the apparatus that can cause a sparking effect is restricted to be installed or mounted inside the enclosure. Following Ex e guidelines regarding enclosures, the ingress protection level is one of the requirements. In addition, Figure 2.10 illustrates the Ex e concept.

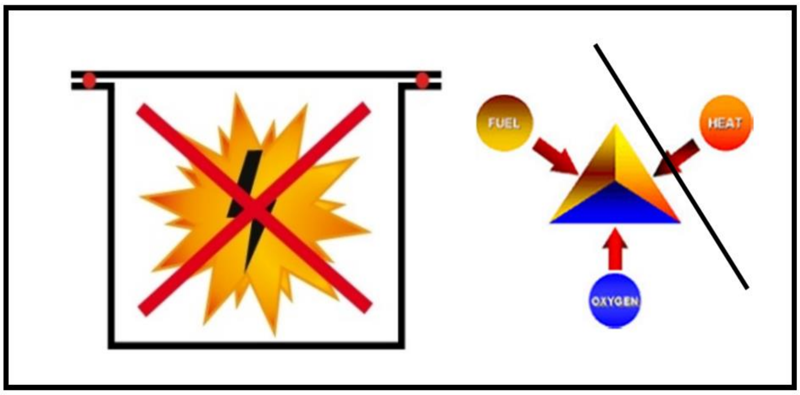


Figure 2.10: Increased Safety (SOURCE IEx, n.d.).

Apart from that, the power emitted from apparatus is also one of the concerns under Ex e. For instance, such power will increase temperature. Moreover, such power has to be evaluated in order to assure that the thermal effect due to such power does not cause ignition. Aside from that, it also provides guidelines regarding terminals. Concerning the terminals, the in-air distance, as well as the distance along the surface, are specified under Ex e. Also, the calculation regarding the maximum number of terminals is covered under the Ex e concept. In a nutshell, Ex e is a kind of preventive protection that takes several measurable factors into consideration to achieve the goal of the elimination of the ignition source (SOURCE IEx, n.d.).

2.5.6 Intrinsic Safety

The concept of intrinsic safety (Ex i) is to implement the restriction of energy. By applying the Ex i method, the energy can be bound below the ignition point. Therefore, it can minimize or eliminate the chances for the events such as a spark or hot surface temperature to happen. In addition, Figure 2.11 illustrates the concept of the Ex i method.

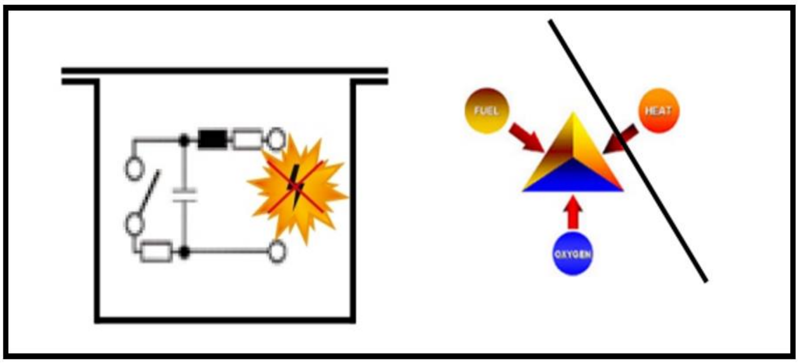


Figure 2.11: Intrinsic Safety (SOURCE IEx, n.d.).

Typically, Ex i is applied for the industry that utilizes a control and instrumentation system. Additionally, such a system requires a relatively small amount of electrical power. For example, sensors or signal converters applied in such a system usually do not need large power consumption. Generally, in the execution of the Ex i method, Zener barriers or isolators are used in order to restrict the power supplied to apparatus in a hazardous area. For instance, in the condition that the voltage surges occur in the non-hazardous area, it will result in extremely high voltage and energy. Without the Zener barrier or isolator, such voltage and energy will directly affect the apparatus in a hazardous area. As a result, the role of Zener barriers or isolators is to prevent the additional energy to enter the circuit in a hazardous area (MTL Instruments, n.d).

One of the outstanding facets of Ex i is that it allows the usage of simple apparatus in a hazardous area without certification. Besides that, Zone 0 is classified as the most hazardous zone and Ex i is the only method that can be applied to such zone. Due to the nature of Ex i, it can assure that the energy maintains at a safe level. In this way, the maintenance or troubleshooting of the circuit can be executed without the removal of the electrical power (Sackett, 2018). Therefore, the operation of the industry will not be affected and the safety of the online maintenance can be assured.

2.6 Overview on Intrinsic Safety

In this section, the overview on intrinsic safety including the subdivision, and configuration of intrinsic safety system are presented.

2.6.1 Subdivision of Intrinsic Safety

In accordance with IEC 60079-14 Clause 16.1, intrinsic safety (Ex i) has three subdivisions, which are 'ia', 'ib' and 'ic'. Based on different levels of risk in hazardous areas, the different subdivisions will be applied (IEC, 2013). Figure 2.12 shows the application of subdivision of Ex i according to different zone and equipment protection levels (EPL).

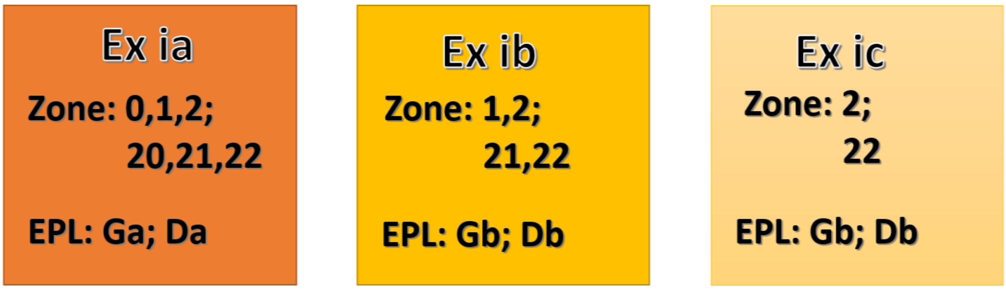


Figure 2.12: Subdivision of Ex i (Radio Academy, 2022).

Furthermore, Ex ia is the technique with the highest level of protection among the subdivision of Ex i. Hence, it can be applied to the most hazardous zone (Zone 0, 20) and the other zones with fewer risks. Besides that, Ex ic can only be applied for Zone 2 or Zone 22. In addition, 'Ga' or 'Da' has the highest protection level. Among the subdivision of Ex i, only Ex ia can comply with the 'Ga' or 'Da'.

2.6.2 Configuration of Intrinsic Safety System

Figure 2.13 shows the typical intrinsic safety (Ex i) configuration.

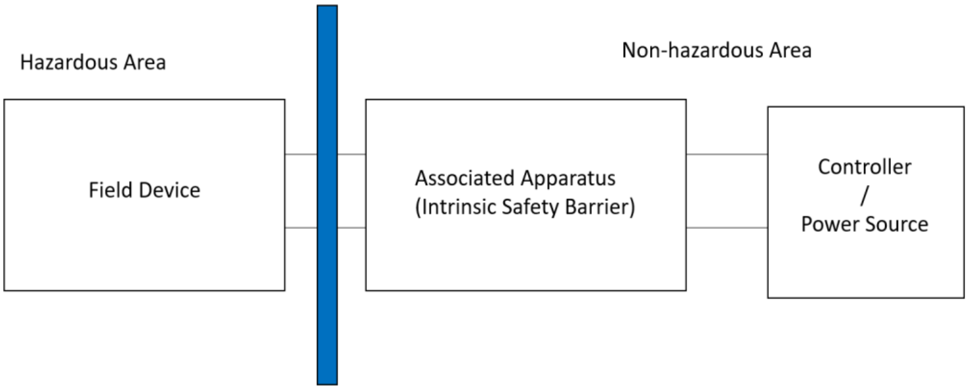


Figure 2.13: Ex i Configuration.

First and foremost, since the Ex i method is mostly applied in control and instrumentation systems. Therefore, the equipment such as the power source or controller is installed in a non-hazardous area.

When implementing an Ex i system, associated apparatus is essential in order to implement the restriction of energy. Furthermore, it is positioned between the field devices and the power source or controller within the system (OMEGA Engineering Inc., 2022). In addition, associated apparatuses are known as Ex i barriers. Typically, such a barrier is positioned in a non-hazardous area. According to IEC 60079-14 Clause 16.1, if the barrier is utilized in a hazardous area, the explosion protection technique other than Ex i method has to be adopted for the barrier (IEC, 2013).

Apart from that, except for simple apparatuses, the field devices or apparatuses utilized in the hazardous area require to be certified prior to the installation. Regarding the installation of simple apparatuses in a hazardous area, certification is not required (MTL Instruments, n.d.).

2.7 Apparatuses Installed in Intrinsic Safety System

In this section, the apparatuses including associated apparatuses and field devices are discussed.

2.7.1 Associated Apparatus (Ex i Barrier)

Referring to IEC 60079-14 Clause 3.5.2, the associated apparatus is regarded as a barrier between the field apparatus and the equipment such as a power source or controller (IEC, 2013). Furthermore, field apparatuses in hazardous areas have to be certified by Ex i. Besides that, the Ex i certification is not necessary for those controllers or power source devices located in non-hazardous areas. In addition, associated apparatuses have to be certified following IEC standards.

Within an Ex i system, an associated apparatus is installed between the field equipment positioned in a hazardous area and the power source or control equipment which is positioned in a non-hazardous area. The purpose of the associated apparatus is to minimize the impact due to the equipment in a non-hazardous area, especially when the events such as voltage surges and short circuits occur (Friend, 2021). Therefore, the energy transferred to the equipment which is located in the hazardous area can be restricted. Apart from that, there are two major types of associated apparatus, namely the Zener barrier and the galvanically isolated barrier.

2.7.1.1 Zener Barrier

Figure 2.14 shows a typical Zener Barrier.

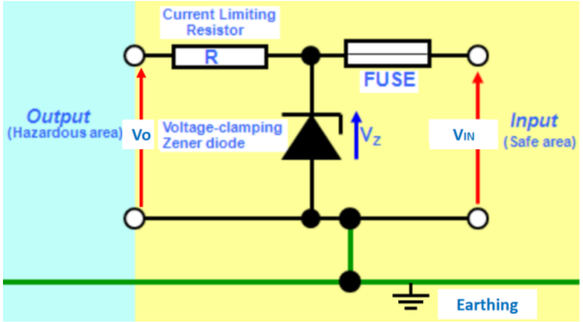


Figure 2.14: Zener Barrier (Friend, 2021).

Referring to Figure 2.14, in the condition that the Ex i system is operating normally, the output voltage, V_o is not going to exceed the voltage across the Zener diode, V_Z. As a result, the major role of the diode in the Zener Barrier is to execute the restriction on V_O. Furthermore, the resistor, R is utilized for the restriction of the current flowing into the circuit in the hazardous area. Besides that, the fuse is utilized to prevent the Zener diode from being destroyed during fault conditions. Apart from that, earthing is essential to be executed when applying the Zener barrier. Therefore, if the fault condition occurs, the additional current and voltage will be transferred to the ground (Friend, 2021). If the number of Zener diodes increases, Ex i system can withstand more countable faults (Mirza, 2015). Table 2.9 shows the relationship among Ex i subdivision, countable fault and number of Zener diode.

Table 2.9: Relationship among Ex i Subdivision, Countable Fault and Number of Zener Diodes (Mirza, 2015).

Ex i Subdvision	**Countable Fault**	**Number of Zener Diode**
Ex ia	2	3
Ex ib	1	2
Ex ic	0	1

2.7.1.2 Galvanically Isolated Barrier (Isolator)

Galvanically isolated barriers are known as isolators. Typically, isolators consist of a transformer or optocoupler (IEC, 2013). Compared with Zener barriers, the outstanding facet of isolators is that they can provide electrical isolation. Therefore, intrinsic safety earthing is not necessary if isolators are applied. Figure 2.15 shows an isolator.

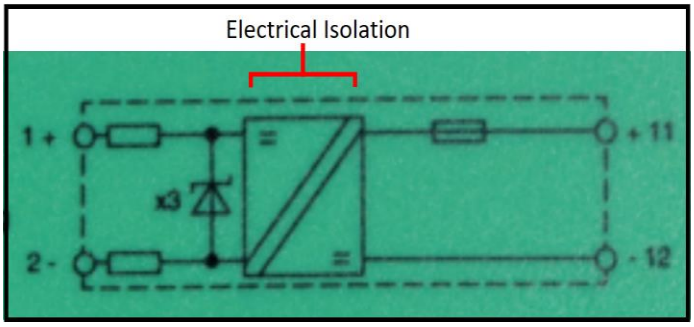


Figure 2.15: Isolator (Protectionic, 2020).

2.7.1.3 Validation Regarding Safety Parameters of Associated Apparatus

The safety parameters of associated apparatus are shown in Table 2.10.

Table 2.10: Safety Parameters of Associated Apparatus.

Safety Parameters of Associated Apparatus	**Abbreviation**	**Unit**
Maximum Output Voltage	U_O	V
Maximum Output Current	I_O	A
Maximum Output Power	P_O	W
Maximum Allowed Inductance	L_O	H
Maximum Allowed Capacitance	C_O	F

In addition, the safety parameters of the associated apparatus can be verified using energy curves. As shown in Figure 2.16, they are resistive energy curve, capacitive energy curve and inductive energy curve. These energy curves are generated using the experimental equipment known as ‘spark test apparatuses’ (Kuan, 2006).

Referring to Figure 2.16, there are different curves for different equipment groups (IIA, IIB and IIC). For instance, if the equipment group of the Ex i barrier is classified as IIC, only the curve of IIC has to be referred to in the verification.

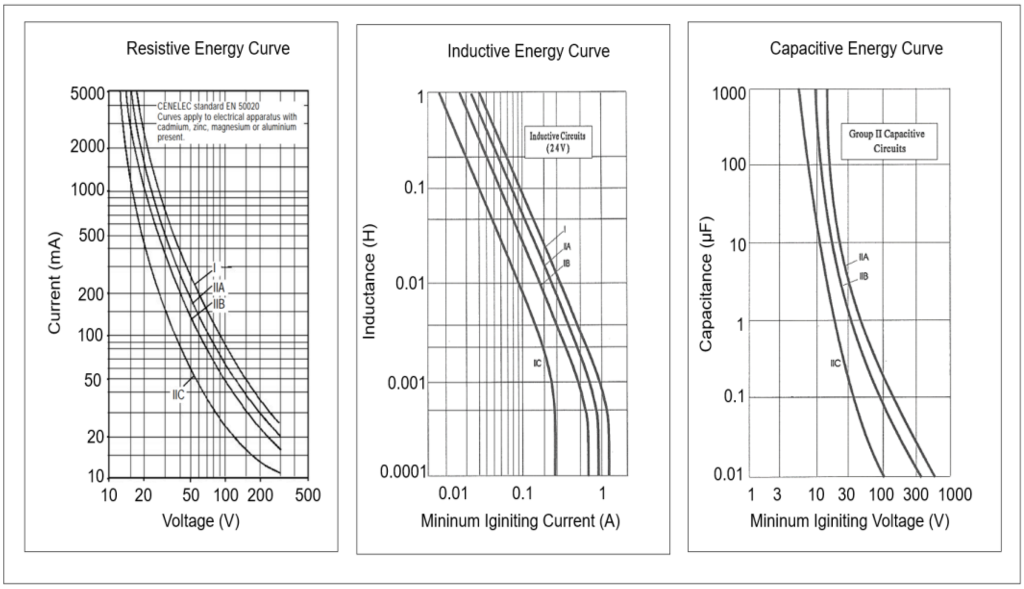


Figure 2.16: Energy Curves (Kuan, Chew and Chua, 2020).

Using a resistive energy curve, the safety parameters including U_o and I_o can be verified. Before utilizing the curve, it is required to multiply Io by a safety factor. In the case that the Ex ic method is applied, the safety factor is 1. For Ex ia and Ex ib, it requires a larger safety factor of 1.5. Thus, Io and U_o multiplied with the safety factor can form a point. The point has to be positioned on the resistive energy curve. If the coordinate point is located below the curve, it can be assured that the voltage and current supplied by Ex i barrier will not ignite the combustible substances (Kuan, Chew and Chua, 2020). Moreover, since $P_O = \frac{I_O U_O}{4}$, P_o will be valid as long as both the U_o and I_o are valid.

After verifying the U_o and I_o, it is required to determine whether the L_o has complied with Ex i method. The verification of L_o is carried out using an inductive energy curve. The safety factor is 1 if the Ex ic method is applied whereas the safety factor is 1.5 for Ex ia and Ex ib. After multiplying I_o by a safety factor, a point formed by L_o and I_o multiplied with a safety factor can be located on the inductive energy curve. If the point is located below or exactly on the curve, L_o is valid (Kuan, Chew and Chua, 2020).

In addition, the C_o is verified using a capacitive energy curve. If Ex ic method is utilized, the safety factor is 1. Besides that, the safety factor is 1.5 if Ex ia or Ex ib method is applied. After multiplying U_o by a safety factor, a point formed by C_o and U_o multiplied with a safety factor can be positioned on the capacitive energy curve. C_o is valid in the condition that the point is located below or exactly on the curve (Kuan, Chew and Chua, 2020).

In short, the safety parameters of Ex i barriers can be verified using the energy curves. Moreover, the safety factor will be different depending on the level of protection of the Ex i method.

2.7.2 Field Device

In this section, field devices including certified field devices and simple apparatuses are discussed.

2.7.2.1 Certified Field Device

In some industries, there is a need to install or apply electrical apparatus in hazardous areas. For example, the apparatuses such as sensors and signal converters are installed in the hazardous area to monitor the process (Phoenix Contact, 2022). Therefore, it is vital to assure such apparatuses will not ignite an explosion.

Following guidelines under IEC standards, except for simple apparatuses, the apparatuses installed in the hazardous area have to be certified (R. STAHL AG, 2020). Such apparatuses certified under Ex i protection are known as certified field devices. To obtain the certification, such apparatuses have to be tested by a notified body to assure their conformity (European Commission, n.d). Furthermore, the compliance of certified field devices can be validated according to IECEx marking.

In short, except for simple apparatuses, all the field devices in the hazardous area are enforced to be certified.

2.7.2.2 Simple Apparatus

As mentioned in section 2.7.2.1, all the devices installed in hazardous areas have to be certified but simple apparatuses are the exception. In other words, certifications are not mandatory prior to the installation of simple apparatuses in hazardous areas.

Referring to IEC 60079-14 Clause 16.4, there are three groups of simple apparatuses. Firstly, the passive elements including resistors, junction boxes and so on are simple apparatuses. Secondly, the elements storing energy such as inductors and capacitors are included under the groups of simple apparatuses. Thirdly, simple apparatuses include elements producing electrical power. For instance, they can be photocells or thermocouples. Additionally, they cannot produce a voltage that is larger than 1.5 V or a current exceeding 0.1 A. Concerning the restriction on power, they cannot produce more than 25 mW (IEC, 2013).

Although simple apparatuses are not required to be certified by Ex i, their thermal effect still has to be taken into consideration. This is because the surface temperature may be the ignition source. Equation (2.1) can be applied to obtain the maximum surface temperature of simple apparatuses (IEC, 2013).

$$\mathrm{T} = \mathrm{P_o R_{th}} + \mathrm{T_{amb}} \tag{2.1}$$

where

T= Maximum surface temperature, °C

P_O = Maximum output power of Ex i barrier, W

R_{th} = Surface Temperature Rise, °C/ W

T_{amb} = Ambient temperature, °C

Furthermore, the temperature class of simple apparatuses can be determined as per Table 2.11.

Table 2.11: Temperature Class of Simple Apparatuses.

Surface Area	**Maximum Surface Temperature**	**Temperature Class**
Less than 20 mm^2	Less than 275 °C	T4
Between 20 mm^2 and 1000 mm^2	Less than 200 °C	T4
Less than 1000 mm^2	Less than 150 °C	T5

Aside from the surface area and the calculation regarding maximum surface temperature, Annex E of IEC 600079-25 has provided another approach to determine the temperature class of simple apparatuses. For the simple apparatuses which are temperature sensing devices such as resistance temperature detectors and thermocouples, the temperature class can be determined based on the maximum measurable temperature (IEC, 2009).

2.8 Intrinsic Safety Loop Verification

In this section, the parameters, steps and formulas to execute the intrinsic safety verification in accordance with IEC 60079-14 are presented.

2.8.1 System with a Single Ex i Barrier

The steps to execute intrinsic safety loop verification for the Ex i system having only one Ex i barrier are stated in IEC 60079-14 Clause 16.2.4.3. Figure 2.17 shows the Ex i configuration with the safety parameters.

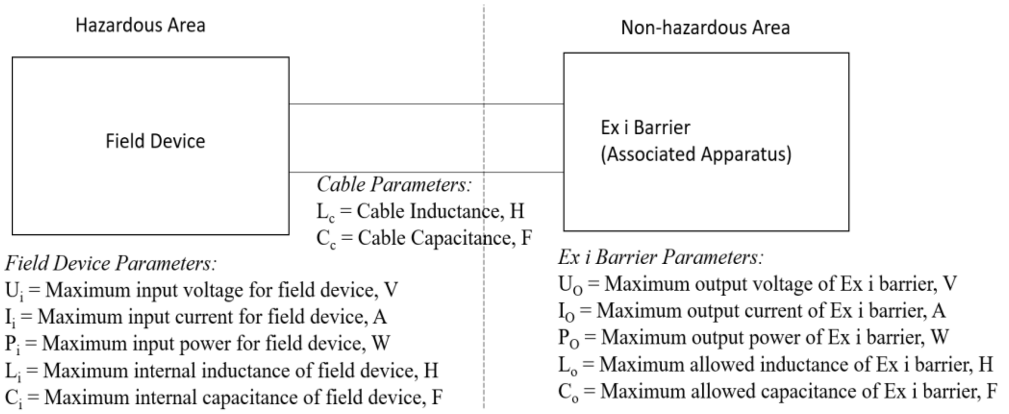


Figure 2.17: Ex i Configuration with the Safety Parameters.

First and foremost, the maximum output voltage of the Ex i barrier has to be less or equal to the maximum input voltage of each of the field devices. For instance, in the condition that there are two field devices in the Ex i system, each of the field devices has a distinct value of maximum input voltage, and each of the maximum input voltage values needs to be larger than or the same as the maximum output voltage of Ex i barrier. Furthermore, Equation (2.2) shows the intrinsic safety verification regarding the voltage.

$$U_o \leq U_i \tag{2.2}$$

where

U_O = maximum output voltage of the Ex i barrier, V

U_i = maximum input voltage for field device, V

With regard to the maximum output current of the Ex i barrier, such value has to be less or the same as the value of the maximum input voltage for each of the field devices. Additionally, Equation (2.3) shows the intrinsic safety verification regarding the current.

$$I_o \leq I_i \tag{2.3}$$

where

I_O = maximum output current of the Ex i barrier, A

I_i = maximum input current for field device, A

Apart from that, the maximum output power of the Ex i barrier is required to be less or equal to the value of the maximum input power for each of the field devices. Furthermore, Equation (2.4) shows the intrinsic safety verification regarding the power.

$$P_o \leq P_i \tag{2.4}$$

where

P_O = maximum output power of the Ex i barrier, W

P_i = maximum input power for field device, W

Besides that, the maximum allowed inductance of Ex i barrier (L_o), the maximum internal inductance of the field device (L_i), and cable inductance (L_c) are important parameters in the verification. In addition, if there is more than one field device installed in a hazardous area, the value of L_i will be the sum of the maximum internal inductance for all the field devices.

Aside from inductance, the maximum allowed capacitance of Ex i barrier (C_o), the maximum internal capacitance of field devices (C_i), and cable capacitance (C_c) are required to be considered in the verification. Furthermore, in the condition that there is more than one field device, the value of L_i will be the sum of the maximum internal capacitance for all the field devices. Figure 2.18 shows the flowchart for the verification regarding the inductance and capacitance value.

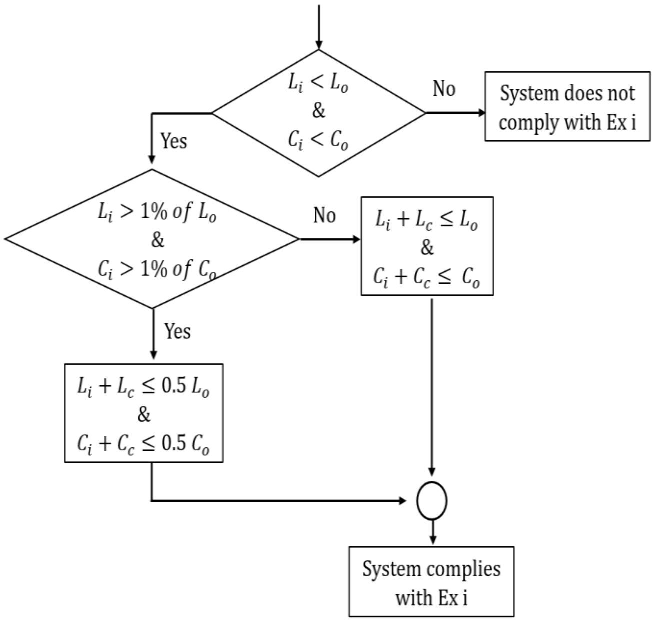
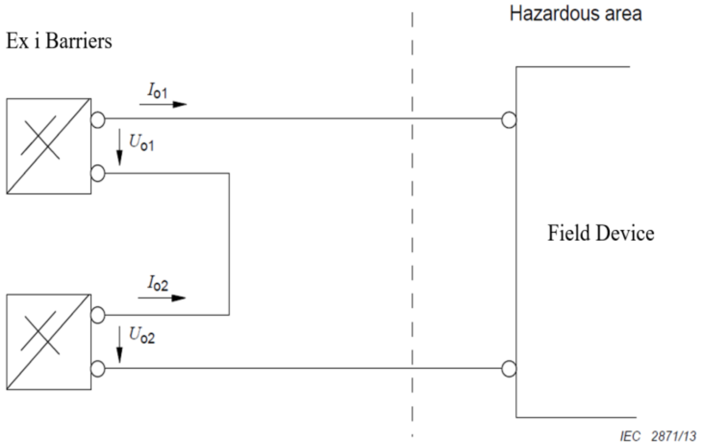


Figure 2.18: Flowchart for Verification Regarding Inductance and Capacitance.

2.8.2 System with Multiple Ex i Barriers

In Annex H of IEC 60079-14, the steps to execute intrinsic safety loop verification for the Ex i system having only one Ex i barrier are provided. In the condition that more than one Ex i barrier is utilized within a system, the maximum output voltage (U_o) as well as the maximum output current (I_o) have to be determined.

Furthermore, there are several types of connection for Ex i barriers. Figure 2.19 shows the way to calculate the U_o and I_o for a series connection.

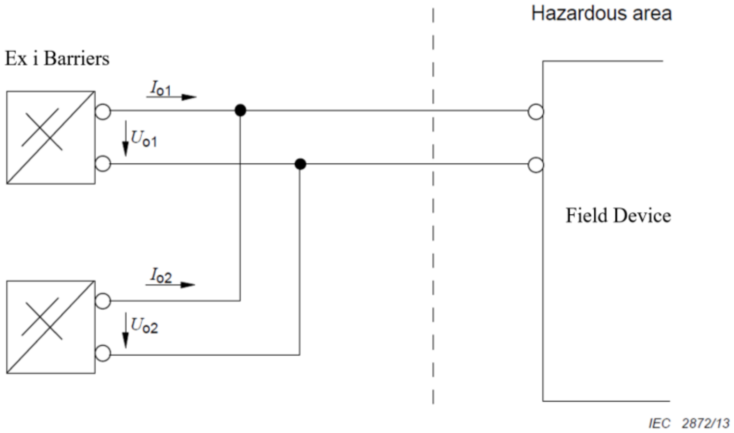


New maximum system values: $U_o = \Sigma U_{oi} = U_{o1} + U_{o2}$

I_o = max. (I_{oi})

Figure 2.19: Series Connection (IEC, 2013).

Besides that, Figure 2.20 provides the guidelines to obtain the U_o and I_o in the condition that the Ex i barriers are connected in parallel.

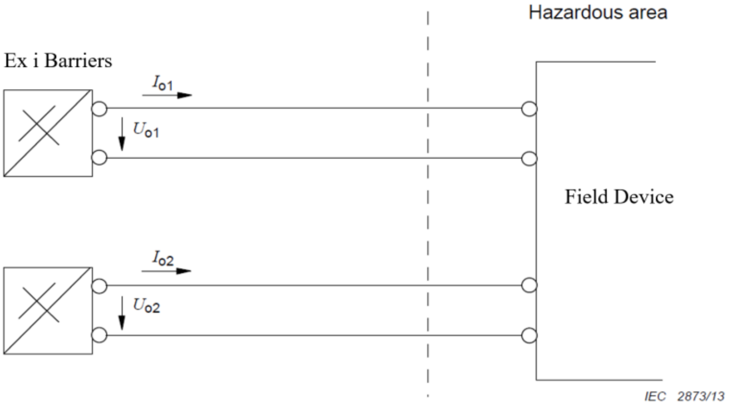


New maximum system values: U_o = max. (U_{oi})

$I_o = \Sigma I_{oi} = I_{o1} + I_{o2}$

Figure 2.20: Parallel Connection (IEC, 2013).

In addition, the method to compute the U_o and I_o for the series and parallel connection is shown in Figure 2.21.



New maximum system values: $U_o = \Sigma\, U_{oi} = U_{o1} + U_{o2}$ $U_o = \max.\,(U_{oi})$

or

$I_o = \max.\,(I_{oi})$ $I_o = \Sigma\, I_{oi} = I_{o1} + I_{o2}$

Figure 2.21: Series and Parallel Connections (IEC, 2013).

After the values of U_o and I_o are obtained, it is required to multiply Io by a safety factor. If Ex ic method is applied, the safety factor is 1. For Ex ia and Ex ib, it requires a larger safety factor of 1.5. Therefore, Io and U_o multiplied with the safety factor can form a point. The point has to be positioned on the resistive energy curve shown in Figure 2.22. If the coordinate point is located below the curve, it is said to be complied with Ex i.

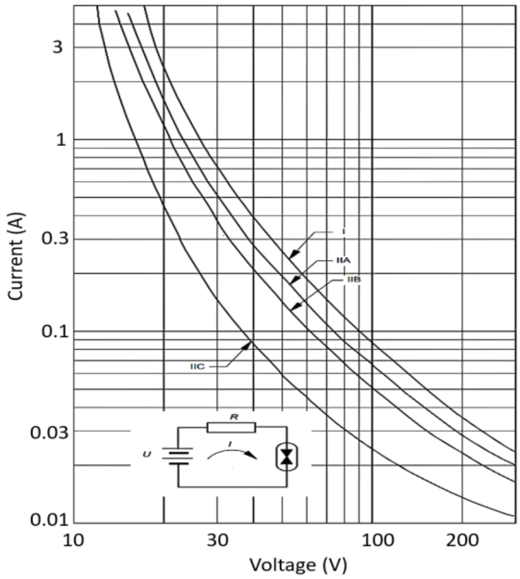


Figure 2.22: Resistive Energy Curve (IEC, 2012).

After the U_o and I_o are verified, it is required to determine the value of L_o using the inductive energy curve shown in Figure 2.23. The safety factor is 1 if Ex ic method is applied. Additionally, it requires the safety factor of 1.5 if Ex ia or Ex ib method is used. Referring to the inductive energy curve, the x-axis is the minimum igniting current. After multiplying I_o by a safety factor, a vertical line, where $x = I_o \times$ (safety factor) can be formed. Thus, the point of intersection between the vertical line and the energy curve can be formed. Based on the coordinate of the point, the value of L_o is obtained.

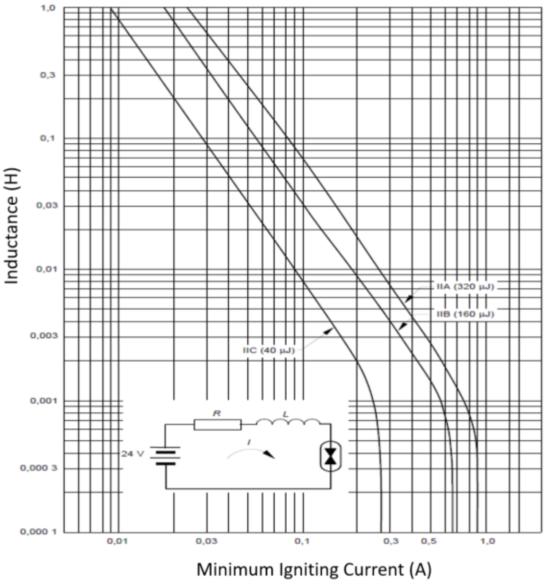


Figure 2.23: Inductive Energy Curve (IEC, 2012).

It has to determine the value of C_o after the value of L_o has been obtained. Moreover, the value of C_o is obtained using the capacitive energy curve shown in Figure 2.24. The safety factor is 1 for the Ex ic method. If Ex ia or Ex ib method is adopted, the safety factor will be 1.5. According to the capacitive energy curve, the x-axis is the minimum igniting voltage. A vertical line, where $x = U_o \times$ (safety factor) is formed after multiplying U_o by a safety factor. Therefore, based on the coordinate of the point where the vertical line and the energy curve intersect with each other, the value of C_o is obtained.

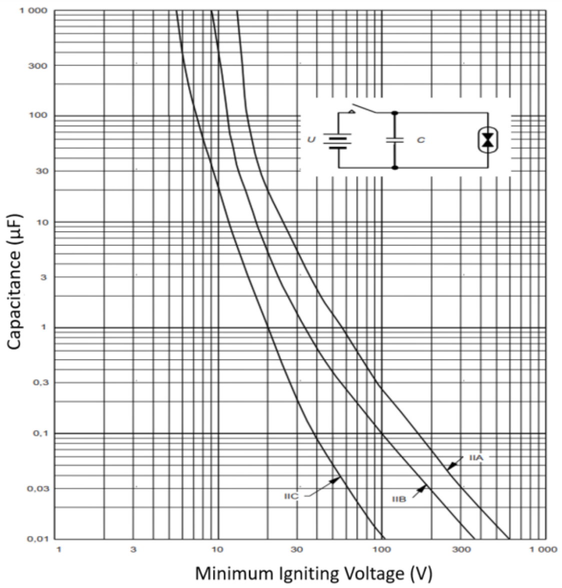


Figure 2.24: Capacitive Energy Curve (IEC, 2012).

After the C_o is verified, the inductance, as well as the capacitance of the field device, Ex i barrier and cable, have to be assessed according to the flowchart shown in Figure 2.18.

Besides that, the maximum output power of Ex i barrier has to be calculated using Equation (2.5) as shown below:

$$P_o = \frac{I_O U_O}{4} \tag{2.5}$$

where

P_O = maximum output power of Ex i barriers, W
I_O = maximum output current of Ex i barriers, A
U_O = maximum output voltage of Ex i barriers, V

After that, Equation (2.2) to Equation (2.4) are used to verify the U_o, I_o, and P_o. Figure 2.25 shows the summary of the way to execute Ex i verification in the condition that multiple Ex i barriers are utilized.

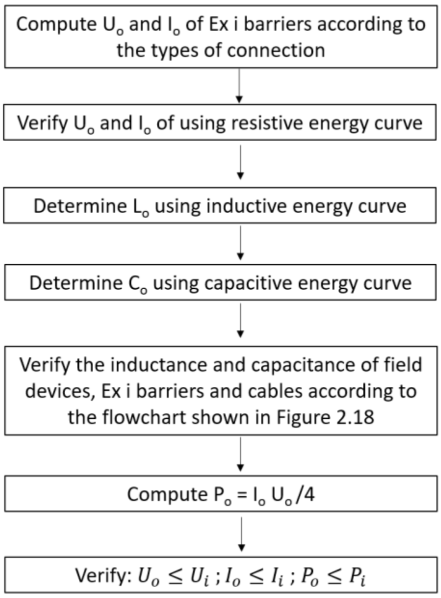


Figure 2.25: Summary of Verification (Multiple Ex i Barriers).

2.9 Intrinsic Safety Installation

In this section, the requirement of cable, wiring and earthing are presented as per IEC 60079-14.

2.9.1 Requirement of Cable

The requirement of cable is stated in IEC 60079-14 Clause 16.2.2.1 and 16.2.2.2. First and foremost, a cable utilized within Ex i system must not be damaged in the condition that the voltage of 750 V DC or 500 V_{rms} AC is applied. Furthermore, the conductor of cable having a diameter that is less than 0.1 mm is strictly forbidden to be utilized in the hazardous area. Additionally, if the Ex i method is applied, the typical capacitance value of cable is 200 pF/m whereas the inductance value is 1 μH/m (IEC, 2013).

2.9.2 Wiring

As per IEC 60079-14 Clause 16.2.2.5, a cable that carries an enormous amount of current may affect the field devices in the hazardous area due to the magnetic field. In this way, such a cable should be placed far enough from the field devices to eliminate the effect due to the magnetic field. Furthermore, cables applied in the Ex i system have to be indicated using light blue (IEC, 2013).

Besides that, according to IEC 60079-14 Clause 16.5, the clearance distance between terminals is the other main concern in the wiring if a terminal box is utilized. The terminal of the Ex i cable must at least keep a clearance distance of 50 mm from the terminal that is not connected to the Ex i system. Aside from that, the terminal of the Ex i cable is required to keep at least a clearance distance of 3 mm from the ground terminal. Regarding the terminals between two Ex i cables, the minimum clearance distance is 6 mm. In addition, Figure 2.26 illustrates the clearance distance for different conditions (IEC, 2013).

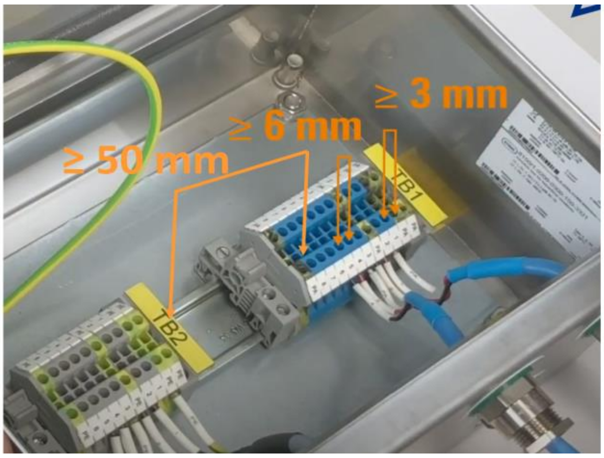


Figure 2.26: Clearance Distance of Terminals (R. STAHL AG, 2022).

2.9.3 Wiring

As per IEC 60079-14 Clause 16.2.3, the earthing of Ex i barriers is the major concern in the installation of the Ex i system. In a system consisting of a Zener barrier and field devices, earthing is necessary to be applied. It is stated that the resistance between the earthing terminal of the Zener barrier and the earth point of the main power system cannot be larger than 1 Ω. Furthermore, the connection between the terminal of the Zener barrier and the earth point is implemented using an earthing conductor. For instance, in the condition that a single earthing conductor is applied, the material of the conductor should be copper and its cross-sectional area could not be less than 4 mm^2. In another case, for a system consisting of an isolator and field devices, there is no specific requirement regarding the earthing (IEC, 2013).

2.10 Summary

In a nutshell, the foundation knowledge regarding explosion protection such as the explosion, fire triangle, zone classification, apparatus marking and several types of explosion protection techniques are explored. Apart from that, the parameters, configuration, apparatus, analysis on safety loop verification and requirement of installation for an Ex i system are studied.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

First and foremost, the validity of four Ex i systems is verified in this project. In this section, the methodology to verify the validity of Ex i systems is presented. Furthermore, the planning for this project is provided.

3.2 Standards

The objectives of this project are to verify the compliance of the apparatuses installed in Ex i systems and execute the analysis on the intrinsic safety loop verification.

In order to achieve the first objective which is the verification of the compliance of the apparatuses, the information of the IECEx marking specifications including equipment group, temperature class, equipment protection level and type of protection is required. Furthermore, the information regarding the IECEx marking specifications is provided in IEC 60079-14, therefore it is taken as the main reference to verify the compliance of the apparatuses.

Regarding the second objective which is the intrinsic safety loop verification, IEC 60079-14 is also taken as the major reference. For instance, IEC 60079-14 provides the steps to execute intrinsic safety loop verification for the system having one Ex i barrier and the system containing multiple Ex i barriers.

Aside from that, the other standards under IEC 60079 series including IEC 60079-11 and IEC 60079-25 are treated as supplementary references. For instance, the energy curves are obtained from Annex A of IEC 60079-11. Besides that, Annex E of IEC 60079-25 provides the approach to determine the temperature class of resistance temperature detectors and thermocouples.

3.3 Methodology

According to the flowchart shown in Figure 3.1, the major tasks for carrying out this project are presented.

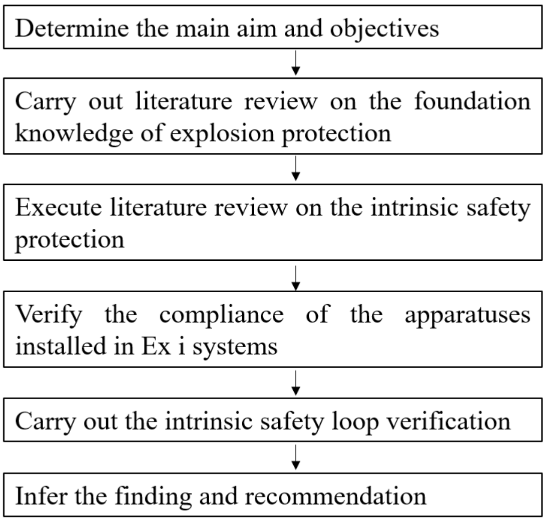


Figure 3.1: Flowchart to Execute the Major Tasks.

In addition, the methodology to verify the compliance of each apparatus installed in Ex i systems is further discussed in section 3.3.1. Also, the methodology to carry out the intrinsic safety loop verification is presented in section 3.3.2.

3.3.1 Methodology to Verify the Compliance of Apparatus

In Ex i systems, the compliances of apparatuses including certified field devices, simple apparatuses and Ex i barriers are required to be validated.

First and foremost, to verify the compliance of the certified field device, the specifications including equipment group, temperature class, equipment protection level and type of protection have to be checked. Referring to Table 3.1, such specifications are required to be verified based on the surrounding gas group, auto-ignition temperature of the gas and zone classification. Such specifications can be obtained from the IECEx marking.

Table 3.1: Verification of the Compliance of the Certified Field Device.

Specifications (Certified Field Device)	**Remarks**
Equipment Group	Equipment group has to comply with the surrounding gas group.
Temperature Class	Temperature class has to be compatible with the auto-ignition temperature of the gas.
Equipment Protection Level	Equipment protection level has to abide by the zone classification.
Type of Protection	Type of protection has to conform to the equipment protection level.

Apart from that, to validate the compliance of the Ex i barrier, the specifications including equipment group, equipment protection level and type of protection have to be examined. According to Table 3.2, such specifications are required to be verified based on the surrounding gas group and zone classification. Same as the certified field device, such specifications are obtained from the IECEx marking. Besides that, the safety parameters including U_o, I_o, P_o, L_o and C_o can be verified using energy curves. Additionally, the steps to verify the safety parameters of Ex i barriers have been presented in section 2.7.1.3.

Table 3.2: Verification of the Compliance of the Ex i Barrier.

Specifications (Ex i Barrier)	**Remarks**
Equipment Group	Equipment group has to be compatible with the surrounding gas group.
Equipment Protection Level	Equipment protection level has to comply with the zone classification.
Type of Protection	Type of protection has to conform to the equipment protection level.
Safety Parameters (U_O, I_O, P_O, L_O, C_O)	Points formed by the safety parameters cannot be above the energy curves.

Aside from that, the first step to verify the compliance of the simple apparatus is to determine whether it fulfils the requirement for being a simple apparatus as per IEC 60079-14 Clause 16.4. After that, the temperature class of the simple apparatus has to be determined. For instance, IEC 60079-14 provides two ways to obtain the temperature class, one of the ways is based on the surface area, and another way is to calculate the maximum surface temperature. Also, IEC 60079-25 provides a way to determine the temperature class based on the maximum measurable temperature, but it is only applicable for resistance temperature detectors and thermocouples. Additionally, the steps to validate the compliance of the simple apparatus have been discussed in section 2.7.2.2.

3.3.2 Methodology to Execute the Intrinsic Safety Loop Verification

According to IEC 60079-14, the steps to carry out the intrinsic safety loop verification for the system having one Ex i barrier and the system consisting of multiple Ex i barriers are provided.

The flowchart to execute the intrinsic safety loop verification for the system with a single Ex i barrier is shown in Figure 3.2. Also, the steps have been presented in section 2.8.1.

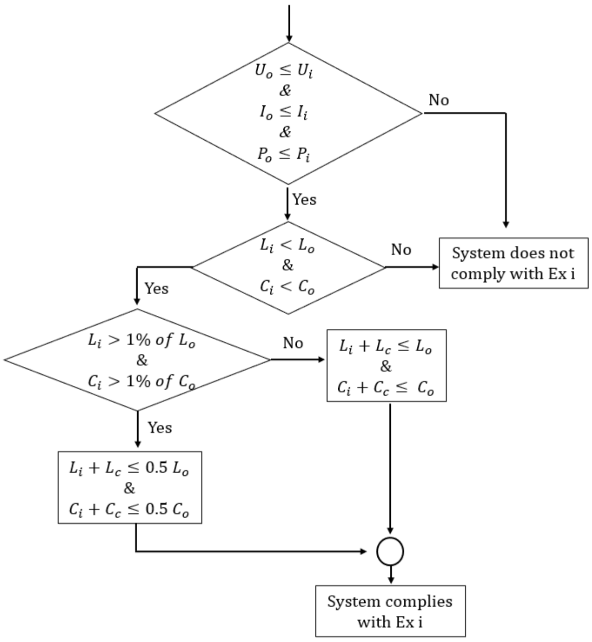


Figure 3.2: Flowchart of the Intrinsic Safety Loop Verification for the System with a Single Ex i Barrier.

The flowchart to carry out the intrinsic safety loop verification for the system with multiple Ex i barriers is shown in Figure 3.3. Furthermore, the steps have been presented in section 2.8.2.

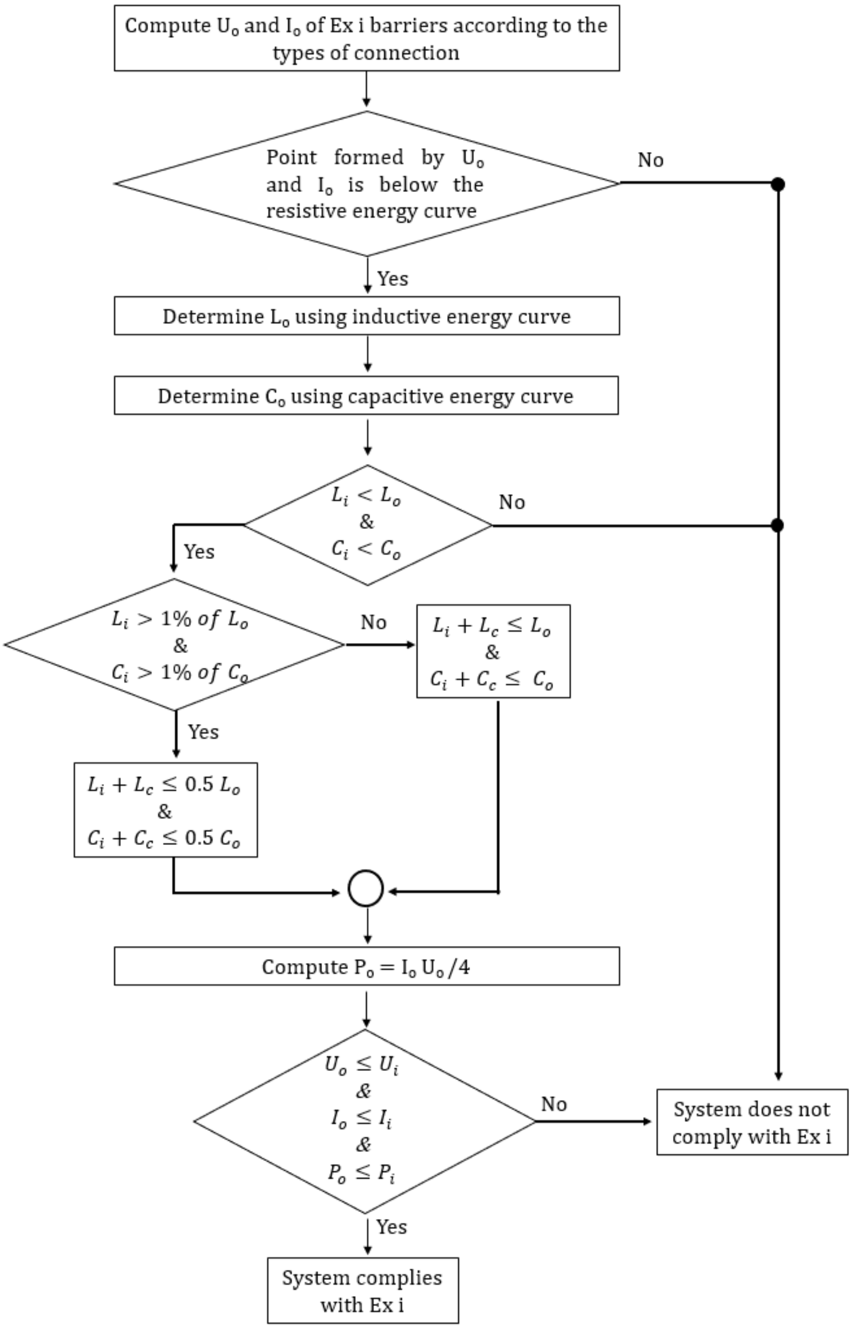
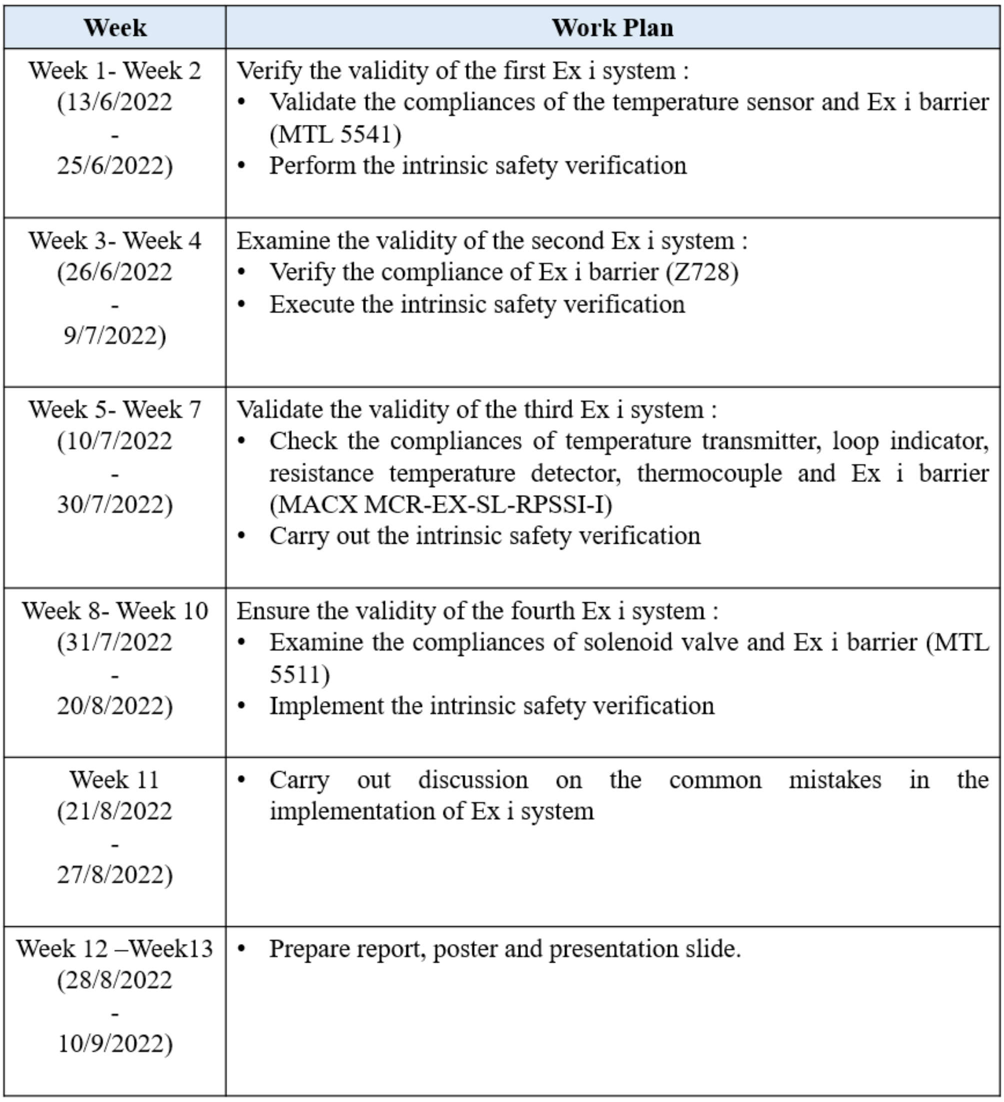


Figure 3.3: Flowchart of the Intrinsic Safety Loop Verification for the System with Multiple Ex i Barriers.

3.4 Work Plan

The work plan for carrying out these three case studies is shown in Table 3.3.

Table 3.3: Work Plan.



Week	Work Plan
Week 1- Week 2 (13/6/2022 - 25/6/2022)	Verify the validity of the first Ex i system : • Validate the compliances of the temperature sensor and Ex i barrier (MTL 5541) • Perform the intrinsic safety verification
Week 3- Week 4 (26/6/2022 - 9/7/2022)	Examine the validity of the second Ex i system : • Verify the compliance of Ex i barrier (Z728) • Execute the intrinsic safety verification
Week 5- Week 7 (10/7/2022 - 30/7/2022)	Validate the validity of the third Ex i system : • Check the compliances of temperature transmitter, loop indicator, resistance temperature detector, thermocouple and Ex i barrier (MACX MCR-EX-SL-RPSSI-I) • Carry out the intrinsic safety verification
Week 8- Week 10 (31/7/2022 - 20/8/2022)	Ensure the validity of the fourth Ex i system : • Examine the compliances of solenoid valve and Ex i barrier (MTL 5511) • Implement the intrinsic safety verification
Week 11 (21/8/2022 - 27/8/2022)	• Carry out discussion on the common mistakes in the implementation of Ex i system
Week 12 –Week13 (28/8/2022 - 10/9/2022)	• Prepare report, poster and presentation slide.

Furthermore, the planning for material and cost is not covered since the experiment and the construction of the prototype are not carried out throughout the project.

3.5 Problems Encountered and Solutions

The first problem faced is that it is difficult to understand the IEC 60079-14 standard. This is because there are a lot of technical terms. To solve the first problem, it is required to obtain some foundation knowledge regarding the explosion protection such as fire triangle, electrical equipment marking, zone classification and so on. With the foundation knowledge, it will be easier to understand the IEC 60079-14.

Besides that, the energy curves including resistive, inductive and capacitive are not provided in the IEC 60079-14. In addition, the energy curves are important to verify the compliance of Ex i barrier and perform the intrinsic safety loop verification. In order to curb the problem, online resources such as datasheets of the company that sells or manufactures Ex equipment can be utilised. Also, the other standards under IEC 60079 series can be referred to. Finally, the energy curves are obtained from Annex A of IEC 60079-11.

Apart from that, IEC 60079-14 provides two approaches to obtain the temperature class of the simple apparatus. One of the approaches is based on the surface area. Another approach is to calculate the maximum surface temperature and it requires the value of R_{th} (surface temperature rise, °C/ W). However, in the datasheet of resistance temperature detectors and thermocouples, both the surface area and surface temperature rise are not provided. Therefore, one of the ways to solve the problem is to find another approach by referring to other resources. Finally, it is found that Annex E of IEC 60079-25 provides the approach to obtain the temperature class of resistance temperature detectors and thermocouples, which is based on the maximum measurable temperature.

Furthermore, in the intrinsic safety loop verification regarding the capacitance and inductance, IEC 60079-14 Clause 16.2.4.3 states that the L_o and C_o values have to be halved in the calculation of the cable length if the total inductance and capacitance values of the field devices are larger than 1% of L_o and 1% of C_o respectively. However, it cannot be confirmed whether the term, ‘total inductance and capacitance’ is referred to the equivalent inductance and capacitance or the sum of the inductance and capacitance. To solve this problem, the standards under IEC 60079 series are utilized to clarify the term. Finally, it is clarified that the ‘total inductance and capacitance’ is referred to the sum of the inductance and capacitance of the field devices according to IEC 60079-25 Annex A.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this section, four Ex i systems shown in Figure 4.1 are verified to ensure their conformity. Furthermore, the validity of the Ex i systems is examined in terms of compliance of each apparatus and intrinsic safety loop verification according to IEC 60079-14.

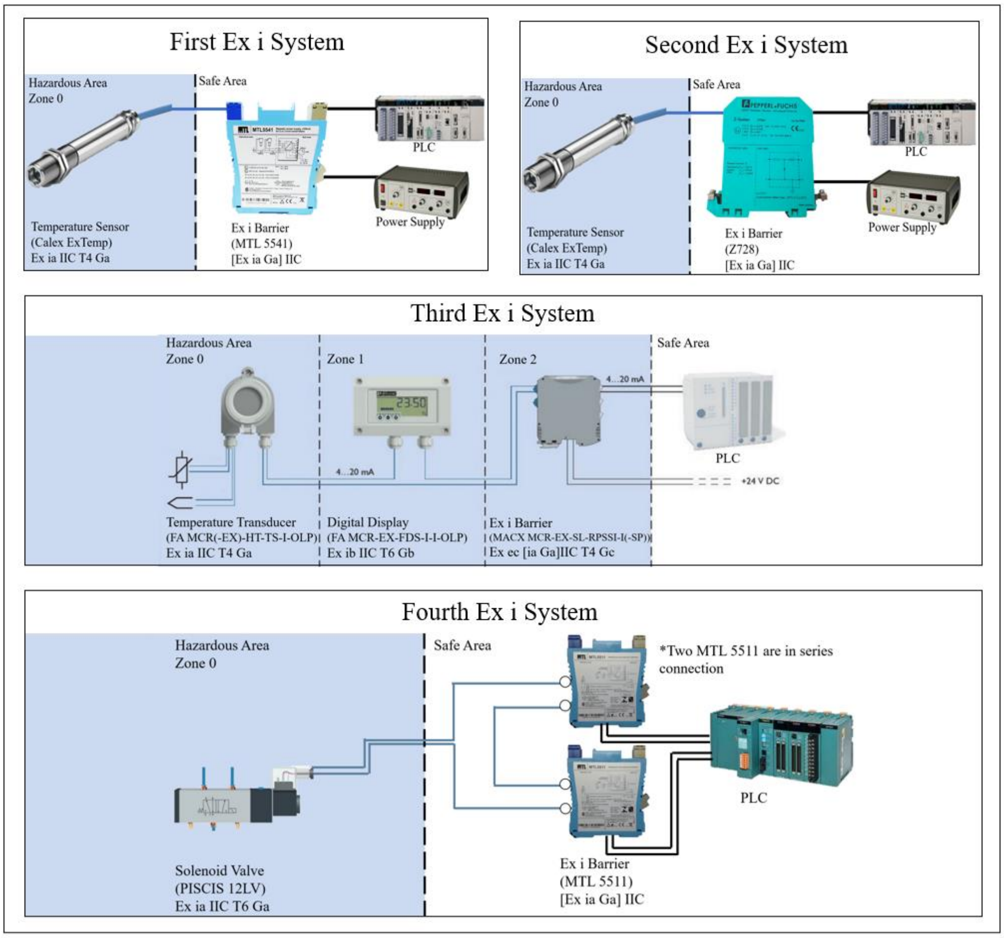


Figure 4.1: Diagram Consisting of All of the Four Ex i Systems.

Apart from that, Table 4.1 shows the apparatuses applied for each Ex i system and the corresponding datasheets.

Table 4.1: Apparatuses and the Corresponding Datasheets.

No.	**Apparatuses**	**Model**	**Ex i System**	**Appendix**
1	Temperature Sensor	Calex ExTemp	First and Second Ex i System	Appendix A
2	Ex i Barrier 1	MTL 5541	First Ex i System	Appendix B
3	Ex i Barrier 2	Z728	Second Ex i System	Appendix C
4	Digital Display	FA MCR-EX-FDS-I-I-OLP	Third Ex i System	Appendix D
5	Temperature transducer	FA MCR(-EX)-HT-TS-I-OLP		Appendix E
6	Resistance temperature detector	RS PRO PT1000		Appendix F
7	Thermocouple	T-type PVC Mini 10ft		Appendix G
8	Ex i Barrier 3	MACX MCR-EX-SL-RPSSI-I(-SP)		Appendix H
9	Solenoid Valve	PISCIS 12LV		Appendix I
10	Ex i Barrier 4	MTL 5511	Fourth Ex i System	Appendix J

According to Table 4.2, the Ex i systems can be classified into three groups based on the configuration. The first and second Ex i systems are the system having a single field device and a single Ex i barrier. The third Ex i system is the system containing multiple field devices and a single Ex i barrier. Furthermore, the fourth Ex i system is the system consisting of a single field device and multiple Ex i barriers.

Table 4.2: Classification of the Ex i Systems Based on the Configuration.

Configuration	**Ex i System**
One field device and a single Ex i barrier	First Ex i System
	Second Ex i System
Multiple field devices and a single Ex i barrier	Third Ex i System
One field device and multiple Ex i barriers	Fourth Ex i System

4.2 System with a Field Device and a Ex i Barrier

In this section, the validity of the first and second Ex i system is verified. For the first and second Ex i system, the field device is the same, which is the Calex Extemp temperature sensor. The difference between the systems is that the galvanically isolated barrier is utilized in the first Ex i system whereas the Zener barrier is applied in the second Ex i system.

4.2.1 First Ex i System

Figure 4.2 shows the first Ex i system. The temperature sensor is installed in the hazardous area while the Ex i barrier is positioned in the safe area.

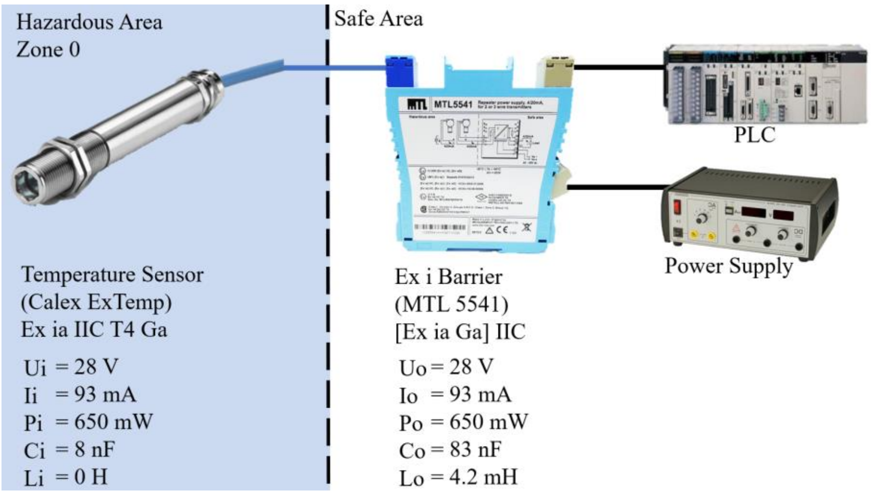


Figure 4.2: First Ex i System.

Referring to Figure 4.2, the parameters including U_i, I_i, P_i, C_i and L_i are the safety parameters of the temperature sensor whereas the parameters such as U_o, I_o, P_o, C_o and L_o are the safety parameters of the Ex i barrier. Furthermore, the safety parameters are utilized in the intrinsic safety loop verification.

Regarding the operational parameters, the temperature sensor requires a voltage ranging from 12 V to 24 V. Hence, the Ex i barrier can provide a maximum voltage of 28 V at 93 mA, which is adequate to let the temperature sensor function.

Apart from that, the hazardous area is classified as Zone 0. The surrounding gas is assumed to be the IIC gas group consisting of hydrogen and acetylene.

4.2.1.1 Verification of the Compliance of Field Device for the First Ex i System

The temperature sensor is a certified field device. Hence, its compliance is validated based on the IECEx marking. For instance, its IECEx marking is labelled as ‘Ex ia IIC T4 Ga’. Firstly, it has the equipment group of ‘IIC’, which is compatible with the surrounding atmosphere classified as the IIC gas group. Due to the temperature class of ‘T4’, its surface can reach a temperature of up to 135 °C. Furthermore, the auto-ignition temperatures of hydrogen and acetylene are 560 °C and 305 °C respectively (Eaton Electric Limited, n.d.). Thus, the surface temperature of 135 °C will not ignite the surrounding gas. Besides that, the equipment protection level of ‘Ga’ allows it to be installed in Zone 0. As per the equipment protection level of ‘Ga’, Ex ‘ia’ is applied among the subdivision groups of the Ex i method. As a result, the compliance of the temperature sensor is proved according to the IECEx marking.

4.2.1.2 Verification of the Compliance of Ex i Barrier for the First Ex i System

Same as the temperature sensor, the Ex i barrier is required to be examined as per the IECEx marking. For instance, the IECEx marking of the Ex i barrier is ‘[Ex ia Ga] IIC’. Firstly, it has the equipment group of ‘IIC’ which complies with the surrounding gas group. Due to the installation of the temperature sensor in Zone 0, the equipment protection level of ‘Ga’ is mandatory. Also, Ex ‘ia’ is applied as per the equipment protection level. In short, the conformity of the Ex i barrier is validated as per the IECEx marking.

Aside from the IECEx marking, the safety parameters of the Ex i barrier are verified using the energy curves. Since the Ex ‘ia’ method is utilized, the safety factor is 1.5.

For the verification of U_o and I_o, the resistive energy curve is utilized. Firstly, it is required to form a point, P (U_o, I_o × safety factor), where the value of the x-coordinate is U_o and the value of the y-coordinate is I_o multiplied by the safety factor. The value of U_o is 28 V while I_o is 93 mA. By multiplying I_o with the safety factor, where $I_o \times \text{safety factor} = 0.093\ \text{A} \times 1.5 = 0.1395\ \text{A}$, the point, P (28 V, 0.1395 A) is formed and positioned on the resistive energy curve. According to the resistive energy curve shown in Figure 4.3, there are multiple curves for different equipment groups including I, IIA, IIB and IIC. Based on the equipment group of the Ex i barrier, the curve for IIC is referred to. The same concept applies to the inductive energy curve and capacitive energy curve. Furthermore, the point is below the curve. Thus, the U_o and I_o are valid. Moreover, since $P_o = \frac{I_o U_o}{4}$, P_o is valid.

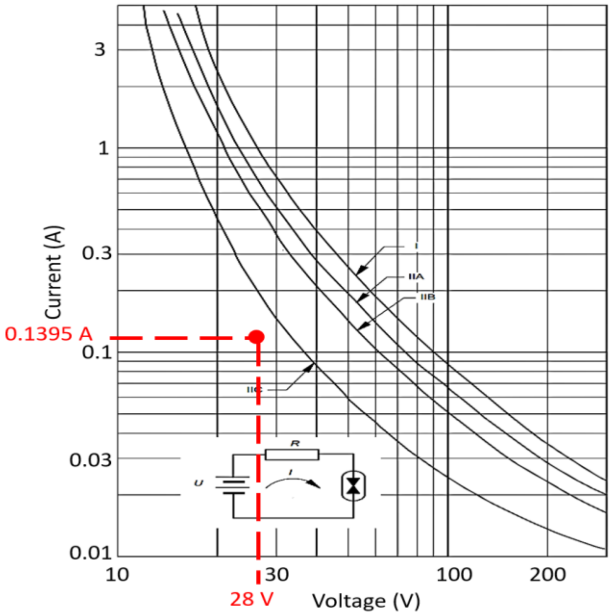


Figure 4.3: Verification of U_o and I_o for the First Ex i System (IEC, 2012).

To verify L_o, the inductive energy curve is used and the point, P (I_o × safety factor, L_o) has to be formed. The value of L_o is 4.2 mH while I_o is 93 mA. Through the multiplication of I_o with the safety factor, where I_o × safety factor = 0.093 A × 1.5 = 0.1395 A, the point, P (0.1395 A, 0.0042 H) is formed. The point is then positioned on the inductive energy curve as shown in Figure 4.4. The point is below the curve for the equipment group of IIC. Hence, the L_o is valid.

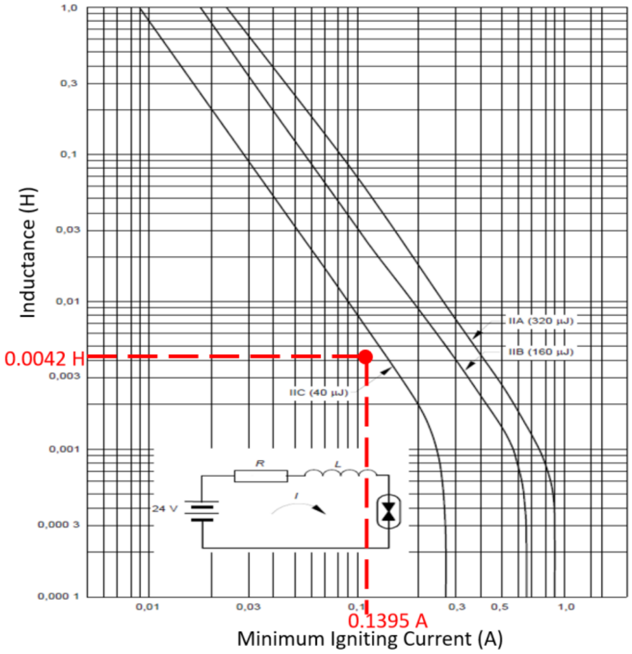


Figure 4.4: Verification of L_o for the First Ex i System (IEC, 2012).

Besides that, the capacitive energy curve is applied in the verification of C_o. Furthermore, the point, P (U_o × safety factor, C_o) is formed. The value of C_o is 83 nF while U_o is 28 V. Through the multiplication of U_o with the safety factor, where U_o × safety factor = 28 V × 1.5 = 42 V, the point, P (42 V, 0.083 µF) is formed. The point is then positioned on the capacitive energy curve as shown in Figure 4.5. For this case, it is hard to determine whether the point is exactly positioned on the curve or above the curve. If the point is exactly positioned on the curve, the C_o is valid. However, if the point is above the curve, the C_o is not valid. To solve this problem, Table A.2 of IEC 60079-11 is applied and it is shown in Appendix K. Table A.2 and the capacitive energy curve shown in IEC 60079-11 represent the same physical quantity, which is the capacitive ignition energy for different equipment groups (IEC, 2012). From Appendix K, the C_o is 0.083 µF when the U_o is 28 V and the safety factor is 1.5. As a result, the point is exactly positioned on the curve for the equipment group of IIC and the C_o is valid. In short, all the safety parameters of the Ex i barrier are valid.

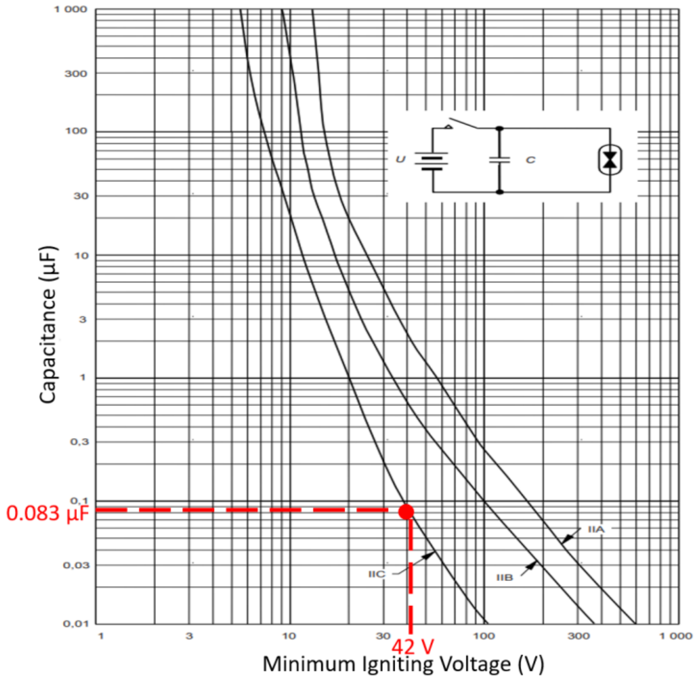


Figure 4.5: Verification of C_o for the First Ex i System (IEC, 2012).

The main role of the Ex i barrier is to restrict the energy transferring to the hazardous area. With the help of the Zener diode inside the Ex i barrier, the voltage can be limited to a maximum value of U_o. The current is restricted to a maximum value of I_o due to the current-limiting resistor inside the Ex i barrier (Rockwell Automation, 2016). As long as the point formed by U_o and I_o is below the energy curve and the intrinsic safety loop is valid, it can be ensured that the energy does not exceed the ignition point. Therefore, the ignition of gas in a hazardous area can be prevented.

Unlike the U_o and I_o, both the L_o and C_o are not defined by the design of the Ex i barrier (Friend, 2020). The L_o and C_o are treated as the guidelines to determine the maximum allowed capacitance and inductance of the field devices and cables in the hazardous area. If the condition, where L_o is valid and $L_i + L_c \leq Lo$ is fulfilled, the inductive energy stored in the field devices will not cause the ignition. The same concept applies to capacitive energy. If C_o is valid and $C_i + C_c \leq C_o$ is fulfilled, the inductive energy stored in the field devices will be bound below the ignition point. In short, the L_o and C_o values of the Ex i barrier provide the guidelines to limit the energy stored in the field devices. In the following section, the conditions including $L_i + L_c \leq Lo$ and $C_i + C_c \leq C_o$ are further discussed.

4.2.1.3 Intrinsic Safety Loop Verification for the First Ex i System

All the safety parameters utilized in the intrinsic safety loop verification are shown in Figure 4.2. The intrinsic safety loop verification for voltage, current and power is as follows:

$$\text{Given that: } \mathrm{U_o} = 28\ \mathrm{V}, \mathrm{U_i} = 28\ \mathrm{V}$$

$$28 \leq 28$$

$$\therefore \mathrm{U_o} \leq \mathrm{U_i}$$

$$\text{Given that: } \mathrm{I_o} = 93\ \mathrm{mA}, \mathrm{I_i} = 93\ \mathrm{mA}$$

$$93 \times 10^{-3} \leq 93 \times 10^{-3}$$

$$\therefore \mathrm{I_o} \leq \mathrm{I_i}$$

$$\text{Given that: } \mathrm{P_o} = 650\ \mathrm{mW}, \mathrm{P_i} = 650\ \mathrm{mW}$$

$$650 \times 10^{-3} \leq 650 \times 10^{-3}$$

$$\therefore \mathrm{P_o} \leq \mathrm{P_i}$$

Therefore, based on the verification shown above, the intrinsic safety loop is valid in terms of voltage, current and power.

In the intrinsic safety loop verification for inductance and capacitance, the first step is to determine whether $\mathrm{L_i} < \mathrm{L_o}$ and $\mathrm{C_i} < \mathrm{C_o}$ and it is shown below:

$$\text{Given that: } \mathrm{L_i} = 0\ \mathrm{H}, \mathrm{L_o} = 4.2\ \mathrm{mH}$$

$$0 < 4.2 \times 10^{-3}$$

$$\therefore \mathrm{L_i} < \mathrm{L_o}$$

$$\text{Given that: } \mathrm{C_i} = 8\ \mathrm{nF}, \mathrm{C_o} = 83\ \mathrm{nF}$$

$$8 \times 10^{-9} < 83 \times 10^{-9}$$

$$\therefore \mathrm{C_i} < \mathrm{C_o}$$

Since $\mathrm{L_i} < \mathrm{L_o}$ and $\mathrm{C_i} < \mathrm{C_o}$, the next step is to check whether $\mathrm{L_i} > 0.01\mathrm{L_o}$ and $\mathrm{C_i} > 0.01\mathrm{C_o}$. Only when $\mathrm{L_i} > 0.01\mathrm{L_o}$ and $\mathrm{C_i} > 0.01\mathrm{C_o}$, the equations $\mathrm{L_i} + \mathrm{L_C} \leq 0.5\mathrm{L_o}$ and $\mathrm{C_i} + \mathrm{C_C} \leq 0.5\mathrm{C_o}$ will be applied. For other conditions, the equations $\mathrm{L_i} + \mathrm{L_C} \leq \mathrm{L_o}$ and $\mathrm{C_i} + \mathrm{C_C} \leq \mathrm{C_o}$ will be used. The computation is as follows:

$$\text{Given that: } \mathrm{L_i} = 0\ \mathrm{H}, 0.01\mathrm{L_o} = 0.042\ \mathrm{mH}$$
$$0 < 0.042\ \times 10^{-3}$$
$$\therefore \mathrm{L_i} < 0.01\mathrm{L_o}$$

$$\text{Given that: } \mathrm{C_i} = 8\ \mathrm{nF}, 0.01\mathrm{C_o} = 0.83\ \mathrm{nF}$$
$$8\ \times 10^{-9} > 0.83\ \times 10^{-9}$$
$$\therefore \mathrm{C_i} > 0.01\mathrm{C_o}$$

Based on the computation above, since $\mathrm{L_i} < 0.01\mathrm{L_o}$ and $\mathrm{C_i} > 0.01\mathrm{C_o}$, the equations $\mathrm{L_i} + \mathrm{L_C} \leq \mathrm{L_o}$ and $\mathrm{C_i} + \mathrm{C_C} \leq \mathrm{C_o}$ are used to obtain the maximum cable length. Furthermore, the cable is connected between the Ex i barrier and the temperature sensor. The typical cable capacitance value of 200 pF/m and the inductance value of 1 µH/m is used (IEC, 2013). The calculation of the maximum cable length is as follows:

Inductance of cable per meter = 1 µH/m (IEC, 2013)
Capacitance of cable per meter = 200 pF/m (IEC, 2013)

With regard to inductance,

$$\mathrm{L_i} + \mathrm{L_c}\ \leq \mathrm{L_o}$$
$$\mathrm{L_c}\ \leq \mathrm{L_o} - \mathrm{L_i}$$
$$\mathrm{L_c}\ \leq 4.2 \times 10^{-3} - 0$$
$$\mathrm{L_c}\ \leq 4.2 \times 10^{-3}$$

$\therefore$ Maximum cable inductance is 4.2×10^{-3} H

$$\therefore \text{As per inductance, maximum cable length} = \frac{4.2 \times 10^{-3}}{1 \times 10^{-6}} = 4200\ \mathrm{m}$$

With regard to capacitance,

$$\mathrm{C_i} + \mathrm{C_c} \ \leq \mathrm{C_o}$$

$$\mathrm{C_c} \ \leq \mathrm{C_o} - \mathrm{Ci}$$

$$\mathrm{C_c} \ \leq 83 \ \times 10^{-9} - 8 \ \times 10^{-9}$$

$$\mathrm{C_c} \ \leq 7.5 \times 10^{-8}$$

$\therefore$ Maximum cable capacitance is 7.5×10^{-8} F

$\therefore$ As per capacitance, maximum cable length $= \dfrac{7.5 \times 10^{-8}}{200 \times 10^{-12}} = 375$ m

As per the calculation shown above, the maximum cable length has to be taken based on the maximum cable capacitance. Hence, the maximum cable length is 375 m. By taking the cable length of 375 m, the $\mathrm{L_c}$ and $\mathrm{C_c}$ are calculated as shown below:

$$\mathrm{L_c} = \text{Inductance of cable per meter} \ \times \text{Maximum Cable Length}$$

$$= 1 \times 10^{-6} \times 375$$

$$= 0.375 \text{ mH}$$

$$\mathrm{C_c} = \text{Capacitance of cable per meter} \ \times \text{Maximum Cable Length}$$

$$= 200 \times 10^{-12} \times 375$$

$$= 75 \text{ nF}$$

The summary of the intrinsic safety loop verification for the first Ex i system is shown in Table 4.3.

Table 4.3: Summary of the Intrinsic Safety Loop Verification for the First Ex i System.

	Ex i Barrier	**Field Device/ Cable**	**Result**
Voltage	$U_o = 28$ V	$U_i = 28$ V	$U_o \leq U_i$, Valid
Current	$I_o = 93$ mA	$I_i = 93$ mA	$I_o \leq I_i$, Valid
Power	$P_o = 650$ mW	$P_i = 650$ mW	$P_o \leq P_i$, Valid
Inductance	$L_o = 4.2$ mH	$L_i = 0$ H $L_c = 0.375$ mH (Cable Length =375m)	$L_i + L_c \leq L_o$, Valid
Capacitance	$C_o = 83$ nF	$C_i = 8$ nF $C_c = 75$ nF (Cable Length =375m)	$C_i + C_c \leq C_o$, Valid

Based on Table 4.3, the intrinsic safety loop of the first Ex i system is valid. During a fault condition, if the voltage, current and power supplied by the Ex i barrier are larger than the maximum input voltage, current and power of the field device, the electrical spark may occur and lead to the explosion. Since $U_o \leq U_i$, $I_o \leq I_i$ and $P_o \leq P_i$, the energy transferring to the hazardous area is limited. Regarding the capacitance and inductance, since $L_i + L_c \leq L_o$ and $C_i + C_c \leq C_o$, the energy stored in the field device and cable is bound below the ignition point.

4.2.2 Second Ex i System

The second Ex i system is shown in Figure 4.6.

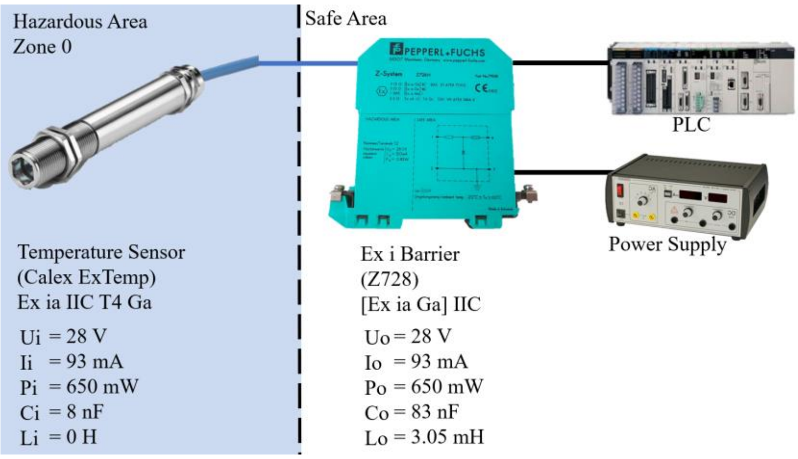


Figure 4.6: Second Ex i System.

The Zener barrier is applied in the second Ex i system whereas the galvanically isolated barrier is utilized in the first Ex i system. Besides that, the second Ex i system has the same field device as the first Ex i system, which is the temperature sensor. Hence, in the later section, the verification regarding the compliance of the temperature sensor as per IECEx marking is not covered.

Referring to Figure 4.6, all the safety parameters are shown. Additionally, the safety parameters are applied in the intrinsic safety loop verification. For the operational parameters, the working voltage of the temperature sensor ranges from 12 V to 24 V. The Ex i barrier can provide the maximum voltage of 28 V at 93 mA, which is enough for the temperature sensor to function.

Furthermore, the hazardous area is classified as Zone 0. The surrounding gas is assumed to be the IIC gas group including hydrogen and acetylene.

4.2.2.1 Verification of the compliance of Ex i Barrier for the Second Ex i System

The Ex i barrier has to be examined referring to the IECEx marking. Moreover, the IECEx marking of the Ex i barrier is ‘[Ex ia Ga] IIC’. It has the equipment group of ‘IIC’ which is compatible to the surrounding gas group. The equipment protection level of ‘Ga’ is required because of the installation of the temperature sensor in Zone 0. According to the equipment protection level of ‘Ga’, Ex ‘ia’ is applied.

According to IEC 60079-14 Clause 16.2.3, the dedicated earthing is enforced to be implemented if the Zener barrier is utilized. Also, only the TN-S system, which is the grounding system having the separated neutral and earth conductor, is applicable (Panchal and Patel, 2020; IEC, 2013). The resistance between the earthing terminal of the Zener barrier and the earth point of the main power system cannot exceed 1 Ω. Furthermore, the connection between the earthing terminal of the Zener barrier and the earth point is implemented using an earth conductor. Hence, the resistance between the earthing terminal and the earth point is determined by the earth conductor.

For instance, if a single earth conductor is applied, its material has to be copper and the cross-sectional area could not be less than 4 mm^2. Using Equation (3.1), the length of the earth conductor is computed (Heaney, 2003).

$$R = \frac{\rho l}{A} \tag{3.1}$$

where

R = resistance of conductor, Ω

ρ = resistivity of conductor material, Ωm

l = length of conductor, m

A = cross-sectional area of conductor, m

Given that:

$R = 1\ \Omega$;

$\rho = 17.241 \times 10^{-9}$ Ωm (Materion Brush Inc., 2017);

$A = 4\ \text{mm}^2 = 4 \times 10^{-6}\ \text{m}^2$

$$R = \frac{\rho l}{A}$$

$$l = R\frac{A}{\rho}$$

$$l = (1)\left(\frac{4 \times 10^{-6}}{17.241 \times 10^{-9}}\right)$$

$$\therefore l = 232\ m$$

Hence, the length of the copper earth conductor having a cross-sectional area of 4 mm^2 cannot exceed 233 m to ensure that the resistance between the earthing terminal of the Ex i barrier and the earth point does not exceed 1 Ω.

Regarding the safety parameters of the Ex i barrier, they are verified using the energy curves. The safety factor is 1.5 is applied as the Ex ‘ia’ method is used.

For the verification of U_o and I_o, the resistive energy curve is utilized. The point, P (U_o, I_o × safety factor) has to be formed. The value of U_o is 28 V while I_o is 93 mA. Through the multiplication of I_o with the safety factor, where I_o × safety factor = 0.093 A × 1.5 = 0.1395 A, the point, P (28 V, 0.1395 A) is formed and positioned on the resistive energy curve. According to the resistive energy curve shown in Figure 4.7, the point is below the curve for the equipment group of IIC. Thus, the U_o and I_o are valid. Furthermore, P_o is valid because $P_o = \frac{I_o U_o}{4}$.

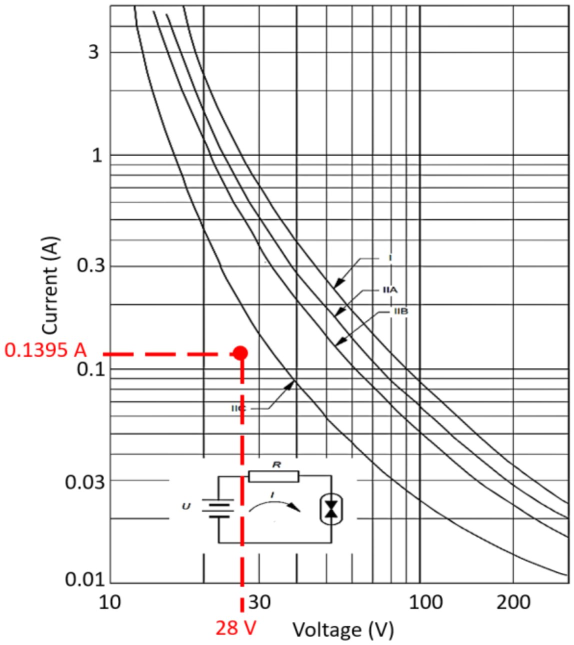


Figure 4.7: Verification of U_o and I_o for the Second Ex i System (IEC, 2012).

Apart from that, the inductive energy curve is used to verify L_o. The point, P (I_o × Safety factor, L_o) has to be formed. The value of L_o is 3.05 mH while I_o is 93 mA. Through the multiplication of I_o with the safety factor, where I_o × safety factor = 0.093 A ×1.5 = 0.1395 A, the point, P (0.1395 A, 0.00305 H) is formed. The point is then positioned on the inductive energy curve as shown in Figure 4.8. As a result, the point is below the curve for the equipment group of IIC and the L_o is valid.

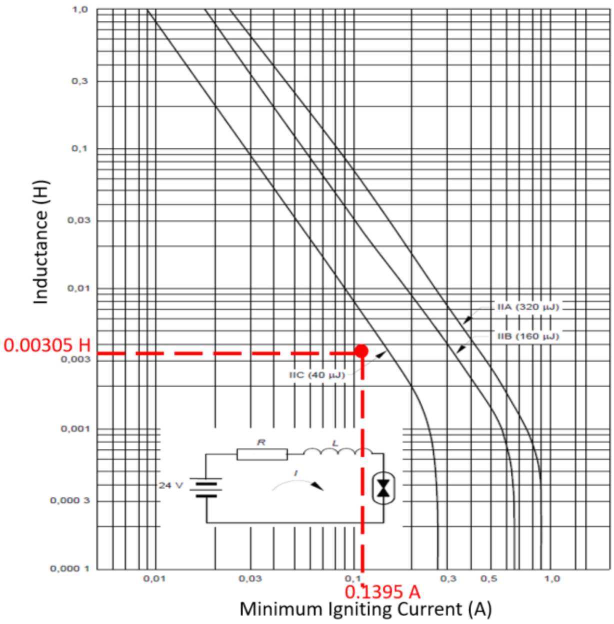


Figure 4.8: Verification of L_o for the Second Ex i System (IEC, 2012).

In addition, the capacitive energy curve is applied to verify the C_o. The point, P (U_o × safety factor, C_o) has to be formed. The value of C_o is 83 nF while U_o is 28 V. Through the multiplication of U_o with the safety factor, where $U_o \times$ safety factor = 28 V × 1.5 = 42 V, the point, P (42 V, 0.083 µF) is formed. It is positioned on the capacitive energy curve as shown in Figure 4.9. Using only the capacitive energy curve, it is hard to determine whether the point is exactly positioned on the curve or above the curve. With the help of Appendix K, it is ensured that the point is exactly positioned on the curve for the equipment group of IIC. Therefore, the C_o is valid. In short, all the safety parameters of the Ex i barrier are valid.

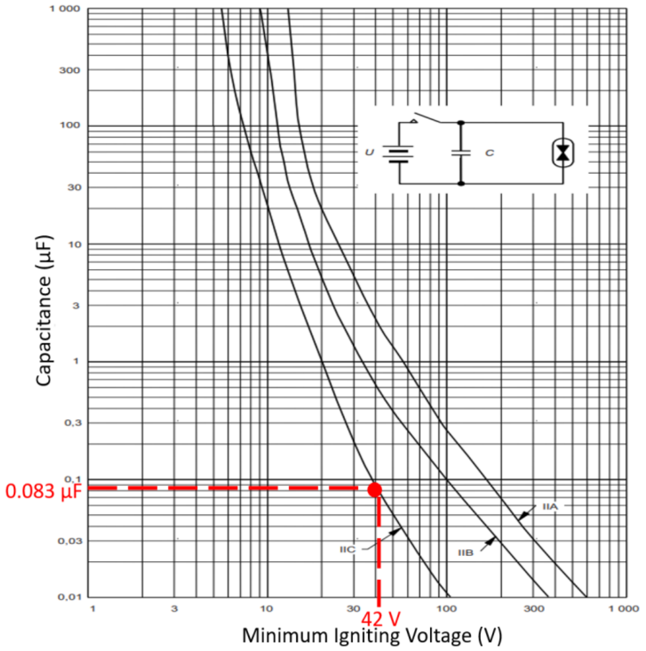


Figure 4.9: Verification of C_o for the Second Ex i System (IEC, 2012).

Therefore, since the U_o, I_o and P_o are valid, it can be assured that the energy supplied by the Ex i is limited below the ignition point. Furthermore, as the L_o and C_o are valid, they can provide the correct guidelines to determine the permitted inductance and capacitance of the field device and cable. However, the validity of the Ex i barrier safety parameters is not enough to prove the conformity Ex i system is valid. The safety parameters of the Ex i barrier have to be compared with the safety parameters of the field device and cable through the intrinsic safety loop verification in the following section.

4.2.2.2 Intrinsic Safety Loop Verification for the Second Ex i System

All the safety parameters used in the intrinsic safety loop verification are shown in Figure 4.6. The intrinsic safety loop verification for voltage, current and power is as follows:

$$\text{Given that: } \mathrm{U_o} = 28\ \mathrm{V}, \mathrm{U_i} = 28\ \mathrm{V}$$

$$28 \times 10^{-3} \leq 28 \times 10^{-3}$$

$$\therefore \mathrm{U_o} \leq \mathrm{U_i}$$

$$\text{Given that: } \mathrm{I_o} = 93\ \mathrm{mA}, \mathrm{I_i} = 93\ \mathrm{mA}$$

$$93 \times 10^{-3} \ \leq 93 \times 10^{-3}$$

$$\therefore \mathrm{I_o} \leq \mathrm{I_i}$$

$$\mathrm{P_o} = 650\ \mathrm{mW}, \mathrm{P_i} = 650\ \mathrm{mW}$$

$$650 \times 10^{-3} \ \leq 650 \times 10^{-3}$$

$$\therefore \mathrm{P_o} \leq \mathrm{P_i}$$

Hence, according to the verification shown above, the intrinsic safety loop is valid in terms of voltage, current and power.

The intrinsic safety loop verification regarding inductance and capacitance is as follows:

Regarding inductance,

$$\text{Given that: } \mathrm{L_i} = 0\ \mathrm{H}, \mathrm{L_o} = 3.05\ \mathrm{mH}, 0.01\mathrm{L_o} = 0.0305\ \mathrm{mH}$$

$$0 < 3.05 \ \times 10^{-3}$$

$$\therefore \mathrm{L_i} < \mathrm{L_o}$$

$$0 < 0.0305 \ \times 10^{-3}$$

$$\therefore \mathrm{L_i} < 0.01\mathrm{L_o}$$

Regarding capacitance,

$$\text{Given that: } \mathrm{C_i} = 8\ \mathrm{nF}, \mathrm{C_o} = 83\ \mathrm{nF}, 0.01\mathrm{C_o} = 0.83\ \mathrm{nF}$$

$$8 \ \times 10^{-9} < 83 \ \times 10^{-9}$$

$$\therefore \mathrm{C_i} < \mathrm{C_o}$$

$$8 \ \times 10^{-9} > 0.83 \ \times 10^{-9}$$

$$\therefore \mathrm{C_i} > 0.01\mathrm{C_o}$$

As per the computation above, since $L_i < 0.01L_o$ and $C_i > 0.01C_o$, the equations $L_i + L_C \leq L_o$ and $C_i + C_C \leq C_o$ are used to obtain the maximum cable length. The calculation of the maximum cable length is as follows:

Inductance of cable per meter = 1 μH/m (IEC, 2013)
Capacitance of cable per meter = 200 pF/m (IEC, 2013)

With regard to inductance,

$$\begin{aligned} L_i + L_c &\leq L_o \\ L_c &\leq L_o - L_i \\ L_c &\leq 3.05 \times 10^{-3} - 0 \\ L_c &\leq 3.05 \times 10^{-3} \end{aligned}$$

$\therefore$ Maximum cable inductance is 3.05×10^{-3} H

$$\therefore \text{As per inductance, maximum cable length} = \frac{3.05 \times 10^{-3}}{1 \times 10^{-6}} = 3050 \text{ m}$$

With regard to capacitance,

$$\begin{aligned} C_i + C_c &\leq C_o \\ C_c &\leq C_o - Ci \\ C_c &\leq 83 \times 10^{-9} - 8 \times 10^{-9} \\ C_c &\leq 7.5 \times 10^{-8} \end{aligned}$$

$\therefore$ Maximum cable capacitance is 7.5×10^{-8} F

$$\therefore \text{As per capacitance, maximum cable length} = \frac{7.5 \times 10^{-8}}{200 \times 10^{-12}} = 375 \text{ m}$$

By taking the cable length of 375 m, the L_c and C_c are calculated as shown below:

$$\begin{aligned} L_c &= \text{Inductance of cable per meter} \times \text{Maximum Cable Length} \\ &= 1 \times 10^{-6} \times 375 \\ &= 0.375 \text{ mH} \end{aligned}$$

$$
\begin{aligned}
C_c &= \text{Capacitance of cable per meter } \times \text{Maximum Cable Length}\\
&= 200 \times 10^{-12} \times 375\\
&= 75\ \text{nF}
\end{aligned}
$$

The summary of the intrinsic safety loop verification for the second Ex i system is shown in Table 4.4.

Table 4.4: Summary of the Intrinsic Safety Loop Verification for the Second Ex i System.

	Ex i Barrier	**Field Device/ Cable**	**Result**
Voltage	$U_o = 28$ V	$U_i = 28$ V	$U_o \leq U_i$, Valid
Current	$I_o = 93$ mA	$I_i = 93$ mA	$I_o \leq I_i$, Valid
Power	$P_o = 650$ mW	$P_i = 650$ mW	$P_o \leq P_i$, Valid
Inductance	$L_o = 3.05$ mH	$L_i = 0$ H $L_c = 0.375$ mH (Cable Length =375m)	$L_i + L_c \leq L_o$, Valid
Capacitance	$C_o = 83$ nF	$C_i = 8$ nF $C_c = 75$ nF (Cable Length =375m)	$C_i + C_c \leq C_o$, Valid

According to Table 4.4, the conformity regarding the intrinsic safety loop of the second Ex i system is proved. When a fault condition occurs, the voltage, current and power provided by the Ex i barrier cannot be larger than the maximum input voltage, current and power of the field device. This may introduce the extra energy in terms of electrical spark or thermal effect, thus leading to ignition of the surrounding gases. Since $U_o \leq U_i$, $I_o \leq I_i$ and $P_o \leq P_i$, the energy transferring to the hazardous area will not exceed the ignition point. Regarding the capacitance and inductance, as $L_i + L_c \leq L_o$ and $C_i + C_c \leq C_o$, the energy stored in the field device and cable is bound below the ignition point.

4.2.3 Summary

In a nutshell, the validity of the first and second Ex i system is proved in terms of compliance of apparatuses and intrinsic safety loop verification. In the first Ex i system, the galvanically isolated barrier is applied and there is no specific requirement for the earthing. For the second Ex i system, since the Zener barrier is applied, the resistance of the earth conductor has to be less than 1 Ω.

4.3 Third Ex i System

Figure 4.10 shows the third Ex i system. It is a system having multiple field devices and a single Ex i barrier.

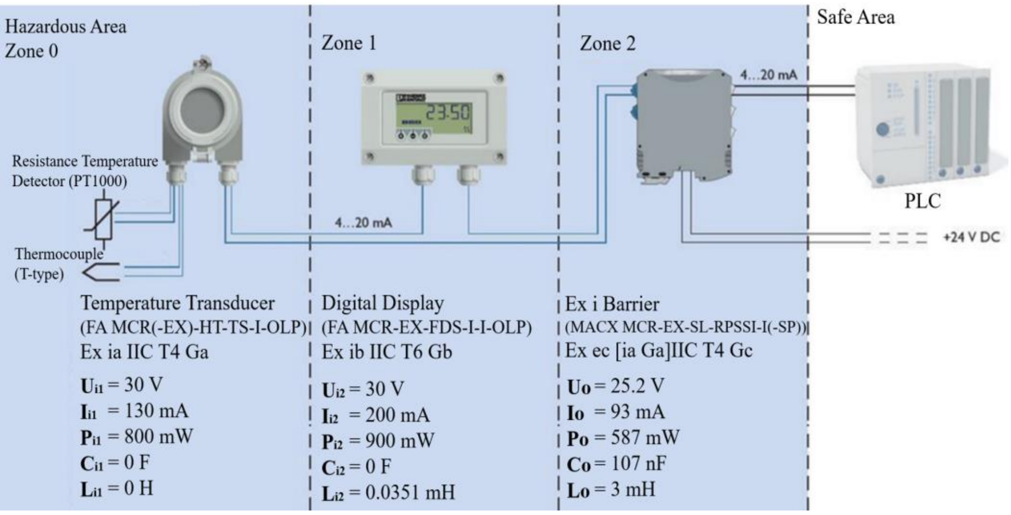


Figure 4.10: Third Ex i System.

Referring to Figure 4.10, the U_o, I_o, P_o, C_o and L_o are the safety parameters of the Ex i barrier. The safety parameters of the temperature transducer are denoted as U_{i1}, I_{i1}, P_{i1}, C_{i1} and L_{i1}. For the digital display, the safety parameters are denoted as U_{i2}, I_{i2}, P_{i2}, C_{i2} and L_{i2}. Furthermore, both temperature transducer and digital display are certified field devices. The sensors including the resistance temperature detector and thermocouple are not certified by IECEx. They are connected to the terminals of the temperature transducer for sensing purposes. Also, it has to be examined whether they are valid to be the simple apparatus.

With regard to the operational parameters, the voltage drop across the temperature transducer is at least 11 V. The digital display requires a voltage of 3.9 V with display lighting. Therefore, the Ex i barrier can provide a nominal voltage of 24 V, which is adequate for both certified field devices to function.

Apart from that, the temperature transducer, digital display and Ex i barrier are installed in the Zone 0, 1 and 2 accordingly. The surrounding gas is assumed to be hydrogen which is classified as the IIC gas group.

4.3.1 Verification of the Compliance of the Certified Field Devices for the Third Ex i System

The temperature transducer and digital display are certified field devices. Hence, the compliance is validated based on the IECEx marking.

For the temperature transducer, its IECEx marking is labelled as ‘Ex ia IIC T4 Ga’. It has the equipment group of ‘IIC’, which is compatible with the surrounding gas classified as the IIC gas group. Based on the temperature class of ‘T4’, its maximum surface temperature is 135 °C. In addition, the auto-ignition temperature of hydrogen is 560 °C (Eaton Electric Limited, n.d.). Hence, the surface temperature of 135 °C will not ignite the hydrogen. Besides that, the equipment protection level of ‘Ga’ enables it to be installed in Zone 0. According to the equipment protection level of ‘Ga’, Ex ‘ia’ is applied. Thus, the conformity of the temperature transducer is proved as per the IECEx marking.

Besides that, the digital display has the IECEx marking labelled as ‘Ex ib IIC T6 Gb’. The equipment group of ‘IIC’ allows it to be installed in the atmosphere filled with hydrogen which is classified as the IIC gas group. Based on the temperature class of ‘T6’, it has a maximum surface temperature of 85 °C which is lower than the auto-ignition temperature of hydrogen of 560 °C (Eaton Electric Limited, n.d.). Aside from that, the equipment protection level of ‘Gb’ enables it to be installed in Zone 1. As per the equipment protection level of ‘Gb’, Ex ‘ib’ is applied. Therefore, the compliance of the digital display is validated according to the IECEx marking.

4.3.2 Verification of the Compliance of the Simple Apparatuses for the Third Ex i System

Apart from the certified field devices, the resistance temperature detector and thermocouple are required to be verified based on the concept of simple apparatus stated in IEC 60079-14. As per IEC 60079-14 Clause 16.4, there are three groups of simple apparatuses as shown below:

- Passive elements such as resistors and junction boxes
- Elements storing inductive or capacitive energy with well-marked parameters
- Elements such as thermocouple that produces electrical power not exceeding 1.5 V, 0.1 A or 25 mW

For a resistance temperature detector, the working principle is to sense the temperature through the varying resistance value. Therefore, it can be classified as passive elements under the concept of simple apparatus as per IEC 60079-14 Clause 16.4. Furthermore, according to Annex A of IEC 60079-25, resistance temperature detectors are also treated as simple apparatuses. Hence, it is proved that the resistance temperature detector is simple apparatus. Apart from that, it is required to determine its temperature class based on the maximum measurable temperature. Referring to Appendix F, its maximum measurable temperature is 100 °C. Hence, its temperature class is T5, which is compatible with the auto-ignition temperature of the hydrogen. As a result, the compliance of the resistance temperature detector is validated.

According to IEC 60079-14 Clause 16.4, it is clearly stated that the thermocouple is simple apparatus. Furthermore, it is classified as elements producing electrical power that does not exceed 1.5 V, 0.1 A or 25 mW. Moreover, thermocouples operate on the basis of generating voltage depending on the temperature (Root, Bechtold and Pham, 2020). Therefore, it is required to verify whether the thermocouple generates less than 1.5 V.

According to Appendix G, the thermocouple can sense the temperature ranging from -250 °C to 105 °C. Based on Appendix L, if the maximum temperature of 105 °C is sensed, the voltage generated by the thermocouple is 4.513 mV given that the temperature of the reference junction is 0 °C. Hence, the voltage of 4.513 mV is less than 1.5 V.

In the worst condition, where the reference junction is -270 °C and the maximum temperature of 105 °C is sensed, the largest voltage of the thermocouple can be obtained. To calculate it, the law of intermediate temperatures such as given in Equation (3.2) is applied (Moris, 2011).

$$V_{(T_M\,,\ T_0)} = V_{(T_M\,,\ T_R)} + V_{(T_R\,,\ T_0)} \tag{3.2}$$

where

$V_{(T_M\,,\ T_0)}$ = voltage of thermocouple for the junctions at T_M and T_o, mV

$V_{(T_M\,,\ T_R)}$ = voltage of thermocouple for the junctions at T_M and T_R, mV

$V_{(T_R\,,\ T_0)}$ = voltage of thermocouple for the junctions at T_R and T_o, mV

T_M = temperature of the measurement junction, °C

T_o = temperature of 0 °C for the reference junction

T_R = temperature of the reference junction, °C

Given that:

$T_M = 105\ °C$; $T_R = -270\ °C$; $T_o = 0\ °C$

$V_{(T_M\,,\ T_0)} = V_{(105\,°C\ ,\ 0\,°C)} = 4.513$ mV (Appendix L)

$V_{(T_R\,,\ T_0)} = V_{(-270\,°C\ ,\ 0\,°C)} = -6.258$ mV (Appendix M)

$$\begin{aligned}
V_{(T_M\,,\ T_0)} &= V_{(T_M\,,\ T_R)} + V_{(T_R\,,\ T_0)} \\
V_{(105\,°C\ ,\ 0\,°C)} &= V_{(105\,°C,\ -270\,°C)} + V_{(-270\,°C,\ 0\,°C)} \\
V_{(105\,°C,\ -270\,°C)} &= V_{(105\,°C\ ,\ 0\,°C)} - V_{(-270\,°C,\ 0\,°C)} \\
V_{(105\,°C,\ -270\,°C)} &= 4.513\ - (-6.258) \\
\therefore V_{(105\,°C,\ -270\,°C)} &= 10.771\ \text{mV}
\end{aligned}$$

Based on the computation above, the maximum voltage generated by the thermocouple is 10.771 mV, which is less than 1.5 V. Therefore, it is proved that the thermocouple is simple apparatus.

Aside from that, the temperature class of the thermocouple has to be determined. Since the maximum measuring temperature of the thermocouple is 105 °C, the temperature class of T4 is assigned to it. Furthermore, the temperature class of T4 complies with the auto-ignition temperature of hydrogen. As a result, the compliance of the thermocouple is validated.

4.3.3 Verification of the Compliance of Ex i Barrier for the Third Ex i System

The Ex i barrier has to be validated referring to the IECEx marking. Moreover, the IECEx marking of the Ex i barrier is ‘Ex ec [ia Ga] IIC T4 Gc’. As per IEC 60079-14 Clause 16.1, in the condition that the barrier is utilized in a hazardous area, an explosion protection method other than Ex i is required to be applied to the barrier (IEC, 2013). In this case, the enclosure certified under Ex e (increased safety) is applied for the Ex i barrier. Since the Ex i barrier is installed in Zone 2, the equipment protection level of ‘Gc’ is adopted and therefore Ex ‘ec’ is applied for the enclosure of the Ex i barrier. Under the protection of Ex ‘ec’, the ingress protection and impact strength of the enclosure can be assured (SOURCE IEx, n.d.).

Regarding the Ex i barrier, it has the equipment group of ‘IIC’ which is compatible with the surrounding gas group. The equipment protection level of ‘Ga’ is required for the Ex i barrier because of the installation of the temperature transducer in Zone 0. As per the equipment protection level of ‘Ga’, Ex ‘ia’ is applied. Furthermore, it can be found that the temperature class of ‘T4’ is assigned to the Ex i barrier. However, in the first and second Ex i system, those Ex i barriers are not assigned with the temperature class. This is because the Ex i barrier for the third Ex i system is installed in Zone 2. The rise of temperature is one of the main concerns in explosion protection. Therefore, the Ex i barrier has the temperature class of ‘T4’, which is to indicate the maximum surface temperature of 135 °C, therefore it is compatible with the auto-ignition temperature of the hydrogen.

Aside from that, the safety parameters of the Ex i barrier are verified using the energy curves. The safety factor is 1.5 is applied since the Ex ‘ia’ method is applied.

To carry out the verification of U_o and I_o, the point, P (U_o, I_o × safety factor) has to be computed. The value of U_o is 25.2 V while I_o is 93 mA. Through the multiplication of I_o with the safety factor, where I_o × safety factor = 0.093 A × 1.5 = 0.1395 A, the point, P (25.2 V, 0.1395 A) is formed. It is positioned on the resistive energy curve. Referring to the resistive energy curve shown in Figure 4.11, the point is below the curve for the equipment group of IIC. Therefore, the U_o and I_o are valid. Since $P_o = \frac{I_o U_o}{4}$, P_o is valid.

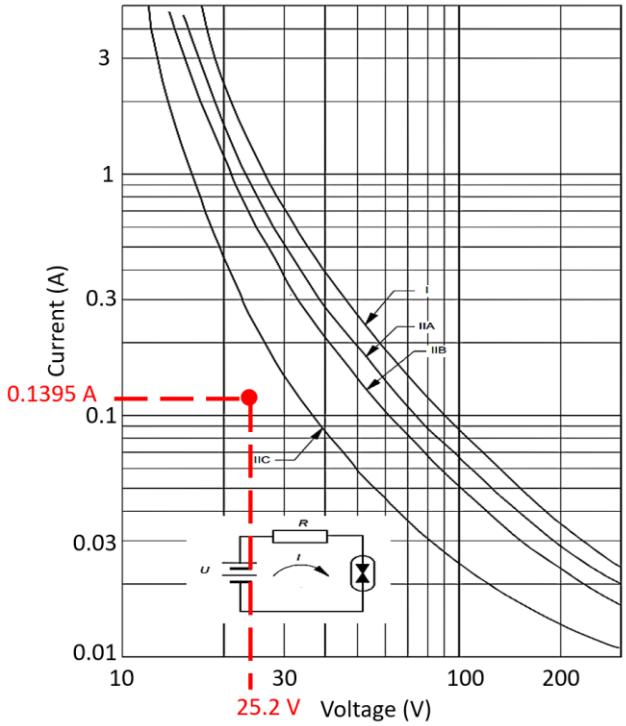


Figure 4.11: Verification of U_o and I_o for the Third Ex i System (IEC, 2012).

Aside from that, the point, P (I_o × safety factor, L_o) has to be formed to verify L_o. The value of L_o is 3 mH while I_o is 93 mA. Through the multiplication of I_o with the safety factor, where I_o × safety factor = 0.093 A × 1.5 = 0.1395 A, the point, P (0.1395 A, 0.003 H) is formed. It is then positioned on the inductive energy curve as shown in Figure 4.12. Thus, the point is below the curve for the equipment group of IIC and the L_o is valid.

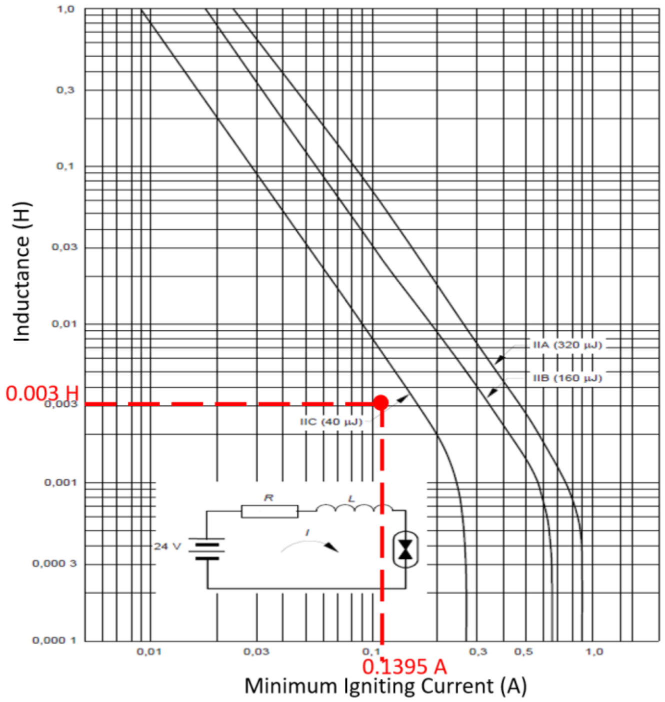


Figure 4.12: Verification of L_o for the Third Ex i System (IEC, 2012).

Besides that, the point, P (U_o × safety factor, C_o) has to be computed to verify the C_o. The value of C_o is 107 nF whereas U_o is 25.2 V. By multiplying U_o with the safety factor, where U_o × safety factor = 25.2 V × 1.5 = 37.8 V, the point, P (37.8 V,0.107 µF) is formed. It is positioned on the capacitive energy curve as shown in Figure 4.13. Referring to Appendix K, the point is exactly positioned on the curve for the equipment group of IIC. Therefore, the C_o is valid. In short, all the safety parameters of the Ex i barrier are valid.

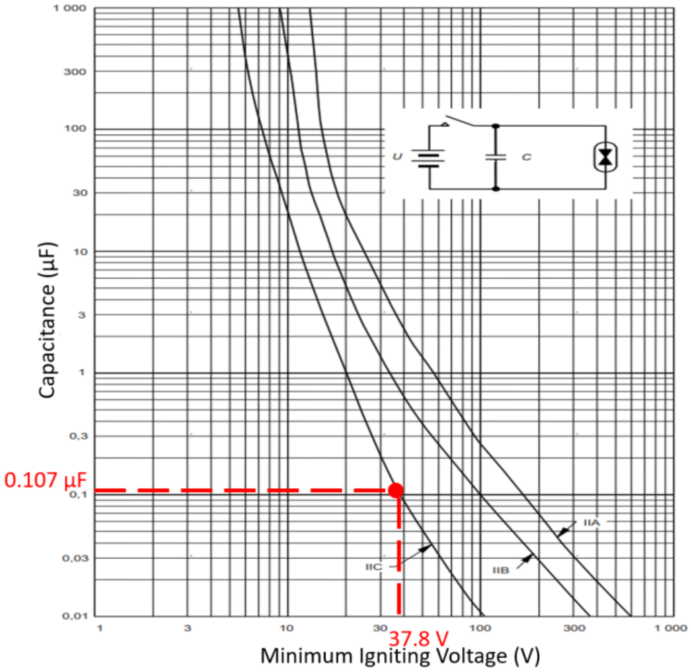


Figure 4.13: Verification of C_o for the Third Ex i System (IEC, 2012).

In short, the safety parameters of the Ex i barrier including U_o, I_o, P_o, L_o and C_o are valid. Therefore, the energy transferring to field devices and energy stored in them can be limited below the ignition point in the condition that the intrinsic safety loop is validated. In the following section, the intrinsic safety loop verification is implemented.

4.3.4 Intrinsic Safety Loop Verification for the Third Ex i System

Referring to Figure 4.10, all the safety parameters used in the intrinsic safety loop verification are shown. As per IEC 60079-14 Clause 16.2.4.3, the U_o has to be less or equal to the U_i of each of the field devices. For instance, there are two certified field devices in the third Ex i system, the maximum input voltage of the temperature transducer and digital display is denoted as U_{i1} and U_{i2} accordingly. The U_{i1} and U_{i2} need to be larger than or the same as the U_o respectively. The same concept applies to the current and power.

The intrinsic safety loop verification for voltage, current and power is as follows:

With regard to the temperature transducer,

$$\text{Given that: } \mathrm{U_o} = 25.2\ \mathrm{V}, \mathrm{U_{i1}} = 30\ \mathrm{V}$$

$$25.2 \ \leq 30$$

$$\therefore \mathrm{U_o} \leq \mathrm{U_{i1}}$$

$$\mathrm{I_o} = 93\ \mathrm{mA}, \mathrm{I_{i1}} = 130\ \mathrm{mA}$$

$$93 \times 10^{-3} \ \leq 130 \times 10^{-3}$$

$$\therefore \mathrm{I_o} \leq \mathrm{I_{i1}}$$

$$\mathrm{P_o} = 587\ \mathrm{mW}, \mathrm{P_{i1}} = 800\ \mathrm{mW}$$

$$587 \times 10^{-3} \ \leq 800 \times 10^{-3}$$

$$\therefore \mathrm{P_o} \leq \mathrm{P_{i1}}$$

With regard to the digital display,

$$\mathrm{U_o} = 25.2\ \mathrm{V}, \mathrm{U_{i2}} = 30\ \mathrm{V}$$

$$25.2 \ \leq 30$$

$$\therefore \mathrm{U_o} \leq \mathrm{U_{i2}}$$

$$\mathrm{I_o} = 93\ \mathrm{mA}, \mathrm{I_{i2}} = 200\ \mathrm{mA}$$

$$93 \ \times 10^{-3} \leq 200 \times 10^{-3}$$

$$\therefore \mathrm{I_o} \leq \mathrm{I_{i2}}$$

$$\mathrm{P_o} = 587\ \mathrm{mW}, \mathrm{P_{i2}} = 900\ \mathrm{mW}$$

$$587 \ \times 10^{-3} \leq 900 \times 10^{-3}$$

$$\therefore \mathrm{P_o} \leq \mathrm{P_{i2}}$$

Thus, through the verification shown above, the intrinsic safety loop is valid in terms of voltage, current and power.

Referring to IEC 60079-14 Clause 16.2.4.3, if the total inductance and capacitance values of the field devices are larger than $0.01L_o$ and $0.01C_o$ respectively, the L_o and C_o values have to be halved in the computation of the cable length. Thus, it cannot be confirmed whether the term, 'total inductance and capacitance' is referred to the equivalent inductance and capacitance or the sum of the inductance and capacitance. As per IEC 60079-25 Annex A, it is clarified that the 'total inductance and capacitance' is referred to the sum of the inductance and capacitance of the field devices. Hence, the calculation of the sum of the inductance (L_i) and the sum of capacitance (C_i) is as follows:

Regarding the sum of the inductance,

$$\text{Given that: } \mathrm{L_{i1}} = 0\ \mathrm{H};\ \mathrm{L_{i2}} = 0.0351\ \mathrm{mH}$$

$$\mathrm{L_i} = \mathrm{L_{i1}} + \mathrm{L_{i2}}$$

$$\mathrm{L_i} = 0 + (0.0351) \times 10^{-3}$$

$$\therefore \mathrm{L_i} = 0.0351\ \mathrm{mH}$$

Regarding the sum of the capacitance,

$$\text{Given that: } \mathrm{C_{i1}} = 0\ \mathrm{F};\ \mathrm{C_{i2}} = 0\ \mathrm{F}$$

$$\mathrm{C_i} = \mathrm{C_{i1}} + \mathrm{C_{i2}}$$

$$\mathrm{C_i} = 0 + 0$$

$$\therefore \mathrm{C_i} = 0\ \mathrm{F}$$

The intrinsic safety loop verification regarding inductance and capacitance is as follows:

Regarding inductance,

$$\text{Given that: } \mathrm{L_i} = 0\ .0351\ \mathrm{mH}, \mathrm{L_o} = 3\ \mathrm{mH}, 0.01\mathrm{L_o} = 0.03\ \mathrm{mH}$$

$$0\ .0351 \times 10^{-3} < 3\ \times 10^{-3}$$

$$\therefore \mathrm{L_i} < \mathrm{L_o}$$

$$0\ .0351 \times 10^{-3} > 0\ .03 \times 10^{-3}$$

$$\therefore \mathrm{L_i} > 0.01\mathrm{L_o}$$

Regarding capacitance,

$$\text{Given that: } \mathrm{C_i} = 0\ \mathrm{F}, \mathrm{C_o} = 107\ \mathrm{nF}, 0.01\mathrm{C_o} = 1.07\ \mathrm{nF}$$

$$0 < 107 \times 10^{-9}$$

$$\therefore \mathrm{C_i} < \mathrm{C_o}$$

$$0 < 1.07 \times 10^{-9}$$

$$\therefore \mathrm{C_i} < 0.01\mathrm{C_o}$$

Referring to the computation shown above, as $\mathrm{L_i} > 0.01\mathrm{L_o}$ and $\mathrm{C_i} < 0.01\mathrm{C_o}$, the equations $\mathrm{L_i} + \mathrm{L_C} \leq \mathrm{L_o}$ and $\mathrm{C_i} + \mathrm{C_C} \leq \mathrm{C_o}$ are used to compute the maximum cable length. The computation of the maximum cable length is as follows:

Inductance of cable per meter (Lc/m) = 1 µH/m (IEC, 2013)
Capacitance of cable per meter (Cc/m) = 200 pF/m (IEC, 2013)

With regard to inductance,

$$\begin{aligned} \mathrm{L_i} + \mathrm{L_c} &\leq \mathrm{L_o} \\ \mathrm{L_c} &\leq \mathrm{L_o} - \mathrm{L_i} \\ \mathrm{L_c} &\leq 3 \times 10^{-3} - 0.0351 \times 10^{-3} \\ \mathrm{L_c} &\leq 2.9649 \times 10^{-3} \end{aligned}$$

$\therefore$ Maximum cable inductance is 2.9649×10^{-3} H

$$\therefore \text{As per inductance, maximum cable length} = \frac{2.9649 \times 10^{-3}}{1 \times 10^{-6}} = 2964.9\ \mathrm{m}$$

With regard to capacitance,

$$\begin{aligned} \mathrm{C_i} + \mathrm{C_c} &\leq \mathrm{C_o} \\ \mathrm{C_c} &\leq \mathrm{C_o} - \mathrm{Ci} \\ \mathrm{C_c} &\leq 107 \times 10^{-9} - 0 \\ \mathrm{C_c} &\leq 107 \times 10^{-9} \end{aligned}$$

$\therefore$ Maximum cable capacitance is 107×10^{-9} F

$$\therefore \text{As per capacitance, maximum cable length} = \frac{107 \times 10^{-9}}{200 \times 10^{-12}} = 535\text{ m}$$

By taking the cable length of 535 m, the L_c and C_c are calculated as shown below:

$$\begin{aligned} L_c &= \text{Inductance of cable per meter } \times \text{Maximum Cable Length} \\ &= 1 \times 10^{-6} \times 535 \\ &= 0.535\text{ mH} \end{aligned}$$

$$\begin{aligned} C_c &= \text{Capacitance of cable per meter } \times \text{Maximum Cable Length} \\ &= 200 \times 10^{-12} \times 535 \\ &= 107\text{ nF} \end{aligned}$$

The summary of the intrinsic safety loop verification for the third Ex i system is shown in Table 4.5.

Table 4.5: Summary of the Intrinsic Safety Loop Verification for the Third Ex i System.

	Ex i Barrier	**Field Device/ Cable**	**Result**
Voltage	$U_o = 25.2$ V	$U_{i1} = 30$ V	$U_o \leq U_{i1}$, Valid
		$U_{i2} = 30$ V	$U_o \leq U_{i2}$, Valid
Current	$I_o = 93$ mA	$I_{i1} = 130$ mA	$I_o \leq I_{i1}$, Valid
		$I_{i2} = 200$ mA	$I_o \leq I_{i2}$, Valid
Power	$P_o = 587$ mW	$P_{i1} = 800$ mW	$P_o \leq P_{i1}$, Valid
		$P_{i2} = 900$ mW	$P_o \leq P_{i2}$, Valid
Inductance	$L_o = 3$ mH	$L_i = 0.0351$ H	$L_i + L_c \leq L_o$, Valid
		$L_c = 0.535$ mH (Cable Length =535m)	
Capacitance	$C_o = 107$ nF	$C_i = 0$ F	$C_i + C_c \leq C_o$, Valid
		$C_c = 107$ nF (Cable Length =535m)	

As per Table 4.5, the compliance of the intrinsic safety loop in the third Ex i system is validated. Since $U_o \leq U_i$, $I_o \leq I_i$ and $P_o \leq P_i$, the energy transferring to the hazardous area will not cause ignition. As $L_i + L_c \leq L_o$ and $C_i + C_c \leq C_o$, the energy reserved in the field devices and cable is limited within a safe level, thus preventing the ignition.

4.3.5 Summary

In the third Ex i system, the compliances of the apparatuses including two certified field devices, two simple apparatuses and a single Ex i barrier are validated. Furthermore, the conformity of the intrinsic safety loop is proved.

4.4 Fourth Ex i System

Figure 4.14 shows the fourth Ex i system. It is a system having a field device and two Ex i barriers.

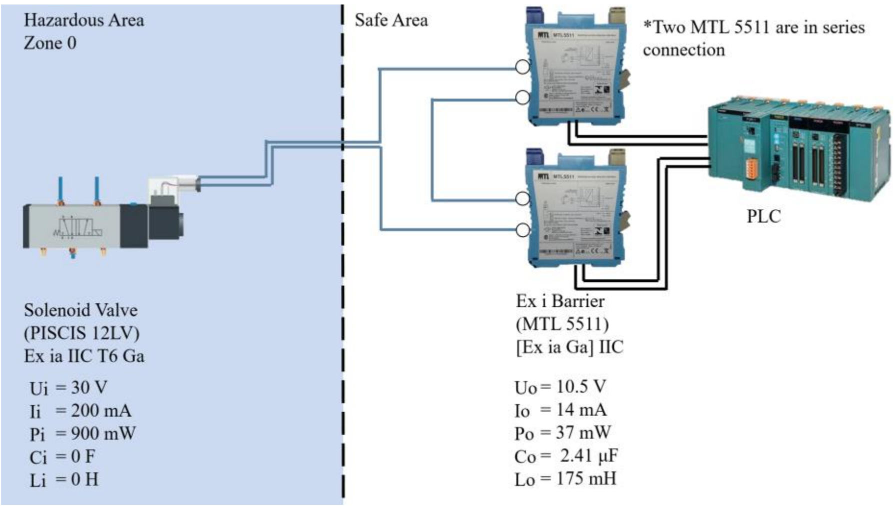


Figure 4.14: Fourth Ex i System.

As per Figure 4.14, the safety parameters of the solenoid valve and the Ex i barrier are shown. Furthermore, the safety parameters are utilized in the intrinsic safety loop verification.

Regarding the operational parameters, the solenoid valve requires the ‘turn on’ voltage ranging from 10.8 V to 16 V. A single Ex i barrier (MTL 5541) only can provide the maximum voltage of 10.5 V at 14 mA, which is inadequate for the solenoid valve to function. Therefore, it requires two Ex i barriers. For instance, two Ex i barriers (MTL 5541) are connected in series, thus producing a maximum voltage of 21 V at 14 mA.

In addition, the hazardous area is classified as Zone 0. The surrounding gas is assumed to be acetylene which is classified as the IIC gas group.

4.4.1 Verification of the Compliance of Field Device for the Fourth Ex i System

The solenoid valve is the certified field device; thus, its compliance is verified as per the IECEx marking. For instance, its IECEx marking is labelled as 'Ex ia IIC T6 Ga'. It has the equipment group of 'IIC', which complies with the acetylene classified as the IIC gas group. Its surface can reach a temperature up to 85 °C as per the temperature class of 'T6'. Additionally, the auto-ignition temperature of acetylene is 305 °C (Eaton Electric Limited, n.d.). Therefore, the surface temperature of 85 °C will not ignite the surrounding gas. Since it is installed in Zone 0, the equipment protection level of 'Ga' is required. Following the equipment protection level of 'Ga', Ex 'ia' is applied. Hence, the conformity of the solenoid valve is validated as per the IECEx marking.

4.4.2 Verification of the Compliance of Ex i Barrier for the Fourth Ex i System

Same as the solenoid valve, the Ex i barrier is required to be examined based on the IECEx marking. For instance, the IECEx marking of the Ex i barrier is '[Ex ia Ga] IIC'. It is the equipment group of 'IIC' which is compatible with the surrounding gas group. The equipment protection level of 'Ga' is applied due to the installation of the solenoid valve in Zone 0. Furthermore, Ex 'ia' is applied based on the equipment protection level. As a result, the validity of the Ex i barrier is proved according to the IECEx marking.

Besides that, the safety parameters of the Ex i barrier are verified using the energy curves. Since the Ex 'ia' method is applied, the safety factor is 1.5.

For the verification of U_o and I_o, the point, P (U_o, I_o × safety factor) is formed. The value of U_o is 10.5 V while Io is 14 mA. By multiplying I_o with the safety factor, where I_o × safety factor = 0.014 A × 1.5 = 0.021 A, the point, P (10.5 V,0.021 A) is formed. It is positioned on the resistive energy curve shown in Figure 4.15. The point is below the curve for the equipment group of IIC. Therefore, the U_o and I_o are valid. Furthermore, since $P_o = \frac{I_o U_o}{4}$, P_o is valid.

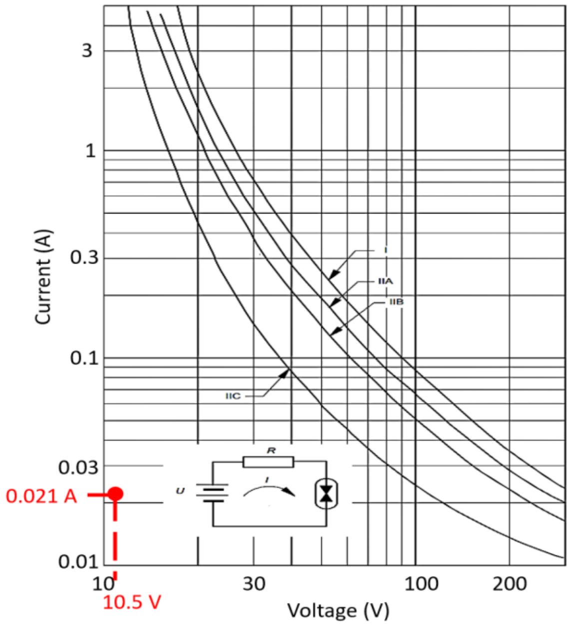


Figure 4.15: Verification of U_o and I_o for a Single Ex i Barrier in the Fourth Ex i System (IEC, 2012).

Aside from that, the point, P (I_o × safety factor, L_o) has to be formed to verify L_o. The value of L_o is 175 mH while I_o is 14 mA. Through the multiplication of I_o with the safety factor, where I_o × safety factor = 0.014 A × 1.5 = 0.021, the point, P (0.021 A, 0.175 H) is formed. It is positioned on the inductive energy curve as shown in Figure 4.16. Thus, the point is below the curve for the equipment group of IIC and the L_o is valid.

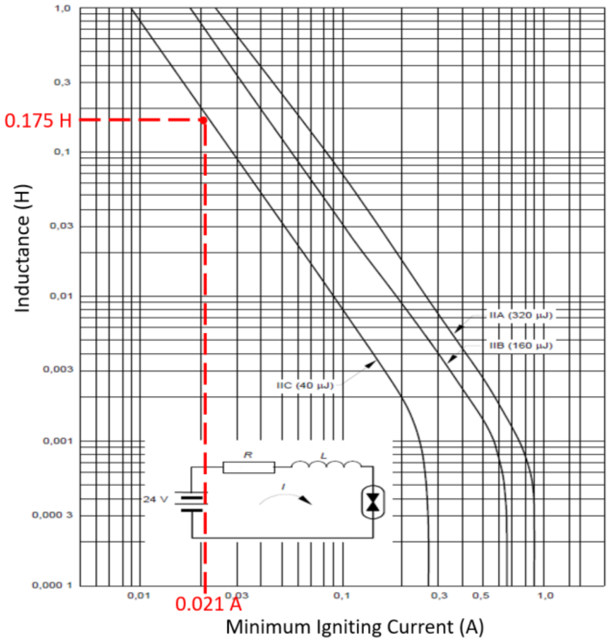


Figure 4.16: Verification of L_o for a Single Ex i Barrier in the Fourth Ex i System (IEC, 2012).

Besides that, the point, P (U_o × safety factor, C_o) is computed to verify the C_o. The value of C_o is 2.41 μF whereas U_o is 10.5 V. By multiplying U_o with the safety factor of 1.5, where U_o × safety factor =10.5 V × 1.5 = 15.75 V, the point, P (15.75 V, 2.41 μF) is formed. It is positioned on the capacitive energy curve as shown in Figure 4.17. Referring to Appendix N, the point is exactly positioned on the curve for the equipment group of IIC. Thus, the C_o is valid. In short, all the safety parameters of the Ex i barrier are valid. In short, all the safety parameters of the Ex i barrier are valid.

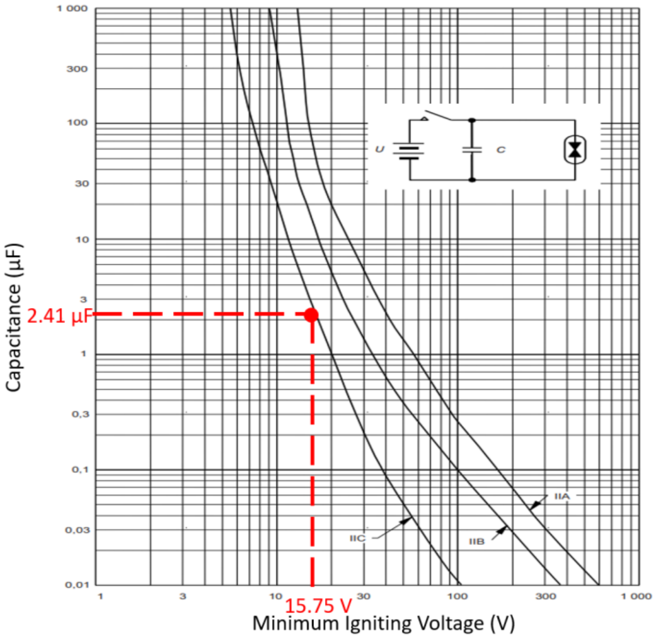


Figure 4.17: Verification of C_o for a Single Ex i Barrier in the Fourth Ex i System (IEC, 2012).

In short, all the safety parameters of a single Ex i barrier are valid. As a result, the energy supplied from the Ex i barrier and energy stored in the field device will not cause ignition given that the intrinsic safety loop of the system is valid. In the subsequent section, the intrinsic safety loop verification is carried out.

4.4.3 Intrinsic Safety Loop Verification for the Fourth Ex i System

As per Annex H of IEC 60079-14, in the condition that the two Ex i barriers are connected in series within a Ex i system, the U_o and I_o have to be calculated as shown below:

$$U_O = U_{O1} + U_{O2} = 10.5 + 10.5 \ = 21 \text{ V}$$

$$I_o = \max.(I_{oi}) = 14 \text{ mA}$$

Regarding the series connection of two Ex i barriers, the U_o is 21 V and I_o is 14 mA. To verify the U_o and I_o, the point, P (U_o, I_o × safety factor) is formed. Since Ex 'ia' method is applied, the safety factor is 1.5. The safety factor of 1.5 also applies to the inductive and capacitive energy curve. By multiplying I_o with the safety factor, where I_o × safety factor = 0.014 A × 1.5 =

0.021 A, the point, P (21 V, 0.021 A) is formed. It is positioned on the resistive energy curve shown in Figure 4.18. The point is below the curve for the equipment group of IIC. Therefore, the U_o and I_o are valid.

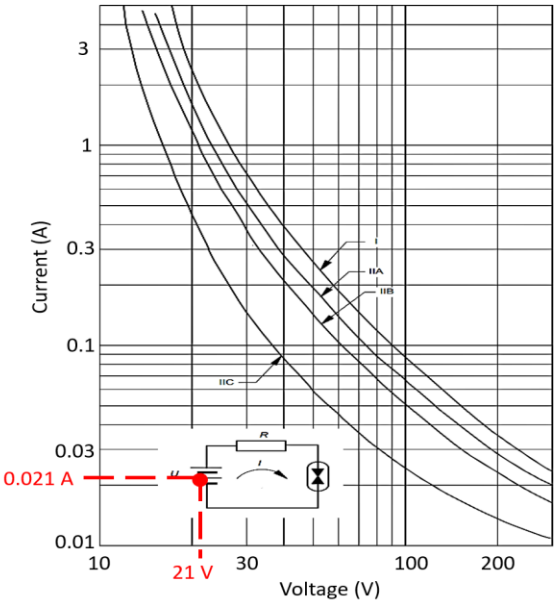


Figure 4.18: Verification of U_o and I_o of Two Ex i Barriers in Series Connection for the Fourth Ex i System (IEC, 2012).

Besides that, it is required to determine the value of L_o based on the Io of 14 mA using the inductive energy curve shown in Figure 4.19. After multiplying I_o by a safety factor, a vertical line, where $x = Io \times (\text{safety factor}) = 0.014 \times 1.5 = 0.021$ A, can be formed. Thus, the point of intersection between the vertical line and the energy curve can be formed. Based on the coordinate of the point, the value of L_o can be obtained. However, using only the inductive energy curve, the exact value of L_o is hard to be determined. Therefore, Equation (3.3) is applied to calculate L_o, where this equation represents the energy reserved in inductive elements (Fitzpatrick, 2007). The computation is as follows:

$$E = \frac{1}{2} LI^2 \tag{3.3}$$

where

E = inductive energy, J

L = inductance, H

I = current, A

Given that:

E = 40 µJ , ignition energy for IIC equipment group (IEC, 2012)

I = 0.021 A

$$E = \frac{1}{2}LI^2$$

$$L = \frac{2E}{I^2}$$

$$L = \frac{2(40 \times 10^{-6})}{(0.021)^2}$$

$$\therefore L = 0.181 \text{ H}$$

Hence, the L_o value is 0.181 H.

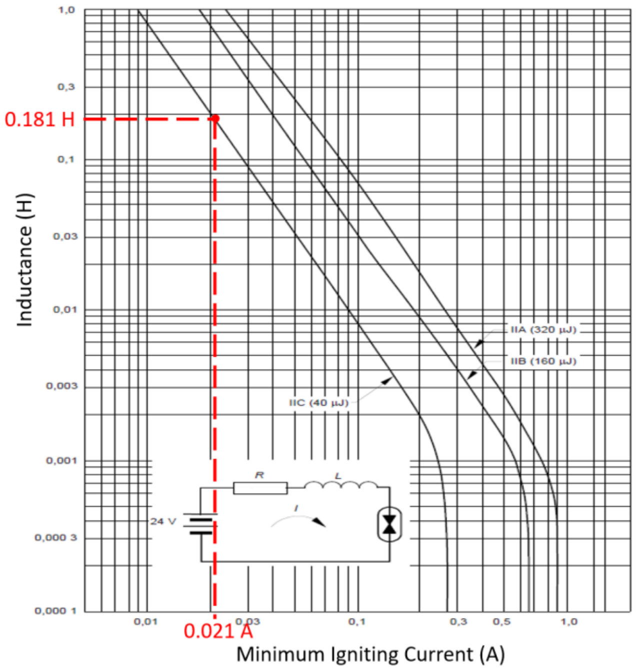


Figure 4.19: Verification of L_o of Two Ex i Barriers in Series Connection for the Fourth Ex i System (IEC, 2012).

To determine the value of C_o based on U_o of 21 V, the capacitive energy curve shown in Figure 4.20 is utilized. A vertical line, where x = U_o × (safety factor) = 21 × 1.5 = 31.5 V is formed after multiplying U_o by the safety factor. Based on the coordinate of the point where the vertical line and the energy curve intersect with each other, the value of C_o can be obtained.

However, using only the energy curve, it is hard to determine the exact value of C_o. Hence, according to Appendix O, the exact value of C_o is 0.188 µF.

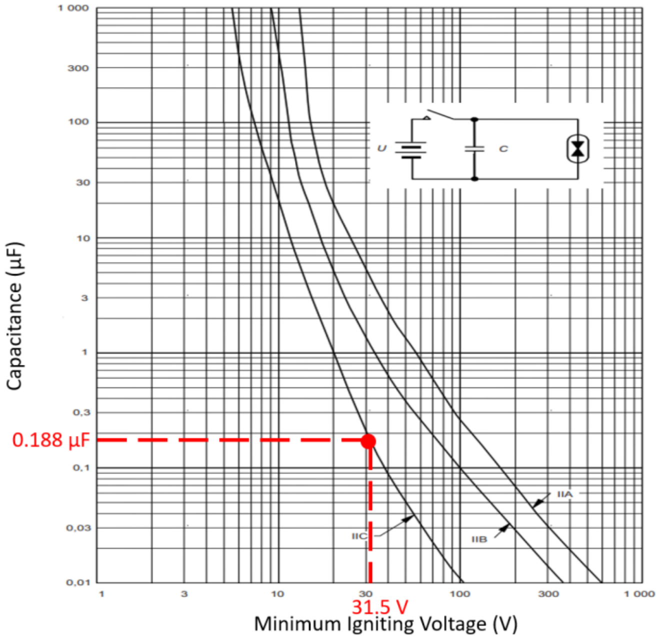


Figure 4.20: Verification of C_o of Two Ex i Barriers in Series Connection for the Fourth Ex i System (IEC, 2012).

Since the U_o, I_o, L_o and C_o of the two Ex i barriers have been determined, the intrinsic safe loop can be verified. The intrinsic safety loop verification regarding inductance and capacitance is as follows:

Regarding inductance,

$$\text{Given that: } \mathrm{L_i} = 0\ \mathrm{H}, \mathrm{L_o} = 181\ \mathrm{mH}, 0.01\mathrm{L_o} = 1.81\ \mathrm{mH}$$

$$0 < 181 \times 10^{-3}$$

$$\therefore \mathrm{L_i} < \mathrm{L_o}$$

$$0 < 1.81 \ \times 10^{-3}$$

$$\therefore \mathrm{L_i} < 0.01\mathrm{L_o}$$

Regarding capacitance,

$$\text{Given that: } \mathrm{C_i} = 0\ \mathrm{F}, \mathrm{C_o} = 0.188\ \mu\mathrm{F}, 0.01\mathrm{C_o} = 0.00188\ \mu\mathrm{F}$$

$$0 < 0.188\ \times 10^{-6}$$

$$\therefore \mathrm{C_i} < \mathrm{C_o}$$

$$0 < 0.00188\ \times 10^{-6}$$

$$\therefore \mathrm{C_i} < 0.01\mathrm{C_o}$$

According to the computation above, since $\mathrm{L_i} < 0.01\mathrm{L_o}$ and $\mathrm{C_i} < 0.01\mathrm{C_o}$, the equations $\mathrm{L_i} + \mathrm{L_C} \leq \mathrm{L_o}$ and $\mathrm{C_i} + \mathrm{C_C} \leq \mathrm{C_o}$ are used to obtain the maximum cable length. The computation of the maximum cable length is as follows:

Inductance of cable per meter = 1 μH/m (IEC, 2013)
Capacitance of cable per meter = 200 pF/m (IEC, 2013)

With regard to inductance,

$$\begin{aligned} \mathrm{L_i} + \mathrm{L_c} &\leq \mathrm{L_o} \\ \mathrm{L_c} &\leq \mathrm{L_o} - \mathrm{L_i} \\ \mathrm{L_c} &\leq 181 \times 10^{-3} - 0 \\ \mathrm{L_c} &\leq 181 \times 10^{-3} \end{aligned}$$

$$\therefore \text{Maximum cable inductance is } 181 \times 10^{-3}\ \mathrm{H}$$

$$\therefore \text{As per inductance, maximum cable length} = \frac{181 \times 10^{-3}}{1 \times 10^{-6}} = 181000\ \mathrm{m}$$

With regard to capacitance,

$$\begin{aligned} \mathrm{C_i} + \mathrm{C_c} &\leq \mathrm{C_o} \\ \mathrm{C_c} &\leq \mathrm{C_o} - \mathrm{Ci} \\ \mathrm{C_c} &\leq 0.188\ \times 10^{-6} - 0 \\ \mathrm{C_c} &\leq 0.188\ \times 10^{-6} \end{aligned}$$

$$\therefore \text{Maximum cable capacitance is } 0.188\ \times 10^{-6}\ \mathrm{F}$$

$$\therefore \text{As per capacitance, maximum cable length} = \frac{0.188\ \times 10^{-6}}{200 \times 10^{-12}} = \ 940 \text{ m}$$

By taking the cable length of 940 m, the L_c and C_c are calculated as shown below:

$$\begin{aligned} L_c &= \text{Inductance of cable per meter } \times \text{Maximum Cable Length} \\ &= 1 \times 10^{-6} \times 940 \\ &= 940\ \mu\text{H} \end{aligned}$$

$$\begin{aligned} C_c &= \text{Capacitance of cable per meter } \times \text{Maximum Cable Length} \\ &= 200 \times 10^{-12} \times 940 \\ &= 0.188\ \mu\text{F} \end{aligned}$$

Besides that, the value of Po for the two Ex i barriers in series connection is computed using Equation (2.5). The computation is as follows:

Given that:

$I_o = 14$ mA; $U_o = 21$ V;

$$P_o = \frac{I_O U_O}{4}$$

$$P_o = \frac{(14 \times 10^{-3})(21)}{4}$$

$$\therefore P_o = 73.5 \text{ mW}$$

The intrinsic safety loop verification for voltage, current and power is as follows:

$$U_o = 21 \text{ V}, U_i = 30 \text{ V}$$

$$21\ \leq 30$$

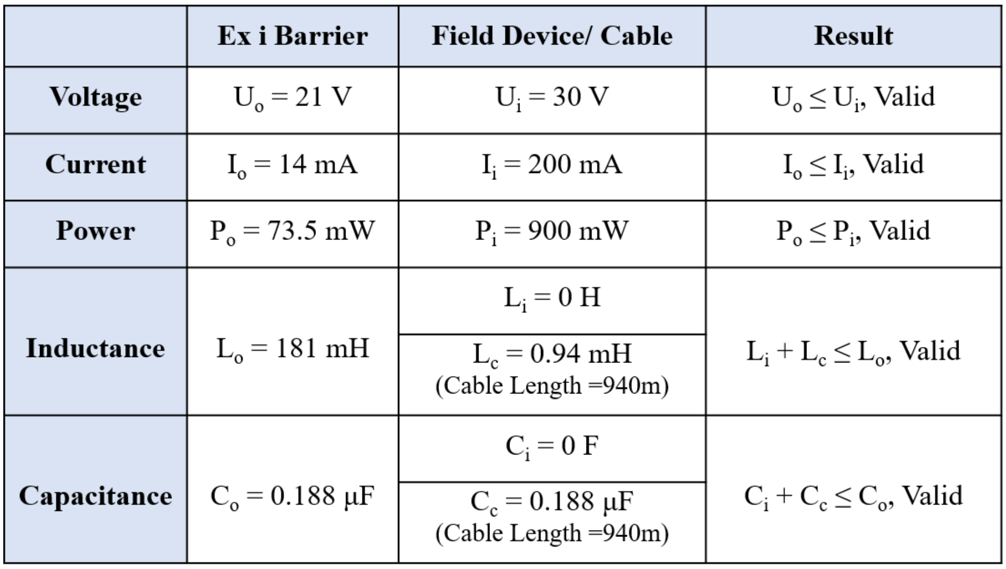
$$\therefore U_o \leq U_i$$

$$\mathrm{I_o} = 14\ \mathrm{mA}, \mathrm{I_i} = 200\ \mathrm{mA}$$
$$14 \times 10^{-3} \ \leq 200 \times 10^{-3}$$
$$\therefore \mathrm{I_o} \leq \mathrm{I_i}$$

$$\mathrm{P_o} = 73.5\ \mathrm{mW}, \mathrm{P_i} = 900\ \mathrm{mW}$$
$$73.5 \times 10^{-3} \ \leq 900 \times 10^{-3}$$
$$\therefore \mathrm{P_o} \leq \mathrm{P_i}$$

The summary of the intrinsic safety loop verification for the fourth Ex i system is shown in Table 4.6.

Table 4.6: Summary of the Intrinsic Safety Loop Verification for the Fourth Ex i System.



	Ex i Barrier	**Field Device/ Cable**	**Result**
Voltage	$U_o = 21$ V	$U_i = 30$ V	$U_o \leq U_i$, Valid
Current	$I_o = 14$ mA	$I_i = 200$ mA	$I_o \leq I_i$, Valid
Power	$P_o = 73.5$ mW	$P_i = 900$ mW	$P_o \leq P_i$, Valid
Inductance	$L_o = 181$ mH	$L_i = 0$ H $L_c = 0.94$ mH (Cable Length =940m)	$L_i + L_c \leq L_o$, Valid
Capacitance	$C_o = 0.188$ µF	$C_i = 0$ F $C_c = 0.188$ µF (Cable Length =940m)	$C_i + C_c \leq C_o$, Valid

Referring to Table 4.6, the conformity regarding the intrinsic safety loop of the fourth Ex i system is proved. As $\mathrm{U_o} \leq \mathrm{U_i}$, $\mathrm{I_o} \leq \mathrm{I_i}$ and $\mathrm{P_o} \leq \mathrm{P_i}$, the energy supplied from the Ex i barrier will not cause the ignition. For the capacitance and inductance, since $\mathrm{L_i} + \mathrm{L_c} \leq \mathrm{L_o}$ and $\mathrm{C_i} + \mathrm{C_c} \leq \mathrm{C_o}$, the energy stored in the field device and cable is inadequate to cause ignition.

4.4.4 Summary

In the fourth Ex i system, the compliances of the solenoid valve and the Ex i barriers are validated. Moreover, the validity of the intrinsic safety loop is verified in the condition that two Ex i barriers are connected in series.

4.5 Common Mistakes in Installation of Ex i Systems

Aside from the compliances of the apparatuses and the intrinsic safety loop, the proper installation measures including segregation of wire, cable gland, marking of Ex i cables and enclosures containing Ex i cables are also essential in the implementation of Ex i systems.

One of the common mistakes is that the segregation of different types of wires is not executed properly. Furthermore, terminal boxes are common tools to implement the segregation of wires. As per IEC 60079-14 Clause 16.5, if terminal boxes are applied, the clearance distance between terminals is the main concern. For instance, the terminal of the Ex i cable must at least maintain a clearance distance of 50 mm from the terminal that is not connected to the Ex i system. Apart from that, the terminal of the Ex i cable is required to keep at least a clearance distance of 3 mm from the ground terminal. Regarding the terminals between two Ex i cables, the minimum clearance distance is 6 mm (IEC, 2013).

According to IEC 61439-1, it is stated that the clearance distance is measured based on the shortest path along the air whereas the creepage distance is taken as the distance along the surface (Tekpan Electric, 2022). Furthermore, Figure 4.21 illustrates the clearance and creepage distance. If there is a mistake in identifying the clearance and creepage distance, the segregation of wires might not be valid. Thus, the concept regarding clearance and creepage distance must be clarified to ensure that the segregation of wires complies with Ex i requirement. In addition, if the space of terminal boxes is limited, a solid insulated part can be placed between the terminals can be utilized to increase the clearance distance.

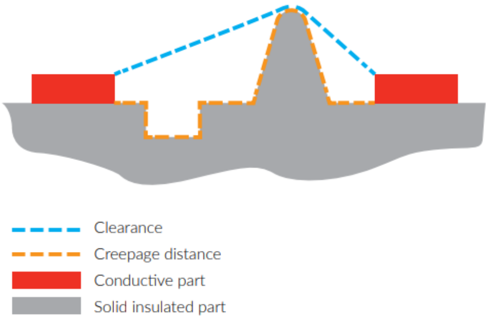


Figure 4.21: Clearance and Creepage Distance (Tekpan Electric, 2022).

Besides that, the improper implementation of cable glands is one of the common mistakes in the installation of Ex i systems. The role of cable glands is to execute the connection between the end of Ex i cables and electrical apparatuses, thus assuring the ingress protection, impact strength and ability to withstand the twisting or tension force (CMP Products Limited, 2022). If cable glands are utilized in a hazardous area, the IECEx certification is mandatory. Regarding the selection of cable glands, IEC 60079-14 Clause 10.2 states that only the cable glands certified by Ex ‘d’ and Ex ‘e’ are allowed to be applied for the Ex i cables. Furthermore, cable glands that do not match the cable diameter are strictly prohibited to be utilized for Ex i cables. Furthermore, any approaches for fitting the cable to the cable gland are forbidden, including using a heat shrink tube or sealing tape (IEC, 2013).

As per IEC 60079-14 Clause 16.2.2.6, Ex i cables have to be indicated using light blue. However, such an indication is an alternative. Only when the colour code is applied for identification of wires, it is compulsory to indicate the Ex i cables using light blue. In the condition that another approach is utilized to identify the wires, Ex i cables are not required to be indicated using light blue. Moreover, according to IEC 60079-14 Clause 16.5.1, the marking to show the presence of Ex i cables has to be implemented for the terminal box containing Ex i cables (IEC, 2013).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The nature of the Ex i method is to restrict the energy transferring to field devices and limit the energy stored in the hazardous area. Unlike other kinds of protection methods such as Ex d and Ex m which only focus on individual apparatus, it is required to consider the compliance of each apparatus and the compatibility of the whole Ex i system. Also, it is inadequate to assure the conformity of explosion protection by just connecting the Ex i barrier between the field devices and the control equipment or power source. It has to be ensured that field devices and the Ex i barriers have the equipment group, temperature class, equipment protection and type of protection which is compatible with the environment of the hazardous area. To ensure the compatibility of the whole Ex i system, intrinsic safety loop verification has to be carried out.

In this project, four Ex i systems have been validated. For the validation regarding the compliances of the apparatuses, there are various kinds of certified field devices including temperature sensors, temperature transducers, digital displays and solenoid valves are verified according to their IECEx marking. Also, the compliance of each Ex i barrier is examined as per the IECEx marking and energy curves. Aside from that, the compliances of simple apparatuses such as resistance temperature detectors and thermocouples are proven. Furthermore, the way to assign the temperature class for simple apparatuses is presented. In short, the ways to verify the compliances for various kinds of apparatuses installed in Ex i system have been demonstrated throughout this project.

Apart from that, the intrinsic safety loop verifications of several Ex i systems having different configurations have been implemented. For instance, three types of Ex i system configurations are covered and they are listed below:

- The system consisting of one field device and a single Ex i barrier
- The system containing multiple field devices and a single Ex i barrier

- The system having a single field device and multiple Ex i barriers

In short, the steps to verify the intrinsic safety loop for several Ex i systems having different configurations have been shown in this project.

In a nutshell, this project has shown the method to implement the validation regarding the compliances of various apparatuses and intrinsic safety loop verification of several Ex i system configurations. As a result, this project provides a better understanding of the implementation of Ex i method according to IEC 60079-14.

5.2 Recommendations for Future Work

In this project, the emphasis is put on the compliance of each apparatus in the Ex i system and the intrinsic safety loop verification. The common mistakes in the installation of the Ex i system are generally discussed. It is recommended that the site visit can be carried out to further highlight the details regarding the installation of the Ex i system including the implementation of cable glands, segregation of wire and mounting method of apparatuses. For instance, some photos can be taken to illustrate the requirement of installation for the Ex i system as per IEC 60079-14.

Furthermore, based on the research conducted by Kuan, Chew and Chua (2020), surge protection devices are applied to Ex i systems to further increase the robustness of the implementation of the Ex i method. For future work, the surge protection devices can be introduced in the four Ex i systems as shown in this project. The introduction of surge protection devices to the Ex i system can be studied based on the different types of surge protection devices, lightning protection zones and lightning protection levels (Kuan, Chew and Chua, 2020). Since the surge protection device is a certified field device, its compliance can be verified according to the IECEx marking. In addition, due to the introduction of surge protection devices, the intrinsic safety loop has to be recomputed.

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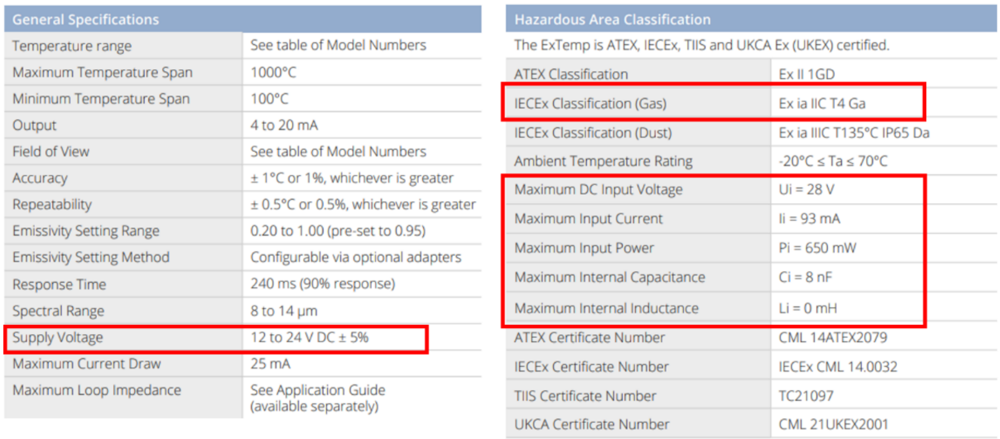
APPENDICES

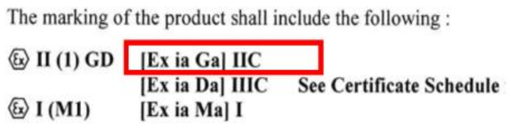
Appendix A: Temperature Sensor - Calex ExTemp (Calex Electronics Limited, 2019).



General Specifications	
Temperature range	See table of Model Numbers
Maximum Temperature Span	1000°C
Minimum Temperature Span	100°C
Output	4 to 20 mA
Field of View	See table of Model Numbers
Accuracy	± 1°C or 1%, whichever is greater
Repeatability	± 0.5°C or 0.5%, whichever is greater
Emissivity Setting Range	0.20 to 1.00 (pre-set to 0.95)
Emissivity Setting Method	Configurable via optional adapters
Response Time	240 ms (90% response)
Spectral Range	8 to 14 μm
Supply Voltage	12 to 24 V DC ± 5%
Maximum Current Draw	25 mA
Maximum Loop Impedance	See Application Guide (available separately)

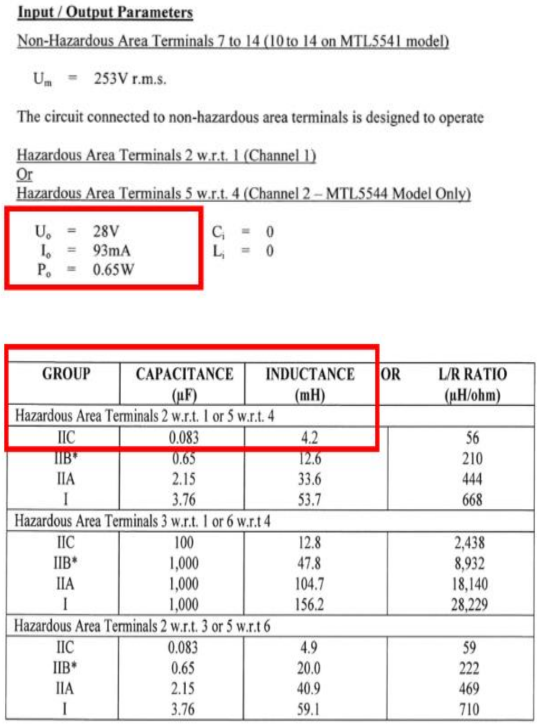
Hazardous Area Classification	
The ExTemp is ATEX, IECEx, TIIS and UKCA Ex (UKEX) certified.	
ATEX Classification	Ex II 1GD
IECEx Classification (Gas)	Ex ia IIC T4 Ga
IECEx Classification (Dust)	Ex ia IIIC T135°C IP65 Da
Ambient Temperature Rating	-20°C ≤ Ta ≤ 70°C
Maximum DC Input Voltage	Ui = 28 V
Maximum Input Current	Ii = 93 mA
Maximum Input Power	Pi = 650 mW
Maximum Internal Capacitance	Ci = 8 nF
Maximum Internal Inductance	Li = 0 mH
ATEX Certificate Number	CML 14ATEX2079
IECEx Certificate Number	IECEx CML 14.0032
TIIS Certificate Number	TC21097
UKCA Certificate Number	CML 21UKEX2001

Appendix B: Ex i Barrier - MTL 5541 (Baseefa, 2018; RS PRO, 2022a).



The marking of the product shall include the following :

Ⓔx II (1) GD [Ex ia Ga] IIC
[Ex ia Da] IIIC See Certificate Schedule
Ⓔx I (M1) [Ex ia Ma] I



Input / Output Parameters

Non-Hazardous Area Terminals 7 to 14 (10 to 14 on MTL5541 model)

U_m = 253V r.m.s.

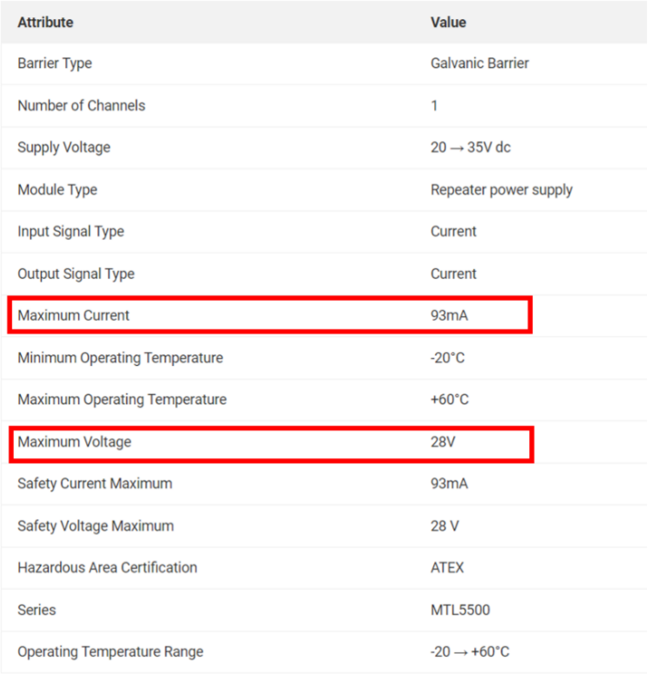
The circuit connected to non-hazardous area terminals is designed to operate

Hazardous Area Terminals 2 w.r.t. 1 (Channel 1)
Or
Hazardous Area Terminals 5 w.r.t. 4 (Channel 2 – MTL5544 Model Only)

U_o = 28V
I_o = 93mA
P_o = 0.65W

C_i = 0
L_i = 0

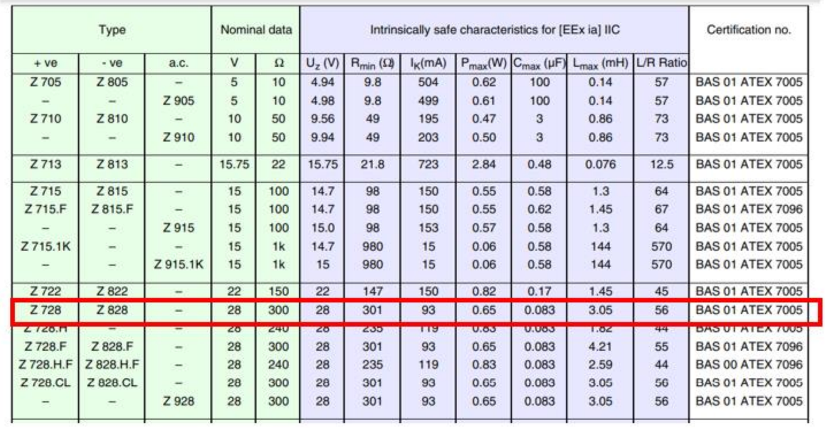
GROUP	CAPACITANCE (µF)	INDUCTANCE (mH)	OR L/R RATIO (µH/ohm)
Hazardous Area Terminals 2 w.r.t. 1 or 5 w.r.t. 4			
IIC	0.083	4.2	56
IIB*	0.65	12.6	210
IIA	2.15	33.6	444
I	3.76	53.7	668
Hazardous Area Terminals 3 w.r.t. 1 or 6 w.r.t 4			
IIC	100	12.8	2,438
IIB*	1,000	47.8	8,932
IIA	1,000	104.7	18,140
I	1,000	156.2	28,229
Hazardous Area Terminals 2 w.r.t. 3 or 5 w.r.t 6			
IIC	0.083	4.9	59
IIB*	0.65	20.0	222
IIA	2.15	40.9	469
I	3.76	59.1	710



Attribute	Value
Barrier Type	Galvanic Barrier
Number of Channels	1
Supply Voltage	20 → 35V dc
Module Type	Repeater power supply
Input Signal Type	Current
Output Signal Type	Current
Maximum Current	93mA
Minimum Operating Temperature	-20°C
Maximum Operating Temperature	+60°C
Maximum Voltage	28V
Safety Current Maximum	93mA
Safety Voltage Maximum	28 V
Hazardous Area Certification	ATEX
Series	MTL5500
Operating Temperature Range	-20 → +60°C

Appendix C: Ex i Barrier - Z728 (Pepperl+Fuchs, 2022).

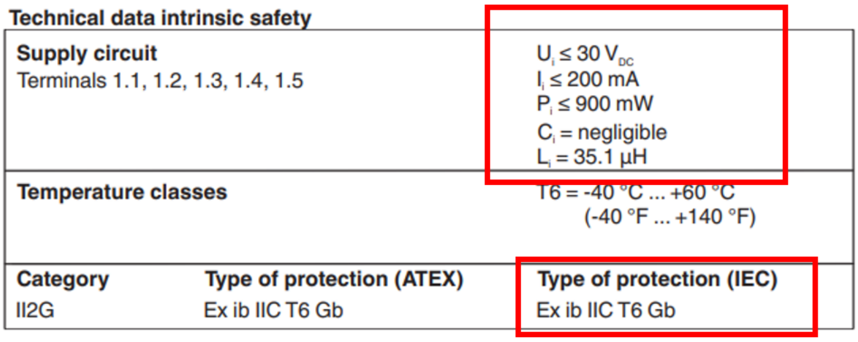
Data for application in connection with hazardous areas	
EU-type examination certificate	BAS 01 ATEX 7005
Marking	Ⓔ II (1)GD, I (M1) [Ex ia Ga] IIC, [Ex ia Da] IIIC, 0/1/2]



Type			Nominal data		Intrinsically safe characteristics for [EEx ia] IIC							Certification no.
+ ve	- ve	a.c.	V	Ω	U_z (V)	R_{min} (Ω)	I_K(mA)	P_{max}(W)	C_{max} (µF)	L_{max} (mH)	L/R Ratio	
Z 705	Z 805	–	5	10	4.94	9.8	504	0.62	100	0.14	57	BAS 01 ATEX 7005
–	–	Z 905	5	10	4.98	9.8	499	0.61	100	0.14	57	BAS 01 ATEX 7005
Z 710	Z 810	–	10	50	9.56	49	195	0.47	3	0.86	73	BAS 01 ATEX 7005
–	–	Z 910	10	50	9.94	49	203	0.50	3	0.86	73	BAS 01 ATEX 7005
Z 713	Z 813	–	15.75	22	15.75	21.8	723	2.84	0.48	0.076	12.5	BAS 01 ATEX 7005
Z 715	Z 815	–	15	100	14.7	98	150	0.55	0.58	1.3	64	BAS 01 ATEX 7005
Z 715.F	Z 815.F	–	15	100	14.7	98	150	0.55	0.62	1.45	67	BAS 01 ATEX 7096
–	–	Z 915	15	100	15.0	98	153	0.57	0.58	1.3	64	BAS 01 ATEX 7005
Z 715.1K	–	–	15	1k	14.7	980	15	0.06	0.58	144	570	BAS 01 ATEX 7005
–	–	Z 915.1K	15	1k	15	980	15	0.06	0.58	144	570	BAS 01 ATEX 7005
Z 722	Z 822	–	22	150	22	147	150	0.82	0.17	1.45	45	BAS 01 ATEX 7005
Z 728	Z 828	–	28	300	28	301	93	0.65	0.083	3.05	56	BAS 01 ATEX 7005
Z 728.H	–	–	28	240	28	235	119	0.83	0.083	1.82	44	BAS 01 ATEX 7005
Z 728.F	Z 828.F	–	28	300	28	301	93	0.65	0.083	4.21	55	BAS 01 ATEX 7096
Z 728.H.F	Z 828.H.F	–	28	240	28	235	119	0.83	0.083	2.59	44	BAS 00 ATEX 7096
Z 728.CL	Z 828.CL	–	28	300	28	301	93	0.65	0.083	3.05	56	BAS 01 ATEX 7005
–	–	Z 928	28	300	28	301	93	0.65	0.083	3.05	56	BAS 01 ATEX 7005

Appendix D: Digital Display - FA MCR-EX-FDS-I-I-OLP (Phoenix Contact, 2022a).

Voltage drop	≤ 1 V ≤ 3.9 V (with display lighting)
Input impedance	⊠ 50 Ω

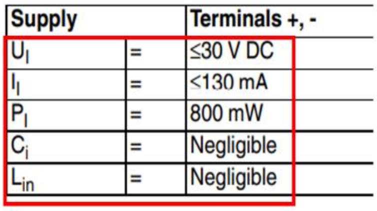


Technical data intrinsic safety

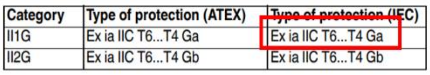
Supply circuit Terminals 1.1, 1.2, 1.3, 1.4, 1.5		$U_i \leq 30\ V_{DC}$ $I_i \leq 200$ mA $P_i \leq 900$ mW C_i = negligible $L_i = 35.1$ µH
Temperature classes		T6 = -40 °C ... +60 °C (-40 °F ... +140 °F)
Category II2G	**Type of protection (ATEX)** Ex ib IIC T6 Gb	**Type of protection (IEC)** Ex ib IIC T6 Gb

Appendix E: Temperature transducer - FA MCR(-EX)-HT-TS-I-OLP (Phoenix Contact, 2022b).

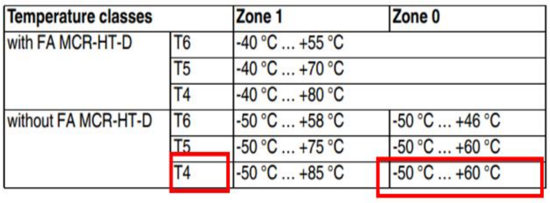
Supply voltage range	11 V DC ... 42 V DC (Standard)
	11 V DC ... 32 V DC (SIL active)
	11 V DC ... 30 V DC (Ex)



Supply		Terminals +, -
U_I	=	≤30 V DC
I_I	=	<130 mA
P_I	=	800 mW
C_i	=	Negligible
L_{in}	=	Negligible

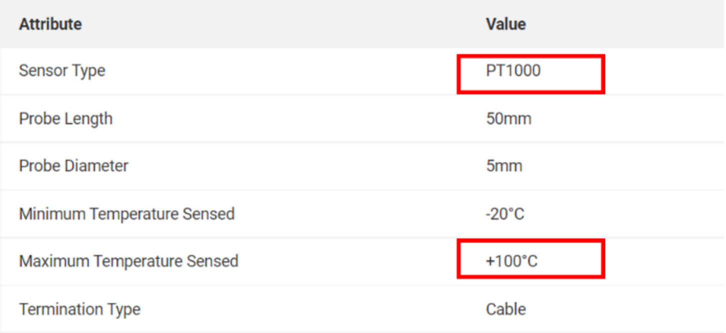


Category	Type of protection (ATEX)	Type of protection (IEC)
II1G	Ex ia IIC T6...T4 Ga	Ex ia IIC T6...T4 Ga
II2G	Ex ia IIC T6...T4 Gb	Ex ia IIC T6...T4 Gb



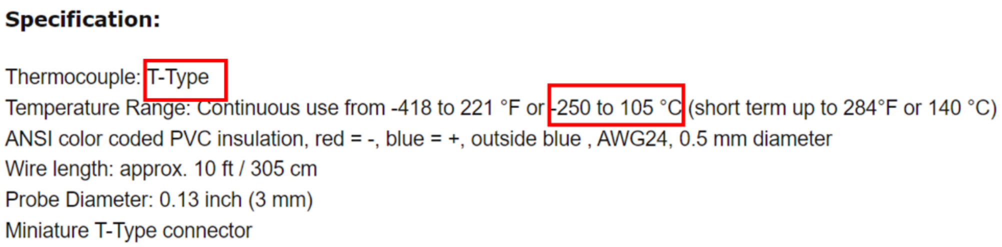
Temperature classes		Zone 1	Zone 0
with FA MCR-HT-D	T6	-40 °C ... +55 °C	
	T5	-40 °C ... +70 °C	
	T4	-40 °C ... +80 °C	
without FA MCR-HT-D	T6	-50 °C ... +58 °C	-50 °C ... +46 °C
	T5	-50 °C ... +75 °C	-50 °C ... +60 °C
	T4	-50 °C ... +85 °C	-50 °C ... +60 °C

Appendix F: Temperature transducer - FA MCR(-EX)-HT-TS-I-OLP (Phoenix Contact, 2022b).



Attribute	Value
Sensor Type	PT1000
Probe Length	50mm
Probe Diameter	5mm
Minimum Temperature Sensed	-20°C
Maximum Temperature Sensed	+100°C
Termination Type	Cable

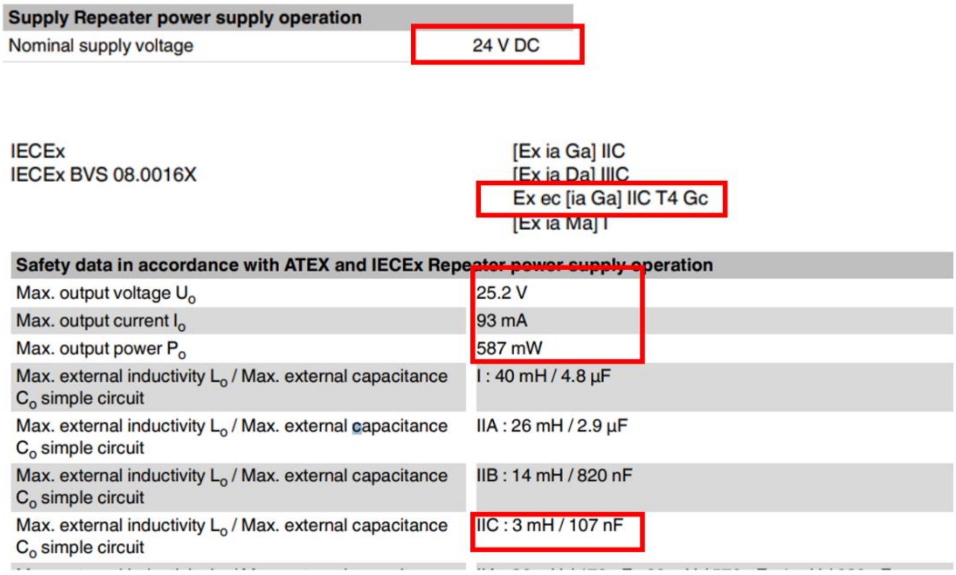
Appendix G: Thermocouple - T-type PVC Mini 10ft (Minnesota Measurement Instruments LLC., 2022).



Specification:

Thermocouple: T-Type
Temperature Range: Continuous use from -418 to 221 °F or -250 to 105 °C (short term up to 284°F or 140 °C)
ANSI color coded PVC insulation, red = -, blue = +, outside blue , AWG24, 0.5 mm diameter
Wire length: approx. 10 ft / 305 cm
Probe Diameter: 0.13 inch (3 mm)
Miniature T-Type connector

Appendix H: Ex i Barrier - MACX MCR-EX-SL-RPSSI-I(-SP) (PHOENIX CONTACT, 2022c).



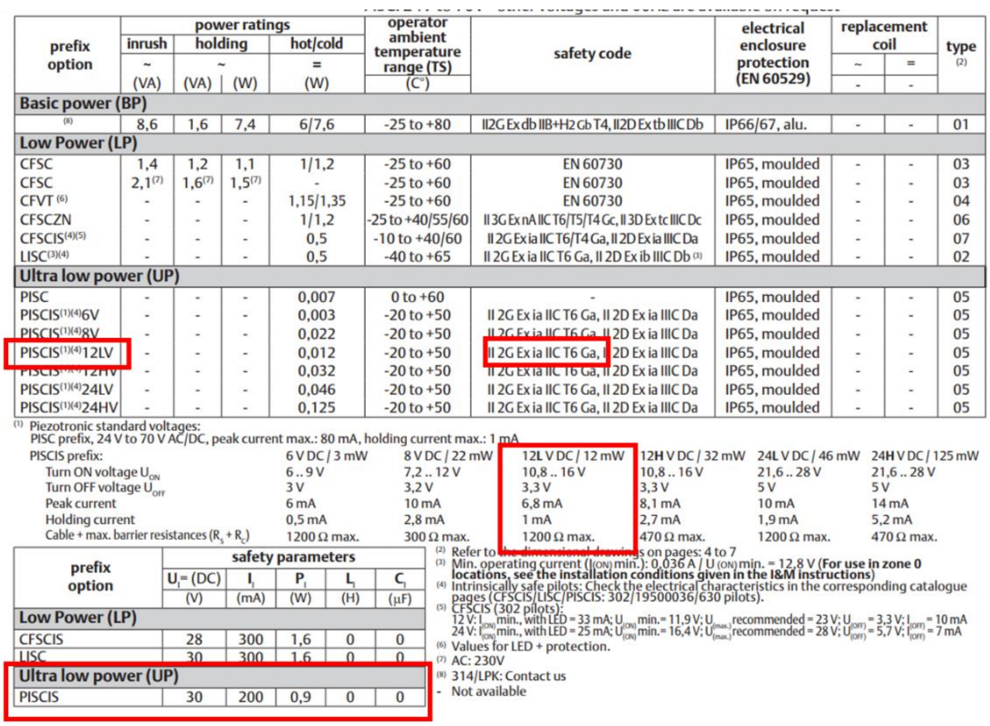
Supply Repeater power supply operation	
Nominal supply voltage	24 V DC

IECEx
IECEx BVS 08.0016X

[Ex ia Ga] IIC
[Ex ia Da] IIIC
Ex ec [ia Ga] IIC T4 Gc
[Ex ia Ma] I

Safety data in accordance with ATEX and IECEx Repeater power supply operation	
Max. output voltage U_o	25.2 V
Max. output current I_o	93 mA
Max. output power P_o	587 mW
Max. external inductivity L_o / Max. external capacitance C_o simple circuit	I : 40 mH / 4.8 µF
Max. external inductivity L_o / Max. external capacitance C_o simple circuit	IIA : 26 mH / 2.9 µF
Max. external inductivity L_o / Max. external capacitance C_o simple circuit	IIB : 14 mH / 820 nF
Max. external inductivity L_o / Max. external capacitance C_o simple circuit	IIC : 3 mH / 107 nF

Appendix I: Solenoid Valve - PISCIS 12LV (Emerson, 2021).



prefix option	power ratings inrush ~ (VA)	holding ~ (VA)	holding (W)	hot/cold = (W)	operator ambient temperature range (TS) (C°)	safety code	electrical enclosure protection (EN 60529)	replacement coil ~	replacement coil =	type (2)
Basic power (BP)										
(8)	8,6	1,6	7,4	6/7,6	-25 to +80	II2G Ex db IIB+H2 Gb T4, II2D Ex tb IIIC Db	IP66/67, alu.	-	-	01
Low Power (LP)										
CFSC	1,4	1,2	1,1	1/1,2	-25 to +60	EN 60730	IP65, moulded	-	-	03
CFSC	2,1(7)	1,6(7)	1,5(7)	-	-25 to +60	EN 60730	IP65, moulded	-	-	03
CFVT (6)	-	-	-	1,15/1,35	-25 to +60	EN 60730	IP65, moulded	-	-	04
CFSCZN	-	-	-	1/1,2	-25 to +40/55/60	II 3G Ex nA IIC T6/T5/T4 Gc, II 3D Ex tc IIIC Dc	IP65, moulded	-	-	06
CFSCIS(4)(5)	-	-	-	0,5	-10 to +40/60	II 2G Ex ia IIC T6/T4 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	07
LISC(3)(4)	-	-	-	0,5	-40 to +65	II 2G Ex ia IIC T6 Ga, II 2D Ex ib IIIC Db (3)	IP65, moulded	-	-	02
Ultra low power (UP)										
PISC	-	-	-	0,007	0 to +60	-	IP65, moulded	-	-	05
PISCIS(1)(4)6V	-	-	-	0,003	-20 to +50	II 2G Ex ia IIC T6 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	05
PISCIS(1)(4)8V	-	-	-	0,022	-20 to +50	II 2G Ex ia IIC T6 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	05
PISCIS(1)(4)12LV	-	-	-	0,012	-20 to +50	II 2G Ex ia IIC T6 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	05
PISCIS(1)(4)12HV	-	-	-	0,032	-20 to +50	II 2G Ex ia IIC T6 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	05
PISCIS(1)(4)24LV	-	-	-	0,046	-20 to +50	II 2G Ex ia IIC T6 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	05
PISCIS(1)(4)24HV	-	-	-	0,125	-20 to +50	II 2G Ex ia IIC T6 Ga, II 2D Ex ia IIIC Da	IP65, moulded	-	-	05

(1) Piezotronic standard voltages:
PISC prefix, 24 V to 70 V AC/DC, peak current max.: 80 mA, holding current max.: 1 mA

PISCIS prefix:	6 V DC / 3 mW	8 V DC / 22 mW	12**L** V DC / 12 mW	12**H** V DC / 32 mW	24**L** V DC / 46 mW	24**H** V DC / 125 mW
Turn ON voltage U_{ON}	6 .. 9 V	7,2 .. 12 V	10,8 .. 16 V	10,8 .. 16 V	21,6 .. 28 V	21,6 .. 28 V
Turn OFF voltage U_{OFF}	3 V	3,2 V	3,3 V	3,3 V	5 V	5 V
Peak current	6 mA	10 mA	6,8 mA	8,1 mA	10 mA	14 mA
Holding current	0,5 mA	2,8 mA	1 mA	2,7 mA	1,9 mA	5,2 mA
Cable + max. barrier resistances ($R_S + R_C$)	1200 Ω max.	300 Ω max.	1200 Ω max.	470 Ω max.	1200 Ω max.	470 Ω max.

prefix option	safety parameters U_i = (DC) (V)	I_i (mA)	P_i (W)	L_i (H)	C_i (µF)
Low Power (LP)					
CFSCIS	28	300	1,6	0	0
LISC	30	300	1,6	0	0
Ultra low power (UP)					
PISCIS	30	200	0,9	0	0

(2) Refer to the dimensional drawings on pages: 4 to 7

(3) Min. operating current ($I_{(ON)}$ min.): 0,036 A / $U_{(ON)}$ min. = 12,8 V (**For use in zone 0 locations, see the installation conditions given in the I&M instructions**)

(4) Intrinsically safe pilots: Check the electrical characteristics in the corresponding catalogue pages (CFSCIS/LISC/PISCIS: 302/19500036/630 pilots).

(5) CFSCIS (302 pilots):
12 V: $I_{(ON)}$ min., with LED = 33 mA; $U_{(ON)}$ min.= 11,9 V; $U_{(max.)}$ recommended = 23 V; $U_{(OFF)}$ = 3,3 V; $I_{(OFF)}$ = 10 mA
24 V: $I_{(ON)}$ min., with LED = 25 mA; $U_{(ON)}$ min.= 16,4 V; $U_{(max.)}$ recommended = 28 V; $U_{(OFF)}$ = 5,7 V; $I_{(OFF)}$ = 7 mA

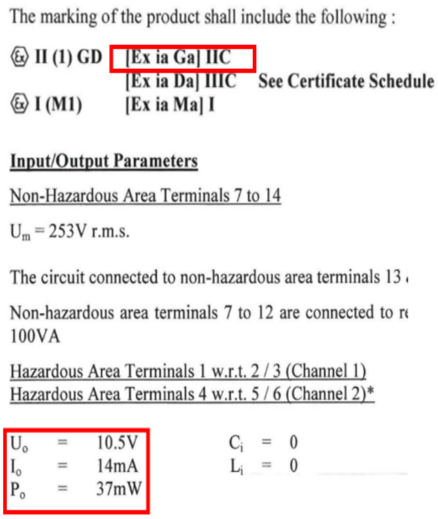
(6) Values for LED + protection.

(7) AC: 230V

(8) 314/LPK: Contact us

\- Not available

Appendix J: Ex i Barrier - MTL 5511 (Baseefa, 2017; RS PRO, 2022b).



The marking of the product shall include the following :

Ex II (1) GD [Ex ia Ga] IIC
[Ex ia Da] IIIC See Certificate Schedule
Ex I (M1) [Ex ia Ma] I

Input/Output Parameters

Non-Hazardous Area Terminals 7 to 14

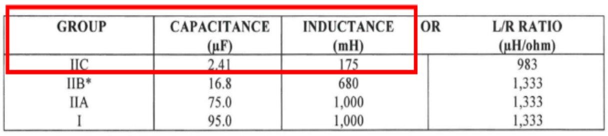
$U_m = 253V$ r.m.s.

The circuit connected to non-hazardous area terminals 13

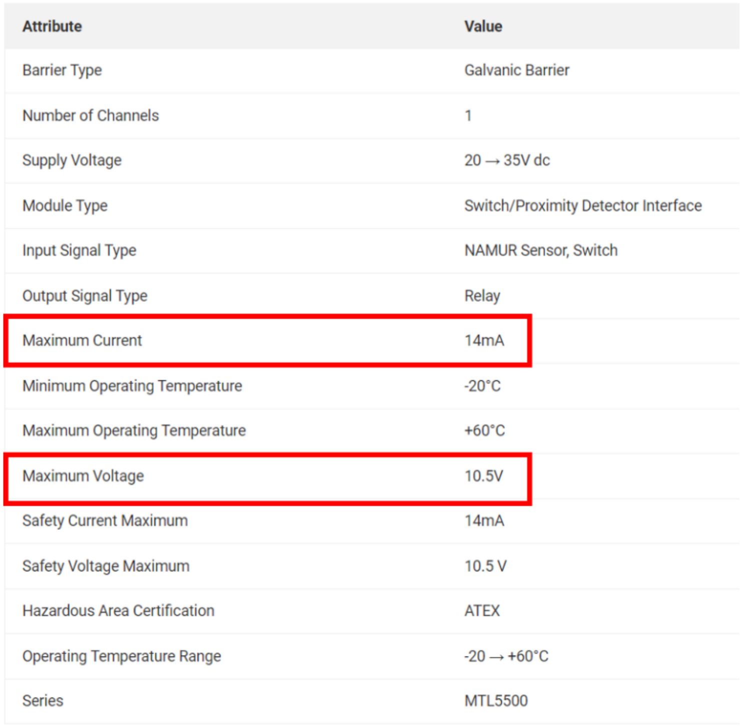
Non-hazardous area terminals 7 to 12 are connected to r
100VA

Hazardous Area Terminals 1 w.r.t. 2 / 3 (Channel 1)
Hazardous Area Terminals 4 w.r.t. 5 / 6 (Channel 2)*

$U_o = 10.5V$ $C_i = 0$
$I_o = 14mA$ $L_i = 0$
$P_o = 37mW$



GROUP	CAPACITANCE (µF)	INDUCTANCE (mH)	OR	L/R RATIO (µH/ohm)
IIC	2.41	175		983
IIB*	16.8	680		1,333
IIA	75.0	1,000		1,333
I	95.0	1,000		1,333



Attribute	Value
Barrier Type	Galvanic Barrier
Number of Channels	1
Supply Voltage	20 → 35V dc
Module Type	Switch/Proximity Detector Interface
Input Signal Type	NAMUR Sensor, Switch
Output Signal Type	Relay
Maximum Current	14mA
Minimum Operating Temperature	-20°C
Maximum Operating Temperature	+60°C
Maximum Voltage	10.5V
Safety Current Maximum	14mA
Safety Voltage Maximum	10.5 V
Hazardous Area Certification	ATEX
Operating Temperature Range	-20 → +60°C
Series	MTL5500

Appendix K: Table A.2 of IEC 60079-11 for the voltages of 25.2 V and 28 V (IEC, 2012).

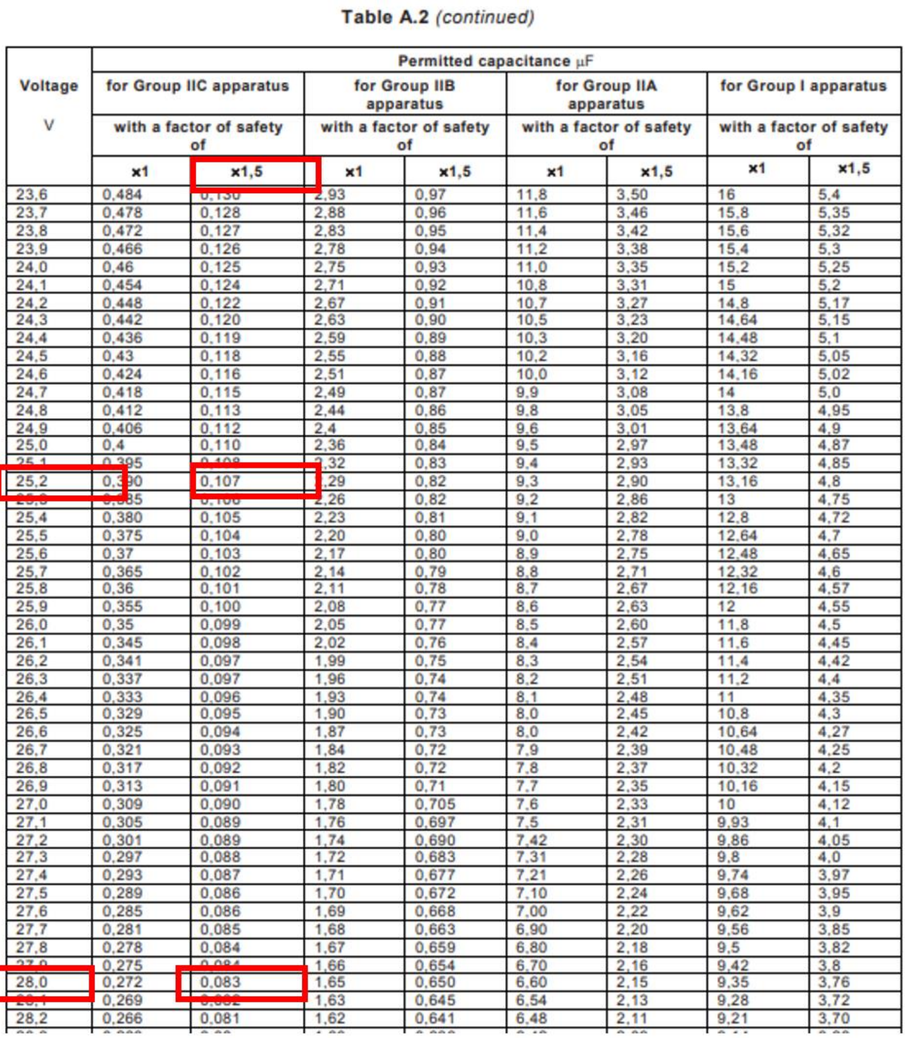
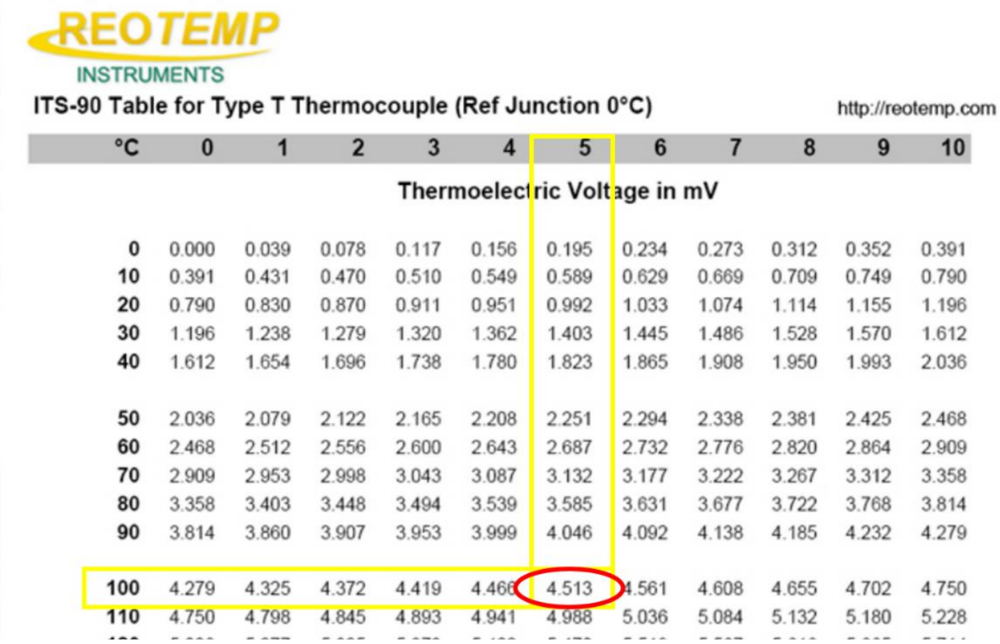


Table A.2 *(continued)*

Voltage V	Permitted capacitance µF							
	for Group IIC apparatus		for Group IIB apparatus		for Group IIA apparatus		for Group I apparatus	
	with a factor of safety of		with a factor of safety of		with a factor of safety of		with a factor of safety of	
	×1	×1,5	×1	×1,5	×1	×1,5	×1	×1,5
23,6	0,484	0,130	2,93	0,97	11,8	3,50	16	5,4
23,7	0,478	0,128	2,88	0,96	11,6	3,46	15,8	5,35
23,8	0,472	0,127	2,83	0,95	11,4	3,42	15,6	5,32
23,9	0,466	0,126	2,78	0,94	11,2	3,38	15,4	5,3
24,0	0,46	0,125	2,75	0,93	11,0	3,35	15,2	5,25
24,1	0,454	0,124	2,71	0,92	10,8	3,31	15	5,2
24,2	0,448	0,122	2,67	0,91	10,7	3,27	14,8	5,17
24,3	0,442	0,120	2,63	0,90	10,5	3,23	14,64	5,15
24,4	0,436	0,119	2,59	0,89	10,3	3,20	14,48	5,1
24,5	0,43	0,118	2,55	0,88	10,2	3,16	14,32	5,05
24,6	0,424	0,116	2,51	0,87	10,0	3,12	14,16	5,02
24,7	0,418	0,115	2,49	0,87	9,9	3,08	14	5,0
24,8	0,412	0,113	2,44	0,86	9,8	3,05	13,8	4,95
24,9	0,406	0,112	2,4	0,85	9,6	3,01	13,64	4,9
25,0	0,4	0,110	2,36	0,84	9,5	2,97	13,48	4,87
25,1	0,395	0,108	2,32	0,83	9,4	2,93	13,32	4,85
25,2	0,390	0,107	2,29	0,82	9,3	2,90	13,16	4,8
25,3	0,385	0,106	2,26	0,82	9,2	2,86	13	4,75
25,4	0,380	0,105	2,23	0,81	9,1	2,82	12,8	4,72
25,5	0,375	0,104	2,20	0,80	9,0	2,78	12,64	4,7
25,6	0,37	0,103	2,17	0,80	8,9	2,75	12,48	4,65
25,7	0,365	0,102	2,14	0,79	8,8	2,71	12,32	4,6
25,8	0,36	0,101	2,11	0,78	8,7	2,67	12,16	4,57
25,9	0,355	0,100	2,08	0,77	8,6	2,63	12	4,55
26,0	0,35	0,099	2,05	0,77	8,5	2,60	11,8	4,5
26,1	0,345	0,098	2,02	0,76	8,4	2,57	11,6	4,45
26,2	0,341	0,097	1,99	0,75	8,3	2,54	11,4	4,42
26,3	0,337	0,097	1,96	0,74	8,2	2,51	11,2	4,4
26,4	0,333	0,096	1,93	0,74	8,1	2,48	11	4,35
26,5	0,329	0,095	1,90	0,73	8,0	2,45	10,8	4,3
26,6	0,325	0,094	1,87	0,73	8,0	2,42	10,64	4,27
26,7	0,321	0,093	1,84	0,72	7,9	2,39	10,48	4,25
26,8	0,317	0,092	1,82	0,72	7,8	2,37	10,32	4,2
26,9	0,313	0,091	1,80	0,71	7,7	2,35	10,16	4,15
27,0	0,309	0,090	1,78	0,705	7,6	2,33	10	4,12
27,1	0,305	0,089	1,76	0,697	7,5	2,31	9,93	4,1
27,2	0,301	0,089	1,74	0,690	7,42	2,30	9,86	4,05
27,3	0,297	0,088	1,72	0,683	7,31	2,28	9,8	4,0
27,4	0,293	0,087	1,71	0,677	7,21	2,26	9,74	3,97
27,5	0,289	0,086	1,70	0,672	7,10	2,24	9,68	3,95
27,6	0,285	0,086	1,69	0,668	7,00	2,22	9,62	3,9
27,7	0,281	0,085	1,68	0,663	6,90	2,20	9,56	3,85
27,8	0,278	0,084	1,67	0,659	6,80	2,18	9,5	3,82
27,9	0,275	0,084	1,66	0,654	6,70	2,16	9,42	3,8
28,0	0,272	0,083	1,65	0,650	6,60	2,15	9,35	3,76
28,1	0,269	0,082	1,63	0,645	6,54	2,13	9,28	3,72
28,2	0,266	0,081	1,62	0,641	6,48	2,11	9,21	3,70

Appendix L: Type T Thermocouple Table to Obtain Voltage at 105 °C (REOTEMP Instrument Corporation., 2011).



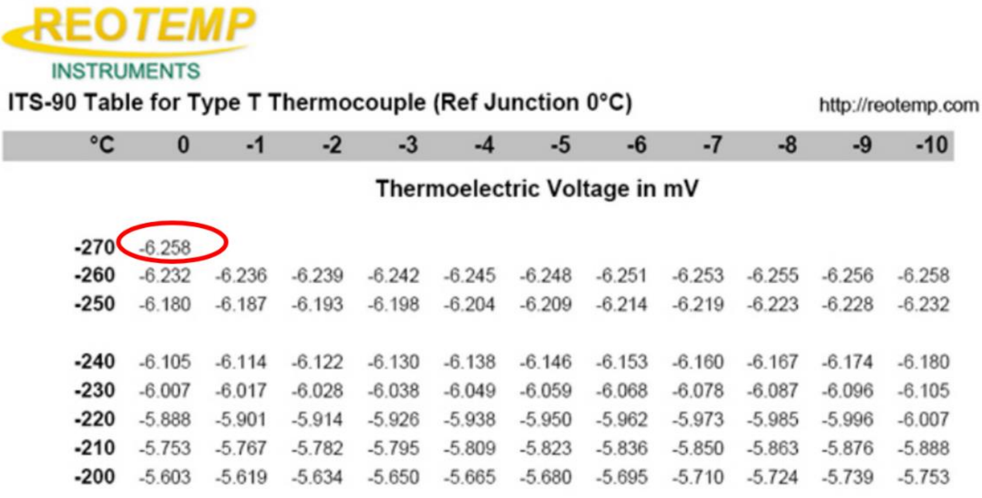
REOTEMP INSTRUMENTS

ITS-90 Table for Type T Thermocouple (Ref Junction 0°C) http://reotemp.com

Thermoelectric Voltage in mV

°C	0	1	2	3	4	5	6	7	8	9	10
0	0.000	0.039	0.078	0.117	0.156	0.195	0.234	0.273	0.312	0.352	0.391
10	0.391	0.431	0.470	0.510	0.549	0.589	0.629	0.669	0.709	0.749	0.790
20	0.790	0.830	0.870	0.911	0.951	0.992	1.033	1.074	1.114	1.155	1.196
30	1.196	1.238	1.279	1.320	1.362	1.403	1.445	1.486	1.528	1.570	1.612
40	1.612	1.654	1.696	1.738	1.780	1.823	1.865	1.908	1.950	1.993	2.036
50	2.036	2.079	2.122	2.165	2.208	2.251	2.294	2.338	2.381	2.425	2.468
60	2.468	2.512	2.556	2.600	2.643	2.687	2.732	2.776	2.820	2.864	2.909
70	2.909	2.953	2.998	3.043	3.087	3.132	3.177	3.222	3.267	3.312	3.358
80	3.358	3.403	3.448	3.494	3.539	3.585	3.631	3.677	3.722	3.768	3.814
90	3.814	3.860	3.907	3.953	3.999	4.046	4.092	4.138	4.185	4.232	4.279
100	4.279	4.325	4.372	4.419	4.466	4.513	4.561	4.608	4.655	4.702	4.750
110	4.750	4.798	4.845	4.893	4.941	4.988	5.036	5.084	5.132	5.180	5.228

Appendix M: Type T Thermocouple Table to Obtain Voltage at -270 °C (REOTEMP Instrument Corporation., 2011).



REOTEMP INSTRUMENTS

ITS-90 Table for Type T Thermocouple (Ref Junction 0°C) http://reotemp.com

Thermoelectric Voltage in mV

°C	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
-270	-6.258										
-260	-6.232	-6.236	-6.239	-6.242	-6.245	-6.248	-6.251	-6.253	-6.255	-6.256	-6.258
-250	-6.180	-6.187	-6.193	-6.198	-6.204	-6.209	-6.214	-6.219	-6.223	-6.228	-6.232
-240	-6.105	-6.114	-6.122	-6.130	-6.138	-6.146	-6.153	-6.160	-6.167	-6.174	-6.180
-230	-6.007	-6.017	-6.028	-6.038	-6.049	-6.059	-6.068	-6.078	-6.087	-6.096	-6.105
-220	-5.888	-5.901	-5.914	-5.926	-5.938	-5.950	-5.962	-5.973	-5.985	-5.996	-6.007
-210	-5.753	-5.767	-5.782	-5.795	-5.809	-5.823	-5.836	-5.850	-5.863	-5.876	-5.888
-200	-5.603	-5.619	-5.634	-5.650	-5.665	-5.680	-5.695	-5.710	-5.724	-5.739	-5.753

Appendix N: Table A.2 of IEC 60079-11 for the voltage of 10.5 V (IEC, 2012).

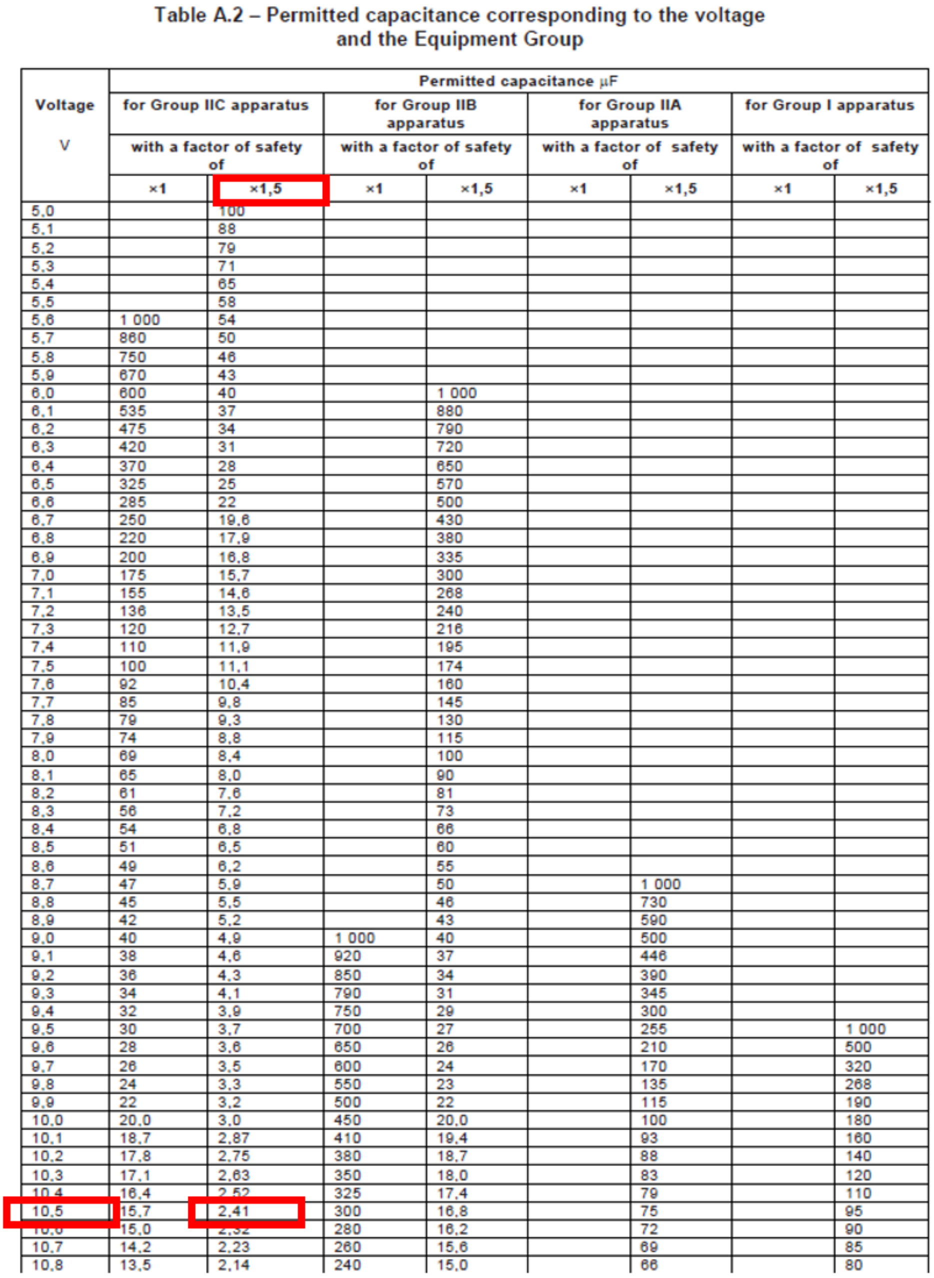


Table A.2 – Permitted capacitance corresponding to the voltage and the Equipment Group

Voltage V	Permitted capacitance µF							
	for Group IIC apparatus		for Group IIB apparatus		for Group IIA apparatus		for Group I apparatus	
	with a factor of safety of		with a factor of safety of		with a factor of safety of		with a factor of safety of	
	×1	×1,5	×1	×1,5	×1	×1,5	×1	×1,5
5,0		100						
5,1		88						
5,2		79						
5,3		71						
5,4		65						
5,5		58						
5,6	1 000	54						
5,7	860	50						
5,8	750	46						
5,9	670	43						
6,0	600	40		1 000				
6,1	535	37		880				
6,2	475	34		790				
6,3	420	31		720				
6,4	370	28		650				
6,5	325	25		570				
6,6	285	22		500				
6,7	250	19,6		430				
6,8	220	17,9		380				
6,9	200	16,8		335				
7,0	175	15,7		300				
7,1	155	14,6		268				
7,2	136	13,5		240				
7,3	120	12,7		216				
7,4	110	11,9		195				
7,5	100	11,1		174				
7,6	92	10,4		160				
7,7	85	9,8		145				
7,8	79	9,3		130				
7,9	74	8,8		115				
8,0	69	8,4		100				
8,1	65	8,0		90				
8,2	61	7,6		81				
8,3	56	7,2		73				
8,4	54	6,8		66				
8,5	51	6,5		60				
8,6	49	6,2		55				
8,7	47	5,9		50		1 000		
8,8	45	5,5		46		730		
8,9	42	5,2		43		590		
9,0	40	4,9	1 000	40		500		
9,1	38	4,6	920	37		446		
9,2	36	4,3	850	34		390		
9,3	34	4,1	790	31		345		
9,4	32	3,9	750	29		300		
9,5	30	3,7	700	27		255		1 000
9,6	28	3,6	650	26		210		500
9,7	26	3,5	600	24		170		320
9,8	24	3,3	550	23		135		268
9,9	22	3,2	500	22		115		190
10,0	20,0	3,0	450	20,0		100		180
10,1	18,7	2,87	410	19,4		93		160
10,2	17,8	2,75	380	18,7		88		140
10,3	17,1	2,63	350	18,0		83		120
10,4	16,4	2,52	325	17,4		79		110
10,5	15,7	2,41	300	16,8		75		95
10,6	15,0	2,32	280	16,2		72		90
10,7	14,2	2,23	260	15,6		69		85
10,8	13,5	2,14	240	15,0		66		80