SAFETY

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1. Introduction

The interactions between the design and application of instrumentation and safety are many and diverse. The correct utilization of instrumentation for monitoring and control reduces risk. An obvious example is a fire detection and control system, but even a simple cistern control which prevents a water tank from overflowing affects overall safety. Any instrumentation which contributes to maintaining the designed status of an installation can arguably affect safety. However, instrumentation can increase the danger in an installation, usually by being incorrectly designed or used. The principal direct risks from electrical instrumentation are electrocution and the possibility of causing a fire or explosion by interaction between the electricity and flammable materials, which range from various insulating materials used on cables to the more sensitive oxygen-enriched hydrogen atmosphere of a badly ventilated battery charging room. Some aspects of the safety of lasers and the risks from radiation are dealt with elsewhere in this reference book, Part 3, Chapters 21, 22, and 24. Toxic materials should also be considered (see *Substances Hazardous to Health* in the References). These risks pale into insignificance when compared with the full range of possibilities of misapplying instrumentation to a process plant, but nevertheless, in an overall safety analysis all risks must be minimized.

It is important to recognize that nowhere is absolute safety achievable, and that the aim is to achieve a socially acceptable level of safety. Quite what level has to be achieved is not well defined; it is perhaps sufficient to say that people are even more reluctant to be killed at work than elsewhere, and hence the level of safety must be higher than is generally accepted. For example, the risk level accepted by a young man riding a motorcycle for pleasure would not be acceptable to a process operator in a petrochemical plant. There are similar problems in determining how much financial expenditure is justified in achieving safety.

As well as the moral responsibilities implicit in not wishing to harm fellow mortals there are, in the majority of countries, strong legal sanctions, both civil and criminal, which can be used to encourage all designers to be careful. In the United Kingdom, the Health and Safety at Work Act 1974, together with the Electricity Regulations, provides a framework for prosecuting anyone who carelessly puts at risk any human being, including himself. (In the United States, the same functions derive from the Occupational Safety and Health Administration, part of the federal government, with similar agencies in each state and some municipal authorities.) The Act places responsibilities on manufacturers, users, and individuals in some considerable detail, and the requirements are applied in almost all circumstances which can conceivably be regarded as work. For example, manufacturers are required to sell only equipment which is safe for its intended use, test it to check that it is safe, provide adequate installation instructions and be aware of the "state of the art." The Act was derived from the Robins Report, which is a very readable, well-argued discussion document which sets a reasonable background to the whole subject of industrial safety. The Act lays great stress on the need to recognize, record, and evaluate levels of danger and the methods of reducing the risk to an acceptable level, and consequently, there is a need for adequate documentation on the safety aspects of any installation. In the majority of installations the enforcing organization is the Factory Inspectorate, who have awesome powers to enter, inspect, and issue various levels of injunction to prevent hazards. Fortunately, the majority of factory inspectors recognize that they do not have quite the infinite wisdom required to do their job, and proceed by a series of negotiated compromises to achieve a reasonable level of safety without having to resort to extreme measures. It is important to realize that the legal requirement in most installations is to take "adequate precautions." However, in the real world the use of certified equipment applied to the relevant British Standard Code of Practice is readily understood, easy to document, and defensible, and is consequently the solution most frequently adopted. In the United States, the National Electrical Code, promulgated by the National Fire Prevention Association, is the controlling set of specifications for electrical safety.

In addition, the reader is referred to ANSI/ISA standards as follows:

ANSI/ISA84.01-1966 "Application of Safety Instrumented Systems to the Process Industries".

ANSI/ISA91.01-1995 "Identification of Emergency Shutdown Systems & Controls That Are Critical to Maintain Safety in the Process Industries".

ANSI/ISA RP12.6-1995 "Recommended Practice for Hazardous (Classified) Locations...".

2. Electrocution risk

In designing any electrical equipment it is necessary to reduce the risk of electrocution as far as possible. Many sectors of industry have special standards of construction and inspection combined with certification schemes to take into account their particular risks. For example, electro- medical equipment has to meet stringent standards, particularly in cases where sensors are inserted in the body.

It is useful to try to assess the equivalent circuit of the human body, and there are a large number of references on the subject which show quite wide discrepancies between experimental results. A few facts appear to be common. Figure 33.1 shows the generally accepted figures for the ability to detect the presence of current, and the level of current which causes muscular contraction, although it must again be stressed that individuals vary considerably. Muscular contraction is a fascinating process, involving an electrical impulse signal releasing a chemical which causes the mechanical movement. The currents required are about 15 mA, and to maintain a muscle contracted it requires about 10 pulses/s. When a direct current is applied it causes the muscle to contract once and then relax; consequently direct current tends to be safer. However, at higher levels direct current does cause paralysis, since variation in body resistance due to burns, etc., causes the current to fluctuate and hence contract the muscles. The 50-60 Hz normally used for domestic supplies is ideally chosen to make certain that paralysis occurs.

Body resistance is quite a complex picture, since much of the initial resistance is in the skin. A dry outer layer of skin, particularly in the areas which are calloused, gives quite high resistance at low voltage, typically 10-100kΩ, but this falls to 1 kΩ at

500 V. Other, more sensitive areas of the body, such as elbows, have a much lower resistance (2 k Ω). Once the outer layer of skin is broken, the layer immediately below it has many capillaries filled with body fluid and has very low resistance. The bulk resistance of humans is mostly concentrated in the limbs and is taken to be 500 Ω. Figure 33.2 shows one curve of body resistance and a possible equivalent circuit of a human being at low voltage when the skin resistance is converted to a threshold voltage.

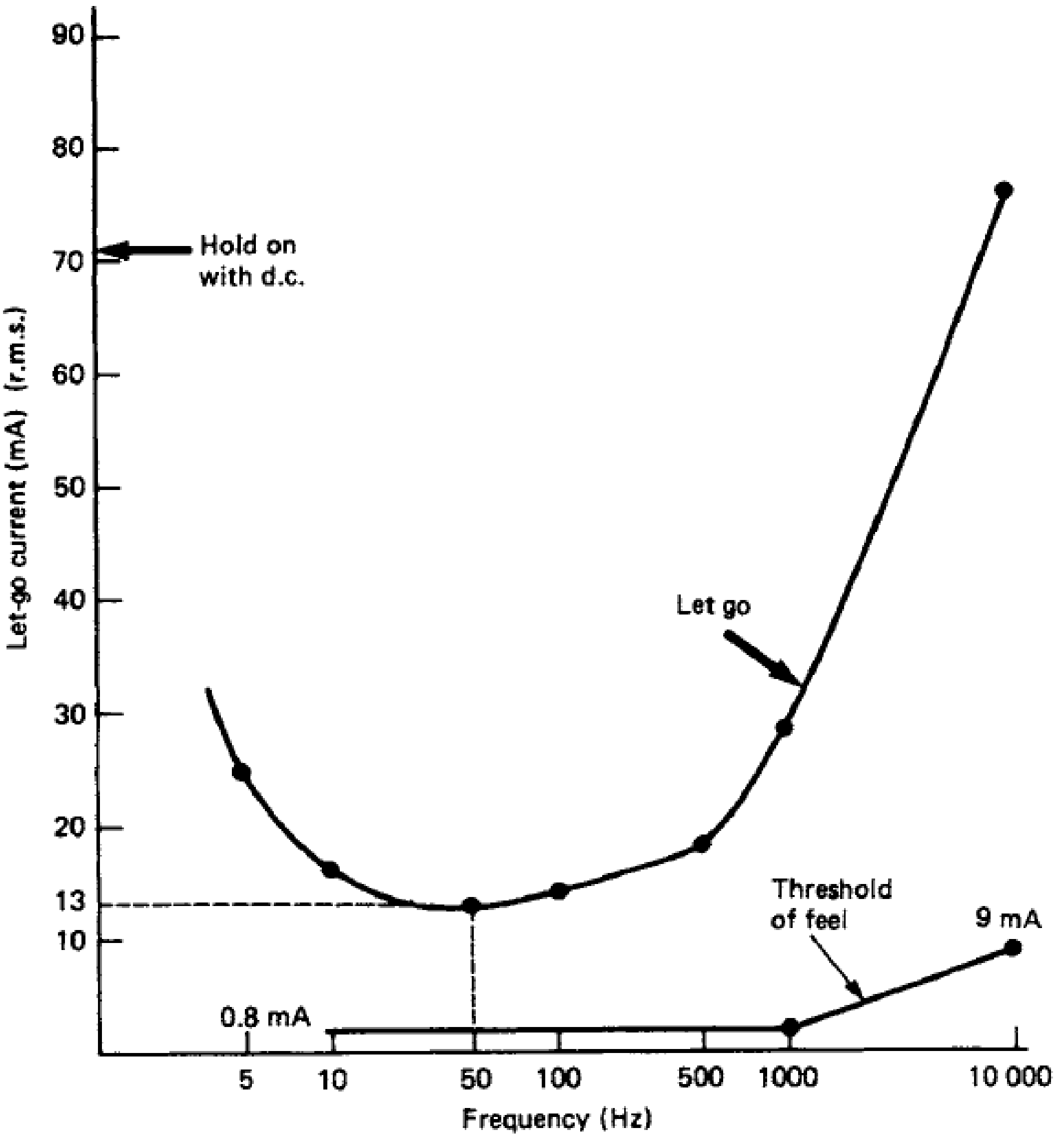

Figure 1. Variation with frequency of let-go current and threshold of feel

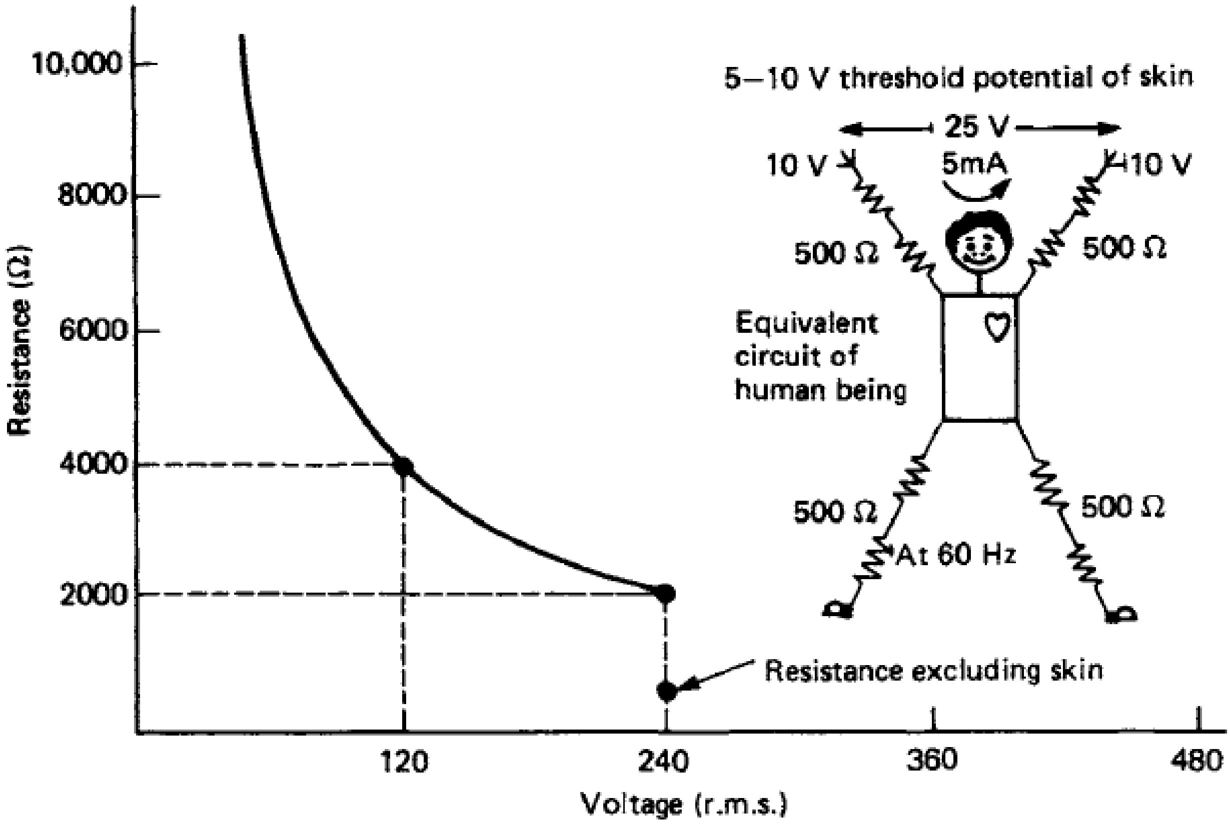

Figure 2 (a) Apparent increase of body resistance (hand to hand--dry) with reduction of voltage; (b) equivalent circuit of human being

The process of killing someone directly by electricity is also quite complex. Generally, it is agreed that a current of 20-30mA applied to the right muscles of the heart would stop it functioning. Just how to persuade this current to flow in the practical problem of hand-to-hand electrocution is widely discussed. Some sources suggest currents of the order of 10A are necessary and others suggest there is a possibility of 40mA being enough. The level of current is further complicated because there is a time factor involved in stopping the heart, and some protection techniques rely at least partially on this effect to achieve safety. The change is quite dramatic. For example, one reference suggests that heart fibrillation is possible at 50 mA if applied for 5 s and 1 A if applied for 10 m s. There seems little doubt, however, that the conventional 250 V 50 Hz supply used in the United Kingdom is potentially lethal, and that standing chest deep in a swimming pool with a defective under-water low-voltage lighting system is one very effective way of shortening a human being's life span.

The majority of modern instrumentation systems operate at 30 V or below, which to most people is not even detectable and is generally well below the accepted level of paralysis. There are, however, circumstances where even this voltage might be dangerous. Undersea divers are obviously at risk, but people working in confined hot spaces where sweat and moisture are high also need special care. Once the skin is broken, the danger is increased, and the possibilities of damage caused by electrodes fastened to the skull are so horrendous that only the highest level of expertise in the design of this type of equipment is acceptable. However, for the majority of conventional apparatus a level of 30 V is usable and is generally regarded as adequately safe. The design problem is usually to prevent the mains supply from becoming accessible, either by breaking through to the low-voltage circuity, making the chassis live, or some other defect developing.

2.1 Earthing (grounding) and bonding

It follows from the previous discussion that if all objects which can conduct electricity are bonded together so that an individual cannot become connected between two points with a potential difference greater than 30 V, then the installation is probably safe. The pattern of earthing (grounding) and bonding varies slightly with the type of electrical supply available. Figure 33.3 illustrates the situation which arises if U.K. practice is followed. The supply to the instrument system is derived from the conventional 440 V three-phase neutral earthed distribution system, the live side being fused. A chassis connection to the neutral bond provides an adequate fault path to clear the fuse without undue elevation of the instrument chassis. All the adjacent metalwork, including the handrail, is bonded to the instrument chassis and returned separately (usually by several routes) to the neutral star point. Any personnel involved in the loop as illustrated are safe, because they are in parallel with the low-resistance bond XX' which has no significant resistance. If the bond XX' were broken then the potential of the handrail would be determined by the ill-defined resistance of the earth (ground) path. The instrument system would be elevated by the effects of the transient fault current in the chassis earth (ground) return, and the resultant potential difference across the human being might be uncomfortably high.

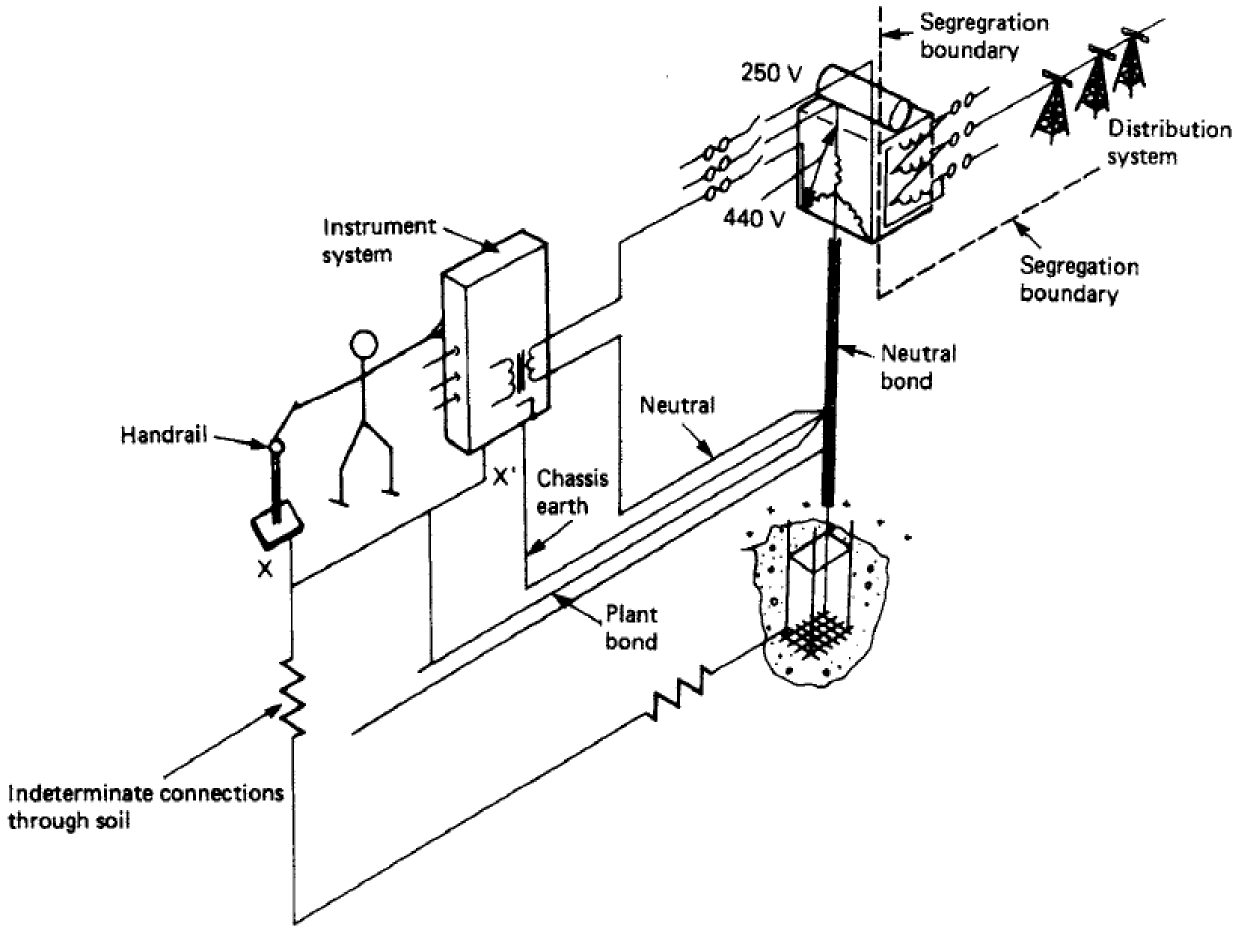

Figure 3 Normal UK installation with bonded neutral.

The fundamental earthing (grounding) requirements of a safe system are therefore that there should be an adequate fault return path to operate any protective device which is incorporated, and that all parts of the plant should be bonded together to minimize potential differences.

There are, however, a number of circumstances where earthing (grounding) is not used as a means of ensuring protection. Large quantities of domestic portable equipment are protected by "double insulation," in which the primary insulation is reinforced by secondary insulation and there would need to be a coincident breakdown of two separate layers of insulation for danger to arise. Similarly, some areas for work on open equipment are made safe by being constructed entirely of insulating material, and the supplies derived from isolating transformers so as to reduce the risk of electrocution.

Where the environment is harsh or cables are exposed to rough treatment there is always the need to reduce working voltage, and there are many variants on the method of electrical protection, all of which have their particular advantages. Figure 33.4 shows the type of installation which is widely used in wet situations and, provided that the tools and cables are subject to frequent inspection, offers a reasonable level of protection.

The transformer is well designed to reduce the available voltage to l l0V, which is then center tapped to earth (ground), which further reduces the fault voltage to earth (ground) to 55 V. Both phases of the supply are fused, but a more sensitive detection of fault current is achieved by using an earth (ground) leakage circuit breaker (ELCB) which monitors the balance of the phase currents and if they differ by more than 20 mA triggers the circuit breaker. This sensitive fast detection combined with the lower voltage produces a reasonably safe system for most circumstances.

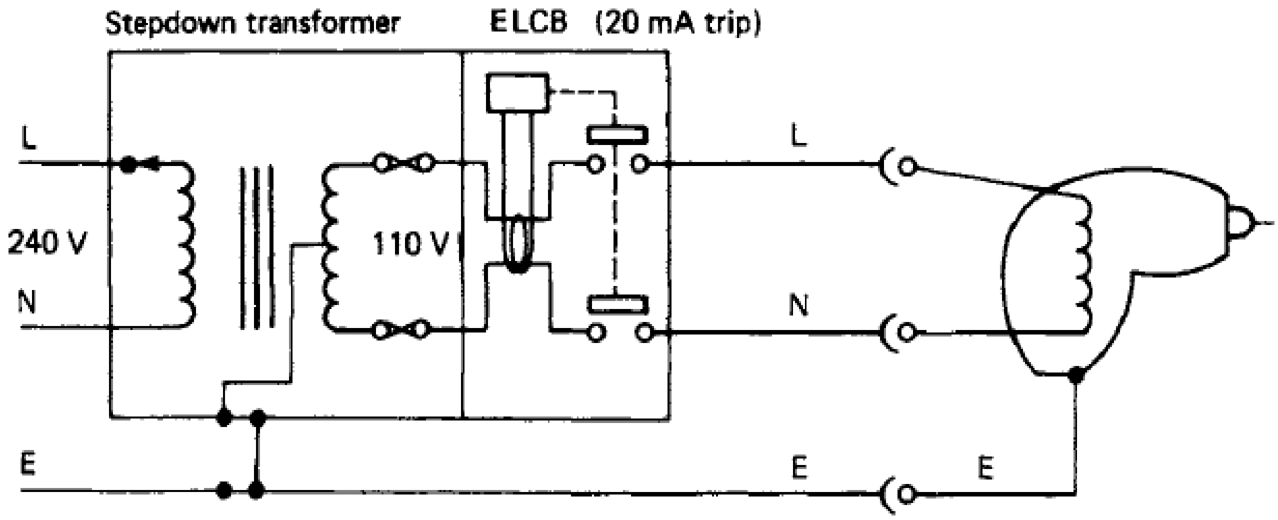

Figure 4 Isolating transformer supplying 110 Vcenter tapped to earth (ground) with earth (ground) leakage circuit breaker

There are therefore many different techniques for reducing electrical shock risk. They all require consideration to be given to the nature of the supply, the design of the equipment, the environment, use, the method of installation, and the frequency and effectiveness of inspection. These factors all interact so strongly that any safe installation must consider all these aspects.

3. Flammable atmospheres

A large proportion of process control instrumentation is used in the petrochemical industry, where there is a possible risk of explosion if the equipment comes into contact with a flammable atmosphere. In practice, similar risks occur in all petrochemical and gas distribution sites, printing works, paint-spray booths, and the numerous small stores of varnish, paint, and encapsulating compounds which exist on most manufacturing sites.

The other related risk is that of dust explosions, which tend to attract less interest but are possibly more important. Almost any finely divided material is capable of being burned (most people are familiar with the burning steelwool demonstration) and, in particular, finely divided organic substances such as flour, sugar, and animal feedstuffs all readily ignite. Dust explosions tend to be dramatic, since a small explosion normally raises a further dust cloud and the explosion rolls on to consume the available fuel. However, in general dusts need considerably more energy than gas to ignite them (milli joules rather than micro joules) and are usually ignited by temperatures in the region of 200^{o}C Frequently the instrumentation problem is solved by using T4 (135^{o}C) temperature- classified intrinsically safe equipment in a dust-tight enclosure.

The basic mechanism of a gas explosion requires three constituents: the flammable gas, oxygen (usually in the form of air), and a source of ignition (in this context an electrical spark or hot surface). A gas-air mixture must be mixed in certain proportions to be flammable. The boundary conditions are known as the lower and upper flammable limits, or in some documents the lower and upper explosive limits. The subject of explosion prevention concentrates on keeping these three constituents from coming together. The usual approach is to attempt to decide on the probability of the gas-air mixture being present and then to choose equipment which is protected adequately for its environment.

The study of the probability of gas-air mixture being present within the flammable limits is called "area classification," and is without doubt the most difficult aspect of this subject. Expertise on all aspects of the plant and the behavior of the gases present is required to carry out area classification well, and hence it is usually done by a committee on which the instrument engineer is only one member. Present practice is to divide the hazardous area according to the IEC Standard 79-10, as follows:

Zone 0: in which an explosive gas-air mixture is continuously present or present for long periods. (Note: The vapor space of a closed process vessel or storage tank is an example of this zone.)

Zone 1: in which an explosive gas-air mixture is likely to occur in normal operation.

Zone 2: in which an explosive gas-air mixture is not likely to occur, and if it occurs it will only exist for a short term.

By inference, any location which is not a hazardous area is a safe area. Many authorities prefer the use of "non-hazardous area," for semantic and legalistic reasons. The use of "safe" is preferred in this document since it is a shorter, more distinctive word than "non-hazardous."

Table 1 Temperature classification

Class	*Maximum surface temperature* (°C)
T1	450
T2	300
T3	200
T4	135
T5	100
T6	85

In the USA, the relevant standard is Article 504 of the National Electrical Code, and the ANSI/ ISA standards that explain it. There are minor differences between Article 504 at this writing and IEC Standard 79-10.

American common practice is still to divide hazardous areas into two divisions. Division 1 is the more hazardous of the two divisions and embraces both Zone 0 and Zone 1. Zone 2 and Division 2 are roughly synonymous. However, this practice is being overtaken by the changes in the National Electrical Code to conform to IEC standards.

The toxicity of many industrial gases means that an analysis of a plant from this aspect must be carried out. The two problems are frequently considered at the same time.

Having decided the risk of the gas being present, then the nature of the gas from a spark ignition or flame propagation viewpoint is considered.

One of the better things that has happened in recent years is the almost universal use of the IEC system of grouping apparatus in a way which indicates that it can safely be used with certain gases. Pedantically, it is the apparatus that is grouped, but the distinction between grouping gases or equipment is an academic point which does not affect safety. The international gas grouping allocates the Roman numeral I to the underground mining activity where the predominant risk is methane, usually called firedamp, and coal dust. Historically, the mining industry was the initial reason for all the work on equipment for flammable atmospheres, and it retains a position of considerable influence. All surface industry equipment is marked with Roman numeral II and the gas groups are subdivided into IIA (propane), IIB (ethylene), and IIC (hydrogen). The IIC group requires the smallest amount of energy to ignite it, the relative sensitivities being approximately 1:3:8. The representative gas which is shown in parentheses is frequently used to describe the gas group.

This gas classification has the merit of using the same classification for all the methods of protection used. The boundaries of the gas groupings have been slightly modified to make this possible.

Unfortunately, the USA and Canada have opted to maintain their present gas and dust classification. The classifications and subdivisions are:

CLASS I: Gases and vapors

Group A (acetylene).

Group B (hydrogen).

Group C (ethylene).

Group D (methane).

CLASS II: Dusts

Group E (metal dust).

Group F (coal dust).

Group G (grain dust).

CLASS III: Fibers

(No subgroups).

Gas-air mixtures can be ignited by contact with hot surfaces, and consequently, all electrical equipment used in hazardous atmospheres must be classified according to its maximum surface temperature. BS 4683: Part 1 is the relevant standard in the United Kingdom, and this is almost identical to IEC 79-8. The use of temperature classification was introduced in the United Kingdom quite recently (the late 1960s), and one of the problems of using equipment which was certified prior to this (e.g., equipment certified to BS 1259) is that somehow a temperature classification has to be derived.

For intrinsically safe circuits the maximum surface temperature is calculated or measured, including the possibility of faults occurring, in just the same way as the electrical spark energy requirements are derived. The possibility that flameproof equipment could become white hot under similar fault conditions is guarded against by generalizations about the adequate protective devices. All temperature classifications, unless otherwise specified, are assessed with reference to a maximum ambient temperature of 40^{o}C equipment is used in a temperature higher than this, then its temperature classification should be reassessed. In the majority of circumstances, regarding the temperature classification as a temperature- rise assessment will give adequate results. Particular care should be exercised when the 'ambient' temperature of a piece of apparatus can be raised by the process temperature (e.g., a pilot solenoid valve thermally connected to a hot process pipe). Frequently, equipment has a specified maximum working temperature at which it can safely be used, determined by insulating material, rating of components, etc. This should not be confused with the temperature classification, and both requirements must be met.

When the probability of gas being present and the nature of gas has been established then the next step is to match the risk to the equipment used. Table 33.2 shows the alternative methods of protection which are described in the CENELEC standards and the areas of use permitted in the United Kingdom.

In light current engineering the predominant technique is intrinsic safety, but flameproof and increased safety are also used. The flameproof technique permits the explosion to occur within the enclosure but makes the box strong enough and controls any apertures well enough to prevent the explosion propagating to the outside atmosphere. Increased safety uses superior construction techniques and large derating factors to reduce the probability of sparking or hot spots occurring to an acceptable level. The other technique which is used to solve particular problems is pressurization and purging. This achieves safety by interposing a layer of air or inert gas between the source of ignition and the hazardous gas.

Table 2 Status of standards for methods of protection (as of January 1984)

Technique	*IEC symbol Ex*	*Standard*			*UK code of BS 5501 part of BS5345*	*Permitted zone of use in UK*
		IEC 79–	*CENELEC EN 50*	*BRITISH BS 5501 Part*		
General requirement		Draft	014	1	1	
Oil immersion	o	6	015	2	None	2
Pressurization	p	2	016	3	5	1 or 2
Powder filling	q	5	017	4	None	2
Flameproof enclosure	d	1	018	5	3	1
Increased safety	e	7	019	6	6	1 or 2
Intrinsic safety	ia	3 Test apparatus	020 Apparatus	7	4	0 ia
	or ib	11 Construction	020 System	9		1 ib
Non-incendive	n(N)	Voting draft	021 (Awaits IEC)	BS 4683 Pt3	7	2
Encapsulation	m	None	028 (Voting draft)	None	None	1
Special	s	None	None	SFA 3009	8	1

Where it can be used, intrinsic safety is normally regarded as the technique which is relevant to instrumentation. Intrinsic safety is a technique for ensuring that the electrical energy available in a circuit is too low to ignite the most easily ignitable mixture of gas and air. The design of the circuit and equipment is intended to ensure safety both in normal use and in all probable fault conditions.

There is no official definition of intrinsic safety. EN 50 020, the relevant CENELEC apparatus standard, defines an intrinsically safe circuit as: circuit in which no spark or any thermal effects produced in the test conditions prescribed in this standard (which include normal operation and specified fault conditions) is capable of causing ignition of a given explosive atmosphere.

There are now two levels of intrinsic safety: "ia" being the higher standard where safety is maintained with up to two-fault and "ib," where safety is maintained with up to one-fault. Equipment certified to "ib" standards is generally acceptable in all zones except Zone 0, and "ia" equipment is suitable for use in all zones. Intrinsic safety is, for all practical purposes, the only acceptable safety technique in Zone 0 (continuously hazardous) and the preferred technique in Zone 1 (hazardous in normal operation).

This technique is frequently used in Zone 2 (rarely hazardous) locations to ease the problems of live maintenance, documentation, and personnel training. Intrinsic safety is essentially a low power technique, and hence is particularly suited to industrial instrumentation. Its principal advantages are low cost, more flexible installations, and the possibility of live maintenance and adjustment. Its disadvantages are low available power and its undeserved reputation of being difficult to understand. In general, if the electrical requirement is less than 30 V and 50mA, then intrinsic safety is the preferred technique. If the power required is in excess of 3 W or the voltage greater than 50 V, or the current greater than 250 mA, the probability is that some other technique would be required. The upper limit is a rash generalization, because, with ingenuity, intrinsically safe systems can safely exceed these limits. Between these two sets of values intrinsically safe systems can frequently be devised.

When there is interconnection between more than one intrinsically safe apparatus, an analysis of the interactions and their combined effect on safety reveals that intrinsic safety is essentially a system concept. It can be argued that the other techniques rely on correct interconnection and the choice of the method of electrical protection. For example, a flameproof motor depends for its safety on having correctly rated switchgear for starting overload and fault protection, adequate provision for earthing (grounding), and a satisfactory means of isolation, all of which constitute a system. However, the danger resulting from the failure of unsatisfactory safe-area equipment in an intrinsically safe system is more immediate and obvious, and hence there is a requirement for a more detailed consideration of all safety aspects which results in a system certificate and documentation. Where a system comprises intrinsically safe apparatus in the hazardous area and a certified source of power and receiving apparatus in the safe area, then the combination can be assessed against the CENELEC system standard EN 50039. The agreed term for equipment intended for mounting in the safe area which is certified as having terminals which may be connected to the hazardous area is "associated electrical apparatus." This inelegant and quite forgettable expression is very rarely used by anyone other than writers of standards, but it does distinguish certified safe-area equipment from equipment which can be mounted in the hazardous area.

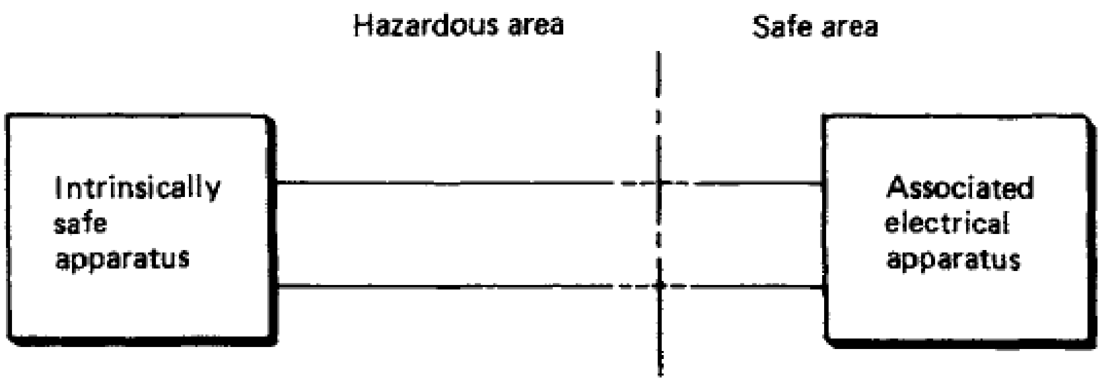

Figure 5 System with certified safe area equipment (associated apparatus)

Where an instrument loop is relatively simple, self-contained, and comprises the same equipment in the majority of applications, then it is usual for both the hazardous-area and safe-area equipment to be certified, and a system certificate for the specific combination to exist as illustrated in Figure 5.

In practice, there are only a few completely self-contained circuits, since the signal to or from the hazardous area is usually fed into or supplied from complex equipment. In these circumstances there is no real possibility of certifying the safearea apparatus since it is complex, and there is a need to maintain flexibility in its choice and use.

The solution in these circumstances is to introduce into the circuit an intrinsically safe interface which cannot transmit a dangerous level of energy to the hazardous area (see Figure 6). The majority of interfaces are designed to be safe with 250 V with respect to earth (ground) applied to them (i.e., the 440 three-phase neutral earth (ground) system commonly used in the United Kingdom).

Whatever the cause of the possible danger and the technique used to minimize it, the need to assess the risk, and to document the risk analysis and the precautions taken, is very important. There is a legal requirement to produce the documentation. There is little doubt that if the risks are recognized and documentary proof that they have been minimized is established, then the discipline involved in producing that proof will result in an installation which is unlikely to be dangerous and is infinitely easier to maintain in a safe condition.

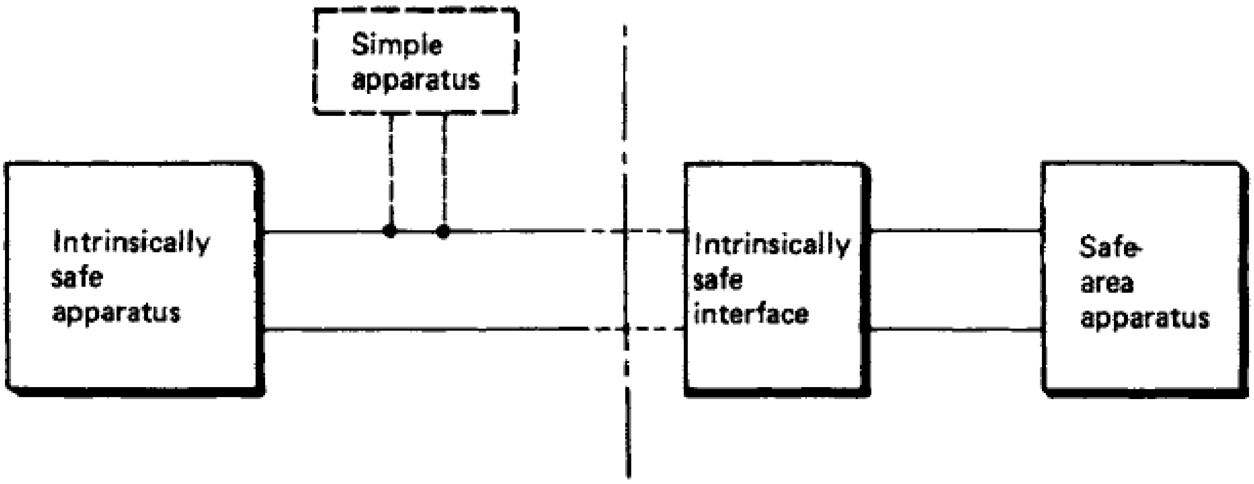

Figure 6 System with certified intrinsically safe interface

4. Other safety aspects

The level of integrity of any interlock or instrument system depends upon the importance of the measurement and the consequences of a failure. It is not surprising that some of the most careful work in this area has been related to the control of atomic piles and similar sources of potential catastrophic failure. The majority of systems are less dramatic, and in the United Kingdom an excellent Code of Practice, BS 5304: 1975, discusses the techniques generally used for safeguarding machinery in non-hazardous circumstances. The general principles to be applied can be summarized as:

1. The failure of any single component (including power supplies) of the system should not create a dangerous situation.

2. The failure of cabling to open or short circuit or short circuiting to ground of wiring should not create a dangerous situation. Pneumatic or electro-optic systems have different modes of failure but may have particular advantages in some circumstances.

3. The system should be easily checked and readily understood. The virtue of simplicity in enhancing the reliability and serviceability of a system cannot be overstressed.

4. The operational reliability of the system must be as high as possible. Foreseeable modes of failure can usually be arranged to produce a "fail-safe" situation, but if the system fails and produces spurious shutdowns too frequently, the temptation to override interlocks can become overwhelming. An interlock system, to remain credible, must therefore be operationally reliable and, if possible, some indication as to whether the alarm is real or a system fault may also be desirable.

These basic requirements, following up a fundamental analysis of the level of integrity to be achieved, form a framework upon which to build an adequate system.

5. Conclusion

It is difficult to adequately summarize the design requirements of a safe system. The desire to avoid accidents and in particular to avoid injuring and killing people is instinctive in the majority of engineers and hence does not need to be emphasized. Accident avoidance is a discipline to be cultivated, careful documentation tends to be a valuable aid, and common sense is the aspect which is most frequently missing.

The majority of engineers cannot experience or have detailed knowledge of all aspects of engineering, and safety is not different from any other factor in this respect. The secret of success must therefore be the need to recognize the danger so as to know when to seek advice. This chapter has attempted to provide the background for recognizing the need to seek expert advice; it is not comprehensive enough to ensure a safe design.

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Many British Standards, IEC Standards, and ANSI/ ISA Standards refer to safety. With the wide availability of these standards on the World Wide Web, the reader is referred to these agencies for an up-to-date listing of relevant standards.