TUTORIAL

Electrical apparatus for flammable atmospheres: intrinsic safety

In a previous article, protection of electrical apparatus by flameproof enclosures was considered. Protection in this context means that, due to its method of enclosure, the apparatus will not cause ignition of a surrounding explosive atmosphere. However, with very low power apparatus such as for instrumentation and process data management, the type of protection known as intrinsic safety is usually more appropriate. Intrinsic safety is defined as a protection technique based on the restriction of electrical energy to a level which is too low to be able to ignite an explosive atmosphere. The following article describes some of the principles involved

by J. M. Adams

To ignite a flammable mixture of gas or vapour with air, energy in the form of heat has to be transferred to the mixture to act as a trigger. The heat produced by combustion round the source of ignition then creates a chain reaction, leading to an explosion.

There are two obvious ways in which a flammable gas can be ignited from an electric circuit:

(*a*) by electrical arcs or sparks
(*b*) by unduly hot wires or components.

For method (*a*) the critical parameters are the current and the restriking voltage at the point where the spark is produced. These must be above certain values for the circuit to be incendive (i.e. capable of igniting a gas/air mixture). For method (*b*) the critical parameters are the surface temperature, the area of the heated surface and the relative velocity of the flammable atmosphere over the surface.

A detailed study of low-voltage signalling circuits at Sheffield University early this century, following some appalling fires in British coal mines, showed that there was a minimum amount of energy which must be transferred to the gas mixture to trigger an explosion. Below this level, an explosion will not take place. The amount of energy required is different for each gas, hydrogen being the most sensitive.

If the ignition is due to an electric spark, the electrical power needed has been found to be a function of many variables including the voltage, current, contact metal and speed of separation of the sparking contacts. A certain period of arcing (a few hundred microseconds) is also necessary, to give the heat from the spark time to enter the gas.

Further research showed that the lowest required igniting current falls very rapidly with rising supply voltage. This is due to the increasing ability of the source to maintain an arc as the voltage is increased.

Work on intrinsic safety, which was pioneered in the UK, led to its wide use here some 30 years before the technique was generally recognised overseas. A British Standard on the subject has existed since 1945 and in the subsequent 20 years over 500 certificates for intrinsically safe designs were issued by the Electrical Branch of the Factory Inspectorate, based on test reports carried out by the Safety in Mines Research Establishment — both now part of the Health & Safety Executive.

Intrinsic safety criteria

The relationship between maximum safe open-circuit voltage and maximum safe short-circuit current is roughly in inverse proportion, as indicated in Fig. 1. If the voltage and current of the circuit lie below this curve at the spark, the circuit is said to be intrinsically safe, or IS at that point.

Although each gas relates to a different 'safe curve', they are all of the same form, being more or less 'parallel' and lie between the extremes of the curve for hydrogen, the most sensitive, and methane, the least sensitive. It is therefore possible to design an IS system for the most sensitive gas concerned and to know that it will not ignite any less sensitive gas. In other words, none of the curves intersects with another.

For commercial reasons, four standardised curves are used. These have been selected so that they respectively cover the same groups of gases as the four flameproof apparatus groups. By European and international (except USA) agreement, these are marked on the apparatus label as I, IIA, IIB or IIC. Group I apparatus indicates only methane-safe and Group IIC indicates hydrogen-safe. Groups IIA and IIB are for intermediate ranges of gases.

It will be seen from the curve in Fig. 1 that at the higher voltages very low values of current in the spark can cause ignition, whereas in the region of 12 V there is apparently no current capable of causing ignition. This is course is not the whole story. A spanner dropped across a car battery, for instance, would certainly be able to ignite petrol vapour, but in this case the transfer of heat to the gas would be from incandescent particles of metal rather than from the actual spark.

Further examination of Fig. 1 shows that the permissible power in the circuit increases markedly at the lower voltages. Thus, with a 100 V source, a 25 mA spark is permissible, corresponding to a circuit power of 2·5 W. With a 15 V source, 1·2 A is permissible, corresponding to a circuit power of 18 W. Intrinsic safety is accordingly a method of protection from ignition which lends itself very well to instrumentation and solid-state technology, where very low voltages and relatively low levels of power can be used. Fig. 2 shows the safe power in a spark at various voltages.

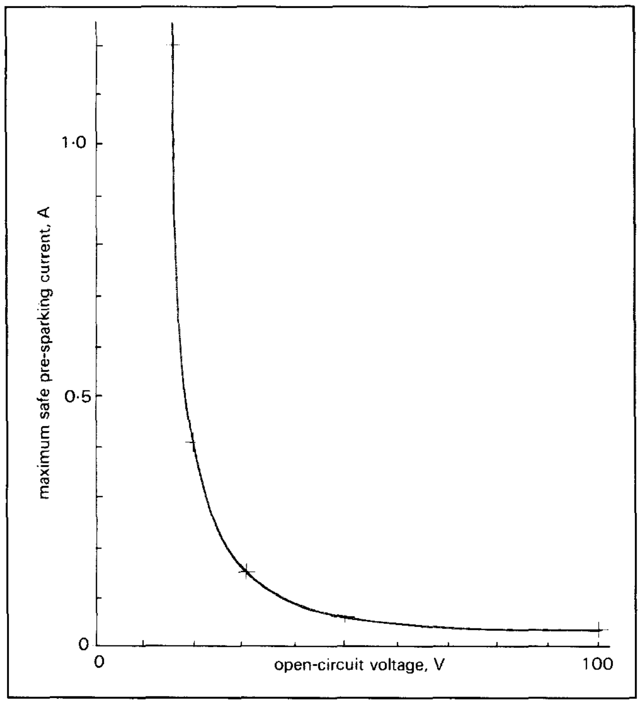
Applications of IS systems

Because IS protection is clearly more applicable to low-power and particularly to very-low-voltage equipment, it has been widely adopted for the explosion protection of instruments, electronic process control and telemetering where all or part of the circuit has to be within a hazardous area. A hazardous area in this context means a zone where an explosive atmosphere could be present, a tank farm or pumping area for example.

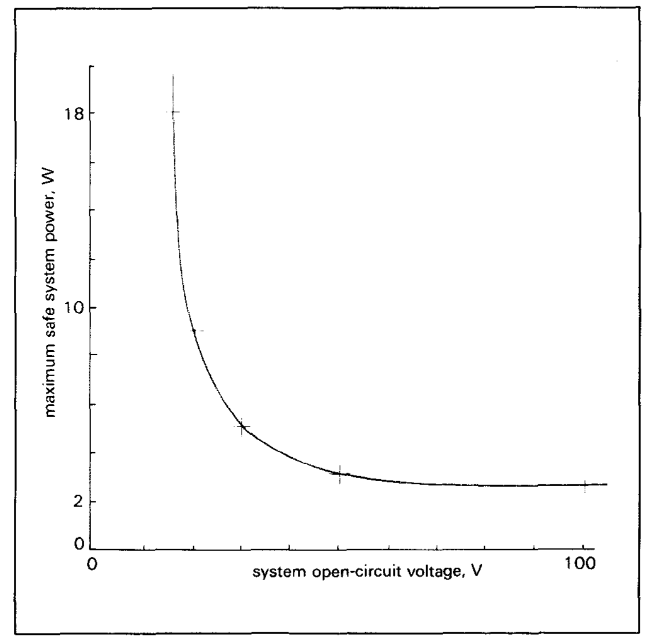
Low-voltage solid-state technology and IS techniques have advanced rapidly together, so that, in the last ten years or so, more electrical equipment has been designed and certified for intrinsic safety than for any other form of explosion protection.

Most of the circuit wiring and apparatus forming an IS system are normally installed and operated in a safe area, such as a control room. Those parts of the IS system which have to be in a hazardous area are usually restricted to simple probes and devices such as float switches, thermocouples, transducers for measuring and transmitting process conditions, and current-to-air pressure transformers for servocontrol. These items present no hazard in themselves as they cannot generate any energy to ignite gas/air mixtures. No adjustments carried out on them can make them dangerous and often they do not even need to be tested for intrinsic safety.

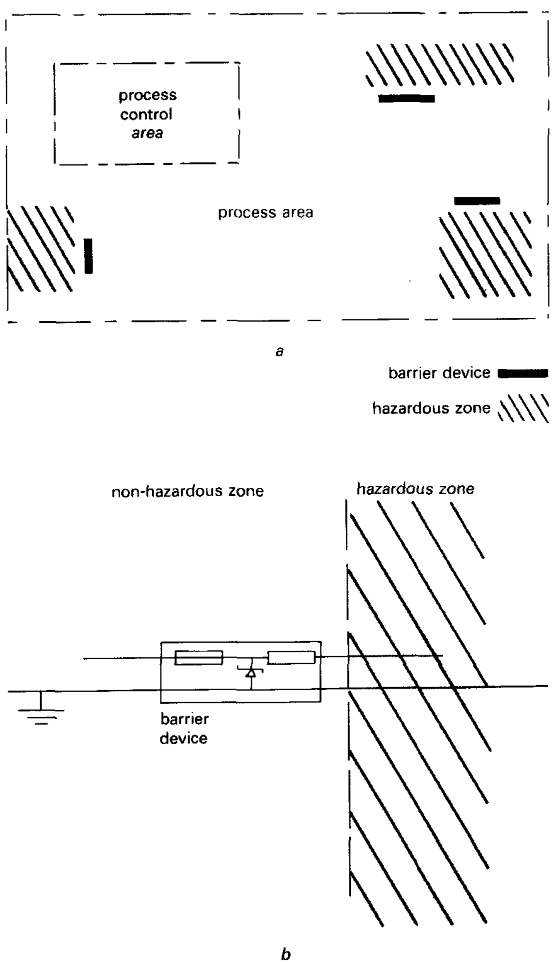
However, the equipment in the safe



1 Maximum safe pre-sparking currents for a stoichiometric mixture of hydrogen and air



2 Increase in permissible IS power source as system voltage is reduced (useful power at matched load impedance will be half these values)



3 Use of barrier devices to limit fault power invading a hazardous area via an IS system.
(*a*) Optimum position of barrier devices with respect to hazardous zones
(*b*) Principle of a commonly used type of barrier. The current-limiting resistor enables the device to be connected to a low source impedance. The fuse protects the Zener diode from undetected damage due to excessive avalanche current

area, to which they may be connected, can create a very considerable hazard by allowing dangerous levels of power to pass from the safe area into the hazardous area loop. It is necessary in some cases to assume that a voltage of 240 V above earth will accidentally become connected to the IS system and so produce a dangerous condition in the hazardous area. By international agreement, the foreseen fault conditions in the safe area will in general include open circuits, short-circuits, component failure and unintentional connection of the LV mains (in the UK, 240 V AC) to some part of the IS circuit.

Accordingly, most of the recent intensive development of IS systems has been concerned, not with hazardous area apparatus at all, but with the safe area equipment which may be connected to it. In fact, *IS protection has very little to do with apparatus in the hazardous area, but is almost entirely concerned with what the hazardous area items are connected to in the safe area; for, in general, this is where the dangerous sources of energy will lie.*

The problems of ensuring intrinsic safety can be greatly simplified by installing suitable 'power transfer limiters' at the point where the hazardous area loop is connected to equipment in the safe area. These so-called barrier devices can take the form of optocouplers, saturable transformers, fused Zener diode circuits and even the simple electric relay.

The choice will depend primarily on the type of information (analogue or digital), the bit rate (bauds) and the power to be transmitted. As shown diagrammatically in Fig. 3, barrier devices should be installed in the safe area, as near as possible to the hazardous area they are protecting because the barrier does not protect its downstream circuits from spurious voltages entering beyond the barrier.

By using certified barrier devices at the boundary between the safe and hazardous areas, the equipment and circuit wiring in the safe area — such as VDUs and process controllers — do not have to comply with the reliability requirements of the IS standards. Because of the barrier, any unsafe voltage or unsafe source impedance will not reach the IS loop in the hazardous area.

Testing for IS

As stated above, for safety reasons faults have to be taken into account in all parts of the circuit, particularly in those parts which extend into the safe or non-explosive area where more carefree methods of maintenance may apply. Laboratory testing for IS certification therefore involves an assessment of the whole circuit or system in both hazardous and safe areas. If certified barriers are not used, possible faults in the safe area must be applied or simulated and at the same time the hazardous area part of the circuit must be interrupted and the resulting spark tested for incendivity in the gas concerned. A sparking test device filled with a specified explosive gas mixture is used for this purpose.

At this point it is necessary for us to consider inductive effects. To produce a spark from an electric circuit the flow of current must be interrupted so that a spark and restriking voltage is produced. The potential difference across the spark gap is determined by the source voltage and the rate of collapse of the magnetic flux. Hence the greater the inductance in the circuit, the lower the current which will be able to ignite gas when the circuit is broken.

Taking circuit inductance into account, Fig. 1 becomes modified to the form shown in Fig. 4. Here, the safe current continues to increase as the voltage is reduced, until a value of current is reached at which the restriking voltage is determined by the circuit inductance rather than by the system open-circuit voltage. The safe current can then no longer be increased by reducing the source voltage.

Clearly the restriking voltage will also increase according to the rate of separation of the sparking contacts. Also, if the electrodes are moving apart quickly, their heat-sink effect will be reduced so that the spark energy will be more effectively transferred to the explosive atmosphere. For these two reasons, the most incendive sparks will be produced by sudden breaks in small electrodes — such as by wires being broken under tension.

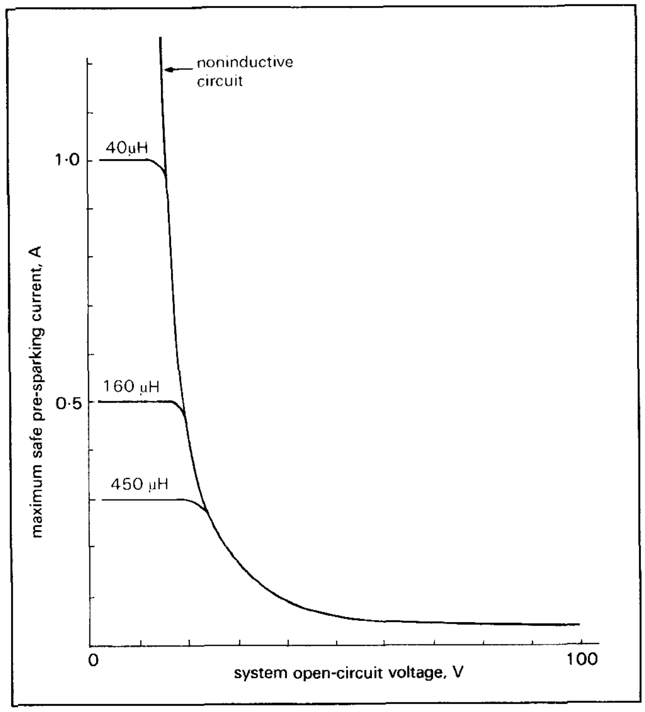
It has also been found that some electrode surfaces can ignite gases more readily than others. For instance, as shown in Fig. 5, a copper wire would not ignite hydrogen by a 50 V spark below 450 mA, whereas if it were cadmium-plated it could cause ignition down to 60 mA. The design of the sparking test apparatus thus has a profound effect on the test results obtained.

The choice of the test device able to create the most sensitive conditions for ignition has been discussed for over half a century, and many different types have been used. The present test apparatus, standardised by the IEC, is of German design and consists of tungsten wires scraping over a rotating grooved cadmium disc. It is described in detail in Annex B of BS 5501 Part 7 'Electrical apparatus for potentially explosive atmospheres — intrinsic safety'. It is intended to produce a series of random sparks which are found to be more likely to ignite an explosive atmosphere than a given sequence of identical sparks (Fig. 6).

Normal test practice is to vary the circuit conditions, using for instance a variable source impedance or current-limiting resistance (CLR) until a borderline between ignition and nonignition is found. A significant safety factor then has to be applied to the result, as the poor repeatability of the test demands fairly wide confidence limits.

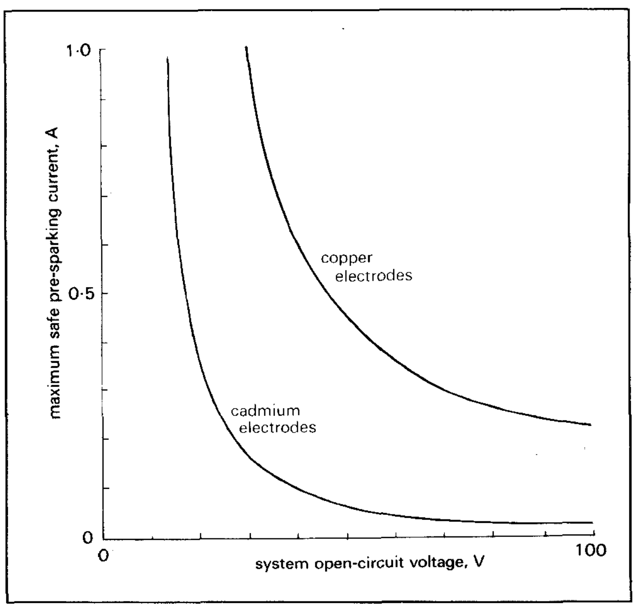
Circuits which have known values of source voltage, source impedance and stored energy can be assessed for IS by evaluation against the limiting safe curves which are published in the above-mentioned standard. On the other hand, the inductance of circuits containing iron, such as miniature solenoid valves, magnetic relays and chokes, will depend on the slope of the *B/H* curve. Because this is not a straight line, the effective inductance in the circuit varies with the degree of saturation and consequently depends on the current value at the moment the circuit is interrupted. Owing to the difficulty of calculating the overall effective inductance in such a circuit, it may then be necessary to demonstrate its intrinsic safety by means of the standardised sparking test apparatus.

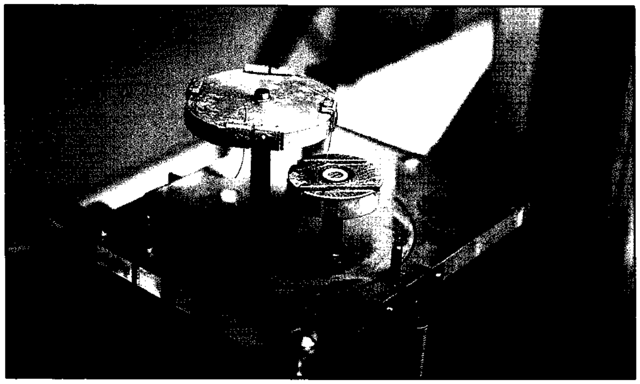
Alternatively, restriking voltages in the hazardous area can be reduced to a safe



4 Effect of inductance in an IS circuit. The maximum safe current is reduced approximately inversely as the square root of the inductance (i.e. $\frac{1}{2}LI^2$ remains substantially constant)

5 Maximum safe pre-sparking current values for H_2 with copper and cadmium electrodes





6 Standard sparking test apparatus with explosive atmosphere-retaining cover removed. The discs rotate at different speeds, four tungsten wires being attached to the upper disc. The lower disc is slotted and made of cadmium

level by a suitable arrangement of diodes across each inductive component.

For the reasons described below, testing may also involve the measurement of the surface temperature of the hazardous area items (Fig. 7).

Ignition by overheated components

As previously mentioned, explosive atmospheres can be ignited by unduly hot wires or components. This imposes an additional restriction on IS systems which is not necessarily covered by the sparking test criterion. Circumstances which have to be considered include wires containing fine stranded conductors, compound resistors and carbonisation of insulation.

The fraying of a flexible lead down to the last unbroken filament can be incendive because very fine wires can become incandescent even at powers too low to cause spark ignition. For this reason specific rules concerning minimum filament size in stranded wires are applied.

Low-wattage resistors having very small surface areas will readily reach excessive temperatures if overloaded. A 2·5 W resistor, for instance, will generate an increase in its surface temperature of up to 100 K/W of heat dissipation. If compound-based resistors are overloaded by relatively minor amounts they can char, or carbonise, so that their resistance decreases with temperature and their loading will then increase until it equals the source impedance. The component can then remain incandescent in this stable, matched-load condition.

This type of resistor is accordingly not suitable in critical parts of the circuit, that is to say, either in the hazardous area or as a CLR in the safe area. It is preferable to use a single-layer wire-wound resistor on a ceramic base as this is unlikely to fail in anything but an open-circuit mode.

Carbonisation of insulation can produce a similar effect to compound resistor charring and applies in particular to IC devices mounted on organic substrata. Here again a ceramic or glass base is preferable.

Conclusions

It will be seen that protection by the method of intrinsic safety has grown rapidly in recent years due to its eminent suitability for programmable process control and information transfer. It differs essentially from all other methods of protection of electrical apparatus for use in potentially explosive atmospheres because the flow of energy from the safe area must be carefully controlled. Its growth has been greatly accelerated by the development of barrier devices which protect the hazardous area from the effects of possible intrusion of dangerous sources of energy from the safe area parts of the system.

In future it is possible that fibre-optic transmission of data will supersede many existing barrier applications for IS systems.

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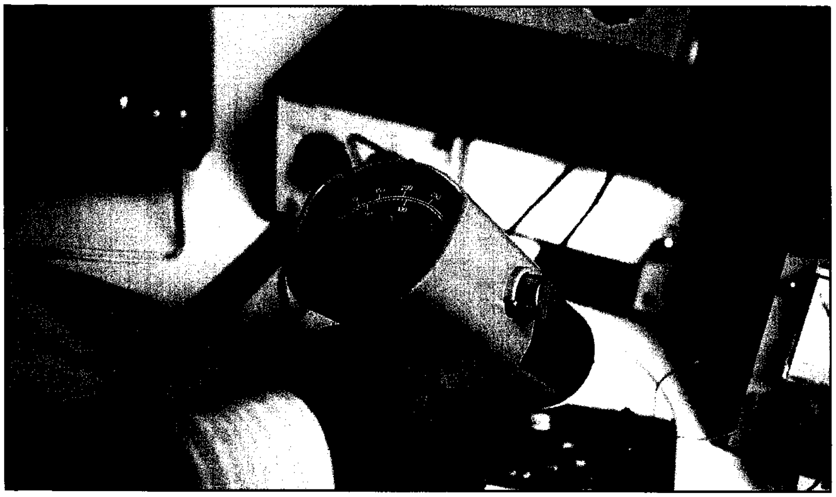

7 Radiation pyrometer used to measure the surface temperature of very small PCB components, where the attachment of a thermocouple would act as a heat sink and give unduly low readings