

## DIFFERENCES BETWEEN DETERMINATIONS OF MAXIMUM EXPERIMENTAL SAFE GAP IN EUROPE AND U.S.A.

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### Summary

The Westerberg apparatus is used by Underwriters Labs (USA) for the determination of Maximum Experimental Safe Gap (MESG). The results are smaller than those obtained in Europe with spherical explosion vessels and the compounds tested are not rated in the same order by degree of hazard.

The difference is explained by the small receptor vessel in the Westerberg apparatus, which means that the external ignition takes place in a hot vitiated atmosphere at elevated pressure. For a few exceptional cases where MESG in the Westerberg apparatus is only about one third of the European value, external ignition was probably the result of spontaneous ignition in the vitiated atmosphere.

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### Introduction

One means of ensuring safety when electrical machinery is used in an atmosphere that might become flammable is to enclose the sparking components in a flameproof enclosure. An operational or accidental spark from the circuit may ignite a flammable mixture inside the enclosure, but the enclosure is so constructed as to contain the explosion and prevent its being transmitted to a flammable atmosphere outside.

This is achieved by making all gaps, tolerances and clearances small: in particular the gap between flange surfaces must be less than the maximum permitted gap specified in national and international standards and codes of practice. The British Standard for flameproof enclosure, BS 5501: Part 5: 1977 [1] is the English language edition of the European Standard EN 50 018 [2] which in turn is loosely adapted from the International standard agreed by the International Electrotechnical Commission [3] and its more recent draft revision [4]. In these standards, electrical apparatus is divided into four groups according to the nature of the gas or vapour that may contaminate the atmosphere. Group 1 is for apparatus to be used in coal mines, where methane is the likely contaminant. Group IIA is suitable where the contaminant has explosion properties similar to those of propane, Group IIB for gases such as ethylene and Group IIC for hydrogen, acetylene and carbon disulphide.

The allocation of fuel gases corresponding to the equipment groups is according to their Maximum Experimental Safe Gaps (MESG). The MESG is the maximum spacing between the flange surfaces of a standard apparatus which just prevents transmission of an explosion. For the purposes of the international standard, the apparatus consists of a 20 ml spherical vessel made in two halves, with 25 mm wide mating flange surfaces. The explosion vessel is contained in an outer vessel (the receptor) of about 2340 ml, so that the volume of the external mixture is about 100 times that of the internal mixture.

In the British version the outer volume is even larger. A full description of the various European apparatuses for determination of MESG is given by Lunn and Phillips [5], together with a list of determinations made with these vessels. Almost identical results were found using the earlier 8 litre vessel; with this the outer explosive mixture was contained in a sleeve of thin plastic film which was burned or ruptured before the external gas pressure was substantially above atmospheric.

Gases and vapours with an MESG above 0.9 mm are allocated to Group IIA, above 0.5 mm but below 0.9 mm are in Group IIB and below 0.5 mm, in Group IIC. Lists of gases and vapours according to Groups appear in [6–8], the latter being based on an IEC draft [9]. All these groupings are based on MESG data from the 20 ml, or the 8 l spherical explosion vessels, where the determination has not been repeated in the smaller vessel or where the 8 l vessel gives a significantly smaller value (only for carbon disulphide).

In the USA, MESG determinations are made by Underwriters Labs in the Westerberg apparatus described by Underwriters Labs. [10–12] and the results are used in the groupings for US Standards [13]. Not only do some of the MESG determinations differ from those obtained in the European apparatuses, but to such an extent that the fuels appear in a different order of hazard ratings, which in turn has a marked effect on the type of electrical apparatus specified for some of the flammable compounds. The discrepancy has been termed “The safe gap anomaly” by Strehlow et al. [14].

### Differences between experiments

Strehlow et al. [14] describe the differences between the experimental apparatuses, and suggest that MESG is an apparatus-dependent measurement. To some extent this is true, in that within certain limits MESG depends on the breadth of the flange surfaces and the volume of the explosion vessel. Up to 50 mm, an increase in flange breadth increases MESG, but above 50 mm has little effect. As a compromise the MESG is usually (in Europe) measured with flanges 25 mm wide. The volume of the primary vessel is important in that reduction below 20 ml results in an increase in MESG. The experiment becomes closer to one of the methods for determining quenching distance. Above 20 ml the effect of size can be neglected, except in the case of carbon disulphide, for which the MESG in the 20 ml vessel is 0.34 mm and in the

8 l vessel, 0.20 mm. This has been explained by reference to theory by Phillips [15] and [16].

The position of the internal spark is chosen so that the MESG determined is the minimum of the different values that might be found by changing ignition position. It was found by experiment that the most favourable position for ignition was about 10 mm away from the inside edge of the flange gap. Moving the ignition source towards the centre of the 8 l sphere increased the MESG for methane, but had no effect for hydrogen. The same is true for the 20 ml vessel, but to a lesser degree.

The volume of the receptor vessel should not be considered a variable although in practice early experiments in Germany showed that too small a receptor could influence results. The industrial situation simulated by the MESG determination is ignition by electrical apparatus of an unconfined cloud of flammable gas or vapour in the atmosphere. To imitate this, the receptor vessel should be so designed that an increase in its size has no effect on the result obtained, which in practice places a lower limit to the receptor volume. Alternatively, the receptor vessel must be able to vent to atmosphere to avoid significant pressure rise. A further requirement of the receptor is that no part of it should interfere with the free discharge of burned gas from the flange gap, or interfere with the formation of the jet of burned gas outside the flange gap. The Westerberg apparatus does not comply with receptor volume requirements and it is probably this aspect of design that led Strehlow et al. [14] to the conclusion that MESG is apparatus dependent.

Strehlow et al. [14] suggested ignition delay as a variable, but this now appears not to be an independent variable; it depends on the ignition mechanism.

## Theory

To understand the effect of variation in apparatus design requires a knowledge of the mechanism for transmission of an explosion through a flange gap. The theory has been outlined by Phillips [15–18], and so that the arguments presented later in this paper can be followed, the salient features of the theory are presented here.

A schematic view of the jet of hot combustion products emerging from a flange gap appears as Fig. 1. In the critical case when the hot jet is only just capable of igniting an external flammable atmosphere, ignition occurs in the vortex at the head of the quasi-steady jet. The development of gas temperature from the time combustion products enter the flange gap can be calculated.

First there is a heat loss to the flange surfaces. Experiment has shown that ignition is favoured by a low velocity through the gap (this is confirmed in a later stage of the analysis) so that Reynolds and Peclet numbers are low and heat transfer can be characterised by a constant Nusselt Number. Thus, for a slot:

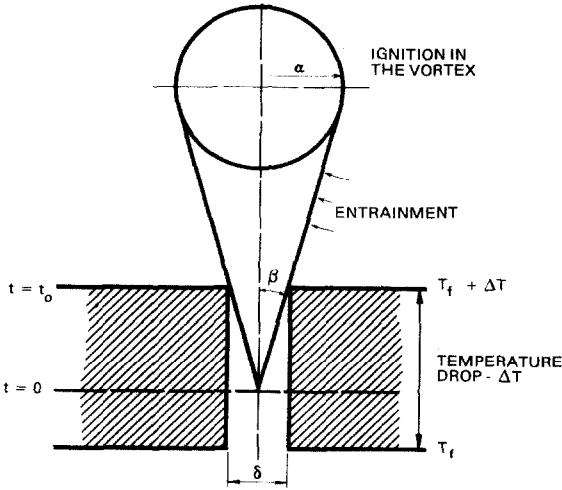


Fig. 1. Model of the hot jet.

$$\frac{\Delta T}{\bar{T}} = \frac{7.6 \lambda l}{\rho C_p V \delta^2} \quad (1)$$

Entrainment of unburned mixture into the jet of burnt products has been described by Phillips [17]. The entrainment rate into both jet and vortex is given by,

$$\frac{1}{m} \frac{dm}{dt} = \frac{z}{t} \quad (2)$$

where  $z$  is a constant that depends on whether entrainment is calculated for the quasi-steady jet or the vortex. The time  $t$  is taken from the virtual origin of the jet, when it has infinite velocity and zero size. In a later stage the value of  $z$  is shown not to be important in the calculation; a change in  $z$  results only in a change in the proportionality constant in the final estimate of MESG.

Equation (2) leads to,

$$\frac{m_0}{m} = \left( \frac{t_0}{t} \right)^z \quad (3)$$

where  $t$  is the time for the jet to progress from its virtual source until it emerges from the flange gap, and  $t_0$  is proportional to flange gap through:

$$\delta = \frac{3}{2} \beta C t_0 V \quad (4)$$

Heat transfer to the slot and entrainment into the jet lead to a drop in temperature of the burnt gas. However, fuel and oxygen are entrained and a

rate of heat release by combustion can be calculated, assuming global reaction kinetics:

$$\dot{m}_f''' = -BC_f^k C_o^s \exp(-E/RT) \quad (5)$$

Putting fuel and oxygen exponents,  $k$  and  $s$ , equal to unity leads to a rate of temperature change in the jet due to combustion:

$$\psi = \frac{BPW}{TR\eta} \frac{a/f}{1+a/f} \left[ 1 - \eta + \frac{m_o}{m} \Delta T \right]^2 \exp(-E/RT) \quad (6)$$

The algebra is given in Phillips [17]. Equations (2)–(6) are combined so that the change of temperature in the jet may be calculated as:

$$\frac{1}{\eta} \frac{d\eta}{dt} + \frac{1}{m} \frac{dm}{dt} = \psi \quad (7)$$

$T$  change    entrainment    combustion

With the initial boundary condition  $\eta = 0$  and  $T$  calculated from eqn. (1), a typical solution is shown in Fig. 2. The curves represent temperature vs. time plots with different values of starting time  $t_0$ . They split into two zones; ignition, where  $\eta$  is asymptotic to flame temperature ( $\eta = 1.0$ ), and non-ignition, where  $\eta$  is asymptotic to ambient temperature ( $\eta = 0$ ). The boundary between the two sets of curves is defined by the critical starting times which, through eqn. (4), are a function of MESG. Variation in the assumed value of  $z$  in eqns. (2) and (3) leads to variation in the value of critical  $t_0$  with  $t_{0crit}$  proportional to  $z$ . Therefore, through eqn. (4), MESG is proportional to  $t_{0crit}$ . The constant of proportionality must be established by experiment. The chemical rate constants of eqn. (5) must also be established before the theory can be used

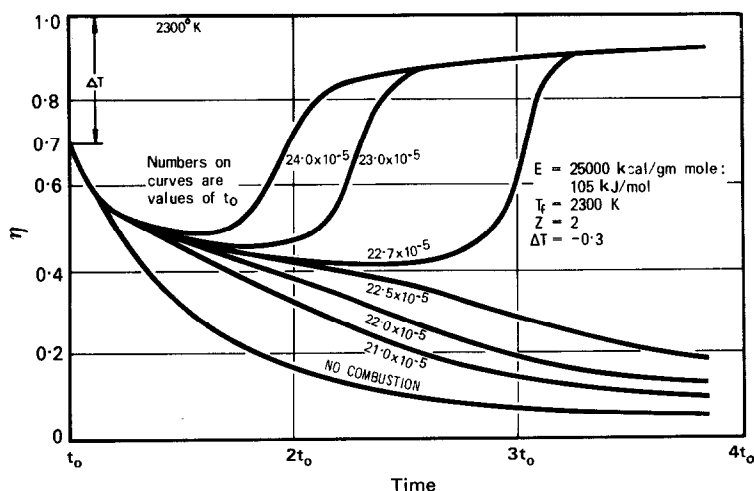


Fig. 2. Vortex temperature.  $\eta$ —non-dimensional temperature  $(T - T_u)/(T_f - T_u)$ .  $t_0$ —starting time in seconds from point source until the vortex fills the orifice.  $T_u$ —ambient temperature, 300 K.

to calculate MESG. This process includes the assumption that  $k = s = 1.0$ . The rate constants used earlier (Phillips [15–18]) are taken from Fenn and Calcote [19].

Global reaction kinetics based on Fenn and Calcote's rate constants are adequate for calculation of MESG's for stoichiometric mixtures and estimation of the effects of variation in pressure, temperature, and diluents, but fail when the mixture departs from stoichiometric. Goh and Ma [20] introduce an extra term into the reaction rate equation to correct for this deficiency for propane–air mixtures. It is not clear whether the same correction applies for other fuels.

If eqns. (1) to (7) are solved with an assumed value for the velocity of gas emerging from the flange gap, an optimum velocity for ignition is obtained by iteration (Fig. 3). For methane the optimum velocity is low, of the order of 150 m/s, but for more reactive fuels, such as hydrogen, the optimum is sonic. Fuels of intermediate reactivity lie between these extremes.

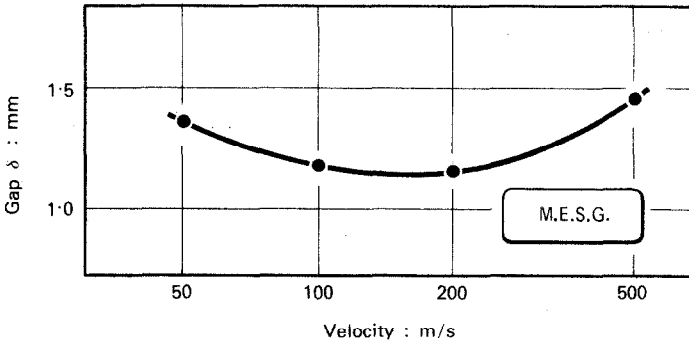


Fig. 3. Calculated values of gap for methane with a range of exit velocity ( $z = 1.0$ ).

The effects of ignition position, primary vessel volume and the area of the flange opening are introduced through a dimensional analysis [15] and [16] which, from a small number of key experiments, yields a value for the optimum velocity for the jet emerging from the flange gap.

In the theoretical treatment, it has been assumed that the external atmosphere contains just fuel and air and is at normal atmospheric pressure. It is possible to calculate the effect of change in pressure; Fig. 4 shows the results for three fuels and experimental curves for comparison [21]. It is not possible to calculate the effects of all possible changes in composition and state of the external atmosphere although trends can be inferred from the theory.

### The Westerberg apparatus

The most significant feature of the Westerberg apparatus that distinguishes it from European apparatus is the small receptor vessel. The receptor volume is less than the primary volume and no vent or pressure relief is provided.

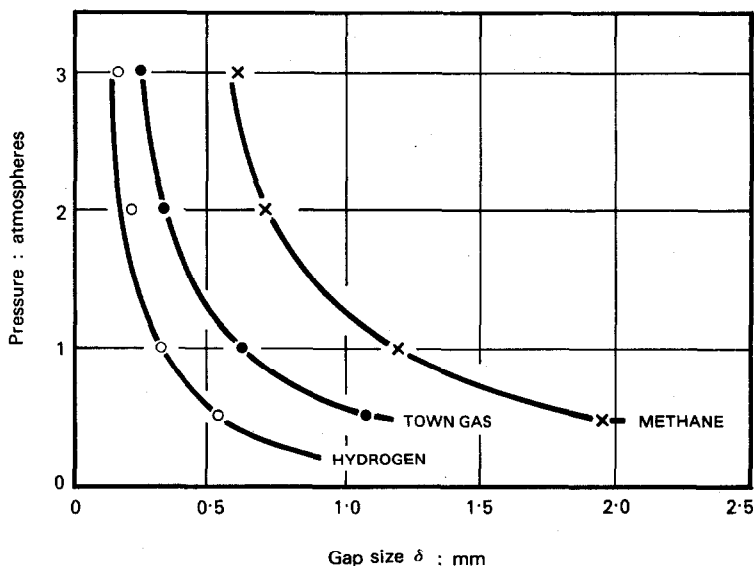


Fig. 4. The effect of pressure; calculated points compared with Grobleben's experimental curves.

### Primary ignition

Events immediately following internal ignition in the Westerberg apparatus should be much the same as in the other apparatuses. Hot burnt products are ejected from the flange gap, slowly at first but at increasing velocity as the explosion pressure develops. As velocity increases it passes through its optimum, when MESG is a minimum. During this phase the receptor vessel contains a fuel/air mixture at ambient pressure and the MESG of the system is the same as in the European apparatuses. No external ignition occurs because the flanges have been set with too narrow a gap. Later events leading to ignition can be inferred, in a qualitative way, by consideration of the theoretical treatment.

As the internal explosion continues to develop, pressure in the primary vessel rises, and the velocity of gases through the gap rises and more hot burnt products are ejected into the receptor vessel. Since velocity rises, the heat loss to the flange surface is reduced (see eqn. (1)). Eventually all the fuel in the primary vessel is consumed, pressure is at a maximum and hot gas is still being transferred to the receptor.

### Critical stages

In the next phase, as more gas is transferred, pressures in the two vessels approach equality and velocity falls; with the fall in velocity the critical gap for ignition also falls to a new minimum so that there is a second optimum velocity for ignition. The hot jet thus has a second chance of igniting the gas mixture in the receptor vessel, at a later stage in the life of the internal ex-

plosion. The two stages at which MESH reaches a minimum are referred to below as the first and second critical stages.

However at the second critical stages the hot gas jet flows into an atmosphere in the receptor which has been heated and pressurised by transfer of gas from the primary vessel and contains an appreciable amount of exhaust products. With this knowledge it is possible to predict the trends of MESH determinations in the Westerberg apparatus, although actual values of MESH cannot be calculated.

The first effect of the gas flow into the receptor vessel is on heat transfer to the flange surface. Equation (1) shows that the temperature drop in the gas is inversely proportional to pressure, so that the gas in the jet is hotter in the second critical stage than in the first.

The fluid mechanics aspect of the jet remains unchanged; see eqns. (2)–(4).

The reaction rate function of eqn. (7) is proportional to pressure, so that, other factors being equal, ignition reactions in the receptor are more vigorous. Vitiation and compression also increase the temperature in the receptor, again leading to an increase in reaction rates, through  $\exp(E/RT)$  in eqn. (5). However, the increase in reaction rate is opposed by the effects of heat losses to the walls of the receptor, and by the effect of dilution of the reacting gases by vitiation ( $C_f$  and  $C_a$  in eqn. (5)). It is not yet possible to quantify the various parameters that affect reaction rate, and so the extent of the reaction rate increase cannot be calculated. The net result of vitiation in the receptor vessel appears to be an increase in reaction rate in the jet. It remains now to consider why MESH in the second critical stage appears to be reduced more for some fuels than for others.

#### *Effects on different fuels*

For methane, illustrated schematically in Fig. 5, the critical velocity is relatively low in the first stage and it is reasonable to assume that the critical velocity in the second stage is similar. There is a relatively long delay between the two critical stages, giving time for heat losses to the apparatus. The reduction in MESH due to increased pressure could be expected to be balanced by an increase due to vitiation and heat losses. A shorter delay will lead to a larger reduction in MESH.

On the other hand, for hydrogen (see Fig. 6) the critical velocity is relatively high with a shorter delay between the two critical stages. There is little time for expulsion of gas between the two critical events and so heat losses are smaller, with only a small transfer of gas for vitiation. Therefore, only a small reduction in MESH could be expected. A longer delay would lead to a larger reduction in MESH.

Thus for the most reactive, and the least reactive compounds, MESH is only slightly reduced in the Westerberg apparatus. For intermediate compounds (see Fig. 7), predominantly those in Group IIB of the IEC classification, the differences are greater. Strehlow et al. [14] list these as 1:1.5 compounds and 1:2 compounds. There appears to be an optimum range between the two extremes for the larger reduction in MESH.



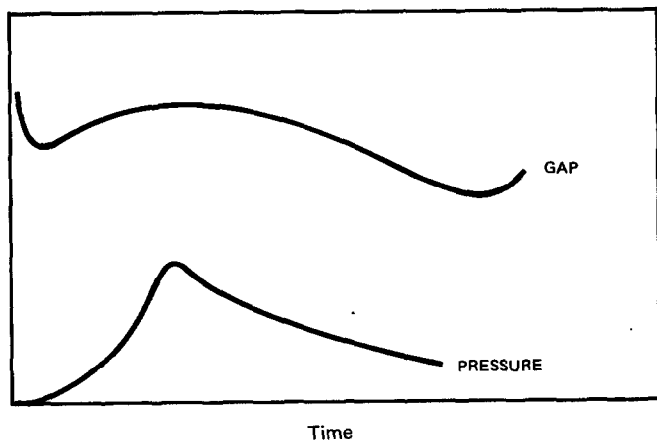


Fig. 5. Sketch of explosion pressure and gap for flame transmission (methane).

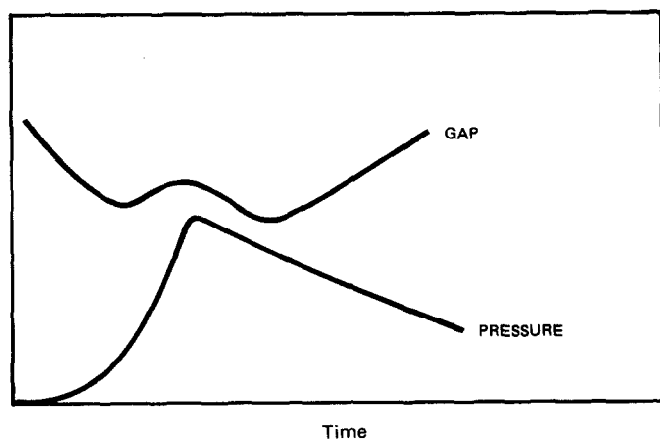


Fig. 6. Sketch of explosion pressure and gap for flame transmission (hydrogen).

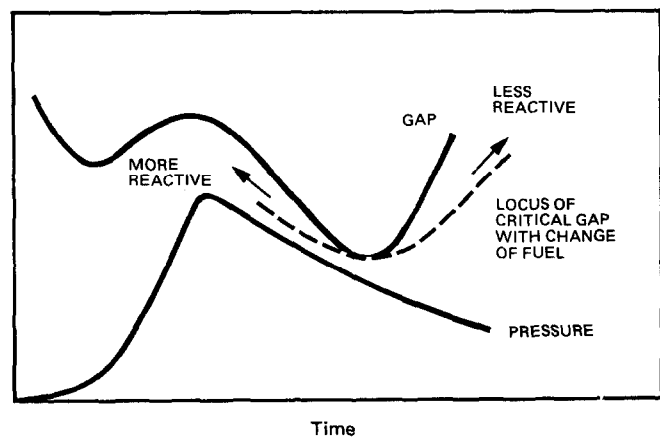


Fig. 7. Sketch of explosion pressure and gap for flame transmission (group IIB fuels).

### Exceptions

There remain a few compounds that do not fit this explanation.

Acetylene has given cause for concern to many workers trying to determine its MESH. In many European experiments it behaves like hydrogen, giving an MESH of about 0.3 mm, but on other occasions decomposition reactions occur on carbon particles and much smaller MESH's are reported, some as low as 0.05 mm. The low MESH value for acetylene reported in the Westerberg apparatus (0.076 mm) suggest that the apparatus may be more consistently affected by the decomposition reactions than European apparatuses.

Diethyl ether and dimethyl ether have very small MESH's in the Westerberg apparatus, about one third of the European values obtained in spherical vessels. Strehlow et al. [14] call these 1:3 compounds or "Mavericks". These two ethers (but not isopropyl ether) are distinguished from other compounds tested in the Westerberg apparatus by their low ignition temperatures, 350°C for dimethyl ether and 160°C for diethyl ether [22], and by a long delay before ignition in the receptor vessel. This points to an auto-ignition mechanism throughout the volume of the receptor vessel rather than a re-ignition in the jet of products entering the receptor. A complete study of spontaneous or auto-ignition in the receptor is not yet possible because there has been no experimental study of spontaneous ignition in similar conditions; i.e. hot vitiated fuel/air mixtures at high pressure in a vessel with cold walls. The effects of vitiation, pressure, and cold walls probably depend on the chemistry of the initiation reactions.

From the results in the Westerberg apparatus it appears that the ignition of pentane may be inhibited by the cold walls because otherwise it might have been expected to appear with the 'Mavericks'. The ignition temperature of pentane is usually reported as 243°C [22].

Carbon disulphide might also be expected to be with the 'Mavericks' on account of its low ignition temperature. In the European apparatuses ignition takes place slowly, through a very narrow gap. In the Westerberg apparatus these conditions lead to maximum heat losses, both to the flange surfaces and to the vessel walls; as a result the temperature in the receptor vessel would not be high enough for spontaneous ignition.

The remaining 'Maverick' is ammonia. At normal ambient temperature and pressure ammonia is barely flammable. Any increase in temperature or pressure might be expected to extend its flammability limits considerably. This is reflected in the large reduction in MESH in the Westerberg apparatus when the jet of combustion products is expelled into vitiated ammonia-air at elevated temperature and pressure.

### Conclusions

The Westerberg apparatus, used for determination of MESH in USA, does not always simulate typical hazard conditions for the ignition of flammable atmospheres by electrical apparatus protected by flameproof enclosure.

Because of its small receptor vessel, the Westerberg apparatus gives much smaller MESG's for some of the compounds tested than European 20 ml and 8 l vessels. Not only are the gaps smaller but the compounds appear in a different order of hazard.

Most of the discrepancies can be explained qualitatively by reference to the theory of Phillips [15–18]. Ignition is not in a relatively undisturbed flammable atmosphere, but in a hot vitiated atmosphere at elevated pressure.

For the few compounds that do not fit this explanation the probable mode of ignition is spontaneous combustion in the hot vitiated atmosphere of the receptor. This behaviour is confined to those fuels with a low ignition temperature.

Special and unique effects appear to dominate the behaviour of acetylene and ammonia in the Westerberg apparatus.

### Symbols

$B$	reaction rate constant
$C$	a constant = 0.2
$C_a$	concentration of air
$C_f$	concentration of fuel
$C_p$	specific heat at constant pressure
$E$	activation energy
$k$	a constant
$l$	flange breadth
$m$	mass
$\dot{m}_f''$	rate of mass consumption per unit volume
$m_0$	initial mass
$P$	pressure
$R$	gas constant
$s$	a constant
$t$	time
$t_0$	initial value of time
$T$	temperature
$\bar{T}$	logarithmic mean temperature
$\Delta T$	temperature drop
$V$	velocity
$W$	molecular weight
$z$	a constant
$a/f$	air/fuel ratio
$\beta$	cone angle of jet
$\delta$	flange gap
$\eta$	temperature rise efficiency
$\lambda$	thermal conductivity
$\rho$	density
$\psi$	reaction rate function

**References**

- 1 British Standards Institution, British Standard No. 5501: Part 5: 1977.
- 2 CENELEC, Standard No. 50 018, 1977.
- 3 International Electrotechnical Commission, IEC Publication 79-1, 2nd edn., 1971.
- 4 International Electrotechnical Commission, IEC Document SC 32 A (Central Office) 23, 1977.
- 5 G.A. Lunn and H. Phillips, Safety in Mines Research Establishment, Report No. 2, 1973.
- 6 British Standards Institution, British Standard No. 5345: Part 1: 1976.
- 7 British Standards Institution, British Standard No. 5501: Part 1: 1977.
- 8 CENELEC, Standard EN 50 014, 1977.
- 9 International Electrotechnical Commission, IEC Document 79-12, 1978.
- 10 R.E. Defour and W.C. Westerberg, Underwriters Labs Inc., Bulletin of Research 58, 1969.
- 11 F.D. Alroth, E.M. Briesch and P.J. Schram, Underwriters Labs Inc., Bulletin of Research 58A, 1976.
- 12 F.D. Alroth and P.J. Schram, Underwriters Labs Inc., Bulletin of Research 58B, 1977.
- 13 National Fire Protection Association, National Electrical Code, Article 500 (ANSI-CI), 1975.
- 14 R.A. Strehlow, E. Magnuson, A. Nicholls and P.J. Schram, J. Hazardous Materials, 3 (1979) 1.
- 15 H. Phillips, Safety in Mines Research Establishment, Research Report No. 257, 1977.
- 16 H. Phillips, Combust. Flame, 20 (1973) 121.
- 17 H. Phillips, Combust. Flame, 19 (1972) 181.
- 18 H. Phillips, Combust. Flame, 19 (1972) 187.
- 19 J.B. Fenn and H.F. Calcote, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, 1953, p. 231.
- 20 S.Y. Goh and A.S.C. Ma, Fourth All-Union Heat and Mass Transfer Conference, Minsk, USSR, 1972.
- 21 K.H. Grobleben, 12th International Conference of Mine Safety Research Establishments, Dortmund, 1976. Paper 36.
- 22 C.J. Hilado and S.W. Clark, Chem. Eng., 79 (1972) 75.