A COMPARISON OF 'STANDARD' METHODS FOR THE DETERMINATION OF MAXIMUM EXPERIMENTAL SAFE GAP (MESG)

Harry Phillips
Health and Safety Executive
United Kingdom

Abstract

Two apparatus have been used for the determination of Maximum Experimental Safe Gap (MESG). An 8-l spherical vessel has been used in the United Kingdom and in Germany. The current international standard is the 20-ml vessel developed in Germany. Results from both vessels are reported. The Westerberg apparatus of Underwriters' Laboratories gives MESGs at variance with the results from spherical vessels. This is due to the confinement of the 'external atmosphere' into a volume smaller than the primary explosion vessel.

SCOPE

MESG determinations have been reported for two types of experimental explosion vessel, the spherical bomb and the Westerberg apparatus. In this section the data from the spherical vessels are reported and the use of the Westerberg apparatus is discussed. Much of the data appeared in Lunn and Phillips (1) and the Westerberg apparatus was considered by Strehlow, Magison, Nicholls, and Schram (2) and by Phillips (3,4).

HISTORY

The first experiments on the transmission of a gaseous explosion through narrow channels were by Davy (5) and Stephenson (6). Stephenson continued to use an array of narrow channels to prevent flame transmission from his flame lamp, the 'Geordie' lamp, but Davy preferred to use a layer of gauze.

Explosion transmission from electrical machines in coal mines was first researched by Beyling (7). He found that transmission of a methane-air explosion could be prevented by a gap between 50-mm flanges of 1.2 mm.

For many years the MESG was determined in an 8-l spherical vessel. The first paper to describe the use of this vessel in the United Kingdom was by Statham and Wheeler (8). They established the use of 1-in. (25-mm) flanges as 'standard', demonstrated that side ignition was more hazardous than central ignition for methane, and that the size of the spherical explosion vessel, in the range 1 to 8 l, had no effect on MESG.

DEFINITIONS

The MESG is defined in the now obsolete British Standard 229:1957 as 'The widest gap which has been found to prevent ignition of the most easily ignited external mixture when the most incendiary mixture of the same combustible is exploded inside the test vessel'. Neither the internal ignition position nor the vessel volume are specified in the definition and the most hazardous combination is implied. The use of different mixtures inside and outside the test vessel was dropped and a more recent definition appears in British Standard 5501: Part 5: 1977. 'The maximum gap of a joint 25 mm in width which prevents transmission of an explosion in 10 tests made under the conditions specified in IEC 79-1A'.

The external flammable atmosphere should represent the atmosphere that might surround electrical apparatus in industry. That is, it should be unconfined so that the external explosion can develop without a significant increase in pressure.

The MESG is the minimum value of the safe gap in the standard apparatus with varying internal ignition position. In the 8-1 spherical vessel this is generally with internal ignition close to the flange gap but exceptionally, for carbon disulfide, the minimum MESG occurs with central ignition. For hydrogen there is no difference between side and central ignition.

The two main types of spherical apparatus are the 8-1 vessel and its modifications and the IEC 20-ml vessel and its modifications. Earlier determinations in other vessels have all been repeated in one of these 'standard' vessels.

EARLY DETERMINATIONS

Some of the early determinations with the 8-1 vessel in the United Kingdom were subject to criticism because the flange gaps sprang open under the internal explosion pressure. With the apparatus shown in Figure 1 the flanges were held closed by 'G' clamps that distorted under load. All the suspect determinations except one have been repeated with more rigid apparatus, Figure 2 (9): the exception is ethyl nitrate and its safe gap reported in BS 229 (10) is stated to be less than 0.025 mm. This value is not included in the list of data at the end of this section.

An early German apparatus used a sphere with the external atmosphere contained within a rigid toroidal enclosure surrounding the equatorial flange gap. (Figure 3, taken from Redeker (11)). For explosion vessel volumes in the range 20 ml to about 500 ml the size of the vessel had no effect on MESG. Above 500 ml the confinement of the external atmosphere played an increasing role in reducing the apparent MESG. (Figure 4, (11)). When the external atmosphere was confined only by a pressure-relieving thin flexible enclosure the MESG remained constant up to the maximum size of the explosion vessel, 8 1 (Figure 5 (11)). This work led to the development of the 20-ml apparatus at PTB and all early German MESG determinations have been repeated in the 20-ml vessel.

EXPERIMENTAL APPARATUS

All the data reported here with one exception was determined in spherical vessels. The apparatus used for the determination for ethyldichlorosilane was not specified, but the data are included because it is the only compound in the list that contains silicon and it has a remarkably low MESG compared with other compounds containing chlorine.

The flange breadth favored for MESG determination is 25.4 mm (1 in.) or 25 mm. Other breadths have been used for research purposes but data for 25-mm flanges are generally accepted as the criteria for grouping the compounds.

For British MESG determinations an 8-1 spherical vessel was used and the two designs are shown in Figures 1 and 2. Figure 1 is the earlier version, but it had the disadvantage that with very small gaps the flanges could spring open to give an erroneously small result. The doubtful values were repeated in the vessel shown in Figure 2 (9) and it is the latter values that are now reported. The internal mixture was not the same as the external; they were both chosen to give the least value of MESG and usually they straddled stoichiometric. Ignition was by a small spark 10 mm inside the flange gap but the result was checked with central ignition. Usually side ignition gave the lower MESG but for gases in Group IIC central ignition was more hazardous. The lower value of MESG is reported. The MESG was the largest gap to give no ignition in 20 repeat trials with the gap varying in steps of 0.025 mm.

The data of Sack and Soder (12) were also obtained in an 8-1 vessel but the experimental procedure was different. (The apparatus is described in the East German Standard TGL 14275 (13)). The mixture inside and outside was the same, chosen to give the least value of MESG and ignition was by a hot wire, 10 mm inside the flange gap. The MESG was the largest gap to give no ignition in 30 trials with 0.05-mm increments.

Determinations by PTB were made in a 20-ml vessel shown in Figure 6, taken from Helwig and Nabert (14). The results were similar to those of the 8-1 vessel with the exception of carbon disulfide. The discrepancy can be explained by reference to the physics of the ignition process. The same mixture was used inside and outside. Ignition was by electric spark 10 mm from the flange gap. The MESG was the gap giving no ignition in three repeat trials with the gap adjusted in steps of 0.02 mm.

The more recent determinations at SMRE by Lunn (15) was also with a 20-ml vessel. The first vessel (Figure 7) was suitable for use at ambient temperature and was an adaptation of an earlier cylindrical vessel (16). A later version, Figure 8, was contained in a glycerine bath and permitted determination at elevated temperature. The MESG was the largest gap that gave no ignition in 20 repeat trials with the gap adjusted in steps of 0.02 mm (15).

Significant features of the new apparatus are the large external vessel and the hand pump for mixing gases. These permitted a rapid approximate assessment of MESG. If a trial resulted in a failure to ignite the external mixture, the gases were mixed and the trial repeated. Five non-ignitions could be checked before the gases were changed. For the final determination gases were changed for each trial. Concentrations were not measured but the quantity of gas of liquid added was varied to find the most dangerous quantity.

THE EFFECT OF PRESSURE

In the PTB vessel the pressure was maintained at 760 mm of Hg. In the United Kingdom, the pressure was the ambient at Buxton, averaging about 730 mm of Hg. For the 20-ml vessel a pressure correction to 760 mm of Hg was applied (See (17)) but for the 8-l vessel the ambient pressure was not recorded and no correction has been applied. Lunn (15) expressed the pressure correction as:

$$\text{Corrected MESG (100 kPa)} - \text{Measured MESG}/(0.35 + 0.0065P)$$

where P is the ambient pressure in kPa.

The Effect of Temperature

There has not so far been any reference to a standard temperature for the determination of MESG. In the United Kingdom work with the 8-l sphere most determinations were made at ambient temperature but a few compounds had flash points that did not permit the mixtures to be prepared at ambient temperature. For these the test temperature was increased to 50°C.

For PTB determinations where ambient temperature (20°C) was not adequate, the test temperature was 5°C above that required to produce a vapor pressure corresponding to the most dangerous mixture.

In recent SMRE determinations with the 20-ml vessel the concentration of the most dangerous mixture was not measured (but the addition of the flammable gas or liquid was regulated to find the most dangerous quantity to inject). When ambient temperature was not high enough the test temperature was 10°C above that required to give a vapor pressure 1.5 times stoichiometric.

Where necessary a temperature correction has been applied to reduce the data to 20°C. The correction was based on experimental evidence of the effect of temperature on the MESG of ethylene. Lunn (15) expressed the temperature correction as:

$$\text{Corrected MESG (100 kPa, 20°C)} = \frac{\text{Corrected MESG (100 kPa)}}{1.1061 - (0.0071 * T)}$$

where T is the experimental temperature in °C.

The Table of Data

In the table the compounds are arranged in order of:
a) increasing number of carbon atoms,
b) increasing number of hydrogen atoms,
c) other atoms in alphabetical order.

Reference to the data is numbered and references appear at the end of the table of MESG determinations.

The name is that given by British Standard BS 2474 (1965) and in general the recommendations of the International Union of Pure and Applied Chemistry (18) have been taken into account.

Grouping of Gases and Vapors According to MESG

The IEC classifies apparatus into groups according to the hazard presented by the flammable atmosphere. Group I is for apparatus to be used in an atmosphere that might contain methane; this group is reserved specifically for coal mine applications. Group II is subdivided into IIA, IIB and IIC with IIA for the least hazardous compounds, pentane and propane being typical, and IIC for the most hazardous, hydrogen being typical.

The demarcation between the groups is according to either the MESG or the Minimum Igniting Current (MIC). Since much more data are available for MESG, and as a link has been established between MIC and MESG it has been usual to accept data for MESG alone. Group IIA is for compounds having an MESG above 0.9 mm; Group IIB between 0.5 and 0.9 mm, and Group IIC below 0.5 mm. It is significant that IEC does not define a lower limit of MESG for group IIC.

There are a number of compounds with their MESGs grouped around the lower limit of Group IIA, 0.9 mm. For these compounds there is a risk that experimental error might be sufficient to decide the allocation of the Group, either IIA or IIB. There is a view that the demarcation might be placed with advantage at 0.8 mm where the data are sparse but this view has not been accepted by the IEC.

Exceptional Compounds

There are two compounds whose data should be interpreted with care.

The MESG of carbon monoxide is stated for a mixture that is moist (not saturated) at ambient temperature. It is well known that addition of moisture, or other hydrogen-bearing compounds, greatly increases the burning velocity of carbon monoxide, and likewise these additions also lead to a significant reduction in MESG.

For acetylene various values of MESG have been reported but under certain ill-defined circumstances external ignition has been reported at flange gaps too small to measure.

The Westerberg Apparatus

In the United States MESG determinations are made with the Westerberg apparatus described by Underwriters' Laboratory (20,21,22) and the results are used in the groupings for U.S. Standards (23). Not only do some of the MESG determinations differ from those obtained in European apparatus but to such an extent that the fuels appear in a different order of hazard rating, 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. (2).

Strehlow et al. (2) described the differences between the experimental apparatus and suggested that MESG is an apparatus-dependent measurement. He tabulated the differences and Table 1 is a shortened version. The discrepancy is illustrated in Figure 9.

Table 1: Comparison of UL and European MESG Data.

Name	MESG mm	
	UL	European
Methylacetylene	0.64	0.74
Dimethyl ether	0.36	0.95
Ethylenediamine	0.74	1.47
Methane	1.12	1.15
Diethyl ether	0.30	0.87
Ethylene	0.69	0.68
Propane	0.94	0.96
Ammonia	1.02	3.18
Hydrogen	0.20	0.28
Propylene oxide	0.53	0.70

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 vapor in the atmosphere. To imitate this, the receptor vessel should be so designed that increases in its size have no effect on the result obtained, which in practice places a lower limit to the acceptor volume. As an alternative the receptor vessel may vent to the atmosphere to avoid significant pressure rise. A further requirement is that no part of the receptor should interfere with the formation of the jet of burnt gas outside the flange gap. The Westerberg apparatus does not comply with the receptor volume requirements and it is probably this aspect of design that led Strehlow to the conclusion that MESG is apparatus dependent. Strehlow et al. (2) suggested ignition delay as a variable, but this now appears not to be the case. The discrepancy in results is a consequence of the ignition mechanism.

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 nor pressure relief is provided.

Primary Ignition

Events immediately following internal ignition in the Westerberg apparatus should be much the same as in the other apparatus. 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 apparatus. 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 of safe gaps developed earlier.

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 flange surfaces are reduced. 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 explosion. The two stages at which MESG reaches a minimum are referred to below as the first and second critical stages.

However, at the second critical stage the hot gas flows into a receptor that has been heated and pressurized 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 MESG determinations in the Westerberg apparatus, although actual values of MESG cannot be calculated.

The first effect of the gas flow into the receptor is on heat transfer to the flange surfaces. The temperature drop in the gas depends inversely on pressure, so that the gas in the jet is hotter in the second critical stage than the first.

The fluid mechanics aspects of the jet remain unchanged.

The rate of combustion 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 the reaction rates. However, the increase in reaction rates is opposed by the effects of heat losses to the walls of the receptor and by the effects of dilution of the reacting gases by vitiation (the concentration terms in the heat release rate equation). 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 MESG in the second critical stage appears to be reduced more for some fuels than for others.

Effects on Different Fields in the Westerberg Apparatus

For methane, illustrated schematically in Figure 10, 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 loss to the apparatus. The reduction in MESG 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 MESG.

On the other hand, for hydrogen (see Figure 11) 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 MESG could be expected. A longer delay would lead to a larger reduction in MESG.

Thus, for the most reactive and the least reactive compounds MESG is only slightly reduced in the Westerberg apparatus. For intermediate compounds (see Figure 12), predominantly those in Group 2B of the IEC classification, the differences are greater. Strehlow et al. (2) 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 MESG.

Exceptional Gases in the Westerberg Apparatus

There are a few remaining compounds that do not fit this explanation.

Acetylene has given cause for concern to many workers trying to determine its MESG. In many European experiments it behaved like hydrogen, giving an MESG of about 0.3 mm, but on other occasions decomposition reactions occur on carbon particles and much smaller MESGs are reported, some as low as 0.05 mm. The low MESG reported for the Westerberg apparatus (0.075 mm) suggests that the apparatus may be more consistently affected by the decomposition reactions than European apparatus.

Diethyl ether and dimethyl ether have very small MESGs in the Westerberg apparatus, about one third of the European values obtained in spherical vessels. Strehlow et al. (2) 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 (24), 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., in hot vitiated fuel/air mixtures at high pressure in a vessel with cold walls. It is probable that neither of the two critical jet events leads to ignition but that after a suitable delay the spontaneous ignition reactions ignite the mixture. It is a feature of spontaneous ignition experiments that at lower ignition temperatures there is a delay between injection of the fuel and its ignition. 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 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 343°C (24).

Carbon disulfide might also be expected to be with the 'mavericks' on account of its very low ignition temperature. In the European apparatus ignition takes place slowly, through a very narrow gap. In the Westerberg apparatus these conditions lead to maximum heat losses, both to the flange surface 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 MESG in the Westerberg apparatus when the jet of combustion products is expelled into vitiated ammonia/air at elevated temperature and pressure.

Summary of the Safe Gap Anomaly in the Westerberg Apparatus

The Westerberg apparatus 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 MESGs 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 theoretical treatment of safe gaps by Phillips (25). Ignition is not in a relatively undisturbed flammable atmosphere, but in a hot, vitiated atmosphere at elevated pressure.

For a 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 behavior is confined to those fuels with a low ignition temperature.

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

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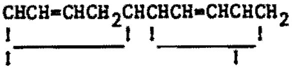
Table.

Name	Structure	Reference	Temperature C	MESG mm	MESG mm Corrected to 20 C
hydrogen	H_2	1,2		0.29	0.29
		37		0.28	0.28
		5		0.20	0.20
ammonia	NH_3	38		3.18	3.18
hydrogen sulphide	H_2S	2a		0.90	0.90
hydrogen cyanide	HCN	1		0.80	0.80
carbon monoxide (moist, see p)	CO	1,2		0.94	0.94
		27		0.91	0.91
carbon monoxide (saturated at 18 C)	CO	4	18	0.84	0.84
carbon disulphide	CS_2	1,2		0.34	0.34
		7		0.20	0.20
formaldehyde	HCHO	4		0.57	0.57
formic acid	HCOOH	4	85	1.75	1.86
chloromethane	CH_3Cl	5		1.00	1.00
nitromethane	CH_3NO_2	4	87	1.11	1.17
methane	CH_4	1,2		1.14	1.14
		9		1.17	1.17
		5		1.15	1.15
methanol	CH_3OH	1,2		0.92	0.92
		15	50	0.91	0.93
		5		0.96	0.95
methylamine	CH_3NH_2	5		1.10	1.10
tetraflouroethylene	$CF_2{=}CF_2$	5		0.60	0.60
acetylene	C_2H_2	1,2		0.37	0.37
(see p 5)		6		<0.025	<0.025
vinilidene chloride	$CH_2{=}CCl_2$	1		3.91	3.91
vinyl chloride	$CH_2{=}CHCl$	1,2		0.99	0.99
		31		0.96	0.96
acetonitrile	CH_3CN	1		1.50	1.50
ethylene	$CH_2{=}CH_2$	1		0.65	0.65
		12		0.68	0.68
1,2 dichloroethane	CH_2ClCH_2Cl	1	33	1.80	1.82
ethylene oxide	$\underbrace{CH_2CH_2O}$	1,2		0.59	0.59
		28		0.66	0.66
acetaldehyde	CH_3CHO	4		0.92	0.92
acetic acid	CH_3COOH	4	73	1.69	1.76
methyl formate	$HCOOCH_3$	4		0.94	0.94
nitroethane	$C_2H_5NO_2$	4	67	0.84	0.87
ethyl nitrite	C_2H_5ONO	29		0.96	0.96
ethane	CH_3CH_3	1,2		0.91	0.91
dimethyl ether	$(CH_3)_2O$	1		0.84	0.84
		5		0.95	0.95
ethanol	C_2H_5OH	1,2	33	0.89	0.91
		22	50	1.01	1.04
ethanethiol	C_2H_5SH	4		0.90	0.90
diethylamine	$(CH_3)_2NH$	5		1.15	1.15

unsymmetrical dimethyl hydrazine	$(CH_3)_2NNH_2$	4a		0.85	0.85
acrylonitrile	$CH_2=CHCN$	1		0.87	0.87
		5		0.90	0.90
propyne	$CH_3C\equiv CH$	4		0.74	0.74
allyl chloride	$CH_2=CHCH_2Cl$	4		1.17	1.17
1-chloro 2,3-epoxypropane	OCH_2CHCH_2Cl	4	58	0.95	1.00
cyclopropane	$CH_2CH_2CH_2$	4		0.91	0.91
propene	$CH_2=CHCH_3$	1		0.91	0.91
		4		0.94	0.94
propylene oxide	CH_3CHCH_2O	1		0.70	0.70
allyl alcohol	$CH_2=CHCH_2OH$	4	30	0.84	0.84
acetone	$(CH_3)_2CO$	4		1.04	1.04
		36		1.01	1.01
ethyl formate	$HCOOCH_2CH_3$	4		0.94	0.94
methyl acetate	CH_3COOCH_3	16		0.99	0.99
1,3,5 trioxane	$OCH_2OCH_2OCH_2$	4	90	0.71	0.75
2-chloropropane	$(CH_3)_2CHCl$	39		1.32	1.32
dimethylformamide	$HCON(CH_3)_2$	4	90	1.02	1.08
1-nitropropane	$C_3H_7NO_2$	4	71	0.81	0.84
propane	$CH_3CH_2CH_3$	1,2		0.92	0.92
		25		0.96	0.96
		5		1.00	1.00
propan,1-ol	$CH_3CH_2CH_2OH$	4	51	0.87	0.89
		5	45	1.15	1.18
propan,2-ol	$(CH_3)_2CHOH$	1	32	0.99	1.00
2-methoxyethanol	$CH_3OCH_2CH_2OH$	4	63	0.81	0.85
trimethylamine	$(CH_3)_3N$	5		1.05	1.05
propylamine	$CH_3(CH_2)_2NH_2$	4		1.13	1.13
furan	$CH=CHCH=CHO$	4		0.68	0.68
thiophene	$CH=CHCH=CHS$	3		0.91	0.91
1-butyne	$C_2H_5C\equiv CH$	4		0.71	0.71
buta,1,3-diene	$CH_2=CHCH=CH_2$	1,2		0.79	0.79
		30		0.83	0.83
crotonaldehyde	$CH_3CH=CHCHO$	4		0.81	0.81
methyl acrylate	$CH_2=CHCOOCH_3$	1		0.85	0.85
		4		0.85	0.85
vinyl acetate	$CH_3COOCH=CH_2$	1		0.94	0.94
ethanoic anhydride	$(CH_3CO)_2O$	4	78	1.17	1.23
but,1-ene	$CH_2=CHCH_2CH_3$	4		0.94	0.94
but,2-ene	$CH_3CH=CHCH_3$	4		0.89	0.89
tetrahydrfuran	$CH_2(CH_2)_2CH_2O$	3		0.87	0.87
		4		0.87	0.87
		5		0.95	0.95
butyraldehyde	$CH_3CH_2CH_2CHO$	4		0.92	0.92
butanone	$C_2H_5COCH_3$	1,2		0.92	0.92
		34		0.84	0.84
ethyl acetate	$CH_3COOCH_2CH_3$	1		0.99	0.99
		19		1.04	1.04

1,4-dioxane	$\underline{OCH_2CH_2OCH_2CH_2}$	4		0.70	0.70
tetrahydrothiophene	$\underline{CH_2(CH_2)_2CH_2S}$	3		0.99	0.99
1-chlorobutane	$CH_3(CH_2)_2CH_2Cl$	1		1.06	1.06
morpholine	$\underline{OCH_2CH_2NHCH_2CH_2}$	4	58	0.92	0.95
butane (mixed isomers)	C_4H_{10}	1,2		0.98	0.98
		26		1.06	1.06
diethyldichlorosilane	$(C_2H_5)_2SiCl_2$	6		0.45	0.45
diethyl ether	$(C_2H_5)_2O$	1,2		0.87	0.87
		33		0.83	0.83
		6		0.90	0.90
butan,1-ol	$CH_3(CH_2)_2CH_2OH$	20	50	0.94	0.96
		4	64	0.87	0.91
2-methyl propan,1-ol	$(CH_3)_2CHCH_2OH$	21	50	0.96	0.98
2-ethoxyethanol	$C_2H_5OCH_2CH_2OH$	4	78	0.78	0.84
diethyl sulphate	$(C_2H_5)_2SO_4$	4	135	1.01	1.11
1-aminobutane	$C_4H_9NH_2$	4		1.16	1.16
furfuraldehyde	$\underline{OCH=CHCH=C}CHO$	4	94	0.88	0.94
methyl methacrylate	$CH_2=CCH_2COOCH_3$	5		0.95	0.95
acetylacetone	$CH_3COCH_2COCH_3$	2	70	0.92	0.96
ethyl acrylate	$CH_2=CHCOOC_2H_5$	1		0.86	0.86
		4		0.86	0.86
cyclopentane	$\underline{CH_2(CH_2)_3CH_2}$	4		1.01	1.01
pentan,2-one	$CH_3COC_3H_7$	4		0.99	0.99
pentan,3-one	$C_2H_5COC_2H_5$	4	48	0.88	0.90
tetrahydrofurfuryl alcohol	$\underline{OCH_2CH_2CH_2CH}CH_2OH$	4	100	0.80	0.85
propyl acetate	$CH_3COOCH_2CH_2CH_3$	1	35	1.04	1.05
pentane (mixed isomers)	C_5H_{12}	1		0.93	0.93
		8		0.99	0.99
isopentane	$(CH_3)_2CHCH_2CH_3$	1		0.98	0.98
amyl alcohol (mixed isomers)	$C_5H_{11}OH$	17	50	0.99	1.02
nitrobenzene	$C_6H_5NO_2$	4	127	0.86	0.94
benzene	C_6H_6	9		0.99	0.99
ethyl methacrylate	$CH_2=CCH_2COOC_2H_5$	4	30	1.01	1.01
cyclohexanone	$\underline{CH_2(CH_2)_4CO}$	1	60	0.95	0.98
ethyl acetoacetate	$CH_3COCH_2COOC_2H_5$	1	104	0.90	0.06
		4	103	0.98	1.04
diethyl oxalate	$(COOC_2H_5)_2$	4	112	0.90	0.97
cyclohexane	$\underline{CH_2(CH_2)_4CH_2}$	1		0.94	0.94

4-methylpentan,2-ol	$(CH_3)_2CHCH_2COCH_3$	1	60	0.98	1.01
butyl acetate	$CH_3COOCH_2(CH_2)_2CH_3$	24	50	1.01	1.04
butylhydroxyacetate	$HOCH_2COOC_4H_9$	1		0.88	0.88
2-ethoxyethyl acetate	$CH_3COOCH_2CH_2OC_2H_5$	4	73	0.91	0.97
n-hexane	$CH_3(CH_2)_4CH_3$	1,2		0.93	0.93
		10		0.96	0.96
hexanol (mixed isomers)	$C_6H_{13}OH$	1	70	0.94	0.98
diisopropyl ether	$((CH_3)_2CH)_2O$	1		0.94	0.94
ethyl digol	$CH_3CH_2OCH_2CH_2OCH_2CH_2OH$	4	120	0.86	0.94
benzotriflouride	$C_6H_5CF_3$	1		1.40	1.40
hept,2-ene	$CH_3(CH_2)_3CH{=}CHCH_3$	4		0.97	0.97
amyl acetate (mixed isomers)	$CH_3COOC_5H_{11}$	18	50	0.98	1.02
heptane	C_7H_{16}	1		0.91	0.91
heptane (mixed isomers)	C_7H_{16}	32		0.91	0.91
heptan,1-ol	$C_7H_{15}OH$	4	100	0.88	0.94
xylene	$C_6H_4(CH_3)_2$	14	50	1.06	1.09
octane	$CH_3(CH_2)_6CH_3$	1		0.94	0.94
iso-octane	$(CH_3)_2CHCH_2C(CH_3)_3$	1		1.04	1.04
		13	50	1.04	1.07
octan,1-ol	$C_8H_{17}OH$	4	116	0.95	1.05
dibutyl ether	$(C_4H_9)_2O$	1		0.86	0.88
		4	50	0.86	0.88
di-tertiary butyl peroxide	$(CH_3)_3COOC(CH_3)_3$	4b	55	0.58	0.56
butyl digol	$CH_3(CH_2)_3OCH_2CH_2OCH_2CH_2OH$	4	133	1.01	1.11
butyl styrene	$C_6H_5C(CH_3){=}CH_2$	3		0.88	0.88
dicyclopentadiene (technical)	 $CHCH{=}CHCH_2CHCHCH{=}CHCHCH_2$	4	70	0.87	0.91
dipentene	$C_{10}H_{16}$	4	68	1.14	1.18
decane (mixed isomers)	$C_{10}H_{22}$(approx)	23	50	1.01	1.05
paraformaldehyde		4		0.57	0.57

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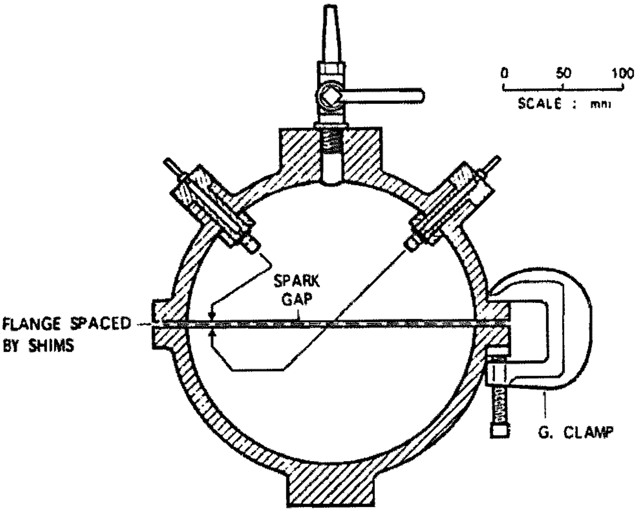


Figure 1 8-1 explosion vessel with 'G' clamps.
(Safety in Mines Research Establishment, United Kingdom)

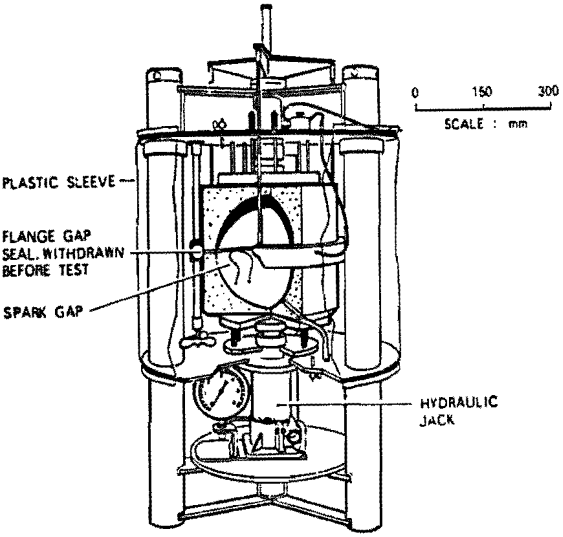


Figure 2 8-1 explosion vessel with improved rigidity.
(Safety in Mine Research Establishment, United Kingdom)

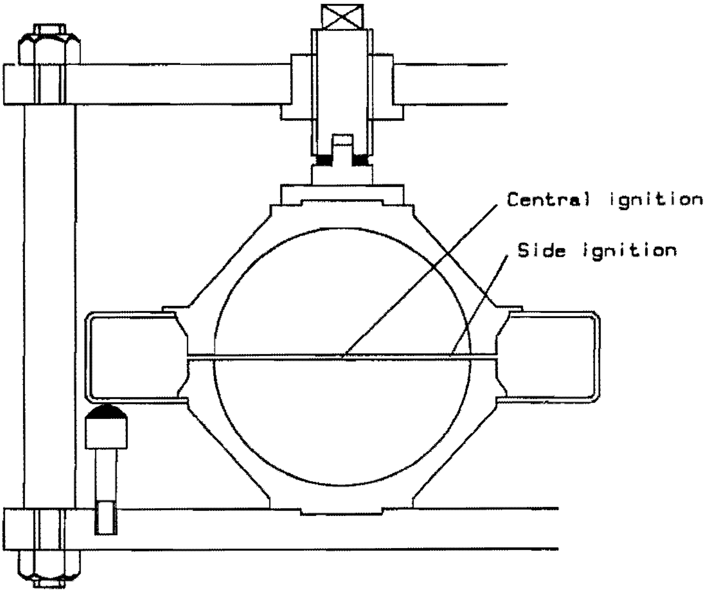


Figure 3 8-l explosion vessel with confined external atmosphere (PTB, Germany).

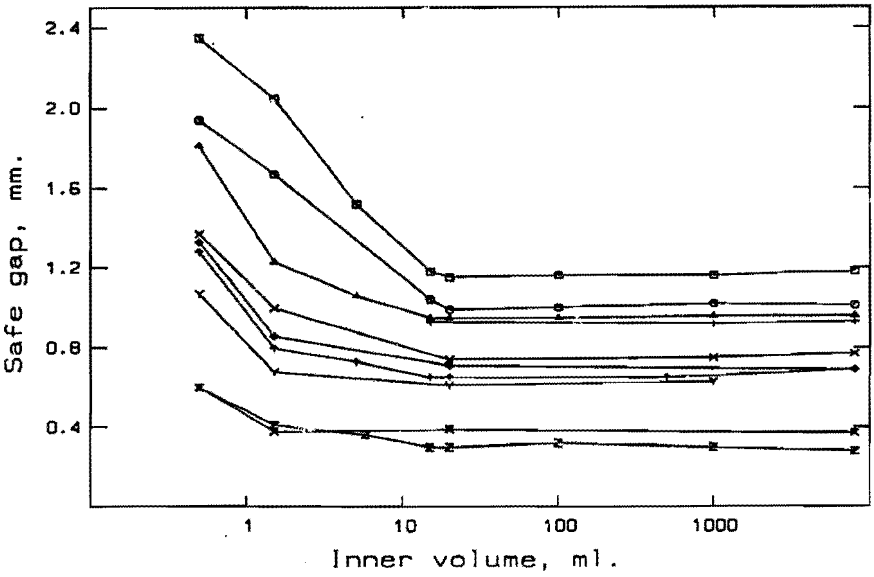


Figure 4 The effect of vessel volume with a confined external atmosphere (PTB).

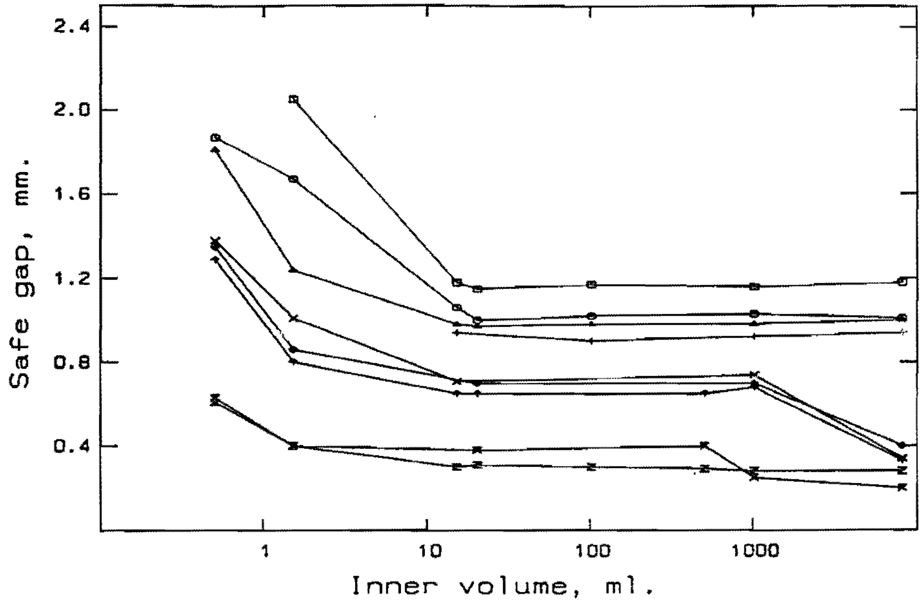


Figure 5 The effect of vessel volume with an unconfined external atmosphere (PTB).

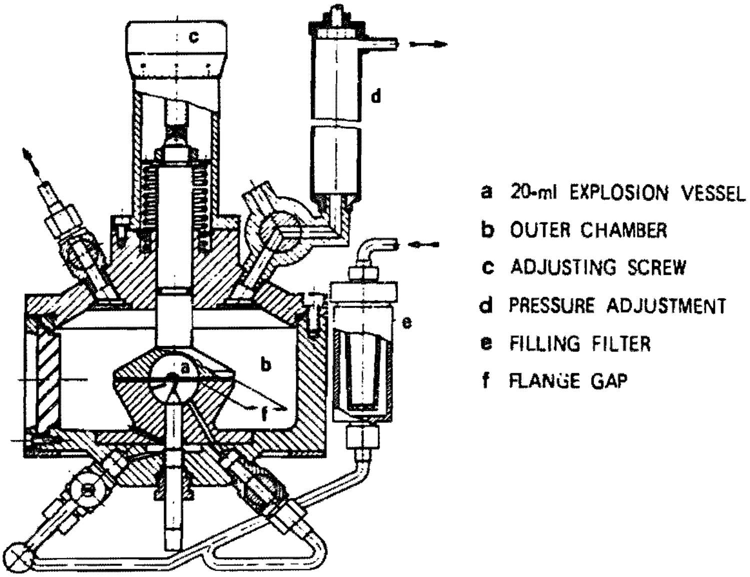
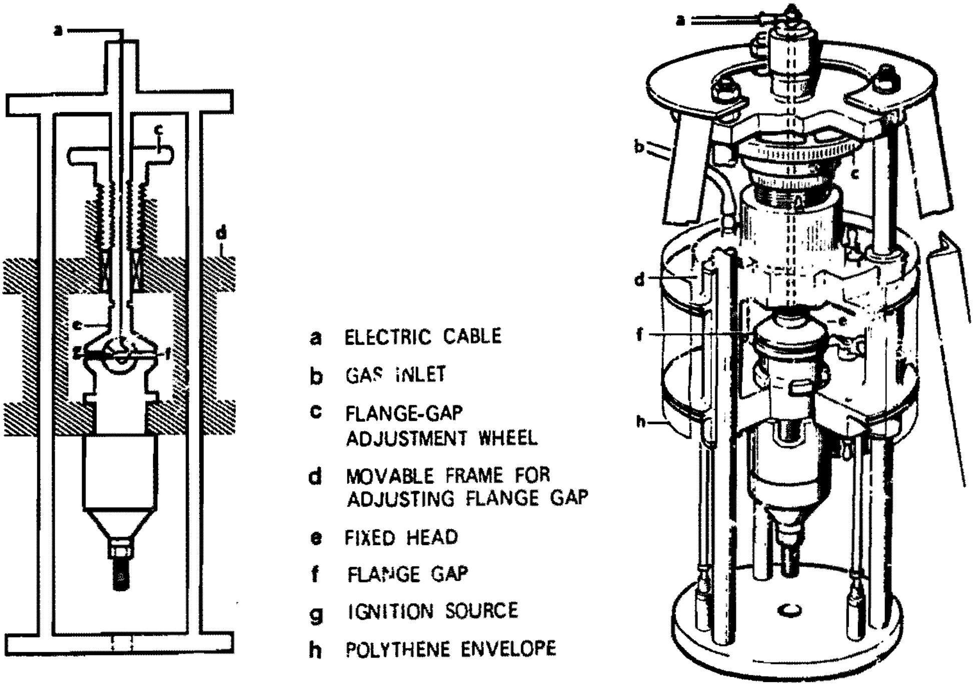


Figure 6 20-ml explosion vessel (PTB).



Principle of operation

General view of apparatus

Figure 7 20-ml explosion vessel (HSE).

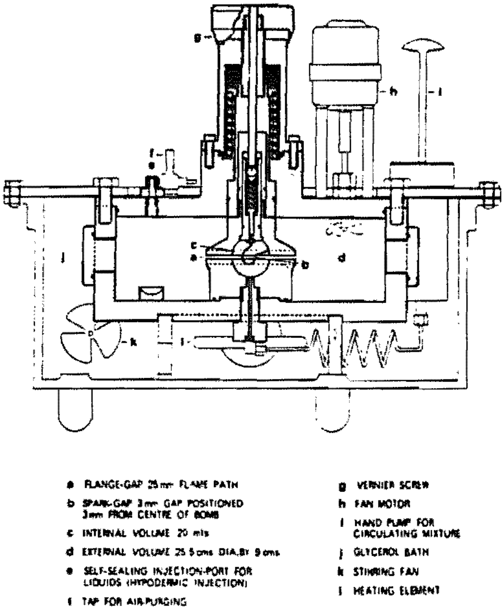


Figure 8 High temperature flange-gap bomb for MESGs (HSE).

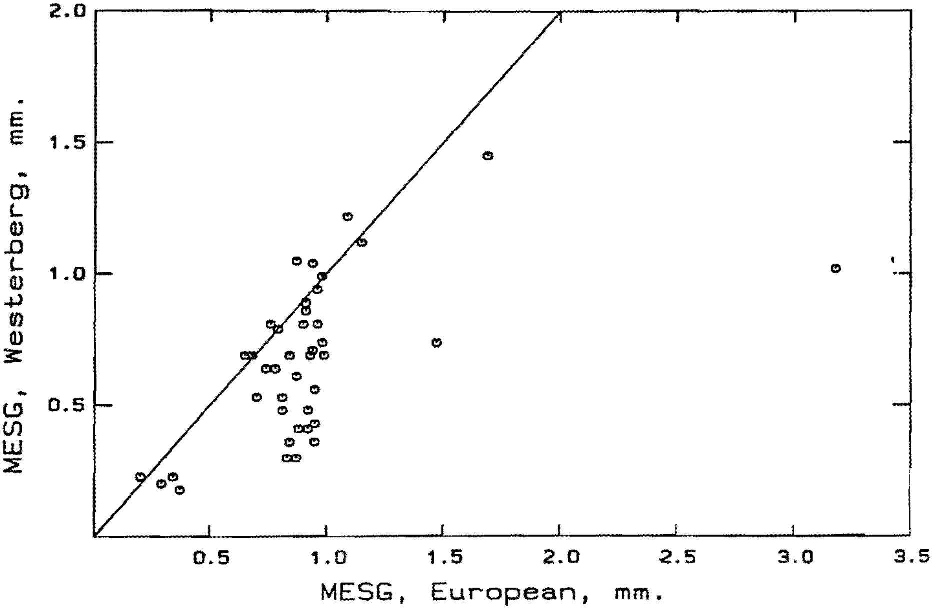


Figure 9 Comparison of MESG determinations in European and in the Westerberg apparatus.

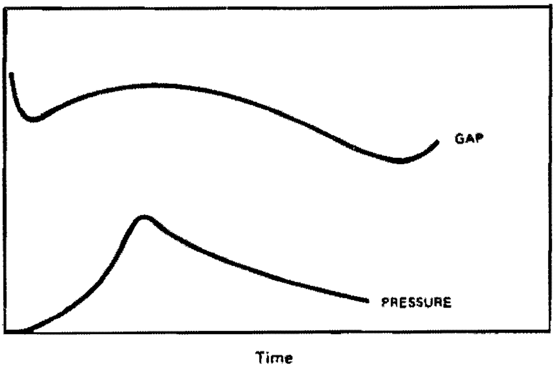


Figure 10 Sketch of explosion pressure and gap for flame transmission (methane).

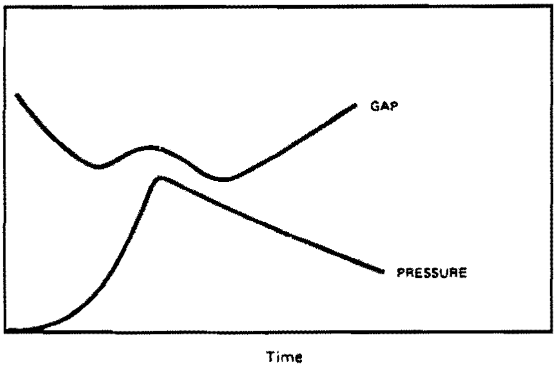


Figure 11 Sketch of explosion pressure and gap for flame transmission (hydrogen).

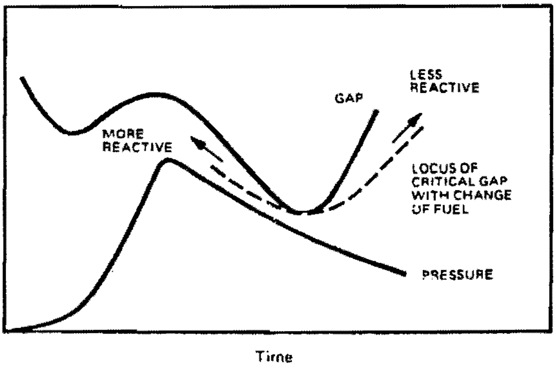


Figure 12 Sketch of explosion pressure and gap for flame transmission (Group IIB gases).

PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON THE EXPLOSION HAZARD CLASSIFICATION OF VAPORS, GASES, AND DUSTS

Organized by the Committee on
Studies on Hazardous Substances

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