

Accidental Ignitions and Explosions of Gases in Ships

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An outline is given of the initiation and development of gaseous explosions, considering in turn the explosive medium, the source of ignition and the behaviour and control of the explosion flame. Emphasis is placed upon those detailed aspects which experience has shown to be relevant to the explosion hazard on ships, and the numerical data quoted for illustration relate to the hydrocarbons, representing petroleum, fuels and lubricants, and to some combustible refrigerants.

INTRODUCTION

Two conditions must be fulfilled in order that the inflammation of a mixture of flammable gas with air may take place. They are:

- 1) The relative proportions of flammable gas and air in the mixture must lie between certain limits.
- 2) A source of ignition must be applied, capable of initiating spreading flame within the mixture.

If these conditions are satisfied, then flame will spread, from the source of ignition, throughout the flammable mixture. The mixture is thus converted progressively, but quickly, into hot products of combustion, and expansion results. Should the mixture be confined in an enclosure of any kind, the progressive expansion of the mixture will result in a progressive exertion of pressure on the enclosure. If the pressure becomes greater than can be borne by the walls of the enclosure, these will fail, and the accompanying projection of debris, associated with the generation of sound and pressure waves, will be characteristic of what is generally understood by an "explosion".

The two conditions just referred to provide a convenient basis for considering the various aspects of gaseous explosion and they will be used here for a general exposition of the subject. It is worth pointing out however that they also provide a foundation for a policy of explosion prevention, since the successful avoidance either of flammable mixtures or of effective sources of ignition will necessarily avert the possibility of an explosion of this type. Again, in the unfortunate event of an explosion having taken place, identification of the explosive medium and of the source of ignition must be the principal objectives of an investigation of the cause.

It must however be remembered that even though an explosion may be initiated through a coincidence of the two essential factors, the resultant damage depends much upon the manner and degree of spread of the explosion flame. For this reason, in the last section of this paper, attention will be given to the factors influencing the development of a gas explosion, once initiated, and particularly to measures that may be adopted to limit its spread and effects.

A difficulty that arises, in attempting to present general information about gas explosions that is of practical value, is that quantitative characteristics differ for different gases and in many cases have not been measured accurately or at all. In a paper on explosions in a context of shipping, however, prominent reference must be made to hydrocarbons (in connexion

with fuels, lubricants, hydraulic oils and petroleum generally) which are particularly well documented on account of their commercial importance. The other class of flammable gases, that is of substantial interest in this area, is that of the refrigerants, exemplified by ammonia and methyl chloride (the freons are non-flammable).

THE EXPLOSIVE MEDIUM

It is to be expected that the most flammable mixture of a fuel gas with air will be that in which the proportions of the constituents are those required to give only the final products on combustion, for example, carbon dioxide and water in the case of a hydrocarbon gas. Dilution of this ideal mixture either with air or with the fuel gas will lead to reduced flammability and, in fact a limit will be reached, in both cases, beyond which, even though a source of ignition is applied, flame propagation will not take place. The limit at which an excess of air is present, and fuel is in defect, is known as the "lower" limit of flammability; whereas that in which the fuel is in excess is known as the "upper" limit. It is often found that the lower limit mixture contains about half the "ideal" proportion of fuel gas, and (although this is liable to even more variation) the upper limit mixture contains about twice this proportion.

Precise values of the limits of flammability—which are of obvious practical importance—are to some extent dependent upon the apparatus in which they are measured. While no particular form of apparatus can be described as "standard", one form at least has been very widely used. This consists of a vertical tube, of not less than 2in. internal diameter and 5-6ft. long closed at the upper end, but open at the lower end—at least when the test takes place. In this tube mixtures are prepared and tested by the application of a small flame at the lower, open end. By trial, lower and upper limit compositions are found at which the flame initiated by the source of ignition just travels the full length of the tube.

Table I shows values of the limits determined in this way for various hydrocarbons and other gases mixed with air. These values are taken from a publication⁽¹⁾ which is a standard source of reference on the subject of limits of flammability generally.

Limit compositions are commonly expressed, as in columns II and IV, in percentage of fuel by volume in the mixture. If, however, units are employed in which the fuel is measured by weight, lower limit values for the hydrocarbons, at least, assume a measure of uniformity. This is illustrated by the figures in column III, which show lower limits in ounces of fuel per cubic foot of air at atmospheric temperature and pressure. From these it can be seen that for the hydrocarbons generally a

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TABLE I—LIMITS OF FLAMMABILITY OF GASES AND VAPOURS IN AIR from Coward and Jones⁽¹⁾ and Burgoyne and Neale⁽³¹⁾

Gas or vapour	Limits of flammability		
	Lower		Upper
	Fuel vol.— per cent (II)	Oz. fuel/ cu. ft. air (III)	Fuel vol.— per cent (IV)
(1)			
Methane	5.3	0.044	14
Ethane	3.0	0.042	12.5
Propane	2.2	0.043	9.5
n-Butane	1.9	0.049	8.5
iso-Butane	1.8	0.048	8.4
n-Pentane	1.5	0.049	7.8
iso-Pentane	1.4	0.046	7.6
n-Hexane	1.2	0.047	7.5
iso-Hexane	1.2	0.047	7.0
n-Heptane	1.2	0.050	6.7
n-Octane	1.0	0.051	(6.4)*
2,2,3 Trimethylpentane	1.1	0.058	(6.0)*
n-Decane	0.8	0.051	(5.4)*
Ethylene	2.95	0.038	28.5
Propylene	2.4	0.046	10.3
Butylene	2.0	0.051	9.6
Acetylene	2.5	0.030	75
Benzene	1.4	0.049	7.1
Cyclopropane	2.4	0.046	10.4
Cyclohexane	1.3	0.049	8
Ammonia	17.2	0.157	25.4
Methyl chloride	10.7	0.241	17.4

*Values in parentheses were not obtained with the 2-in. tube.

Lower limit value of about 0.045 oz./cu. ft. can be accepted. This is obviously of value in considering mixed hydrocarbon gases (as in petroleum) since the composition of the fuel gas mixture is immaterial to the limit value. It is further useful to remember that the metric unit, gm. fuel/litre of air, is very nearly the numerical equivalent of oz./cu. ft. Unfortunately upper limits are susceptible to no such simplification, but in safety practice upper limit values are very much less used than lower limit values. It is usually more satisfactory to provide for an adequate dilution of fuel gases with air than to limit the amount of air present. The complete exclusion of air is of course a common aim, but clearly this does not involve a knowledge of the upper limit value.

It is useful, at this stage, to relate limits of flammability with the conception of "flash-point". The latter is an index of the flammability of a liquid which is measured in certain conventional forms of apparatus. Their design has a certain influence on the results obtained. In principle however, the "closed flash-point" of a liquid is that temperature at which its vapour pressure is such that the saturated vapour just reaches the lower flammability limit concentration in air at atmospheric pressure. Therefore, if a liquid, in sufficient quantity, stands at its closed flash-point temperature in a closed vessel containing air in the ullage space, this space above the liquid will in due course become filled with vapour at the lower limit concentration. Ignition in the space can therefore lead to a vapour explosion at this, or some higher temperature, but not at a lower temperature. If, on the other hand, the liquid, at its closed flash-point temperature, stands in an open vessel, air circulation will dissipate the vapours released, but at the very surface of the liquid a flammable mixture will be present. If a source of ignition is applied here a flash will be obtained. If the temperature is raised somewhat, to the "fire-point", such ignition will lead to continuing burning of vapour evolved from the liquid as a "fire". If the source of ignition is applied at some distance above the liquid surface, ignition will only be obtained if the liquid is again at a temperature somewhat above its closed flash-point. The necessary temperature, known as the "open flash-point", depends upon the height of the source above the liquid surface, and is not a characteristic property of the liquid, unless this height is defined.

Although increases in temperature and pressure tend to widen the range of flammability of a gas, normal atmospheric variations do not have an appreciable effect. Although a sufficient pressure reduction below atmospheric will narrow, and ultimately extinguish, the range completely, increases of even a few atmospheres have a very small effect on the lower limit. The effect of increasing pressure in increasing the flash-point of a liquid is therefore determined by the need to increase the saturated vapour pressure in proportion to the air pressure.

In the case of the higher hydrocarbons, a sufficient increase in pressure and/or temperature will raise the upper limit abnormally due to the incidence of "cool flames" over an extended range of rich mixture composition⁽²⁾.

Combustible liquids of high flash-point can give rise to explosive mixtures if finely divided and dispersed in air. If the droplets are less than about 0.015 mm. in diameter, the suspension can be inflamed just like a gas/air mixture and has similar properties because the droplets are completely volatilized by heat transfer from the oncoming flame before being consumed by it⁽³⁾. With larger drops, the process of volatilization may not be complete before the flame arrives, and drops of liquid become involved in it. The flame is then controlled and extended by the relatively slow process of evaporation prior to combustion. For droplet sizes below about 0.015 mm. diameter the lower limit of flammability, expressed in weight of fuel per unit volume, is the same as for the vapour, being about 0.045 oz./cu. ft. for the higher hydrocarbons. For larger drop sizes, the lower limit appears to drop a little and then to increase⁽⁴⁾. A suspension of drops exclusively of the order of 1 mm. diameter or more is not readily flammable, except in the face of a fast explosion that may disrupt the drops into smaller ones before the flame arrives.

Mist and spray explosions are of interest in ships in connexion with crankcase explosions, the best known example of which in recent years was that in the m.v. *Reina del Pacifico* in 1947. The most usual explanation of an explosion of this type is believed to be that lubricating oil, in contact with some overheated part, forms a very fine flammable mist by an evaporation-condensation process and this is fired by the hot surfaces⁽⁵⁾. It is possible that the initial explosion flame causes some disruption of the larger oil drops present due to mechanical dispersion in the same or adjoining crankcases. Thus the explosion may be permitted to extend.

In practice, the usefulness of precise flammability limit values is limited because frequently the fuel vapour is not uniformly mixed with the air. In these circumstances the "average" composition gives an unrealistic picture. The explosion of unmixed gases is a neglected subject, but in the last year or two attention has been given to it at the Safety in Mines Research Establishment, Buxton. In the coal mines, methane ("fire-damp") issuing from the coal measures is apt, being lighter than air, to form an unmixed layer beneath the roof of the workings. In such circumstances, ignition at an appropriate level will lead to the propagation of flame at the interface of the layer with air. The rate of progress of the flame is controlled by the mixing of the methane with the air and is at first comparatively slow. As the flame progresses however, the resultant disturbance may well promote the mixing of the layer with air ahead of the flame and so the latter accelerates. In due course, the mixing ahead of the flame becomes so effective that the latter is progressing through thoroughly mixed gas at the normal explosion speed.

Behaviour of an unmixed layer of higher hydrocarbon vapour is analogous, but in this case of course, the vapour, being heavier than air, accumulates along the ground, in the bottom of tanks and in similar situations. If the vapour is completely stratified, it will burn slowly when ignited, as a "fire" rather than an explosion. Insofar as mixing has occurred, before ignition, to form a mixture within the limits of flammability, or insofar as the spread of burning can continue far enough to promote pre-mixing, something more akin to an explosion will occur.

A travelling explosion flame not only promotes the mixing

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ahead of stratified gas, but also, if its speed is greater still, liquid or solid deposits of combustible material. It has long been known, that the extension of coal mine explosions (usually originating with a gas ignition) through great lengths of roadway, is due to the involvement of deposited coal dust. The classical remedy of spreading incombustible stone dust over the coal dust deposits in the roadways takes advantage of this knowledge and of the fact that the stone dust and the coal dust will be raised together by an oncoming explosion, to form, if the proportion of stone dust be great enough, a non-flammable cloud.

In recent years, Loison⁽⁶⁾ has shown that, in a compressed air system, if an explosion is initiated in the presence of some added gas, and attains sufficient speed, oil films on the inner walls of the piping can become involved and can ultimately continue the explosion in the compressed air unaided by the original gas. It is believed that the explosion in the starting air system of a large passenger liner, in 1960, was of this nature.

It is clear, therefore, that although a small amount of gas/air mixture within the flammable range of composition is necessary to initiate an explosion, it is by no means to be assumed that the subsequent spread of the explosion flame will be limited to such pre-formed mixture. Initially unmixd combustible matter in the form of a layer of gas or vapour, a dust deposit, or a liquid film may well become involved if the impetus of the initial explosion flame is great enough. The precise conditions under which such involvements occur provide excellent opportunities for further research.

Flame propagation is suppressed in narrow spaces. A 2-in. diameter tube is used for measuring limits of flammability because at this size the results obtained are substantially independent of the tube diameter. If, however, the tube diameter is substantially reduced, the measured range of flammability is narrowed and ultimately flame propagation becomes impossible. The largest diameter at which this is so is known as the "quenching diameter" for the particular gas in air. Its value does not depend upon the material from which the tube is made. The "quenching distance", relating to marginal flame suppression between parallel surfaces, is a little less than the "quenching diameter", for the same gas/air pair. Table II shows minimum quenching diameter values for certain gases in air at atmospheric pressure (the quenching diameter is approximately inversely proportional to the absolute pressure of the gas mixture). It must be emphasized that these values relate to a stationary gas mixture. Should

TABLE II

- (a) Minimum quenching distances in air at 100 deg. C. (212 deg. F.) and atmospheric pressure.
 (b) Maximum experimental safe gaps in air at atmospheric temperature and pressure.

Fuel	(a) M.Q.D.(in.)	(b) M.E.S.G.(in.)
Methane	0.076	0.046
Propane	0.067	0.038
n-Butane	—	0.042
n-Pentane	0.0682	0.035
n-Hexane	0.0680	0.038
n-Heptane	0.0655	0.036
n-Octane	0.0653	—
iso-Octane	0.0734	0.041
n-Nonane	0.0648	—
n-Decane	0.0664	0.040
Ethylene	0.0440	0.028
Acetylene	0.018	—
Benzene	0.0622	0.039
Toluene	0.0775	—
o-Xylene	0.0807	—
m-Xylene	0.0865	} 0.042
p-Xylene	0.0865	
Ethylbenzene	0.0622	
Ammonia	—	0.125

the gas be flowing in the direction of flame propagation, a smaller diameter will be necessary to quench flame. On the other hand, should the gas be flowing against the flame propagation, a larger diameter will stop the flame. With a sufficient gas speed the explosion flame, propagating against the flow, may be stabilized at a constriction, remaining there indefinitely and possibly causing damage by local heating.

The range of flammability is also narrowed by the presence in the mixture of added non-flammable gas (such as nitrogen, carbon dioxide, or steam). A sufficient addition will suppress flammability completely. Minimum quantities necessary to do this are shown in Table III⁽⁷⁾. Generally

TABLE III—MINIMUM ADDED INERT GAS CONTENT IN AIR FOR SUPPRESSION OF FLAMMABILITY OF VARIOUS FUELS

Fuel	Requisite added inert gas content of air (vol.—per cent)		
	Nitrogen	Carbon dioxide	Methyl bromide
Methane	38	24	5.3
Ethane	46	33	—
Propane	43	30	—
n-Butane	41	28	—
iso-Butane	41	27	—
n-Pentane	43	29	—
n-Hexane	42	29	7.2
Ethylene	50	41	12
Propylene	43	30	—
Cyclopropane	43	31	—
Cyclohexane	—	—	7.6
Benzene	45	32	—

speaking the effectiveness of an inert gas in this application is related to its heat capacity, since the function of the additive is to lower the temperature of the explosion flame. Certain extinguishing materials, exemplified by halogen derivatives of the hydrocarbons (methyl bromide, carbon tetrachloride, chlorobromomethane) have a specific chemical effect in suppressing the flame.

SOURCES OF IGNITION

A short survey of 16 serious explosions that have occurred in ships since the Second World War has shown that the predominant cause of ignition was the exposure of hydrocarbon vapours in air to high temperatures in hot spaces or near overheated surfaces. In just half of the cases, including two crankcase explosions and one air-starting line explosion, this was, or was thought to be, the mechanism of ignition. In a further four cases, discharges of static electricity from steam equipment were strongly suspected, and in two instances the striking of a mechanical spark was the most likely cause of ignition. Of the remaining two cases, one was attributed to the rupture of a live electrical lead, but in the other the cause of ignition was too uncertain to mention possibilities.

This brief review illustrates the point that sources of ignition are somewhat diverse in practice. The point is further emphasized on looking more closely at the records of the explosions and noting the lack of certainty with which the "most probable cause of ignition" could be identified. Usually an alternative explanation at least merits consideration. One is left with the impression that sources of ignition are elusive in practice and that it is best, in trying to avoid explosion, not to rely exclusively on their elimination, since this must be uncertain. Rather it is advisable to control, as far as possible, the handling of the flammable materials so that explosive mixtures are not formed.

From a scientific point of view, it is profitable to distinguish two ways in which ignition may take place: spontaneously, throughout a volume of gas mixture, due to the conditions of temperature prevailing, and locally, from a small source of energy, followed by flame spread through the relatively cool mixture.

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Spontaneous Ignition

If a combustible gas mixture is introduced into a sufficiently heated enclosure it will undergo a chemical reaction, known as "slow combustion". This results in the release of heat, but, because this heat is released slowly, it is discharged to the walls of the enclosure as it is released and there is no significant rise in temperature of the gas. At higher temperatures, this reaction takes place more quickly and there comes a temperature at which the heat is released more rapidly than it can be discharged to the enclosure. In these circumstances, the gas mixture self-heats, the reaction self-accelerates and flame appears throughout the mixture. The mixture is then said to have ignited spontaneously and the lowest temperature at which this happens is the spontaneous ignition temperature (S.I.T.) for that mixture. Variation in the ratio of fuel gas to air in the mixture gives rise to some variation in the S.I.T. found, but a lowest value can be distinguished corresponding to an optimum ratio, which represents the minimum S.I.T. in air for the fuel gas concerned. Methods of measuring the S.I.T. for liquid, as well as gaseous fuels are fully discussed by Mullins⁽⁸⁾, who also gives a compendium of results. Table IV shows the lowest ascertainable S.I.T. for the hydrocarbons and other gases in air at atmospheric pressure.

TABLE IV—MINIMUM SPONTANEOUS IGNITION TEMPERATURES FOR VARIOUS FUELS IN AIR AT ATMOSPHERIC PRESSURE

Fuel	S.I.T. deg. C.	Fuel	S.I.T. deg. C.
Methane	537	Cyclopropane	498
Ethane	472	Cyclohexane	246
Propane	466	Ethylene	485
n-Butane	405	Propylene	458
iso-Butane	462	1-Butene	384
n-Pentane	258	1-Pentene	298
iso-Pentane	420	1-Hexene	272
n-Hexane	240	1-Heptene	263
iso-Hexane	307	1-Octene	256
n-Heptane	223	1-Decene	244
n-Octane	220	1-Tetradecene	239
2, 2, 3 Trimethyl-pentane	420	1-Hexadecene	240
n-Nonane	206	1-Octadecene	251
iso-Nonane	227	Acetylene	305
n-Decane	206	Benzene	562
n-Dodecane	203	Toluene	536
n-Tetradecane	202	Ethylbenzene	432
n-Hexadecane	202	n-Propylbenzene	456*
n-Octadecane	235	n-Butylbenzene	412
n-Nonadecane	237	Ammonia	651
n-Eicosane	240	Methyl chloride	632

*Probably too high.

Consideration of the figures relating to the normal paraffin hydrocarbons shows a continual drop in the S.I.T. with increasing molecular weight, corresponding to increasing reactivity towards oxygen. Between n-butane and n-pentane however, there is a sudden drop from above 400 deg. C. (725 deg. F.) in the former case to well below 258 deg. C. (496 deg. F.) in the latter. This corresponds with the incidence of "cool flame" ignitions at atmospheric pressure in the latter case. Such ignitions are obtainable under atmospheric pressure with all the higher paraffins, but with n-butane and lower members, only at elevated pressures, when the S.I.T. in these cases too, comes down below 300 deg. C. (572 deg. F.). Only methane is exceptional, for in this case cool-flame ignitions are not obtained and the S.I.T. is always above 400 deg. C. (752 deg. F.) even at quite high pressure. The branched-chain (iso-) paraffins are less reactive to oxygen than the straight-chain (normal) paraffins of similar molecular weight and amongst these compounds, the transition to low S.I.T. at atmospheric pressure does not occur until the iso-nonanes are reached. The trend to lower S.I.T. continues with increasing molecular weight towards the higher hydrocarbons, but with those of very high molecular weight (beyond n-hexadecane [cetane]) low volatility apparently prevents optimum mixtures being obtained,

even in the S.I.T. range, and so the observed ignition temperatures tend to rise.

The paraffin hydrocarbons have been most fully investigated in this connexion because of their availability and importance. There is every reason to think however, that other hydrocarbon series, and indeed other organic fuel series generally, show analogous S.I.T. trends with increasing molecular weight. Usually the first member of each series does not give low temperature (cool-flame) ignitions even at elevated pressure.

Spontaneous ignition of any gas mixture is associated with a definite delay period varying from a fraction of a second to many minutes, during which certain chemical reactions, necessary to initiate the ignition process, are going on. With increasing temperature of ignition, this delay is progressively shortened and the minimum S.I.T. corresponds with a maximum delay period for the mixture concerned. It can be seen from this that in the case of a gas mixture flowing through a heated enclosure (in contrast to residing there indefinitely) spontaneous ignition will only occur if the residence time of the mixture in the space equals or exceeds the ignition delay period for the temperature concerned. Thus if the mixture is flowing quite slowly, ignition will take place at the minimum S.I.T. For faster flows however, the temperature for ignition will be raised in accordance with the rate of flow. The relationship existing between the ignition temperature and the volumetric rate of gas flow is usually of the form:

$-\log(\text{flow rate}) = A/\text{absolute temperature} + B$, where A and B are constants, whose value depends upon the nature of the fuel and the fuel/air ratio in the mixture concerned.

Ignition by Local Sources

If a local source of heat is immersed in a gas mixture, convection currents are set up which cause the mixture to flow upwards past the hot source. The residence of the mixture in the neighbourhood of the source is therefore automatically limited. In this case however, a temperature difference exists between the source and the gas, and there are temperature gradients in the gas itself. It is to be expected therefore that the source temperature for ignition of the gas will be high compared with the S.I.T., and particularly so as the source is made smaller. Thus Guest⁽⁹⁾ has shown that when methane/air mixtures are ignited by hot metal strips $4\frac{1}{2}$ in. long, $\frac{1}{8}$ in. wide and 0.04 in. thick, strip temperatures of well over 1,000 deg. C. (1,832 deg. F.) are required. Compared with this, the S.I.T. for methane in air is 537 deg. C. (999 deg. F.). In experiments on the ignition of gas mixtures flowing under forced convection past hot rods and filaments, some success has been achieved in correlating the reciprocal of the source absolute temperature for ignition with the logarithm of the ratio, source dimension/gas velocity, the latter being a measure of the residence time of the gas mixture near the hot source⁽¹⁰⁾. Different regimes prevail, of course, according as the flow of the gas around the source is laminar or turbulent.

With local ignition sources however, it is not sufficient, as in spontaneous ignition, to bring a volume of the gas mixture to a certain temperature for a certain time for ignition to succeed. It is necessary also that the volume of gas so treated shall be above a certain minimum if the resultant ignition is to give rise to a continuing flame throughout the rest of the mixture. Thus Rae, Singh and Danson⁽¹¹⁾ have shown that, to ignite a methane/air mixture by a small hot patch in a cold wall— an area of at least 18 mm. square at 1,000–1,100 deg. C. (1,832–2,012 deg. F.) or 3 mm. square at 1,600 deg. C. (2,912 deg. F.) is required.

The point is made more clear by a consideration of ignition by electrical discharges. If the discharge of a condenser of capacitance, C charged to a voltage V is employed to ignite a gas mixture, the energy dissipated is $E = \frac{1}{2} CV^2$ and if the circuit is free from resistance and inductance, most of this energy is imparted to the gas. It is found that the gas mixture will only be ignited if the energy discharged exceeds a certain amount. Clearly, the necessary condition for ignition is that the energy imparted must be sufficient to inflame

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the minimum volume of gas necessary to give a spreading flame. If the gas mixture is flowing past the source, the volume that has to be inflamed is directly related to the flow velocity and a linear connexion usually exists between the flow rate and the ignition energy.

For a given gas, the ignition energy for the stationary mixture varies somewhat with the fuel/air ratio, but a minimum value can be distinguished, usually corresponding to a mixture in the middle of the flammable range. In Table V are some

TABLE V—MINIMUM IGNITION ENERGIES FOR VARIOUS FUELS IN AIR AT ATMOSPHERIC PRESSURE AND TEMPERATURE

Fuel	Minimum ignition energy (millijoule)
Methane	0.29
Ethane	0.24
Propane	0.25
n-Butane	0.25
n-Hexane	0.25
n-Heptane	0.25
Cyclopropane	0.17
Cyclohexane	0.24
Benzene	0.22
Ethylene	0.12
Acetylene	0.02
Hydrogen	0.019

values of minimum ignition energies for some hydrocarbons with air. Apart from their theoretical significance, they are of practical value as a basis for assessing the hazard of ignition due to discharges of static electricity. The accumulation of static electricity on equipment, or on the human body, is in effect, the charging of a condenser, and if the capacitance of this condenser is known, or can be measured, and the maximum voltage that can be achieved is ascertained, the energy stored in the condenser is immediately calculable. If the discharge of this amount of energy could ignite a gas or vapour at risk, then the situation is hazardous, and steps should be taken to limit the voltage attainable, usually by bonding and earthing the unit or body concerned.

A condenser discharge is the most efficient known ignition source for a gas mixture, in that every other kind of source dissipates more energy in igniting the same gas mixture. No doubt the highly localized character of the condenser discharge, both in space and in time, explains this fact.

A more common type of electrical discharge, in practice, is that from the breaking of an inductive circuit during the passage of current, for example, at a switch, relay or accidental rupture. In this instance the energy in the discharge represents primarily that in the field of the inductance prior to breaking the circuit, but further energy may be released due to the continuation of current flow as an arc between the separating contacts. To such circuits, particularly where the circuit voltage is low (below ca. 30 volts), the principle of "Intrinsic Safety" may be applied to avert a gas ignition risk. This consists in applying to the inductive elements in the circuit, shunts (e.g. rectifiers) which will not interfere with the normal operation of the elements, but which will dissipate some of the current generated by the elements on opening the circuit, and so reduce the amount of energy available at the discharge. If the voltage, or other circumstances, are such that this preventive is not available "Flameproof Enclosure" may be employed. This consists in enclosing the potentially sparking equipment (e.g. an electric motor, or switch) in a metal box which:

- i) is strong enough to contain an internal explosion of the gas at hazard;
- ii) has all necessary gaps (e.g. alongside spindle or shaft) between inside and outside, too narrow to permit the passage of an explosion flame. Thus although internal sparking may occur, and gas mixture may be ignited, this will not give rise to explosion outside the enclosure.

Table II shows maximum gap widths that will avoid the

transmission of explosion, occurring within an enclosure, to surrounding gas/air mixture, for hydrocarbons and other gases. These widths, known as maximum experimental safe gaps (M.E.S.G.) were measured in a standard form of apparatus in which the gap was formed between a pair of flat equatorial flanges associated with a spherical explosion vessel. The breadth of the gap was one inch and although reducing this breadth tended to decrease the critical gap width in a particular case, increasing the breadth did not affect the result.

It will be noticed that the gap widths concerned, are substantially less than the quenching distances for the same gases, although some correlation is observable. This is because the internal explosion causes expansion of gas mixture through the gap, so that when the explosion flame arrives there it is travelling, not through a stationary mixture, but through one flowing in the direction of flame propagation.

Data of the kind shown in Table II form the basis of a U.K. system of classifying flammable gases with respect to the specification of flameproof equipment⁽¹²⁾. Clearly those gases having small M.E.S.G. values are more exacting in their requirements. Four groups are distinguished, in order of increasing hazard:

- Group I—Methane (reserved for coal mine applications).
- Group II—Other saturated hydrocarbons and most solvent vapours.
- Group III—A)—Ethylene, and a few other organic gases of particular hazard.
B)—Carbonization gases, e.g. coal gas, coke-oven gas, which contain substantial proportions of hydrogen.
- Group IV—Hydrogen, acetylene, carbon disulphide, and other materials of exceptional hazard.

Flameproof equipment is not at present approved in the U.K. for Group IV gases, on account of the very small M.E.S.G. values. For these "excluded gases" electrical equipment must be either isolated or situated in enclosures pressurized with air so as to prevent admission of the gas concerned.

A somewhat similar system of classification of gases is adopted with respect to intrinsically safe circuits⁽¹³⁾.

M.E.S.G. data provide a very useful basis for the classification of flammable gases generally with regard to their ability, in admixture with air, to become ignited by a small source and to propagate an explosion flame. Minimum ignition energies and quenching distances fall into line and indicate, for example, that:

- a) the saturated hydrocarbons are generally similar to one another in susceptibility, but methane is markedly less susceptible than the rest;
- b) the unsaturated hydrocarbons are more hazardous, according to the degree of unsaturation: thus, ethylene is more hazardous than the paraffin hydrocarbons, and acetylene particularly so;
- c) hydrogen is of particular susceptibility to ignition and inflammation and represents the extreme of hazard amongst common gases: in mixtures in which it appears, the degree of susceptibility is in relation to the proportion of hydrogen present;
- d) ammonia and methyl chloride are of low susceptibility to ignition and inflammation, being if anything less hazardous than methane in these respects.

Ignition by Compression and Shock Waves

One method of heating a gas mixture and causing it to ignite spontaneously is by sudden compression in a cylinder. This method has been extensively used in experimental work since, not only is it clearly relevant to Diesel engine applications, but it lends itself to precise studies of ignition delay.

The adiabatic compression of a gas mixture, initially at pressure p_1 and absolute temperature T_1 , to a higher pressure p_2 raises the temperature to

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

where γ = adiabatic index for the mixture concerned, often approximated by the value for air. Thus, if T_1 is 273 deg. K.

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(0 deg. C.), some values of T_2 corresponding to certain compression ratios, p_2/p_1 , are as follows:

p_2/p_1	T_2 deg. C.
2	57
5	153
10	242
50	521

At the pressures concerned, most hydrocarbons are ignitable in the low temperature (cool flame) range so that compression ratios of 10-15 suffice. For those ignitable only above 400 deg. C. (752 deg. F.) (e.g. methane, ethylene, benzene) compression ratios of the order of 30 are necessary.

Provided the piston velocity is less than the molecular velocity for the gas, compression in a cylinder is adiabatic (isentropic) as has been indicated. Ignition may also be brought about by the release, into a flammable mixture, of a shock wave, due for instance to a sudden release of gas through a bursting diaphragm; compression proceeds at a supersonic rate and entropy is not conserved. In these circumstances, the temperature in the shock wave exceeds the adiabatic value corresponding to the intensity (p_2/p_1) of the wave. Thus for $p_2/p_1 = 50$, the shock temperature is 987 deg. C. (1,809 deg. F.) compared with the adiabatic value of 521 deg. C. (970 deg. F.) given earlier. Moreover, a shock wave passing through a mixture in any enclosed system is likely to receive reinforcement from reflection or focussing effects and a three-fold increase in the shock (absolute) temperature might well result from this. When these effects are allowed for there seems no reason to doubt that ignition of a particular mixture in a shock wave takes place in accordance with ordinary spontaneous ignition relations, for the mixture, between temperature, pressure and delay period (i.e. time of residence in the shock wave). Having regard to the short residence times appropriate to shock wave ignitions, the ignition, even of hydrocarbons, in the low temperature range is unlikely. For high temperature ignition, a shock wave of Mach. No. approximately 3 (p_2/p_1 , say, 11) may be effective in a closed system, without focussing effects⁽¹⁴⁾. It has been shown that both the sudden release of air into a flammable mixture, and the release of a mixture, or even the flammable gas alone, into air, can give rise to shock ignitions⁽¹⁵⁾. The release of high pressure air into a pipe-system containing flammable material may give ignitions, even though the material is initially in the form of a liquid film on the pipe wall. According as the release is more or less rapid, the mechanism may be by shock (non-isentropic) or piston (adiabatic) compression.

Ignition by Friction and Impact

The hazard of gas ignition due to mechanically-produced "sparks" has long been recognized. Recent research has shown however, that a number of factors may contribute to the igniting power of such sources and that the visible "sparks" are not always necessarily involved.

Pure impact, without abrasion, is not an effective means of ignition unless one of the impacting materials fractures. Abrasion however leads to a rise in temperature between the rubbing surfaces which is limited only by the softening temperature of the more fusible material. At this stage welding of the surfaces together occurs, followed by tearing and the ejection of hot particles of the weaker material. From this description it is to be expected that hard materials that maintain their hardness to high temperatures contribute to ignition effectiveness. This is seen with rock materials which offer the greatest hazard on abrasion when they have a high content of quartz. It is thus advantageous, other things being equal, to use soft materials in regions of ignition hazard. With such materials as copper, bronze, lead and wood, this is the case although it must be remembered that with repeated use on hard materials, hard fragments become embedded in the soft material, so losing the advantage. Some soft materials, notably the light metals, magnesium, aluminium and titanium, and their alloys tend to burn as fine particles when discharged into air. Clearly, if this occurs, the particles become more hazardous. It is particularly likely to occur with the light

metals, if these strike an oxidized iron steel surface, for in these circumstances the heat of rubbing starts a "thermite" reaction between say, the aluminium, and the iron oxide, and this in turn ignites the metal particles ejected^(16, 17). If the light metal is smeared upon the oxidized iron surface, a particularly hazardous situation arises in which an impact with almost any material on the intimate light metal/iron oxide mixture will emit bulky and dangerous sparks⁽¹⁸⁾. A similar hazard arises from the coating of oxidized steel surfaces with aluminium paints⁽¹⁹⁾.

THE DEVELOPMENT AND LIMITATION OF AN EXPLOSION

When a flammable gas mixture in a sealed enclosure is ignited, the subsequent spread of the explosion flame, by converting cold mixture into hot products, results in a progressive rise in pressure. Since the pressure rise, which has its origin at any moment in the flame-front reaction, is communicated about the enclosure at sonic velocity, the instantaneous pressure may be thought of as being everywhere the same within the enclosure, provided that the latter is reasonably compact. For hydrocarbon/air mixtures, initially at atmospheric temperature, the overall pressure rise ranges from about six times with near-limit mixtures to eight to nine times in the middle of the flammable range. Expressed in this way, the increase is substantially independent of the size of the enclosure and of the initial pressure, but the pressure increase ratio decreases with a rise in the initial temperature.

The time to attain the maximum explosion pressure with a given mixture increases with increasing size of enclosure but usually rather less than might be expected if the explosion flame always travelled into the flammable mixture at the same rate. In larger enclosures therefore, the flame is usually somewhat accelerated. With hydrocarbon/air explosions, the time of pressure rise is usually too long for dynamic loading of the enclosure to occur. The ability of the enclosure to withstand the explosion pressure can therefore be judged by its strength under static pressure test.

The explosion flame is also accelerated by stirring the gas mixture during ignition or by any comparatively minor obstruction that might lead to self-stirring of the mixture during the explosion. On the other hand, the sub-division of the enclosure into a multiplicity of passages will prolong the explosion and, if carried far enough, will suppress it completely.

The rate of rise of pressure in a closed vessel gas explosion is initially very slow. It is therefore quite practicable to install a pressure detector which will observe the onset of the explosion and, through suitable circuitry, initiate preventive action. In the commercial application of this idea, the action initiated may be to switch off associated machinery, to shut off gas channels by automatically closing valves, to open pressure reliefs, and to inject suppressant fluids into the explosion space. The first and last are most commonly combined and provide an effective means of automatic explosion suppression, suited to enclosures of reasonable size and explosive media of moderate explosion rate.

The presence of an opening in an explosion enclosure of course limits the explosion pressure rise in relation to the size of the opening. For near-cubical enclosures it has been found⁽²⁰⁾ that for larger covered openings, bringing the maximum explosion pressure down to a few pounds per square inch at the most, there are two explosion pressure peaks, one (p_1) as the covering opens under the influence of the developing pressure, and a second (p_2) where the rate of combustion reaches its greatest value. Their values are given in general by:

$$p_1 = \frac{Su}{V^{1/3}} (0.30 KW + 0.40) \text{ lb./sq. in. gauge}$$

$$\text{and } p_2 = 0.26 Su K \text{ lb./sq. in. gauge}$$

where, Su = burning velocity for gas mixture (ft./sec.)

V = enclosure volume (cu. ft.)

W = pressure to open covering (lb./sq. ft.)

K = ratio: $\frac{\text{area side of enclosure}}{\text{area of opening}}$

Maximum values of the burning velocity range from 1.2ft./sec.

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for methane/air to 1.3ft./sec. for the higher paraffins and 2.3ft./sec. for ethylene.

For smaller openings, leading to higher explosion pressures, the situation becomes somewhat complicated by abnormally fast explosions and it seems best to refer to empirical data for the nearest analogy in any particular case^(21, 22, 23).

For an explosion in a compact sealed enclosure of approximately cubical or spherical shape, heat loss during the explosion is relatively small and the maximum pressure attained corresponds quite closely to the value calculated on the assumption that the explosion is adiabatic, i.e. that all the heat released is devoted to heating the products of combustion. If however, the enclosure is lengthened in one dimension, the explosion is prolonged and relative heat losses become more significant. In changing therefore from a closed box to a closed duct, the overall pressure rise, for the same gas mixture, is decreased in relation to the length/diameter ratio of the duct. In the very elongated conditions of a pipeline, it is no longer justified to assume that the pressure rises uniformly throughout the exploding mixture. Rather is a pressure peak associated with the explosion flame-front and this becomes more pronounced the faster the flame is travelling. In considering the propagation of a gas explosion through a pipeline, therefore, it becomes appropriate to examine the variation in rate of travel of the flame-front as it progresses from one end to the other.

If ignition takes place near to an open end of a long pipe containing flammable mixture, the flame sets off at a speed of some 3ft./sec. in the case of a hydrocarbon/air mixture. This speed remains uniform for a time while the hot expanded products of combustion flow freely from the open end. As the inertia and resistance to flow of the lengthening column of products increase, however, the pressure behind the flame-front rises and compression of the unburnt mixture ahead begins. As a result, the mixture through which the flame is in progress begins to flow in the direction of flame travel and so the flame accelerates. Acceleration of the flame is accompanied by continually increasing pressure in the flame-front and the emission of a series of pressure waves which coalesce into shock waves. These travel to and fro in the pipe system at a speed greatly in excess of that of the flame, with the general effect of further accelerating the flame. The mixture streaming ahead of the flame may now become turbulent still further expediting flame propagation. If all these accelerating processes are permitted to continue for long enough the flame speed may become supersonic and the flame-front becomes associated with a shock wave in the state of "detonation". This is a stable state in which the combustion takes place under the conditions of temperature and pressure prevailing behind the shock-front and the release of the energy of combustion sustains the shock intensity against the normal processes of degradation.

"Detonation" is in contrast with the state of "deflagration", or normal flame propagation, in which the flame progresses by diffusional processes of energy transfer from the burning to the unburnt gas. Detonation can only be achieved at all with mixtures having a sufficient content of combustion energy. Ranges of composition for detonation are narrowed by comparison with limits of flammability and some fuels cannot produce detonable mixtures with air at atmospheric pressure. The saturated hydrocarbons appear to be of this category, although the unsaturated ethylene and acetylene can form detonable mixtures with air, as can saturated hydrocarbons with oxygen, or with air under pressure.

As has just been described, a certain "run-up distance" permits the attainment of detonation of detonable mixtures in a long pipe. This distance is shortened in a pipe closed at the ignition end or in a pipe containing partial obstructions or merely rough walls. The latter influences cause turbulence in the exploding mixture and so accelerate the flame. Detonation may also be initiated by the use of a percussive ignition source (e.g. a detonator) which creates a shock wave at the outset. On expanding spherically into a larger volume of gas, the detonation wave tends to fail and so detonation spreading in a compact vessel is difficult to achieve.

The characteristics of detonation are that very high, though transitory, pressures are associated with the detonation-front and these are also very suddenly applied, so that the loading of equipment in which detonation occurs is dynamic and the mechanical stress is increased accordingly. Because, too, of the suddenness of pressure loading due to a detonation-front, it is difficult to control detonation by the normal methods available for explosion. It is therefore of particular importance to prevent the condition of detonation from arising.

One method of doing this is to apply explosion reliefs at intervals in a pipeline that may contain an explosive mixture. A great deal of experimental work on this topic has been carried out in recent years at the Fire Research Station, Boreham Wood^(24, 25), using propane/air mixtures as typical of hydrocarbon risks. It has been shown, for example, that for a straight unobstructed pipe, in which the propane/air mixture at atmospheric pressure is either stationary, or flowing at a rate of less than 10ft./sec., reliefs, equal in area to the cross-section of the pipe situated at intervals of 60 pipe diameters, will control the speed of the explosion flame to a reasonable value and will limit the maximum pressure in the pipe to about 2.4lb./sq. in. gauge. The reliefs are still more effective if placed more frequently, and areas of one-eighth of the pipe cross-section, every 15 diameters, limit the maximum explosion pressure to 1.5lb./sq. in. gauge. Bends and obstacles in the pipe and rates of gas flow in excess of 10ft./sec. accelerate the explosion flame and render relief requirements more onerous, but for information on these aspects the original papers should be consulted.

An alternative method of limiting the spread of explosion through pipes and avoiding the attainment of dangerous explosion flame velocities is through the use of flame arresters. These may be defined as devices which permit the flow of air or gas without undue pressure loss, but prevent the passage of an explosion flame. This purpose is achieved by subdivision of the pipe cross-section into passages which individually in cross-section are below the quenching dimension for the flowing gas mixture concerned. The form of the device may, for example, be a gauze or pad of gauzes, a perforated plate or a crimped-ribbon spiral.

Whether or not an arrester will stop the flame of a particular gas mixture depends not upon the nature of the mixture as such, but upon the flame speed attained at the point where the arrester is placed^(26, 27). It has been shown that in any particular case there is a maximum speed of flame that can be successfully arrested which is related to the characteristics of the arrester by the expression:

$$\text{Critical speed} = \frac{0.5 a v}{d^2} \text{ ft./sec.}$$

where a = proportion (0 to 1) of cross-sectional area of arrester which is free to gas flow;

y = depth of arrester (front to back, in.);

d = diameter of individual apertures, or hydraulic diameter in the case of non-circular shapes (in.), not more than the minimum quenching diameter for the gas.

Clearly, it is advantageous for the arrester to be placed near to the source of ignition (if this can be foreseen), near to an open end, or near to an explosion relief, so that the flame speed, with which it may have to cope, is minimized.

Investigations at the Gas Council's Midlands Research Station, Solihull⁽²⁸⁾, have shown that even detonations, at least of coal gas/air mixtures, can be arrested by the use of arresters of the crimped-ribbon type provided the crimp height is 0.017in. (the smallest manufactured) and the front-back depth of the arrester is not greater than given by: $y = 1.3 V^{1/5} - 4.4$ in., where V is the detonation velocity in feet per second. The task of the arrester is facilitated in this case if it is placed in an enlargement of the pipe to some 3.5 diameters. The emergence of a detonation into such an enlargement causes a temporary degradation to deflagration which is more readily suppressed.

In the applications of flame arresters so far envisaged, the

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source of ignition is pictured as somewhat remote from the arrester so that the flame approaches it preceded by a stream of flammable mixture. If ignition occurs near to the arrester, so that the explosion flame travels away from it, a stream of hot products flows through the arrester and the danger is that these may cause ignition on the other side. This is essentially the situation in partition flame traps, which have been suggested for limiting the spread of a crankcase explosion between neighbouring crank chambers^(29, 30). Here the chief function of the arrester is to cool the products sufficiently. It has been concluded that if the thermal capacity of the arrester is such that it can remove at least 46 per cent of the available heat of combustion of the exploding mixture, without itself being heated above 500 deg. C. (932 deg. F.) it is likely to be effective. A somewhat similar application of a flame arrester is to cool the hot explosion products issuing from the explosion relief valve of a crankcase (or other explosion vessel) sufficiently to avert personal injury.

REFERENCES

- 1) COWARD, H. F. and JONES, G. W. 1952. "Limits of Flammability of Gases and Vapours". Bureau of Mines Bull. 503.
- 2) HSIEH, M. S. and TOWNSEND, D. T. A. 1939. "The Inflammable Ranges of Higher Paraffin Hydrocarbons in Air". J.Chem. Soc., p. 341.
- 3) BURGOYNE, J. H. and COHEN, L. 1954. "The Effect of Drop Size on Flame Propagation in Liquid Aerosols". Proc.Roy.Soc., Vol. A.255, p. 375.
- 4) BURGOYNE, J. H. 1963. "The Flammability of Mists and Sprays". I.Chem.E. Second Symposium on Chemical Process Hazards, p. 1.
- 5) BURGOYNE, J. H. and NEWITT, D. M. 1955. "Crankcase Explosions in Marine Engines". Trans.I.Mar.E., Vol. 67, p. 255.
- 6) LOISON, R. 1952. "The Mechanism of Explosions in Compressed Air Pipe Ranges". Seventh International Conference of Directors of Safety in Mines Research, Paper No. 26.
- 7) BURGOYNE, J. H. and WILLIAMS-LIER, G. 1948. "Limits of Inflammability of Gases in the Presence of Diluents". Fuel, Vol. 27, p. 118.
- 8) MULLINS, B. P. 1955. "Spontaneous Ignition of Liquid Fuels". Butterworths, London.
- 9) GUEST, P. G. 1930. "Ignition of Natural Gas/Air Mixtures by Heated Surfaces". Bureau of Mines Technical Paper 475.
- 10) KUMAGAI, S. and KIMURA, I. 1957. "Ignition of Flowing Gases by Heated Wires". Sixth Symposium (International) on Combustion, p. 554.
- 11) RAE, D., SINGH, B. and DANSON, R. 1964. "The Size and Temperature of a Hot Square in a Cold Surface Necessary for the Ignition of Methane". Safety in Mines Research Establishment Research Report No. 224.
- 12) British Standards Institution. 1957. B.S.229—"Flame-proof Enclosure of Electrical Apparatus".
- 13) British Standards Institution. 1958. B.S.1259—"Intrinsically Safe Electrical Apparatus and Circuits".
- 14) FAX, J. 1953. "Some Experiments on the Initiation of Detonation in Hydrogen/Oxygen Mixtures by Uniform Shock Waves". Fourth Symposium (International) on Combustion, p. 501.
- 15) PAYMAN, W. and SHEPHERD, W. C. F. 1949. "The Ignition of Gas Mixtures by Impulsive Pressures". Third Symposium on Combustion Flame and Explosion Phenomena, p. 301.
- 16) TITMAN, H. 1955-56. "A review of Experiments on the Ignition of Inflammable Gases by Frictional Sparking". Trans.I.Min.E., Vol. 115, p. 536.
- 17) RAE, D. 1959. "The Ignition of Gas by the Impact of Light Alloys on Oxide Coated Surfaces". Safety in Mines Research Establishment, Research Report 177.
- 18) RAE, D. 1960. "The Ignition of Methane/Air by the Glancing Impact of Metal on Smears of Light Alloys on Rusty Surfaces". Safety in Mines Research Establishment, Research Report 190.
- 19) KINGMAN, F. E. T., COLEMAN, E. H. and ROGOWSKI, Z. W. 1952. "The Ignition of Inflammable Gases by Sparks from Aluminium Paint and Rusty Steel". J.Appl. Chem., Vol. 2, p. 449.
- 20) SIMMONDS, W. A. and CUBBAGE, P. A. 1960. "The Design of Explosion Reliefs for Industrial Drying Ovens". I.Chem.E. Symposium on Chemical Process Hazards, p. 69.
- 21) CREECH, M. D. 1941. "Combustion Explosions in Pressure Vessels Protected with Rupture Discs". Trans. A.S.M.E., Vol. 63, p. 583.
- 22) COUSINS, E. W. and COTTON, P. E. 1951. "The Protection of Closed Vessels against Internal Explosions". Chem.Eng., Vol. 58, p. 133.
- 23) BURGOYNE, J. H. and WILSON, M. J. G. 1960. "The Relief of Pentane Vapour/Air Explosions in Vessels". I.Chem.E. Symposium on Chemical Process Hazards, p. 25.
- 24) RASBASH, D. J. and ROGOWSKI, Z. W. 1960. "Gaseous Explosions in Vented Ducts". Combustion and Flame, Vol. 4, p. 301.
- 25) RASBASH, D. J. and ROGOWSKI, Z. W. 1960. "Relief of Explosions in Duct Systems". I.Chem.E. Symposium on Chemical Process Hazards, p. 58.
- 26) PALMER, K. N. 1959. "Quenching of Flames by Wire Gauzes". Seventh Symposium (International) on Combustion, p. 497.
- 27) PALMER, K. N. 1960. "Quenching of Flame by Perforated Sheeting and Block Flame Arresters". I.Chem.E. Symposium on Chemical Process Hazards, p. 51.
- 28) CUBBAGE, P. A. 1959. "Flame Traps for Use with Town Gas/Air Mixture". Gas Council Research Communication GC 63.
- 29) MANSFIELD, W. P. 1956. "Crankcase Explosions: Development of New Protective Devices". Proc.I.Mech.E., Vol. 170, p. 825.
- 30) BROWN, K. C., COOK, R. JAMES, G. J. and PALMER, K. N. 1962. "Crankcase Explosions in Marine Oil Engines, The Efficacy of Gauze and Crimped-ribbon Flame Traps". Trans.I.Mar.E., Vol. 74, p. 261.
- 31) BURGOYNE, J. H. and NEALE, R. F. 1953. "Some New Measurements of Inflammability Ranges in Air". Fuel, Vol. 32, p. 5.

Discussion

MR. R. E. KNOWLES, M.B.E. (Member) said that Dr. Burgoyne's paper was undoubtedly a lucid exposition of an extremely complex subject. Those who were concerned in the elimination of accidental ignition and explosions of gases in ships now had before them a comprehensive reference on hydrocarbon gases. As one who had an interest in ship casualties of this nature and had had the pleasure of collaborating with the author in investigating the circumstances attending a major ship explosion and fire, and also having a great respect for the author's superior knowledge in this subject, he would take the liberty of saying how pleased they were that Dr. Burgoyne had consented to deliver this excellent paper that evening.

Factors such as the increasing quantities of crude oil carried nowadays at sea, the effect of the oil pollution regulations necessitating the more frequent washing of cargo tanks for the reception of clean ballast, and the catastrophic results of some post-war ship explosions, had probably influenced shipowners, and in particular tanker owners, to devise measures whereby the combustible hydrocarbon gases were made innocuous, or that such gases were rapidly purged out of oil tanks. The former method was achieved by arranging that the tanks were filled with inert gas when cargo oil or dirty water ballast was being discharged, whilst the latter method was effected by the use of large capacity blowers.

Both systems attempted to achieve a common object, namely, to remove from the explosion equation the obvious one of the two essential factors necessary to cause combustion of a suitably concentrated air/gas mixture.

However, informative as the paper unquestionably was, there were a number of points he wished to put to the author. In the section on the "Limits of Flammability" he referred to the safety range below the lower explosive limit. Whilst Mr. Knowles agreed wholeheartedly with this statement, the author must surely agree that if the atmosphere in a tank were maintained in the over-rich phase or above the upper explosive limit, this also was a safe range in normal operations. In fact, this principle was adopted in ships engaged in the carriage of liquefied hydrocarbon gases. One disadvantage with a cargo tank full of over-rich gas was that when the tank was breached, as in a collision, the heavy gas might pour out and be rapidly replaced by air, thus diluting the tank atmosphere through the explosive range. Fortunately, any sparking which might occur when the colliding ships came apart might cause a fire in the tank rather than an explosion, this probably because the development of an explosion was more positive in a closed vessel than in an open one.

In the second paragraph, on the right hand side of page 130, the author referred to cool flames and in this context he stated that the relevant circumstances appeared to be rather unusual in ships. To quote from an earlier work of his on the subject of explosions, he said, "Ignition in the cool-flame range of mixtures is not usually possible with short lived sources such as sparks, but only with long lived sources such as hot surfaces or other flames."

Accepting this statement with the respect it deserved, it therefore seemed most unlikely that cool flames could be initiated by sparking in cargo or fuel oil tanks, but surely this phenomenon could be apparent when combustible air/gas

mixtures were in contact with such hot surfaces as exhaust pipes, high temperature steam pipes and boiler fronts. Townend and McCormac in their paper on the "Inflammation of Hydrocarbon/Air Mixtures" stated that the critical oxidation of the higher paraffin hydrocarbons commenced at relatively low temperatures and pressures, with cool flames propagating through the media. Could Dr. Burgoyne enlighten them a little more on this phenomenon?

Also on page 130, the author referred to the crankcase explosion in 1947 in the m.v. *Reina del Pacifico*. Unfortunately, other instances of such explosions had since occurred. More recently the development of flame in an empty oil cargo tank was actually observed some seconds before the secondary and more violent explosion occurred. In fact, the men who were working nearby had sufficient time to run to safety. Analysing the evidence of those who had been close to these incidents, it appeared that these explosions were propagated in the following way. A hot spot or spark ignited the gas; combustion occurred but was limited in intensity, probably due to the air and gas mixture being too near the upper explosive limit of combustion or that the oxygen supply was deficient; pressure and temperature rise of the gas occurred as a result of combustion; relief took place through relief devices or rupture of the containment; drop in pressure was accompanied by drop in temperature to possibly sub-atmospheric conditions; this caused an inrush of air to bring about rapid mixing with the unconsumed combustibles; and finally, with the air and gas mixtures suitably concentrated, a secondary and more violent explosion occurred. Such, it would appear, was the mechanism of a typical crankcase or even a tank explosion, and Dr. Burgoyne's comments on the validity of this assessment would be welcomed.

In the section dealing with sources of ignition, mention was made of the generation of static in steam clouds. There was reason to believe that two violent oil tank ship explosions in the post-war years were the result of probes in the form of tank washing equipment, short circuiting static charges present in steam clouds. It was now well known that large voltages were readily generated in such environments.

It was hoped that Dr. Burgoyne could have discussed this phenomenon a little more, since it was a hazard which had to be guarded against in all processes involving the use or carriage of combustible gases. In the marine field CO₂ was probably the most common substance used for fire prevention or extinction. However, in recent years, confidence in the use of CO₂ in gassy spaces had been a little shaken, following a disastrous explosion in an underground tank partly filled with kerosene near Bittburg, Germany, in September 1954, when 29 persons were killed, and, in May 1955, an explosion which occurred in a low pressure gas holder at Hanover. In both cases the explosions occurred almost immediately following the admission of CO₂ gas into the tanks, the first in the course of a test of a fixed CO₂ extinguisher installation and the second in the course of rendering the tank atmosphere inert. Subsequent experiments and research by German scientific workers seemed to indicate that the catastrophes were probably caused by a build-up of an electrical charge in CO₂ clouds. In the course of the experiments with CO₂ ejection, sparks of some millimetres in length were observed at the outlet orifices of

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the jets and, whilst the appearance of a spark was no indication as to its ability to ignite a gas mixture, it would appear that when CO₂ was used in a gassy atmosphere, care had to be taken as to how it was admitted. Perhaps Dr. Burgoyne might care to comment on this aspect of electrostatics.

The aspects of bonding and earthing were particular to ships carrying petroleum products, where stray currents were often readily generated due to the movement of the petroleum and other extraneous causes. To reduce effectively the build-up of electrostatic charges, bonds of exceptionally low value of resistance were very necessary.

He now wished to refer to the part of the paper dealing with the subject of spontaneous ignition. In recent years a number of fires had occurred in ships' machinery spaces due to fuel oil, lubricating oil or paraffin oils overflowing, spilling or spraying on hot surfaces such as superheated steam pipes, exhaust pipes and manifolds, to result in spontaneous ignition.

In one case, a typical marine Diesel oil overflowed on to an exhaust manifold, spontaneous ignition of the evolved gases took place, and a disastrous fire resulted. The temperature of the exhaust gas at the time might have been as low as 315 deg. C. (600 deg. F.).

When reference was made to Table IV, one wondered whether spontaneous ignition at this temperature was possible. Mullins (reference 1 of the paper) described various methods of determining minimum spontaneous ignition temperatures and almost in each case the methods described involved the use of oil drops in hot crucibles. It would appear that the manner in which tests for self-ignition were carried out had a marked effect on the results.

In 1938, in an endeavour to substantiate this, tests were carried out using a turbine oil falling on to a heated pipe, 6in. in diameter. The conclusions were that as the quantity poured on the pipe was progressively increased, so there was a progressive reduction in the self-ignition temperature.

For instance, when a quantity equal to two drops was allowed to fall on the pipe, the temperature of the pipe had to be 450 deg. C. (840 deg. F.) before ignition took place. Increasing the quantity to, say, 5 c.c., ignition took place at 380 deg. C. (720 deg. F.). When the pipe was flushed with 50 to 60 c.c. of oil, ignition took place practically every time at temperatures in the order of 315 deg. C. (600 deg. F.), showing that spontaneous ignition temperatures obtained from a drop of oil could be reduced considerably when a larger quantity of oil was used.

On the basis of these tests it would therefore appear that spontaneous ignition of fuel oil could occur even at temperatures below 315 deg. C. (600 deg. F.). Perhaps the author would care to comment on this and also briefly refer to the thermal or chemical reactions that would initiate ignition of fuel or lubricating oils at these depressed temperatures.

Table V showed the minimum ignition energies for various fuels in air. It was once mentioned to Mr. Knowles that such fuels in the Table as comprised the saturated hydrocarbons, when mixed in the right proportion in air, could be ignited by the flash at the switch of a three-cell torch, but not by a two-cell torch. Since these were practical values, could the author say if there was any significance in the remark?

It was pleasing to note that a part of the paper was devoted to ignition by shock waves, since it was understood that an expanding gas with the correct resonance could burn a hole in a piece of wood in a matter of seconds, showing that stagnant volumes of gas, when resonated to the optimum frequency, generated heat of such intensity that excessive pressure build-up could only be avoided by suitable relief or drainage arrangements.

In the matter of flame arresters in gas vent lines, it would seem that such appliances became ineffective when placed in positions more than 30 diameters from the vent pipe outlets. The author's comment on this would be also welcomed.

In conclusion, he wished to express his appreciation at being given the opportunity of opening the discussion on such

an invaluable paper, which had been delivered in an admirably clear and concise manner.

MR. J. McNAUGHT (Member) said that the author had referred to an explosion in an air starting system caused by oil films. He showed some slides giving some idea of the damage which could result from such an explosion. The diagram in

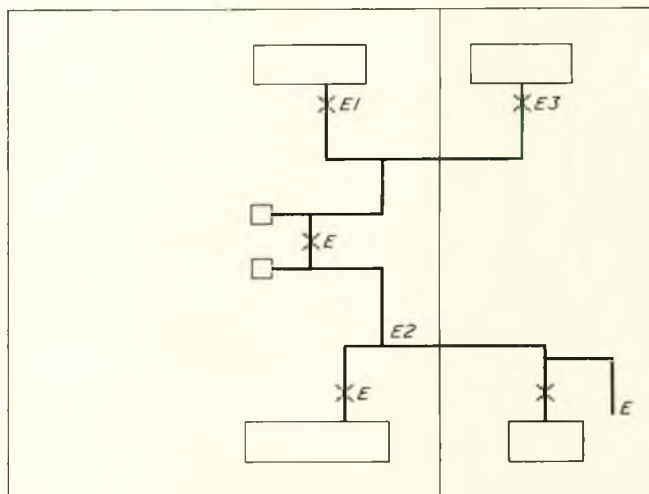


FIG. 1—Diagram of explosion in an air starting system—Points of damage

Fig. 1 would help to understand the illustrations, which showed damage at E1, E2 and E3 (see Fig. 2a to f).



FIG. 2a—Port main engine room main air receiver—Main stop valve and pipeline

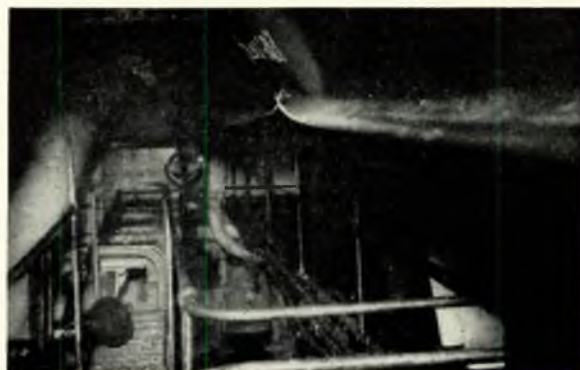


FIG. 2b—Port main engine room main air receiver—Damaged craneblock grinder



FIG. 2c—Starboard main engine room—Damaged scavenge air blower outlet trunking and starboard main air line “T branch”



FIG. 2f—Port generator room main air receiver—
—Damaged first section of main air pipeline from main stop valve

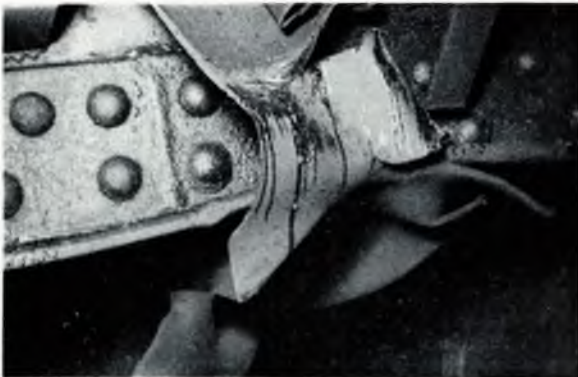


FIG. 2d—Starboard main engine room—Damaged main air pipeline from starboard main engine room “T branch” leading to starboard main engine duplex valve



FIG. 2e—Port generator room main air receiver—
Damaged first section of main air line, scorched air receiver and pipeline flange

The relief valves were all damaged, their spindles were cracked, and the air compressor relief valve casting was fractured completely.

Following the serious damage shown in the illustrations, the difficulty was to decide what to do to restore confidence on the ship and ensure that there would be no recurrence. A number of possible courses were examined, some of them as mentioned by the author in his paper—flame arresters, explosion reliefs, ensuring that there were no hydrocarbon oils in the starting air lines, and prevention of ignition. The prevention of ignition was difficult. Although the cylinder valves could be kept in good condition, there was always a chance of something going wrong. Flame arresters had been used for many years in other countries. Explosion reliefs were also considered, but at the time it was not thought to be a practical proposition. Bearing in mind the complexity of the average starting air system, he wondered how many of these would have to be fitted to avoid such an explosion happening, the main feature being that it burst out in so many different places (E in Fig. 1) around the system. In the end the course chosen was to use, in the short term, a phosphate ester synthetic lubricant in the air compressors, which was successful; the machines were still running on this lubricant. Experience of synthetic lubricants in ships was limited, but, with regard to explosions, they appeared, from published data, to be safer than conventional lubricants. For the long term, ceramic and carbon three-stage filters were fitted to each air compressor, which prevented any oil entering the air starting lines. This was the simplest way of ensuring safety. Such filters had been fitted in all his company's ships.

DR. F. E. T. KINGMAN said that it was particularly timely and useful that the Institute should have been given this broad and authoritative survey of the general aspect of explosions, and he had technically very little comment to make. But, having written this contribution, on his way to the meeting he had noticed the newspaper placard announcing an explosion on a ship. This reinforced what he was saying, and he felt there were two reasons why this subject should be looked at as a whole in the way that Dr. Burgoyne had done in his paper. Firstly, there was no doubt that in the shipping industry, as in most other industries, the extent of the hazards due to combustible liquids was growing, not only in size, but in complexity. There was not only the carriage of petroleum in ships, but also the more recent developments of materials like liquid methane. The second reason why it was important to have this broad overall look at the problem was that there was a great tendency for industries which had explosion hazards to imagine that their problems were peculiar to them alone. It was true that the marine transport industry, like other industries, had its own peculiarities and had some distinct features about its explosion hazards, but in general there was more in common between them than most industries

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realized, and it was very profitable in matters like this to learn from other people's unfortunate experience. In this respect, for example, he was particularly interested to notice the reference in Dr. Burgoyne's paper to the hazards of sparking with light metals such as magnesium and aluminium, and his mind went back to the inquiry into the *Stanvac Japan* explosion, which Mr. Knowles would remember very well. In this inquiry the question of the hazard of sparking due to the striking of magnesium and aluminium against rusty steel was described and discussed in very considerable detail, and possibly in more detail than previously occurred as far as sea-going vessels were concerned. It was interesting to know that this problem arose first of all in general industry but then became a very serious problem in the mining industry, and for that reason was investigated in very great detail by the Safety in Mines Research Establishment; and the main witness at the inquiry on this particular facet was a member of the staff of that establishment.

What he was really asking was that the marine industry, like other industries, should really try to learn first of all the broad, general lines of the problem, as outlined by Dr. Burgoyne, and secondly, that the marine industry should learn from the mistakes of other people.

In the discussion of the hazard due to frictional sparks from light metals on page 134, Dr. Burgoyne had necessarily compressed this section and ended by saying that a similar hazard arose from the coating of oxidized steel surfaces with aluminium paint. This was in general correct, but, lest unnecessary alarm should be raised, it should be stated that most commercial paints, and certainly most oil-bound paints, although they might give sparks, would not give a spark which was capable of igniting, for instance, a petroleum mixture or even a coal gas mixture, unless at some time previous to the striking the paint surface had been heated to a temperature above 150 deg. C. (302 deg. F.).

MR. M. P. HOLDSWORTH, M.Eng. (Member) said that the author had stuck to the facts and had not ventured any opinions on the practical application of them to ships.

Table III on page 131 of the paper gave the figures for the minimum added inert gas content in air for the suppression of flammability of various fuels. The method used at the moment more and more in the marine field for suppressing flammability in cargo tanks was the flue gas system. The figures of Table III were very relevant if one were talking about injecting pressurized CO₂ into an engine room, but they were not relevant to the flue gas system, where it was not so much a matter of adding dilutant to the atmosphere so much as removing the oxygen. The carbon dioxide content of effective flue gas could be as low as ten per cent. In such a case the oxygen content would be around eight per cent, which was a considerable reduction from the usual 21 per cent, and this was what gave the protection.

He was very glad that Dr. Kingman had mentioned the question of aluminium paint. There was a useful reference in this connexion: it was, in fact, a paper which Dr. Kingman's own Research Station had put out (reference 19 of the paper).

There was at the moment in the marine industry apparently a scare arising concerning the question of aluminium paint. As would be seen from this reference paper, it was also produced to quell exaggerated fears which were current at that time, despite work that had been done in the early 'forties on the subject. There was an addendum to the paper, written by a Mr. Wilkes, who was then Senior Chemical Inspector of Factories, and his recommendations therein put the matter in perspective. His recommendations were: "Aluminium paint may be used on iron even when the surrounding atmosphere may be flammable but with the following exceptions: (a) those paints with a cellulose nitrate base should not be used in flammable atmospheres, and (b) no aluminium paint whatever should be used in a flammable atmosphere if the paint is likely to be heated to the temperature of 150 deg." The author of that paper went on to say that if it was desired to use a paint contrary to these recommendations, then the paint in question

should be tested in the way that the paints in the paper were tested, to see whether it was safe or not. One of the points brought out in the paper was that if the paint formulation contained some degree of resinous material, this usually reduced the likelihood of producing an incendiary spark.

He had been very interested to see the low speeds involved where an explosion was initiated. Dr. Burgoyne, in his presentation, showed a slide giving the rise of pressure against time for an explosion in a closed tank. He imagined that this must have been a small tank since the full explosion pressure was reached in a matter of milliseconds. One imagined that in a ship's tank, with dimensions or the order of 50ft. cubed and more, the time involved from initiation to even a few pounds pressure in the tank might very well be expressed perhaps in seconds. In reading reports of cargo tanker explosions he had often noticed statements occurring in witness's evidence that a rumbling noise preceded the explosion. That a rumbling should have been noticed so often in these very stressful moments would seem to indicate that it was pronounced and prolonged. Could this rumbling be due to the slow initiation of burning before the pressure increased enough to disrupt the tank?

He was a little puzzled concerning the rates of travel of flame. On the last line of page 134 of the author's paper it was stated that "Maximum values of the burning velocity range from 1.2ft./sec. for methane/air to 1.3ft./sec. for the higher paraffins and 2.3ft./sec. for ethylene". But further down on page 135 the statement appeared that "If ignition takes place near to an open end of a long pipe containing flammable mixture, the flame sets off at a speed of some 3ft./sec." He was not sure why there was this discrepancy between the two statements.

Mr. Knowles mentioned the question of flame traps in gas lines. The ideal place for a flame trap was right at the top of the mast, the assumption being that any gas coming up the mast might be ignited at the top by lightning or corona. In fact, when the flame trap was up there it was completely useless. It could not be reached and very soon became clogged with corrosion products, when it either over-pressurized the tanks during loading or was itself disrupted by the ensuing back pressure. On older ships with such mast-head gas vents, his company had brought the flame trap down to deck level, where at least it could be maintained, but they had been a little worried as to whether the flame trap, in this position, would be effective against the higher flame speeds resulting from the, say, 40ft. travel from the point of ignition. However, in his company's experience of an enormous number of tanker voyages, they knew of no case where lightning had resulted in an ignition travelling down the vent riser to the tanks below, and certainly there was no question, as far as he knew, of detonation occurring.

It was stated in the paper that the saturated hydrocarbons were rather sluggish in gathering speed. It would be useful to have any advice that the author could offer in this respect. In the newer ships, these gas lines had been dispensed with because of the difficulty of maintaining flame traps, because of the difficulty of maintaining the various valves and connexions, and also—and much more important—because these gas lines, which ended up in an interconnecting network on the deck, had so many times propagated an explosion from one tank into another tank in a different part of the ship. This effect greatly increased the hazard of explosion in tankers and, in one case, sank the ship, where it otherwise would not have been sunk.

Mr. Knowles had talked about stray current arising from the handling of petroleum and the necessity for bonds of exceptionally low values of resistance. Mr. Holdsworth had not understood this at all, because there were no "stray currents", in the normal jargon used, arising from the handling of petroleum. Mr. Knowles might have meant the minute currents arising from static electricity in the handling of petroleum, and in this case it really did not matter whether one had a very low resistance bond or not. Quite high resis-

Discussion

tance bonds were perfectly adequate. There were "stray currents" in the normal meaning of the term, but these arose, not from static or from the handling of petroleum as such, but from electrolytic conditions between ships and the jetties and shore pipeline systems to which they connected.

Some work done recently by the Electrical Research Association for the Institute of Petroleum, suggested that the only effective way to avoid the incendive danger arising from breaking these stray currents was to prevent them running at all in hazardous locations; for instance, by introducing an insulating flange in the flexible hose between ship and shore. The traditional method of reducing this particular hazard by endeavouring to provide an alternative path for the ship to shore electrolytic current was shown to be largely ineffective, because an extraordinarily low resistance bond, between ship and shore, was required in order to make any realistic reduction on the current flowing through the hoses. Furthermore, if such a very low resistance bond was provided, it would itself carry a very high current indeed, and this could give rise to an additional hazard in the case of breakage or mal-connexion.

Mr. Knowles had also talked about one way of perhaps overcoming the explosion hazard in cargo tanks, and that was by having them over-rich, as is the case in recent methane ships. This was a very positive and good way of guarding against any internal ignition source, but Mr. Knowles went on to suggest that it might be a sufficient protection in the case of a collision in which a rich vapour-containing tank might be breached. Mr. Knowles suggested that if air did come in and there was ignition, possibly from the tearing metal, the tank might merely burn slowly, but without an explosion. Mr. Holdsworth then described, with the aid of coloured slides, an experiment which his company had conducted on this question. A one-twentyfourth linear scale model of a

wing tank of a 32,000-d.w.t. tanker was equipped with an openable slit to simulate a collision breach and with spark plug igniters surrounding the lips of the slit. The tank was filled with an over-rich hydrocarbon vapour, the slit opened and the spark plugs energized. Immediate ignition was rarely obtained, but, if ignition was delayed for some tens of seconds, a fairly rapid burning, ultimately of all the vaporous contents of the tank, could ensue. Depending upon the delay of ignition and the size of the slit, the pressure rise in the tank varied up to 0.75lb./sq. in.

In order to investigate scale effects, the series was repeated with a one-twelfth linear scale model. Here, the pressure rises were up to 2.5lb./sq. in. Unfortunately, as far as he knew, no mathematical basis existed, as yet, for the scaling up of the pressure rise in such explosions, where both dilution and relief egress were relevant factors. However, since the one-twentyfourth scale model gave a rise of 0.75lb./sq. in. and the one-twelfth scale model gave a rise of 2.5lb./sq. in., it was a sound assumption that a full-scale tank could generate a pressure rise well outside the limits of the tank structure. Thus, whilst over-rich inerting, where it could be practised, was certainly an excellent protection against internal sources of ignition where there could be no question of dilution, it could not be regarded as an absolute safeguard in the case of collision above water.

The CHAIRMAN (Mr. B. Hildrew, M.Sc., D.I.C., Member of Council) referred to the validity of model work in determining the adequacy of measures for the prevention of explosions and said that it was obvious that Mr. Holdsworth's company were looking very hard at this, as were all tanker companies, and it was perhaps desirable that a greater range of scale variation should be available in order to extrapolate to the full-size tank.

Correspondence

DR. E. M. GUENAUlt felt that one or two points, on which research was still in progress, perhaps merited some amplification.

The first concerned quenching distances and the safe gaps in flameproof enclosures, discussed on pages 131 and 133, and illustrated in Table II. It was stated that these safe gap widths were substantially less than the quenching distances quoted, because the explosion flame entering the gap was then travelling through a mixture flowing in the same direction as the flame. However, it was believed this was not the complete explanation and that the safe gaps were in fact less than could be accounted for by the above effect. Recent work by Phillips* and others led to the view that the external explosion which occurred with a gap just greater than the critical safe value, was not due to transmission of flame through the gap, but was in fact due to ignition of the external atmosphere, at a short distance away from the gap, by mixing with the emerging jet of hot combustion products. The important part played by such mixing processes outside the gap or orifice was illustrated by the fact that if the point of ignition inside an enclosure was such that gas was moving rapidly through the orifice before the flame reached it, the safe size of gap or orifice increased, and in extreme cases might be much greater than the quenching distance as normally determined.

On the propagation of flame in unmixed gases, as for example where there was a layer of methane along the roof of a smooth duct, the rate of progress of the flame would depend to a large extent on the relative thickness of the

layer. In initially stagnant conditions, if the layer was thin relative to the height of the duct, and if the concentration of methane at the roof was such that there was, within the layer, a stratum of stoichiometric mixture, then it was found that the flame would continue to travel at a constant speed of about 6ft./sec., the head of the flame travelling through this part of the layer and further burning occurring due to mixing behind the primary flame. In these conditions there was insufficient expansion from the burning of the relatively thin layer to cause appreciable disturbance ahead of the flame. With layers thicker relative to the size of the duct, the expansion might become sufficient to cause movement and blast ahead of the flame. In these conditions the flame accelerated, due not only to mixing, but also to the gross gas flow and turbulence produced ahead of the flame.

MR. A. J. S. BENNETT, M.B.E. (Member) wrote that Dr. Burgoyne's paper covered a subject of rapidly increasing importance to marine engineers. Since the ultimate object of the paper was presumably the prevention of explosions, it should embrace the needs of ships' personnel, as well as those of the experts.

He thought that the paper was sufficiently readable to achieve both these objects and in addition to provide educational material for the future.

Mr. Bennett's remarks concerned the terms used and he thought that Dr. Burgoyne could have departed from the traditional word "inflammable" and used "flammable" instead, as was done in several sets of modern Rules. Otherwise, one found oneself, as happened in the paper, using the words "incombustible" (will not burn) and "inflammable", very close together. Dr. Burgoyne had avoided "non-inflammable",

*Phillips, H. 1963. "On the Transmission of an Explosion through a gap smaller than the Quenching Distance". *Combustion and Flame*, Vol. 7, p. 129.

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which must crop up unless one watched for it. Since he imagined that Dr. Burgoyne must often use "flammable" and "inflammable" to mean the same thing, depending upon who was listening, Mr. Bennett suggested that he was the best person to set, or rather to support, a standard on behalf of marine engineers.

He liked Dr. Burgoyne's definition of flash-point, which related temperature with vapour pressure. If more people would think of flash-point in terms of "gassing", which could be said to be the "alarm" stage, instead of associating it with combustion, there would be a clearer understanding generally.

Although "gassing" characteristics were not emphasized in the vast investigations of specific hydrocarbons shown in the paper, they were a useful guide for commercial cargoes, where the constituents might mix. Would Dr. Burgoyne please comment on the desirability of recommending the general use of Reid Vapour Pressure for light petroleum liquids, so that the layman's attention was drawn to "gassing", which was definite, as opposed to using flash-point alone, which, he regretted to say, led to misconceptions.

MR. R. A. JONES (Associate Member) wrote that, from the basic work undertaken by Dr. Burgoyne and others as the result of the *Reina del Pacifico* disaster, referred to on page 130 of the paper, the foundation was laid for the practical development of crankcase oil mist detectors, which were now virtually standard equipment in motor ships today.

Regarding that part of the paper, on page 134, dealing with "The Development and Limitation of an Explosion", it would be of interest to describe briefly the explosion suppression system, referred to by Dr. Burgoyne. Fig. 3 showed the basic simple circuit, together with the pressure time curve for an explosion in a 100-gal. tank at normal temperature and pressure.

Due to the large volumes on board ship, it was not an economic proposition to use such a system of explosion suppression, and another method must be used.

The latest method, now being employed in some Continental-built tankers, was "continuous gas detection". The principle of operation was to employ, at strategic positions

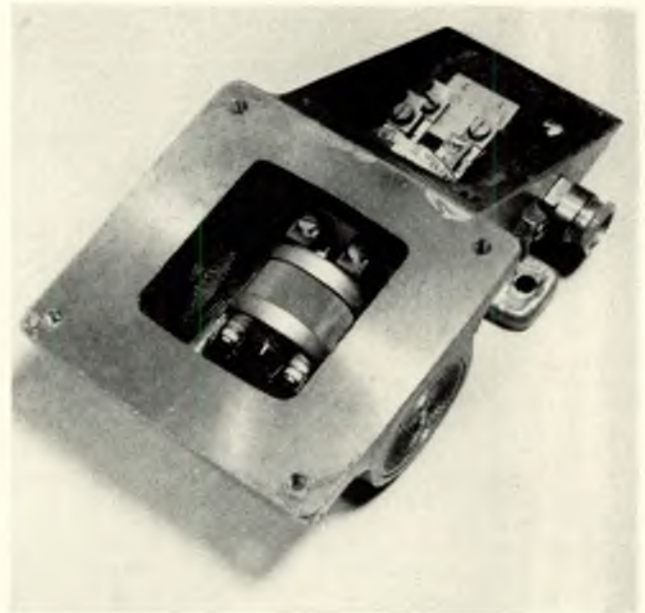


FIG. 4—Sensing head

such as pump room, cofferdams, etc., gas "detection heads", each connected to a central alarm panel, which would give a warning of a dangerous gas concentration—the warning could be pre-set to any value below the lower explosion limit as given in Table I of Dr. Burgoyne's paper.

The "sensing heads" detected and measured the gas concentration by catalytic reaction between hydrocarbon/air mixture and a permanently heated platinum filament within the sensing head. Fig. 4 showed such a sensing head.

As the reaction took place, the visual radiation of the platinum filament increased and the change in radiation was monitored by a photo-cell.

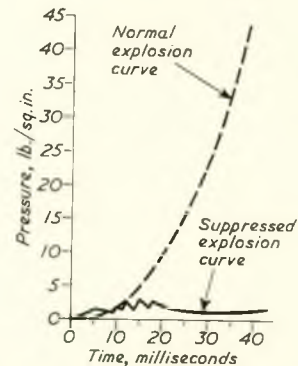
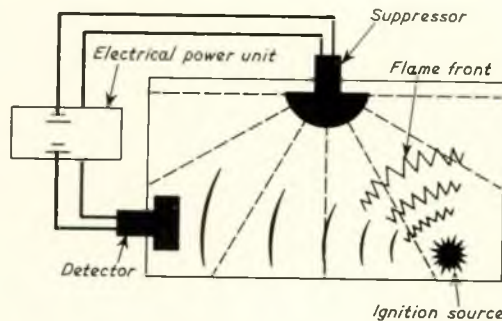


FIG. 3—Explosion suppression system—The detector senses the incipient explosion and the agent is dispersed explosively—The agent extinguishes the explosion flame by chemical action and cooling, and also inerts the unburned explosive mixture—The graph shows the comparison between a normal explosion and a suppressed one—Note the low pressure (less than 3 lb./sq. in.) attained in a suppression.

Author's Reply

Dr. Burgoyne in his verbal reply said that the subject was one of almost unlimited breadth, and his biggest problem in preparing the paper had been to know where to stop. What he had aimed to do—as Dr. Kingman had very kindly emphasized in the discussion—was to provide a general fundamental background, with as much quantitative information as possible that could be applied in various directions. He had been looking forward to the discussion of practical applications at this and the other meetings of sections of the Institute at which he was to be privileged to speak at later dates.

The first discussion had helped very much in this way, in that there had been a considerable amount of reference to practical applications. The proper place for this *was* at a discussion, and he was most grateful to the contributors for providing it in such good measure. He was grateful also for a number of suggestions that had been made as to how the paper could be improved and made more useful and acceptable in the marine field. These had been embodied as far as possible in the final version of the paper.

Mr. Knowles had made a number of important points in this category and he was very grateful to him for these suggestions, which he promised very carefully to consider. He would say a few words, as Mr. Knowles had requested, on the subject of cool flames, and on the generation of static electricity in various circumstances. The important thing about cool flames really was that they were the reason why one experienced low spontaneous ignition temperatures, particularly with rich mixtures. This was really covered by the data given in the table on spontaneous ignition temperatures, but if anyone wanted to know why it was that ignition could arise at temperatures as low as 200 deg. C. (392 deg. F.), the answer was that this was due to a cool flame mechanism. He had, however, felt that, in view of the length of the paper and the scope of the subject, it would not really be justified to say a great deal about the chemical mechanism of cool flames as such, about which there was a great deal to be said.

The generation of static, of course, was a matter of very great interest and importance to this industry. Mr. Knowles had referred to the generation of static in steam clouds and in carbon dioxide discharges. In order to get the generation of static one must have a separation of surfaces from one another. The static in the cases mentioned arose, generally speaking, from the separation of droplets or particles from the solid surface of the nozzle. The great danger arose when the charge was allowed to impart itself to an isolated conductor to achieve a high voltage, and a dangerous spark to earth might then occur.

He entirely agreed with Mr. Knowles' interpretation of the occurrence of double explosion in a crankcase.

Mr. Knowles had mentioned the question of ignition, in particular circumstances, by the flash at the switch of a three-cell torch but not by a two-cell torch and had asked whether there was any significance in this. Some work had been done at the Safety in Mines Research Establishment on ignition in non-inductive circuits and it appeared to be quite relevant to this particular question. It had been shown that at these voltages the current required for ignition went up quite sharply with decreasing voltage. The answer to Mr. Knowles' question presumably was

that with the three-cell torch, one had enough voltage to effect ignition, but in the two-cell torch, one had not.

He was very grateful to Mr. McNaught for his amplification of the starting air line explosion referred to in the paper. It was undoubtedly an historic occurrence in this particular science. A very significant point, which had been illustrated by Mr. McNaught's slides, was that the principal damage occurred at changes of section or changes of direction in the pipeline. The work of the Fire Research Station had shown how this was due to the promotion of turbulent combustion in the neighbourhood of obstacles or changes of direction and to the consequent impulse which arose from the rapid acceleration of combustion.

He had expressed his appreciation of Dr. Kingman's remarks on the general nature of this paper and the importance of profiting from the consideration of fundamentals and from the experience of other industries in this field. It was extremely important to emphasize this and he was grateful to Dr. Kingman for doing so. He accepted Dr. Kingman's point about the aluminium paint hazard—that the hazard really arose in most practical cases with commercial materials where the under-surface was at an elevated temperature.

A point arising from Mr. Holdsworth's contribution was that in Table III, where suppression by the addition of inert gases was dealt with, the possibility of giving oxygen concentration values might be considered. It really amounted to the same thing, but it would possibly be more useful in practice if information were given upon the level to which the oxygen concentration in air (normally 20.9 vol. per cent) had to be lowered in order to suppress combustion by the use of the particular inert gas.

The answer in the case of flue gases would lie between carbon dioxide and nitrogen, in whatever terms one expressed the situation, and rather near to the nitrogen side because, as Mr. Holdsworth had pointed out, the flue gas did not in fact contain nearly as much carbon dioxide as nitrogen.

Mr. Holdsworth also mentioned the difference between the burning velocity values of about 1½ ft./sec. and the initial speed of movement of the flame in a pipe. The burning velocity was the speed of the flame relative to the unburnt gas, measured normally to the flame front. If one had a flame front which took the form of a flat disc and could move through a pipe in that way, it would move at the burning velocity, provided that the gas mixture was not disturbed. In point of fact, the flame did not assume that form in a tube; it assumed more a hemispherical or paraboloidal form; and because the rate of combustion was constant per unit area, the rate of movement of the flame was multiplied by the ratio of this curved area to the flat area. That ratio happened to be about two. So the initial speed of movement of the flame in its real form was about twice the burning velocity, which was really the fundamental quantity.

One or two references had been made to the placing of flame arresters at a distance from the open ends of pipes. He could only mention here that the work of the Fire Research Station—to which some reference was made in the paper—related the effectiveness of flame arresters to the velocity of the flame as it approached them. The Fire Research Station had also produced some information on the velocities achieved by flames at

Accidental Ignitions and Explosions of Gases in Ships

various distances from the open end of the pipe, and the use of this information usually provided the answer to such questions as had been raised concerning the effectiveness of arresters placed at a distance from the pipe end. They did become less effective, of course, but there was no reason why a flame arrester of adequate specification should not be effective at reasonable distances, at any rate, from the open end of the pipe.

A very valuable written contribution from Dr. Guenault had been read. Dr. Guenault had also written to him pointing out a couple of corrections that ought to be made, in the light of the most recent knowledge, in Table II on page 131 of the paper. The corrections related to the third column, headed "M.E.S.G.", where the figure for Ammonia had apparently recently been re-determined at 0.125 in., instead of 0.133 in. as shown. The figure for Acetylene had also been re-determined, and although Dr.

Guenault was not able to give the exact figure at the moment, the idea that the gap was less than 0.001 in., which had been published in the past, was incorrect. The maximum experimental safe gap in Acetylene was certainly considerably higher than 0.001 in.

In a further written reply Dr. Burgoyne wrote that as the time available at the meeting did not permit every point raised in the discussion and written contributions to be dealt with fully a short supplementary reply, therefore, seemed desirable.

Mr. Holdsworth's contribution suggested that oxygen limits for the suppression of flammability by inert gas additions would be useful and these were given in the accompanying supplementary table, which presented the information of Table III in this alternative form.

Mr. Holdsworth had also raised a point about the effect of vessel size on the duration of an explosion. In principle, the duration of the explosion was proportional to the linear dimension of the vessel, but in larger vessels the pressure rise might be completed in a rather shorter time than this would suggest. The rumble which was heard in the early stages of a tank explosion was probably due to the initial pressure rise, causing the tank walls to vibrate prior to rupturing. It did illustrate the significant length of time during which the rise of pressure took place in gas explosion on the large scale.

He agreed with Mr. Bennett's comments on terminology, and the paper in its final form had been revised to employ "flammable" to denote "capable of flame propagation", and "combustible" to denote "capable of any form of combustion".

Reid Vapour Pressure was certainly a guide to flammability amongst liquids of a similar kind, such as the petroleum hydrocarbons. In this context, a value about 0.15 lb./sq. in. might be said to indicate a danger of ignition by small sources and an explosion hazard in free spaces.

In conclusion, he wished once more to thank all those who had contributed to what had been, to him, an extremely valuable discussion.

TABLE IIIa.—MAXIMUM OXYGEN CONTENT OF AIR IN THE PRESENCE OF ADDED INERT GAS FOR SUPPRESSION OF FLAMMABILITY OF VARIOUS FUELS.

Fuel	Requisite oxygen content of air + inert gas (vol.—per cent)		
	Nitrogen	Carbon dioxide	Methyl bromide
Methane	13.0	15.9	19.8
Ethane	11.3	14.0	—
Propane	11.9	14.6	—
n-Butane	12.3	15.0	—
iso-Butane	12.3	15.3	—
n-Pentane	11.9	14.8	—
n-Hexane	12.1	14.8	19.4
Ethylene	10.5	12.3	18.4
Propylene	11.9	14.6	—
Cyclopropane	11.9	14.4	—
Cyclohexane	—	—	19.3
Benzene	11.5	14.2	—

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at the Memorial Building on Tuesday, 8th December 1964

An Ordinary Meeting was held by the Institute on Tuesday, 8th December 1964, when a paper entitled "Accidental Ignitions and Explosions of Gases in Ships" by J. H. Burgoyne, D.Sc., Ph.D., F.R.I.C., M.I.Chem.E., F.Inst.F., was presented by the author and discussed.

Mr. B. Hildrew, M.Sc. (Member of Council) was in the Chair and ninety-five members and visitors were present.

Four speakers took part in the discussion which followed and two written contributions which had been received were read out by the Assistant Secretary of the Institute.

A vote of thanks to the author was proposed by the Chairman and was accorded an enthusiastic response.

The meeting ended at 7.25 p.m.

The Institute of Marine Engineers Guild of Benevolence The Guild House Charity Ball 1965

The Guild House Charity Ball was held at Grosvenor House, Park Lane, London, W.1 on Friday, 23rd April 1965.

The Patron, Mrs. J. H. Houston Jackson, and Mr. W. Lynn Nelson, O.B.E. (Honorary Vice-President) Chairman of the Guild Committee, with Mr. J. H. Houston Jackson (Companion) and Mrs. W. Lynn Nelson, received the 327 guests. Music for dancing was played by The Sydney Jerome Dance Orchestra and among those who appeared in the cabaret were Los Seguras, Esme Levante and Edmund Hockridge.

During the evening the winning ticket in a raffle for a KB Portable Television Set was drawn and some 250 prizes were distributed by tombola. It is estimated that a profit of approximately £1,200 will be made and will be used towards meeting the expenses of the Guild House.

The Chairman of the Committee is extremely grateful to those who supported the Ball and donated prizes for the tombola.

Section Meetings

Auckland

An ordinary meeting was held in Auckland at 8 p.m. on Friday, 2nd April, with Mr. H. Whittaker (Local Vice-



At the Guild House Charity Ball held on Friday, 23rd April 1965, at Grosvenor House, Park Lane, London, W.1. Mr. W. Lynn Nelson, O.B.E. (Honorary Vice-President) (right), Chairman of the Institute of Marine Engineers Guild of Benevolence, with the Patron Mrs. J. H. Houston Jackson (left), Mr. J. H. Houston Jackson (Companion), and Mrs. Nelson

Institute Activities

President) in the Chair. Mr. Whittaker welcomed Mr. R. A. Newman, who presented his lecture on "Non-destructive Testing of Materials", to an audience of twenty-six members and fourteen guests. After the lecture, the author ably answered questions brought forward by members.

A vote of thanks to Mr. Newman, proposed by Eng. Cdr. C. W. Shoter, R.N.Z.N., was heartily endorsed by all present. The evening concluded with a short film on "Cavitation", loaned by courtesy of Shell Oil N.Z.

Kingston upon Hull and Humber Area

The Second Dinner Dance of the Section was held on Friday, 2nd April 1965, at the New York Hotel, Kingston upon

had subscribed in recognition of his fourteen years' service as Honorary Secretary which ended last January.

Dancing continued until 1.00 a.m. when another successful dinner dance was concluded.

North East Coast

The Annual Dinner and Dance of the Section was held on Friday, 5th February 1965, at the Royal Station Hotel, Newcastle upon Tyne. The principal guests included The Right Worshipful, The Lord Mayor, Alderman P. H. Renwick, and the Lady Mayoress, the President of the Institute, Mr. A. Logan, O.B.E. (Member), and Mrs. Logan, the President of the North East Coast Institution of Engineers and Shipbuilders, Mr. W.



Photograph by Hull Daily Mail.

Kingston upon Hull Second Dinner Dance

The President of the Institute, Mr. A. Logan, O.B.E. (Member) left, and Mrs. Logan, look on with Mr. G. A. Skelton, M.B.E. (Chairman of the Section) as Mrs. J. Lancaster (centre), representing Mrs. Skelton, receives a bouquet from Mrs. D. A. Taylor, wife of the Honorary Secretary Mr. D. A. Taylor (seen on right) at the Dinner Dance held at the New York Hotel, Kingston upon Hull

Hull, when one hundred and eighty members and their ladies enjoyed a memorable evening.

This year the Section was honoured by the presence of the President, Mr. A. Logan, O.B.E., and Mrs. Logan, who, supported by the Chairman of the Section, Mr. G. A. Skelton, M.B.E. and his daughter Mrs. J. Lancaster, received the guests as they entered for dinner.

Unfortunately Mrs. Skelton was unable to attend owing to illness and Mrs. Lancaster received a bouquet on her behalf, together with the best wishes of the Section for a speedy recovery.

During dinner the President proposed the toast to "The Ladies" and said that the occasion gave him added pleasure, as this and other occasions during his term of office, had given him the opportunity to meet members in all ten sections of the Institute.

Also during dinner, Mr. Skelton presented Mr. C. J. Potter

with a transistor radio, to which eighty members of the Section F. Blackadder, D.S.O., O.B.E., B.A., and Mrs. Blackadder, and Mr. J. Stuart Robinson, M.A. (Secretary of the Institute), and Mrs. Robinson.

The total attendance was 248 and although all applications for tickets were met, it was felt that the demand for tickets was beginning to be rather pressing on accommodation.

Brief, but excellent speeches by both the President and the Lord Mayor, added to a thoroughly enjoyable evening which included a very good cabaret show later.

Joint Meeting

A joint meeting with the North Eastern Branch of the Institution of Mechanical Engineers was held at Stephenson Building, University of Newcastle upon Tyne, at 6.15 p.m. on Thursday, 29th April, when a paper entitled "Some Factors Affecting the Selection of Systems for Automatic Control of

Institute Activities



At the Annual Dinner and Dance of the North East Coast Section. From left to right: Mr. E. C. Cowper (Vice-President), Mr. D. H. Sword (Chairman of the Section), and Mrs. Sword, Mrs. A. Logan, the President of the Institute, Mr. A. Logan, O.B.E. (Member) and Mrs. E. C. Cowper

Marine Machinery" by Ll. Young (Member) and P. J. Wheeler, B.Sc., was presented by the authors.

Mr. D. H. Sword (Chairman of the Section) invited Mr. H. Watson-Jones (Chairman of the North Eastern Branch of the Institution of Mechanical Engineers) to take the Chair; Mr. Watson-Jones introduced the speakers.

After Mr. Young had given a clear exposition lasting 20 minutes, Mr. Watson-Jones opened the meeting to informal discussion, and many questions were brought up and further contributions made. The authors replied ably to questions as they arose.

A vote of thanks was proposed by Mr. Sword, who said that it was evident from the number of contributions that there was great interest, and congratulated the authors on their paper. He also thanked Mr. Watson-Jones for presiding at the meeting.

Mr. Young said in response that they had had a pretty good discussion and offered to reply in writing to any further points.

West of England

A combined junior and senior meeting of the Section was held on Wednesday, 7th April 1965, in the City of Bath Technical College, at 7.00 p.m., when a lecture on Marine salvage entitled "Typical Examples of Salvage by Re-floating" by Commander C. G. Forsberg, O.B.E., R.N., and P. F. Flett, O.B.E., was presented by the authors.

Mr. J. P. Vickery (Chairman of the Section) presided over the meeting, at which forty-four members and visitors were present.

In presenting the paper Commander Forsberg spoke first and explained the "No cure—no pay" clause which is found in the bye-laws of the Corporation of Lloyds, adding that it was necessary to have 100 per cent salvage to qualify for an award. He outlined the various types of salvage vessels and their gear which were available at the present time and spoke of some of the more difficult examples of salvaging wrecks, especially where they were in navigable waters, either on hard or soft ground. Commander Forsberg enumerated some of the operations he had attended, such as raising the block ships in Dover Harbour after the last war, raising sixteen of the twenty-two vessels sunk at the mouth of the Suez Canal at the time of the Suez crisis, and later, raising the Comet aircraft which crashed and sank off the Isle of Elba.

Mr. Flett then continued the lecture by showing some of his numerous slides. These gave details of the many stranded and sunken vessels which he had been instrumental in salvaging, also some of the salvage vessels and equipment used in these operations. These ranged from vessels with a powered side lift of 3,500 tons, down to horizontal cylinders called camels which were capable of lifting up to 80 tons each.

In conclusion, Mr. Flett spoke of the future and said that with the advent of 150,000 d.w.t. tankers, nuclear vessels and cargo submarines, no spectacular break through in salvage equipment, or ideas, could be foreseen should any of these types of vessels require salvage assistance.

Many questions were asked by a most interested audience and a vote of thanks to the speakers was proposed by the Chairman and warmly applauded.

The meeting closed at 8.45 p.m.

OBITUARY

RICHARD DOUGLAS APSIMON (Member 12909) died on 16th February 1965, after a short illness, at the age of fifty-one years.

Mr. Apsimon served his apprenticeship with A. and R. Brown Ltd. of Liverpool, and went to sea with New Zealand Shipping Co. Ltd. as junior engineer in 1935. He gained his First Class Steam Certificate in 1940, and his Combined Certificate in 1946. He was appointed assistant superintendent engineer in Liverpool in 1952, and West Coast superintendent in 1957. In January 1963, he was promoted to deputy chief superintendent engineer in London.

A member of the Institute since 1950, Mr. Apsimon leaves a widow and one son.

WILFRID COATES (Member 8882), a Member of this Institute since 27th March 1939, died on 24th December 1964, in his eighty-seventh year.

He served a five-year apprenticeship with Newsome and Asplam at Batley, after which he joined Blair and Co. Ltd. of Stockton-on-Tees, as guarantee engineer. His first sea voyage was made to South Africa, where he helped to repair and bring back the vessel *Mariposa* which had been burnt out during the South African War. Altogether he spent six years at sea, during which time he served in the vessels, *Southport*, *Burgundy*, *Shardon Wiltshire*, *Karoon*, *Teesport* and *Evelyn*, and gained a First Class Board of Trade Certificate of Competency. He left the sea in 1909 to go into business with his brother as mill furnishers and engineers' stores contractors.

He returned to the service of Blair and Co. Ltd. for the period of the First World War, where he was engaged in the installation of engines into "Q" ships and also in taking these vessels on their trial runs.

Mr. Coates retired from business in 1946, owing to ill-health and, at the time of his death, had been an invalid for some years. He is survived by his wife, Florence, and a son.

MARINO T. GEORGIADIS (Member 8200) died in Genoa on 18th January 1965, in his seventy-eighth year.

He served an engineering apprenticeship, from 1904 to 1909, after which he embarked on a seagoing career which lasted for eleven years and during which he gained a First Class Certificate issued by the Greek Ministry of Marine. From 1921 to 1927, he was technical manager with the "San Giorgio del Porto" ship and engine repairing works in Genoa. In 1928, he became sole consulting engineer, for Italy, on behalf of the most important Greek shipping companies and, on occasion, acted for a number of private shipowners.

Mr. Georgiadis was elected a Member of this Institute on 6th July 1936; he was also an Associate Member of the Royal Institution of Naval Architects.

HERBERT HAMILTON (Member 3905), holder of a First-Class Board of Trade Certificate, died on 20th December 1964 at his home, aged seventy-nine.

Mr. Hamilton served his apprenticeship with John W. Wilson and Co. Ltd. and was at sea for a total of nine years, including his service with the R.N.R. as Engineer Lieutenant during the First World War. After a brief period in business on his own account as an engineers' agent, he was called up again to the Service in 1940. Later he was at the Mersey Dock

and Harbour Board, where he stayed until his retirement at the age of sixty-five.

ALEXANDER HARKES (Associate Member 27219) died on 27th December 1964, as the result of injuries received in an accident. He was thirty years of age.

He received his engineering education at Rutherglen Technical College and was apprenticed, for five years, to Harland and Wolff Ltd., in Glasgow. At the age of twenty, he went to sea as a junior engineer with the Burmah Oil Co. Ltd. and subsequently served in various ships of the company's fleet. He later sailed in vessels owned by the Henderson Line, W. Robertson Ltd., Watts, Watts and Co. Ltd., and Wm. Cory and Son Ltd. At the time of his election to Associate Membership of this Institute, on 23rd September 1963, he was chief engineer in m.v. *Dukesgarth*, owned by the last named company. In order to gain experience for a Steam Endorsement to his First-Class Motor Certificate he had latterly served for a year in R.M.S. *Queen Elizabeth* and, at the time of his tragic death, had come ashore to commence a course of study at Stow College of Engineering, prior to sitting the examination for that endorsement.

GEOFFREY FAITHWAITE HINDE (Member 18939) died suddenly, at his home in Little Neston, near Wirral, Cheshire, in February 1965.

Mr. Hinde served his apprenticeship with the Ellerman Engine Works, Liverpool, and in 1927, joined the Ellerman and Papayanni Lines Ltd., serving as fourth and third engineer. In 1936 he gained his First Class Certificate, while serving with John Holt and Co. Ltd., as third engineer. He became an engineer surveyor in 1937, with the London and Lancashire Insurance Co. Ltd., and in 1939 joined the Mersey Docks and Harbour Board as an inspector of steel and ironwork. He was promoted to deputy marine assistant to the engineer-in-chief in 1948, which post he held until his death. He and his wife had just moved into a bungalow in preparation for retirement at this time.

Besides his widow Mr. Hinde leaves a son.

He was elected a Member of this Institute on 15th May, 1957.

JAMES WILLIAM LAW (Member 5810) died on 9th January 1965, after a period of ill health.

Mr. Law served his apprenticeship with A. W. Penrose Ltd., and in 1914 enlisted in the Royal Army Ordnance Corps, with whom he served in France, Germany and Italy; he was demobilized in June 1919 with the rank of Sergeant-Major. In 1921, he went to sea to obtain his First Class Certificate and then became a marine representative for the Vacuum Oil Co. During the depression of the 1930's, he became redundant, and went to work at Woolwich Arsenal, and later at the Ministry of Supply.

During the Second World War, Mr. Law spent periods at Bridgend and Aycliffe engaged on the inspection of gauges, and later he returned to Woolwich Arsenal, where he stayed until his retirement in 1959. He was elected a Member of the Institute on 5th September 1927.

Mr. Law is survived by his wife and a daughter.