Crankcase Explosions in Marine Oil Engines, The Efficacy of Gauze and Crimped-ribbon Flame Traps

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This paper describes an experimental and theoretical investigation into the use of oil-wetted flame traps to suppress the flames emitted from the safety vents of a marine Diesel engine during a crankcase explosion. Two possibilities have been considered: venting of the product of combustion into the engine room and venting into adjacent compartments of a partitioned crankcase, the area available for venting relative to the volume, the "vent ratio", being much greater in the latter than in the former. Gauze assemblies and a crimped ribbon trap have been investigated.

In the practical investigation reported in Part I, tests were conducted in explosion vessels of 200 and 66 cu. ft. capacity under conditions which subjected the trap to the greatest amount of heating possible, while keeping the pressure developed in the explosion to a low level. Weak pentane/air mixtures were used in the earlier gauze assembly experiments and also in testing the crimped ribbon trap. Oil mist explosions were used in the later tests with gauzes. To investigate the case of the partitioned crankcase, the two vessels, both filled with oil mist, were coupled together with the flame trap between them and the mixture in one vessel was ignited.

With a vent ratio of 2·3 sq. in./cu. ft. twelve layers of mild-steel gauze (the maximum used in most of the tests) could not be relied on to resist melting. With larger vent ratios, 4·8 and 6.85 sq. in. /cu. ft. no flame was seen to pass through the trap and melting occurred in only one of the twenty-one tests, although the temperatures measured in the effluent gases reached values which would be dangerous to personnel. A few tests with Monel gauzes failed to indicate that this metal had any significant advantage over steel. In the coupled vessel experiments, no transmission of flame occurred in any of the tests, but in some cases high temperatures were measured in the gauze assembly separating the vessels. The crimped-ribbon flame trap was highly effective in preventing the transmission of flame and appeared to be more effective than the gauze assemblies tested in reducing the temperature of the effluent gases, but the trap was more liable to suffer damage than heavy gauze assemblies. In a test with a crimped-ribbon flame trap having a vent ratio of 1·7 sq. in./cu. ft. nearly half of the total trap width of 2in. was melted.

Part II of the paper presents a method of estimating the required flame trap size, both for gauzes and for the crimped-ribbon type of trap, and compares the values obtained by it with the practical tests of Part I. Reasonable agreement is obtained, with the method tending to err on the side of optimism. It is estimated in Part II that, using twelve layers of gauze as the maximum practicable, a vent ratio of 7·8 sq. in./cu. ft. would be required to quench the flame and resist melting.

In Part III, the findings of Parts I and II are considered in relation to main propelling Diesel machinery. It is concluded that it is not practicable with machinery of this type to provide sufficient area of flame trap to suppress with certainty the flame from a "mild" explosion and that reliance should be placed upon suitable siting and shielding of the vents rather than upon the degree of protection afforded by flame traps of inadequate area.

It is further concluded that practical considerations are against the fitting of flame traps to separate adjacent crankchambers in such engines; it is considered that this will emphasize the importance of avoiding explosions by suitable design, by careful maintenance, and by the fitting of oil mist detectors to give warning of the onset of a dangerous condition. It is suggested that such an approach is fundamentally sounder than allowing an explosion to take place and then trying to mitigate its effects.

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PART I—AN EXPERIMENTAL INVESTIGATION

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INTRODUCTION

The provision of explosion relief to prevent damage by an explosion in the crankcase of a Diesel engine has been the subject of several recent investigations(1, 2, 3) and where such reliefs are provided, some form of protection is required to prevent danger from the emission of flame and hot gases. Wire-gauze flame traps have been suggested for this purpose and some success has been reported in their use(1, 3). A suggestion has also been made by Southwell in the discussion on the paper by J. Lamb(1) that gauze traps might be used to separate one crankchamber from the next, in order to prevent the spread of an explosion throughout the whole crankcase.

Recent experimental work at the British Internal Combustion Engine Research Association(4) has shown that the efficacy of a wire-gauze flame trap in preventing the transmission of flame is increased by coating the gauzes with lubricating oil and, further, that coated gauzes could be used successfully for preventing the flame from the town gas explosions from spreading from one crankchamber to another in a running engine of 30 cu. ft. crankcase capacity.

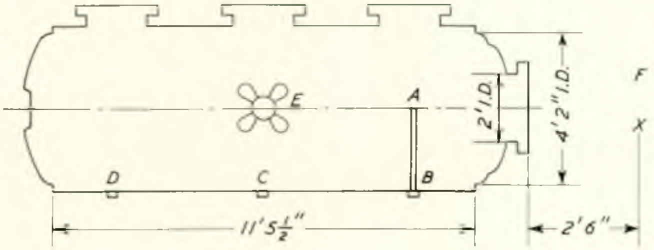
The experiments described in the present paper were carried out for The British Shipbuilding Research Association and their object was to test, on a larger scale than hitherto, the performance of oil wetted gauzes in mild, non-turbulent explosions of pentane and of oil mists in air. More precisely the objects were twofold, namely:

a) To ascertain whether oil-wetted gauze flame traps would prevent the emission of flame from a small vent, bearing in mind that the minimum standard recommended by the Marine Safety Division of the Ministry of Transport is a vent of such a size that the ratio of its area to the volume of the vessel is 0·5 sq. in./cu. ft.

b) To ascertain whether an oil-wetted gauze flame trap mounted between two chambers would prevent the spread of an explosion from one chamber to the other. Partitioning of a crankcase in such a manner, if successful, would not only mean that the volume of combustible mixture involved in any explosion is greatly reduced but also, by venting each crankchamber into the adjacent ones, the area available for the purpose would be greatly increased.

The pressures, which the crankcases of large marine engines can withstand, are low, probably of the order of 2lb./sq. in. and so a limit of 20lb./sq. in. was set on the pressures to be reached in the test explosions. In order to facilitate control of the peak pressures, the initial experiments were conducted using pentane; later, when the requisite apparatus became available, oil mists were used.

The work was planned in consultation with the B.S.R.A. and formed part of the programme of the Joint Fire Research Organization of the Department of Scientific and Industrial Research and Fire Offices' Committee; it was carried out at the Ministry of Power, Safety in Mines Research Establishment, Buxton.



A) Igniter supported by rod inserted through tapped opening B).
C) and D) Alternative positions of igniter.
E) Fan (10in. below top of vessel).
F) Site of thermometer.
Manometer connexion situated 4½in. below D).

Fig. 1—*Plan of 200-cu. ft. explosion vessel*

TESTS WITH GAUZE FLAME TRAPS

Apparatus

Two explosion vessels were used in the investigation. The larger one was a marine boiler shell of about 200 cu. ft. capacity; it was fitted with a 24in. diameter flanged opening at one end and with three 18in. diameter openings along one side (Fig. 1).

Table I.

	Volume of vessel, cu. ft.	Diameter of opening, in.	Vent ratio, sq. in./cu. ft.
Larger vessel	200	24	2·3
		18	1·3
Smaller vessel	66	24	6·85

The volume of the smaller vessel was about 66 cu. ft. and it had a 24in. diameter opening, matching that on the larger vessel, at each end. Table I shows the ratios of the areas of each of the various openings to the volumes of the vessels; these ratios will, for convenience, be termed "vent ratios".

Assemblies of wire gauze with the coarsest gauze facing the interior of the explosion vessel and a heavy ½in. mesh support on the outside were bolted over the openings by means of mounting rings.

For the tests requiring oil mists, a generator similar to that described in reference(3) was constructed; in this generator, lubricating oil was sprayed into a hot plate vaporizer and the oil vapour produced led into a pipe through which a stream of air was blown. In the tests, the resulting condensed oil mist was admitted to the explosion vessel.

The source of ignition in the pentane experiments was a low tension fusehead wrapped with a 2in. length of guncotton; in the later experiments a cerium fusehead was used. In each case, the fuse was mounted on the end of a metal rod so that it could be screwed into the required aperture (Fig. 1) to reach the axis of the vessel.

The pressures developed in the explosions were measured by means of an S.M.R.E. piezo-electric manometer(5) and were recorded photographically; the moment of ignition and a time scale were also recorded.

The temperature of the explosion products after they had passed through the gauzes was recorded in many of the experiments by means of a resistance thermometer. The thermometer head was designed to respond rapidly to changing temperature and it consisted of a 5 cm. length of 0·002in. diameter platinum-10 per cent rhodium wire which formed one arm of a bridge energized by alternating current of 1·5 kc./sec. frequency; a cathode ray oscilloscope was used as an indicator. The bridge was balanced at ambient temperature and any change in the resistance of the wire due to heating caused a deflexion of the oscilloscope beam, which was recorded photographically. The system was calibrated directly. The thermometer head was placed 2ft. 6in. from the gauze in line with the axis of the vessel (position F, Fig. 1). In some experiments, a number of small pieces of oily cotton fabric were suspended from the framework on which the thermometer head was mounted and the effect of the explosion products on them was observed. Also, in some of the oil mist explosion experiments, an estimate of the temperature of the gauzes was obtained by means of a chromel/alumel thermocouple mounted centrally within the assembly.

Experimental Methods and Conditions

As a starting point in the tests, gauze assemblies similar to those of previous workers(1, 3, 4) were used and changes were made as experience was gained.

Before each experiment, the gauze assembly was thoroughly wetted with Shell Talpa 30 lubricating oil and was then allowed to drain in a horizontal position. Some measure of control over the severity of each test was obtained by altering the position of the point of ignition. Thus, in the tests with a single vessel, placing the fuse near the gauzes would lead to the most severe conditions; with the fuse remote from the gauzes, some of the mixture would be driven out of the vessel unburnt and the total heat release would therefore be less.

After every explosion, the gauze assembly was dismantled for examination and any damaged layers were replaced.

Results of Tests

i) *Pentane/Air Explosions:* The pentane/air explosion tests were carried out in the 200 cu. ft. vessel. The mixtures of pentane vapour and air were made by spraying the required quantity of liquid pentane into the explosion vessel; a fan inside the vessel was then left running for a few minutes to circulate the vapour.

Preliminary experiments showed that the lowest explosible concentration of pentane, with which reasonably consistent ignitions could be obtained, was 2 per cent by volume and, since mild explosions were required, this concentration was adopted as standard.

The results of the experiments are set out in Table II, which shows the position of the ignition point, the assembly of gauzes used, the maximum explosion pressure, the maximum indicated temperature of the effluent gases, and any general observations that were made. Because of the low luminosity of the flame and the dense cloud of white vapour given off the oil wetted gauzes, it was often difficult to be certain whether or not a flame had passed through the gauze assembly; flame was not always seen even when the gauzes melted. The recorded gas temperatures and the amount of damage suffered by the cloth strips may have been affected by oil spray from the gauzes; both also may have been influenced on occasion by deflexion of the hot gas stream by strong winds.

As can be seen from Table II, the first results (experiments 1 to 3) showed that the conditions were too arduous for the initially chosen assemblies and the severity was therefore reduced by moving the point of ignition away from the gauzes. With ignition remote from the gauzes, satisfactory performance was only obtained with a six layer combination (2 × 10, 2 × 20, 2 × 40; experiments 6 and 9), but this combination permitted flame to pass with central ignition (experiment 10). A nine layer combination (3 × 10, 3 × 20, 3 × 40) successfully with-

TABLE II.—2 PER CENT PENTANE EXPLOSION EXPERIMENTS IN 200 CU. FT. VESSEL WITH 24 IN. DIAMETER OIL WETTED GAUZE ASSEMBLIES.

Vent ratio 2·3 sq. in./cu. ft.; mild-steel gauzes except where otherwise stated.

	Wire sizes:	
Mesh	S.W.G.	In. diameter
10	21	0·032
20	26	0·018
40	34	0·009

Experiment No.	Position of ignition point	Gauze assembly, number of layers × meshes per in.	Maximum pressure, lb./sq. in.	Maximum indicated temperature of effluent gases, deg.C	Observations
1	Centre	2 × 20 copper	—	—	Gauzes melted; flame seen.
2		2 × 40	—	300	
3		3 × 20 copper 3 × 40	1	>800	Gauzes melted; no flame seen.
5	Remote from gauzes	2 × 20 2 × 40	2·5	250	Gauzes undamaged; flame seen.
7		1 × 10 2 × 20 2 × 40	2	600	Gauzes undamaged; no flame seen.
8			2	170	Gauzes undamaged; no flame seen; cloth strips unaffected.
6		2 × 10 2 × 20 2 × 40	1·5	20	Gauzes undamaged; no flame seen.
9			7·5	150	Gauzes undamaged; no flame seen; one cloth strip smouldering
10	Centre		2·5	150	Gauzes undamaged; flame seen: cloth strip smouldering.
11		3 × 10 3 × 20 3 × 40	2	< 80	Gauzes undamaged; no flame seen; cloth strips unaffected.
13	Near gauzes		4·5	150	Gauzes red hot and outer melted locally; no flame seen.
14			4	150	Gauzes red hot and melted; no flame seen.
15		4 × 10 4 × 20 4 × 40 Clamped together	1·5	< 50	Gauzes undamaged; no flame seen.
16			1	80	Three persistent red-hot spots on gauzes; local melting; no flame seen.

stood central ignition (experiment 11) but melted when subjected to ignition near the gauzes (experiments 13 and 14) although no flames were seen and the measured gas temperatures were low. It has been reported in previous work[(1)] that local red hot patches may appear in gauze assemblies where the layers are not in close contact and so an effort was made to improve the mutual contact of the gauzes. An assembly of twelve gauzes (4 × 10, 4 × 20, and 4 × 40) was clamped between two steel spiders before mounting on the explosion vessel. The first test with this arrangement (experiment 15) was successful but in the second, three red hot patches appeared, persisting for about one minute after venting had ceased.

The persistence of the red hot patches in the gauzes in experiment 16 suggested that some form of exothermic chemical reaction may have been taking place on the gauzes and so contributing to their melting. To obtain further evidence of this possibility and to investigate other combinations of gauze, further tests were carried out with the results shown in Table III. To conserve available stocks of gauze, the tests were carried out with smaller areas exposed to the flame. The gauzes were clamped over a 9in. diameter hole cut in a steel plate which was bolted over the 24in. diameter opening in the explosion vessel; around the 9in. hole, eight holes 2¼in. diameter were cut and these were left unobstructed during the tests. This arrangement with the twelve layer assembly of gauzes had a similar resistance to a low rate of air flow as the assembly over a 24in. diameter opening. In explosions, however, its resistance appeared to be somewhat greater but the explosion pressures were still well within the prescribed limit and it is assumed that the overall effect was slightly to increase the severity of the tests. In the series, experiments were made with both dry and wetted gauzes for comparison. Eleven experiments were made with the twelve layer combination (4 × 10, 4 × 20, and 4 × 40) and in every case the gauzes melted and incandescent particles were blown out; this occurred with dry gauzes, oil and water wetted gauzes, and finally gauzes wetted with water thickened by a chemical additive (to increase the amount of water adhering to the gauze). In a further five experiments with dry gauze assemblies of eight, ten, twelve, fourteen and sixteen layers respectively of 10 mesh gauze, the gauzes melted.

TABLE III.—2 PER CENT PENTANE EXPLOSION EXPERIMENTS IN 200 CU. FT. VESSEL WITH 9 IN. DIAMETER MILD STEEL GAUZE ASSEMBLIES.

Ignition point near gauzes; gauzes dry except where otherwise stated.

Experiment No.	Gauze assembly, number of layers × meshes per in.	Maximum explosion pressure, lb./sq. in.	Observations
17	4 × 10 4 × 20 4 × 40	—	Gauzes melted; incandescent particles blown out and sucked into vessel. (In experiment 23 gauze became hotter after venting ceased).
18		4	
23		1	
24		5	
30		—	
19	4 × 10 4 × 20 oil wetted 4 × 40	4	
32		—	
20	4 × 10 4 × 20 water wetted 4 × 40	6	
31		—	
22	4 × 10 wetted with 4 × 20 thickened 4 × 40 water	4	Gauzes melted; fewer particles blown about than above.
29		—	
25	8 × 10	—	Gauzes melted; incandescent particles blown out and sucked into vessel.
21	10 × 10	3	Gauzes red hot; inner eight layers melted.
26	12 × 10	2	
27	14 × 10	2	Gauzes red hot and became hotter after venting ceased; inner nine layers melted.
28	16 × 10	3	Gauzes red hot; inner eleven layers melted.

The observations during this set of experiments confirmed that oxidation of the steel wire was likely to be contributing to the melting of the gauzes and so laboratory tests were made to try to ascertain whether this was possible. A number of strips of steel gauze were heated electrically to red heat (estimated at 900-1,000 deg. C.) in an atmosphere of nitrogen, to simulate the heating of gauze assemblies in the hot products of combustion; on exposing them, still being heated, to the air, they became white hot and then melted, throwing off incandescent particles in the process. It was then thought possible that a more suitable gauze material might be found. Of the commoner metals, nickel and copper have a much lower heat of oxidation than steel and, of the two, nickel appeared to be preferable because of its much higher melting point (1,450 deg. C. as opposed to 1,080 deg. C.). Gauzes of Monel metal, an alloy of nickel and copper with a melting point of about 1,350 deg. C. were commercially available and tests were carried out on these; the experiments are described in the section dealing with oil mist explosions. Further laboratory experiments were conducted to compare the behaviour of Monel with that of steel. Coils of each wire were heated in nitrogen to red heat, but with the Monel visibly hotter than the steel. On exposure to air while still being heated, the steel wire became hotter than the Monel until ultimately it threw off hot particles and melted. These experiments indicated that Monel gauzes might be expected to resist melting under conditions where steel gauzes would fail. The use of such materials would represent a

TABLE IV.—OIL MIST EXPLOSION EXPERIMENTS IN 200 CU. FT. VESSEL WITH OIL WETTED GAUZE ASSEMBLIES OF MILD STEEL.

Ignition point near gauzes. Vent ratio 2·3 sq. in./cu. ft. Gauze assembly 4 × 10, 4 × 20, 4 × 40 mesh.

Experiment No.	Quantity of oil vaporized, pints	Nominal concentration, oz./cu. ft.	Maximum explosion pressure, lb./sq. in.	Observations
48	1½	0·12	20	Gauzes and spiders severely damaged; no flame seen.
56	1	0·08	0	Gauzes undamaged; no flame seen.
57	1	0·08	4	Red hot patch on gauze, local melting; no flame seen.
58	1¼	0·1	6	Gauzes melted; no flame seen.

marginal precaution which could only be effective where the gauzes were near melting.

It is evident from the pentane explosion experiments described that the heaviest assembly of steel gauzes tested cannot be relied upon to resist melting under all conditions of test when covering an opening of vent ratio 2·3 sq. in./cu. ft. and hence that under these conditions the emission of flame and hot gases may not be prevented. It was considered that it would not be advisable to make the assembly any heavier since the effective area of venting might be restricted too much.

At this stage, as the oil mist generator was ready for use, it was decided to begin experiments with oil mist explosions under conditions similar to those in experiments 15 and 16 (Table II) in order to compare the effect of the two types of explosion on the gauzes.

ii) *Oil Mist Explosions:* Previous work has shown that it is difficult to obtain reproducible results with oil mists. This has been confirmed, but it was found possible to produce a series of explosions of limited violence in which the pressures were within the prescribed limit of 20lb./sq. in.

In experiments in the 200 cu. ft. vessel, explosions could be obtained when one pint of oil was vaporized, the "nominal concentration" calculated from this quantity of oil and the volume of the vessel being about 0·08 oz./cu. ft. It is safe to assume that the actual concentration was lower than this, since some of the mist would be lost by condensation in the pipes and vessels but it could not be lower than 0·049 oz./cu. ft. the lower explosive limit for the oil in use(2). Nominal concentrations up to 0·2 oz./cu. ft. were used in the 200 cu. ft. vessel, and up to 0·48 oz./cu. ft. in the 66 cu. ft. vessel. Measurements of concentration made by a gravimetric method after filling the vessel with mixture gave inconsistent results and were eventually discontinued. In order to reduce losses by condensation to a minimum, the igniter was fired as soon as possible after the vessel had been filled with mixture.

The mist was produced from Shell Talpa 30 lubricating oil. This particular oil was adopted partly because it had been used in an earlier investigation(2) and partly because it is a widely used oil and is readily available; there is no suggestion that it is more liable to give rise to explosive mists than any other oil.

a) Experiments in the 200 cu. ft. vessel. The oil mist experiments began with explosions carried out under similar conditions to those used for experiments 15 and 16 in the pentane series (Table II) namely with an oil wetted assembly of twelve layers covering the 24in. diameter opening, with the point of ignition near the gauzes.

The results are set out in Table IV, which shows the amount of oil vaporized, the nominal concentration of the oil mist mixture, and the maximum explosion pressure, together with the observations made. The first explosion (experiment 48) was unexpectedly violent and the assembly, which was clamped between two metal spiders to prevent bulging, but was without other external support, was torn out of its mounting and damaged severely, together with its mounting ring and the spiders. In all later experiments the spiders were not used and the assembly was supported externally by a layer of ½in. mesh. The second explosion was weak and the gauzes were undamaged, but in the third (experiment 57) a red hot

TABLE V.—OIL MIST EXPLOSION EXPERIMENTS IN 200 CU. FT. VESSEL WITH OIL WETTED GAUZE ASSEMBLY OF MONEL METAL.

Vent ratio 2·3 sq. in./cu. ft. Gauze assembly 4 × 10, *4 × 20, 4 × 40 mesh.

Experiment No.	Position of igniter	Quantity of oil vaporized, pints	Nominal concentration oz./cu. ft.	Maximum explosion pressure, lb./sq. in.	Maximum indicated temperature, deg. C.		Observations
					Gauze	Effluent gases	
106	Centre	1	0·08	0	20	130	Gauzes undamaged; no flame seen.
107	Centre	2	0·16	1	300	20	Gauzes red hot locally but undamaged; no flame seen.
108	Centre	2	0·16	0·5	400	600	Gauzes undamaged; no flame seen.
109	Near gauzes	1¼	0·1	2	—	700	Gauzes red hot all over; internal layers melted. Flame seen in colour film.

*22 S.W.G. wire.

Table VI.—Oil mist explosion experiments in 200 cu. ft. vessel with oil wetted gauze assemblies of mild steel.

Gauze assemblies over all vents, ignition point near gauzes. Vent ratio 4·8 sq. in./cu. ft. Gauze assemblies 4 × 10, 4 × 20, 4 × 40 mesh.

Experiment No.	Quantity of oil vaporized, pints	Nominal concentration, oz./cu. ft.	Maximum explosion pressure, lb./sq. in.	Maximum indicated temperature of effluent gases, deg. C.	Observations
61	1	0·08	0·5	—	Gauzes undamaged; no flame seen during explosion; oil on gauzes caught fire later.
62	1	0·08	—	500	All gauzes hot; 40 mesh on 24 in. vent fused; no flame seen.
63	1½	0·12	4	200	All gauzes hot but undamaged; no flame seen.
64	2	0·16	9	400	
65	2½	0·2	3	400	

patch appeared and local melting took place in some of the inner layers. In the fourth test (experiment 58) the gauzes became red hot and large areas of all gauzes melted. No flame was seen to pass through the gauzes in any of the tests but, as in the pentane tests, it may have been obscured by the dense cloud of white mist given off by the oil wetted gauzes.

It is appropriate to describe here the results of four tests with Monel gauzes which were actually carried out at the end of the investigation. Owing to its high price, only sufficient gauze was obtained to make one assembly of twelve layers and this was used under conditions similar to those of experiments 48 to 58 (Table IV); the results are set out in Table V. As only one set of gauzes was available, the igniter was inserted in the central position during the first three tests to make the conditions less severe and the gauzes remained undamaged, although in one test they became red hot and in another a high indicated gas temperature was recorded. For the fourth test (experiment 109), the igniter was inserted near the gauzes to

Table VII.—Oil mist explosion experiments in 66 cu. ft. vessel with oil wetted gauze assembly.

Vent ratio 6·85 sq. in./cu. ft.; ignition point near gauzes. Gauze assembly 4 × 10, *4 × 20, 4 × 40 mesh.

Experiment No.	Quantity of oil vaporized pints	Nominal concentration of oil mist, oz./cu. ft.	Maximum explosion pressure, lb./sq. in.	Maximum indicated temperature, deg. C. Gauze	Maximum indicated temperature, deg. C. Effluent gases	Observations
68	¾	0·18	0	—	< 50	Gauzes cool and undamaged; no flame seen.
69	¾	0·18	0	200	150	Gauzes hot but undamaged; no flame seen.
70	1	0·24	1·0	500	600	
80	1	0·24	—	450	500	
81	1	0·24	0·3	500	—	
83	1	0·24	4·0	350	—	
86	1	0·24	1·0	550	—	
71	1½	0·36	—	550	550	
72	1½	0·36	2·0	600	600	
74	1½	0·36	3·0	600	600	
75	1½	0·36	1·5	650	—	
76	1½	0·36	0·5	550	550	
77	2	0·48	0·5	500	550	
78	2	0·48	0·3	350	200	
79	2	0·48	0·4	550	450	
82	2	0·48	0·5	400	—	

*22 S.W.G. wire.

increase the severity of the conditions and to make the test directly comparable with experiment 58 (Table IV). During the explosion, the whole of the gauze was raised to bright red heat and it remained hot for about half a minute. No flame was seen but a colour cine film showed a sheet of flame a few feet long, apparently separated from the gauzes by a gap of a few feet; the flame persisted for only about 150 m. sec. A temperature of about 700 deg. C. was recorded in the effluent gases; no record was obtained of the gauze temperature as unfortunately a short circuit developed in the thermocouple leads. On dismantling the gauzes it was found that several layers had melted over a large area. The damage was severe, but was less than that in experiment 58 in which large areas of all the steel gauzes melted; in the latter test, however, a higher explosion pressure developed: 6 as against 2lb./sq. in. In experiment 107 the gauzes were heated less strongly and only a dull red patch appeared; there was no damage to the gauzes at this spot. In tests with steel gauzes where local red hot patches appeared (experiment 16, Table II and experiment 57, Table IV) the gauzes melted at the hot spot. These comparisons may perhaps indicate that Monel gauzes were slightly more resistant to melting than steel, but with so few tests the evidence must be considered inconclusive.

The results of these oil mist explosion experiments make it clear that, as in the tests with pentane explosions, heavy gauze assemblies covering an opening of vent ratio 2·3 sq. in./cu. ft. cannot be relied upon to survive exposure to the hot products of combustion under all conditions, and it may safely be inferred that gauzes covering smaller vents, nearer in size to the minimum standard of 0·5 sq. in./cu. ft. would certainly not resist melting.

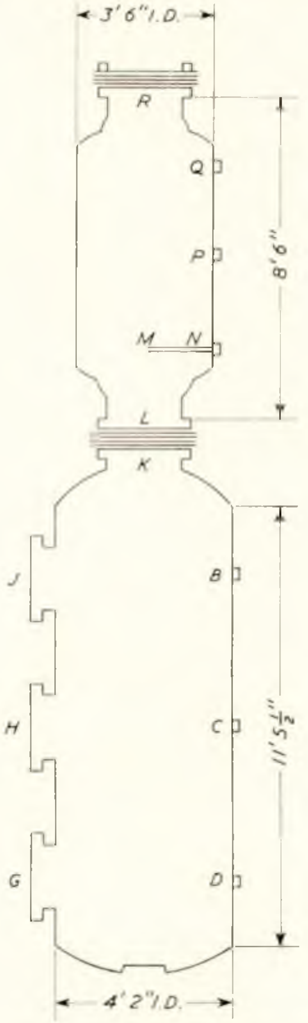
Before the beginning of the second part of the investigation (to determine whether or not flame could be prevented from passing through a flame trap separating one vessel from another) it was necessary to establish experimental conditions under which the gauzes separating the vessels would not melt. To do this it was evidently necessary to increase the vent ratio of the openings on the explosion vessel and initially this was done by using two of the 18in. diameter openings on the side of the 200 cu. ft. vessel in addition to the 24in. diameter opening used hitherto; the total vent ratio was thus increased to 4·8 sq. in./cu. ft. Each of the three openings was covered by twelve layers of gauze. The results obtained are set out in Table VI. In the five experiments carried out, damage occurred to the gauzes only once (experiment 62). Although no flame was seen, the indicated gas temperatures were high and it was noted that not only were the assemblies hot immediately after the test, but that their temperature tended to rise during the next minute or two, though not to the point of red heat; it was during this stage that the oil remaining on the gauzes ignited in experiment 61, and an occurrence of this kind would, of course, be a considerable hazard in practice. Further experiments with a still larger vent ratio were evidently required and these were carried out in the 66 cu. ft. vessel.

b) Experiments in the 66 cu. ft. vessel. In order to provide a greater vent ratio than could be obtained in the 200 cu. ft. vessel further experiments were carried out in the 66 cu. ft. vessel with gauze assemblies covering one of the 24in. diameter openings, giving a vent ratio of 6.85 sq. in./cu. ft. The results are summarized in Table VII. In these tests an approximate indication of the temperature at a point within the gauze assembly was obtained by means of a chromel/alumel thermocouple.

No flame was seen to pass through the gauzes and no damage occurred to them in any of these tests but it will be seen that the gauzes became hot, although not red hot, and the effluent gases were hot in all tests except for the first. Continued heating was detected only in experiment 78 in which the gauze temperature rose from 300 to 350 deg. C. two minutes after the explosion.

It was considered that the absence of visible flame and of damage to the gauzes in these tests justified going on to the next stage in the investigation, which was to determine whether the gauzes would prevent transmission of flame from one vessel to another.

c) Experiments in coupled explosion vessels. Two series of tests were carried out in which the two explosion vessels were coupled together with a gauze assembly between them. The general arrangement was as shown in Fig. 2, the gauze assembly under test being bolted between the flanges of the 24in. diameter openings, L and K, in the two vessels. In the first series of tests, the opening R in the small vessel was closed by a steel blank so that the vent ratio in the vessel was 6·85 sq. in./cu. ft.; in the second series, the opening R was covered with a gauze assembly similar to that between the vessels so that the vent ratio was 13·7 sq. in./cu. ft. Both vessels were filled with oil mist mixture and the mixture in the smaller vessel was ignited. To enable any ignition of the mixture in the larger vessel to be detected and to prevent as far as possible any damage to the gauzes consequent on such an ignition, bursting panels were provided over the three 18in. diameter openings, G, H, and J, on the larger vessel. After the explosion and after the gauzes had begun to cool, a supplementary igniter was fired in the large vessel; the purpose of this was partly to test whether an explosive mixture had been present and partly to dispose of the mixture. It must be emphasized,



N), P), Q) Alternative positions of igniter.
G), H), J) 18-in. Diameter openings.
K), L), R) 24-in. Diameter openings.
M) Igniter supported by rod inserted through tapped opening N).
Manometer connexion situated 1ft. below P).

FIG. 2—*Plan of coupled explosion vessels*

TABLE VIII.—OIL MIST EXPLOSION EXPERIMENTS IN COUPLED 66 CU. FT. AND 200 CU. FT. VESSELS (FIG. 2), WITH OIL WETTED GAUZE ASSEMBLIES OF MILD STEEL.

Ignition point within the small vessel. Nominal concentration of oil mist in large vessel 0·16 oz./cu. ft.
Gauze assembly 4 × 10, *4 × 20, 4 × 40 mesh.

Experiment No.	Position of ignition point	Oil vaporized in small vessel, pints	Nominal concentration, oz./cu. ft.	Vent ratio in small vessel, sq. in./cu. ft.	Maximum explosion pressure, lb./sq. in.	Maximum indicated temperature of gauze between vessels, deg. C.	Observations
88	Near gauzes (N, fig. 2)	1	0·24	6·85	5·0	850	No transmission of flame.
90		1	0·24	6·85	2·5	850	
93		1	0·24	6·85	4·0	600	
89	Remote from gauzes (Q, fig. 2)	1	0·24	6·85	5·0	100	
91		1	0·24	6·85	4·0	350	
92		1	0·24	6·85	1·5	100	
94	Near gauzes (N, fig. 2)	1½	0·36	6·85	3·0	600	
95		1½	0·36	6·85	5·0	100	
97	Near gauzes (N, fig. 2)	2	0·48	13·7	1·5	100	
98		2	0·48	13·7	2·0	40	
99	Central (P, fig. 2)	1	0·24	13·7	—†	850	No transmission of flame, but flame seen at other end (see text).
100		2	0·48	13·7	2·5	300	No transmission of flame.
101		2	0·48	13·7	1·0	20	
103		2	0·48	13·7	2·0	50	
104		2	0·48	13·7	4·0	300	
105		2	0·48	13·7	1·2	—	

*22 S.W.G. wire. †Pressure too high to be recorded.

however, that failure to ignite in any particular case could be due to weakening of the mixture by condensation during the period of waiting or to dilution with exhaust products from the initial explosion. In fact, the mixture in the larger vessel failed to ignite in only three of the sixteen experiments.

The results of the tests are set out in Table VIII. The assemblies used consisted of twelve layers of mild steel gauze placed so that the coarsest mesh was towards the interior of the smaller vessel. No transmission of flame occurred and no damage was done to the gauzes in any of the first eight experiments in which the vent ratio was 6·85 sq. in. /cu. ft. With the ignition point near the gauzes, however, high gauze temperatures up to 850 deg. C. were recorded. It is possible that the mixture in the large vessel did not ignite in these tests because it was not in contact with the hot gauzes but was separated from them by the products of combustion of the explosion, or because the outer gauzes were cooler than those inside the assembly. Heating to this extent is, however, potentially dangerous and further experiments were therefore undertaken with the maximum amount of venting attainable: a vent ratio of 13·7 sq. in./cu. ft. with the openings at both ends of the smaller vessel in use and covered with gauzes. In this series of tests (experiments 97 to 105, Table VIII) the explosion took place in a vessel that was vented at both ends, and in these circumstances a central position for the igniter would be expected to produce the most severe conditions, six of the eight tests were carried out with the igniter in this position (inserted at P, Fig. 2). It will be seen from Table VIII that there was again no transmission of flame, no ignition of the mixture in the large vessel and no damage to the gauzes in any of the tests, except in experiment 99. The explosion in this experiment was exceptionally violent and the pressure was too high to be recorded (maximum recordable pressure at the time was about 8lb./sq. in.); the wooden annulus holding the gauze assembly in position at R (Fig. 2) was shattered and the assembly of gauzes was forced away from the flange at one place leaving a small unscreened opening. A large flame was seen on the outside of the gauzes at this end of the vessel. This experiment must be discarded because of the violence of the explosion and the physical damage to the gauzes.

These experiments show that an oil-wetted gauze assembly may prevent the transmission of an explosion from one chamber to another when sufficient vent area is available and the explosions are limited in violence. The occurrence of temperatures of 850 deg. C. in the gauzes in two tests with vent ratio 6·85 sq. in./cu. ft. (experiments 88 and 90) and in experiment 99 with a vent ratio of 13·7 sq. in./cu. ft. (though this was a particularly violent explosion), indicates that the factor of safety may not be high.

A striking feature of many of these experiments was the occurrence of loud humming noises of changing pitch, which began soon after the initial explosion had taken place. The vibrations appeared to be related in some way to the temperature of the gauzes, as a revival of the sound occurred when the mixture in the larger vessel was ignited causing renewed heating of the gauzes (in two cases residual oil on the gauzes caught fire).

d) Experiments in a closed vessel. At the end of the investigation two tests were carried out in which oil mist explosions were produced in a closed vessel. The 200 cu. ft.

vessel was used and the ignition point was central. In the first test, one pint of oil was vaporized (nominal concentration 0·08 oz./cu. ft.) and a pressure of 94lb./sq. in. was obtained; in the second test, two pints were vaporized (nominal concentration 0·16 oz./cu. ft.) and a pressure of 73lb./sq. in. was obtained. These pressures are comparable with those obtained by previous workers(2) in a 60 cu. ft. vessel (range 87 to 112lb./sq. in.).

TESTS WITH CRIMPED-RIBBON FLAME TRAP

It was decided to supplement the results of the tests on gauze flame traps with a few tests with a flame trap of the crimped-ribbon type. The objects of the tests were to ascertain how this type of flame trap behaved when used to cover a vent in an explosion vessel, i.e. its efficacy in limiting the temperature of the effluent gases and preventing the passage of flame; the tests were also intended to indicate the extent to which uneven heating of the trap would lead to damage of the inner face during the venting.

Apparatus

The experiments were carried out in the 66 cu. ft. vessel described on page 2. The flame trap was attached at one end and the other end was usually closed by a bursting panel to limit the maximum explosion pressure as far as possible to not more than 5lb./sq in.

The flame trap was obtained to the following specification: circular matrix of 24in. diameter and 2in. depth made of cupronickel ribbon (melting point 1,180 deg. C.) of 0·002in. thickness with crimp height 0·048in., wound in two sections contained within inner and outer steel rings and mounted in a flanged adapter to fit the 24in. diameter openings in the 66 cu. ft. vessel. The assembly was to be of sufficient mechanical strength to withstand an explosion pressure of 5 to 10lb./sq. in. and the matrix was reinforced by rods passing radially through it from the rings to the central boss. Further support was given on the outside by a metal spider (see Fig. 3). The weight of the assembly with its rings and reinforcing rods was 56½lb. and the estimated weight of the crimped element alone was about 28lb.; the flanged adapter weighed 75½lb. According to the makers, the total effective open area of the trap was 342 sq. in., i.e. about 76 per cent of the nominal area.

The source of ignition consisted of a low tension fusehead wrapped with a 2in. length of guncotton.

The temperature of the hot gases issuing through the trap was measured by three chromel/alumel thermocouples placed symmetrically at a distance of 12in. from the outer surface of the trap; their indications were recorded on a four channel oscilloscope. As a further indicator of temperature, a grid of nylon threads of 0·004in. diameter spaced 3in. apart, was mounted on a frame and placed about 8in. behind the thermocouples. The approximate melting point of the threads used was 230 deg. C.

Colour cine films (16 mm.) were taken at 16 frames per second of all experiments.

Experimental Conditions

Weak pentane mixtures (about 2 per cent in air) were employed; the required quantity of liquid pentane was sprayed into the explosion vessel and a 24in. fan was run for four minutes; a sample was then taken for analysis.

In the first six tests, the vent ratio was 6·85 sq. in./cu. ft., in the remaining tests, parts of the arrestor were masked off and the vent ratios were 3·4 and finally 1·7 sq. in./cu. ft.

In all tests except the first, the trap was wetted with Shell Talpa 30 oil.

Results of Tests

Ten tests were carried out and the results are set out in Table IX.

After the first two tests, the trap was reversed so as to expose its undamaged side to the hot gases. During the next

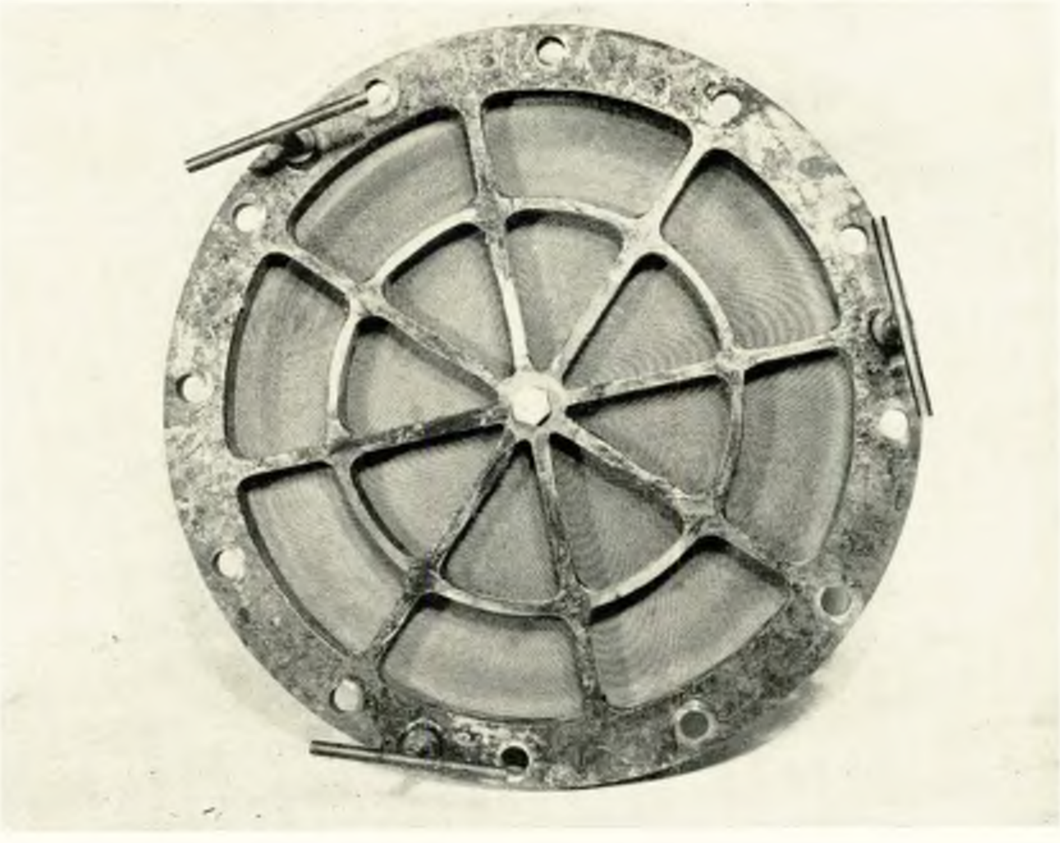


FIG. 3—*Flame trap mounted in adapter*

TABLE IX.—2 PER CENT (NOMINAL) PENTANE EXPLOSION EXPERIMENTS IN 66 CU. FT. VESSEL WITH CRIMPED-RIBBON FLAME TRAP. TRAP OIL WETTED EXCEPT IN EXPERIMENT 106.

Experiment No.	Vent ratio sq. in./cu. ft.	Closure at remote end		Position of igniter	Per cent pentane by analysis	Effluent gases, maximum temperature rise, deg. C.	Nylon grid after experiment	Maximum pressure, lb./sq. in.	Maximum depth of melting of trap, in.	Remarks*
		Material	Condition after experiment							
106	6·85	Single sheet brown paper	Intact	Central	—	105	Melted	0·8	0·06	Some damage over two-thirds area.
107	6·85				1·8	45	Intact	—	0·06	Weak explosion. Oil ignited on inside of trap.
108	6·85			Near trap	1·6	None		0	None	No damage. Oil ignited. Very weak explosion.
109	6·85				2·0	75		1·5	0·33	Heavy damage. Oil ignited.
110	6·85		Burst	Remote from trap	2·0	30		2·1	—	Little venting through trap owing to burst closure; no damage. Oil not ignited.
111	6·85	Wood blank	Intact		2·2	75	Melted	12	—	Slight damage in small area. Oil ignited.
112	3·4	Single sheet brown paper	Burst	Near trap	2·4	None	Intact	2·2	—	No venting through trap. Oil not ignited.
113	3·4	Double sheet brown paper			2·3	—		—	—	
114	3·4	Klingerit, $\frac{1}{64}$ in. thick	Intact		2·2	190	Melted	3·2	0·8	Very heavy damage. Oil ignited.
115	1·7		Burst (after short delay)		2·2	110		6·8	0·9	

*No flame was seen to pass through trap in any test.

two tests, the trap suffered severe damage and for the remaining tests, the original side, now the least damaged, was exposed to the gases.

In none of the tests was flame observed to pass through the trap. In this important respect it is evident that the trap was very efficient. Although the highest temperature recorded by the thermocouples was 190 deg. C. (experiment 114) it is clear that the effluent gas temperatures were somewhat higher than this, since in several tests the nylon threads melted; it is probable that the thermocouples were slower in response than the resistance thermometer used in the earlier tests where the measured temperatures reached 600 deg. C. (Table VII). Nevertheless it seems possible that the crimped-ribbon flame trap may have been more effective than the gauze assemblies in keeping down the effluent temperature.

Except in tests where there was very little venting through the trap because of the bursting of the panel at the remote end or because the explosion was very weak indeed, the trap suffered damage even with weak explosions with central ignition and the maximum vent ratio of 6·85 sq. in./cu. ft. (experiments 106 and 107). In experiment 111 with a violent explosion, only a small area of the trap was damaged and that only slightly; this was probably because remote ignition was used so that much of the mixture would be blown out of the vessel unburnt. With reduced vent areas (experiments 114 and 115), the trap suffered heavy damage, extending nearly half-way through the matrix locally, even though in the last test the panel eventually burst so that not all the products of combustion passed through the trap.

In the parts where the outside ends of the passages were blocked by the spider, no damage was suffered on the inner face, suggesting that the heat transfer across the trap was not very rapid. Where severe damage was done to the trap it was evident that a considerable number of the channels in the trap were blocked by molten metal, hence presumably reducing the capacity of the trap for relieving pressure. Further, the matrix tended to shrink towards the centre, leaving a gap around the periphery (see Fig. 4), but this gap was usually covered wholly or partially by the supporting spider on the outside. Nevertheless, even after severe damage, the trap was still usable and prevented the emission of flame in further tests.

The oil on the inside surface of the flame trap ignited in all the tests in which there was any appreciable amount of venting through the trap. The flames were visible from the outside through the trap but showed no tendency to spread to the outside; they were easily extinguishable by a jet of water.

CONCLUSIONS AND GENERAL DISCUSSION

It is concluded from the experiments that have been described that the oil-wetted gauze assemblies tested cannot be relied upon to resist melting, when used to cover an opening of vent ratio 2·3 sq. in./cu. ft. or less and hence they may not prevent the emission of flame and hot gases. With vent ratio 4·8 sq. in./cu. ft. melting occurred in one case only and with 6·85 sq. in./cu. ft. the gauzes resisted melting in every case, although the temperatures measured in the effluent gas streams reached values which would be dangerous to personnel in practice. The experiments were carried out so as to subject the gauzes to the greatest amount of heating possible while keeping the pressure developed in the explosion to a low level. In practical conditions, however, explosions that occur accidentally may happen to be very weak, perhaps because the explosive atmosphere is localized or because of the position of the source of ignition in relation to the flame trap; in such cases it is possible that some degree of protection may be afforded by gauzes covering a small vent.

The experiments with coupled explosion vessels show that the oil-wetted gauze assemblies tested are capable of preventing

Fig. 4—*Flame trap after Experiment 109 showing damaged areas*

the transmission of an explosion from one chamber to another, when used to cover a vent of sufficient area, no failures having occurred with vent ratios of 6·85 and 13·7 sq. in./cu. ft. there were, however, indications that the factor of safety was not very high, particularly with the lower ratio.

No particular advantage is claimed for the assembly of gauzes used in most of the tests; it was built up from a successful combination used by earlier workers, and is only one of the very large number of possible combinations of commercially available gauzes. No basic information exists at present to indicate whether combinations of gauzes of differing mesh are more or less effective than assemblies of a single gauze. It is considered that any appreciable increase in the number of gauzes would be even more cumbersome than the twelve layers used, and might cause excessive restriction of the area of the vent. In the few tests that were possible, an assembly of Monel gauzes did not appear to have any significant advantage over the steel assembly.

The crimped ribbon arrestor tested proved to be highly effective in preventing the emission of flame and there were indications that it was more effective than gauze assemblies in limiting the temperature of the effluent gases.

At maximum vent ratio, the crimped ribbon trap was more liable to suffer damage than the heavy assemblies of gauze used earlier in the tests. At low vent ratios damage was heavy, nearly half the total thickness of the matrix being melted in one test where the area of the trap exposed was equivalent to a vent ratio of 1·7 sq. in./cu. ft. which is itself over three times the minimum standard recommended by the Ministry of Transport. At a similar vent ratio (2·3 sq. in./cu. ft.) gauze assemblies were also liable to melt. It was evident that the heat transfer from the products of combustion to the matrix of the crimped ribbon trap was far from being uniform throughout the trap.

ACKNOWLEDGEMENT

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PART II—A THEORETICAL CONSIDERATION

By K. N. Palmer, M.A.

INTRODUCTION

In considering the action of a flame trap, it is usually assumed that the trap absorbs heat from the gases flowing through it and that, if the gases can be cooled sufficiently, combustion will cease and hence flame will not pass through the trap. The action of a trap is usually twofold: to abstract heat from the flame quickly enough to prevent it from propagating through the trap and to be sufficiently massive to absorb, without overheating, the heat from combustion products that may be expelled through the trap. In the present case it is assumed that the dominant factor is the ability of the trap to absorb heat and not the rate at which the trap abstracts heat from the gases passing through it. This assumption is supported by the experimental evidence in Part I, in which the appearance of flame outside the explosion vessel was nearly always accompanied by heating or melting of the flame trap. The heat to be absorbed by the trap depends on the volume of the vessel and the heat released per unit volume during combustion. In the investigation reported in Part I, the position of the igniter affects the total heat produced in the vessel since, with the igniter remote from the trap, some mixture will be driven unburnt through the flame trap. The amount of heat the trap can take up depends on its mass and specific heat and the permissible temperature rise.

In the following analysis the method of calculation will be to compare the amount of heat the trap can take up with the minimum quantity of heat that is required to be absorbed from the flame, if propagation of flame through the meshes of the arrester is not to occur. If the heat that can be taken up is greater than the absorbed heat, it is concluded that the trap will quench the flame. A factor of two is assumed necessary before the behaviour can be regarded as certain; where it does not exist the behaviour is only regarded as probable. In this method, it is assumed that the trap extracts only sufficient heat from the flame and combustion products to prevent re-ignition outside the vessel, i.e. that the flame is only just quenched by the arrester. If more heat were in fact abstracted, the trap would become hotter than predicted and might even be destroyed; thus a trap which would be expected to quench an explosion might then fail to do so. In predicting the capabilities of the various flame traps, the theory is likely to err on the side of optimism. However, the experimental evidence in Part I showed that on two such occasions a flame did in fact propagate through a gauze pack, without damaging the pack (Table II), and this indicates that the arresters did not in fact abstract considerably more heat from the flame than was necessary to quench it. Because of the above assumptions, and other simplifications, only approximate agreement with experiment could of course be expected.

The amount of heat that must be abstracted from a flame in order to quench it has been investigated in other experiments on flame arresters(6). It was estimated that $2{\cdot}32 \times 10^{-2}$ cal./c.c. of flame must be abstracted from a 4 per cent (stoichiometric) propane/air flame in order to quench it. However, the total heat released is $10{\cdot}1 \times 10^{-2}$ cal./c.c. so that the proportion which must be removed is $\frac{2{\cdot}32}{10{\cdot}1}$, i.e. 0·23. Other work(7) carried out with propane has indicated that the proportion of the heat release which must be removed to extinguish the flame varies with the mixture strength. For stoichiometric mixtures (4 per cent propane), it was necessary to remove 5 cal./cc. of propane, whereas with a weak mixture (2·5 per cent propane) the required amount was only 1·8 cal./c.c., so that the proportion of heat was reduced in the ratio $\frac{1{\cdot}8}{5}$ and the actual amount of heat from a given volume of mixture in the ratio $\frac{1{\cdot}8}{5} \times \frac{2{\cdot}5}{4}$ (= 0·225). Similar tests with pentane have not been carried out, but with all paraffin hydrocarbons, the heat developed in burning stoichiometric mixtures is approximately constant at about 100 B.t.u./cu. ft. The heat release at the lower limit of flammability also is roughly constant. It will, therefore, be assumed in the following analysis that the proportion of heat to be removed, in order to quench a flame, depends only on the total heat release per unit volume, whether the fuel used be propane, pentane, or oil mist; the assumed proportions will be 0·23 in the case of stoichiometric flames and $0{\cdot}23 \times \frac{1{\cdot}8}{5}$, i.e. 0·083 in the case of weak flames.

Table X.—Heat to be abstracted by the arrester for three igniting positions (cal.).

Mixture strength	Volume of vessel cu. ft.	Position of igniting source		
		At gauze	Central	Remote
Stoichiometric (4 per cent) propane	200 66	$1{\cdot}13 \times 10^6$ $3{\cdot}73 \times 10^5$	$5{\cdot}66 \times 10^5$ $1{\cdot}87 \times 10^5$	$2{\cdot}83 \times 10^5$ $9{\cdot}35 \times 10^4$
Weak (2·5 per cent) propane	200 66	$2{\cdot}54 \times 10^5$ $8{\cdot}37 \times 10^4$	$1{\cdot}27 \times 10^5$ $4{\cdot}19 \times 10^4$	$6{\cdot}35 \times 10^4$ $2{\cdot}09 \times 10^4$

APPLICATION OF ANALYSIS TO TESTS DESCRIBED IN PART 1

Calculation of heat to be abstracted from flame

Two cases will be considered; stoichiometric and weak flames.

i) Stoichiometric Mixture (4 per cent propane/air)

For the 200 cu. ft. vessel.

The volume of the vessel = 200 × 28·3 litres.

If all the mixture is burnt inside the vessel.

The total amount of heat released

$$= \frac{200 \times 28{\cdot}3 \times 0{\cdot}04 \times 488000}{22{\cdot}4}$$

$$= 4{\cdot}93 \times 10^6 \text{ cal.}$$

If the flame is to be quenched, the arrester must abstract

$$4{\cdot}93 \times 10^6 \times 0{\cdot}23 = 1{\cdot}13 \times 10^6 \text{ cal.}$$

With the 66 cu. ft. vessel, the amount is

$$1{\cdot}13 \times 10^6 \times \frac{66}{200} = 3{\cdot}73 \times 10^5 \text{ cal.}$$

ii) Weak Mixture (2·5 per cent propane/air)

For explosions in the 200 cu. ft. vessel.

Heat to be abstracted

$$= \frac{200 \times 28{\cdot}3 \times 0{\cdot}025 \times 488000}{22{\cdot}4} \times 0{\cdot}083$$

$$= 2{\cdot}54 \times 10^5 \text{ cal.}$$

The corresponding value for the 66 cu. ft. vessel is $8{\cdot}37 \times 10^4$ cal.

Position of source of ignition

For simplicity, it will be assumed that when the igniter is near the vent no mixture escapes unburnt; when ignition is central, half of the mixture escapes and when the ignition is towards the closed end, three-quarters escape. These three positions are shown as: "at gauze", "central", and "remote" respectively in Table X, which gives the amounts of heat to be abstracted by the arrester for quenching of the explosion after ignition at the three positions.

Heat Capacity of Gauzes

The weights per unit area of the 10, 20, and 40 mesh steel gauzes used in the tests reported in Part I were 0·25, 0·2, and 0·1 gr./sq. cm. respectively when dry. The mean weight per unit area is therefore taken as 0·18 gr./sq. cm. per layer of gauze in all the following calculations, although this value will only be strictly accurate when equal numbers of layers of each mesh of steel gauze were put into the array, as was usually the case. The oil added to the gauzes boiled at about 400 deg. C., its specific heat was 0·63 cal./gr./deg. C., and its latent heat was 70 cal./gr. In a twelve layer array, which contained four layers of each mesh gauze and weighed 7,400 gr., the weight of oil added was 171 gr.

Then for one layer of dry gauze cut to a 2ft. diameter circle:

Mass of gauze = $\pi \times 30{\cdot}5^2 \times 0{\cdot}18$ gr.

Thermal capacity = $\pi \times 30{\cdot}5^2 \times 0{\cdot}18 \times 0{\cdot}1$ cal./deg. C.

Assuming that the gauze can be heated to about 480 deg. C. (900 deg. F.) before failure of the arrester occurs (e.g. because of gas mixture igniting spontaneously in contact with hot metal), the permissible temperature rise is 450 deg. C. approximately.

So, heat capacity of dry gauze

$$= \pi \times 30{\cdot}5^2 \times 0{\cdot}18 \times 0{\cdot}1 \times 450 \text{ cal.}$$
$$= 2{\cdot}37 \times 10^4 \text{ cal.}$$

If the gauze is oil wetted the heat capacity increases by a factor of

$$\frac{7400 \times 0{\cdot}1 \times 450 + 171\,(0{\cdot}63 \times 370 + 70)}{7400 \times 0{\cdot}1 \times 450} = 1{\cdot}16$$

to a value $2{\cdot}37 \times 10^4 \times 1{\cdot}16 = 2{\cdot}74 \times 10^4$ cal.

For six layers of gauze these values increase to

$1{\cdot}42 \times 10^5$ (dry)
$1{\cdot}64 \times 10^5$ (wet)

For twelve layers of gauze these values increase to

$2{\cdot}84 \times 10^5$ (dry)
$3{\cdot}28 \times 10^5$ (wet)

COMPARISON OF CALCULATIONS WITH EXPERIMENTAL RESULTS

The predicted behaviours of various gauze assemblies are compared in Tables XI to XIV with the experimentally observed results. Since the pentane tests were conducted with fairly weak mixtures, they have been compared with the 2·5 per cent propane case. In the oil mist explosions, the comparison between calculation and experiment cannot be expected to be as clear cut as in pentane tests because the composition of the combustible mixture is not known within wide limits. In addition, the extent to which oil from the mist is deposited on the gauzes during the explosion is difficult to assess; it is neglected here. The experimental results would be expected to lie somewhere between the calculated values for weak and for stoichiometric mixtures.

The theory suggests that twelve layers of oil wetted gauze over a 2ft. diameter vent are very unlikely to quench a stoichiometric explosion under the severest conditions with ignition near the gauze (Table XIII) and cannot be relied upon for weak explosions (Table XI). It can be calculated that under the severest conditions a total of fortytwo layers of oil wetted gauze $= \dfrac{1{\cdot}13 \times 10^6}{2{\cdot}74 \times 10^4}$ would be necessary probably to quench an explosion. However, if twelve layers is the practical maximum, then the area of the vent should be increased accordingly. The required diameter would be at least 3·72ft., giving a vent ratio of 7·8 sq. in./cu. ft.

USE OF CRIMPED-RIBBON FLAME TRAPS

The following estimate was made of the thickness of a crimped ribbon trap capable of quenching a stoichiometric explosion in the 66 cu. ft. vessel, with ignition near the trap. The trap was of the Amal type, crimp 0·048in., and was assumed to be dry.

Then heat to be absorbed $= 3{\cdot}73 \times 10^5$ cal. (Table X).

Since permissible temperature rise was taken as 450 deg. C.

$$\text{Mass required} = \frac{3{\cdot}73 \times 10^5}{450 \times 0{\cdot}1} = 8{\cdot}31 \times 10^3 \text{ gr.}$$

The total weight of the trap was 56½lb. and the supporting bands and rods were estimated to weigh 28lb. The weight of the boss was neglected. Hence 1 cu. in. of the crimped area of the trap was estimated to weigh 15·65 gr.

Therefore, volume of trap required $= \dfrac{8{\cdot}31 \times 10^3}{15{\cdot}65} = 531$ cu. in.

The free area through which gas could flow was 342 sq. in.

So, required thickness of trap $= \dfrac{531}{342} = 1{\cdot}55$in.

The calculated behaviour tends to be slightly optimistic (Tables XI to XIV), so that a trap 1·55in. thick might not stop explosions in the 66 cu. ft. vessel under the most exacting conditions. The actual trap tested was 2in. in thickness and was usually wetted with oil; the pentane/air mixtures were not stoichiometric (2·55 per cent), but were weaker, and averaged about 2·1 per cent (Table IX). The experimental conditions were thus not the most severe possible with full venting through the trap and, on theoretical grounds, it could be expected that the trap would withstand the explosion without failure due to complete melting of the whole trap.

TABLE XI.—PENTANE EXPLOSIONS IN 200 CU. FT. VESSEL. WEAK MIXTURES. OIL WETTED GAUZE.

Vent ratio 2·3 sq. in./cu. ft.

Ignition position / Number of layers of gauze	At gauze		Central		Remote	
	Calculated	Experimental	Calculated	Experimental	Calculated	Experimental
1	F		F		F	
4			F*	F, F	Q*	F
5					Q	Q, Q
6	F*		Q*	F, F	Q	Q, Q
9	F*	F, F	Q*	Q	Q	
12	Q*	Q, F, $\mathrm{F_B}$	Q		Q	

F—Arrester fails to quench explosion.
Q—Arrester quenches explosion.
*Position marginal, but probability as indicated.
Subscript B refers to experiments with 9 in. diameter gauze assemblies (Part I, Table III).

TABLE XII.—PENTANE EXPLOSIONS IN 200 CU. FT. VESSEL. WEAK MIXTURES. DRY GAUZE.

Vent ratio 2·3 sq. in./cu. ft.

Ignition position / Number of layers of gauze	At gauze		Central		Remote	
	Calculated	Experimental	Calculated	Experimental	Calculated	Experimental
1	F		F		F	
6	F*		Q*		Q	
12	Q*	$\mathrm{F_B}$	Q		Q	

Symbols as in Table XI.

TABLE XIII.—OIL MIST EXPLOSIONS IN 200 CU. FT. VESSEL. TWELVE LAYERS OF OIL WETTED GAUZE.

Vent ratio 2·3 sq. in./cu. ft.

Ignition position / Mixture	At gauze		Central	
	Calculated	Experimental	Calculated	Experimental
Weak	Q*	F, F, F, Q, F_M	Q	Q_M, Q_M, Q_M
Stoichiometric	F		F*	

Subscript M refers to experiments with Monel gauze (Part I, Table V).
Other symbols as in Table XI.

TABLE XIV.—OIL MIST EXPLOSIONS IN 66 CU. FT. VESSEL. TWELVE LAYERS OF OIL WETTED GAUZE.

Vent ratio 6·85 sq. in./cu. ft.

Ignition position / Mixture	At gauze			Remote		
	Calculated	Experimental		Calculated	Experimental	
		Vessel alone	Vessel coupled		Vessel alone	Vessel coupled
Weak	Q	16 × Q	5 × Q	Q		3 × Q
Stoichiometric	F*			Q		

16 × Q indicates sixteen tests in which flame was quenched.
Other symbols as in Table XI.

DISCUSSION

The agreement between the predicted and actual behaviour of both dry and wet gauze traps is quite good for both pentane and oil mist explosions, and for the two vent ratios. There may be a tendency for the calculated behaviour to be a little optimistic, in several cases an arrangement which seemed probably capable of quenching the explosion in fact failed to do so. However, in no case where it was possible to give a firm estimate was the experimental result contradictory. Considering the theoretical assumptions involved and the difficulties of experimentation, this position is reasonably satisfactory.

With oil mist explosions the unknown variability in the composition of the oil mists prevents close comparison, but it seems feasible from Table XIV that the most rigorous conditions, which might lead to failure of the gauze trap, were not in fact tested.

The crimped ribbon trap was successful in withstanding explosions in the smaller vessel, as would be expected on theoretical grounds, but some melting of the trap also occurred. It is clear that during the explosion the distribution of the heat through the trap was not uniform, as had been assumed, but that the leading portions of the crimped ribbons took up more than their share of the heat abstracted from the gases. The leading edges of the ribbon reached at least 1,180 deg. C., the melting point of the metal, whereas the theory assumed that the whole trap would rise in temperature uniformly by 450 deg. C. When the area of trap exposed to the flame was reduced to a half or a quarter, the theory would predict probable failure of the trap and very heavy damage did in fact occur. However, because of the uneven distribution of heat in the trap during the explosion it is unlikely that vent ratios considerably smaller than 6·85 sq. in./cu. ft. could be effectively protected solely by increasing the thickness of the trap.

The theory described is thus in reasonable agreement with the results obtained with wire gauze and crimped-ribbon flame traps. It indicates that no great advantage is likely to be obtained from minor alterations in the design of either type of trap.

PART III—A DISCUSSION OF THE APPLICATION OF FLAME TRAPS TO MARINE ENGINES

By R. COOK, M.Sc.

INTRODUCTION

The work of Burgoyne and Wilson(8, 9) has shown that in the large crankcases of marine Diesel engines, which are necessarily weak to internal pressure, no feasible provision of explosion reliefs will be capable of handling the most violent explosions that could arise. It has therefore been concluded that for more complete protection emphasis should be placed upon the avoidance of explosive conditions by automatic devices giving warning of the appearance of oil mist combined, if possible, with provision for injection of an inert gas such as carbon dioxide(10, 11, 12).

Nevertheless, both experiment and practical experience have shown that pressure relief is capable of dealing with the milder explosions which form the majority of those encountered, at least in so far as avoidance of structural damage is concerned. Explosion relief valves are required by the Ministry of Transport on Diesel engined passenger ships and they have been fitted over a number of years to the engines of tankers and cargo vessels. There have been a number of reported instances of the successful functioning of these devices and it may well be some time before they are supplanted by a relatively untried oil mist detector. There remains, therefore, the problem of disposing of the ejected flame which accompanies the operation of any explosion relief device and which not only constitutes a grave danger to anyone near at hand, but may also present a serious fire risk. The investigations described in Part I give information regarding the efficacy of wire gauze and crimped-ribbon flame arresters for this purpose; they also provide information upon which an assessment can be made of the merits of using flame traps between adjacent crankchambers so as not only to prevent the spread of the explosion but also to vent the explosion from one crankchamber into the remainder, thereby reducing the maximum explosion pressure. Let us consider these data in relation to main propelling Diesel machinery.

SUPPRESSION OF FLAME FROM EXPLOSION RELIEF VALVES

Considerations of cost and available space have restricted the area of crankcase relief valves fitted to main propelling machinery to something of the order of ½ sq. in./cu. ft. of crankchamber volume. The present investigation makes it clear that to be reasonably certain of suppressing flame from even a mild explosion, the vent ratio (i.e. area of flame trap to crankchamber volume) would have to be very substantially in excess of this figure and probably of the order of 7 to 10 sq. in./cu ft. This is especially the case when it is remembered that not only must the passage of flame be prevented but also the temperature of the gases must be reduced to a point where they are unlikely to cause damage to personnel. Provision of explosion relief valves with an opening in the crankchamber wall of this order of area is clearly impracticable. An alternative would be to arrange for the relief valve to discharge into a cylindrical space with the gauzes arranged around the circumference. To visualize what this would mean, let us consider the case of a Doxford engine of 670 mm. bore and 2,320 mm. combined stroke. The internal volume of one crankchamber of this engine (less 10 per cent for running gear) is approximately 720 cu. ft. To provide a relief area of ½ sq. in./cu. ft. requires the provision of two valves having an opening of 15in. diameter or one valve having an opening of 21in. diameter; to provide flame trap area at the rate of 8 sq. in./cu. ft. would require the addition of a cylinder 30in. long and 30in. diameter to each 15in. diameter valve or the addition of a cylinder 42in. long and 42in. diameter to the 21in. diameter valve. Moreover, the weight of gauze alone required to be attached would approximate 100lb. in the case of each 15in. valve and some 220lb. in the case of the single 21in. diameter valve.

These considerations suggest that it is not practicable, in the case of the slow-speed main propelling engine, to provide sufficient area of wire gauze to suppress with certainty the flame from a "mild" explosion and that, where explosion relief valves are to be fitted, reliance should be placed upon suitable siting and shielding rather than upon the degree of protection afforded by the fitting of gauzes of inadequate area.

USE OF FLAME TRAPS TO SEPARATE ADJACENT CRANKCHAMBERS

Table XV shows the volume of each crankchamber and the number and total area of the openings in each crankchamber side wall for four typical main propelling engines.

It will be seen that in each case the area of the openings is sufficient to provide a vent ratio of 8 sq. in./cu. ft. or greater in respect of the inner cylinders, but with two representative engines this would not be possible in respect of the end cylinders. Moreover, in the case of the two engines having sufficient area to give the requisite vent ratio with the end cylinders, this could only be obtained by making use of a large number of openings (eight in one case and thirteen in the other). Thus, existing designs of engine are not well adapted to this purpose.

Many of these flame traps would require removal before overhaul and inspection of bearings and, when the difficulties of handling these heavy pieces of equipment in the confined space of a crankchamber are remembered, it is clear that both time and expense of overhaul would be materially increased. A further point to be borne in mind is that there would be considerable likelihood of blockage of the gauze assemblies with lubricating oil sludge.

It would seem therefore that practical considerations are against the fitting of flame traps between adjacent crankchambers in this type of engine. Moreover, venting the explosion from one crankchamber into the remaining crankchambers would certainly effect a material reduction in the maximum pressure attained, but it is equally certain that with the worst possible explosion this reduction would not be sufficient to avoid disintegration of the relatively weak crankchambers of these large marine oil engines. Thus, the protection afforded by such devices, even if it were possible to fit them, can never be more than partial. Avoidance of explosions by careful design, by careful maintenance, by the fitting of oil mist detectors to give adequate warning of the onset of dangerous conditions, and by the fitting of carbon dioxide injection equipment would seem to be preferable not only on practical grounds but because it would seem sounder policy to avoid such explosions rather than to try and mitigate their effects.

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Table XV

Engine type	Number of openings in each side wall	Total area, sq. ft.	Volume of each crankchamber (less 10 per cent for running gear), cu. ft.	Ratio area/volume, sq. in./cu. ft.		Approximate weight of gauze required at 8 sq. in./cu. ft. (twelve layers), lb.
				End cylinders	Inner cylinders	
Doxford 670 mm × 2,320 mm	8	45	720	9	18	220
Harland & Wolff Type S.A.2.C.P.I.	3	28·4	733	5·6	11	225
Harland & Wolff Type S.A.	1	22·4	733	4·25	8·5	225
Sulzer Types S.60, S.D. 60	13	13	214	8·75	17·5	65

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Discussion

Mr. P. Jackson, M.Sc. (Member of Council) said that the authors were to be congratulated on the work they had done and on showing the results of the experiments and investigations which they had carried out. Crankcase explosions had caused considerable damage and there had been loss of life under appalling conditions, so that anything which could be done to avoid such happenings was worth while studying. Crankcase explosions could, he considered, be avoided by investigation firstly into design, as to their cause, secondly into maintenance and thirdly by precautions and preventions such as warning devices, and fourthly, by trying to reduce the danger and damage by devices such as described in the paper.

In his opening remarks, the Chairman had stated that the number of crankcase explosions was increasing. Well, there were more engines at sea and of larger powers and numbers of cylinders, but no-one should run away with the idea that it was only on Diesel engines that such explosions occurred. He had known of them on steam engines and of many cases with small engines, but little damage was done because the volume of the crankcase was so small. He knew of one case on a motor car engine, where the explosion blew out the dipstick, which only made a dent in the cover.

If the tests described in the present paper were considered, the variation of pressures and temperatures that could be obtained from what were almost the same conditions (in this case in the boiler shell) became apparent, varying from a few pounds to 20lb./sq. in. of explosion pressure. It would also be noticed that the release valves and flame traps were beneficial, because an explosion, without a relief valve present, caused pressures of 73 and 90lb./sq. in., whereas the relief valve reduced these pressures to 5 or 6lb./sq. in. or in many cases to 1 and 2lb./sq. in. in the same sort of explosion.

In fitting protective devices it had to be remembered that the pressure had to be relieved, and Mr. Brown had made that point.

He had wondered what would happen if both gauze and ribbon traps were tried, and did it much matter if the gauze or the ribbon melted, provided that the hot gases were prevented from emerging into the engine room and injuring personnel. Far better if these materials did not melt, but he would have no objection to replacing a few gauzes worth under £20 if damage were avoided in that way.

The history of relief valves was interesting. Harland and Wolff were the first people to fit relief valves, which consisted of flying doors held in place by spring loaded snecks which were intended to open at a few lb./sq. in. of explosion pressure. His company had developed a similar relief door loaded with a weight, which they considered was better than a sneck.

It became apparent during tests that the gases emerging from these relief valves were very hot and could injure personnel, so B.I.C.E.R.A. and W. H. Allen, Sons and Co. Ltd. carried out experiments and evolved the oil-wetted gauze trap, which on the small engines with which they were concerned, was effective in preventing the flame emerging into the engine room.

Later B.S.R.A. carried out experiments to ascertain whether these traps were suitable for large engines and the results were shown in the paper. Mr. Cook and his staff were to be congratulated on the energy and ingenuity which they had put into their investigations.

On their P type engine, his company were fitting the B.I.C.E.R.A. type of flame trap. Each cylinder crankcase volume was about 480 cu. ft. The first flame trap was designed by his company with oil-wetted gauze, but when a description of it was published, he had had a letter from B.I.C.E.R.A. saying that they had a patent on such a device. He had asked for the terms of their royalty and was told that it was one shilling per h.p. which on a 10,000 h.p. engine was £500, but they also told him that a company called Pyropress was making the B.I.C.E.R.A. flame traps under licence. He then asked this company for a quotation and found that the 12 traps required for a 10,000 h.p. engine would cost only £264, or £22 each, so that his company could buy the traps at a cheaper price than the royalty or cheaper than making them!

A method of avoiding these explosions was to fit a warning device such as the Graviner smoke detector which had been developed and sponsored by B.S.R.A. His company had fitted the Graviner instrument to a few engines at the special request of the shipowners and it was a good device, although on occasions it had given warning, when subsequent examination had failed to show any cause. On one occasion there was a hot bearing in one cylinder crankcase but the detector fitting in another crankcase gave the warning. Nevertheless it was a very useful application and, in addition, to giving warning of an explosive mixture, it did indicate when there was a hot bearing, a blowing piston, or similar circumstance.

Regarding maintenance, piston rings, pistons and bearings should all be maintained and kept in good order and in true alignment. So often heated bearings came from misalignments. Mr. Jackson said he preferred to consider the design and review the causes of all these explosions. There were several papers published some five or six years ago showing the causes of explosions. Bronze bearings had caused a number of explosions in marine engines and copper-lead main bearings in the high speed engines of American locomotives. So on his company's engines there were no bronze bearings inside the crankcase, all bearings being white metal lined.

Similarly, chain wheels had caused explosions due to chains rubbing. In the past year a report was sent out privately by Det Norske Veritas giving the causes of some 38 explosions. One was due to the glands of telescopic pipes and the recommendation of the report was that the glands of the telescopic pipes, even for oil cooling, should be external to the engine. He had written objecting to this, as he could not see the reason and it was certainly going to cause some design difficulties if it became a rule.

Some few years ago, when a paper was presented to the Institute on this same subject, he had made the claim that he knew of no crankcase explosion on any of his company's engines. One should not speak too early. There had been, to his knowledge, three since! The first one was due to the choking of an oil filter. One big tanker-owner required an Auto-clean filter—a very fine one, of 3 thou. mesh—on the supply of the oil to the thrust block. This filter, not being attended to, became choked up, the oil supply failed and the white metal on the thrust pads melted; the bronze of the thrust pad then caused a spark and the resulting explosion blew off the cover of the thrust block, which thus relieved the pressure. No-one was hurt. It happened to be at the after end of the engine. In the second case, a piece of broken piston ring of about ¾-in. width was trapped between the piston skirt and the cylinder liner and was scraped up and down until it caused a spark and in that case the crankcase door was blown off and a man was burnt, not severely, but he was in hospital for a few days.

What should be done in these cases? As regards the piston ring, he did not know what could be done to avoid such a happening. A relief valve on the crankcase, with gauze flame traps would probably have prevented the man being burnt. There was another explosion due to the damper on the chain coming loose at one end and the chain, hitting it, created a spark and that again caused a minor explosion, but no-one was hurt. About two years ago there was an explosion which was really serious, on a Dutch-built Doxford engine; the doors were blown about the engine room and the ladders and gratings were twisted, due to quite a violent explosion. Four men were killed and only one man in the engine room remained alive. Mr. Jackson considered that it was not primarily a crankcase explosion and he would try to explain what did happen. He had investigated the circumstances with Mr. Meijer of Wilton Fijenoord and they came to a certain conclusion. Subsequently a Committee was appointed and he was asked if he would be a member of that Committee and he had assented, but had never received any advice of any meeting, nor did anyone from his company give evidence. However, in his opinion the cause of the explosion was as follows. It was an old engine with the old type of fuel injection gear, where there was a pilot ram on one fuel valve which was leaking badly and allowing fuel to get into the engine cylinder. The engine had been stopped at 3 a.m. The log said that the fuel valves had been leaking and the priming pump had been used to keep up the pressure, because the switch was in, although the fuse was burnt. Also the camshaft was broken and had been breaking for some time, the fatigue fracture being due to misalignment. The engine had stopped with No. 6 fuel cam and No. 6 starting air valve on top centre, so that when an attempt was made to restart the engine, after the stop, there would be compressed air and fuel both entering that particular cylinder throughout the full stroke due, to the broken camshaft and, in his opinion, the resulting explosion in the cylinder blew the pistons apart and passed into the exhaust pipe, blowing off the end covers of the exhaust pipe, but, worse than that, these passed into the entablature through the scavenge ports and blew off the cover of the scavenge pumps and thus got into the crankcase, where he believed there was a second explosion on the three end cylinders. He did not know what could be done to avoid such a happening. A camshaft breaking was practically unknown and he doubted whether the severity of that explosion would have been relieved by any type of relief valve. He agreed with Mr. Cook with regard to the matter of relieving cylinder crankcases into adjacent cylinders. It just seemed impracticable.

He would impress upon everyone that he and others concerned with the design and development of large marine engines were doing everything known to avoid these disastrous explosions.

Mr. K. H. Gray explained that he was present only because Dr. Mansfield, the originator of the oil-wetted flame trap, was unfortunately not able to be so as he was abroad on business. He had not himself been closely associated with the experiments which Dr. Mansfield had described in his paper to the Institution of Mechanical Engineers in 1956 (reference 4 of the present paper), so his contribution would be a poor substitute for that which Dr. Mansfield would have made had he been present.

In that paper Dr. Mansfield had written "The reason for the remarkable effectiveness of coating the gauzes has not yet been clearly established". He had gone on to a discussion of possible explanations, and rounded it off with the words: "These various considerations indicate that the process is complex, and that a detailed investigation would be necessary to obtain a full understanding". B.I.C.E.R.A. had not yet made such a detailed investigation so they had reason to be grateful to the authors of today's paper for having provided additional information which should serve to dispel any dangerous misunderstanding about the oil-wetted flame trap.

The figure of 9·3 sq. in. of gauze assembly per cu. ft. of explosion vessel which Dr. Mansfield had proposed for a six-gauze assembly, was based on considerations of pressure relief and was 90 per cent greater than that needed for the complete suppression of flame under the most severe conditions, provided the assembly was evenly coated with a weight of oil equal to 13·6 per cent of its own dry weight—i.e. 0·19lb. of oil on the gauze assembly used, which weighed 1·4lb.

In Part I of the present paper it was stated that "the gauze assembly was thoroughly wetted with Shell Talpa 30 lubricating oil and was then allowed to drain in a horizontal position". How long it was allowed to drain in that position and how long in the vertical position after installation in the explosion vessel was not stated, but from Part II it was learned that 171 grammes of oil was added to 7,400 grammes of gauze. Even if "was added" should read "remained at the time of the explosion", the weight of oil used in these tests was only 2·31 per cent of the weight of gauze, and even this small quantity might not have been quite evenly distributed by the time the explosion occurred. At best, therefore, these tests had been done with only 17 per cent of the weight of oil per pound of gauze that was used in the B.I.C.E.R.A. tests. This almost certainly accounted for the results being less impressive than B.I.C.E.R.A.'s, for their tests had shown the oil to be, weight for weight, a far more effective flame-quencher than the gauze; in fact, 0·19lb. of oil was approximately equivalent in this respect to 1·4lb. of gauze; in other words, the oil had doubled the effectiveness of the trap.

A recent set of weighings had shown that a six-gauze assembly from a commercial version of the B.I.C.E.R.A. flame trap, after being soaked in Shell Rotella 30 lubricating oil at room temperature and then allowed to drain for one minute, held a weight of oil equal to 31¼ per cent of its own dry weight. (When dripping wet it held 50 per cent.) If, for simplicity and to err on the pessimistic side, it was assumed that in service the gauze would hold oil equal to 23·1 per cent of its dry weight, and Mr. Palmer's formula was used to calculate the factor by which this amount of oil would increase the heat capacity of the flame trap, a factor of2·556 was obtained, which was 2·2 times as great as the factor of 1·16 calculated at the top of page 273, column 1. However, it was known from the B.I.C.E.R.A. experiments that heat capacity was not the only factor, so there was plenty in hand. All the assumptions and omissions were on the pessimistic and therefore safe side.

In his paper to the Institution of Mechanical Engineers Dr. Mansfield had left no room for doubt about what he meant by "oil-wetted"; for example, one passage read: "There can be little doubt that oil at crankcase temperature sprayed liberally on to such a gauze assembly would give complete protection from flame", and in his reply to the discussion he had written that "for large engines a properly arranged supply of oil to the flame traps was certainly essential . . ." However, it did no harm to stress once again the important rôle played by the oil. Even on the basis of heat absorption alone, it was the major contributor if the gauze was well drenched with it. In fact, the gauze could be regarded as a means of holding the oil in position: if it were possible to make a self-supporting screen of 13·6lb. of oil it should be about as effective as 100lb. of gauze. This very important point had evidently not been appreciated by the authors of the present paper, for when their early experiments gave poor results they used more and more gauze instead of merely using more oil. (They did, incidentally, use more oil, because presumably the gauze was containing, pound for pound, the same quantity as before, but they could have got this result simply by increasing the oil without increasing the quantity of gauze.) There was no doubt in his mind that the damage suffered by their twelve-gauze assemblies, and the continued heating by exothermic reaction, had resulted from their reliance on the gauze to deal with 86·2 per cent of the heat abstracted instead of a mere 39·1 per cent as would have been the case (even assuming heat capacity to be the only factor) had the oil been equal in weight to 23·1 per cent of the gauze instead of only 2·31 per cent. They would have done better to use half as much gauze and five times as much oil. If the test arrangements did not permit this condition to be examined, then they had failed to reproduce the true operating condition.

At B.I.C.E.R.A. it had been found that increasing the number of layers of gauze beyond eight did more harm than good by giving rise to the same kind of exothermic reaction as was described in this paper. It was clear that a thick assembly could hold enough heat to support such a reaction; and, as six well drenched layers were sufficient for effective flame quenching, they had chosen that number and relied mainly on the far greater effectiveness of the oil.

All their work had been planned on the assumption that sometime, somewhere, by a highly improbable combination of circumstances, a crankcase might become completely filled with a uniform explosive mixture and that this might be touched off at the precise instant when it reached its most dangerous proportions. That such a thing would ever really happen seemed almost beyond belief; nevertheless their recommendation of 3 sq. in. of relief area per cu. ft. of crankcase was based on the gloomy assumption that it could. They believed it would be possible to prepare most engines for even this unlikely eventuality, by providing adequate relief valves shielded on the inside by oil-drenched gauze and, in the case of large engines, by also subdividing their crankcases with oil-drenched gauze screens, which need not be heavy and could be made in sections for convenience in handling. But since the concern here was with an area/volume ratio, there must obviously be some point on the scale of crankchamber size where the ideal became impracticable. Whether that point lay within the range embraced by actual engines he did not know, but his belief was that the ideal would not be unattainable even in a very large engine if the problem were tackled at the design stage and not as an afterthought. Even if he was wrong, it was surely better to provide for the less improbable explosions than to make no provision at all.

There might be no great difficulty in detecting the conditions conducive to a really violent explosion involving a large quantity of explosive mixture, but such explosions were extremely rare. The majority of crankcase explosions appeared to result from the ignition of relatively small pockets of explosive mixture; but even these could be calamitous if they occurred in a large engine, and could produce a hazardous emission of flame even when too weak to shatter the crankcase. He doubted if any warning device existed which could be wholly relied upon to give warning of this less improbable type of explosion, so the commonsense thing to do was surely to provide as much vent area and as much flame trap area as the design of the engine would allow, and to arrange for the flame traps to be thoroughly drenched with oil at all times when an explosion could occur. It was important that all vents, not only the relief valves, be guarded by flame traps.

By all means let warning devices be used, but he confessed he was apprehensive at the suggestion to rely for safety solely on a mist detector. There was not time now to go over all the arguments so well presented by Dr. Mansfield in his reply to the discussion of his paper (reference 4) so he would have to content himself with a plea to all concerned to study that reply carefully and with an open mind.

MR. I. M. LORIMER (Member) said that his only regret was that the colour ciné-films, referred to in this interesting paper, were not shown. However, he was in full agreement with the general conclusions reached by the authors as the result of their experiments, and felt that they confirmed that the existing regulations relating to the safety aspect in Diesel engine crankcases were, in fact, fairly adequate.

While it might be impracticable to increase the vent ratio of pressure relief doors of crankcases on large engines, experience had proved the value of the doors as fitted on many engines by affording a safe relief after an explosion had occurred. In such circumstances protection of personnel was essential, and this had in most cases been achieved by the provision of hoods or shields on the doors, so deflecting the flame in a safe direction. This flame emission should not be under-estimated; a case had been reported where flame reached the skylights. There was a definite problem here and in spite of some unsatisfactory tests, oil-wetted flame traps could provide a very useful additional safety device. Incidentally, the figure of 0·5 sq. in. of relief per cu. ft. of crankcase volume required on passenger vessels was based on the gross volume (without reduction for running gear).

In Part II of the paper it was rather surprising that the increase of heat capacity factor of oil-wetted gauzes was stated to be only 1·16, in view of Mansfield's paper (reference 4) where it was found that coating the wire gauze with lubricating oil "greatly increased" the effectiveness of the flame trap, so that an oil-wetted trap of less than half the original size was fully effective.

Regarding the crimped-ribbon flame trap, it was noted that in most cases oil remained ignited on the inside of the trap after an explosion and this would seem to be an undesirable feature.

While the subdivision of large crankcases was indeed desirable he thought that many of those present must have been concerned at some time with trying to devise an easily removable and sufficiently close-fitting large gauze appliance, and at the same time wondering what would happen to it during engine overhauls. The original idea was to reduce the volume available to combustion so that each compartment could stand the pressure generated.

In the experiments there was a considerable variation of maximum pressures, and experiment 99 indicated the possibility of the occasional freak effect where presumably all the most favourable conditions for explosion were achieved simultaneously. This was the sort of thing which happened in a ship once in a while, giving rise to a more or less serious casualty.

It seemed to him that the almost certainty of an eventual explosion in a crankcase, when a hot spot developed, pointed to the necessity for prevention rather than an optimistic attempt to mitigate the effects after an explosion had occurred.

Neither design nor maintenance could ensure freedom from the risk where enclosed crankcases containing lubricating oil, air and moving parts were concerned. There remained therefore the oil mist detector, and where this device was capable of giving an alarm at about 2½ per cent of the lowest explosive mist concentration level one could have confidence of receiving adequate warning, even with the most rapid oil mist generation.

Another speaker had mentioned that a further advantage of such a detector was the early warning of engine defects, so avoiding expensive breakdowns and delays.

In his opinion oil mist detectors were the logical, necessary and inevitable answer to the problem. It was not suggested that relief doors should be abolished altogether; one did not dispense with safety valves because a pressure gauge was provided.

The usual disclaimer was made that the oil used in the tests was no more liable to give rise to explosive mists than any other oil, and he had no reason to doubt this statement. Nevertheless, in view of the incidence of crankcase explosions nowadays he wondered whether lubricating oil was what it used to be.

The introduction of CO_2 gas as a means of extinguishing fires was satisfactory but the rapid injection of CO_2 gas into compartments containing explosive mixtures for the purpose of inerting might require careful consideration because of the static electricity hazard.

Mr. R. A. Jones (Associate Member) thanked the authors for a most interesting and instructive paper and said that it would seem conclusive from the tests carried out that the large slow running marine Diesel could not be adequately protected from the full violence of a crankcase oil mist explosion, and that the ensuing flame could not be prevented from causing injury to personnel.

In the absence of positive safeguards, an element of uncertainty in the running of Diesel engines must always be present, and as the necessary equipment for ensuring complete safety was both available and simple to apply, there was no need, in his opinion, for the continuance of this uncertainty.

In this respect he would agree with Mr. Cook that the fitting of an oil mist detector was a sound approach, as the installation of such a device made possible the avoidance of both the explosion and damage to running gear.

In view of the importance of avoiding explosions he thought it would be of interest to say something about the oil mist detectors, with which he was familiar, as applied to the large marine Diesel.

As a result of research work undertaken by Burgoyne and Newitt in 1955, the British Shipbuilding Research Association initiated the development of the detector referred to under item 11 in the list of references.

The detector proved to be both a practical and reliable means of safeguarding against the explosion hazard by giving warning should the crankcase oil mist level reach a concentration of 1·25 milligrammes of oil per litre, which was 2½ per cent of the lowest concentration at which ignition could occur.

Crankcase explosions were fortunately not an everyday occurrence, but the overheating of engine components, which were the cause of crankcase explosions, were common.

As a result of the experience gained from the B.S.R.A. detector his company had developed a dual purpose detector which would still retain the tried and proven principle of photo-electric detection but would meet the following two requirements: 1) Be highly sensitive in order to detect "hot spots" within the crankcase before serious mechanical damage occurred, and at the same time give automatic warning and indication of the crankchamber where the overheat had occurred. 2) Give separate and early warning should the overall crankcase oil mist level rise above a predetermined level.

These requirements were met by employing a new concept of "differential" sampling by means of a rotary valve whereby each crankchamber could be separately compared against its neighbours on a sensitive scale whilst the overall crankcase atmosphere could be compared against fresh air as a reference on a less sensitive scale. It might be of interest to note that the average oil mist level of all large marine engines when running normally at their rated output lay within the range of 0·06 to 0·12 milligrammes of oil per litre.

Over 80 vessels were in service using this new type detector, whilst 77 further vessels would be entering service in the near future.

In conclusion he would say that oil mist detectors could contribute much to the efficient and safe working of Diesel engines.

Mr. A. R. Hinson (Associate Member) said that the authors of the paper had made it quite clear that there was great difficulty in retaining the flames inside a crankcase while letting the pressure out in a safe manner. The experimental results that he had seen in the paper indicated that the explosions of hydrocarbon/air mixtures were often unpredictable, even when closely controlled. For example, in experiment 6 the maximum pressure recorded was only one-fifth of that in experiment 9, while the initial conditions were presumably similar. Again, in experiment 56, the gauze was undamaged, while in experiment 57, local melting occurred. It did not appear to have been possible to reproduce, at will, results which agreed closely. Indeed, in reference (3), there was a photograph of a shed, in which explosion experiments had been carried out, and the sides had been blown off. It gave the impression that the generation and precise control of explosions was difficult. But even if it had been possible to perform experiments under control and reproduce results, he thought it would still be agreed that prevention was better than cure; and while looking for a cure, it was as well to look for the causes.

An examination of the Records of Lloyd's Register of Shipping for crankcase explosions in the years 1958 to 1961 showed that there were twenty-four. They were from all types of engine and the ships were not always classed with Lloyd's Register.

The causes of the explosions were as follows:

Number of explosions	*Causes*
5	Hot main bearings or bottom ends
5	Hot thrust bearings
5	Hot pistons
2	Piston blow-by
1	Hot crosshead

Six miscellaneous causes included:—one hot chain wheel sprocket bearing; one slack chain vibration damper; one faulty blower coupling which had caused misalignment so that a bearing had overheated; one from a hot piston rod, bent due to water in the cylinder. In most of these cases the damage caused was slight.

It could only be concluded from these facts that the main cause of crankcase explosions was failure to adjust and lubricate bearings correctly, with failure to maintain piston rings, liners and cylinder lubrication coming second. Perfect maintenance was the answer. But this was obviously only an ideal and some form of flame trap was essential.

The paper had served a useful purpose in drawing attention once more to these traps. Surveyors had occasionally reported that sheets of brass or jointing had been fitted over relief valve apertures, presumably to prevent oil leakage from the crankcase. It was to be hoped that the publication of the paper would end this practice.

Mr. G. Victory (Member) said that Part I of the paper demonstrated that in certain circumstances no practical size of flame trap could hope to cope with the effects of crankcase explosions. On first sight it also appeared to cut the ground from under Dr. Mansfield's paper, read at the Institution of Mechanical Engineers (reference 4 in this paper). He was rather pleased that Mr. Gray had, to some extent, restored the balance, for he felt that the conclusion in that paper was that the reason for the apparent increase in the efficacy of oil wetting might not be found only in the purely calorific computation, which was carried out in Part II of the present paper. It might be that a more uniform heat distribution was effected, for the oil would vary the relative velocity of the gases through the gauze.

He was glad that Mr. Cook had referred verbally to the value of crankcase explosion doors, because, as written, Part III of the paper gave the impression that if one could not have perfection one should have nothing at all and, in stressing the impracticability of providing 100 per cent protection, it appeared to evade the question of whether explosion doors and flame traps of a more practical nature had any virtue. In fact, Mr. Cook ignored them in his final conclusion. Mr. Victory's own opinion was that half a loaf was better than no bread and, in the matter of safety at sea, sometimes that was about all that could be achieved. Otherwise the industry would finish up with the "safe ship" that all had heard about, which was so filled with safety devices that it could carry neither cargo nor passengers! Admittedly this paper and others had demonstrated that, in the worst case of an explosion, no practical combination of explosion doors or gauze divisions between crankcases could be considered absolutely safe. But it had also been stated in the paper, given in the bibliography as item 3), that photo-electric monitoring of crankcase gases could not be relied upon to give due warning of every circumstance which might lead to an explosion. Most people who were not manufacturers of monitoring devices would agree with this. As an example, a monitoring device had been shown which had five sampling tubes, leading to what was presumably a 4-cylinder engine plus a thrust block. Who could say that in all cases the spread of vapour around the crankcase would be so rapid or so uniform that it would give immediate detection to the one sampling position in that unit? Yet Mr. Cook appeared willing to pin his faith in "the fitting of oil mist detectors".

Mr. Victory felt that this paper seemed to lose sight of the fact that these explosions, occasioned by the positive ignition of a pre-mixed oil vapour, might be in some way different to those which occurred in a Diesel engine crankcase, where the source of heat forming the oil vapour was probably the source of ignition also. Under these conditions it was possible that the mechanism would be that when the vapour in the immediate vicinity of the heat source reached the explosive range, it would produce a localized explosion, which might not involve more than a small portion of the crankcase volume. This was the type of incident for which explosion doors and gauze diaphragms of a practical size had proved to be suitable. It appeared, therefore, that it might be possible to provide reasonable cover for such occurrences, particularly if a monitoring device was used to ensure that the worst possible case of an explosion, in a crankcase entirely filled with an explosive mixture, could not take place. By all means endeavour to avoid explosions by careful design and by careful maintenance, but, human nature being what it was, that was not enough. He agreed that prevention was better than cure, and the fitting of oil mist detectors was a very desirable aim, but explosion doors should be fitted as well, even if the area provided could not be as large as most people would like, for it had been proved that such doors would prevent the damage due to minor explosions and possibly obviate the risk of a secondary explosion of a more violent nature. Fit these doors with oil-wetted flame traps and with properly sited deflectors to reduce the dangers to personnel, and carry out an investigation into the value of crankcase divisions of a more practical nature than was envisaged in the paper, or even of the permanent inerting of the contents of the crankcase.

Finally, the Ministry of Transport "minimum requirements" for explosion doors in passenger ships had been referred to in the paper as a "recommendation". What had not been made clear was that the Ministry, apart from recommending that centre divisions be fitted in engines having more than six cylinders, did prefer and advise the fitting of monitoring devices to detect oil vapour before it reached a dangerous mixture strength. Two such devices had in fact been approved and were usually fitted in Diesel engine passenger ships of today.

With such arrangements, a reduction of explosion door area to not less than 0·25 sq. in./cu. ft. of crankcase volume was permitted—a figure which was still greater than that required under the 1962 Lloyd's Rules. This combination of monitoring device with explosion doors, preferably with flame traps and deflectors, would appear to result in an arrangement giving a good standard of safety, allied with practicability and reasonable cost. Perhaps Mr. Cook could specify a practical arrangement which he would prefer.

Mr. L. M. Roper said that, as flame trap manufacturers, the company he represented had been interested in what would be considered satisfactory for dealing with crankcase explosions. This present paper gave a very excellent picture and was the more interesting because it included a restricted test of crimped-ribbon type flame traps.

With regard to the crimped-ribbon arresters, firstly they appeared to have been very efficient in the tests concerned, and although suffering damage did appear to reduce the temperature of the hot products being vented and arrest any flame. An interesting point that occurred to him regarding the damage suffered by the crimped arrester was how frequently crankcase explosions occurred, because even if the crimped-ribbon flame trap, or indeed any other type, was almost completely melted but still carried out the job efficiently of reducing the temperature and preventing flame, did it matter. The flame arrester could be replaced after the explosion. The flame trap would have done its job in preventing a possible serious accident.

Referring to the sequence of tests which were carried out on the crimped-ribbon arrester, one of the early ones partly damaged by melting the face of the arrester, he was wondering whether on the subsequent tests this did indeed subject the flame trap to a more severe vent ratio than was actually shown, as of course any damage to the crimp would to a degree affect the free passageway available for venting.

Another point which might be of interest was what would have been the result of increasing the thickness of the crimped material? As was known, the crimped-ribbon arrester had a plain strip and a corrugated strip in alternate layers. In these particular experiments the crimped materials were approximately 0·002in. thick. It would have been interesting to see what would have happened if these had been stepped up to say 0·004in.

Apart from crankcase explosions this work was very valuable regarding flame trap procedure in general, because there were other types of flame trap applications in the petrochemical field and suchlike, where concern was with large volumes of combustion products having to be passed through the flame traps.

Mr. L. Greenacre said that with regard to the prevention of crankcase explosions, the company he represented were of the opinion that although the chances of a crankcase explosion occurring were statistically small, it was none the less prudent and desirable to take all reasonable and practical precautions, in view of the possible consequences. Because of the practical difficulties involved in quenching anything but a very mild explosion, his company supported the view that a constant check should be maintained on crankcase conditions in order that any build-up of vapour might be detected before a dangerous concentration was reached.

Their recent general purpose motor ships of about 7,500 horsepower had been equipped with the high sensitivity type of Graviner oil mist detector, and they had had about a year's experience with this instrument. Reports from the ships had been generally satisfactory, and although no incident had occurred, fortunately, which might have put the instrument to the ultimate test, the impression gained by their operating engineers was that the sensitivity of the instruments was such that a "hot spot" would be indicated at a very early stage.

Mr. S. J. Wood said that he was rather disappointed to see that there were no check valves used in the experiments to prevent the return flow of air into the vessel after venting. In practice a non-return valve would always be fitted, and its absence in those tests on flame traps appeared to reduce the real value as an exercise in engine protection. This was borne out by the indications of after-burning which took place, sometimes at the outer face as well as the inner face of the flame trap. Evidence of this was given in the observations on experiments 3, 13, 14, 16, 57, 58, 107 and 109. Incandescent particles were also observed being blown out of and drawn back into the vessel in most of the observations in Table III. Secondary combustion also appeared to have taken place in experiments 61, 62, 107, 108, 109, 111 and 114, which suggested that a fire was being supported by the stream of air returning to the exhausted vessel, and the final damage suffered by the flame trap material was not necessarily due entirely to the initial explosion.

In experiment 115 there seemed to have been a violent secondary explosion because the closure burst off at the end of the vessel. A previous speaker had mentioned that the volume of oil played an important part in quenching the flame, as was shown in the calculations. He suggested that this additional protection was achieved with the crankcase relief valve and gauze flame trap, jointly developed by his company and B.I.C.E.R.A. and which was continuously wetted by oil thrown from the bottom end bearing or other means.

The various classification society rules made it obligatory to fit crankcase relief valves to marine engines above a certain cylinder size, and he was sure that these valves must be backed up with an effective flame trap.

Early warning devices of the oil mist detection type could play a very useful part but they depended upon dangerous conditions being already present before giving a signal. Thereafter little time was available for human action, and the subsequent protection must be fully automatic.

Correspondence

Mr. J. A. Duncan (Member) wrote that this interesting paper clearly showed, once again, the difficulty of reconciling practicability with safety. He agreed generally with the conclusion drawn by Mr. Cook that prevention was better than cure, but was inclined to differ about the manner of achieving it. He was not certain that in the case of crankcase explosions the fitting of oil mist detectors would completely eliminate the risk.

As Mr. Cook pointed out, prevention could only be achieved by a combination of factors such as good design, proper maintenance and so on. Mr. Duncan was concerned mainly with the running and maintenance of marine engines and in this field he considered that the modern trend towards monitoring everything requiring supervision was not perhaps the most desirable practice. Proper control of marine machinery required constant careful observation if it was to be satisfactory, and the most important function of the watchkeeping engineer was to exercise this observation. The fitting of alarms to various systems to give warning of deteriorating conditions or faults tended to create in him a complacent attitude towards his duties in this respect. In the end he came to have an implicit reliance on the warning systems, to the exclusion of the proper supervision of the machinery in his care. It might be argued that if the alarm systems were reliable this relaxation would not be of great importance, but this was not so; the important thing was the attitude of mind in the watchkeeper towards his duties, and anything which induced carelessness was adversely affecting it.

It was agreed, however, that a distinction could be drawn between alarms giving warning of the onset of dangerous conditions, and alarms which merely informed about inconvenient failures. It was obvious that there must be a compromise and that each case must be judged on its merits. There was also to be considered the coupling of alarm systems to servo devices which would bring into action the necessary safety devices. In the case under consideration, for instance, i.e. that of crankcase explosions, the proposed oil mist detector should not only detect the oil mist which indicated dangerous overheating in some part of the engine, but should also immediately, on detection, bring about the stopping of the engine.

Mr. Cook's views on this aspect of the problem would be appreciated.

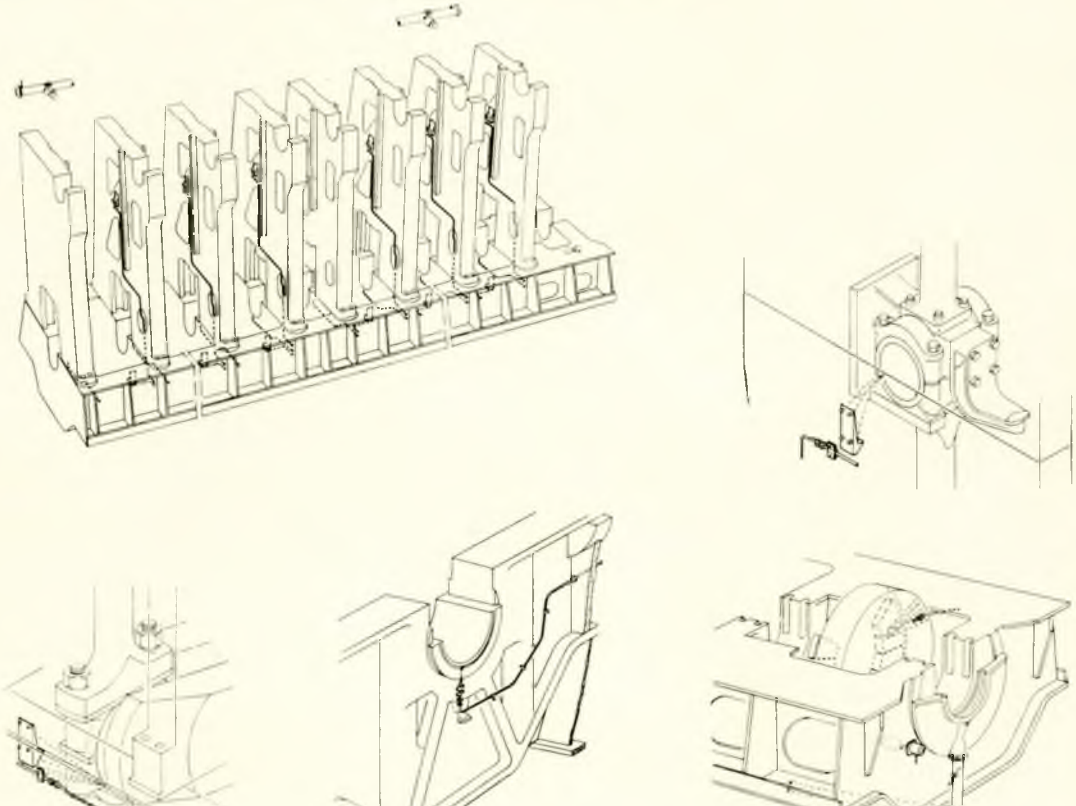


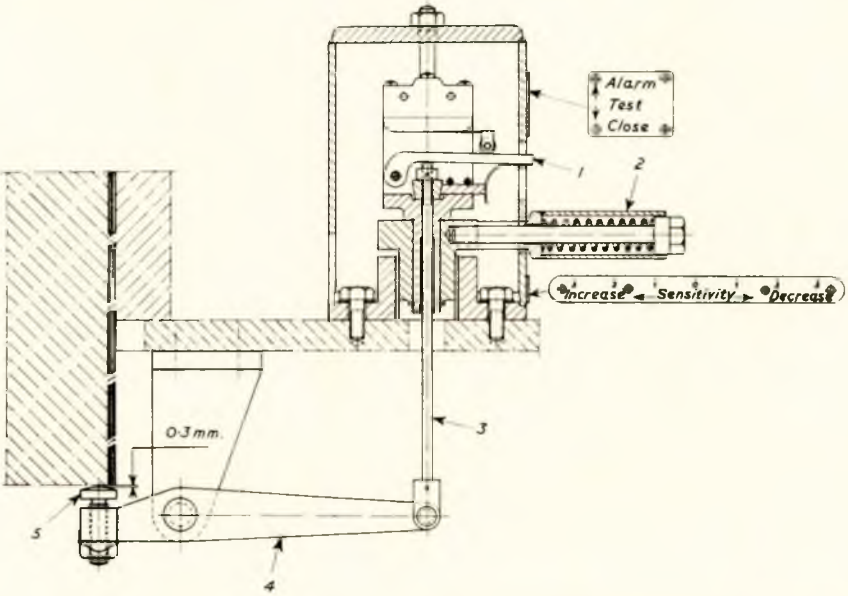
Fig. 5

Mr. G. Hellstrom, in his contribution, wrote that the paper presented by the authors had been found most interesting and informative and since there had been several cases reported in recent years, in which serious explosions of this nature had occurred, the paper was both timely and valuable in that much information was given on a subject which was very much to the fore in the minds of all who were concerned with marine Diesel engine design, construction and operation.

In the course of the discussion which took place, after presentation of the paper, Mr. Jackson stated that in the case of the explosions experienced in locomotive engines in the United States, these explosions were attributable to the use of copper lead bearings. He further pointed out that the Doxford marine engine did not utilize any bearings in which the bearing metal was copper lead. It had, however, come to his company's notice, in various technical publications in which the latest type of Doxford engine had been described, that the crosshead carried a central bearing pad, in addition to the usual bearings in way of the pins, and, in the articles which they had seen, it had been stated that this pad had a copper lead bearing surface. This would seem to be at variance with Mr. Jackson's statements.

In Scandinavia there had been much discussion concerning the use of oil *vis-à-vis* water as a cooling medium for Diesel engine pistons. It had been argued that in the case of the pistons in the new large bore turbocharged engines, the high temperatures which obtained gave rise to cracking of the oil where oil was used as the coolant. It was stated that, in consequence of this cracking of the oil, inflammable gases were generated which tended to accumulate in the crankcase and heavier products were produced which, in the passage of time, could result in the bearing surfaces being affected in a manner detrimental to the operation of the engine. In this way, it was argued, the use of oil as a piston cooling medium could create conditions which could enhance the risk of a crankcase explosion occurring and the company with which the writer was connected had received a communication from Det Norske Veritas (Arbeids gruppe 1) in which it was recommended that water be used as the coolant in the pistons of large bore engines where high pressure/temperature conditions applied.

They had considered this recommendation and had raised certain objections to it. The reasons for these objections were given as follows.



The alarm apparatus is mounted on the lower edge of the guide plane and it gives a signal as soon as the lower edge of the guide shoe has "sunk" beyond its normal position. The guide shoe then presses against the setting screw 5, which must have a clearance of about 0·3 mm. for a cold engine. When the guide shoe is in contact with the setting screw the motion is transferred via the lever 4 and the thrust bar 3 to the lever 1 which influences a circuit breaker which in its turn lights a signal lamp and engages a siren. Because of a retardation arrangement and a spring the lever 1 remains in the top position which it has reached owing to the contact of the guide shoe with the setting screw 5. If the handle 2 is brought sideways against "increased sensitiveness" the clearance at setting screw 5 is reduced. By touching lever 1 it can be checked that the setting screw 5 and the guide shoe are in contact. The engine must be run at full speed and the handle must be set to the position for "increased sensitiveness".

Each step of the handle decreases the clearance against the guide shoe by about 0·1 mm. The handle should be set one mark from the position where the contact with the guide shoe can be felt. This is valid for normal load of the engine. With this setting false alarms may possibly occur if the engine races, for instance at rough sea. When the alarm signal is given the lever 1 is pressed down and the signal stops. If there still is a contact with the setting screw 5 this may be due to worn bearings in the crankcase. If the engine cannot be stopped for inspection the handle is displaced towards "decreased sensitiveness" and the crankcase is carefully observed. If there is another alarm signal after a short while the engine should be stopped for inspection.

An alarm signal is obtained when the wear is about 0·3-0·5 mm. at correct setting of the clearance. As a routine the alarm apparatus should be checked at regular intervals. When bearings or crosshead pins are exchanged the setting screw 5 is adjusted to the clearance mentioned.

Fig. 6

When the pistons for their new large bore, turbocharged engine were designed, many proposals were considered and much experimental work was carried out. During the initial shop testing special techniques were evolved which made it possible to measure and record the temperatures and thermal stresses, etc. which were obtained in the piston crowns. The internal temperatures and stresses, likewise the temperature gradient, were found to be of very reasonable magnitude, in fact, lower than the values previously recorded in the engines of smaller piston diameter.

Further temperature readings were taken and recorded over a period of six months actual service in the vessel which was fitted with the first of these large bore engines, and in consequence, a wealth of data had been accumulated, including data obtained under operational conditions in tropical waters. The figures obtained indicated that the piston temperature did not, under any conditions encountered in service, approximate to that temperature which would result in deterioration and/or cracking of the oil. For example, the maximum temperatures were obtained during full load conditions and it was established that, in the centre of the crown, the temperature was about 115 deg. C. and, at the sides, about 180 deg. C. It had been stated by the oil companies that the lubricating oil could not crack at temperatures below 300 deg. C., hence, it could be stated that in the case of his company's engine, turbocharging had not increased the thermal loading of those parts which formed the combustion space, nor had the larger bore increased this thermal loading. Furthermore, it should be mentioned that no trace of carbon deposits had been found in those pistons which had been inspected up to the present time.

In consequence of the foregoing, no necessity was seen to resort to water cooling for the pistons of the large bore turbocharged engines built by his company. Water cooling complicated the engine design and could give rise to trouble in the event of leakage into the crankcase.

In order to ensure reliability in their engines the company were continually endeavouring to select the most suitable materials and were continually trying to improve their designs. Reliability in service, however, was largely dependent on efficient maintenance. If the oil should become contaminated the lubrication could be adversely affected, bearing damage might result and conditions could be created which would greatly increase the risk of a crankcase explosion. There were many ways in which the oil could become contaminated and increased rate of oxidation be brought about, hence, it was essential that the engine be kept as clean as possible and everything should be done to maintain the engine in the best condition. A further factor of importance was to ensure adequate separator capacity being available for purification of the oil and a regular check on the pH value of the oil should be obtained.

An important factor in considering crankcase explosions, and the likelihood of their occurrence, was the provision of adequate and efficient alarms and safety devices. At Gotaverken, various oil mist detectors had been installed but it was recommended that the following equipment be installed:

1) Carbon dioxide or vapour injection equipment.
2) Temperature gauges which sound an alarm when temperatures reach an unusually high value.

This type of installation had been developed in close collaboration with the thermometer manufacturer and had proved to be most efficient under operation conditions (Fig. 5).

3) An indicating device which sounds an alarm immediately in the event of any abnormal "wear down" occurring in either main journal bearings, crankpin bearings or crosshead bearings.

This device was actuated by the bottom of the crosshead guide shoe and the same type of instrumentation could be applied to the thrust bearing to indicate any longitudinal displacement of the crankshaft.

It had been found in practice that this system would instantly indicate bearing "wear down" and/or shaft displacement where the relative displacement value was as low as 0·3 mm. (Fig. 6).

Mr. J. A. Smith (Member) felt that the authors had very competently closed a chapter on a subject about which a good deal had been said and written, presenting conclusions with which no doubt many shipowners would be in agreement.

A. G. Arnold, in the discussion on Dr. Burgoyne's paper (reference 2 of this paper) given before the Institute in 1955, outlined a policy with which no doubt the authors would agree. It was that efforts should first be directed to the prevention of crankcase explosions, both by the design of engine and lubricating oil system and by proper operation and watchkeeping, provision being made for explosions, if they should occur, to be vented as far as possible in a safe manner. This policy represented the accepted practice of many shipowners, at the time.

In addition a number of shipowners had since then participated in the evaluation of the oil mist detectors mentioned by the authors. The earlier models were rather crude and cumbersome, but the latest commercial design appeared to be quite simple and reliable. There was an interesting possibility of this type of detector giving warning of incipient main engine trouble at an early stage. Mr. Smith's company had been operating them experimentally for some years, but the two ships selected, fortunately for the operator's unfortunately for the investigators, had run trouble free. This was a very desirable state of affairs although limiting knowledge of the effectiveness of the oil mist detector.

With regard to the paper itself nothing could be found in it to quarrel with in the limited fields which were covered, but it seemed as though the subject was becoming exhausted, and this might be the last paper for some time. It was regretted, therefore, that it did not include any statistical survey of crankcase explosions in the marine field over the past years. Fires and explosions were hazards which could be seen to be on the increase, although crankcase explosions were not listed separately in the reports of the insurance societies. According to one of the latter the number of fires and explosions in the last five years had risen from 382 in 1957 to 470 in 1961. It was interesting to note from the same report that over the same period damages to machine shafts and propellers were reduced from 1,637 to 1,401. It might be concluded from the last that although machinery was becoming more reliable, the danger of fire and explosion in ships was increasing, but it might be quite wrong to assume, therefore, that crankcase explosions were on the increase.

Mr. A. Thomson (Associate Member) wrote that it would appear that the vessel to atmosphere tests, referred to in Part I of the paper could not be regarded as truly simulating explosion conditions in an engine crankcase, which would normally be effectively sealed and not open to atmosphere as was the vessel in question.

This somewhat major deviation from the actual conditions being considered was no doubt partly responsible for the significant difference in results obtained in these tests compared with the B.I.C.E.R.A. tests, reported in the paper presented to the Institution of Mechanical Engineers by Dr. Mansfield in 1956, which were carried out on an engine employing low pressure operated, spring loaded relief valves fitted with internal oil-wetted gauze flame traps.

In these latter tests, the relief valves provided re-closed immediately following release of the pressure developed by the explosion, so preventing more oxygen being drawn into the combustion zone. In the tests under discussion such restriction was not present, and must have led to certain additional damage being suffered by the flame traps due to oxidation and after-burning.

It was however, of interest to note that the ratio of flame trap area to crankcase volume deemed adequate on page 275 the paper, corresponded favourably with the figure of 9 sq. in. of 6-layer gauze assembly per cu. ft. crankcase volume, established by Dr. Mansfield. Determination of whether this was significant or merely a coincidence was however, clouded by the substantial difference in test conditions referred to above.

Referring to Part III of the paper, it was noted that the case for flame-trapped relief valves and partition flame traps as applied to large marine engines were considered separately, but not combined, as was proposed in Dr. Mansfield's paper. On this latter basis, and re-considering the four typical engines referred to, it would then become perhaps, not too impractical to provide the requisite flame trap area on the end cylinders by a combination of flame-trapped relief valves and partition flame traps.

Finally, while the authors' closing comments on a fundamental approach to the problem by elimination of such explosions were commendable, they demanded by reason of the possible penalties in human life, a 100 per cent compliance which many members might regard as somewhat difficult to achieve in the manner proposed.

MR. F. G. VAN ASPEREN (Member) wrote that he had found the new approach to the problem very interesting, but, as the authors had already stated, of little practical value. It was the opinion of his company that the best practical measures to be taken, were those which were laid down in the Rules of Lloyd's Register of Shipping or other well known classification societies, together with the application of the Graviner-B.S.R.A. oil mist detector.

It would seem to be of advantage if those Rules were mentioned more precisely in the paper and especially in the reference list.

Authors' Reply

The authors, and Dr. E. N. Guenault, M.Sc.,* who opened the presentation of the paper, were very pleased to have Mr. Jackson's remarks; coming from such a noted designer they were most valuable.

Mr. Cook noted that Mr. Jackson had quoted three recent cases of crankcase explosions within his experience, due respectively to an oil supply failure to the thrust bearing, to a broken piston ring, and to mechanical failure of a chain damper. In the case of the thrust bearing, there must have been a substantial generation of oil mist before the affected parts became sufficiently overheated to act as a source of ignition, therefore this incident should never have occurred if an efficient type of oil mist detector had been fitted. In the other two cases, it was conceivable that sparks could have occurred before substantial mist generation but it was unlikely that such sparking would ignite the normal crankcase atmosphere. It was much more probable that explosion did not occur until oil mist had been generated in substantial amounts so that here again the presence of an oil mist detector would in all probability have given adequate notice of the existence of a dangerous condition. Several cases were known to the authors where broken piston rings had been detected by a mist detector before a dangerous condition had arisen and before the watchkeeper was aware of any trouble.

Mr. Jackson had mentioned the objections of Det Norske Veritas to telescopic piping glands inside the crankchamber. The authors understood that Det Norske Veritas also criticized the fitting of the thrust block inside the crankchamber and would certainly agree with them on this point. As Mr. Hinson had pointed out, hot thrust bearings in the crankchamber were known to have been responsible for a relatively large proportion of crankcase explosions.

On the use of flame traps, Mr. Jackson asked whether both gauze and ribbon could be used, and did it matter if the material melted provided the trap had done its work. Dr. Guenault and Mr. Palmer wished to emphasize that the trap had not only to control the passage of flame and hot gases but had to allow adequate venting of the explosion pressure. Therefore, increasing the thickness of the flame trap could not be carried very far without prejudicing the adequacy of the venting. As to melting of the trap, the danger here was if this occurred sufficiently early and caused a hole to be burnt through the trap while dangerously hot products, and possibly flame, could still be projected. If, as in the tests with the crimped-ribbon trap, the damage was confined to the inner side of the trap, this would not be serious and the trap could be replaced as Mr. Jackson suggested.

In reply to Mr. Gray, Mr. Palmer and Dr. Guenault agreed that the amount of oil on the traps in the present tests was much less than that used by Dr. Mansfield in demonstrating the advantages of oil-wetting, and that this would reduce the efficiency of the protection afforded by the traps. In the experiments described in Part I of the paper the weight of oil on the gauze at the time of the explosion was estimated to be 2·3 per cent of the weight of the gauze. In Dr. Mansfield's experiments an addition of 0·19lb. of oil per 1·4lb. of gauze, i.e. 13·6 per cent, was reported. The value of 2·3 per cent was that obtained after thoroughly wetting the gauze assembly and allowing it to drain.

Accurate comparison of results of tests made under widely different conditions was difficult, since it was not easy to take into account the effects of the scale factor and of the point of ignition. However, assuming an addition to the gauzes of 13·6 per cent oil in large scale experiments, the theory in Part II of the paper could be extended to compare with Dr. Mansfield's results. Calculations showed that with this addition of oil the heat capacity of the gauze assembly was increased by a factor of 1·94 instead of the factor of 1·16 obtained with a 2·3 per cent addition of oil. Using the factor of 1·94, the vent ratio required to probably quench the severest explosions was reduced from 7·8 sq. in./cu. ft. for a 12-gauze assembly to a value above that of 4·9 sq. in./cu. ft. found by Dr. Mansfield for a 6-gauze assembly but well below his recommended value of 9·3 sq. in./cu. ft. These calculations reinforced Mr. Gray's statement that the difference

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* Ministry of Power, Safety in Mines Research Establishment.

between the results of the experiments reported in Part 1 and Dr. Mansfield's work was almost certainly due to the different amounts of oil added to the gauze.

Even with the greater amount of oil-wetting it would appear that severe damage could sometimes occur to a flame trap at vent ratios several times greater than that of only 0·5 sq. in./cu. ft. However, it was agreed, that in practical conditions explosions that occurred accidentally might happen to be very weak, perhaps because the explosive atmosphere was localized or because of the position of the source of ignition in relation to the flame trap; in such cases it was possible that a useful degree of protection might be afforded by gauzes covering even a small vent.

Mr. Cook thought Mr. Gray had made a powerful and well reasoned plea for oil-wetted gauzes: he would agree with this in so far as engines of the size dealt with by B.I.C.E.R.A. were concerned; it was only in respect of the large slow speed main propelling engines that he parted company with Mr. Gray's conclusions. Mr. Gray based his belief of the potentialities of the oil-wetted gauzes for these very large engines on the assumption that it was practical to fit flame traps between adjacent crankchambers. The consensus of opinion in the marine engineering industry was against this for the reasons given in the paper. Mr. Jackson's remarks on this should be noted.

The whole essence of the authors' case was not that relief valves and gauzes should not be employed but rather that their limitations should be realized, particularly in the case of very large engines. Mr. Gray doubted whether oil mist detectors could be relied upon to detect small pockets of explosive mixture but he should bear in mind, in the first place, that there was very considerable turbulence so that any oil mist generated spread very rapidly throughout the crankchamber. This had been shown experimentally on large slow speed engines on a number of occasions. In the second place oil mist detectors were capable of detecting a concentration of less than one per cent of the lower explosive limit. There were now a large number of such instruments in service and already a number of cases had been reported where incipient overheating had been detected long before the operators were aware that anything was wrong.

Mr. Lorimer's contribution was most valuable. As one who was closely concerned in dealing with the problem in the course of his duties his views were deserving of respect and it was gratifying to find that they tallied so closely with those expressed in the paper.

Mr. Cook noted that Mr. Lorimer quoted a figure of 2½ per cent for the setting of oil mist detectors. This figure applied to the earlier version of the B.S.R.A.-Graviner instruments; the latest version of this instrument was more sensitive and could be set to give an alarm at concentrations as low as 0·6 per cent of the lower explosive limit. Mr. Lorimer raised the question of the comparative behaviour of lubricating oils. The authors would venture to doubt whether there was any connexion between the type of lubricating oil and the present incidence of crankcase explosions. Some years ago the British Shipbuilding Research Association investigated the possibility of using non-inflammable lubricants, i.e. lubricants consisting of hydrocarbons in which an appreciable proportion of the hydrogen was being replaced by chlorine or fluorine, silicone compounds and a number of synthetic lubricating oils. With such lubricants the explosion risk could be greatly reduced but with a worsening of viscosity characteristics and lubricating properties. Moreover, they were very expensive.

Mr. Lorimer referred to the use of hoods or shields fitted to relief vents, as also did Mr. Victory, to deflect flame in a safe direction. Dr. Guenault and Mr. Palmer agreed that these could be extremely valuable. Although they had not been tried in the present experiments they had been used in tests on the venting of dust explosions and it had been found that they could be satisfactorily fitted to lifting-plate relief valves without affecting the efficiency of venting.

Mr. Lorimer and other contributors had mentioned the oil that occasionally burned on the flame trap after the explosion. Whilst burning oil was undesirable, it was not likely to have caused a significant amount of damage to the flame traps, particularly the crimped-ribbon trap. The provision of an explosion relief valve that would close immediately after an explosion would in practice discourage oil from burning.

On the variations in the observed explosion pressures, a point also mentioned by Mr. Jackson and Mr. Hinson, this was not altogether surprising in experiments under these conditions. In a vented vessel, the spread of flame and hence the resulting explosion pressure could be considerably influenced by the precise point of ignition and the initial movement of flame. With the igniter used, namely a cerium fuse-head, in some instances reinforced by a short length of guncotton, the initial spread of flame could be subject to variation.

Mr. Cook was indebted to Mr. Jones for his contribution and for giving details of the oil mist detector marketed by his company. His firm had had a long and difficult task in connexion with this device but they persevered and the outcome had been very successful. Mr. Cook wished at this point to express his gratitude to the various shipping companies who so kindly had provided facilities for prototype trials, in some cases lasting up to two years. These facilities were invaluable.

The analysis of the records of Lloyd's Register for crankcase explosions in the years 1958-61, provided by Mr. Hinson, showed that in the overwhelming majority of cases overheating was present and they therefore strengthened the case for continuous observation of the crankcase atmosphere.

Mr. Victory's contribution provided an opportunity for correcting what the authors considered to be a slight misapprehension. The experimental work described in the paper was not undertaken to show that relief valves were of no use. Certain information became available in regard to gauze flame traps which had been obtained on small engines. This information was made available through the kindness of W. H. Allen, Sons and Co. Ltd. On examining this information it was felt by the British Shipbuilding Research Association that it was desirable to see how far it was applicable to the large slow speed oil engines and the programme of work which had been described was put in hand. Earlier B.S.R.A. work had shown the limitations of relief valves from the point of view of pressure relief.

Mr. Cook would certainly not wish to argue that relief valves should not be fitted. Indeed in the paper he had stated that "Both experiment and practical experience have shown that pressure relief is capable of dealing with the milder explosions which form the majority of those encountered" but their limitations with large engines, particularly as regards injury to personnel, had to be realized.

He was indebted to Mr. Victory for detailing the recommendations of the Ministry of Transport in respect of passenger ships: in his view these could hardly be faulted. As regards "Investigation of the value of crankcase divisions of a more practical character than was envisaged in the paper" he would refer Mr. Victory to the contribution of Mr. Jackson.

Mr. Cook was pleased to note Mr. Greenacre's remarks on the views of Shell Tankers Ltd., regarding the desirability of oil mist detectors and their experience with instruments of the Graviner high sensitivity type would be watched with interest.

Mr. Duncan's thoughtful remarks were appreciated. Oil mist detectors would only eliminate the risk of crankcase explosions if they proved reliable in service and if the appropriate steps were then taken either automatically or by the watchkeeper. It would obviously be some time before the complete reliability of oil mist detectors in service could be established and until then the wisdom of fitting relief valves could not be questioned. While Mr. Cook agreed with Mr. Duncan on the dangers of monitoring everything requiring supervision, it had to be remembered that dangerous conditions could arise very quickly in an engine crankcase and might well elude the most vigilant watchkeeper. The case for monitoring the crankcase atmosphere was therefore a strong one.

In Mr. Cook's opinion it was not desirable that oil mist detectors be arranged to bring about stopping of the engine when a dangerous condition was indicated. Apart from the operational drawbacks of such a course (incidents of this sort had an unfortunate habit of occurring at a time when the ship was in narrow waters or off a lee shore) there was some evidence to suggest that stopping might precipitate the very state of affairs it was desirable to avoid. Immediate injection of an inert gas such as carbon dioxide was, however, very desirable since the engine could then be rendered completely safe from the point of view of explosion. It was a matter of opinion whether this should be carried out automatically or left to the watchkeeper; Mr. Cook was inclined to favour automatic injection.

Mr. Cook was gratified to find that the views of Mr. Van Asperen's company on the practical measures to be taken were so closely in accord with the Classification Society's and his own. The point regarding Classification Society rules had already been made good by Mr. Victory so far as the Ministry of Transport was concerned.

Mr. Hellstrom's remarks on the use of oil vis-à-vis water as a piston cooling medium were interesting. Mr. Cook knew of no evidence to suggest that oil cooling increased the explosion hazard and was in complete agreement with comments made by Mr. Hellstrom in this respect. Choice of cooling media should be made upon other considerations.

He was interested to find that Mr. Hellstrom's company recommended use of carbon dioxide or vapour injection equipment but in his own opinion oil mist detectors were preferable to temperature and wear-down gauges.

Mr. Cook was pleased to find that Mr. Smith's views were in general agreement with his own. As the result of extensive experimental work by a number of authorities over the last 15 years the causes of crankcase explosions were now well understood and the limitations of various remedial methods had been fairly closely defined. It would seem that no further experimental work was called for but a close watch would have to be kept on the incidence of explosions and the effectiveness of the various remedial methods.

It was possible, as Mr. Roper suggested, that the damage to parts of the crimped-ribbon trap in the earlier tests would affect the evenness of venting in the subsequent tests, but it was not possible to estimate the extent of this effect.

Mr. Roper asked about the effect of increasing the metal thickness of the ribbon on the performance of the crimped-ribbon trap. Increase of the ribbon thickness would benefit the performance of the trap by reducing any melting of the leading edge of the ribbon and by increasing the mass of the trap. A disadvantage was that the blockage of the flow of the explosion gases would be increased, and the explosion pressures would then increase. There would thus be an optimum thickness of ribbon, above which an undesirable amount of interference with the explosion venting would occur. What the optimum value was could not at present be stated.

Mr. Wood, and also Mr. Thomson, raised the point that in these experiments no check valves were used to prevent the return flow of air into the vessel after venting. Dr. Guenault and Mr. Palmer agreed that where these could be fitted in practice, e.g. in the crankcase relief valves, they would be useful in minimizing any hazards from continued combustion. It was thought doubtful, however, that the damage to the flame traps observed was due to any very large extent to the effects of oxidation and after-burning. The few tests made with gauzes of Monel metal, while not conclusive, suggested that the major damage was not due to oxidation.

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at The Memorial Building on Tuesday, 27th February 1962

An Ordinary Meeting was held by the Institute on Tuesday, 27th February 1962 at 5.30 p.m., when a paper entitled "Crankcase Explosions in Marine Oil Engines" by the late K. C. Brown, B.Sc., M.Sc.Tech., R. Cook, M.Sc. (Member), G. J. James, B.Sc., Ph.D. and K N. Palmer, M.A. was presented by Dr. E. M. Guenault, M.Sc., Mr. Cook and Mr. Palmer and discussed.

Vice-Admiral Sir Frank Mason, K.C.B. (Vice-Chairman of Council) was in the Chair and eighty-five members and guests were present.

In the discussion which followed nine speakers took part.

A vote of thanks to the authors present and to Dr. Guenault, was proposed by the Chairman and greeted by acclamation.

The meeting ended at 7.50 p.m.

OBITUARY

MORESHWAR GOPAL DAMLE (Associate Member 17623) was born in 1924 in Poona. He received his primary and secondary education in Satara and passed the matriculation examination of the University of Bombay with high marks. In 1942 he obtained a Government of India Scholarship in mechanical engineering and took up an apprenticeship with Alcock Ashdown and Co. Ltd., a ship repairing firm in Bombay. During this period he attended evening classes at the Victoria Jubilee Technical Institute and again passed his final examinations with credit.

In 1947 he commenced sea service as Fifth Engineer with the Scindia Steam Navigation Co. Ltd., with which company he continued to serve until his untimely death on 19th March 1962 as the result of an accident which occurred while he was carrying out inspection duties. In the course of his service he had achieved the grade of Chief Engineer, and obtained his First Class Certificate in 1955. He had always shown great keenness in the execution of his duties and was held in high esteem by the company with which he served.

Mr. Damle, who was elected an Associate Member of the Institute on 19th June 1956, leaves a widow and two children.

WILLIAM FREDERICK JACOBS (Member 4773) died on 2nd June 1962 at the age of 75 years. Born on 3rd May 1887, the son of William Edwin and Harriet Mary Jacobs, he was educated privately and at Queen Mary College London, subsequently serving his apprenticeship in the maintenance workshops of the London and India Dock Company.

He first went to sea in 1907 in s.s. *Wakool,* a vessel of the Lunds Blue Anchor Line, with which he served until it was bought by the P. & O. Company. In all, Mr. Jacobs spent 41 years at sea in numerous ships, including s.s. *Cumberland,* in which he was serving when the vessel was sunk by enemy action in 1940.

He was promoted Second Engineer in 1912 and Chief Engineer in 1923, the year in which his only son was born. In 1936 he was transferred to the New Zealand Shipping Co. Ltd., with whom he served until his retirement in 1948.

He was a man to whom engineering was more than a career—it was a way of life, but he had had so many interesting experiences and could talk of them so fluently that people rarely found it boring, even if they did not understand the finer technical points involved. A remark made by the Rev. Colin Weller, minister of the Cranbrook Road Baptist Church, at which Mr. Jacobs worshipped for many years gives a wonderfully apt picture of the man. Mr. Weller said that his most vivid memory of him was his entering the church through the vestry door when he had been attending the heating system, which he had cared for for many years, with a hymn book in one hand and enormous spanner sticking out of his pocket.

Mr. Jacobs was elected a Member of the Institute on 5th February 1923 and subsequently became a Life Member.

He was predeceased by his wife, Ann Rebecca, whom he married in 1916, and leaves a son and two daughters.

DANIEL HORRIGAN (Member 10556) was born on 25th January 1895, and served his apprenticeship with Harland and Wolff Ltd. at Liverpool. He held a First Class Ministry of War Transport Steam Certificate with Motor Endorsement.

During the First World War, Mr. Horrigan served with the Royal Engineers; part of his service included a tour of duty with the Army of Occupation on the Rhine. Shortly after this, he began a long association with the Blue Funnel Line which continued until World War II, and was, in a sense resumed in 1945 when he joined the Straits Steamship Co. Ltd. (another Alfred Holt company) in Singapore. During the second war Mr. Horrigan served in a number of ships and in all theatres of operations except the Arctic. His was one of the first ships into Bone, Algeria and also into Antwerp after the Liberation. At least two of the vessels in which he had served were subsequently sunk, but in each case he survived unhurt.

Somewhere around 1953-54 a vessel in which he was chief engineer, the *Darvel,* was used to evacuate personnel of the Shell Petroleum Company from Indonesia, and Mr. Horrigan afterwards received a presentation for his part in the conduct of this episode. In 1959 he retired from his active career and returned to the United Kingdom in June of that year. In the last years of his life he lived in Winchester, where he concentrated his energies on building up a fine garden. He was recently admitted to the Royal Hampshire County Hospital, Winchester and died on 17th May 1962. He leaves a widow and one daughter. He became a Member of the Institute in 1945.

WILLIAM JAMES TEDFORD (Member 7696) died on 13th December 1961 at the age of 80 years.

Apprenticed between 1896-1902 to The Caledonian Railway Company, Mr. Tedford began his seagoing career in 1902 with the Clan Line of Glasgow. Except for a year ashore in the First World War, when he acted as assistant superintendent engineer at Liverpool, he continued to hold seagoing appointments with the Clan Line until 1927, when he was transferred to Glasgow as an assistant superintendent. Three years later, with the expansion of the Clan-Houston-Shire Group and the removal of its head office to London, Mr. Tedford moved down to London, where he was based until the outbreak of the Second World War.

After the bombing of the docks in 1940, he was transferred to Liverpool and served there as superintendent engineer up to the conclusion of hostilities. He returned to London in 1945 as senior assistant superintendent retaining the post until his retirement in 1951.

Mr. Tedford joined the Institute in 1934.