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AIRCRAFT FIRE SAFETY

Paper #1

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SUMMARY

Development in the UK of aircraft fuels which resist fire in a crash has concentrated almost entirely on polymeric additives which prevent fuel mist formation. At 0.3% concentration these prevent kerosine fires under realistic crash conditions with both flame and heated duct ignition sources. High internal phase ratio emulsions gave no fire resistance in these tests.

Early additives caused considerable pumping difficulties at low temperatures. The latest additive, FM9, has largely overcome these. After degradation immediately before the engine control system, FM9 modified kerosine raised no serious problems during an eight hour Spey engine test. Degradation, which is necessary before the engine, must not be allowed to occur too early in the fuel system however, otherwise fire resistance would be lost; much effort is currently devoted to this aspect. Methods of introducing the additive are also under investigation as is the possible extent of water compatibility and filtration problems.

1 INTRODUCTION

In 1967 work was begun in Materials Department, RAE, aimed at producing fuels which would withstand fire in a severe but survivable aircraft crash. It was assumed that in a typical crash the aircraft would be damaged while still moving forward and that fuel could leak from damaged tanks or lines into a high speed airstream. This would lead to the formation of a fine mist which could readily ignite, thereby covering large areas of the aircraft in a fireball. While the burning mist might only last for a few tens of seconds it would inevitably ignite any major fuel spillage in the vicinity of the aircraft, thereby producing a longer lasting and therefore more destructive, fire. It was therefore argued that three properties would be important in affecting the incidence of fire and subsequent evacuation of passengers and crew:

1) Fuel mobility.

2) Tendency to form mists.

3) Rate of flame spread over spilled fuel.

Some work has been done on thickened fuels (mainly high-internal-phase-ratio emulsions) since fuels of this type should spill less readily from a damaged aircraft. By far the greater part of the programme, however, has been devoted to fuels containing mist-suppressing additives developed and produced under Ministry Contract by ICI Ltd, Paints Division. Although these additives pose problems it was felt that they would be more easily overcome than those arising from the use of conventional thickened fuels. Clearly fuels can be ignited through the vapour or through the mist and there is no point in suppressing mist formation in a volatile fuel where the former mechanism is possible. Mist-suppressing additives are therefore only of use in fuels which are below their flash points and have only been considered in this programme for use in aviation kerosine.

2 FIRE RESISTANCE

During the safety fuel development programme, a large number of different candidate fuels has been considered. To assess the fire resistance of these materials it has been necessary to use a screening test needing only a small quantity of fuel. The minitrack test[1] has been used for this purpose. A cylindrical fuel tank (40 cc) is accelerated to a speed of $38 ms^{-1}$ and then rapidly decelerated by a braking system (average deceleration 30 g). Immediately deceleration is applied the tank is opened up and fuel is spilled onto a series of ignition sources; the amount of flame produced is judged visually and depends on the fire resistance of the fuel. The speed and deceleration were adjusted to enable a correlation to be made between this test and full scale tests made using a rocket sled. It was found that the best fuel additives produced no flame in the minitrack test at a concentration of 0.1% w/w. By contrast conventional fuels such as kerosine, petrol or gas oil produced ten foot flames, the amount of flame being very little affected by the volatility of the fuel since, under these conditions, misting readily occurs.

Screening by the minitrack enabled the many hundreds of candidate fuels to be reduced to less than ten serious contenders. The fire resistance of these was investigated using a rocket-powered sled. The "standard" two-rocket test has been more fully described elsewhere[2]. In essence a tank containing 45 litres of fuel is accelerated on a rocket sled up to a speed of $57 ms^{-1}$ and then decelerated (8-10 g) by an aircraft arrester wire. On deceleration a slit on the forward facing edge of the tank is opened up and fuel is allowed to fall upon an array of ignition sources consisting of thirty six kerosine diffusion flames arranged on three gantries across the track. This test was chosen because of its severity and because the air shearing forces to which the fuel is subjected are similar to those to be expected in a severe but potentially survivable crash occurring at 80 mph. Such crash conditions were postulated using data supplied by USAAVLABS[2] and the detailed arguments are set out in a previous AGARD paper[3]. Fuel containing FM3, the first additive to be produced, did not pass the standard test at 0.5% w/w although it passed a less stringent test using only one rocket and having lower speeds and decelerations. Six other additives, FM4-FM9, all showed no trace of fire in the "standard" test at a concentration of 0.3% w/w.

The fire resistance of three thickened fuels was investigated by this method, using a slit of 760 mm x 25 mm. The three fuels were Dow gel CX-7038, Petrolite emulsion EFA-104, both being studied at the time by FAA and one of the emulsions produced in our programme, Shell emulsion SE9. All three fuels produced large fires similar to kerosine. While these fuels have the advantage that under some conditions they would be retained more easily within the tanks, their fire resistance under the highly disruptive conditions to be found in a severe aircraft crash appears to be low. For this reason and because of the problems posed by the use of such materials in aircraft fuel systems, no further work on thickened fuels was done and the programme has been concentrated entirely on anti-misting kerosine. Typical fires produced by kerosine, an anti-misting fuel and a thickened fuel in the "standard" two-rocket test are shown in Figs 1, 2 and 3. Two additives, FM4 and FM9, both in Avtur at 0.3%, have been subjected to somewhat more severe conditions than the "standard" rocket sled test. The speed of the sled immediately before the arrester wire was raised to 78 ms^{-1}, corresponding to a severe crash at about 120 mph, without any trace of fire. This higher speed is now considered more applicable to landing and take-off conditions for modern aircraft.

An increase in fire resistance is also observed with the modified fuels when the ignition source is a heated duct: a horizontally mounted heated stainless steel duct, 610 mm long and 130 mm in diameter, was used for this purpose. With kerosine three types of behaviour were observed. At low duct temperatures no ignition occurred. At intermediate temperatures small fires occurred in the immediate vicinity of the duct after an ignition delay of some seconds; no mist explosion occurred because during the ignition delay period the mist had settled. Above a critical temperature, which in our experiments was about 500°C but which will depend on the exact experimental conditions, large fireballs were produced. Under these conditions the ignition delay is short in comparison with the mist settling time so that when the fuel reaching the duct spontaneously ignites the flame is able to propagate through the mist cloud.

With Avtur containing 0.3% FM4 this more hazardous high temperature region was prevented. At low duct temperatures no ignition occurred, while at higher temperatures (up to 645°C) only small localised fires were obtained; no fireballs were produced because there was no mist to allow propagation of these local fires. This is the behaviour to be anticipated with anti-misting kerosine since the mist-suppressing additives were considered unlikely to have any effect on the spontaneous ignition temperature of the fuel. Although such fuels do ignite they are considerably safer than kerosine because the fires produced are likely to be very much more localised. Typical fires produced by a hot duct from Avtur at temperatures above and below 500°C and from modified fuel at a temperature above 500°C are shown in Fig 4. Fire test results on the rocket sled at normal ambient temperatures are summarised in Table 1.

Recently, as a result of discussions with FAA, we have undertaken rocket sled tests of a number of fuels which have been used in the FAA aircraft crash test programme. Several of these fuels have been studied at elevated temperatures and the concentrations needed to pass the test at 95°F have been established where possible. These tests were undertaken as a result of the recognition that the two-rocket sled test represented one of the most severe of the smaller scale tests which have been used to study safety fuels. As such it should give a correlation with full scale crash tests and to enable such a correlation to be more readily established a large scale propane torch was included with the "standard" ignition array in a few runs, as was the case with the fourth FAA crash test. Some typical results are summarised in Table 2. For the limited range where comparison can be made the results are in agreement with the full scale tests. Dow fuel, for example, passed the test at a concentration of 0.7% and at normal ambient temperature as was found with the third FAA crash test. When the concentration was lowered to 0.5% it failed even at ambient temperature and would certainly have done so at 95°F, the conditions of the fourth crash test.

As the next part of the fire test programme we plan to run the rocket sled test with a Viper engine as the ignition source. In a short programme various engine running conditions will be investigated and attempts made to ingest both kerosine and FM9 modified kerosine into the engine intake to see whether there is any significant difference in behaviour.

3 HANDLING PROPERTIES

The work described in the previous section clearly demonstrates the considerable increase in fire resistance to be obtained from mist-suppressing additives when used in fuels at temperatures below their flash points. In order to achieve this fire resistance the physical and rheological properties of the base fuel have been altered and this might be expected to lead to problems elsewhere in the aircraft.

The first problem to arise was that of low temperature pumping. The first modified fuel to be used, containing FM3, caused a drop in the efficiency of a conventional aircraft centrifugal pump of about a factor of ten below that obtained with kerosine at -30°C[4]. Later fuel modifiers, however, have given much more encouraging results. Using a miniature centrifugal pump as a screening test it has been possible to assess the relative pumpability of a number of modified fuels. This minipump has been used for candidate safety fuels in much the same way as the minitrack was used to screen fire resistance. From a 100 litre sample it is possible to obtain curves of pump efficiency vs delivery pressure over a range of pump speeds (2000 to 10,000 rpm) and temperatures (-35° to +20°C). Furthermore the results appear to correlate well with data for pumpability obtained using full scale aircraft fuel pumps[5], where large enough samples have been available for full scale tests to be made. Miniature pumping test results are shown in Table 3 for five mist-suppressing additives. It can be seen how pumping efficiency has improved until with fuel containing the latest additive, FM9, a centrifugal pump gives efficiencies about 90% as high as with aviation kerosine at -35°C. FM9 fuel is also outstanding in that its pumpability is apparently independent of time. With other fuel modifiers the results were dependent on the length of time at which the fuel had been kept at low temperature. Table 3 also shows that with FM5 fuel pumping efficiencies are very low. For this reason FM5, an excellent additive in certain respects, was discarded early in the programme.

Although initial tests on many of the mist-suppressing additives studied in this programme indicated that there might be difficulties in the presence of water, work carried out by Shell Research Ltd has so far indicated no insuperable problems with anti-misting fuels[6]. Thus kerosine containing any of the additives FM4, 6, 7, 8 or 9 produced white lacy deposits when shaken with free water and bottle storage tests at Shell Research Centre with FM4 and FM9 showed that both fuels took up water far in excess of saturation levels for Avtur. However, pick up from an underlying water layer could be limited by venting the ullage space. In a simulated flight environmental rig, FM9 fuel was subjected to 100 six-hour flight cycles in which the fuel was progressively cooled with a reducing tank pressure and moist air was then admitted during the descent phase. At the end of the test there were no emulsified deposits in the tank, suggesting that, under practical conditions, water compatibility problems with FM9 fuel may not be as severe as was feared. This work is continuing.

Filtration tests at ambient temperature led to blockage of discs of less than 142 μ m porosity unless the fuel had been previously degraded. Using 10 μ m Purolator aircraft filter paper, four shearings through a diesel injector degraded FM9 fuel sufficiently to give acceptable filtration performance. With FM4 fuel this treatment was not quite sufficient.

Work on both the Thornton Flask test and a gas-driven coker without the test filter led Shell to conclude that FM9 fuel poses no great threat to the thermal stability of Avtur, although the effect on borderline fuels remains to be determined. Heat transfer coefficients of modified fuel are decreased by about 50% below that of base Avtur. This effect diminishes as the fuel is degraded, however, and after four passes through a diesel injector FM9 fuel produces a reduction in heat transfer coefficient of 5-11%. Apart from a slightly adverse effect on the wear of bronze on steel contacts, FM9 fuel appears to be beneficial to the lubricity of Avtur. It also raises the conductivity of base Avtur above that obtained with the recommended concentration of antistatic additive. This could pose some problems with fuel capacitance guages.

While the six additives FM4-FM9 are all very similar with respect to fire resistance, the handling tests described in this section have shown marked differences between them. In particular the pumping results in Table 3 show that FM9 has considerable advantages over the other fuels. FM5 fuel was so difficult to pump that it was discarded, despite the fact that it and FM3 alone of the additives we have investigated showed no problems of water compatibility. Of the other additives, none show any advantage over FM9 and, on balance, FM9 is regarded as the best available mist-suppressing additive available to date.

4 ENGINE PROBLEMS

The fire resistance of FM9 fuel and similarly modified Avtur has been obtained at the price of making formation of fuel mists more difficult and the combustion chamber is therefore an area in which we must look for problems.

Early work on an Avon chamber showed that atomisation and combustion of FM3 modified Avtur was satisfactory provided that the fuel system was arranged to produce maximum degradation of the fuel upstream of the atomiser[7]. Some deposits were formed at idling conditions but were burned off at the cruise conditions. Tests on FM4 fuel included both spray and vaporising systems. In the former system an Avon chamber was again used, while vaporising chamber tests were done on a Mamba combustion chamber with "walking stick" type vaporisers. FM4 modified Avtur showed satisfactory combustion properties in both types of chamber. Once again, with the spray chamber the engine fuel system had to be run in such a way as to impose maximum degradation on the additive before a suitable spray pattern could be achieved. In the vaporising chamber no pre-degradation was necessary. In both chambers black deposits were formed which could be removed at take-off conditions. It was considered possible that such deposits might cause problems with jet pipe instrumentation or in blocking nozzle guide vanes after a prolonged period of idling.

More recent tests on FM9 fuel at Rolls-Royce (1971) Ltd using an M45H chamber with a row of stators and at NGTE using an Avon chamber with a two-dimensional cascade of cooled stators downstream showed no trace of deposit on the nozzle guide vanes; in the NGTE tests some liquid deposits formed but these simply ran off. The Rolls-Royce tests used undegraded FM9 fuel while NGTE used FM9 fuel which had been degraded in a diesel injector.

In October 1974 the first full scale engine test was made with a Spey-Phantom engine at NGTE. It had been found in earlier tests that FM9 modified Avtur produced blockage of the fine orifices of a "Moog" valve used in the fuel control system and the fuel was therefore degraded by four passes through a diesel injector rig. Runs were made at jet pipe temperatures of 550°, 500°, 450° and 400°C and the engine was stopped and restarted a number of times on the modified fuel (including one restart after being left over a weekend). More than eight hours' testing was done and at all conditions the engine's performance was indistinguishable from that obtained with Avtur. No problems occurred either with nozzle guide vanes or jet pipe instrumentation. Rupture of a fuel filter did occur and this is currently being investigated to see whether it was due to the modified fuel. Deposits found in the fuel bowser after the test appeared to be due to water contamination and these are also being checked.

At this stage we regard the engine problems as less exacting than those in other areas. Providing that a means of degrading the fuel before it reaches the fuel control system can be found which can be used on an aircraft, the atomisation and combustion of such fuels appears to be perfectly feasible. There may be problems with engine designs giving lower temperatures than the Spey and the aspect of atmospheric pollution has not yet been covered. Nevertheless, no more work is planned in this area until several more pressing Problems have been overcome.

5 DEGRADATION

The mist-suppressing additives developed during the course of this programme are all high molecular weight polymers. A property of such materials is their tendency to degrade under shearing conditions. The process is associated with the breakdown of the larger molecules to form materials of lower molecular weight and a number of the problems discussed above are alleviated by such degradation. Indeed, substantial degradation appears to be essential if anti-misting fuels are to be filtered or be made acceptable to the engine fuel control system. Mechanical devices are available which will produce the requisite amount of degradation and large batches of fuel were prepared by means of a diesel injector for use in the Spey engine test. Unfortunately no mechanical device is yet available which would be suitable for aircraft use.

In addition to making the fuel easier to handle, degradation also destroys the fire resistance conferred by the anti-misting nature of the fuel. The signs are that relatively small amounts of degradation will substantially affect fire resistance. The problem is then two fold:

(1) the fuel must be handled in the low pressure fuel system in such a way as to avoid degradation;

(2) it must then be rapidly and substantially degraded before encountering the engine fuel control system.

The adverse effect of fuel system components on the fire resistance of anti-misting kerosine has been known for some time. A few passes through a centrifugal pump is sufficient to remove much of the fire resistance of the fuel[8]. It is planned to subject FM9 modified fuel to an aircraft fuel system in the very near future. More information should then be available on the amount of degradation to be expected under operating conditions. It is possible that some effort may have to be devoted to the design of components which will handle materials of this type without causing degradation.

Considerable effort is being devoted to methods of achieving degradation with a view to producing a degrading unit for aircraft use. Early work was hampered because of the difficulty of defining and measuring a degree of degradation. As the additive is a very high molecular weight polymer, with any sample there is a certain spread of molecular weight. It is believed that only the largest molecules are capable of conferring fire resistance and it is these molecules which are most readily broken down. For moderate amounts of shear, therefore, it is possible to lose all fire resistance while still retaining material of moderately high molecular weight. Such a sample would appear to be completely degraded if degradation were assessed by means of a fire test; its flow properties, however, might be very different from that of kerosine and certainly its ability to form deposits in a combustion chamber would differ very little from that of the undegraded fuel. Very different estimates of the degree of degradation would, therefore, be obtained from different types of measurement. In early work the minitrack was used to measure the degree of fuel degradation and this method is particularly useful for the low degradation area where we are considering loss of fire resistance due to various fuel system components. However, it leads to high apparent degrees of degradation when only relatively small changes have occurred in the additive. More recently, the measurement of spread of molecular weight in a degraded sample has been used at RAE as a more fundamental method of measuring degradation. Gel permeation chromatography (GPC) has been utilised and the method has yielded useful results. It has confirmed that only small changes in molecular weight are needed before extensive loss of fire resistance. Furthermore, it has shown that even four passes through a diesel injector, which to date is the most effective mechanical degrader we have found, produces only a moderate fall in molecular weight. Fortunately this moderate fall is sufficient to make the fuel acceptable to the engine. The degraded fuel is still capable of forming chamber deposits under certain conditions, however, and very much greater amounts of degradation would be needed to overcome completely this problem; again it is fortunate that these deposits do not appear as serious as was first thought possible.

A number of methods of producing degradation have been investigated. Of the purely mechanical methods the diesel injector is so far the most promising but others are being investigated. Ultrasonic methods have also been studied but are thought to be impractical. Large irradiation times are needed and the results show no improvement over those obtained with mechanical degraders[9]. A number of chemical methods of degradation have recently been studied at RAE. These produce very considerable degradation, molecular weights one or two orders of magnitude lower than those obtained by the best mechanical methods being observed[10]. While the methods so far discovered are unlikely to be applicable to aircraft use, the study of chemical degradation is continuing. The simplest type of in-flight degrading unit would undoubtedly be a mechanical one. The amount of energy required to degrade the additive is extremely small and the problem is one of efficiently imparting this energy to the polymer molecules rather than to the base kerosine. So far this efficiency has not been achieved but to date very little effort has been devoted to the design of a degrader and only items of existing equipment have been investigated. It is planned to devote more effort to this key aspect in future. The measurement of degradation by GPC is time consuming. It is used, therefore, as a primary standard and a number of flow experiments are currently being developed to study degradation. One of these in particular has proved most useful and once the method has been calibrated against the GPC it has yielded useful results.

6 CONCLUSIONS

The use of mist-suppressing additives in low concentrations has been shown to increase markedly the fire resistance of kerosine type fuels under simulated crash conditions. The fire resistance of fuels of this type appears to be much greater than that of conventional thickened fuels.

The use of mist-suppressing additives introduces a number of handling problems. So far as the engine is concerned, while combustion chamber deposits have been observed under idling conditions these have caused no serious problems in the turbine or with jet pipe instrumentation. So long as the fuels were subjected to moderate degradation before the engine no serious engine problems were observed. In the fuel system, while early fuels gave serious pumping difficulties these have largely been overcome with FM9 fuel. Filtration and water compatibility problems exist with this material; the former can be overcome however by degrading it while the latter is now thought less serious than was at first feared. The problem of degradation is a key aspect of the whole programme. It is necessary to avoid degradation of the fuel additive in the low pressure fuel system otherwise loss of fire resistance would occur. It is also necessary to produce moderate degradation upstream of the engine fuel control system and before meeting fine filters. Both these aspects of degradation are currently receiving much attention.

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Table 1

FIRE TEST RESULTS FOR AVTUR AND FOR FM4 MODIFIED AVTUR USING "STANDARD" TWO-ROCKET SLED TEST CONDITIONS IN THE PRESENCE OF A VARIETY OF IGNITION SOURCES

Fuel	Ignition Source	Remarks
Avtur	One kerosine flame	Intense fireball covering wide area
Gas oil	36 kerosine flames	Intense fireball covering wide area
Avtur containing 0.3% FM4	36 kerosine flames	No ignition
Avtur containing 0.3% FM5	36 kerosine flames	No ignition
Avtur containing 0.3% FM6	36 kerosine flames	No ignition
Avtur containing 0.3% FM7	36 kerosine flames	No ignition
Avtur containing 0.3% FM8	36 kerosine flames	No ignition
Avtur containing 0.3% FM9	36 kerosine flames	No ignition
Petrolite emulsion EFA-104	36 kerosine flames	Large and intense fireball similar to that produced by Avtur
Dow gel CX7038	36 kerosine flames	Large and intense fireball similar to that produced by Avtur
Shell emulsion SE-9	36 kerosine flames	Large and intense fireball similar to that produced by Avtur
Avtur	Electric arc	Intense fireball covering wide area
Avtur containing 0.3% FM4	Electric arc	No ignition
Avtur	Heated duct, 610 mm x 130 mm, stainless steel; duct temperature 610°C	Intense fireball covering wide area
Avtur containing 0.3% FM4	Heated duct, 610 mm x 130 mm, stainless steel; duct temperature 610°C	Small fire confined to immediate vicinity of duct. No further propagation
Avtur	Duct as above, duct temperature 410°C	Small fire confined to immediate vicinity of duct. No further propagation
Avtur containing 0.3% FM4	Duct as above, duct temperature 410°C	Small fire confined to immediate vicinity of duct. No further propagation

TABLE 2

FIRE RESISTANCE OF SOME SAFETY FUELS OVER A TEMPERATURE RANGE USING RAE "STANDARD" SLED TEST

Fuel Additive	Concentration	Temperature	Test Result
FM4	0 3%	70°F	Pass
FM4	0.3%	95°F	Fail
FM4	0.4%	95°F	Pass
Conoco	Unknown (as supplied)	62°F	Fail
Conoco	Unknown (as supplied)	95°F	Fail
Dow	0.5%	65°F	Fail
Dow	0.7%	66°F	Pass
Dow	0.7%	95°F	Fail

TABLE 3

MINIATURE PUMPING TEST DATA FOR ANTI-MISTING FUELS

Fuel Additive	Maximum pump efficiency with fuel at 0.3% concentration relative to that with Avtur at −35°C and 8000 rpm	Time dependence of pump efficiency
FM4	0.33	Time dependent: varies from 0.25–0.33
FM5	Very low; fuel tended to gel	–
FM7	0.33	–
FM8	0.44	Time dependent: varies from 0.33–0.44
FM9	0.88	Independent of time.

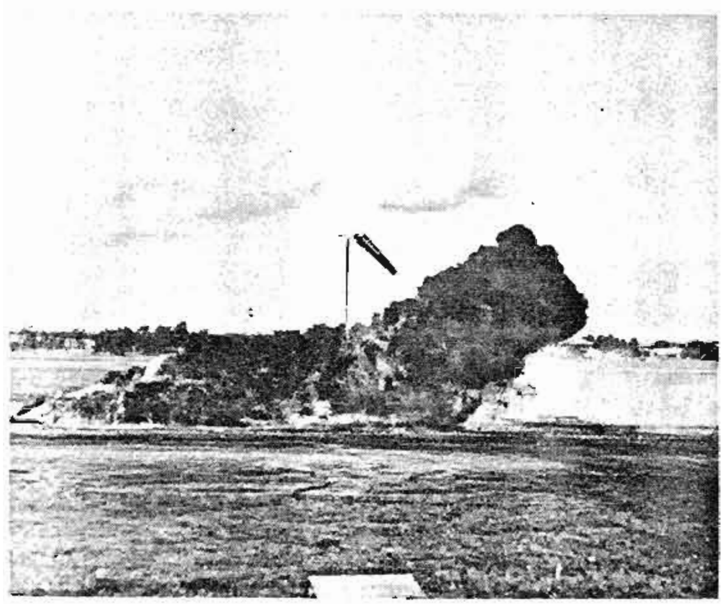

FIG 1 STANDARD FIRE TEST WITH AVTUR

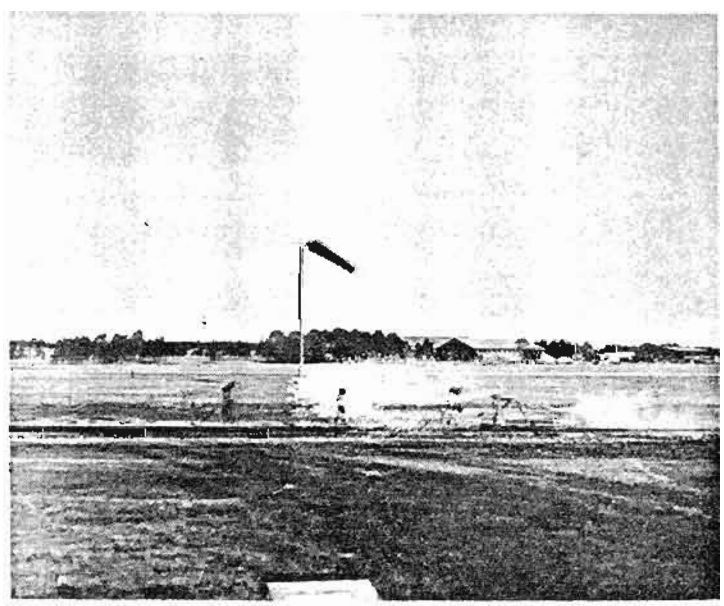

FIG 2 STANDARD FIRE TEST WITH FM4 MODIFIED AVTUR

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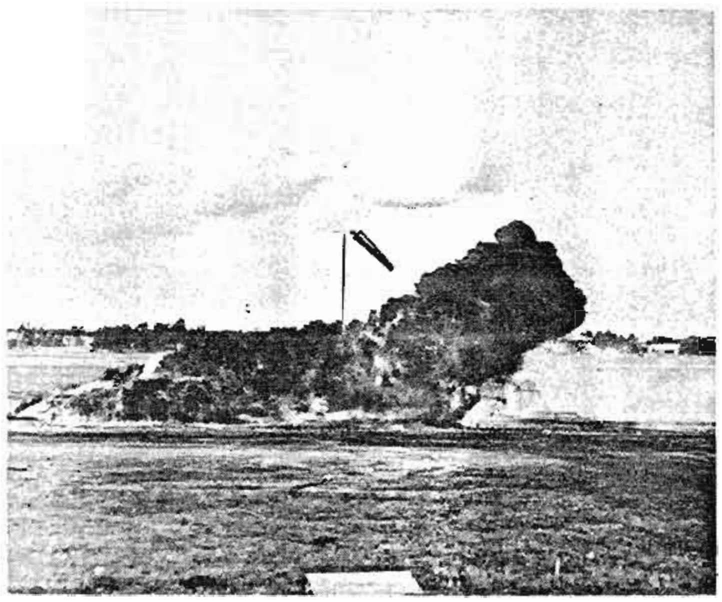


FIG 1 STANDARD FIRE TEST WITH AVTUR

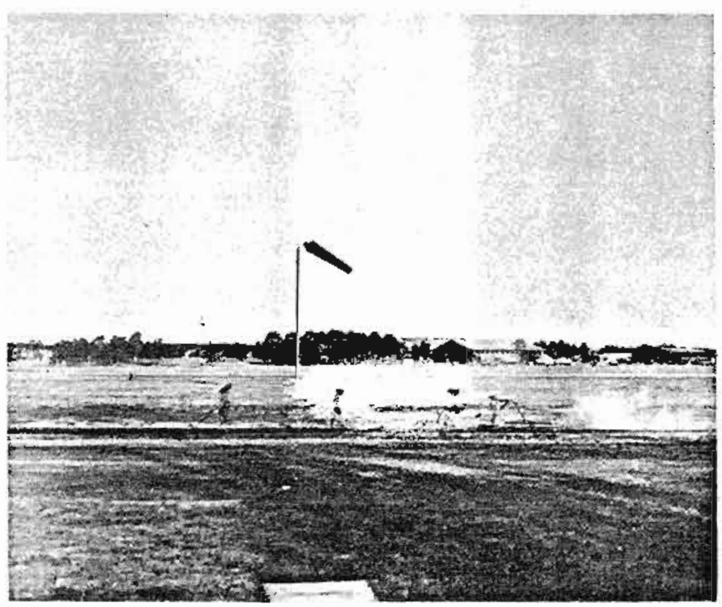


FIG 2 STANDARD FIRE TEST WITH FM4 MODIFIED AVTUR

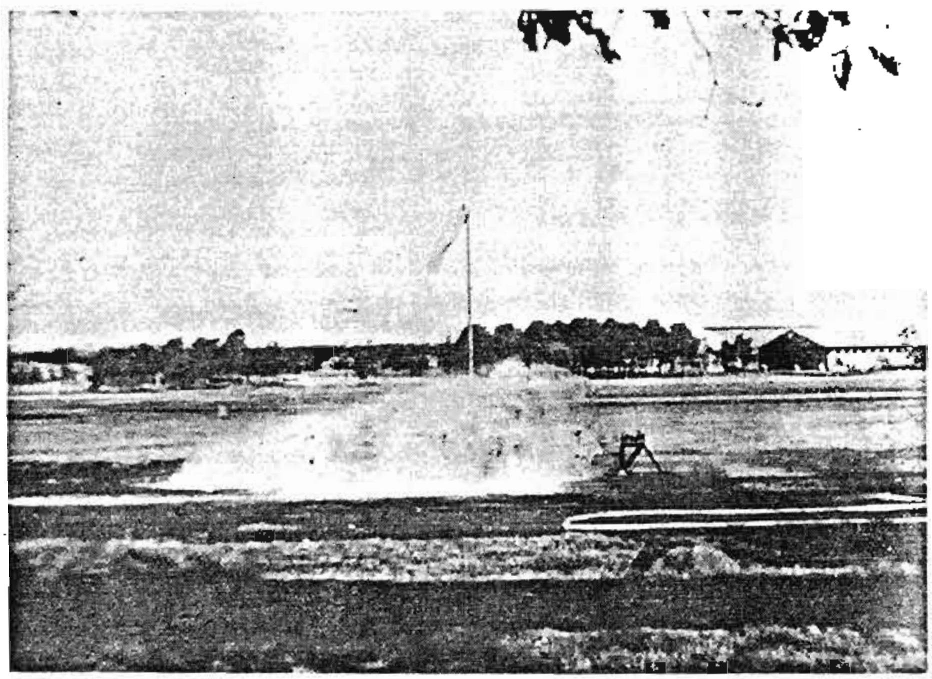
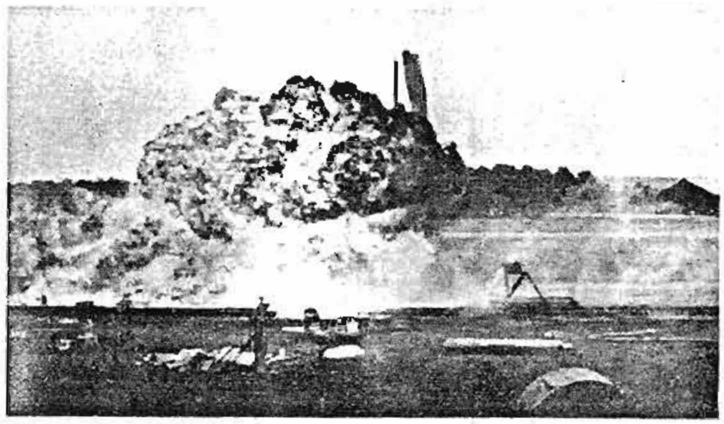
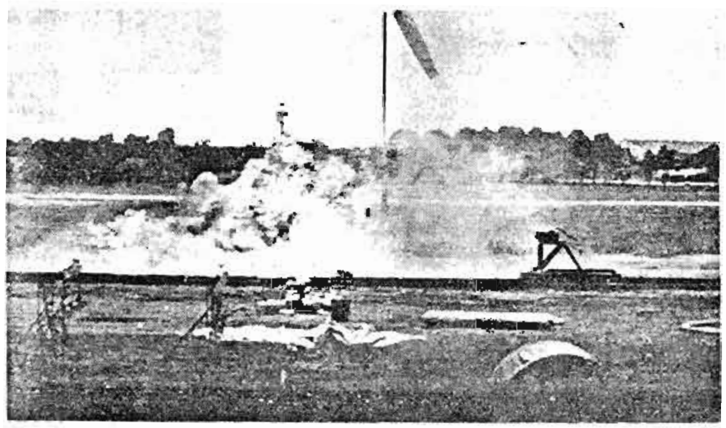


FIG 3 STANDARD FIRE TEST WITH CONVENTIONAL THICKENED FUEL
(SHELL SE9 EMULSION)

(a) Avtur at
T 500°C



(b) Avtur at
T 500°C



(c) FM4 fuel at
T 500°C

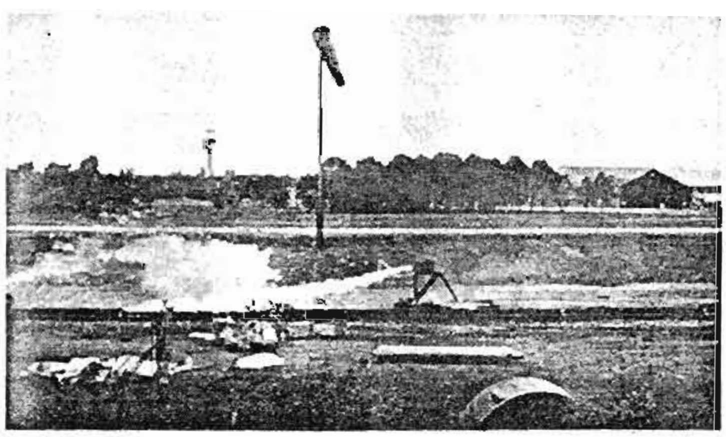


FIG 4 SLED TESTS USING A HEATED DUCT AS THE IGNITION SOURCE – SPONTANEOUS IGNITION OF AVTUR AND FM4 MODIFIED AVTUR

Note: A Consolidated Discussion was conducted for Papers 1-3. It is documented at the end of Paper 3.