Fire Research Note No. 641

SYMPOSIUM PAPER No. 2.

"RESEARCH ON AIRCRAFT FIRES"

by

P. NASH, B.Sc., M.I.Fire.E.,

FIRE RESEARCH STATION

SYMPOSIUM ON MAJOR AIRCRAFT FIRES

9th December, 1966

at

Ministry of Technology and Fire Offices' Committee
Joint Fire Research Organization

FIRE RESEARCH STATION
Melrose Avenue, Boreham Wood, Herts.

PAPER NO.2.

"RESEARCH ON AIRCRAFT FIRES"

Presented by

Mr. P. Nash, B.Sc., M.I.Fire E.,
Joint Fire Research Organization

Paper No.2.
F.R. Note No.641.

Research on Aircraft Fires

Contents

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

Paper No.2
F.R. Note No.641.

Research on Aircraft Fires

1. Introduction

The modern aircraft is one of the strongest structures for its weight created by man, as it has to withstand a range of conditions of high loading, vibration and temperature. These conditions have been closely specified, through the medium of the British Civil Airworthiness Requirements, by the Air Registration Board, and it has been the task of the aircraft designer to provide the competitive performance, within the scope of these conditions, so essential for commercial success. It follows that little extraneous weight has been available for additional strengthening to permit the aircraft to withstand unusual loadings not occurring with its normal operating condition, or within such emergency conditions as are closely akin to normal. Other speakers to follow will, I know, concern themselves with methods of avoiding the full effects of the catastrophic condition, the major aircraft fire, either by designing vital parts of the aircraft structure to avoid these effects, or by modifying the fuel itself to reduce or eliminate its hazard.

In this paper I hope to examine the present and potential effectiveness of external fire fighting in terms of the research that has been carried out in this country and in the United States, on the assumption that a serious but survivable crash has occurred and has resulted in a large fuel spillage and a major fire.

2. Research on the development of major aircraft fires

A study of individual aircraft fires shows that they range from the minor fire from which personal escape is readily possible, to the extreme non-survivable crash in which the outbreak of fire has little, if any, further effect on the casualty rate. Between these extremes is the crash which is itself survivable by a proportion of the occupants, but which generally results in a fire which is rapid and severe enough to cause their deaths. It has been shown[1] that in this country about 30 persons lose their lives annually in aircraft crashes and of these about 10 per cent probably die as a result of the ensuing fire rather than the crash itself. In the United States the figures are substantially higher, even taking into account the difference in population and the proportionally greater use of air transport. Any means which increases the number of occupants who survive the initial crash will increase the relative importance of fire-avoiding and fire-fighting measures. It has also been shown that the increasing size of aircraft does not of itself give an increase in personal safety, and with the advent of much larger passenger-carrying aircraft and the popularization of cheaper air travel, we can look to the need for really effective fire-fighting measures in the future.

It is customary in military circles to measure the effectiveness of offensive and defensive weapons in terms of three quantities, viz. speed, range and "fire power", and these three quantities will also serve as a useful measure of the performance of future aircraft fire-fighting appliances. The values to be placed on each of the quantities can be deduced from aircraft fire-statistics, and from the experimental aircraft fires that have been conducted in this country and the United States.

The pioneer work of Pinkel, Preston and Pesman[2,3] of the N.A.C.A. Cleveland Lewis Flight Propulsion Laboratories during 1949-1953 provides valuable data on the initiation and growth of aircraft crash fires. They conducted a series of experiments using surplus C-46 (low-wing) and C82 (high wing) transport aircraft, with which they simulated take-off and landing crash fires by accelerating each aircraft up to about 100 m.p.h. before crashing it into a barrier devised to smash off the landing gear and penetrate the fuel tanks. These crashes were considered to be within the range likely to give a high chance of impact deceleration survival, but maximum fire risk. That is, they represented the type of crash in which the effect of fire on casualty rate was likely to be at its highest. These workers studied the distribution of airborne fuel mist and liquid fuel spillage, and the growth of fire from various ignition sources within these distributions. They also studied deceleration effects on the main components of the aircraft and on the simulated occupants, and the growth of temperatures and toxic gas concentrations within the personnel compartments.

The airborne fuel mists were found to occur in all the experiments, as they arose when the fuel tanks were ruptured and the fuel was projected by its impetus through the gashes, to be dispersed immediately in droplet form in the surrounding air. A lesser source was the air/fuel mixture from broken induction systems of reciprocating engines. These mists usually ignited almost immediately from various sources (i.e. in 0 to 4 seconds after impact) and the burning fuel cloud often enveloped a major part of the aircraft fuselage. Little if any difference in ignitability of the mists was discernible between gasolines and the lower volatility turbine fuels. Although the mists burnt out rapidly (in less than 15 seconds), they served to ignite liquid fuel spillages within the ruptured main planes or on the surface of the fuselage or ground.

Thus there could be a diminution of radiant intensity as the fuel mist burned off, and before the ground spillage fire gained its full intensity. The extent of this diminution depended greatly on the rate of spillage of fuel and the degree to which the spillage had been spread out by the movement of the aircraft. Where spillages within the mainplane structure became ignited, they sometimes caused explosions which shattered the mainplane and caused massive deposition of the fuel contents resulting in a major spill fire around the fuselage.

Pesman[4] concluded from the results of these experiments that the survival times of the "occupants" of the aircraft determined by skin burning, respiratory injury and toxic gases did not differ markedly, and ranged from 50 to 300 seconds where the fuselage remained intact, but could be less than 50 seconds where apertures were opened (e.g. escape hatches) or where flame contact with the fuselage was extensive and severe. He recommended the development of an internal lining or shield capable of providing substantial protection against radiated heat, hot gases and toxic vapours and concluded that existing thermal and sound insulation was ineffective for this purpose. He noted that escape routes were available in several of the experiments for part or all of the 5-minute period after the aircraft had come to rest.

A second series of full-scale aircraft fire experiments[5,6] was carried out by the U.S. Federal Aviation Agency at their National Aviation Facilities Experimental Centre (NAFEC), Atlantic City, New Jersey between June 1 and October 7, 1964. These experiments were primarily intended as studies of aircraft fire-fighting, unlike those of the N.A.C.A., which were to study the factors influencing the growth of an aircraft fire and the possibility of suppressing ignition sources. NAFEC made seven tests using surplus C-97 4-engined propeller-driven aircraft, similar in size to modern jet engined passenger aircraft. The insulation of the cabins was brought up to modern passenger standards, and the temperature and heat radiation levels within were measured, as well as carbon monoxide and carbon dioxide concentrations. All the tests were made in a "standard" way (Fig. 1) in that the aircraft was lying on its belly in a sandy area, and aircraft turbine fuel (JP4) was released from 4 outlets to front and rear of the inboard engine nacelles at rates of 50 U.S.gal/min per outlet for the first minute after ignition, 125 U.S.gal/min for the second minute and 250 U.S.gal/min for the third and subsequent minutes until the experiment was concluded.

In the first test, no fire-fighting was attempted, but the "escape time" was assessed. The time was defined as the elapsed time from the instant of fuel ignition to the time when the human tolerance limit was reached, after which an occupant could not escape by his own efforts.

This parameter was therefore similar to the "survival time" used by the N.A.C.A. in their tests, and was based on unbearable pain due to heat exposure on the skin, collapse due to carbon monoxide exposure, or collapse due to momentary exposure to an air temperature of 390°F or more. The remaining six experiments were devoted to studies of fire-fighting using helicopters and/or foam appliances for fire control. They will be discussed in Section 3. Thus the FAA tests differed substantially from the NACA tests in that the effect of aircraft movement on the creation of a fuel mist was not present, the liquid fuel spillage was introduced artificially and not by gushing from ruptured tanks, and no rupturing of the fuselage by an impact occurred. Nevertheless, the escape times in the "standard" test was of the same order as the "survival time" in the NACA tests. The cabin temperature remained constant at 55°F for just over 135 seconds after ignition and then rose extremely rapidly to the "escape" limit of 390°F after a further 10 seconds and to much higher temperatures shortly after. The escape limit, based on unbearable pain, occurred at 138 seconds.

It has been shown[1] that about 90 per cent of aircraft accidents occur within 4 miles of fire-fighting equipment, and this is usually the specialised aircraft fire-fighting equipment based at airfields. We may regard the remaining 10 per cent of accidents as likely to include those aircraft accidents which, because they were not on a runway, have a high proportion of impact casualties.

Within the 90 per cent, there will therefore be a proportionately greater number in which occupants could be saved from the effects of fire. In bringing effective fire-fighting to bear on such crashes, the time delays will be

a) time to locate and notify crash, and alert fire service
b) time for fire-service to respond and become road or air borne
c) time for appliances to reach the scene of the incident

In Fig.2 (a)(b)(c) is shown the likelihood of the fire service reaching the incident, assuming time delays of 0, $\frac{1}{2}$, 1 minute for intervals (a + b), and various average speeds of the appliance for interval (c).

If we assume that at least 1 minute of fire-fighting is necessary to obtain sufficient control of the fire to prolong substantially the escape time of the occupants, we may deduce the following effective ranges for appliances of different average speed capabilities, based on the maximum survival time (N.A.C.A.) and escape time (F.A.A.), and 0, 30 and 60 seconds delay in response. No appliance, however fast, could reach the scene of the incident within the minimum (N.A.C.A.) survival time, and have time for effective fire-fighting.

Table 1

Effective range of fire appliances at various average speeds

Average speed m.p.h.	Min. N.A.C.A. time	Max. N.A.C.A. time	F.A.A. time
	Effective ranges (miles) for zero response delay		
30	Not effective	2.00 miles	0.62 miles
60	"	4.00	1.25
120	"	8.00	2.5
240	"	16.00	5.1
480	"	32.00	10.2
	Effective range (miles) for 30 sec response delay		
30	"	1.75 miles	0.4 miles
60	"	3.5	0.8
120	"	7.0	1.6
240	"	14.0	3.2
480	"	28.0	6.4
	Effective range (miles) for 60 sec response delay		
30	"	1.5 miles	0.15 miles
60	"	3.0	0.30
120	"	6.0	0.60
240	"	12.0	1.2
480	"	24.0	2.4

This table shows the very limited capability of land-borne appliances which, if they were able to maintain an average of 60 m.p.h. in todays' traffic conditions, a highly unlikely possibility, could only just reach the desired effective range of 4 miles if the maximum escape time occurred. In practice they are unlikely to average more than 30 m.p.h. and their effective range under the best conditions could then be a mere 2-miles, or 1.5 miles if a 1 minute response delay occurred. Land-borne appliances can therefore only be regarded as effective on or closely adjacent to the airfield. Neglecting the air-cushion vehicle as being subject to the same limitations of movement as land-borne appliances except for special uses in marshy or tidal areas, the helicopter is the next possible basis for a fire-fighting appliance. With a potential average speed in the range 120 - 240 m.p.h., its effective range lies between zero and 16 miles, dependent upon the response delay and survival time. The next possibility would lie in the VTOL aircraft which, with a speed range of 0 - 480 m.p.h. could provide the ability to hover for fire-fighting, and an effective range from zero to 32 miles, according to response delay and survival time. Figure 3 shows the effective range of appliances of different average speeds, assuming a 1 minute delay in the response of the brigade, and 1 minute for gaining effective control of the fire.

Before examining fire-fighting aspects, it is opportune to consider the effect of extending survival time. For a land-borne appliance averaging 30 m.p.h. and subject to a 1 minute response delay, a survival time of 10 minutes would be necessary to enable the appliance to achieve an effective range of 4 miles. A survival time of 14 minutes would be required if only 20 m.p.h. could be achieved under the traffic conditions around the airfield.

If we envisage VTOL fire appliances, the required survival time, allowing for response delay and time for fire-fighting of 1 minute each, will be at least 3 minutes and could be considerably higher if a greater response delay occurs. For helicopter fire appliances, the survival time must be at least 4 minutes, and would again be greater for any response delay beyond 1 minute. For air cushion and land-borne appliances, survival times of at least 6 and 10 minutes respectively are likely to be necessary, and these are subject to further increases for delayed response and for the traffic difficulties which are all too likely at major airports. To cover all cases and to give an additional safety factor it is suggested that future passenger carrying aircraft should give a survival time of at least 15 minutes.

Such an extension of survival time can clearly best be achieved by suppressing or limiting fuel spillage, and this aspect is being considered by other speakers[7,8]. Should the major fire condition occur, however, there are still ways in which its effects might be mitigated, at least sufficiently long for fire-control to permit saving of life. If the disposition of the major assemblies of the aircraft were such that the personnel compartments were not penetrated in a survivable crash, it would remain for the wall of the fuselage to withstand the effects of fire for the required limited period for escape. It is not the main purpose of this paper to discuss such matters, but studies of the potentialities of built in impact and fire resistance would clearly be worth while. The cabin structure could possibly be made stronger and less distortable than a baggage compartment below, the latter then acting as a crushable barrier. Fire-retardant paints of the intumescent type might be capable of adding a few minutes additional resistance to fire penetration even to a light aluminium alloy structure, but present-day products are not really suitable for exterior use. It has been shown to be possible to expose aluminium alloy structures, and even untreated canvas, to intense fire conditions including flame contact, providing an adequate water film can be maintained on the surface. This was done in a series of experiments[9,10] on "fire-resisting" lifeboats carried out in 1960, in which the boats were totally enveloped in the flames from oil burning on the surface of the water on which they floated. Such a method is likely to involve a very high weight penalty, however, if the water has to be carried aboard. This penalty could be reduced somewhat by "foaming" the water with a foaming agent, so that its rate of run-off could be reduced. Even so, the lower areas of the fuselage, where fire intensity is likely to be greatest, would be the areas most likely to "dry out" and burn through. Another possibility is to provide a double skin[11] to the fuselage as a water-jacket through which water could be pumped, to emerge at spill holes near the top centre line of the fuselage. This would ensure the longest protection where it is most vital, in the lower areas, and the quantity of water needed would again be considerably less than that required for the water-film or foam-film method. The double-skinning would need to provide its contribution to structural strength if an undue weight penalty were not to be incurred.

3. Research into the extinction of major aircraft fires using protein foams

The function of the aircraft fire appliance on arrival at an aircraft fire is to convert a rapidly-growing fire into an even more rapidly diminishing one. It is suggested that 1 minute is a realistic time in which to obtain substantial control of the fire, that is, to bring the fire to a stage where it can no longer menace the occupants of the aircraft by its radiant heating or toxic gases. Final suppression of the fire, after the initial control around the fuselage is secured, can proceed more slowly and methodically, particularly in the more remote areas which are, say, at least one-fourth of the wing span away from the fuselage laterally, or one-fourth of the aircraft length longitudinally. The method of control must be such that once the fire is subdued, it remains in a safe condition over a period of say, at least 1 hour, so that rescue can proceed without further danger to occupants or rescuers. Experimental major aircraft fires using actual aircraft are made by our own Air Ministry and Board of Trade Fire Services as well as at the Civil Aviation Safety Centre, Lebanon. As there are speakers or delegates from these Organisations here today, I will leave it to them to tell us their conclusions from these fires.

The series of full scale fire experiments[5,6] using C-97 aircraft made by NAFEC at Atlantic City in 1964 was referred to in the last section. It comprised a total of 7 fires of which the first was a "standard" fire in which no fire control measures were used before the limit of human survival was reached. The remaining six fires were to study the use of a helicopter and land-borne foam appliances, separately and in conjunction, for fire control. The C-97 aircraft were resting on their fuselages in a sandy area, and turbine fuel was supplied to four bunded areas at the nose and tail of each of the inboard engine nacelles. The aggregate area of these bunds was about 400 ft^2, and the fuel was supplied at the total rate of 200 U.S.gal (167 Imp.gal) in the first minute, 500 U.S.gal (416 Imp.gal) in the second minute and 1000 U.S.gal (833 Imp.gal) in the third and subsequent minutes. In 2 of the 7 tests (Nos.2B and 4 below) half the rate of fuel supply was pumped to the starboard bunded areas only. Details of the fire control method etc., are given in the Table 2 below. In all the tests but 3B, the pilots' and co-pilots windows and a porthole each side of the nose section were open. Two 16 in x 36 in holes were cut in the rear fuselage to simulate open exit doors. In test 3B, 4 emergency hatches, 2 each side of the midships fuselage, were also open in addition. The helicopter used in the studies was a U.S. Navy HH-43B with a gross weight of 7000 pounds. The test arrangements are also shown in Figs 1 and 4.

Table 2

FAA (NAFEC) Fire Test Schedule, C-97 Aircraft, 1964

FAA Test No.	Detail
1	Standard Test. Full fuel supply. No fire control. Wind front starboard quarter (N.W.) 8-12 m.p.h. Aircraft nose due west in all 7 tests.
2	Full fuel supply. Fire control by helicopter only, port front quarter (S.W.) approach. Wind S.W. 8-12 m.p.h.
2B	Half fuel supply (starboard side only). Fire control by helicopter, port beam approach (S). Wind S.W. 8-12 m.p.h.
3	Full fuel supply. Fire control by two foam appliances (800 U.S.gal/min foam solution each) from port and starboard front quarters. (N.W. and S.W.) Wind N.W. 8-12 m.p.h.
3A	As test 3.
3B	As test 3, but 4 additional escape hatches open in mid-fuselage. Wind from S.W., not N.W. 8-12 m.p.h.
4	Half fuel supply (starboard side only). Fire control by helicopter, starboard front quarter approach (N.W.) and by one (800 U.S.gal/min) foam appliance (N.W. approach) Wind N.W. 8-12 m.p.h.

In the tests where the helicopter was used to aid fire control, the pilot was called immediately after the ignition of the fuel in the bunded areas, which took place immediately after the fuel flow commenced. The helicopters arrival time varied from 15-35 seconds after ignition - short in comparison with the time we have generally considered in Section 2 for the fire appliances to be notified and to arrive. The helicopter stationed itself with rotor 30 $\pm$ 10 feet above the ground, and in an arc of 30 $\pm$ 10 feet radius, using the C-97 nose as centre. The bearing of the helicopter in relation to the longitudinal axis of the C-97 was from due west to the nose to 30° upwind. The helicopter normally continued its suppression action, using the downwash from the rotors to blow the flames away from the fuselage and to ventilate the cabin if possible, until it was notified that human tolerance limits had been reached within the cabin.

The land-borne foam appliances were in a state of operational readiness, stationed one each side of the nose of the C-97, prior to ignition of the fuel. In Test 4, only the appliance on the starboard bow was stationed, but the other appliance was at readiness for support action. The procedure adopted was to cool and protect the fuselage with foam and then, working out from the fuselage, to extinguish the ground fire progressively. Each appliance discharged continuously at its maximum flow rate of 800 U.S.gal/min (667 Imp.gal/min) of foaming solution. The appliances were replenished continuously from back-up equipment to extend their maximum operating time from 2 minutes to 7 minutes.

The NAFEC tests showed that the use of helicopter downwash was effective only when there was fire on the upward side of the fuselage and the flames could be "bent" away from the fuselage, thus reducing direct heating of the fuselage by flame contact, avoiding blackening of the fuselage and its attendant increase of absorption of radiant heat, and reducing radiant heating by reduction of flame-height and "configuration factor". In conjunction with one foam appliance, the survival time in Test 4 was increased from the 138 seconds of Test 1, the "standard" test, to 334 seconds. Where the fire was on both sides of the fuselage, the survival time was reduced from the 138 seconds of Test 1 to 127 seconds (Test 2), due to increased radiant and convective heating. In Test 2B, with fire on the upwind side of the fuselage, and a helicopter beam approach, the fuselage was cooler at the centre, but hotter at the ends than in the standard test. The resultant survival time was less than in the standard test (123 seconds). It is clear from these results that the use of helicopter downwash is likely to be unreliable as the sole instrument of fire control, although in favourable circumstances, and when backed by foam it may well provide a useful extension in survival time. The extension is not, however, likely to be large enough to be decisive, and therefore does not avoid the need for additional fire resistance in the aircraft itself. The ability of the land-borne foam appliances to control the fire prior to the survival limit was found to be very much dependent upon the preburn time, i.e. the time after ignition when foam application commenced, and whether the additional emergency doors were open or closed. In Test 3, with 75 seconds preburn, fire control was achieved and escape time was extended indefinitely. Test 3A, with a preburn of 115 seconds, gave an escape time of 115 seconds, so that the onset of fire-fighting would have been simultaneous with the death of the occupants. The test was, however, somewhat more severe than "standard" in that the fuselage had already been blackened and weakened in Test 3, and the test site was saturated with water, giving greater-than-standard fuel spread. Test 3B, with the 4 additional emergency exits open, gave a survival time of only 50 seconds, and fire-fighting did not commence until 60 seconds after ignition of the fuel. These results, and the conclusions drawn by NAFEC are summarised in Table 3.

Table 3

Results of NAFEC C-97 tests (1964) using land-borne foam appliances

FAA Test No.	Foam application commenced (sec after ignition)	Estimated survival time (sec)	NAFEC conclusions
3	75	Infinite	Satisfactory fire control and life-saving possible.
3A	115	115	Preburn time too long for life-saving. Test more severe than standard, however.
3B	60	50	Severe reduction in survival time due to opening of additional escape hatches adjacent to fire. Life-saving not possible.

While one cannot but agree with the conclusions drawn by NAFEC on these three tests, it is also clear that the preburn times considered are substantially below those likely to occur in practice where an appliance has to be alerted and has then to proceed to the site of the fire. Unless the appliances and crew have been alerted before the incident occurs, and can proceed to the likely crash area, e.g. in a crash or emergency landing, response times as short as 75 or 115 seconds are very unlikely to be realised. This underlines again the need for a substantial increase in the fire resistance of the fuselage structure, and/or the rendering safe of the fuel contents.

At the rate of foam application used control of all these test fires was fairly rapid. Thus in Test 3, the critical zone nearest the fuselage was extinguished in 70 seconds, the foam being directed alternately at fuselage and ground spillage. 1700 U.S.gal of foaming solution were used for the operation. In Test 3B, the foam was directed continuously at the fuselage and allowed to run off onto the ground, with the result that the ground fire adjacent to the fuselage was controlled in 150 seconds, using 3800 U.S.gal of foaming solution. It was concluded that, apart from an initial cooling of the fuselage, it was much more effective to concentrate on extinguishing the fire, than protecting exposures against it, especially if emergency hatches were open. If the fuselage were intact and hatches were closed, there would be a greater argument for cooling the fuselage to maintain its integrity, provided this did not seriously affect control of the ground fire. The time required to control the fire in the critical access areas close to the fuselage, taking all 6 fire tests, ranged from 30 seconds for a small fire to 200 seconds for a large one, giving an average control time of 140 seconds. NAFEC concluded that even higher discharge rates than the 1600 U.S.gal/min (1333 Imp.gal/min) were necessary to achieve this more rapid control, and/or that improved extinguishing agents or concepts were necessary to provide an even faster general reduction in heat radiation levels, particularly near the fuselage.

In addition to their fire control studies, NAFEC also studied the possibility of keeping open "escape routes" from the aircraft to safer areas, using helicopters and foam appliances. The helicopter downwash was found to reduce radiant heat intensities drastically, but working on its own, the helicopter was unable to free the escape route completely from flame where free fuel was present. In conjunction with ground-based foam land-lines used with technique and experience, the cutting of a safe rescue path was a possibility.

Another major series of aircraft fire experiments[12] was carried out at Stansted Airport, Essex in 1964-65, at the Board of Trade Fire Service Training School. These experiments were made by the Joint Fire Research Organization, in conjunction with the Air Ministry, Board of Trade, Ministry of Aviation, Ministry of Works, etc. Their object was to determine the significance of the various physical properties of protein-based fire-fighting foams in the rapid control of aircraft fires.

For this purpose a special gas-turbine operated foam generator (TURbine FOam GENerator = TURFOGEN) was developed by J.F.R.O.[13] to give a range of rates of foam application varying from 50 - 250 gal/min of foam making solution. In this generator, the compressed air output from a small gas turbine-compressor unit (2 lb free air/sec at 38 lb/in^2 and 200°C) was used to expel a premixed aqueous solution of protein-based foam liquid from a 650 gal tank, and to force it through a foam generator in which it was mixed with further air from the same source to make foam, which was then ejected from a monitor onto the fire. The rate of flow of liquid, and the foam properties[14] could be adjusted to give the ranges of properties shown in Table 4 below.

Table 4

Application rates and physical properties of TURFOGEN foam

Variable	Overall range available	Values used in experiments
Rate of application of foaming solution	50 - 250 gal/min	50, 125, 200 gal/min
Foam expansion	5 - 25 approx.	6, 13, 20 approx.
Critical shear stress	150 - 1500 dyn/cm^2	$<$ 275, 400 - 750, $>$ 825 dyn/cm^2
Drainage ($\frac{1}{4}$ drainage time)	2 - 200 min.	$<$ 10, 20 - 60, $>$ 70 min.

The experiments consisted of a series of "standard" simulated aircraft fires in a 25 x 35 ft bunded area in which about 250 gal of aviation turbine fuel (AVTUR) could be burnt. In the centre of the area was a mock aircraft fuselage made from a 5 ft dia. x 20 ft long steel tube, with four 40 gallon steel drums to represent main planes and engine nacelles (Fig.5). The surface of the bund was covered first with approximately 1 inch of water, and the Avtur was poured onto this, the quantity being sufficient to give about 5 minutes burning over the area. "Control" of the fire was measured by the time taken to reduce the radiant intensity of the fire from its initial free-burning value, to 1/10th of this value, the radiation being measured by 4 radiometers connected in series and facing inwards towards the fire from positions facing the corners of the rectangular bund. This time was described as the "time to gain 9/10 control" or, more simply, the "9/10 control time".

In each test, the fuel was primed with a little petrol, ignited, and allowed to burn for 60 seconds, by which time the whole area was involved. Foam application then commenced from a position upwind of one of the corners of the bund. The experiments were made on days when the wind velocity was less than 15 ft/sec, and an experienced fireman was used as operator. In all, a total of over 30 experiments were made, 5 to give the operator experience on the particular fire so as to reduce his "learning factor" to the minimum, 14 at a rate of application of foaming liquid of 50 gal/min, 6 at 125 gal/min and 7 at 200 gal/min. The large number at the lowest rate were made to give comparison of the various foam properties, after the significance of rate of application had been established. A typical experiment is shown in Fig.6.

Analysis of the results of the experiments showed that by far the most significant factor in rapid fire control was the rate of application of foaming solution. The faster the foam was applied, the sooner the fire was controlled and vice versa. The rates of application used represent 0.06 - 0.23 Imp.gal/ft^2 min^{-1} on the 875 ft^2 area, considerably lower than the rates used in the NAFEC experiments, which ranged from about 0.20 to 0.50 Imp.gal/ft^2 min^{-1} for estimated initial fire areas of 3000 to 5000 ft^2. The NAFEC fires were, however, more complex than the Stansted fires, in that a much larger fuselage obstructed the fire area.

The actual quantities of foaming solution used to gain control of the J.F.R.O. fires were in the range 0.08 - 0.15 Imp.gal/ft^2. Again, this is substantially lower than the comparable NAFEC results. The times for 9/10 control of the fires varied between 20 - 40 seconds at the highest rates, 35 - 65 seconds at the intermediate rate and 65 - 120 seconds at the lowest rate, according to the actual physical properties used.

Expansion of foam, that is, the ratio of the volume of the made foam to the volume of foaming solution used, did not appear to have a significant effect on control of the fire, in the range 6 - 20 used in the experiments.

Critical shear stress, a measure of the work used in forming the bubble structure of the foam, gave a minimum value of control time for values of the critical shear stress which varied between about 300 and 500 dyn/cm^2, according to the rate of application used. As the control time tends to rise more sharply on the lower side of the optimum range than on the upper side where the foam is more stable, it is suggested that a value of about 400 - 500 dyn/cm^2 should be aimed at in practice.

Drainage from foam represents loss of resistance to fire, and hence loss of stability both during extinction and afterwards when the area must be secured for rescue operations to proceed. The values of "$\frac{1}{4}$ drainage time" varied in these experiments between 2 and 200 minutes. It is suggested that a value in the range 15 - 30 minutes should be aimed at, in order to give a good stable foam.

4. Use of other agents for aircraft fire-fighting

Protein-based fire-fighting foam has always been pre-eminent for the major aircraft fire, being the only agent available which could give post-extinction security to a fire, and indeed its high natural fire resistance has meant that rescue operations could proceed before the whole fire was extinguished, with the knowledge that those areas already covered would be safe from re-ignition for a period of at least several minutes. No other agent, including dry powders and inerting gases, has given this security under the turbulent open-air conditions prevailing. They have all required complete extinction before application ceases, and even then the fire area has been left in a condition where re-ignition could readily occur from hot metal etc. left in the fire zone. In this respect they have fallen short of the requirements for a mass aircraft fire-fighting agent.

Foam solution has, however, the disadvantage of its comparative weightiness, and its lack of ability, when used on its own, to secure a rapid reduction in radiant intensity. Studies of the diminution of radiant intensity in the foam-controlled fires at Stansted showed a reduction approximately proportional to elapsed time, up to 9/10 control time.

The Naval Research Laboratory has developed the use of "light water"[15] a perfluorinated surface active fire-fighting agent which can be used either on its own or in conjunction with a potassium bicarbonate based dry powder. Figures produced by the N.R.L., using light water with or without pot. bicarbonate powder on a 400 ft^2 petrol fire containing a small obstruction in the centre[16], provide interesting comparison with the results obtained at Stansted in the 875 ft^2 fire in turbine fuel, using foam alone. Thus, using light water alone, a total of 0.06 Imp.gal/ft^2 of light water solution was required (i.e. 0.6 lb/ft^2 weight of solution) to extinguish the fire. Protein-based foam on the 875 ft^2 Avtur fire required 0.08 – 0.15 gal/ft^2 (0.8 – 1.5 lb/ft^2) for extinction, and on another series of tests on a 900 ft^2 petrol fire with obstructions, it required 0.12 – 0.32 gal/ft^2 (1.2 3.2 lb/ft^2). Choosing optimum rates of application, a petrol fire of this size should therefore be extinguished for the expenditure of not more than 0.15 gal/ft^2 (1.5 lb/ft^2) of solution. If both water and active material have to be carried to the fire, the light water shows a weight advantage of about $2\frac{1}{2}$: 1 over the protein foam. If only the active material has to be carried – not usually applicable in the aircraft fire case – the protein foam would show a 2 : 1 weight advantage over the light water as it requires only about 1/5 of the solution strength. From the cost point of view, light water will extinguish a given fire for an expenditure of 10 to 15 times that of protein foam at prevailing prices. A less expensive formulation of "light water", both in solution strength and cost of active agent, is becoming available.

It is of great interest that during this current year and early 1967, NAFEC is carrying out an extensive programme of aircraft fire extinction experiments using dry powders, protein-based foams, specially stabilised protein foams, high-expansion air foams, "light water" with and without dry powder etc., at various rates of application to different sizes of fires in obstructed areas and around DC 8 fuselages, in order to compare the effectiveness of the different agents in this difficult problem, the major aircraft fire.

The mass application of dry powders to aircraft fires has been tried in this country, in France and in Canada, and has been shown to be capable of rapid fire reduction. It suffers, however, from the failure to secure the fire area against re-ignition, so essential for safe rescue operations. Efforts to avoid this defect by the joint use of dry powder and foam have also been made, but it is the writers' impression that this technique has not yet fully been worked out. The effect of mass dry powder discharge on the occupants would also need to be determined.

Finally, an agent which has so far not been considered for major aircraft fires is liquid nitrogen, which has the advantages of high cooling effect on the liquid fuel and surrounding surfaces, a useful inerting effect as the nitrogen is vaporised in the fire zone, and reduced toxic effects compared with mass application of carbon dioxide.

5. Conclusions

From the foregoing research work, certain general conclusions may be drawn regarding the future of aircraft fire fighting. These are:

a) The "fire resistance" of modern aircraft is not high enough to ensure the safety of the occupants from a major fire incident. The fire must either be avoided by rendering the fuel safe, or the aircraft must be given additional fire resistance to enable it to withstand the effect of a major fire for a period of several minutes.

   To give world-wide coverage at all types of air fields, a period of fire resistance of not less than 15 minutes is suggested.

b) Land-borne fire appliances under todays' conditions are really only effective for incidents on or immediately adjacent to the airfield. With the additional fire resistance of (a) above, they could give reasonable coverage up to 4 miles, provided there were no undue delays in reporting and responding to the incident. For wider coverage, or to give a greater measure of protection within the 4 mile range, airborne appliances should be considered.

c) Full-scale aircraft fire tests have led NAFEC to suggest that greater rates of foam output may be necessary per appliance, than those in use today (500 - 800 Imp.gal/min of foaming solution). The need for this will depend largely on whether fuel can be rendered safe, but in the meantime research should proceed to evaluate present agents, used singly or in conjunction, and to assess the need for improved agents and techniques to ensure rapid reduction of the fire.

6. Future airborne fire appliances

The principle of the gas-turbine operated foam generator used in the Stansted experiments[12] could readily be applied to an airborne helicopter or VTOL appliance. Thus, in a twin-engined twin-rotor helicopter appliance, each of the two main gas-turbine engines could provide a small proportion of its compressed air (say 3 - 5 per cent) to make and eject foam onto the aircraft fire. Delivery could be either from flight upwind of the fire, or from the ground nearby. Dispensing foam from the air would have the advantage that the foam could be carried into the fire by the downwash from the rotors, but there are clearly some operational problems to be worked out.

The flow diagram (Fig.7) shows that air from the compressor of the gas-turbine is used to eject a premixed solution of foam compound from the tank, valve B being open and A closed. Further air from the same source is mixed with the solution and the foam is formed in a "foam improver" from whence it passes to the foam monitors. In another arrangement (valve B closed and A open) the foam solution is pumped from the tank by an engine driven pump and all the air from the compressor is used to provide the air phase of the foam[17].

A suggested arrangement for a twin-rotor helicopter foam appliance is shown in Fig.8, and some projected performance figures in Table 5, (1) and (2).

A helicopter fire appliance could also be designed to disperse dry powders or high-expansion air foams.

Table 5

Twin-rotor helicopter foam appliance

(1)

Weight and performance summary	
Design wt. (empty)	11,532 lb.
Payload	6,600 lb.
Max. take-off weight	18,700 lb.
Av. cruising speed	150 m.p.h.
Range at 6,600 lb payload	115 miles

(2)

Foam laying performance summary	
Wt of tankage, pipe-work monitors	1,000 lb.
Wt of 550 gal. of foaming solution	5,500 lb.
Rate of discharge at 2 lb/sec compressed air	250 gal/min.
4 lb/sec compressed air	500 gal/min.
Max. fire area coverage - approx.	3,500 sq.ft.

References

(1) Joint Fire Research Organization Internal Notes Nos. 93, 103, 113 and 134.

(2) PINKEL, I. Irving, PRESTON, G. Merritt and PESMAN, Gerard J. "Mechanism of Start and Development of Aircraft Crash Fires". National Advisory Committee for Aeronautics. Washington, U.S.A. N.A.C.A. RM.E52F06 (August, 1952).

(3) PINKEL, I. Irving, PRESTON, G. Merritt and PESMAN, Gerard J. "N.A.C.A. Aircraft Crash Fire Tests". National Fire Protection Association Quarterly (October, 1953). Vol.47, No.2, pp.121-138.

(4) PESMAN, Gerard J. "Appraisal of Hazards to Human Survival in Airplane Crash Fires". National Advisory Committee for Aeronautics. Washington, U.S.A. Technical Note 2996 (September, 1953).

(5) CONLEY, D.W. "Post-Crash Fire-Fighting Studies on Transport Category Aircraft". Federal Aviation Agency. New Jersey. U.S.A. Report No.RD-65-50 (May, 1965).

(6) MIDDLESWORTH, Charles M., CONLEY, D.W., BRIDGES, John W. and RYAN, John J. "Federal Aviation Agency's Crash Fire Tests". National Fire Protection Association, 60 Batterymarch St., Boston, Mass., U.S.A. M.P.65-2.

(7) MILLER, R. E. "Some Aspects of Aircraft Fuel Safety". (Paper No. 7. Symposium on Major Aircraft Fires (December, 1966)).

(8) LYDIARD, W. G. "Design Aspects Relating to Aircraft Fires". (Paper No.8. Symposium on Major Aircraft Fires (December, 1966)).

(9) NASH, P. "Fire-resistant Lifeboats for Oil Tankers". The Engineer. (April, 1st 1966).

(10) NASH, P. and BIGMORE, R. H. British Patent Application No.31258/60.

(11) NASH, P. and BIGMORE, R. H. British Patent Application No. 37927/60.

(12) NASH, P., FITTES, D. W. and RICHARDSON, D. D. "Foam for Aircraft Crash Fires (3)". F.R. Note No.615.

(13) NASH, P. and FITTES, D. W. "Foam Generator for Aircraft Fire Control".

(14) NASH, P. "Recent Research on Foam in the United Kingdom". Foam Symposium, Mearl Corporation, U.S.A. (August, 1959).

(15) TUVE, R. L., PETERSON, M. B., JABLONSKI, E. J. and NEILL, R. R. "A New Vapor-securing Agent for Flammable Liquid Fire Extinguishment". U.S. Naval Research Laboratory Report 6057.

(16) TUVE, R. L. "'Light-water' and Potassium Bicarbonate Dry Chemical - A New Two-Agent Extinguishing System". National Fire Protection Association Quarterly (July, 1964).

(17) CLIFFORD, W. J. and Pyrene Co. Ltd. British Patent No.715,124.

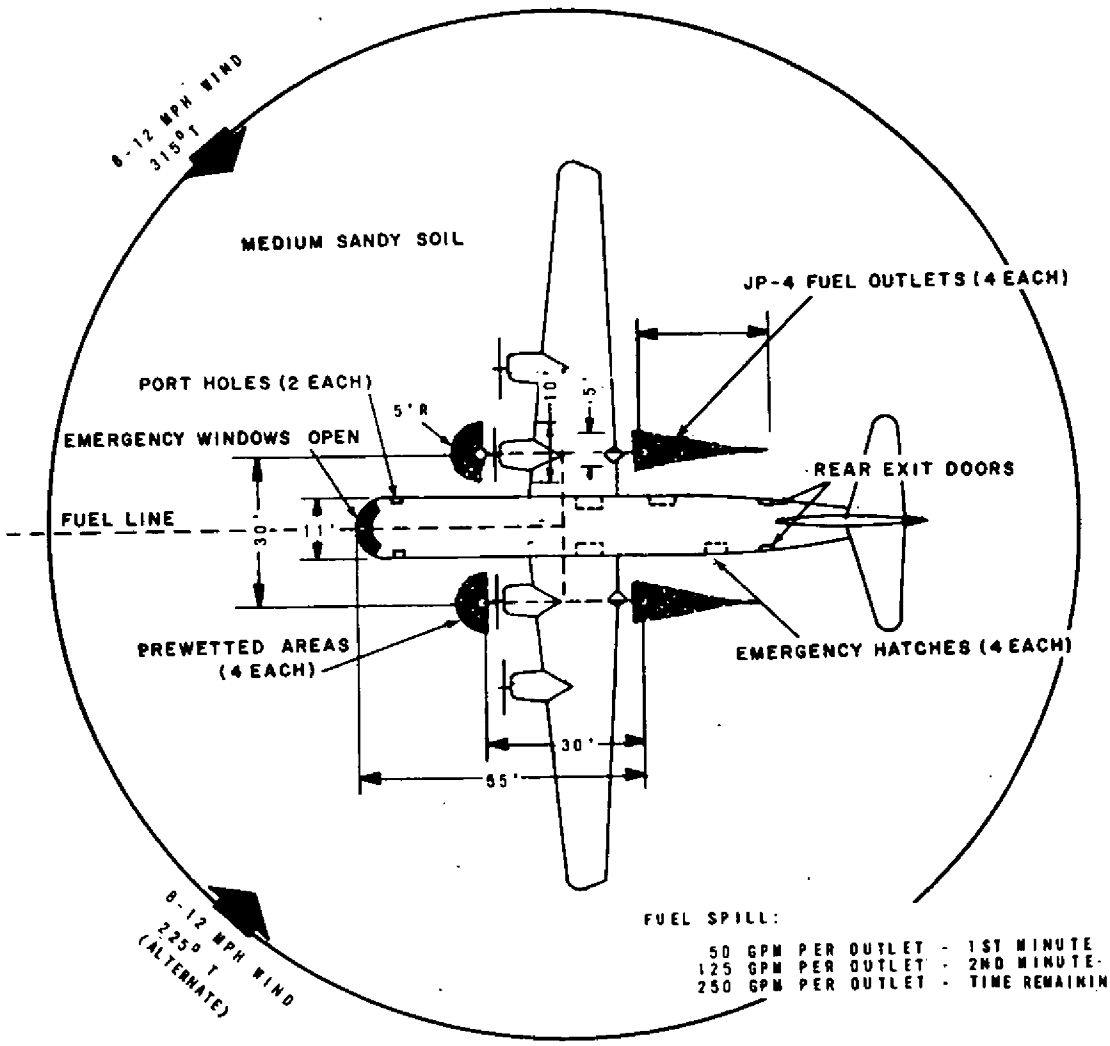

FIG. 1. F.A.A. (N.A.F.E.C.) C-97 AIRCRAFT FIRES, 1964 — STANDARD TEST CONDITIONS

From F.A.A. Report No. R.D.-65-50

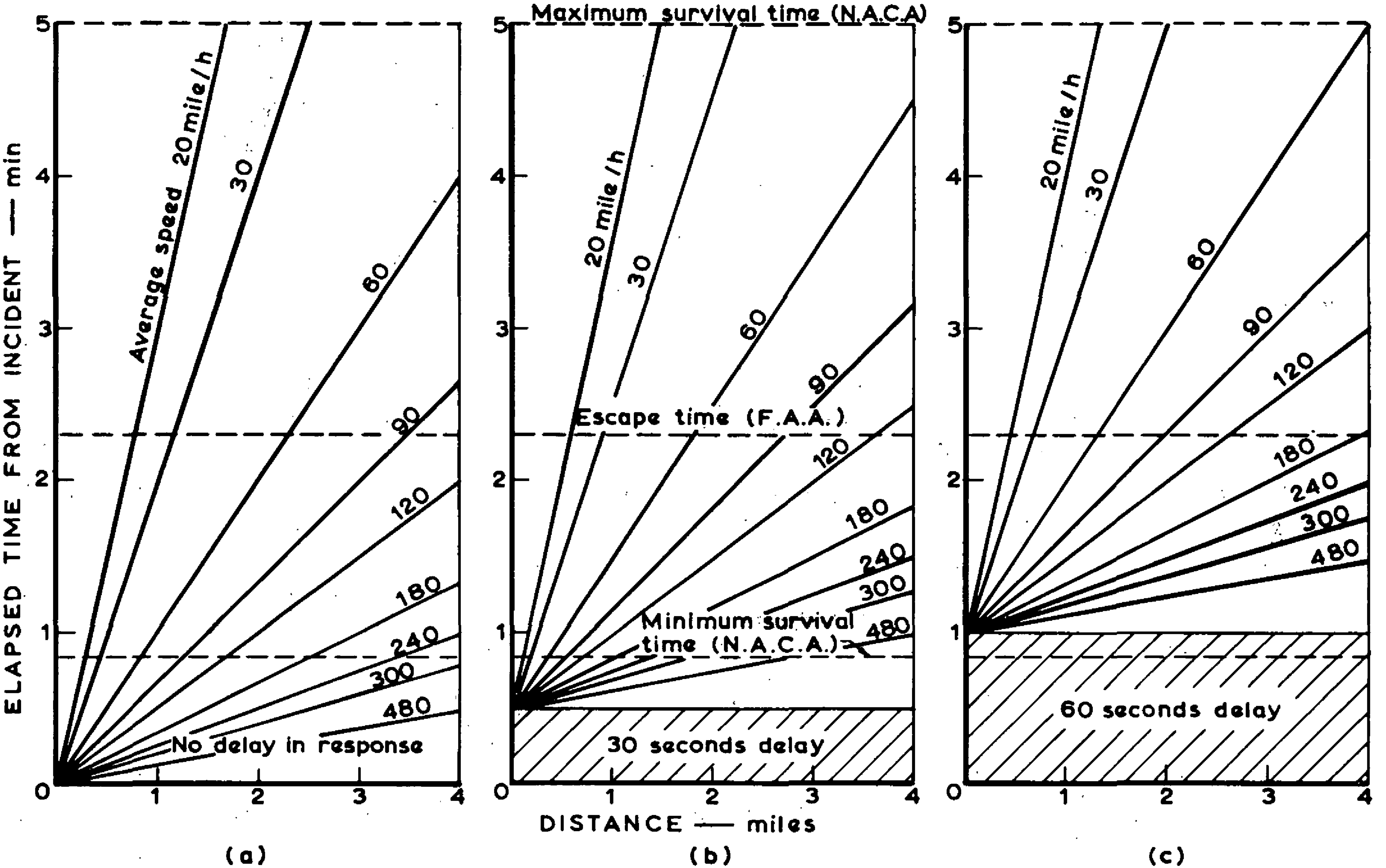

FIG. 2. EFFECT OF APPLIANCE SPEED ON ARRIVAL AT INCIDENT

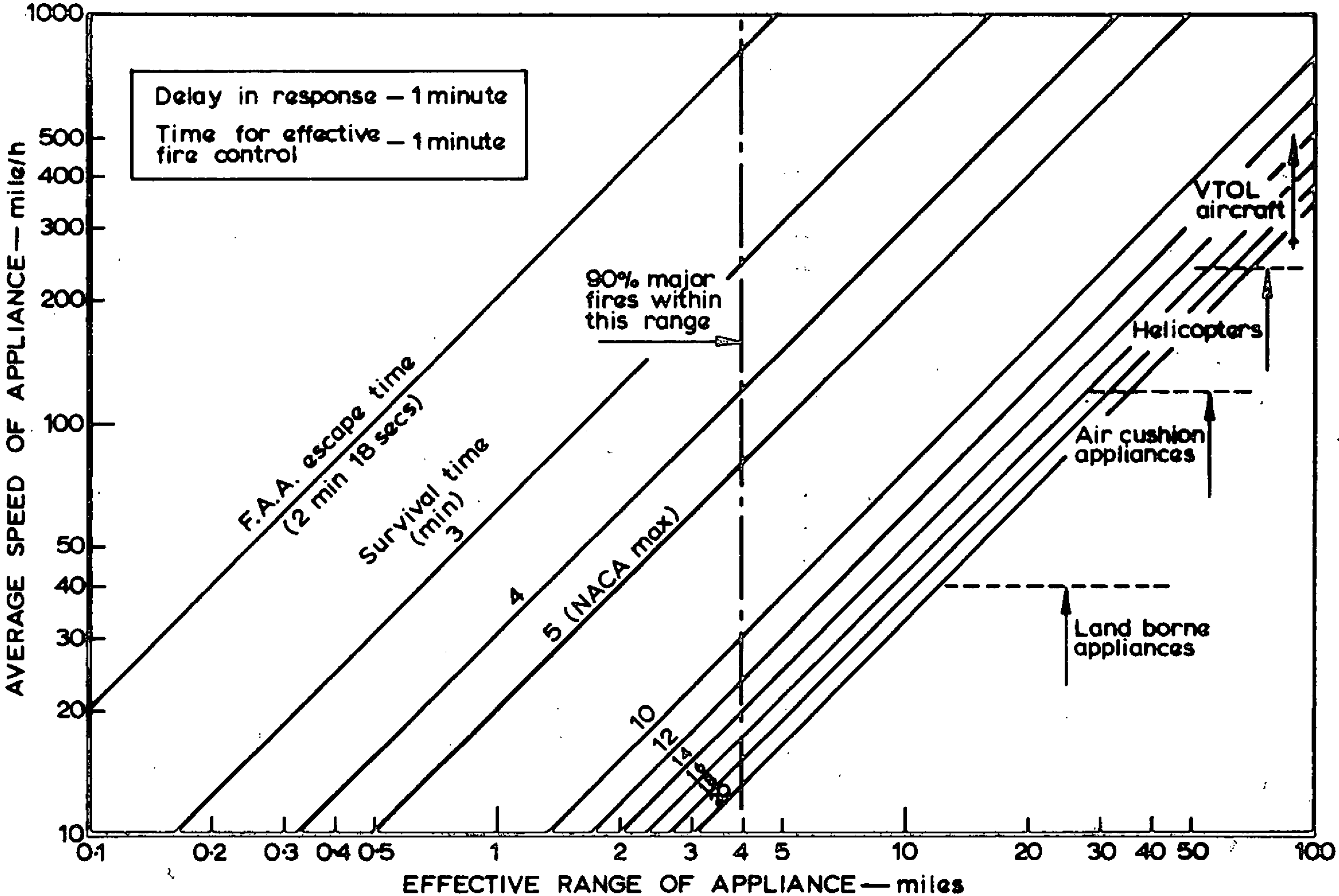

FIG. 3. EFFECT OF APPLIANCE SPEED ON ITS EFFECTIVE RANGE

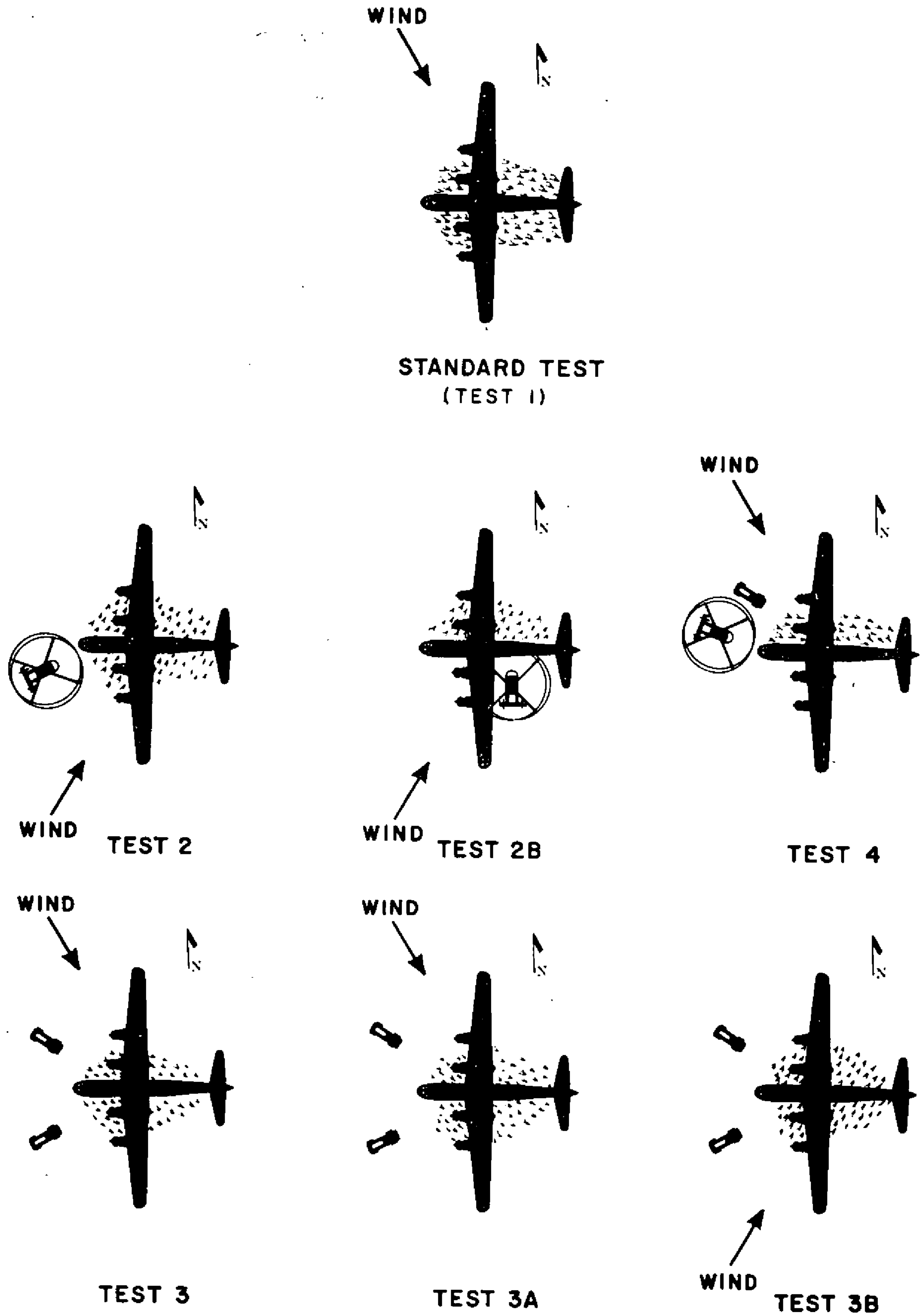

FIG. 4. F.A.A. (N.A.F.E.C.) C-97 AIRCRAFT FIRES, 1964 — STANDARD TEST CONDITIONS

From F.A.A. Report No. R.D.-65-50

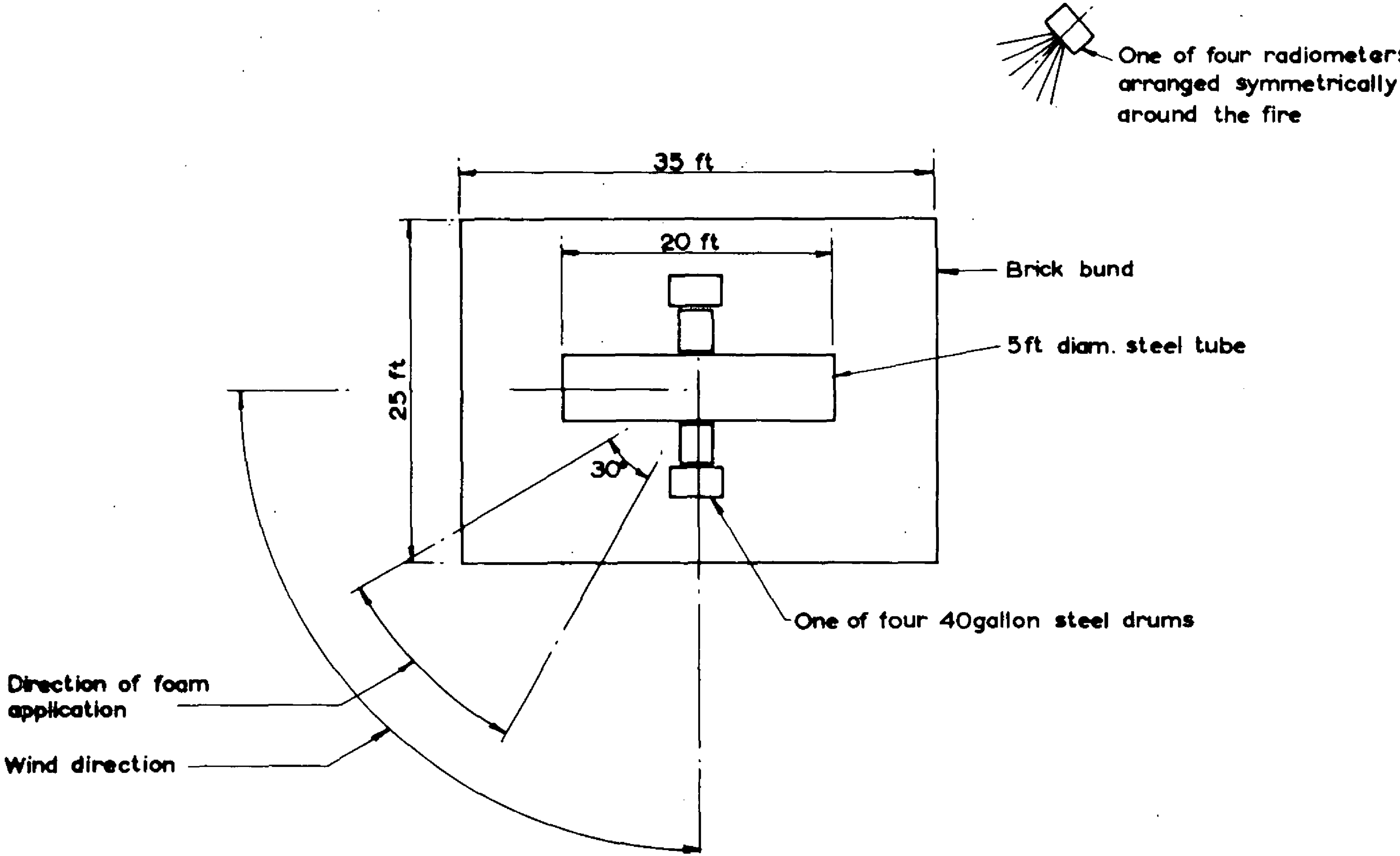

FIG. 5. J.F.R.O. AIRCRAFT FIRES, STANDARD TEST CONDITIONS

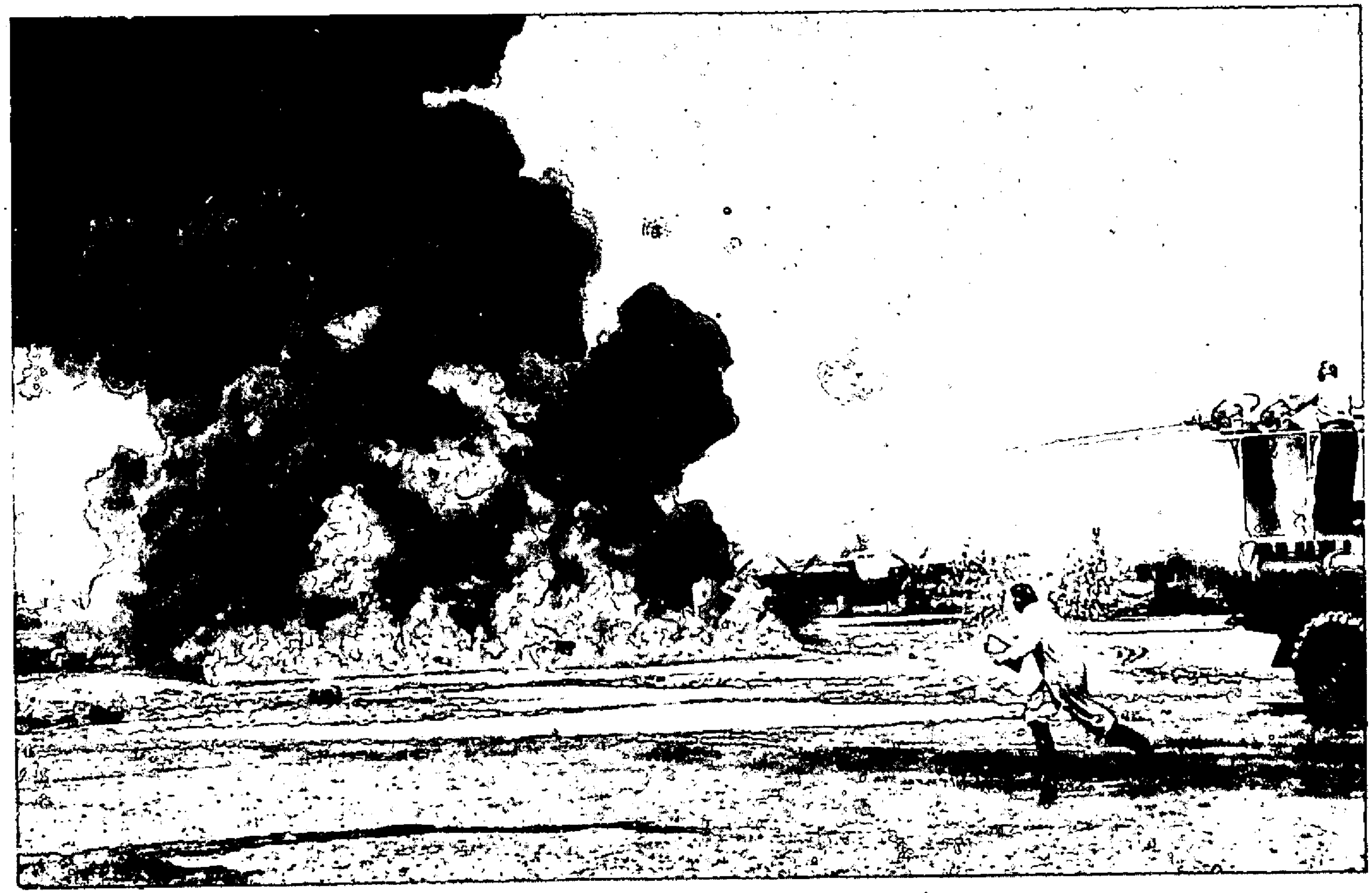

FIG. 6. TYPICAL J.F.R.O. SIMULATED AIRCRAFT FIRE

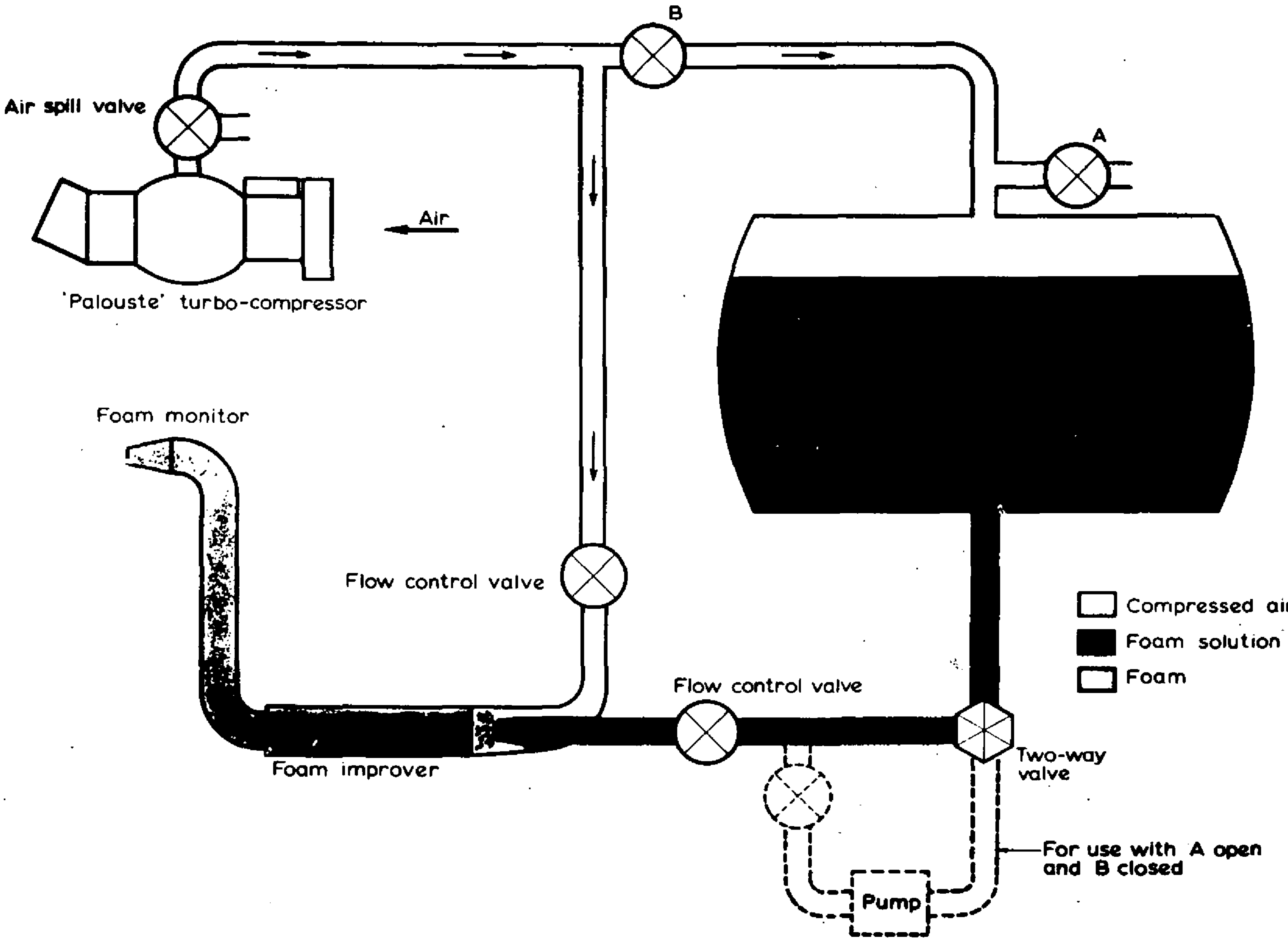

FIG. 7. FLOW DIAGRAM — GAS-TURBINE FOAM GENERATOR

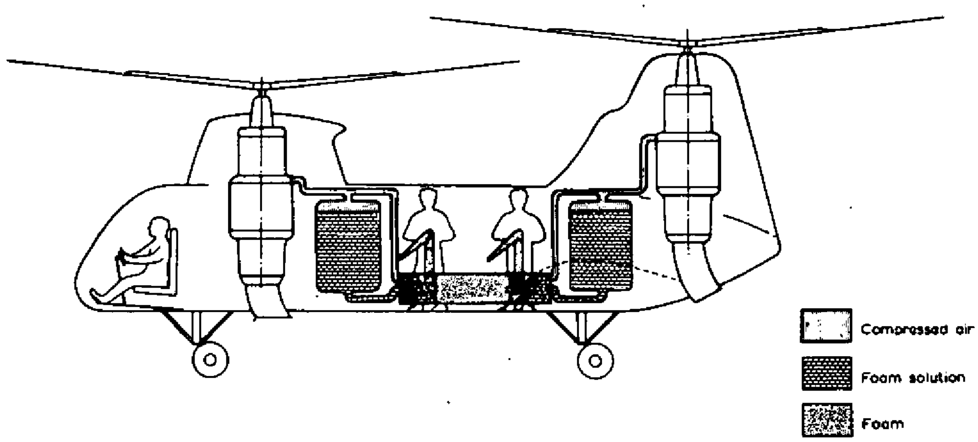

FIG. 8. APPLICATION OF FOAM GENERATOR TO TWIN-ROTOR HELICOPTER