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AN APPRAISAL OF THE POSTCRASH FIRE ENVIRONMENT

Neva B. Johnson, et al

Dynamic Science
Phoenix, Arizona

September 1969

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TECHNICAL REPORT

70-22-CE

AN APPRAISAL OF THE POSTCRASH FIRE ENVIRONMENT

by

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A Division of Marshall Industries
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Contract No. DAAG17-69-C-0115

Project Reference:
1J662708D504

Series: C&PLSEL-70

September 1969

Clothing and Personal Life Support Equipment Laboratory
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FOREWORD

This study was conducted under authority of AMCR 11-16, to appraise postcrash fire environment in helicopters and light aircraft and to define areas where further research is needed. Catastrophic ignition of fuel is a major casualty-producing factor in helicopter crashes. Increasing use of these aircraft for transportation, deployment, tactical and logistical support of troops may aggravate this problem.

The available data have been analyzed, and the scope of the additional effort required to obtain further essential data has been estimated. Particular consideration has been given to factors involved in personnel protection during escape from postcrash fires.

Information developed in this study is also applicable to civil and military aspects of aircrew training, safe aircraft design, and to the nature of crash injuries.

This investigation was performed by Dynamic Science (The AvSER Facility), a Division of Marshall Industries, under Contract No. DAAG-17-69-C-0115 and conducted under Project No. 1J662708D504, Individual Combat Protective Clothing and Equipment, Exploratory Development. Dr. John H. Cornell, research chemist, served as Project Officer.

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ABSTRACT

A program was conducted to define the postcrash fire environment for helicopters and light aircraft, and to recommend additional testing, where necessary, to elevate the state of fire knowledge to a useful level.

A thorough literature search indicated that man's survival in an aircraft crash fire is predicated on four main factors: (1) circumambient heat; (2) circumradiant heat; (3) toxic fumes; and (4) the obstruction to his vision. The magnitude of these factors, however, is dependent upon a variety of circumstances, including the degree of structural breakup, type of airframe structure, interior materials, and type of terrain surrounding the crash site.

A summary of all available data indicates that, while a great deal of knowledge does exist about fires, applying it meaningfully to the aircraft crash fire environment has only begun. Most fire test data found were for large transport-type aircraft. Some data were found for smaller aircraft; however, more data must be accumulated and analyzed before the small aircraft crash-fire environment can be defined.

AN APPRAISAL OF THE POSTCRASH FIRE ENVIRONMENT

Introduction

The majority of fatalities and injuries in light aircraft accidents occur in those accidents which involve postcrash fire. The U. S. Army's increasing use of helicopters and light aircraft makes the reduction of this high casualty rate imperative.

Protection of personnel during escape from postcrash fires requires a knowledge of the extent and intensity of the fire itself, as well as associated hazards such as toxic gases and lowered visibility due to smoke. Thirty-eight crash tests were conducted on small, medium, and large size aircraft, fixed- and rotary-wing, during the last eight years.* A fixed-wing aircraft crash test program was previously conducted in the mid-1950's and considerable data were compiled on postcrash fire environment.** In 1963, the Army crashed three light-observation helicopters at Ft. Rucker, Alabama, in an investigation of postcrash fire problems. Some work was also performed by the Federal Aviation Administration in 1956 when fuel distribution and potential ignition sources were studied.

The purpose of this study was to collect, validate, and analyze the above test data, as well as any other pertinent data available in the literature, about aircraft types presently in U. S. Army service. Further objectives were to define areas for future research based on this analysis and recommend a test program for carrying out this research.

An extensive literature survey was conducted to collect all information that would help define the postcrash fire environment in aircraft accidents. Since any measure of the fire threat ultimately is based upon an occupant's escape time, literature discussing human tolerance to the hazards present in the fire environment was also reviewed.

Most fire test data found were for large transport-type aircraft. These data are not directly applicable to Army helicopters and light airplanes. Because of the general similarities between all aircraft postcrash fires, however, these data have been presented in detail. Any dissimilarities which might be present in helicopters and light airplanes have been carefully pointed out.

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* Dynamic Science (The AvSER Facility)
** National Advisory Committee for Aeronautics

The results of the literature survey are presented in Part I. Part II analyzes the knowledge obtained during the literature search as it applies to Army aircraft. Areas requiring further research are also defined. Part III presents a recommended test program for future research.

I. DISCUSSION OF POSTCRASH FIRE ENVIRONMENT

A. Statistical Appraisal of Postcrash Fire Hazard

Accident statistics show that a high percentage of fatalities occur in aircraft crashes involving postcrash fire. This statement is true for all types of fixed-wing and rotary-wing aircraft. It would be logical to assume, however, that the degree of hazard is not the same for rotary- and fixed-wing aircraft or for large and small aircraft. Accident statistics support this assumption.

A summary of crash-fire and injury rates in helicopter accidents for the period 1952 through 1957[1] reveals that fire was experienced in 8.7 percent of rotary-wing accidents. However, this 8.7 percent of the accidents accounted for 60.4 percent of all fatalities. More recent statistics generated by the U. S. Army indicate that this high fatality rate in postcrash fire accidents is being maintained, if not increasing[2,3,4]. Table I lists the percentage of fire accidents and the percentage of fatalities due to these accidents.

Although the helicopter accidents involving postcrash fires are generally the more severe accidents, 72 percent of the fires erupted in crashes where the forces were within the limits of human survivability. Fifty-five percent of the fatalities in these accidents were attributed to thermal injuries.

Fixed-wing aircraft accident statistics involving fire are not as plentiful as those of helicopters. In a study by the U. S. Army of fixed-wing aircraft accidents between July 1957 and June 1960[5], it was found that 3.9 percent of the total accidents involved fire, but these accidents accounted for 37 percent of all the fatalities. Sixty percent of all thermal injuries experienced in these fixed-wing accidents were fatal.

Civil aircraft experience is very similar to that of the Army for small fixed-wing aircraft. Civil aircraft statistics for 1967 show that crash-fires occurred in 4 percent of the accidents, but these accidents accounted for 30 percent of all fatalities[6].

A comparison of U. S. Army rotary- and fixed-wing fire accident experience is given in Table II[7]. This comparison indicates that rotary-wing aircraft accidents are accompanied by fire more frequently and more severely than are those of fixed-wing aircraft.

TABLE I. HELICOPTER ACCIDENTS INVOLVING FIRE			
Dates	Percent Fire Accidents	Percent Fatalities In Fire Accidents	Report Reference
1952 - 1957	8.7	60.4	1
7/57 - 6/60	7.0	63.0	2
7/59 - 6/60	7.0	62.0	3
7/60 - 6/63	9.5		3
7/62 - 6/63	11.0	72.0	4
7/64 - 6/65	15.0		4

TABLE II. COMPARISON OF ARMY ROTARY-WING AND FIXED-WING AIRCRAFT ACCIDENTS INVOLVING FIRE, JULY 1957-JUNE 1960		
Item	Rotary-Wing (Percent)	Fixed-Wing (Percent)
Percent of major accidents with postcrash fire	7.0	3.9
Percent of personnel involved receiving thermal injuries	44.0	37.5
Percent of total fatalities occurring in postcrash fire accidents	63.0	35.0
Chances for survival if postcrash fire occurs	Decreased 22 times	Decreased 13.3 times

The fire statistics involving large U. S. air carriers show a somewhat lower fire-fatality rate. Out of 153 accidents involving fire which occurred from 1955 to 1964, 297 people, or 15 percent of the total fatalities, died as a direct result of the fire and its effects, while the rest died of impact injuries(8). A detailed study of eight of these accidents involving 221 fatalities indicated that all of these persons could have survived if fire had not occurred. This represents 41 percent out of the 45 percent of fatalities in these accidents(9).

B. Fire Environment

1. General Discussion

The postcrash fire environment in an aircraft consists of a combination of many interacting hazards. To better understand this environment and its effects on the occupant, these hazards must first be analyzed separately.

The main hazards of the fire environment which affect the occupant are:

- Heat
- Smoke
- Toxic gases

The magnitude and threat of each of these hazards varies from accident to accident and from aircraft to aircraft. Each of these hazards is discussed in the following sections, along with the particular factors affecting its magnitude. Where test data are lacking or incomplete, recourse has been made to actual accident records to help define the factors involved in the postcrash fire environment.

2. Heat

Temperatures recorded at various locations are a convenient measure of the fire environment. Unshielded thermocouples record the temperature caused by the combined effects of radiant heat from hot objects and from the flames themselves, as well as the heat from the ambient air around the thermocouples. Shielded thermocouples record only ambient air temperatures. Unless stated specifically in this discussion, all temperatures given will be those from unshielded thermocouples.

Temperature by itself, however, is not a complete measure of the fire threat. Temperature merely measures the

relative hotness or coldness of an object or atmosphere. The most important factor is the total amount of heat that is transmitted to the vicinity of the occupant. The amount of heat depends not only on the fire temperature but also on the size of the fire, its duration, and its proximity to the occupant. Factors which affect the magnitude of total heat are: (1) the type, quantity, and spillage rate of the fuel; (2) the type of terrain where the crash has occurred; (3) wind direction and velocity; and (4) the aircraft structure itself. Each of these factors will be discussed separately.

a. Fuel Type, Quantity, and Spillage Rate

A study of the temperature distribution within aircraft fuel fires contained in 12 by 24 ft. pans[10] has shown that the point of hottest temperature within the fire is in the center, between 30 and 50 inches above the surface of the fuel. The interior of the fire is hotter than the edges at all heights 18 in. or greater above the fuel surface. It was found that JP-4 aviation fuel burns with a slightly hotter flame temperature than 100/130 octane aviation gasoline. However, the degree of difference is minimal. Average fire temperatures found 30-50 inches above the surface were 1700°F for the JP-4 fuel as compared to 1500°F for the aviation gasoline. There was no difference in the average flame temperature of fires burning different quantities (800 and 1200 gallons) of the same fuel.

The quantity of fuel does influence the total amount of heat, however. The more fuel that is available to spread over a given area, the greater will be the size of the fire, and the total amount of heat will be proportionately greater. The spillage rate not only affects the quantity of fuel available, but also the spread of the fuel around the crashed aircraft. In this respect, then, the quantity and spillage rate definitely affect the magnitude of heat transmitted to the occupant.

Whether the type of fuel is really significant in the postcrash fire threat is still a matter of controversy. As stated above, the maximum temperature difference between aviation gasoline and JP-4 fuel fires is insignificant when comparing these high temperatures to man's low survival limits. The threat of the fire definitely depends, however, on its size, which is affected not only by the quantity and spillage rate, but by the burning rate of the fuel. Laboratory tests comparing flame spread rates of pooled fuels indicate that this rate is solely a function of fuel vapor pressure[11]. The burning rate, measured at a wind velocity of 4-1/2 mph and fuel temperatures in the ambient temperature range, was

800 fpm for gasoline as compared to only 35 fpm for low volatility fuel. This same trend has been observed in more recent studies[12,13]. The rate of flame spread was shown to vary with the fuel temperature, with Jet-A (kerosene) and JP-4 having the same flame spread rate of over 700 fpm when the fuel was above 180°F.

Perhaps a more meaningful laboratory comparison of JP-4 and Jet-A fuels is found in the fireball tests run by the U. S. Department of Interior, Bureau of Mines[13]. The fireball size was determined by dropping 5 pounds of fuel contained in a glass flask from 20 feet onto a concrete or asphalt surface. The fuel was ignited by a torch positioned near the point of impact that was removed after ignition. High-speed movies were used to measure the maximum fireball size at various intervals. The maximum fireball width for JP-4 was 19 feet compared to only 9.7 feet for Jet-A fuel. The maximum fireball height for JP-4 was 11.3 feet compared to 3.6 feet for the Jet-A. A comparison of thermal radiation data from this same test showed that the maximum radiation intensity from the JP-4 was 540 mw/sq cm within 10 seconds after ignition, as compared to only 50 mw/sq cm for the Jet-A fuel.

The meaningfulness of these laboratory tests in the actual crash-fire environment is still questionable. Tests conducted by NACA[14,15,16] have shown no differences in the history of crash fires involving low volatility fuels and those involving gasoline. Although the differences between the fuels might make a difference in ignition possibilities, there seems to be no difference once a crash fire has actually started. A detailed investigation of an Electra crash at LaGuardia Airport[17] substantiates this statement. Although it was speculated that the fire might have been more intense had aviation gasoline been present, rather than kerosene, this would have made no difference in the evacuation of the occupants because of the innumerable other factors involved in the total crash-fire environment. It must be concluded, therefore, that the difference in properties between kerosene and aviation gasoline are probably insignificant in the total crash-fire picture, and that, once the fire is started, it will be essentially the same regardless of which fuel is present.

The NACA crash tests, as well as later tests conducted by Dynamic Science, have shown that the flame spread rate through fuel mist is considerably greater than that over the surface of liquid fuel. Pinkel et al.[14] found that fire can spread through fuel mist with a lineal flame propagation speed up to approximately 70 fps, while the flame spread rate of the spilled fuel was measured at approximately 13 fps. This high speed of propagation through the mist is provided in part by the rapid expansion of the burning atmosphere of fuel,

mist, and air. If considerable mist is present when ignition occurs, the heat released from its combustion often represents most of the total heat released in the early phase of the fire. The fuel mist seldom persists more than 20 seconds, and the heat radiated dissipates rapidly as the mist rises.

b. Terrain

The type of soil, slope of the ground, and flora present in the impact area affect the size and location of the fire by modifying the quantity of fuel available and the area over which the fuel is spread. For instance, impacting upon sandy, loose soil would allow any spilled fuel to soak into the ground, isolating the bulk of it from the aircraft, whereas landing on a non-porous surface, such as cement, would allow the fuel either to puddle under the aircraft or spread around the aircraft. The same considerations apply to the slope of the terrain. If the slope is steep, the fuel will run either under the aircraft or away from it, depending on the spillage area and the aircraft position. The type of flora around the aircraft will determine whether the fire is magnified by burning plants and grasses[4]. In one Army helicopter accident, the helicopter rolled over following a hard landing and one of the fuel tanks struck the ground, producing two slit-like ruptures. Minimal leakage occurred because the aircraft was practically out of fuel. However, a small exhaust stack fire followed, igniting dry grass beneath the helicopter.

c. Wind Direction and Velocity

The wind velocity has a direct bearing on the flame spread rate of spilled fuel. A study conducted by NACA[11] indicates that the flame spread rate is drastically reduced if the fuel is burning against the wind. While the flame spread rate of gasoline with the wind was 800 fpm, it was only 400 fpm against the wind. This ratio would be expected to vary, however, depending on the wind velocity.

The wind direction greatly affects the fire pattern around the aircraft. This, in turn, affects escape paths available to the occupants. Actual accidents have shown that the wind direction and velocity were factors in escape. In the LaGuardia Airport Electra crash discussed earlier, the wind was blowing at 23 mph and almost in line with the fuselage, blowing the fire away from the exits at the rear of the fuselage. In a Boeing 727 crash at Salt Lake City, one of the reasons the occupants in the tail were able to survive was that the tail of the airplane swung around into the wind, which helped keep the flames away from this section of the aircraft[18].

Even with identical wind conditions, crash tests conducted by NACA[15] have shown that the resultant escape paths can be extensively modified by other variables. An example of this effect was shown in comparing the escape avenues for two crashes in which the wind and terrain conditions were similar. The escape avenue for one crash was toward the right front, while for the second crash escape was possible from either side of the rear end of the airplane, both upwind and downwind.

d. Aircraft Structure

(1) Burn-Through Time

The amount of heat that is transmitted to an occupant depends upon the structural integrity of the aircraft after the crash. As long as the fire is completely outside the fuselage, the fuselage will reflect a great deal of the radiant heat, keeping it from the occupants. However, if flames are in direct contact with the fuselage wall, fuselage burn-through is a certainty. Once burn-through has occurred, the radiant heat is more readily transmitted to the occupants. The increase in cabin temperature in some crashed and burning passenger/cargo fixed-wing aircraft is shown in Figure 1. The rapid rise in the radiant temperature corresponds to the average burn-through time of 80 seconds[19].

As with other factors present in the crash environment, burn-through times will vary with different skin thicknesses and crash conditions. In a fire test made on a typical transport configuration with a .035-inch-thick fuselage skin, burn-through occurred in 63 seconds[20]. Test data obtained by Dynamic Science on four crashed helicopters indicate the burn-through time of the fuselage wall was only 20-35 seconds[21].

> "This very rapid burn-through time is probably attributable to the fact that the spillage pattern resulted in flames coming into direct contact with the fuselage wall and because of the very thin materials used as helicopter fuselage skin."

In the NACA test series[15], a fuselage skin burn-through occurred in only 7.5 seconds when there was direct contact between flame and fuselage while the airplane was sliding to a stop.

The type of construction also has an effect on the burn-through time. In order to compare the burn-through times of insulated and uninsulated walls, two

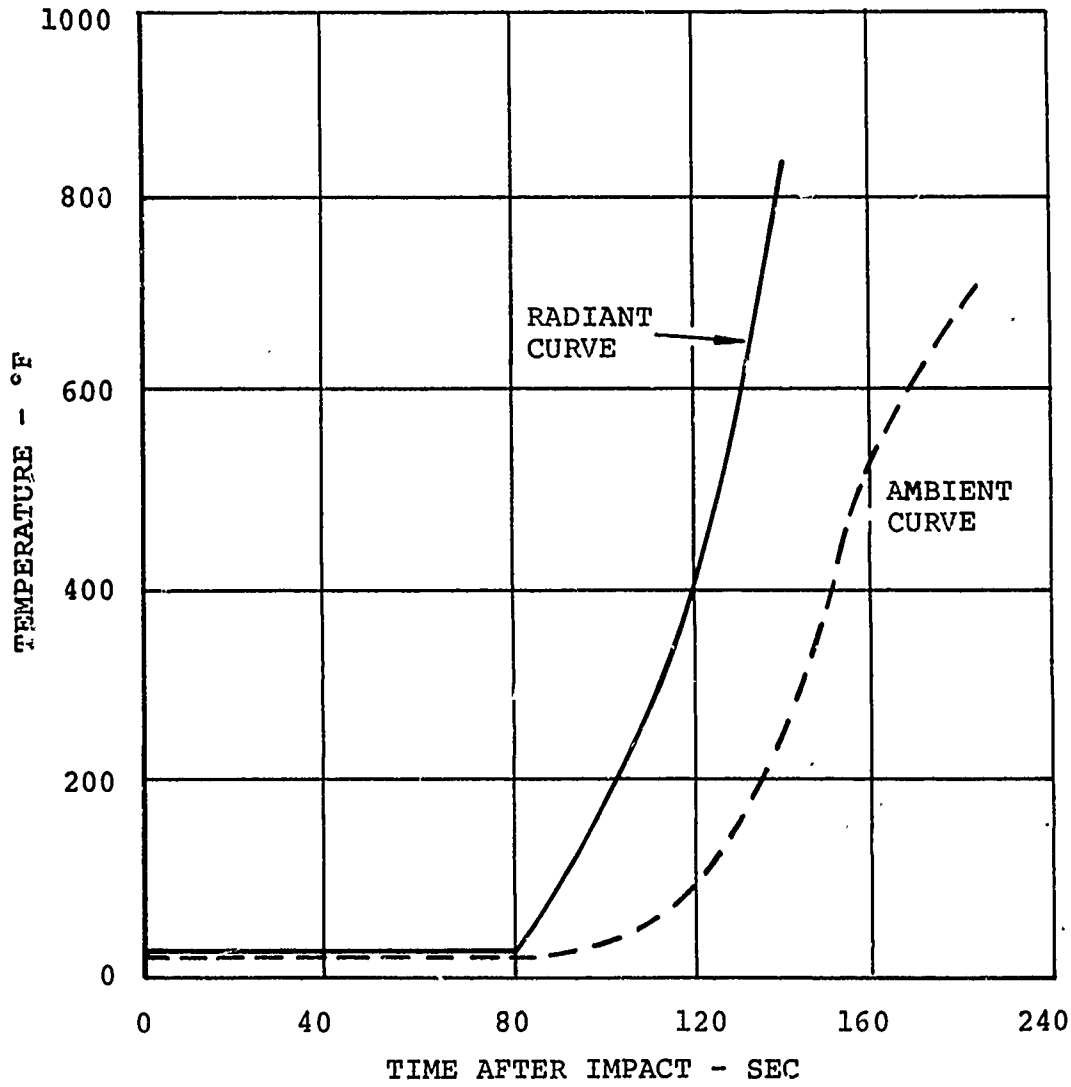


Figure 1. Average Recorded Ambient and Radiant Temperatures in Various Compartments of Several Crashed, Burning Passenger/Cargo Fixed-Wing Aircraft.

identical enclosures, one uninsulated and the other provided with two inches of glass wool insulation, were subjected to fuel fires[15]. The test results showed that the insulated enclosure burned through completely in 7.5 minutes, while the uninsulated enclosure burned through 12 minutes after the test was started. Although these times are not necessarily applicable to an actual crash, the comparison between the burn-through times is applicable. The uninsulated skin melted away more slowly because the heat from the fire could re-radiate from the opposite skin surface; this was impossible with the insulation present. This same mechanism probably accounts for the burn-through rate differences between sheet aluminum skin and honeycomb aluminum skin. Although no actual test data are available, visual observations have noted that the honeycomb burns through faster than the sheet aluminum.

(2) Interior Materials

Once skin burn-through occurs, the fire is free to enter the interior of the aircraft and the cabin interior materials become important in propagating the fire. In an extensive series of tests conducted on aircraft cabin interior materials by the FAA[22,23,24], it was found that the most important factor affecting the fire hazard inside the cabin was the flammability of the materials. Laboratory tests of over 100 materials established that the majority were self-extinguishing once the flame was removed. It was also discovered, however, that materials at elevated temperatures are much more flammable than indicated by the standard Bunsen burner tests run under normal ambient conditions. The tests indicated that the new high-temperature plastics containing flame-retardant additives are much more fire-resistant than the natural fibers, such as wool and leather, or even the earlier plastics used in aircraft cabins. The use of a fiberglass covering material to protect more flammable underlying material, such as foam padding, was found effective in reducing the extent of the fire damage.

In large-scale fire tests it was discovered that the more flammable interior materials used in passenger cabins can produce a flash fire with little or no warning[23]. In one such fire, the rate of flame propagation was estimated at 68 fpm. Damage to the interior of the cabin by the flash fire was extensive, with most damaged areas occurring above the window level, especially along the ceiling. Occurrence of the flash fire was accompanied by a rapid increase in flame propagation, smoke density, temperature, air pressure, carbon monoxide, and oxygen depletion.

(3) Structural Breakup

Openings in the fuselage, such as might occur because of structural breakup, allow air and radiant heat to enter the aircraft interior, regardless of whether the fire itself has a chance to enter. The effect of fresh air on the burning rate of an interior fire was demonstrated in a fire test[23]. A violent flash fire occurred just after fresh air had been admitted to a cabin containing a smoldering fire. In tests of postcrash fire-fighting on transport category aircraft[25], it was noted that the radiant heat intensity from a fuel fire located next to fuselage openings was of sufficient strength to cause interior materials to ignite, resulting in a flash fire within the passenger cabin. These tests showed that the escape time (as measured by the cabin temperature) with the emergency doors open was less than half the escape time with the doors closed. It was concluded that:

> "The chance of surviving a crash involving fire in which the fuselage is broken open from impact or where openings exist in the fuselage is less than for an intact or relatively closed fuselage."

e. Aircraft Configuration

The configuration of the aircraft, whether fixed-wing or rotary-wing, and whether large or small, also definitely influences the crash-fire environment. This has been established by studies of detailed accident reports as well as by instrumented full-scale crash tests. Factors affecting the environment include: (1) the location of the fuel in relation to the occupiable area; (2) the typical crash forces and attitudes of the different aircraft; (3) the typical structural deformation; and (4) the varying fuel spillage patterns noted in the different aircraft.

(1) Transports

This literature survey found more information, both in detailed accident reports and in full-scale crash tests, for transport category aircraft than for any other type. The classic full-scale crash tests run by NACA in the early 1950's[14,15] were highly instrumented and very fruitful in their discoveries.

The crashes in the NACA series were designed to simulate takeoff accidents in which the airplane fails to become airborne, strikes an embankment, shears off propeller(s) and landing gear, strikes trees or poles, ruptures fuel tanks, then slides along the ground to a standstill.

The tests thus contained elements for a very severe fire hazard, although they were considered survivable for the majority of occupants from an impact standpoint[26].

The general development pattern of crash fires that evolved from the NACA tests shows that the fuel mist ignites first and spreads flames rapidly. In the first few seconds following ignition, the fire also propagates through all the fuel spilled previous to the ignition, which burns rapidly. As the spilled fuel is consumed, the fire begins to die down. From this point on the fire continues to burn by feeding on fuel draining from damaged fuel tanks, oil from the lubricating system, hydraulic fluids, and the aluminum skin structure. The fire reaches several secondary peaks. The first is reached when fuel spillage increases by fire enlarging the fuel tank opening or opening undamaged tanks. The second peak comes when the fire burns through the fuselage skin and gets to the combustibles within. The fuselage fire attains its peak when a large hole burns through the skin near the top, creating a chimney effect.

A characteristic ground-wetting pattern for both high-wing and low-wing transports was discovered. The fuel trail was composed of two separate bands, one for each wing, which tended to broaden and finally coalesced in the neighborhood of the aircraft. In general, the inertia of the fuel carried it forward of the airplane rest point. The volume of fuel mist generated with a given rate of fuel spillage was greater for the high-winged planes, because the fuel of the low-wing aircraft was intercepted by the ground before appreciable atomization occurred. In the low-wing aircraft, the fuel swept forward from the wing leading edge, fanning out on the ground, and attaining significant spanwise extension in liquid form. Most of these crashes, therefore, resulted in severe fire environments.

Ignition times were quite rapid, ranging from 1/2 to four seconds in most cases. The flame spread was also rapid, even after the mist fire had died down. There was, however, some time lag between the start and development of the fire and a rise in cabin temperatures. The average temperatures (Figure 1) did not begin to rise until skin burn-through took place in approximately 80 seconds. Although the fuel mist ignited and large mist fires developed, these fires burned away in 15-20 seconds. Because the mist fires rose away from the airplane and burned out in a few seconds, ambient and radiant temperatures inside the fuselage did not increase.

Although these tests were conducted on reciprocating engine aircraft, later tests conducted on turbojet aircraft[16] showed that, once the fire was started, it was basically the same as the fires of reciprocating engine aircraft. Ignition times on the turbojets were approximately 2.6 seconds after initial impact, with the whole wing being engulfed at the end of four seconds.

A more recent full-scale test on a DC-7 aircraft[27] showed substantially the same type of spillage pattern that was found in the NACA tests. The left wing completely separated from the fuselage during this crash, but the fuel spillage patterns from the right wing tanks were thoroughly studied. Although there was only a small quantity of fuel on the aircraft, the main tanks being filled with colored water, a fire ignited in the fluid mist occurring from the ruptured fuel and oil lines when the engines tore free during impact. The conclusion reached was:

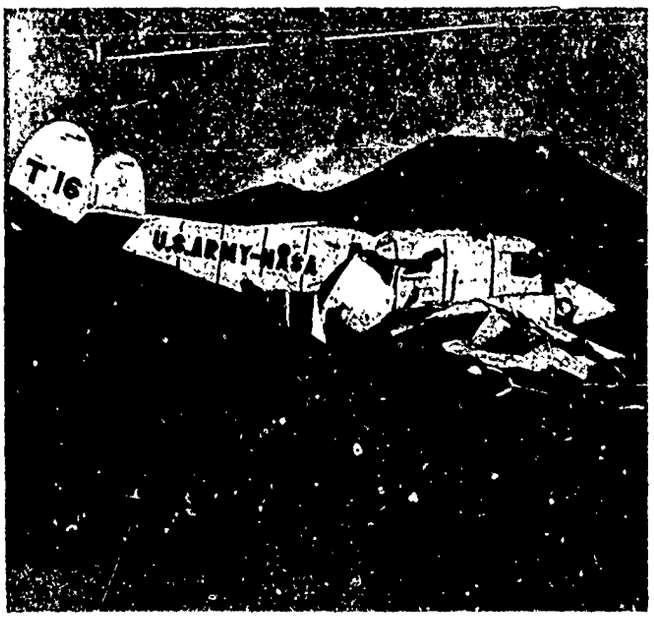
> "The ignition potential of reciprocating engines is such that any release of either fuel or oil during a crash to the extent experienced in this crash may be expected to result in an immediate fire."

Also, the fuel spillage and spray pattern which surrounded the aircraft, both while it was in motion and after it came to rest, should be similar for any aircraft with fuel tanks and structure similar to the DC-7.

(2) Small Multi-Engine, Fixed-Wing Aircraft

Tests run on smaller fixed-wing aircraft (C-45's) indicate that the crash fire environment might be more severe for smaller aircraft[28,29]. Two postcrash views of structural damage occurring during test crashes are shown in Figure 2. Notice that the wings have been torn free from the aircraft but are still in close proximity to the fuselage, thus indicating that a severe postcrash fire could develop.

The structural breakup and the fuel spillage pattern of another C-45 test is shown schematically in Figure 3. In this test the fuel ignited two seconds after impact and the aircraft was enveloped in flames one second later. Figure 4 gives the average time history of the temperatures within the cockpit and cabin of this aircraft during the postcrash fire. By comparing Figure 1 with Figure 4, it may be seen that the temperatures rose more quickly in the smaller C-45 than in the larger transport-type aircraft. The difference in the fire environment between the larger and smaller planes is undoubtedly due to the difference in metal



Damage To Right Side of Test Aircraft

Damage To Left Side of Test Aircraft

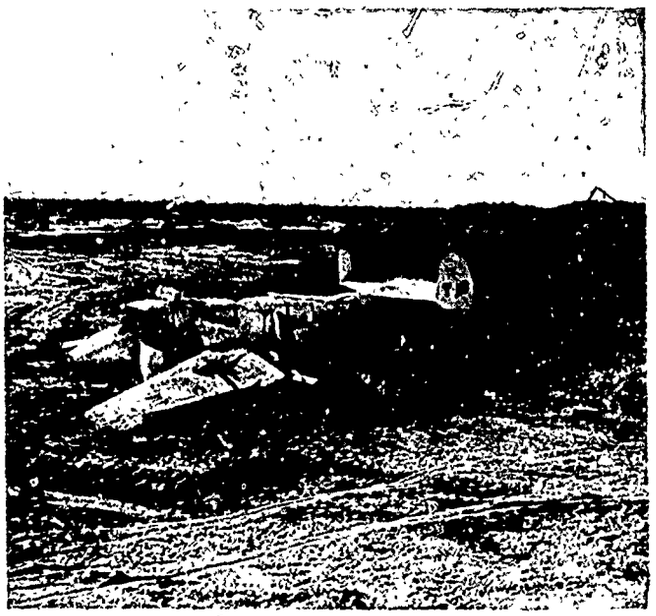


Figure 2. Posttest Position of C-45 Aircraft After Impacting and Passing Over Barriers.

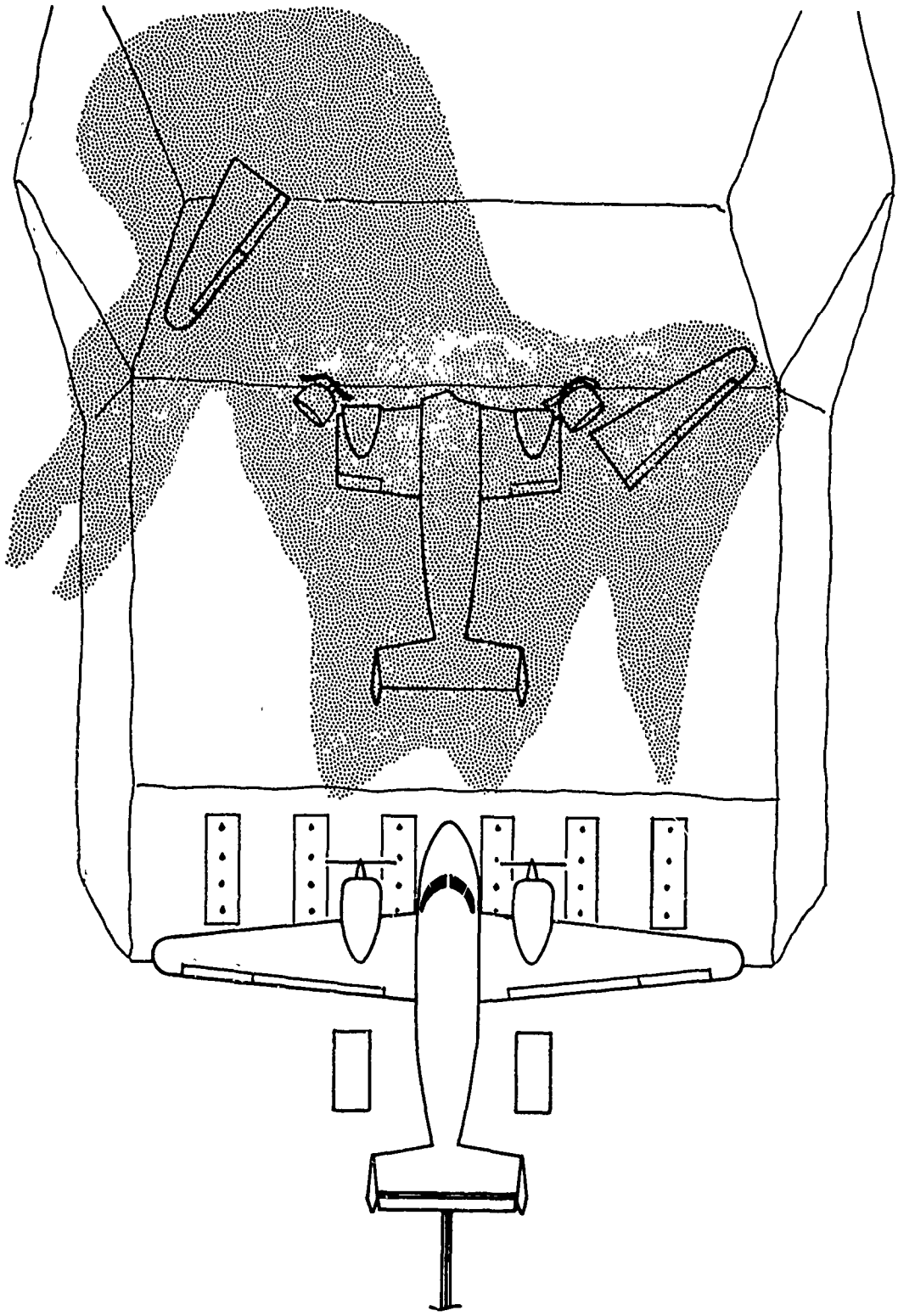
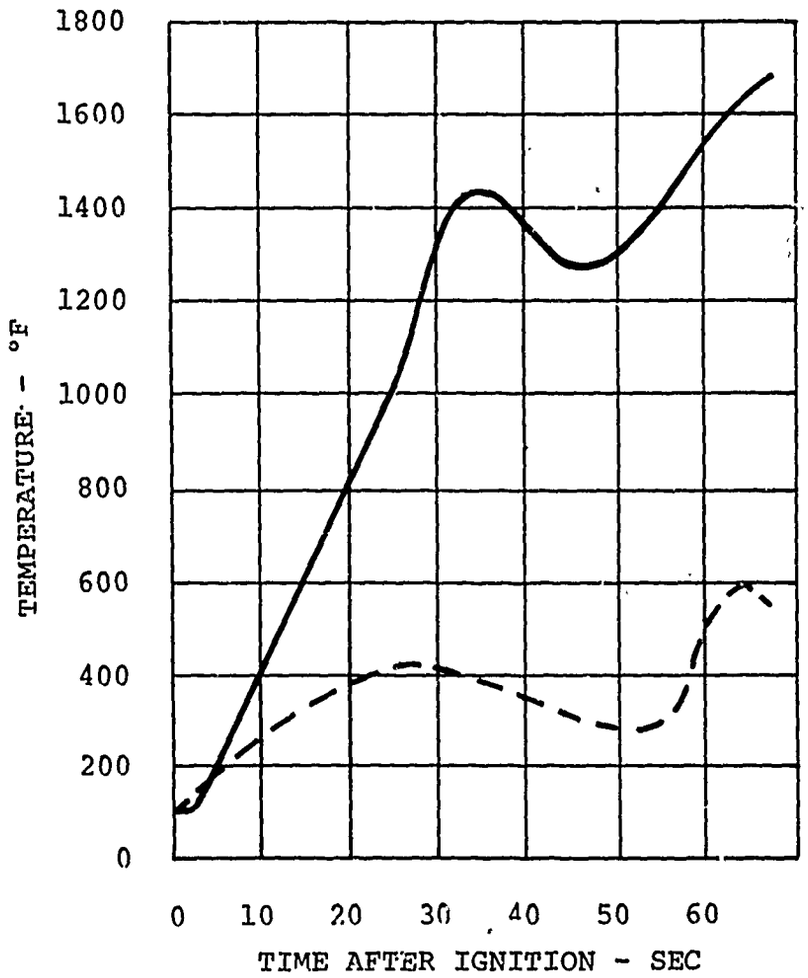


Figure 3. Fuel Spillage Pattern of Crashed C-45.



——— Average Temperature of Roof Thermocouples in the Cabin and Cockpit.

– – – Average Temperature of Floor Thermocouples in the Cabin and Cockpit

Figure 4. Recorded Temperatures in Crashed, Burning C-45.

skin thickness and the closer proximity of the occupiable area to the fuel tanks in the smaller planes.

(3) Small Single-Engine, Fixed-Wing Aircraft

The statistics cited in Section I.A. show that the postcrash fire is a very significant hazard in crashes of small fixed-wing aircraft such as the O-1 and U-6. However, very little data are available on crashes of this type of aircraft. The only crash tests that have been performed were conducted by NACA in 1953[30]. These crashes were designed to simulate the stall-spin accidents common to light airplanes. The main purpose of the tests was to study acceleration levels during crash impact. The fuel tank was filled in only one of the tests, with dyed water to prevent the possibility of postcrash fire. The fuel spread pattern of this crash revealed a heavy concentration of fuel around the engine, throughout the cabin, and over approximately 66 percent of the under-surface of the right wing. Medium to light concentrations were observed over the entire rear fuselage and around the fuselage and tail. The report[30] concluded that:

> "The fuel spillage within the passenger compartment and on both dummies, if ignited, would have completely inflamed their clothing. In the two crashes in which a dummy was installed in the front seat, the manner in which its foot was pinned in the wreckage indicates that, if fire were to occur, a human occupant in the same position would experience extreme difficulty in extricating himself before fire enveloped the entire airplane."

The relevance of this crash to the present-day problem is somewhat questionable because the fuel tank was located in the fuselage between the cockpit area and the engine. Most light airplanes now in use contain the fuel in the wings. The postcrash fire threat is still quite pronounced, however. A report of an Army O-1 aircraft accident[31] showed that fire enveloped the aircraft immediately after it stopped. This was not a typical accident in that the wing and roof structure separated from the fuselage during impact. This was probably of benefit to the occupants, however, because of the severity of the fire. It is doubtful whether they would have had time to evacuate the aircraft had they not been thrown through the opening where the wing and roof structure had separated.

To help define the postcrash fire environment in light aircraft, 280 selected accident reports were reviewed at the Bureau of Aviation Safety, Washington, D.C.

These accidents were selected from over 900 light aircraft crashes occurring between 1964 and 1967 that resulted in post-crash fires. The accidents were selected on the basis of impact survivability and, of the 128 accident reports containing sufficient fire data to be useful, 87 percent reported at least one survivor.

Data from the above survey provided general information on fire ignition times, fire intensity, and fire locations. A typical small fixed-wing airplane fire pattern emerged in which the cockpit/cabin area was completely gutted or consumed by the fire. This occurred in approximately 80 percent of the accidents. The severe intensity of the fire could be inferred from the complete destruction of the cockpit/cabin structure, as well as from the lack of smoke traces on unburned portions of the fuselage and wings.

In the majority of these accidents, the postcrash fires erupted on or immediately after impact. These rapid ignition times, coupled with the location and intensity of the fires, would account for the high rate of fire injuries and deaths noted in the accident statistics discussed in Section I.A.

(4) Helicopters

The crash-fire environment in a helicopter accident differs significantly from that in the larger fixed-wing aircraft accidents. This is to be expected for several reasons. A helicopter behaves quite differently than a fixed-wing airplane during a crash. Fixed-wing aircraft crashes generally have a dominant forward component in contrast with the high vertical and lateral forces generated in helicopter crashes. In addition to this difference, the fuel in most fixed-wing aircraft is carried outside the fuselage in the wings. In the majority of helicopters the fuel is contained within the fuselage in close proximity to the occupiable area. Many of the fuel tanks in helicopters are installed near the bottom of the fuselage, which is subjected to high forces during impact. The probability of the fuel cells rupturing in helicopter accidents is therefore quite high. Statistics have shown that 90 percent of the fires in helicopter accidents occur on or immediately after the initial impact during the crash sequence[4].

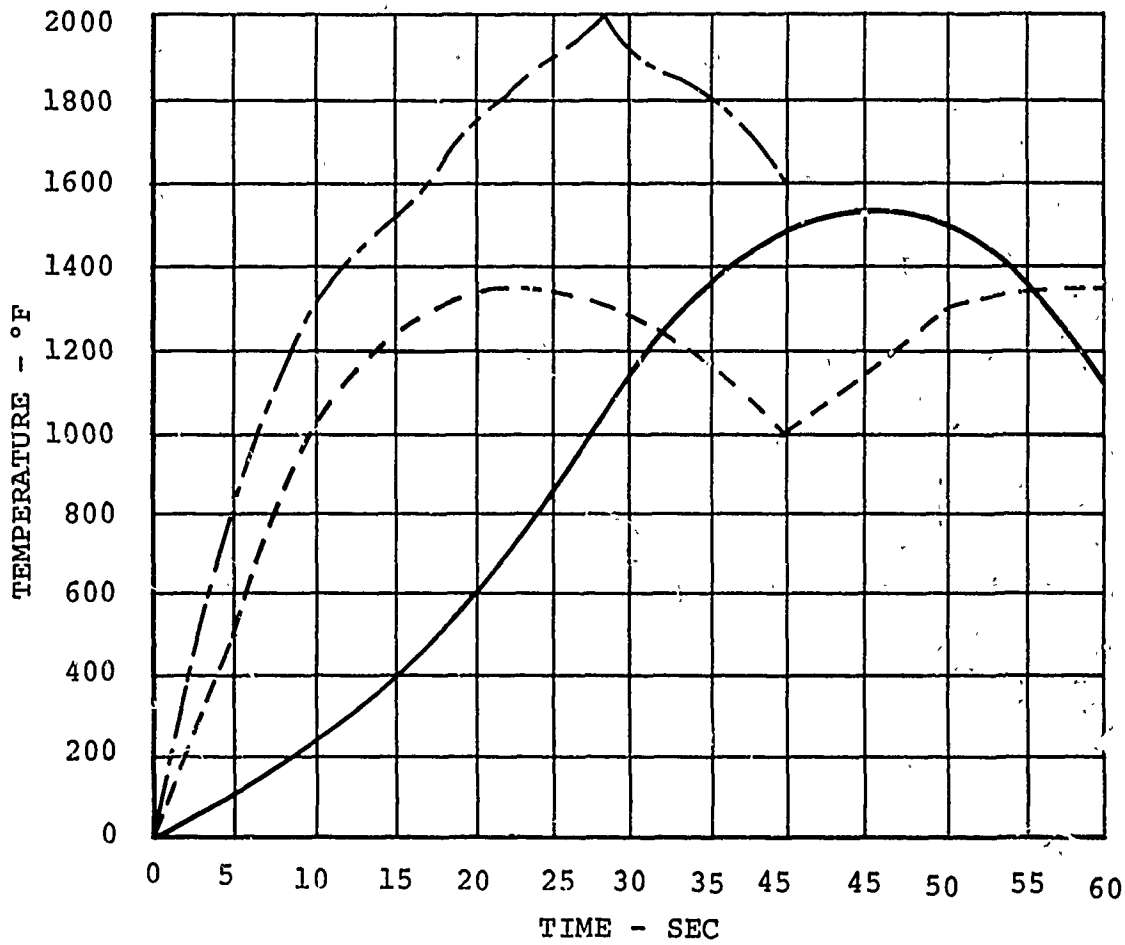
A continuing series of helicopter crash tests has been conducted by Dynamic Science[21,29,32,33,34,35]. Many of these tests involved fires. In cases where no fires were desired, fuel spillage patterns were obtained by using dyed water in the fuel tanks. These tests documented the fuel

tank failures which occur during helicopter accidents. The predominant fuel spillage pattern occurs around and immediately underneath the helicopter fuselage, thus making the fire threat to the occupant very high. On the basis of these crash tests, evidence has been obtained that time-to-ignition for accidents specified as survivable may be as little as 0.2 second, since massive fuel spillage has been observed in this length of time. In those tests where ignition took place after the initial crash impact, ignition occurred 1 to 2-1/2 seconds after impact.

The severity of postcrash fires in helicopters may be seen from the time-temperature curves obtained in these crash tests. In one series of tests, four cargo-type helicopters, with colored water in the fuel tanks, were crashed to obtain the fuel spillage patterns. After these crashes, fuel was distributed in the same spillage pattern and ignited. Temperatures were recorded inside the helicopters by shielded thermocouples, thus giving ambient air temperatures. These average recorded temperatures are shown in Figure 5. In Figure 5 zero time denotes the start of the fire, and crashes involving external and/or internal fuel spillage are plotted separately. As may be seen from the graph, the fire environment is more hazardous with internal and external spillage than with external spillage only, as the rapid rise in temperature severely limits the escape time of the occupant.

One crash-fire test was conducted with a small observation type helicopter. Unshielded thermocouple readings for this test are also shown in Figure 5. Internal spillage was evident and helps account for the rapid rise in temperature inside the occupiable area. The higher recorded temperatures for this test, as compared with the cargo helicopter test in which internal spillage occurred, could be due to several factors. The cargo helicopter test recorded ambient temperatures only, whereas the observation helicopter test temperatures are ambient, radiant, and flame temperatures combined. One would expect the fire environment to be more severe for the smaller helicopter due to the close proximity of the fuel to the cockpit. However, because similar temperature sources were not measured in each test, direct comparison of the test data is questionable. As with the other times plotted in Figure 5, the time versus temperature distribution is recorded from the moment of fire ignition, not impact. Ignition in this test occurred 2.2 seconds after initial impact.

The respective locations of the occupiable area and the fuel tanks must be taken into consideration when judging the fire environment that will be present in any



Average Recorded Ambient Temperature in the Cabin Area of Four Burning Passenger/Cargo Type Helicopters, External Spillage Only (From Reference 21).

Recorded Ambient Temperature in the Cabin Area of a Burning Passenger/Cargo Type Helicopter, Internal and External Spillage (From Reference 21).

Recorded Radiant and Ambient Temperature in the Cockpit Area of a Burning Observation Type Helicopter, Internal and External Spillage (From Reference 29).

Figure 5. Time-Temperature Curves of Crashed, Burning Helicopters.

helicopter. This fact can be illustrated by analyzing the arrangement of the OH-13 helicopter, in which the fuel tanks are mounted outside of the fuselage but above and directly behind the cockpit area. In one series of tests conducted with these aircraft[36], a test helicopter was crashed in a manner to insure that the crash forces would be entirely within human tolerance. However, this crash was determined to be nonsurvivable due to the catastrophic fire which developed upon impact. The relatively high fire-injury record of the OH-13[4], which accounted for 38 percent of the postcrash fire accidents over an eight year period, points out the undesirability of the fuel being located above and adjacent to the cockpit. A typical accident report[4] is as follows:

> "When the aircraft fell over, the bubble broke and the right tank ruptured releasing fuel which ignited on the hot manifold. It then spilled into the cockpit seating area. The spray of burning fuel on the pilot's face, hands, and clothes continued to burn as he exited through the shattered plexiglass..."

It is obvious, then, that any consideration of the fire environment in helicopters must specify the configuration of the helicopter.

3. Smoke

a. General

Aircraft crash-fires generate great quantities of dense smoke consisting of unburned particles of carbon, ash, and gaseous combustion products. In this report, smoke will be considered strictly as the unburned solids, and gaseous combustion products will be discussed as toxic gases.

The first effect of smoke is to obscure vision. Bieberdorf and Yuill, in their investigation of building fires[37], made the following statement:

> "In summary, the preponderance of informed opinion appears to be that the initial hazard of smoke is related to visibility and, to a lesser extent, to panic."

There is no reason to suspect that the effects of smoke in aircraft fires would be any different from those in building fires. Only the amounts and types of smoke generated would be expected to vary.

b. Sources of Crash-Induced Smoke

The smoke during an aircraft postcrash fire is generated from the burning of fuel, oil, hydraulic fluid, and interior materials. Because of the diversity and number of different materials used in aircraft interiors, the FAA ran an extensive series of tests to determine the amount of smoke generated by each of these materials[22,23,24]. These studies revealed that the smoke factor generally increased with increasing thickness and weight of the material as well as with increasing flammability. Many of the plastic materials exhibited both heavy smoke and acrid odors. Vinyl-coated fabrics showed smoke factors twice those of uncoated fabrics. Materials containing vinyls or other plastics produced greater quantities of smoke than did cellulose-derived materials of the same flammability range. Subsequent tests by the National Bureau of Standards[38] revealed that sheets, films, and laminates had a much higher smoke density than did fabrics.

c. Smoke Distribution within Occupiable Areas

Although the measurement of smoke is not difficult, the correlation between smoke densities and actual subjective hazards is not well defined. The National Bureau of Standards study was concerned with the problem of measuring the optical density of smoke as it relates to the obscuration of human vision. An attempt was made to relate the specific optical density of smoke obtained in laboratory tests to cabin volumes and surface areas to provide guidelines for cabin area limitations or to estimate time periods available for escape or defensive action. The study emphasized, however, that additional experimental verification should be provided before smoke hazard limits could be set for interior materials. Another limiting factor was that no attempt was made to evaluate complications due to eye irritations, to respiratory effects from inhaled smoke particles, or to hysteria or associated physiological or psychological factors.

Because of the complications in correlating laboratory tests with actual conditions, the only way to assess the value of smoke hazards thoroughly is from actual crash tests or from survivor's accounts of aircraft accidents. In fire tests using a large transport passenger cabin as a test article, it was concluded the

> "Smoke during the early part of the fire would likely be sufficient to cause serious discomfort and panic before the more serious effects of carbon monoxide and heat were felt."[23]

In another full-scale fire test conducted on an unventilated simulated aircraft passenger cabin[20], stratification of the smoke inside the cabin was quite pronounced. A smoke detector only six inches from the ceiling showed smoke saturation, while at the same time a detector 14 inches lower indicated only 30 percent saturation. These smoke densities were measured 2-3/4 minutes after ignition.

In building fires, the amount of smoke in a given area and the time within which the smoke reaches a particular density varies markedly with the structure and with conditions which affect the fire size and velocity. Although no test data are available on similar conditions in aircraft fires, the same effects should be noticed. In referring to actual accident reports, one can see some of these effects. In the Boeing 727 accident in Salt Lake City, in which fire occurred inside the aircraft immediately after impact, survivors complained of the dense smoke obscuring their vision and making breathing difficult from the very beginning of the fire[18]. In another aircraft accident[39], smoke was present inside the fuselage before any fire entered the cabin area. As soon as the exits were opened, dense smoke began to funnel back through the entire cabin, making sight and breathing extremely difficult.

4. Toxic Gases

a. Gases Generated in the Crash-Fire Environment

The generation of toxic gases during a fire is a well-known phenomenon and has been studied fairly extensively in building fires[37]. The most common products of combustion when any organic material is burned are carbon monoxide and carbon dioxide. The ratio of these two gases produced depends upon the oxygen supply. A limited oxygen supply will give a much higher percentage of carbon monoxide than a plentiful supply. Thus, the conditions present during a fire determine, to a large extent, the kind of gases produced. The many variables which can influence the oxygen supply make it difficult to predict the relative amounts of carbon monoxide and carbon dioxide. Testing must be done under varying conditions to arrive at some conclusion as to the relative amounts of these gases which may be expected during any postcrash fire.

Several other toxic gases may also be generated, depending on the material being burned. These gases, although not generated in the same amounts as carbon monoxide, must nevertheless be considered a threat because of their high toxicity to human beings. The results of some laboratory burn

tests conducted by Marcy[23] are summarized in Table III. Most samples that were studied generated significant amounts of at least three other toxic gases in addition to carbon dioxide and carbon monoxide. In another extensive series of laboratory burn tests run by Gross[38], it was noted that carbon monoxide was produced by almost all of the samples in varying amounts, depending on the type of material. In addition, hydrogen chloride was produced by polyvinylfluoride and modacrylic materials; hydrogen fluoride from polyvinylfluoride; hydrogen cyanide from wool, urethane, acrylonitrile-butadiene-styrene resins (ABS), and modacrylics; and sulfur dioxide from polysulfone and rubber materials. Hydrogen sulfide is also generated in significant quantities during the burning of wood, wool, and rubber insulation[37].

b. Gas Concentrations

It is impossible to compare quantitatively the studies mentioned above because of the varying test conditions and sample sizes. Gross[38] has pointed out that the amount of a given gas produced during pyrolysis and its rate of generation are strongly temperature-dependent. He found that the majority of materials produced more smoke and toxic gases under active flaming conditions than under smoldering conditions, although certain materials produced significantly more smoke in the absence of open flaming. Gas concentrations from the laboratory burn tests were scaled up to large volume areas comparable to those found in aircraft cabins. However, as Gross points out, such scaled estimates assume similar or uniform distribution of the gaseous components and also neglect large differences which may result in the case of active gases and vapors which tend to be absorbed on surfaces.

Roebuck[40] has combined Marcy's data and appropriate short-term exposure limits into the form shown in Table IV. This table shows the amounts of various materials which can be burned safely in one cubic meter of space and also gives the limiting smoke constituent. Although these weights should not be taken as absolute because of the reasons pointed out above, they do give valid comparisons between the different materials. This table shows that the most common smoke constituent to create a toxic hazard is carbon monoxide, although, in some cases, chlorine, hydrogen cyanide, hydrochloric acid, or hydrobromic acid are the limiting constituents.

Although the above discussion points out the need for determining toxic gases during actual crash-fire conditions, only limited data have been obtained in this manner. During fire tests conducted inside an aircraft cabin,

TABLE III. CONTAMINANTS PRODUCED BY COMBUSTION

(MILLIGRAMS OF CONTAMINANT PRODUCED BY THE COMBUSTION OF 1 GRAM OF MATERIAL)

Item	CO_2	CO	HCL	SO_2	Benzene	Unsat. Hydrocarbons (1)	NO_2	HCN	CL_2	Arsine	Phosgene
Acrylic	63.82	26.04									
Latex foam	553.50	56.33	0.49	0.006	3.92	0.44					
Leather	247.50	3.53		0.006			0.04	.005	.045		
Mi[illegible]al wool	340.2	46.37					0.10				
Modacrylic	46.62	26.69	1.38	0.001		63.05		2.52			
Polyurethane foam	445.5	15.45				9.59					
Plywood	246.63	42.15				5.92				1.3	
Simulated leather	75.82	33.94				11.29					0.05
Vinyl foam	116.6	29.37			6.46	0.72					
Wool	90	2.86		0.013							

(1) Determined as acetylene

TABLE IV. CRITICAL WEIGHTS AND SMOKE CONSTITUENTS

Material	Weight to Produce Critical Limit, Grams	Smoke Constituent Producing Critical Limit	Reference
Acrylic	66	Carbon monoxide	1
Latex foam	30	Carbon monoxide	1
Leather	267	Chlorine	1
Mineral wool	37	Carbon monoxide	1
Modacrylic	26	Hydrogen cyanide	1
Polyurethane foam	111	Carbon monoxide	1
Plywood	41	Carbon monoxide	1
Insulated leather	51	Carbon monoxide	1
Vinyl foam	58	Carbon monoxide	1
Wool	600	Carbon monoxide	1
DER*331 + CA**	0.2	Hydrobromic acid	2
DER 542 + MDA**	0.3	Hydrobromic acid	2
DER 542 + MNA**	0.6	Hydrochloric acid	2
DER X-3448 + MDA**	0.2	Hydrochloric acid	2
DER X-3448 + MNA**	0.6	Hydrochloric acid	2

References:

1. Marcy, J. F., "A Study Of Air Transport Passenger Cabin Fires and Materials," FAA Report ADS-44, December 1965.
2. Thrune, R. I., "Gases Released When Fire Resistant Epoxy Resins Are Burned," American Industrial Hygiene Association Journal, 24(5):475, 1963.

*Dow epoxy resin
**Curing agent

it was found that all the samples of the cabin interior materials tested produced a large number of trace toxic gases in addition to carbon monoxide. However, carbon monoxide occurred in greater toxic concentrations than that of any other gases present[23]. During the series of transport crash tests conducted by NACA[15], time histories of carbon monoxide, carbon dioxide, and oxygen concentrations in the pilot and passenger compartments were recorded. Inspection of the gas concentration histories showed that the composition of the cabin atmosphere can vary widely with time from crash to crash. During two fuselage hulk fires the carbon monoxide concentration reached a maximum value of approximately four percent. The crash-fire data showed, however, that higher carbon monoxide concentrations are possible, since one concentration of 12 percent carbon monoxide was measured. Combustion studies indicated that such concentrations are possible, when the oxygen supply is limited. Figure 6 shows the average carbon monoxide concentrations versus times recorded during these crash tests.

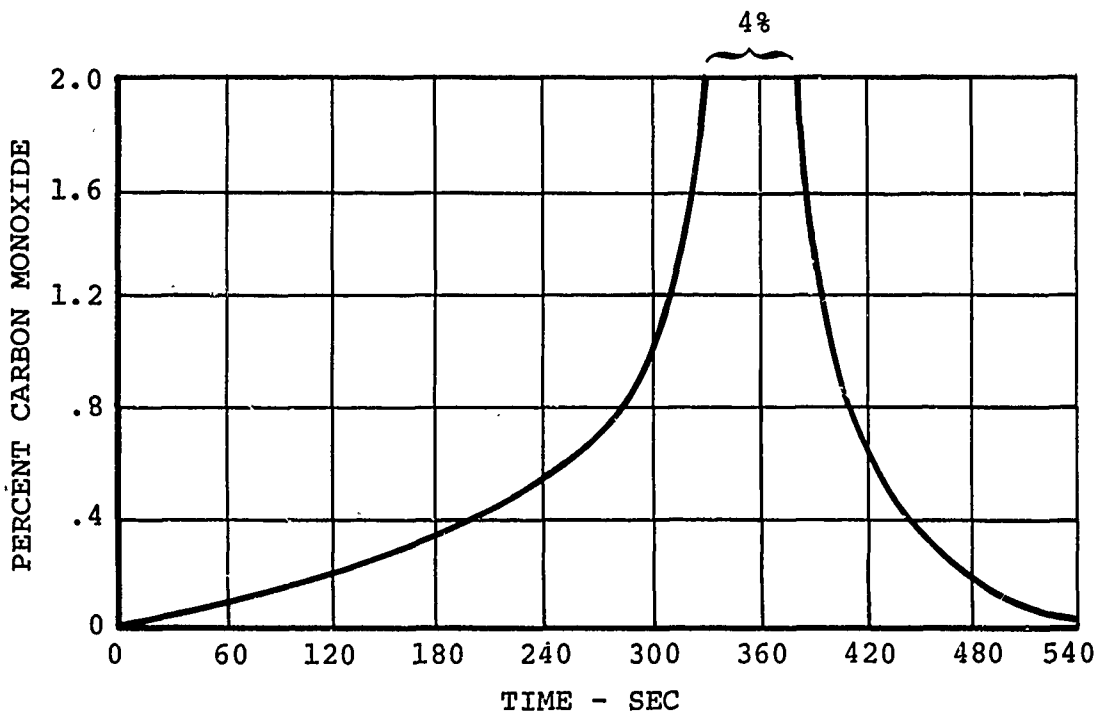


Figure 6. Average Recorded CO Concentrations in Several Crashed, Burning Passenger/Cargo-Type Aircraft.

The average recorded carbon monoxide concentrations in several cargo-type helicopters crash-tested by Dynamic Science are shown in Figure 7[19]. In comparing Figure 6 with Figure 7, it can be seen that the carbon monoxide buildup was much more rapid in the crashed helicopters than in the crashed cargo-type airplanes. However, the maximum concentration was less in the helicopters, and the carbon monoxide dissipated quite rapidly. This illustrates the wide variation in toxic gas levels that can be encountered with varying conditions. The rapid increase in carbon monoxide in the helicopter crashes was probably due to the fuel distribution being quite near the wreckage, allowing rapid smoke and flame entry into the fuselage. The carbon monoxide dissipated after 45 seconds due to two factors. First, the helicopter fuselages were nearly consumed by the fire in 45 seconds; thus, they could no longer act as shells to hold the fumes in the area. Second, only small quantities of fuel were used during these helicopter tests.

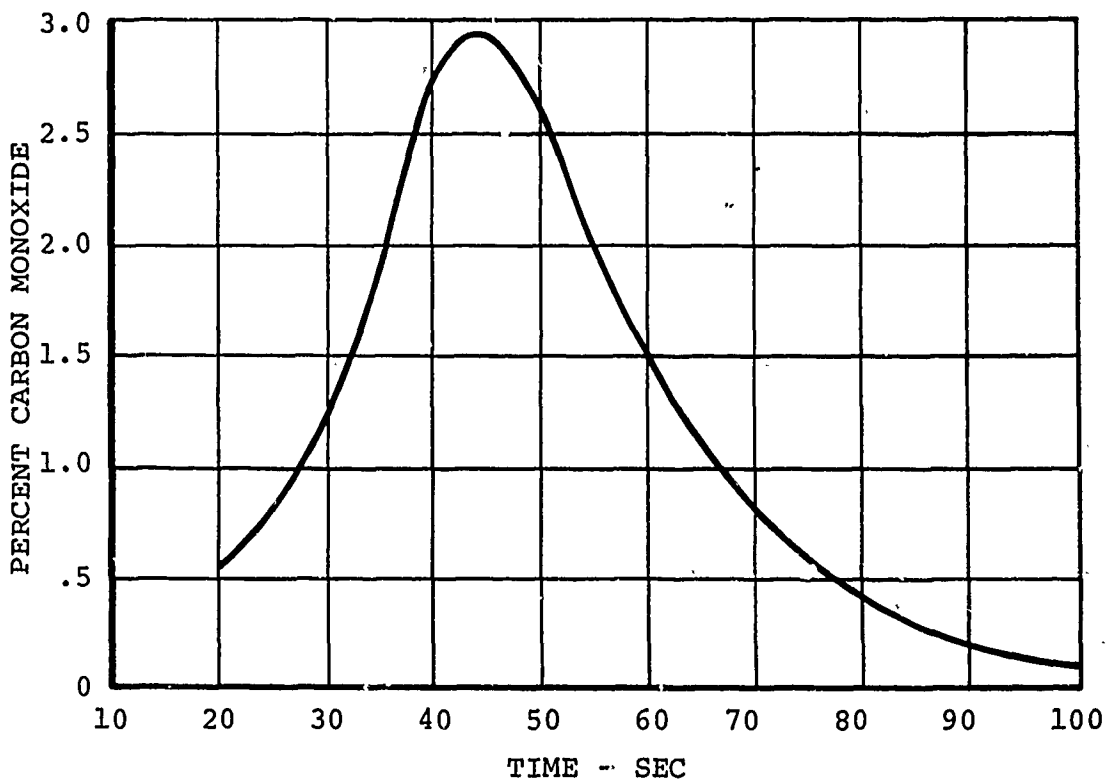


Figure 7. Average Recorded CO Concentrations in Several Crashed, Burning Passenger/Cargo-Type Helicopters.

C. Human Tolerance and Escape Time

1. General Discussion

The two fire threats that limit an aircraft occupant's survival and egress the most are heat and toxic gases. Other factors, such as obstructions to vision and obstacles from structural breakup, can usually be overcome in time providing that heat and toxic gases do not exceed the human tolerance limits. As pointed out in Section I.B., there are many variables that influence the magnitude of these threats. These variables differ from aircraft to aircraft, and even from crash to crash in the same type of aircraft. In order to assess an occupant's chances of survival during a crash-fire environment, the various threats, along with the human tolerance levels to them, must be considered individually. The following section will present the estimated tolerances and escape times as limited by

- Heat
- Toxic Gases
- Miscellaneous Factors

Escape time, as defined in this report, is the time during which a person can escape under his own power. Survival time, that time until death occurs, is generally somewhat longer. Even when accidents occur where fire-fighting facilities are immediately available, the fire is more often than not uncontrollable until well past the survival time for most occupants. Therefore, the actual human survival limiting factor is the escape time that an uninjured occupant has to remove himself from the fire environment.

Escape time is limited by physiological tolerances to heat and toxic gases. Depending upon the particular crash and the aircraft involved, either of these may be the limiting factor, so both must be considered in any analysis of escape time from a postcrash fire.

2. Influence of Heat on Escape Time

a. General

As mentioned earlier, heat is transmitted to man by the conduction and convection of hot air and radiation from hot surfaces and gases. The amount of heat transferred by each of these means depends upon the temperature and size of the source, upon the distance from the source, and upon the relative wind direction and velocity. In the postcrash fire

environment, heat is mainly transmitted to the occupant by convection of hot air and by radiation from hot fuselage walls and flames.

Skin burns and respiratory injuries are the common physiological reactions to the abnormally high temperatures encountered in the fire environment. Skin burns result from convection (circumambient heat) and from radiation (circumradiant heat), while respiratory injuries result only from the inhalation of hot air. Extensive work has been performed on human tolerance to heat, and an excellent review of this work has been compiled[41]. The results are sometimes confusing and misleading, however, because of the different experimental conditions and the lack of information on any protective measures which were used.

b. Skin Temperature Criteria

The most useful measure of human tolerance to circumambient and circumradiant heat is the skin temperature at which pain occurs and at which skin burning occurs. Moritz and Henriques[42] cite the pain threshold skin temperature as being between 117° and 119°F, while Buettner[43] cites the pain threshold temperature as being between 108° and 113°F. This discrepancy could very well be due to the differences in the experimental procedures. Moritz used heated liquids while Buettner used an electric radiator as the heat source. However, even with these two completely different heat sources, the pain threshold skin temperature falls within a fairly narrow range. Buettner gives the skin temperature for unbearable pain as 124°F. This agrees well with another study that recorded a skin temperature of 126°F as "resulting in distinct pain."[44] Buettner also states that burns will occur whenever the skin temperature exceeds 129°F.

Moritz and Henriques[42] found that, when the temperature of the skin is held at 111°F, the rate of injurious change barely exceeds that of recovery, with an exposure of six hours required before irreversible damage is sustained. They also found that the rate of irreversible cellular injury which was sustained increased rapidly as the skin surface temperature was raised, and for each degree rise in surface temperature between 111° and 124°F, the time required to produce such injury was reduced by approximately one-half. At a surface temperature of 158°F and higher, the rate of injury so far exceeded that of recovery that less than one second was required to cause irreversible injury.

The experimental data on the physiological effects of elevated skin temperatures are summarized in Figure 8.

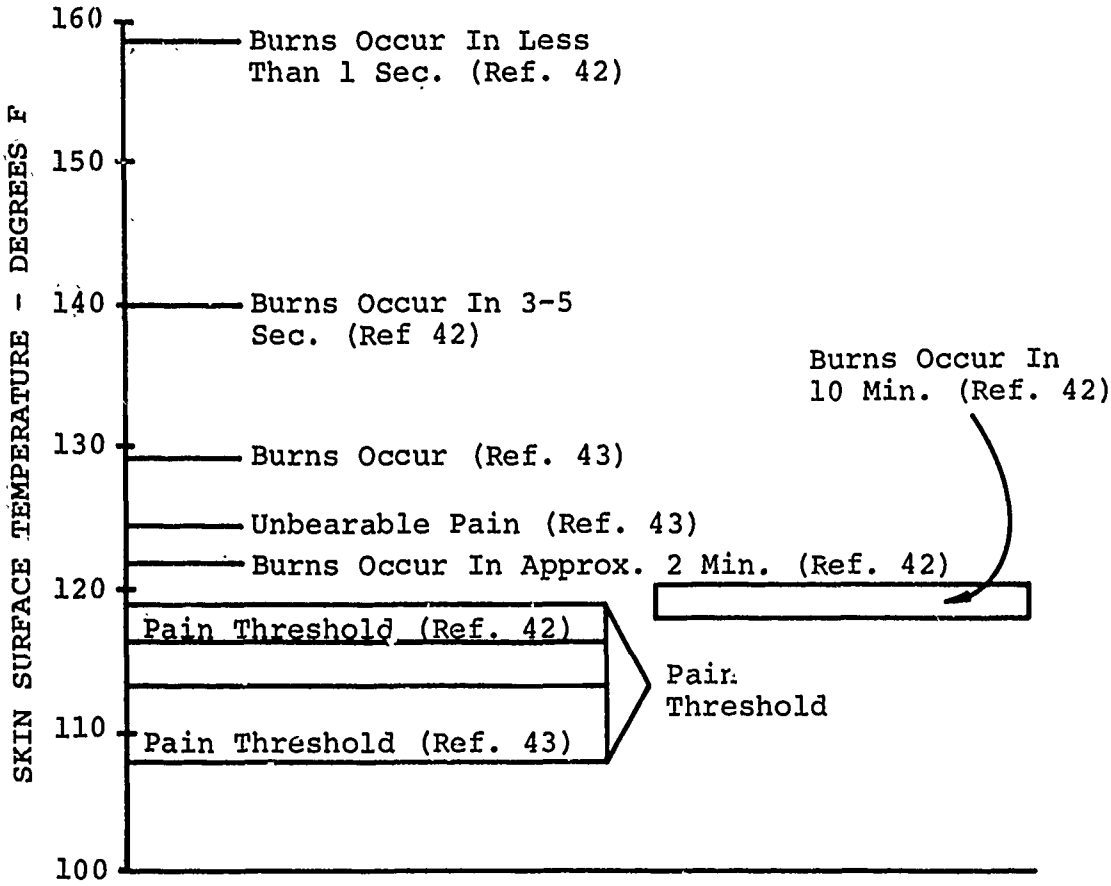


Figure 8. Physiological Effects of Elevated Skin Temperatures.

Although the skin temperature values that determine pain and burning times are a convenient and precise way to define human tolerances, they must be related to measurable parameters of the actual fire environment to be of any benefit in estimating escape times. Since the rise in skin temperature is due to the total heat flux striking the skin from both circumambient air and radia. . heat sources and since the mechanisms of transfer are not related, these sources can be considered separately.

c. Circumradiant Heat Tolerance

The effect produced by any kind of heat depends on the amount of heat transmitted per unit time, which, in turn, depends on the temperature of the source. When considering radiant heat, one additional factor must also be considered; that is, the radiating surface visible to the exposed area, since the amount of radiation received by the skin depends not only on the temperature of the source but also on the solid angle of radiation. A hemisphere (Figure 9) is considered as the maximum possible radiating space angle. Figure 10 gives pain threshold times as determined by temperature of the radiative source for several angles of radiation. If the entire hemispheric surface were at an elevated temperature, as would be the case for an occupant inside a fuselage with the walls completely engulfed in flames, curve A ($F_a = 1$) would apply. If only 50 percent of the hemispheric surface were at such temperature, curve B ($F_a = 0.50$) would apply. In general, postcrash fires will involve only part of the surrounding hemisphere, but the many variables involved make it difficult to predict just how much of the hemisphere will be acting as a radiative source. Additional crash-fire data must be obtained before such predictions can be made with any degree of reliability.

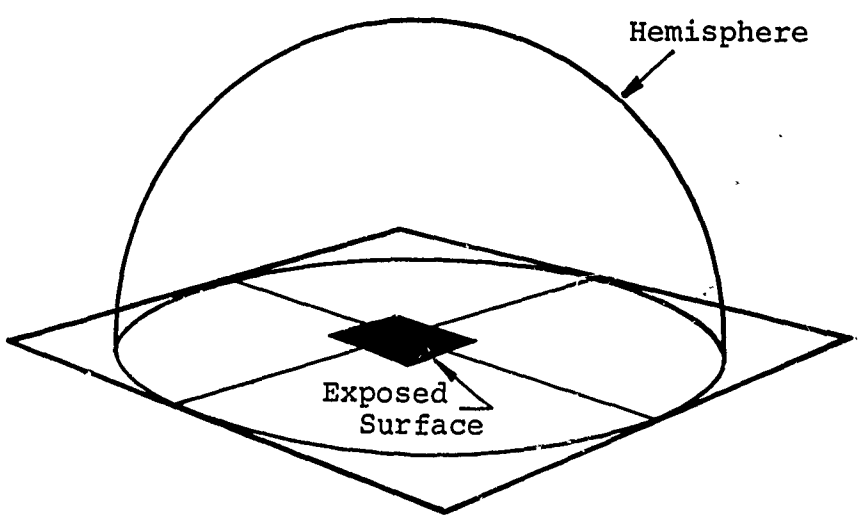


Figure 9. The Hemisphere of Radiant Heat Concept.

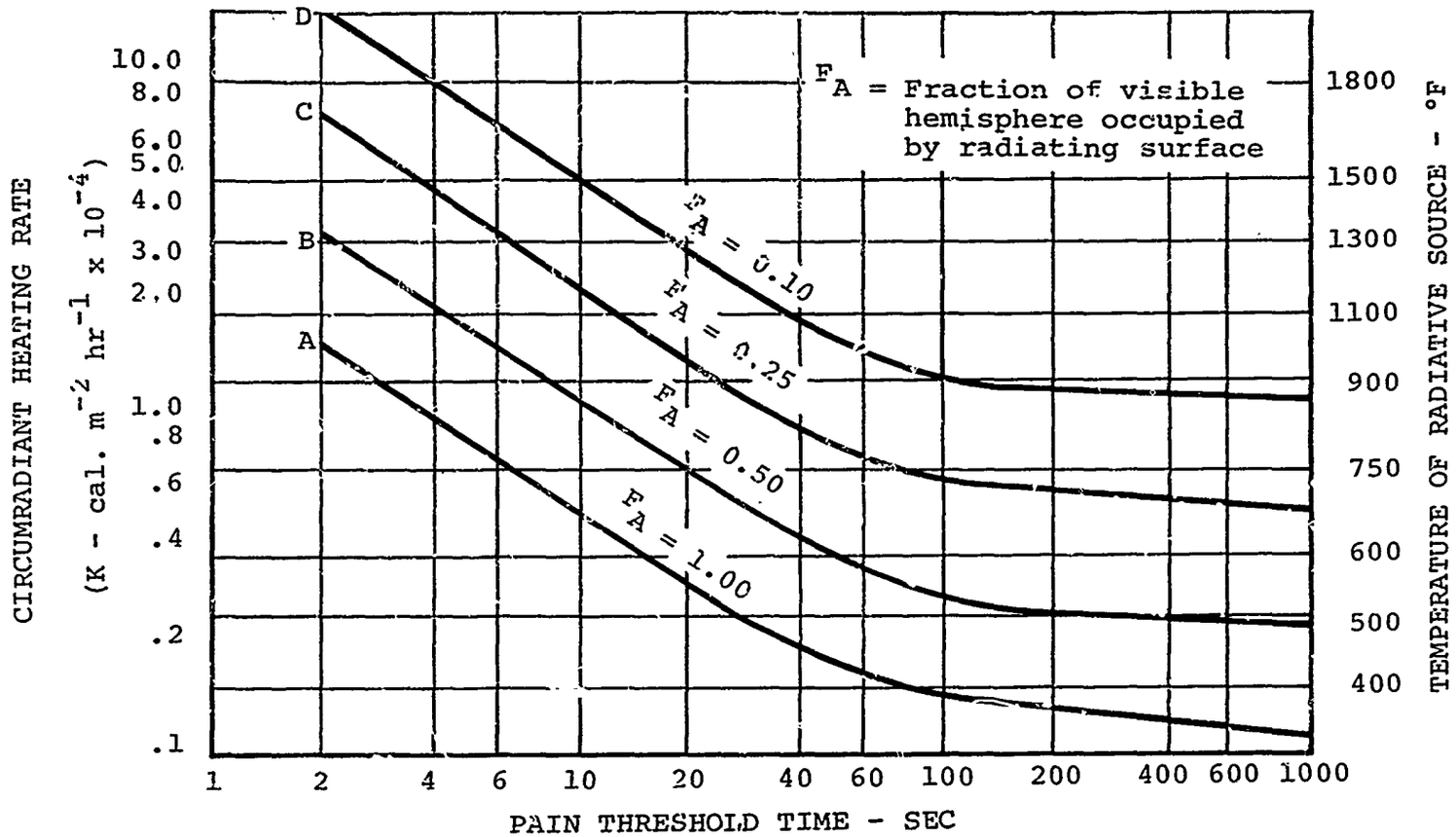


Figure 10. Pain Threshold Time As A Function Of Temperature of Radiant Heat Source. (From Reference 19)

d. Circumambient Heat Tolerance

Human tolerance limits to circumambient heat are less well defined than are the limits to circumradiant heat. Some studies have been conducted at elevated temperatures, but actual tolerance times at high temperatures have only been estimated.

Studies of human thermal tolerance have been conducted using heat pulse ovens[45,46]. The maximum air temperature in one study was 285°F, while the other study used only 265°F. Exposure times at these peak temperatures were only one to two minutes, although exposures to the total heat pulses lasted approximately 20 minutes. In general, the exposures were well tolerated and pain was never a problem. Nose breathing was impossible and mouth breathing somewhat uncomfortable when air temperatures were over 150°F, but there was no physiological difficulty in breathing.

Buettner[43] states that calm, dry air of more than 284° to 320°F will cause unbearable pain to unprotected skin prior to the physiological breakdown of the whole body. Table V presents his estimates of the minimum time required for collapse to occur when a human is subjected to various surrounding air temperatures. The higher temperature of 390°F was based on a semi-accident, where only the face, already covered with perspiration, was exposed to the heated air. There were no respiratory injuries from this exposure; however, one small second degree burn did occur on the face where perspiration was not available to protect the skin.

The curve in Figure 11 represents man's tolerance to calm, dry, heated ambient air, as determined from the work conducted to date. The curve has been extrapolated above 360°F to give approximate tolerance levels for dry skin at the higher temperatures.

e. Tolerance to Inhaled Heat

Very little experimental data are available on respiratory injuries due to the inhalation of hot air, and clinical data derived from fire accidents are ambiguous because of the added presence of smoke and toxic gases inhaled during the fire. In one extensive study on the effects of inhaled heat on the air passages and lungs of animals, Moritz and co-workers[47] found that air hot enough to burn the skin of the face can be inhaled without causing damage to the trachea or lungs. If the air is inhaled in a normal manner and at a high enough temperature to damage the lower air passages, it is likely to cause death from obstructive edema

TABLE V. MINIMUM COLLAPSE TIME IN HEATED, CALM AIR	
Temperature	Escape Time From a Heated, Enclosed Space
122° F	Several hours
158° F	1 hour
265° F	15 minutes
390° F	3 to 4 minutes*
* Estimated - based only on approximate data with wet skin.	

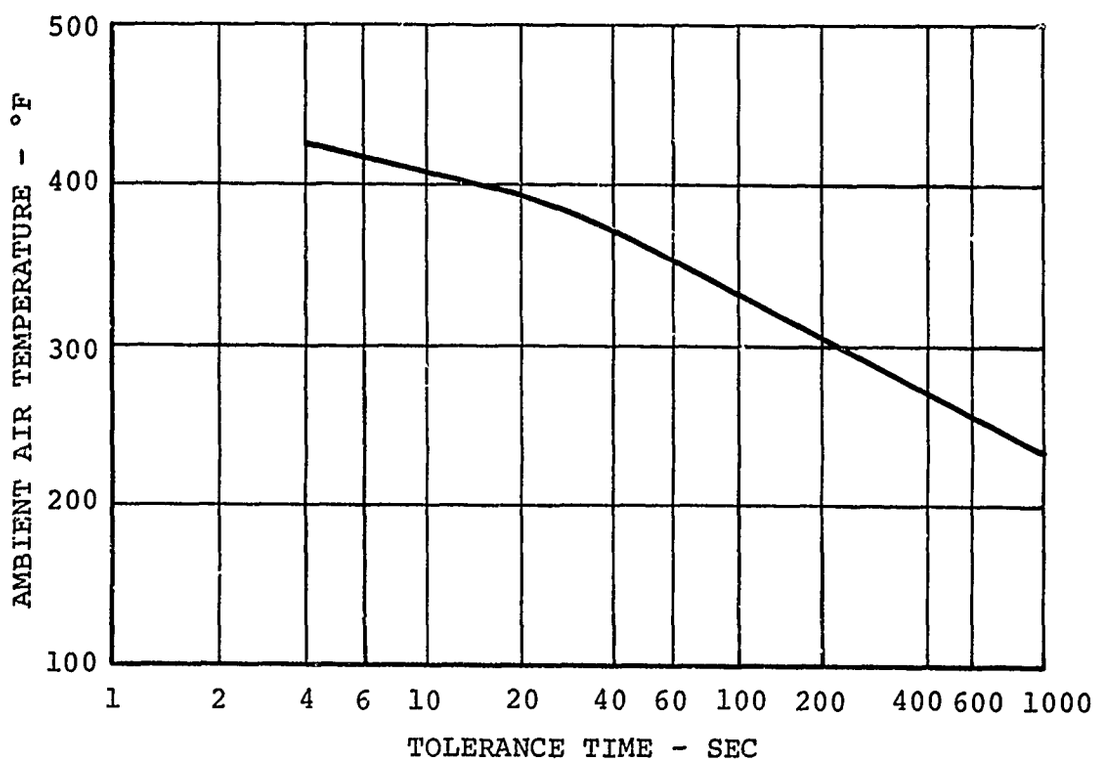


Figure 11. Human Tolerance to Calm Dry Ambient Air Temperatures. (From Reference 19)

of the laryngopharynx and larynx before sufficient time has elapsed for damage in the deeper portions of the respiratory tract. The data, however, does not indicate a sharply defined threshold temperature for respiratory injuries. Since 390°F is the known upper temperature to which a man has been exposed without respiratory injuries, this temperature can be used as a threshold limit for the inhalation of hot air.

f. Relation Between Human Tolerance and Escape Time

In using the above tolerance limits to estimate escape times from an actual crash-fire environment, one must be careful to distinguish between the relative hazards of skin burns and respiratory injuries. Whenever an occupant is surrounded by hot fuselage walls, as would be the case when the cabin area is surrounded by flames, the majority of the total heat will be contributed by radiant heat. This can be seen in Table VI, which was taken from Reference 48. Since heated air can be inhaled without danger to the respiratory tract even after the onset of skin burns, the only time that respiratory system tolerances should be used are when hot gases are blown into a relatively cool compartment. Examples of this will be discussed later.

To relate the criteria of skin temperature to escape times in crash-fire tests of aircraft, temperatures must be measured by means of calorimeters. The temperature-time curves thus obtained must be converted to total heat which would be felt by the occupant. This may be done by the use of the following formula:

$$\left(\frac{dq}{dt}\right)_{total} = R - (seT^4)_{skin} + K\,(T_{air} - T_{skin}) \qquad (1)$$

In this equation

$\left(\frac{dq}{dt}\right)_{total}$ heat absorbed by skin, cal/(sq cm/min)

R radiant heat absorption by skin, cal/(sq cm/min)

s Stefan-Boltzmann constant, 8.2×10^{-11} cal/(sq cm/min/°K^4)

e emissivity

T temperature of skin surface, °K

K Convective heat-transfer coefficient, cal/(sq cm/min/°C)

T_{air} ambient air temperature, °C

TABLE VI. ESTIMATED CALORIC UPTAKE OF A PIG INSIDE A HEATED ENCLOSURE

Wall Temperature, C.	Air Temperature, C.	Caloric Uptake in Calories per Sq. Cm. per Min.			Percent of Total Contributed by Radiant Caloric Uptake
		Nonradiant (Ambient)	Radiant	Total	
85	70	0.2	0.2	0.4	50
120	100	0.5	0.6	1.1	55
180	150	1.0	1.4	2.4	58
235	200	1.7	2.6	4.3	61
300	250	2.2	4.2	6.4	65
370	300	3.0	6.2	9.2	68
420	350	3.8	9.8	13.6	72
4[illegible]5	400	.5	17.0	21.5	79
540	450	5.5	24.0	29.5	81
600	500	6.5	35.0	41.5	85

The term R in the equation is the only unknown if the skin temperature is assumed constant. R can be evaluated in several different ways, depending on the type of calorimeter used. Pesman[15] gives a detailed method for the use of a copper globe calorimeter, which is a common method of measuring the heat evolved in a crash-fire. The calculated heat absorbed by the skin can then be related to the time at which unbearable pain occurs, as detailed in Pesman's report.

Although a person can survive with fairly extensive second degree burns, the pain tolerance of individuals varies markedly; what would be tolerable to one person and not impede his escape would be enough to hamper the escape of another person considerably. According to lay reports, the feeling of facial pain may be strong enough to delay one from taking preventive measures to escape the fire[43]. Therefore, in setting a tolerance limit to circumradiant and circumambient heat, the skin temperature corresponding to unbearable pain should be used rather than the higher temperature corresponding to second degree burns (Figure 8).

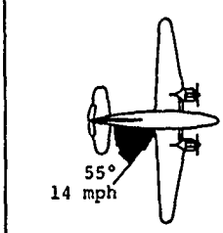
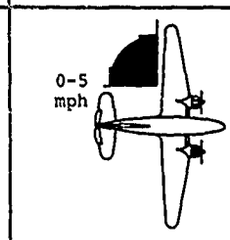
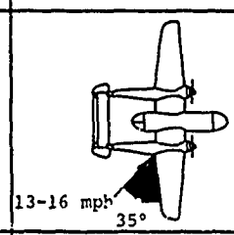
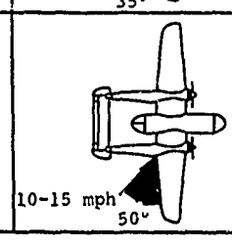
g. Heat-Limited Escape Times in Transports

The results of Pesman's extensive series of crash tests conducted on transport/cargo-type aircraft indicate that approximately 50 seconds would be available for escape in all but the most severe fires, although in some cases passengers must move away from areas of burned-through fuselage skin in as few as 7-1/2 seconds. The wide variation in escape times between the different crashes is shown in Table VII, which is taken from Pesman's report.

> "The variation in escape time with position in a particular airplane during a fire and from one crash-fire to another depends on the position of the passenger with respect to the main bulk of the fire, the wind direction and velocity, the area over which fuel is spilled during a crash, and the terrain on which the airplane comes to rest."

The shorter escape times available in Crash 3 as compared to Crash 1 (Table VII) were the result of wind speed, wind direction, and terrain. A fairly brisk wind during Crash 1 carried the flames away from the passenger compartment in the fuselage. The airplane also came to rest on level ground, with the result that spilled fuel remained pooled under the wings and the area of the fire did not increase rapidly. During Crash 3 there was little wind, and flames from both sides of the fuselage tended to merge, forming a canopy of flames around and over the fuselage. The airplane

TABLE VII. ESCAPE TIME AVAILABLE BASED ON SKIN BURNING AND RESPIRATORY DAMAGE THRESHOLDS.

Crash	Position In Airplane	Severe Pain and Skin Injury Begin Sec After Impact	Minimal Second-Degree Burn, Sec After Impact	Respiratory Limit (390° F), Sec After Impact	Airplane	Wind Direction and Speed	Fuel
1	Left front fuselage	180	224	251	C-46		Gasoline
	Right front fuselage	[illegible]	260	292			
	Left rear fuselage	174	306	296			
	Right rear fuselage	163	180	288			
3	Pilot's compartment	182	203	182	C-46		Gasoline
	Front fuselage	92	101	151			
	Rear fuselage	90	100	138			
6	Pilot's compartment	144	150	60	C-82		Gasoline
	Fuselage	53	59	131			
7	Pilot's compartment	93	97	112	C-82		Low-volatility fuel
	Fuselage	92	95	93			

also came to rest on an upslope, which caused the fuel to run back toward the tail, allowing the resulting fire to envelop the fuselage more completely. As a result, the escape time in the fuselage during Crash 3 was little more than half that of the same location for Crash 1.

In one case (Crash 6, Table VII) the respiratory threshold was reached prior to the skin-burning threshold. In this instance hot gases were being carried into the pilot's compartment by wind and convection inside the fuselage, while the wind direction was such that the passenger compartment in the fuselage was almost completely bathed in flames. Although the escape times do vary widely depending upon crash conditions and occupant position within the aircraft, it should be noted that at no time did the escape limit extend longer than five minutes, even when using the second degree burn criteria rather than the severe pain criteria as the tolerance level. The average escape time for this series of large airplane tests was 135 seconds.

A more recent test series conducted with transport size airplanes (C-97's) resulted in escape times of the same order of magnitude, as may be seen in Table VIII[25]. These tests involved intact airplanes with fires continually fed with JP-4 fuel burning on both sides of the fuselage. Again, a pronounced variation in escape time can be seen from one location to another in the cabin. In this case unbearable pain was the limiting criteria. For two similar tests conducted in this series, the escape time with emergency doors open was equal to only 50 seconds, whereas the escape time was 115 seconds with the doors closed. The time difference is attributable to the effect of an increased supply of oxygen on the intensity of the fire.

h. Heat-Limited Escape Times in Helicopters

During the instrumented crash tests of cargo helicopters discussed earlier, only circumambient air temperature was recorded and not the combined effects of radiant and ambient heat[21]. The average escape time for this series of tests, based on the criterion of inhaled hot air, was only 17 seconds. Since crash tests and accident reports of helicopters have shown that fires break out immediately or very shortly after the initial impact, and that these fires tend to engulf the whole fuselage, it is quite possible that intolerable pain will be the limiting escape factor. Thus, the escape time for helicopters, considering only thermal data, is probably considerably less than 17 seconds.

TABLE VIII. ESCAPE AND SURVIVAL TIMES IN A FIRE TEST OF A LARGE CARGO/TRANSPORT AIRPLANE.			
Escape/Survival	Cabin Location		
	Station 326 (sec.)	Station 550 (sec.)	Station 1074 (sec.)
Escape Time			
390° F.	320	174	160
Unbearable pain	152*	176 (138**)	118
Carbon monoxide	Not attained	Not attained	Not attained
Survival Time			
752° F.	382	186	164
Severe burns	160	183 (141**)	161
Carbon Monoxide	Not attained	Not attained	Not attained

*Computed from globe thermometer (calorimeter) at Sta. 300.

**Computed from globe thermometer (calorimeter) at Sta. 884.

3. Influence of Toxic Gases on Escape Time

a. General

As previously mentioned, the most common toxic gases in a fire environment are carbon monoxide and carbon dixoide. For this reason more human tolerance studies have been conducted with these two gases than with any of the other gases common to the crash-fire environment. Most of these studies have been conducted at room temperature, however, and the effect of heat on the toxicity of these gases is not known. In addition, more than one toxic gas is usually present during a fire, and synergistic effects of combinations of gases have not been studied. Therefore, the tolerance limits given in

the following discussion must be considered as estimates only, and human tolerance limits in a crash-fire environment might be considerably less.

Human tolerance limits for those gases which have not been extensively studied are even more uncertain. Industrial hazard limits, which are determined for low concentrations and long-term exposures, cannot be extrapolated to acute conditions with any degree of reliability. If the concentration of a gas remains below the industrial hazard limit, there is no danger, but if the concentration rises above this limit, human tolerance to the gas cannot be accurately estimated.

b. Carbon Monoxide Tolerance

Carbon monoxide (CO) does not act as a poison in the usual sense of the word, but, rather, as an asphyxiant. Carbon monoxide combines with the hemoglobin in the blood, thus preventing oxygen from being carried through the body. The affinity of carbon monoxide for hemoglobin is 200-300 times greater than that of oxygen[41]. Thus, carbon monoxide will preferentially displace oxygen if the carbon monoxide is present in any appreciable quantity in the air.

Carbon monoxide limits can be expressed in either percent carbon monoxide in the inspired air or percent carboxyhemoglobin (percent of saturation of the blood) in the body. Since the percent carbon monoxide in the body is governed by the respiration rate and lung volume of the individual concerned, which varies from person to person, the measurement of the carboxyhemoglobin is a more accurate means of determining tolerance limits. However, when one is discussing survival times in carbon monoxide atmospheres, it is more useful to discuss toxic limits in percentages of carbon monoxide present in the air.

Forbes, et al., in an extensive study of the rate of carbon monoxide uptake by normal men[49], studied the correlation between the amount of carbon monoxide absorbed and the ventilation rate, which varies with the degree of activity of the subject. These studies showed that the percentage of CO saturation in the blood (percent COHb) is given by the concentration of CO in the inspired air multiplied by the minutes of exposure multiplied by a constant which varied for the type of activity involved. Pesman[15] assumed that the activity of a person trying to escape from a burning aircraft would correspond to those activities required for light work in Forbes' report. The constant found for light work was equal to 8. Thus, the percent carbon monoxide in the fire environment

atmosphere can be translated into percent carboxyhemoglobin by using the following formula:

$$COHb = 8 \times CO \times T \qquad (2)$$

where COHb = percent of carboxyhemoglobin formed

CO = percent of CO in the air

T = exposure time in minutes.

Figure 12, developed from the above formula [illegible] the [illegible] lationships between percent CO in the air, [illegible] and exposure time.

The physiological effects of various carboxyhemoglobin percentages are shown in Figure 13[illegible] [illegible] his studies, chose 35 percent carboxyhemoglobin [illegible] the escape limit, which agrees well with the data in Figure [illegible] the 35 percent COHb level as the escape limit, [illegible] that an individual will reach this limit in approximately 90 seconds when he is breathing an atmosphere containing three percent carbon monoxide. This should be taken as a maximum escape limit, however, as studies have shown that a rise in air temperature will increase the toxic effect of carbon monoxide(41).

c. Carbon Dioxide Tolerance

Carbon dioxide is not considered a toxic gas as such, but induces axphyxia through the exclusion of oxygen. This effect is accelerated by the carbon dioxide, which causes a stimulation of the respiratory center and results in an abnormally high respiration rate. Studies have indicated that as little as two percent carbon dioxide in the inspired air effectively stimulates respiration and three percent doubles the lung ventilation rate(41).

Tolerance limits are not well defined for carbon dioxide and there is wide variation among investigators as to tolerance times. In addition, many of the limits are given for long-term exposures, which do not apply to this study. Pryor and Yuill(41) give a tolerance time of five minutes for a five percent carbon dioxide concentration in the inspired air. Pesman(15) concluded that individuals could perform useful tasks in concentrations up to and above four percent for periods of 10 minutes. Reference 50, which is a more recent review of carbon dioxide tolerance studies, cites one case where subjects breathed five percent carbon dioxide for 16 minutes. Although the respiration rate and lung volume

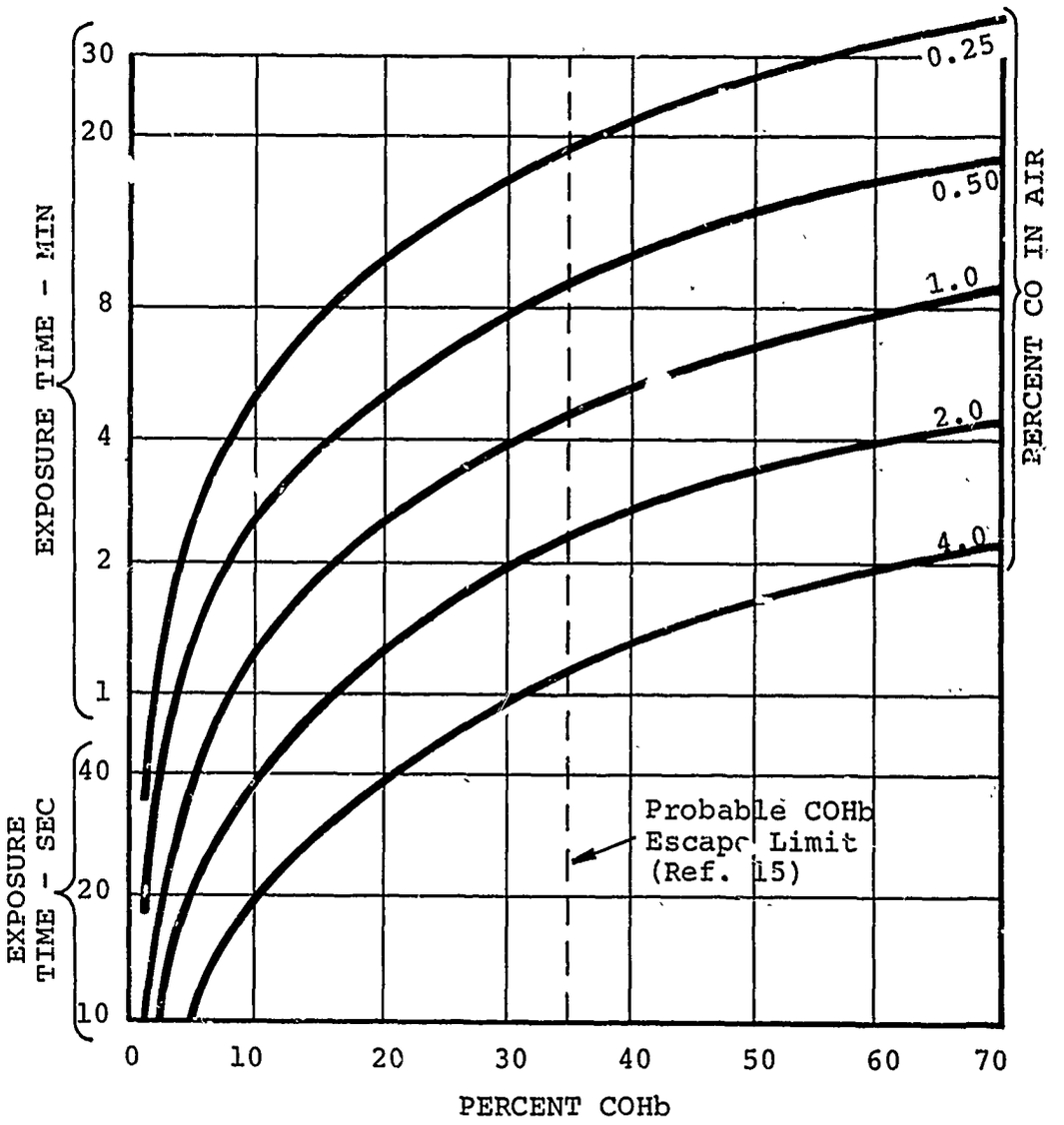


Figure 12. Relationship Between Percent CO in Air, Exposure Time, and Percent COHb For Average Individual Performing Light Work.

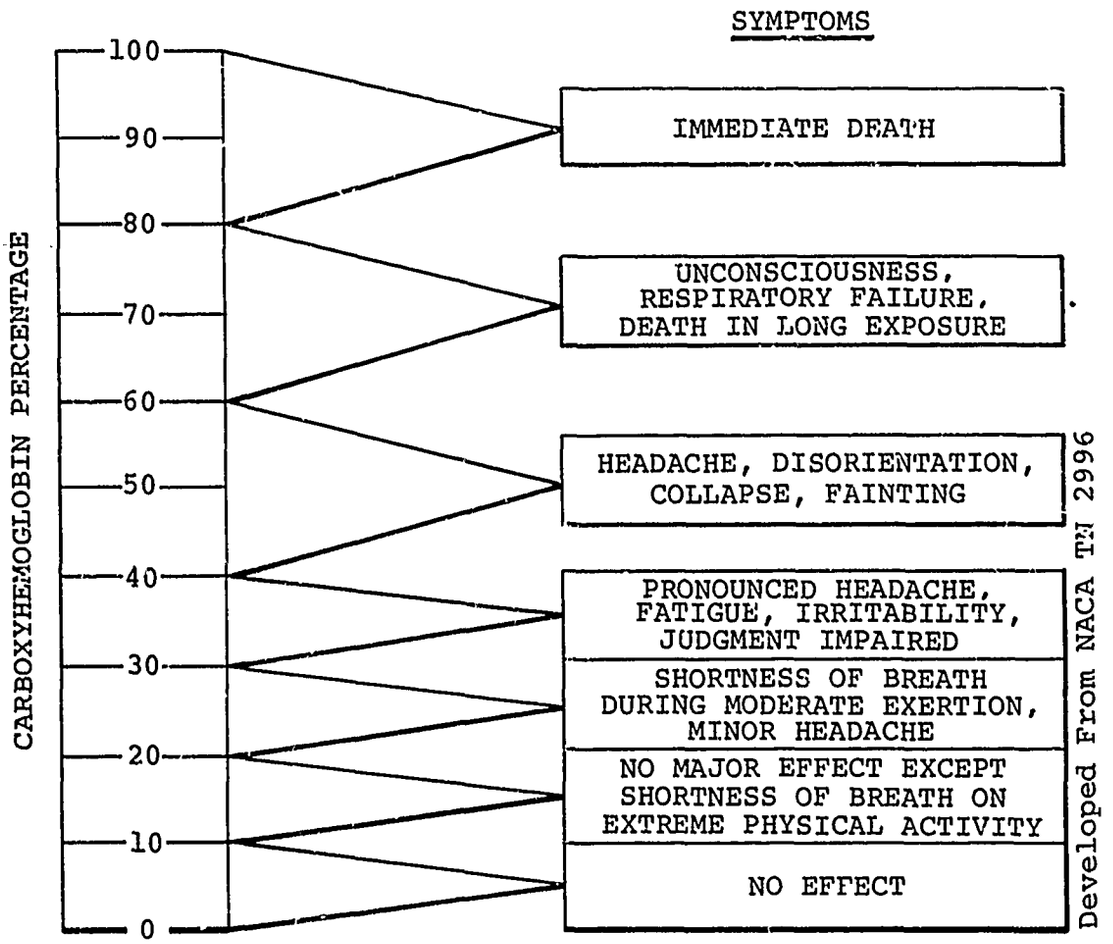


Figure 13. Physiological Effects of Various CO Hemoglobin Percentages.

increased markedly, the subjects made no significant errors in multiple card-sorting studies. Therefore, the limits that Pesman set in his study of aircraft crash-fires seem to be reasonable.

d. Tolerance to Combinations of Carbon Monoxide and Carbon Dioxide

In determining escape times as limited by carbon monoxide and carbon dioxide, one must consider the combined effects of these two gases, since both are formed during

combustion. Oxygen is also consumed and, if the available supply of air is limited, as might well be the case in a survivable aircraft crash, oxygen depletion occurs.

Human tolerance limits are strongly dependent on the synergistic effects of these three gases. Zapp[51] found that a combination of carbon monoxide and low oxygen was more lethal than either the carbon monoxide or low oxygen by themselves. Carbon dioxide, by increasing the respiration rate, increases the amount of carbon monoxide that is inhaled in any given time period. Thus, extreme caution must be used in determining escape times as limited by these gases, and any times so determined must be thought of as maximum escape times.

e. Tolerance to Other Toxic Gases

In addition to carbon monoxide and carbon dioxide, which are generated in all fires, attention must be given to the other toxic gases which can be generated by the combustion of aircraft interior materials, see Section I.B.4.a. Table IX, taken from Reference 40, lists the short-term exposure limits for some of these gases. Again, it should be mentioned that a straight-line correlation does not necessarily hold between higher concentrations and shorter times than those given in the table. However, these exposure limits do give some idea of the toxicity of these gases, and it can be seen that all of them are much more toxic than carbon monoxide. Thus, the interior materials of the aircraft have a great deal of bearing on human tolerance to the crash-fire environment.

In addition, these gases can enter into synergistic effects with other gases. Bieberdorf and Yuill[37] cite an example where concentrations of carbon monoxide and hydrogen sulfide combined were fatal although neither gas existed in fatal concentrations by itself. The Departments of the Air Force and Army comment on industrial hazard limits of toxic gases with the statement

> "When two or more hazardous substances are present, their combined effect, rather than that of either individually, should be given primary consideration. In the absence of information to the contrary, the effects of the different hazards should be considered as additive."[52]

This statement should also be applied to the crash-fire environment.

TABLE IX. SHORT-TERM EXPOSURE LIMITS FOR SMOKE CONSTITUENTS

Constituent		Parts Per Million	mg/m^3	Remarks	Reference
Arsine	(AsH_3)	30	96	6 to 30 ppm can be inhaled for 1 hour without serious consequences.	1
Benzene	(C_6H_6)	3,000	9,570	3,000 to 4,700 ppm can be inhaled for 1 hour without serious consequences.	1
Bromine	(Br_2)	4	26	Maximum allowable conc. for 30 to 60 minutes.	1
Carbon dioxide	(CO_2)	50,000	90,000	Navy permits 1 hour emergency exposure to this level. 50,000 ppm provides signs of intoxication on 30 minutes exposure.	2 5
Carbon monoxide	(CO)	1,500	1,717	NRC emergency exposure limit for 10 minutes.	3
Chlorine	(Cl_2)	4	12	Maximum allowable concentration for 30 to 60 minutes.	1
Fluorine	(F_2)	3	5	NRC emergency exposure limit for 10 minutes.	3
Hydrobromic acid	(HBr)	30	99	By analogy to HCl and Cl_2	
Hydrochloric acid	(HCl)	30	45	NRC emergency exposure limit for 10 minutes.	3
Hydrocyanic acid	(HCN)	60	66	50 to 60 ppm for 1 hour has no serious consequences. 45 to 54 ppm for 30 to 60 minutes without immediate or late effects.	1 4
Hydrofluoric acid	(HF)	20	16	NRC emergency exposure limit for 10 minutes.	3
Nitrogen dioxide	(NO_2)	30	56	NRC emergency exposure limit for 10 minutes.	3
Phosgene	($COCl_2$)	3.0	12	3.1 ppm is least amount causing immediate throat irritation; 4.0 causes immediate irritation of the eyes; 4.8 causes coughing; 25 ppm is dangerous for even short exposures.	1
Sulfur dioxide	(SO_2)	30	79	NRC emergency exposure limit for 10 minutes.	3

References:
1. Henderson, Y., and Haggard, H. W., Noxious Gases and the Principles of Respiration Influencing Their Action, Reinhold Publishing Co., New York, 1943.
2. Submarine Atmosphere Habitability Data Book, NAVSHIPS 250-649-1, September 1962, Navy Dept.
3. Smyth, H. F., Jr., "Military and Space Short-Term Inhalation Standards," Arch. Environ, Health 12:488-90, 1966.
4. Patty, F. A. (Editor), Industrial Hygiene and Toxicology, Second Revised Edition, Vol. 2, 1963, Interscience Publishers, New York.
5. A.C.G.I.H. Committee on Threshold Limit Values "Documentation of Threshold Limit Values, Rev. Edition, 1966 American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.

f. Escape Times in Transports

Several fire tests of transport/passenger-category aircraft have been instrumented to collect data on toxic gases present during combustion. In one such test, Marcy found that carbon monoxide occurred in greater toxic concentrations than any other gas(23). This was not a typical crash-fire, however, since the fire was ignited inside the cabin in the interior materials and no fuel was present. Conley(25) found that the escape time for carbon monoxide was never attained during his tests, and that the escape time depended solely on the temperature generated by the fire.

The carbon monoxide concentrations obtained during Pesman's study[15] have already been shown in Figure 6. Figure 14 presents these data again, with the addition of the calculated carboxyhemoglobin levels that would be experienced by an occupant in this environment. It can be seen that the average escape time as limited by the carboxyhemoglobin concentration would be approximately 370 seconds. (The lag of the carboxyhemoglobin level, as compared to the carbon monoxide percentage in the air, is due to the time taken for the carbon monoxide to be absorbed into the occupant's circulatory system.) This escape time is considerably longer than the heat-limited escape time of 135 seconds that was found in this study. In one test, however, carbon monoxide was the limiting factor. Pesman points out that,

> "Although the escape times as limited by carbon monoxide poisoning are longer than those limited by thermal skin injury, the difference does not justify disregarding carbon monoxide as a hazard."

Pesman's statement is entirely appropriate in view of the reports on two loss-of-life accidents[39,53]. Sixteen passengers died in the crash of a DC-8 at Denver, Colorado. These passengers were found in aisle seats different from those for which they were ticketed, indicating that they were standing in line to get out of a single exit when overcome by carbon monoxide poisoning. In the Boeing 727 crash at Salt Lake City, 43 of the 91 occupants died. The Civil Aeronautics Board (CAB) report states,

> "Our preliminary findings indicate that none of these fatalities were due to traumatic injuries but all died from suffocation during the resultant fire. This is evidenced by the elevated carboxyhemoglobin concentrations in the victims and lack of trauma."

Pesman also measured the carbon dioxide concentrations during the series of fire tests. The physiological tolerance limit for carbon dioxide was reached only once during the 10-minute sampling period for these fires. In no case did carbon dioxide limit the escape time; thus, carbon dioxide was not considered as important a hazard as either carbon monoxide poisoning or thermal injury.

The odor of some gas samples in this series of tests indicated that aldehydes were also present. Analysis of one sample indicated an aldehyde concentration of approximately 1/2 percent. In this concentration aldehydes are very irritating to the eyes and respiratory system, but an escape time

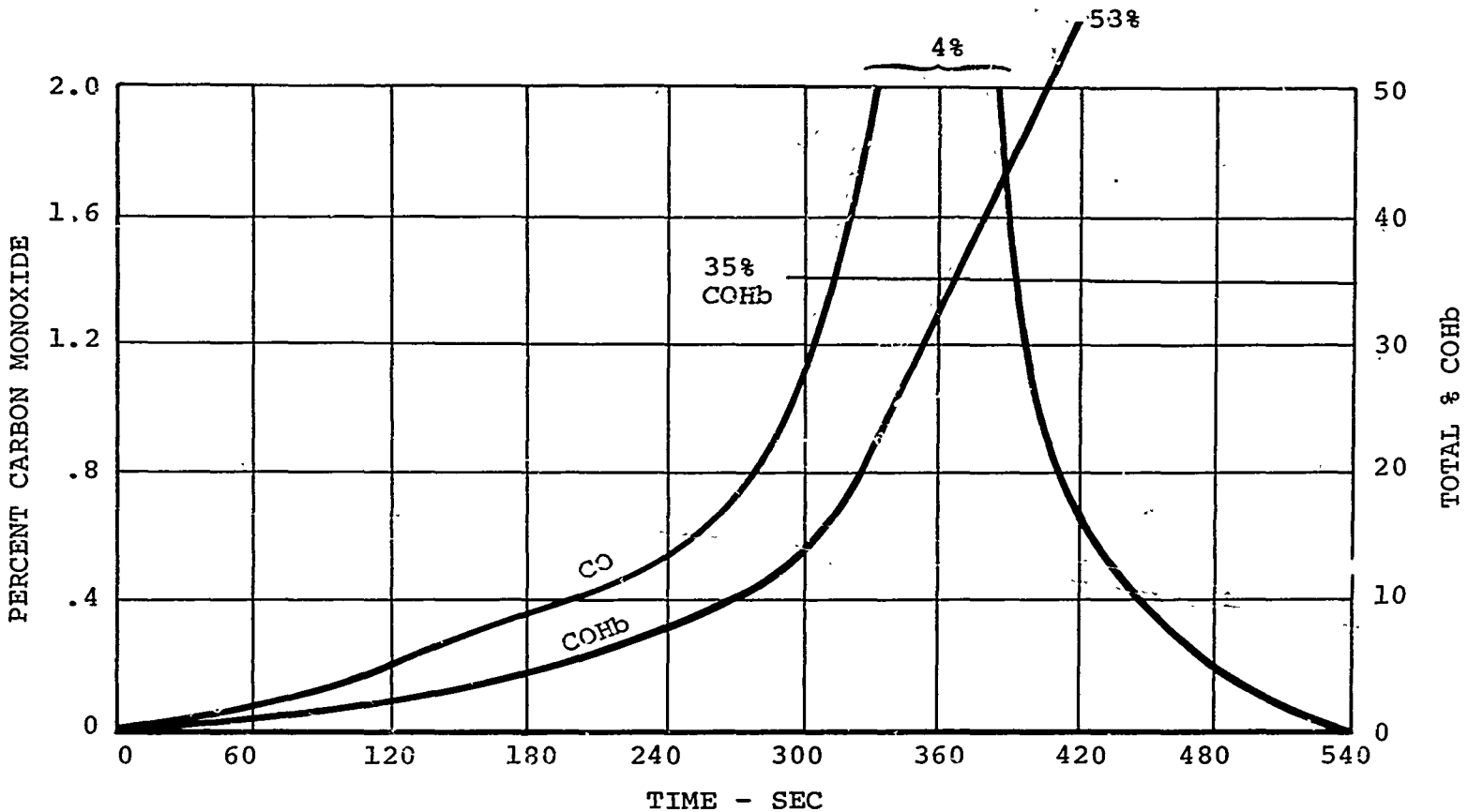


Figure 14. Average Recorded CO Concentrations and Calculated COHb Levels in Several Crashed, Burning Passenger/Cargo-Type Aircraft.

could not be calculated because of insufficient physiological data.

g. Escape Time in Helicopters

Only one series of fire tests involving five cargo-type helicopters has been instrumented for carbon monoxide concentrations[21]. The average carbon monoxide concentrations were given in Figure 7. Figure 15 shows these concentrations again, along with the calculated carboxyhemoglobin levels that would be present in an occupant in this environment. It can be seen that carbon monoxide was not a factor in the escape time since it never exceeded the tolerable limits. However, in a helicopter crash at Idlewild Airport, three of the six occupants who died in the crash were asphyxiated by combustion products and did not die as a direct result of the impact[8]. Thus, carbon monoxide should not be ruled out as an escape-limiting factor, especially in the larger helicopters.

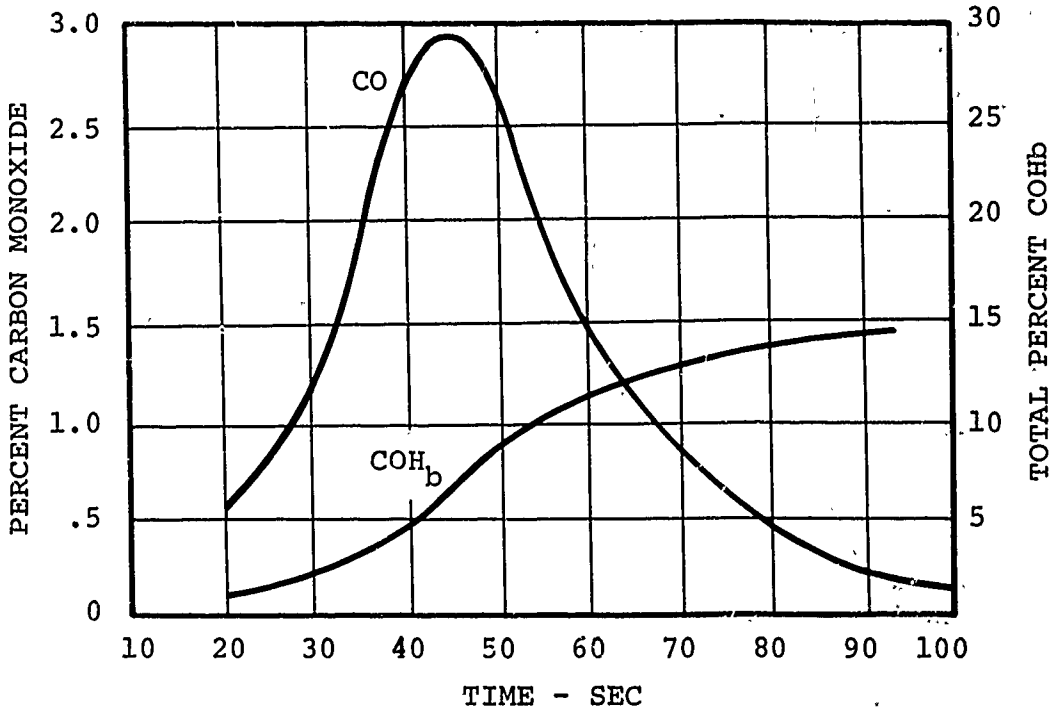


Figure 15. Average Recorded CO Concentrations and Calculated COHb Levels in Several Crashed, Burning Passenger/Cargo-Type Helicopters.

4. Miscellaneous Factors Influencing Escape Time

a. General

Miscellaneous factors affecting escape time are:

- Smoke
- Obstructions to Vision
- Structural Breakup
- Aircraft Orientation
- Obstacles Within the Cabin
- Panic of the Occupants

These are all rather intangible factors and have not been adequately measured. These factors vary from crash to crash, with the exception that smoke will always be present in a postcrash fire. The amount of smoke, however, and its location with respect to the aircraft structure will vary.

This search uncovered only one series of tests studying these miscellaneous factors. The effect on passengers' reactions and egress of smoke, debris in the aisles, unnatural floor angles, and varying light conditions were studied in emergency evacuation tests of a previously crashed Lockheed Constellation[54].

b. Smoke

In studying the effect of smoke during these tests, it was found that the smoke which was released into the cabin was so dense that the aft stewardesses couldn't see two rows away. People under poor visibility conditions depended upon persons in front of them for directional guidance and had to follow those passengers making sounds or talking.

The hazards of smoke in postcrash fires can also be estimated from accident reports. In two survivable accidents[18,39] heavy smoke was reported inside the cabin area immediately after impact. This smoke made breathing extremely difficult and obscured vision to a great extent. In fact, in the crash of the Boeing 727 at Salt Lake City, a woman was seated in a window seat next to a window exit. A man opened the exit beside her while the aircraft was still moving. She reported that the smoke made it impossible to see the exit, but she could feel the air and knew where the opening was.

c. Obstructions to Vision

Obstructions to vision, other than smoke, include darkness and structural obstacles. In the Lockheed Constellation evacuation tests, the time required to evacuate the airplane cabin at night was significantly longer than during the day (approximately three minutes at night compared to two minutes during the day). Survivors of the Salt Lake City crash reported that the lack of visibility due to darkness hampered their escape.

An example of structural obstructions to vision can be found in the accident report of the DC-8 crash at Denver, Colorado. In this accident most of the passengers in the tourist compartment tried to exit through the one available door in the rear of the aircraft, although there were exits in the first class compartment which many passengers could have used. The analysis of the accident indicated that a floor-to-ceiling partition, which separated the tourist cabin from the first class section, effectively blocked from the view of the tourist passengers any sight or sign of the overwing exits available in the first class cabin. Undoubtedly, more of the occupants would have survived had they used these overwing exits.

d. Structural Breakup

Aircraft structural breakup definitely influences the intensity and location of the postcrash fire, mainly by affecting fuel spillage patterns and internal air flow, but these effects are difficult to predict. Examples of the effects of varying fuel spillage patterns are illustrated in the following two accidents. In the crash of a Lockheed Constellation at Richmond, Virginia[8], the wings tore free on impact, spraying burning fuel on the fuselage, resulting in the deaths of 77 of the 79 people aboard in the ensuing fire. However, in the crash of a Lockheed Electra at LaGuardia Airport[17], the left wing separated from the fuselage at impact, taking that source of fuel away from the occupiable area. There were no fatalities among the 76 occupants, although a sizeable postcrash fire did occur.

The effects of air flow within the fuselage on the available escape time have not been thoroughly studied. Internal air flow will increase the intensity of the fire, as discussed in Section I.B.2.d., and will also distribute smoke and toxic gases throughout the fuselage structure. The magnitude of the internal air flow is predicated on the size and number of openings in the fuselage structure. Test results have shown that the air velocity increases as the size and

number of openings increase until the chimney effect is destroyed, after which the air velocity decreases. Unpublished data from Dynamic Science indicate internal air flows in crashed, burning helicopters can range from 20 to 35 mph, even when atmospheric wind conditions are calm. These high internal air flow velocities would certainly decrease the available escape time, but the magnitude of the decrease is unknown.

e. Aircraft Orientation

Abnormal orientation of the fuselage after a crash could cause difficulties, but it does not seem to be a major hazard. The evacuation tests of the Lockheed Constellation indicated that, although the fuselage was resting on its belly facing up a 20-degree hill, the slope of the cabin did not hinder emergency evacuation. In the Lockheed Electra crash, in which the fuselage ended up in an inverted position, evacuation was orderly and efficient. The crew stated that they were momentarily confused by the inverted position and were hunting for the side window latch, normally at the bottom, on what was actually the top of the window. It was evident to rescuers, however, that they would have found the latch in a short time. Fuselages which come to rest on their sides probably create more confusion than either the upright or inverted positions.

Probably the greatest hazard from structural breakup and orientation occurs when one or more of the emergency exits become inoperable. This hazard appeared in the DC-8 crash at Denver, Colorado, where one of the two exits in the tourist compartment was blocked when the skidding aircraft hit a pickup truck and wedged a door shut(39). This left only one exit for the 81 tourist passengers. Only 51 of the 67 attempting to use this rear exit succeeded in leaving the aircraft.

f. Obstacles within the Cabin

Obstacles within the cabin compartment would generally be small debris from the galley area or the overhead racks, although obstacles from structural deformation, such as loose seats, may sometimes be present. In the evacuation tests of the Lockheed Constellation, it was found that preplaced debris piled in the aisles or flying debris off the overhead racks caused a minimum of difficulty in evacuations. In the DC-8 crash cited above, however, paraphernalia was ejected from an upper storage locker and deposited in a "knee-deep" pile against the passenger door. The stewardess did not attempt to open the door because of the debris. This is the door that was wedged shut and could not have been opened

anyway, but in other circumstances the debris could have prevented passengers from using an otherwise available exit.

g. Panic of the Occupants

Panic is probably the most intangible factor of all and is not always present. The incidence of panic apparently depends somewhat on the crash-fire environment but, even more importantly, on the individuals involved. In two air-carrier accidents involving postcrash fire (Lockheed Electra and DC-8), no panic was reported although 16 of the occupants in the DC-8 were killed in the ensuing fire. However, in the Boeing 727 crash in Salt Lake City, although panic was not rampant, the stewardess could not get to the front entrance because of the crowd of people already around it. It is also interesting to note that in the evacuation tests of the crashed Lockheed Constellation, approximately 50 percent of the subjects reported some panic feelings during the test, although they realized they were not in an actual fire environment.

In a study of the psychophysiological factors in U.S. Air Force aircraft mishaps involving ground egress[55], it was found that egress difficulties occurred in 42 percent of the accidents with fire, whereas difficulties occurred in only [illegible] percent of the accidents without fire. Even in a highly trained population, such as Air Force pilots, degraded or ineffective performance with fire occurred in 13-1/2 percent of the cases, but without fire in only four percent of the cases.

It should also be noted that, of the commercial airliner accidents mentioned above, only in the case of the Boeing 727 was fire actually present inside the cabin. Since this was the only accident cited where any panic was noticed, these examples seem to support Bieberdorf and Yuill's statement that, in considering flame

> "Only as the visible evidence of fire, the primary hazard would appear to be the psychological one of panic."[37]

D. Summary

The preceding survey has documented the information available to date on aircraft postcrash fire environments and the fire hazards thus presented to an aircraft occupant. The magnitude of these hazards, coupled with human tolerance limits, determine the escape time available to the occupant.

The major hazards of a postcrash fire are circumambient heat, circumradiant heat, toxic gases, and smoke. The

magnitude of these hazards is dependent on many factors present in the postcrash situation. The following discussion summarizes the information on these factors.

Fuel Type

Laboratory tests and full-scale fire tests have shown that although the volatility of the fuel affects ignition time, it has little effect on the fire environment once ignition has taken place. Differences in flame-spread rates and flame temperatures of the fuels are insignificant compared to the total fire propagation rate and temperature.

Local Terrain

Enough information exists to determine the general effects of various ground surfaces on the fire environment. Not enough information is available, though, to determine accurately the magnitude of the various effects. For example, the spillage rate will be greater on a cement surface, where the fuel can spread, than on sandy surfaces. The intensity and duration of the fuel fire, however, could be greater on the sandy soil, where the fuel is held in a small area, than where the fuel is spread thinly over a cement surface.

Aircraft Structure

Intact aircraft structure affects escape time by protecting an occupant inside the fuselage from the heat, smoke, and toxic fumes of an external fire. Burn-through time is, therefore, a predominant consideration. Some data have been obtained on several thicknesses of sheet-aluminum skin. Several of the newer aircraft, however, have skin thicknesses greater than those tested, and information must be obtained for these thicker skins. No information was found on burn-through times for honeycomb structures, whether of metal or synthetic composition.

Insulation

It has been established that some types of insulation on the inside of the aircraft will allow the skin to burn through more rapidly than without insulation. There are other insulative materials now available, however, for which no data were found. In addition, the effect of insulation on protecting an occupant inside the fuselage from an external fire has not been established.

Interior Materials

Extensive laboratory tests have been conducted on a wide variety of aircraft interior materials. Extrapolation of these laboratory tests to actual aircraft crash-fire environments is difficult and uncertain, and only a few tests have been conducted within aircraft fuselages. Thus, although a great deal is known about the burning properties of the materials themselves, not much is known about their contribution to the overall fire environment. Additional information is needed concerning the effect of various materials on the total circumambient and circumradiant heat loads, as well as their contribution to the total amount of smoke and toxic gases present in the crash-fire environment.

Structural Breakup

The main influence of structural breakup is the regulation of the amount of flame and air entering the fuselage. The amount of flame which is allowed to enter is also dependent on the fire size and location with respect to the structural openings. The chimney effect, which pulls in air and increases internal fire intensity, is solely dependent on the size and number of the openings in the fuselage. No data are available on the effect on the fire environment of the location, size, and number of openings in relation to the size of the total fuselage. It is impossible at this time to state whether the fire will be more severe with 10 percent, 90 percent, or 50 percent of the fuselage structure destroyed.

Fire "Wind"

The fire "wind", or internal air flow caused by the fire, has been recorded in some large helicopter fire tests, but has not been measured in any other type of aircraft. Because of the high air flow recorded in these tests and evidence of fire "winds" in other aircraft tests, efforts should be made to determine the internal air flow rates present in all types of aircraft. In addition, the effects of the internal air flow on the dissipation of smoke, toxic fumes, and hot air, as well as flame-spread rates, should be determined.

Aircraft Configuration

The one variable that probably has the most effect on the postcrash fire environment is the configuration of the aircraft involved. Although it is impossible to say that all crashes involving a particular type of aircraft will be identical, there are enough similarities so that a general fire environment can be defined for each type.

Since this study is primarily directed toward U. S. Army helicopters and light aircraft, only these two configurations will be summarized here.

Statistics indicate that postcrash fire is a much greater hazard for helicopters than for fixed-wing aircraft. In helicopters the fuel tanks are generally located inside the fuselage, while in fixed-wing airplanes the fuel tanks are usually located in the wings. The fire environment in helicopters is probably more severe, therefore, because of the closer proximity of the fuel tanks to the occupiable area. In addition, accident reports indicate that the primary cause of injury and death in helicopter postcrash fires is heat and not toxic gases, whereas in large fixed-wing aircraft accidents, toxic gases have a much greater part in causing fatalities. Again, this difference is probably due to the closer proximity of the occupants and the fuel, and also to the smaller amount of occupiable space in the helicopters.

Whether this is a general rule for all helicopters, however, is open to question. In crashes of large passenger-carrying helicopters, occupants have been asphyxiated by combustion products. This suggests that the larger occupiable area and the greater distance between the occupants and the fuel tanks in the larger helicopters might make their postcrash fire environments comparable to those of large fixed-wing aircraft. There is no way to substantiate this, however, as the limited number of helicopter crash-fire tests have not furnished enough data to define differences between the large and small helicopters.

One might expect the postcrash fire environment in small fixed-wing airplanes to be comparable to that of helicopters because of the small amount of occupiable space and the proximity of the fuel to the occupants. The intense fires in the cockpit/cabin area which were noted in the light aircraft accident reports indicate a similarity to helicopter crash-fires. Statistics, however, show that the postcrash fire hazard is not as serious for light airplanes as for helicopters. This could be because the fuel is contained within the fuselage of the helicopters while it is contained within the wings of the light airplanes. The similarities and differences between the two aircraft cannot be defined, however, since no testing has been done on postcrash fires of light aircraft.

Although the complete series of tests conducted 20 years ago by NACA defined the large fixed-wing aircraft fire environment in detail, these data must be extrapolated to the smaller aircraft for use in this study. Since there is a definite lack

of information concerning the fire environment in smaller aircraft, testing offers the only reliable method of obtaining these data.

II. ASSESSMENT OF SPECIFIC FIRE HAZARDS IN RELATION TO AIRCRAFT TYPE

A. Introduction

Part I of this report summarized the available knowledge of the aircraft fire environment and the human tolerance to such an environment. No attempt was made to correlate the current state-of-the-art with the level of knowledge required to support engineering studies to improve human survival in postcrash fires. This section of the report provides an assessment of the foregoing literature search and applies the knowledge to selected sizes and shapes of Army aircraft.

As discussed in Part I, the magnitude of the postcrash fire hazard is dependent on many variables present in the postcrash situation. The predominant variables which must be considered are reiterated below:

- Aircraft Structure
- Structural Breakup
- Insulation
- Fuel Type
- Fluid Spillage Rate
- Fire Size and Location
- Local Terrain
- Fire "Wind"
- Interior Materials

The previously mentioned variables combine to produce a time/development history of each of the major hazards (circumambient heat, circumradiant heat, toxic fumes, and smoke). This time/development history, coupled with the effects of the hazards on the occupant's vision and his tolerance limits, determines the escape time available to the occupant.

The time/development histories for these major hazards are roughly defined for some aircraft in all sizes except for single-engine light aircraft. No full-scale crash-fire tests have been conducted on the single-engine light aircraft. Any assessment of the hazards involved in their crash-fires must be estimated from accident reports involving similar size and shape aircraft.

The information obtained during this study was assessed regarding the information necessary to define adequately the overall postcrash fire environment in four classes of Army aircraft. These classes, along with examples of the aircraft contained in each class, are as follows:

(1) Large, rotary-wing aircraft

UH-1D Iroquois

CH-47 Chinook

(2) Small, rotary-wing aircraft

OH-6 Cayuse

OH-13 Sioux

(3) Light, single-engine, fixed-wing aircraft

O-1 Bird Dog

U-1A Otter

(4) Light, multi-engine, fixed-wing aircraft

U-21 Ute

OV-1 Mohawk

The information available on each of the main hazards of circumambient heat, circumradiant heat, toxic fumes, and smoke was evaluated in relation to the influencing factors discussed above. The evaluation scale consists of five levels of knowledge, as follows:

(1) Area defined to a very accurate level by fully instrumented and high-speed film recorded tests, detailed accident and laboratory case studies, and thorough engineering analyses.

(2) Area defined to a reasonably accurate level by instrumented and high-speed film recorded tests, accident and laboratory case studies, and comparative engineering analyses.

(3) Area roughly defined by testing, high-speed film study, accident case review, engineering opinions, and some data extrapolation.

(4) Area defined by data extrapolation and by engineering opinions.

(5) Area undefined.

B. Discussion of Influencing Factors

The evaluations for each class of aircraft are shown in Tables X through XIII.

Since escape time is the ultimate measure of any postcrash fire threat, the magnitude of the factors used to estimate the escape time must be defined to a reasonably accurate level.

As can be seen in the tables, the magnitude of the factors which govern the escape time, when applied to various aircraft sizes and shapes, is not very well known. In fact, some areas are not defined at all.

An overall evaluation of the tables indicates that one could estimate the probable escape time from a large rotary-wing aircraft more accurately than from any of the other three types. The evaluation also indicates that one could not evaluate the fire environment in a small single-engine aircraft accident, even to the 4 (engineering opinion) level.

As discussed earlier, the fire environment for large transport-size aircraft is somewhat defined. However, most of these data are not readily applicable to the Army size aircraft.

So that the reader may more clearly understand the rating system as shown in the tables, the following discussion of the ratings given to one of the Escape Time Limiters, that of circumambient heat, as shown on the Light Multi-Engine Fixed-Wing Aircraft Table (XIII), is presented.

1. Effect of Different Structures

Data concerning burn-through times exist for some sheet metal structures. However, no data are available for composite materials such as honeycomb. Consequently, the state of the knowledge concerning this overall effect is 4.

2. Effect of Structural Breakup

Data concerning flame entry into fuselages through damaged structure have been obtained during several burn tests. The data did not define differences between damage locations. However, the effects of openings in the fuselage are generally understood. A rating of 3 is given.

TABLE X. ASSESSMENT OF THE KNOWLEDGE OF HAZARDS TO HUMAN ESCAPE FROM LARGE ROTARY-WING AIRCRAFT CRASH FIRES

Escape Time Limiters	Influencing Factors											
	Effect of Different Structures	Effect of Structural Breakup	Effect of Insulation	Effect of Fuel Type	Effect of Fluid Spillage Rate	Effect of Fire Size and Location	Effect of Local Terrain	Effect of Fire "Wind"	Effect of Interior Materials	Time/Development History	Effect on Vision	Human Tolerance Limits
Circumambient Heat	4	3	4	2	3	3	3	4	3	3	4	2
Circumradiant Heat	4	3	3	2	3	3	3	4	3	3	4	1
Toxic Fumes	4	3	4	2	4	3	4	3	3	3	3	3
Smoke	3	3	4	2	4	3	4	3	3	3	3	3

CODE

1. Area defined to a very accurate level by fully instrumented and high-speed film recorded tests, detailed accident and laboratory case studies, and thorough engineering analyses.
2. Area defined to a reasonably accurate level by instrumented and high-speed film recorded tests, accident and laboratory case studies, and comparative engineering analyses.
3. Area roughly defined by testing, high-speed film study, accident case review, engineering opinions, and some data extrapolation.
4. Area defined by data extrapolation and by engineering opinions.
5. Area undefined.

TABLE XI. ASSESSMENT OF THE KNOWLEDGE OF HAZARDS TO HUMAN ESCAPE FROM SMALL ROTARY-WING AIRCRAFT CRASH FIRES

Escape Time Limiters	Influencing Factors											
	Effect of Different Structures	Effect of Structural Breakup	Effect of Insulation	Effect of Fuel Type	Effect of Fluid Spillage Rate	Effect of Fire Size and Location	Effect of Local Terrain	Effect of Fire "Wind"	Effect of Interior Materials	Time/Development History	Effect on Vision	Human Tolerance Limits
Circumambient Heat	4	3	4	2	3	3	3	4	3	3	4	2
Circumradiant Heat	4	3	3	2	3	3	3	4	3	3	4	1
Toxic Fumes	4	3	4	2	4	4	4	4	3	4	4	3
Smoke	3	3	4	2	4	3	4	3	3	3	3	3

CODE

1. Area defined to a very accurate level by fully instrumented and high-speed film recorded tests, detailed accident and laboratory case studies, and thorough engineering analyses.
2. Area defined to a reasonably accurate level by instrumented and high-speed film recorded tests, accident and laboratory case studies, and comparative engineering analyses.
3. Area roughly defined by testing, high-speed film study, accident case review, engineering opinions, and some data extrapolation.
4. Area defined by data extrapolation and by engineering opinions.
5. Area undefined.

TABLE XII. ASSESSMENT OF THE KNOWLEDGE OF HAZARDS TO HUMAN ESCAPE FROM LIGHT SINGLE-ENGINE, FIXED-WING AIRCRAFT CRASH FIRES

Escape Time Limiters	Influencing Factors											
	Effect of Different Structures	Effect of Structural Breakup	Effect of Insulation	Effect of Fuel Type	Effect of Fluid Spillage Rate	Effect of Fire Size and Location	Effect of Local Terrain	Effect of Fire "Wind"	Effect of Interior Materials	Time/Development History	Effect on Vision	Human Tolerance Limits
Circumambient Heat	4	3	4	2	3	3	3	4	3	4	4	2
Circumradiant Heat	4	3	3	2	3	3	3	4	3	4	4	1
Toxic Fumes	4	3	4	2	4	4	4	4	3	5	4	3
Smoke	3	3	4	2	4	4	4	4	3	5	4	3

CODE

1. Area defined to a very accurate level by fully instrumented and high-speed film recorded tests, detailed accident and laboratory case studies, and thorough engineering analyses.
2. Area defined to a reasonably accurate level by instrumented and high-speed film recorded tests, accident and laboratory case studies, and comparative engineering analyses.
3. Area roughly defined by testing, high-speed film study, accident case review, engineering opinions, and some data extrapolation.
4. Area defined by data extrapolation and by engineering opinions.
5. Area undefined.

TABLE XIII. ASSESSMENT OF THE KNOWLEDGE OF HAZARDS TO HUMAN ESCAPE FROM LIGHT MULTI-ENGINE, FIXED-WING AIRCRAFT CRASH FIRES

Escape Time Limiters	Influencing Factors											
	Effect of Different Structures	Effect of Structural Breakup	Effect of Insulation	Effect of Fuel Type	Effect of Fluid Spillage Rate	Effect of Fire Size and Location	Effect of Local Terrain	Effect of Fire "Wind"	Effect of Interior Materials	Time/Development History	Effect on Vision	Human Tolerance Limits
Circumambient Heat	4	3	4	2	3	3	3	4	3	3	4	2
Circumradiant Heat	4	3	3	2	3	3	3	4	3	3	4	1
Toxic Fumes	4	3	4	2	3	4	4	4	3	4	4	3
Smoke	3	3	4	2	3	3	4	3	3	3	3	3

CODE

1. Area defined at very accurate level by fully instrumented and high-speed film recorded tests, detailed accident and laboratory case studies, and thorough engineering analyses.
2. Area defined to a reasonably accurate level by instrumented and high-speed film recorded tests, accident and laboratory case studies, and comparative engineering analyses.
3. Area roughly defined by testing, high-speed film study, accident case review, engineering opinions, and some data extrapolation.
4. Area defined by data extrapolation and by engineering opinions.
5. Area undefined.

3. Effect of Insulation

Some insulations placed inside the fuselage can cause external flames to burn through the fuselage skin faster than if there were no insulation. This phenomenon has been determined for only a few types of insulations. It has not been determined if an early burn-through is actually undesirable. For example, an uninsulated fuselage, when heated from the outside, will immediately radiate heat on the inside; however, the ambient heat level will remain relatively low until burn-through. Conversely, the insulated fuselage will have a relatively low ambient and radiant temperature rise until burn-through occurs, whereupon both hazards will immediately rise. It is not known which of these two situations, insulated or uninsulated, will provide a longer escape time. Only an engineering opinion can be offered; consequently, a 4 rating is given.

4. Effect of Fuel Type

All reviewed data indicate that while there are differences in fuels, these differences are insignificant when subjected to the crash fire environment. There is considerable data to substantiate the conclusions; consequently, a rating of 2 is given.

5. Effect of Fluid Spillage Rate

Overall fire size can be affected by spillage rate. Fire size directly affects the temperature/time history for any given aircraft size. Fire sizes have been measured both by instrumentation and by photographic coverage. They do not apply to all aircraft because of aircraft size differences; however, a realistic extrapolation can be made. A rating of 3 is given.

6. Effect of the Size and Location

Different fire sizes at several different locations have been measured in some test burns. Their effect can be extrapolated to other aircraft of the same size and shape. However, the heat influence of different structural materials and fire locations in other areas is unknown. Still, enough data does exist to allow a rough estimate of the overall effect. A rating of 3 is given.

7. Effect of Local Terrain

Fires have been observed on a variety of different terrain conditions. The behavior of the fires during different

spillage rates and quantities, however, is not reliably documented. The influence of such features as vegetation or sand has been occasionaly reported. A rough appraisal of the overall fire effect can be obtained; consequently, a rating of 3 is given.

8. Effect of Fire "Wind"

The internal fire wind has been observed during several burn studies; however, its actual effect on the overall fire kinematics is unknown. It can be theorized that the wind might bring in more fresh air, which would support a more complete combustion; however, this fresh air may also allow the occupants to sustain themselves by breathing it instead of toxic or smoky air. Any attempt to appraise the actual effect, at this time, is purely speculative. A rating of 4 is given.

9. Effect of Interior Materials

Many interior materials have had their flammability properties studied in detail. Others have never been studied. Because of this large spread in knowledge, a 1 or a 5 cannot be given. An average (3) is assigned, because there is accurate data available for many of the current materials, although some still must be studied.

10. Time/Development Histories

All factors discussed so far can affect the time history. Some will influence it more than others, but all will affect it. A temperature/time history for the circumambient heat has been measured in several multi-engine, fixed-wing aircraft. The environment can be extrapolated to some other aircraft of the same size and shape with a reasonable degree of accuracy. For others, extrapolation would be much more difficult. Overall, this factor is rated 3.

11. Effect on Vision

The effect of hot air blowing in the face of an aircraft occupant has never been studied. Moving hot air in all burning aircraft has been recorded. One can theorize about the effects, and can substantiate that the moving air is there. Its actual effects on vision, however, can only be guessed. A rating of 4 is given.

12. Human Tolerance Limits

The medical study of human tolerance to circumambient temperatures has been extensively studied. While

there are some areas which could be studied in more detail, such as the influence of humidity and protective coverages, a reasonably accurate appraisal of man's reaction to hot air has been obtained. This area is given a rating of 2.

C. Criteria for Additional Work

The above discussion shows that while much information is known about the crash fire environment, much more data must be obtained to define a fire environment accurately for a specific aircraft. Each of the hazards, and thus the probable escape time must be defined to a knowledge level corresponding to a 2 on the valuation scale. Additional studies and tests must be conducted in all areas with a rating of 3 or below to gain needed information.

Tables X through XIII show that the only areas not requiring further study are those of the effect of fuel type on the fire environment and of human tolerance limits to circumambient and circumradiant heat. All other areas need additional study. The relative amount of effort which must be expended in each area can be judged by the evaluation numbers. Recommendations for further research in these areas are presented in Part III.

III. RECOMMENDATIONS FOR FUTURE RESEARCH

A. Introduction

Part II of the report presented a summary of today's understanding of the aircraft postcrash fire environment. The tabulation brought to focus numerous deficiencies in understanding the postcrash fire environment and, consequently, the inability to predict escape time. The results of this literature study emphasize the need for well-instrumented tests to upgrade the level of knowledge. A series of such tests specifically selected to improve the overall knowledge of the postcrash fire environment for Army aircraft is now presented.

The complexity of the postcrash fire environment resulting from the many variables involved makes it virtually impossible to conduct enough tests to obtain all the answers. However, an approach can be taken to maximize the results of an empirical test program of limited size. This concept is based upon the thesis that an accurately defined crash-fire environment for a typical aircraft size and shape can be realistically applied to any other aircraft of the same general size and shape, if influence factors between the two fire environments are known.

The recommended test program is separated into three parts: Basic Fuselage Fire Characteristic Tests; Full-scale Aircraft Fire Tests; and Human Tolerance Tests. The Basic Characteristic Tests can be further divided into Simulated Structure Burn Tests, Fuselage Skin Burn Tests, and Terrain Burn Tests. The following text briefly describes each series of tests and the associated data acquisition and hardware.

B. Basic Fuselage Fire Characteristic Tests

The basic fuselage fire characteristic test series shown under Item 1 in Table XIV will yield data which are applicable to any type of aircraft crash environment. The objective of this test series is to obtain meaningful data on factors which influence postcrash fires at a minimum of expense.

1. Simulated Structure Burn Tests

It is recommended that two different sizes of steel frame structures simulating large and small Army aircraft be utilized in this test series. The frames should have movable skin panels made of steel and other materials. The test structures should be instrumented to provide the detailed data required for the variables shown in Table XIV.

TABLE XIV. CRASH FIRE STUDY PROGRAM

METHOD	Specific Study Areas											
	Effect of Different Structures	Effect of Structural Breakup	Effect of Insulation	Effect of Fluid Spillage Rate	Effect of Fire Size and Location	Effect of Local Terrain	Effect of Fire Wind	Effect of Interior Materials	Effects on Vision	Fire Development/ Time History	Human Tolerance Limits	Probable Escape Time
1. BASIC FUSELAGE FIRE CHARACTERISTIC TEST												
Simulated Structure Burn Tests		X	X	X	X		X	X	X			
Fuselage Skin Burn Tests	X		X		X							
Terrain Burn Tests				X		X						
2. FULL-SCALE AIRCRAFT FIRE TESTS												
Actual Aircraft Burn Tests					X				X	X		X
3. HUMAN TOLERANCE TESTS												
Vision									X		X	X
Synergistic Toxicity Tests											X	X

By varying the skin panel locations and types, data can be generated to determine the effects of structural break-up, fluid spillage rate and location, internal wind, and vision obscuration. The test structures can also be used to gather empirical data to describe the influence of insulation and other interior materials on the severity of the postcrash fire environment.

2. Fuselage Skin Burn Tests

This burn study program should be designed to subject an array of aircraft skins to various types and sizes of fires. Sections of different aircraft and a variety of different insulative materials would be evaluated during the series. By testing assorted skin types and insulative materials, general knowledge concerning the differences in burn-through times with various fire sizes and locations can be gained.

3. Terrain Burn Tests

This series of tests should be designed to study fuel spillages under different terrain conditions. A test area containing an array of terrain features, including various slopes, soil consistencies, and flora, would be subjected to different fuel spillage rates and quantities. The relationship between fire duration and size would be obtained for an assortment of terrain conditions.

4. Test Equipment

A suggested list of equipment for the Basic Characteristic Test series is as follows:

- 1 ea. Fuselage Wreckage Simulator (CH-47 size)
- 1 ea. Fuselage Wreckage Simulator (OH-6 and U-6A size), Assorted sheets of steel, aluminum, and honeycomb
- 1 ea. Fuel Spillage Simulator
- 1 ea. Terrain Condition Simulator
- 2 ea. Aluminum Honeycomb Airframes, preferably hulks or wreckages from the UH-1 series
- 2 ea. Sheet Metal Airframes, preferably hulks or wreckages of the thin-skinned OH-6
- 2 ea. Sheet Metal Airframes, preferably hulks or wreckages of the thinner-skinned UH-19, CH-34, or CH-21

C. Full-scale Aircraft Fire Tests

While the programs previously described will yield much information which can be used to help define various aircraft crash-fire environments, they, by themselves, cannot define the actual crash fire. This can only be defined by burning actual aircraft. The recommended test series would subject four specific types of Army aircraft to carefully controlled burn tests. Suggested test setups are presented in Figures 16, 17, 18, and 19.

Multiple burn tests will be conducted to insure accuracy of the data. A combination of the data obtained in this part with the basic characteristic data will provide the tools for predicting postcrash fire environments in aircraft other than those specifically studied.

The following Army aircraft are recommended for characterizing the postcrash fires discussed:

Small Rotary-Wing Aircraft

2 ea. OH-6's*

2 ea. TH-55's*

Large Rotary-Wing Aircraft

2 ea. CH-47's*

Small Single-Engine Fixed-Wing Aircraft

2 ea. O-1's*

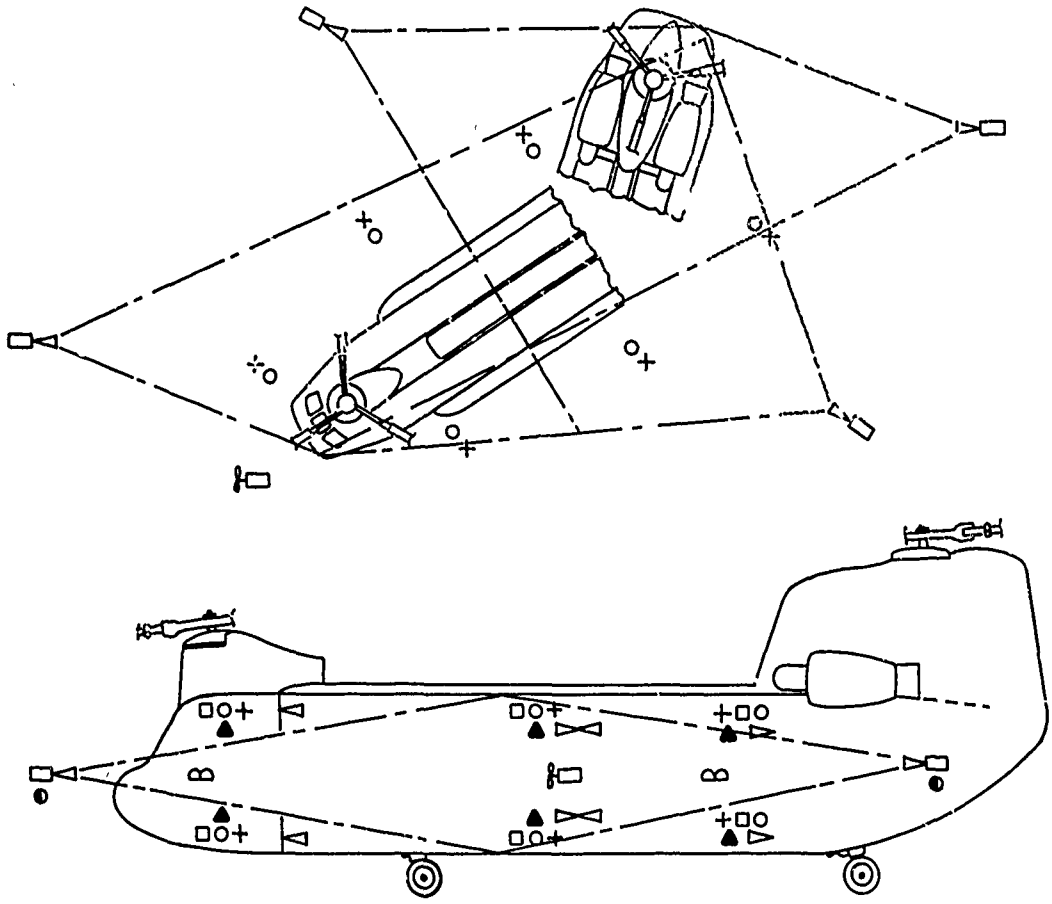
2 ea. U-6's*

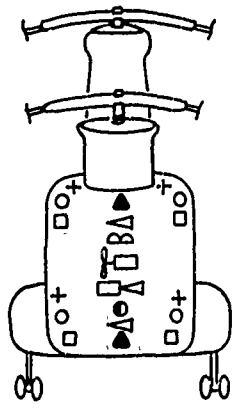
Small Multi-Engine Fixed-Wing Aircraft

3 ea. U-8's* or U-21's* or combination thereof

The airframes need not have rotor blades or engines; however, they should have cowlings, doors, transmissions, flooring, seats, upholstering, and typical accessories such as fire extinguishers and first aid kits. If wrecks are used, the wrecks in each class should be similar. The degree of damage should be light rather than extensive.

*All listed aircraft must be reasonably intact.





LEGEND

▲ = Gas Sampling

□ = Skin Temperature Sensor

o = Radiant Temperature Sensor

+ = Ambient Air Temperature Sensor

◁ = Single Direction Lamp

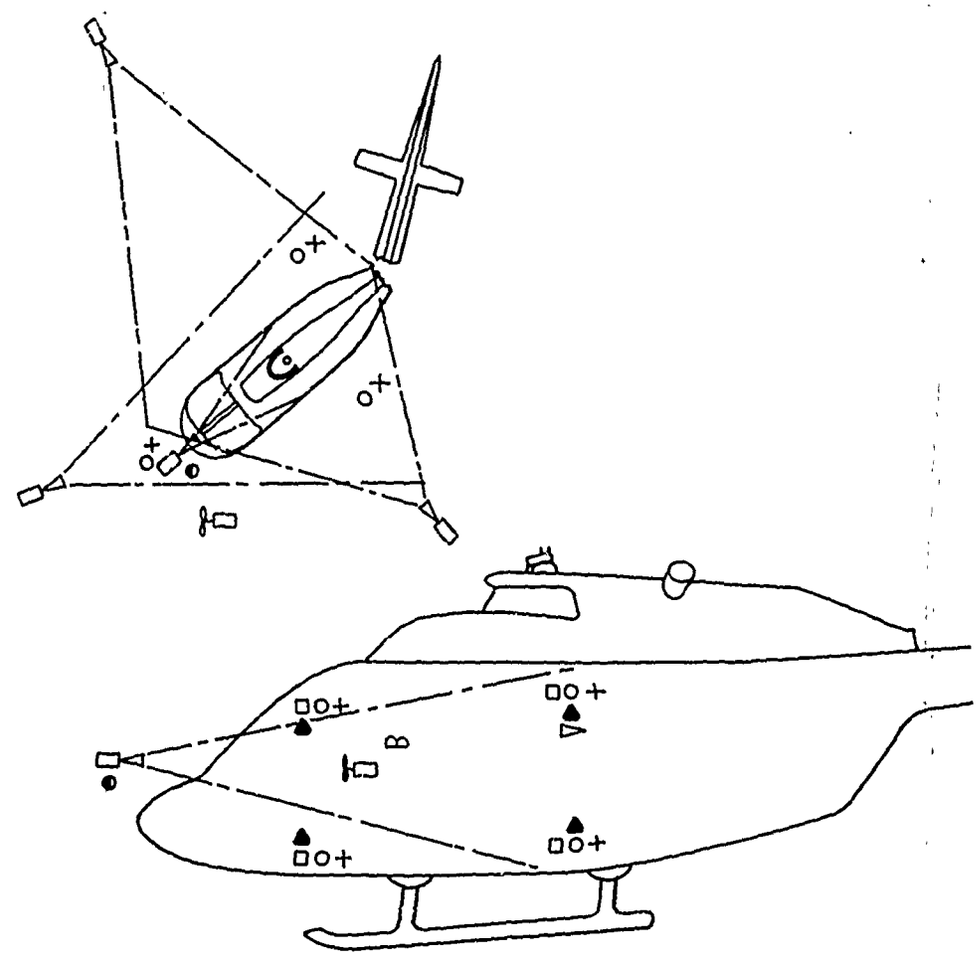
= Airspeed Recorder

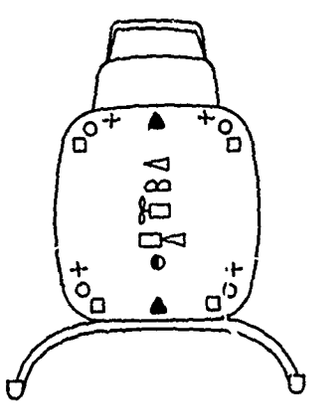
◐ = Optical Smoke Density Detector

= Camera

= Smoke Particle Counter

Figure 16. Suggested Test Setup For Large Rotary-Wing Aircraft Burn Studies.

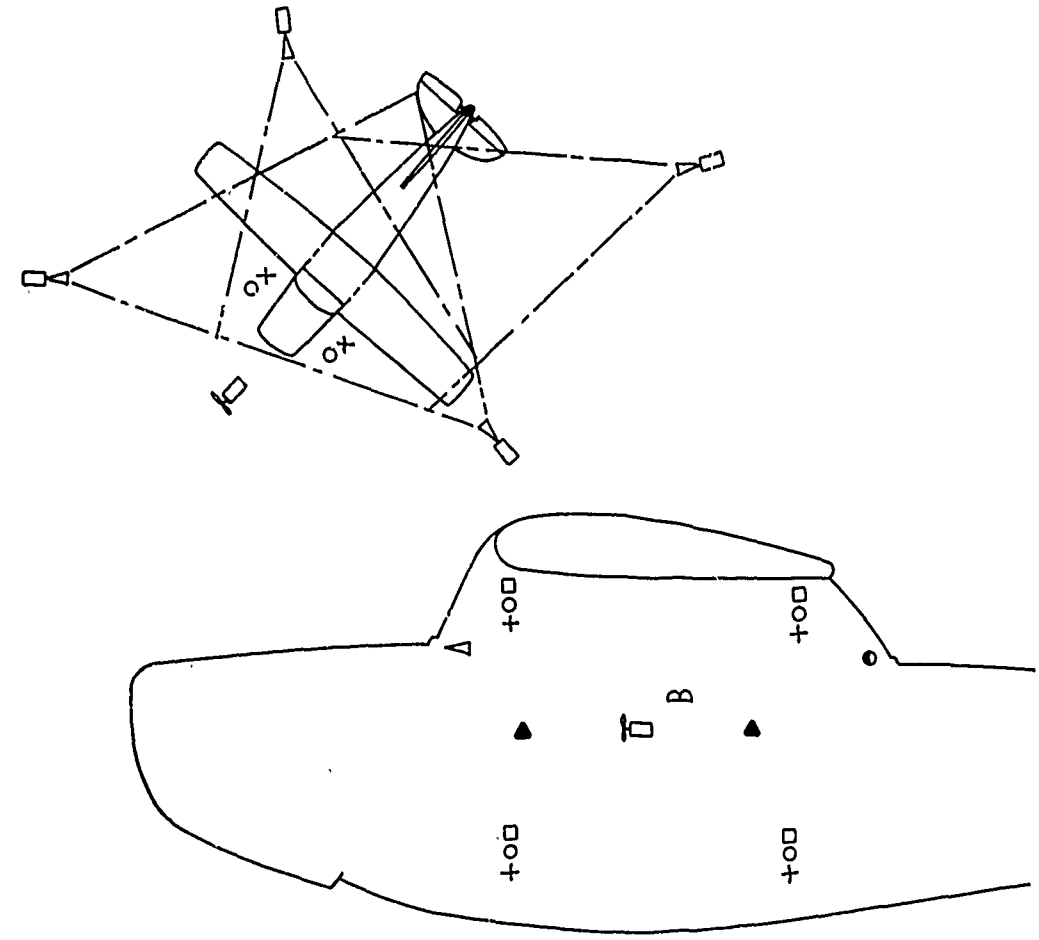


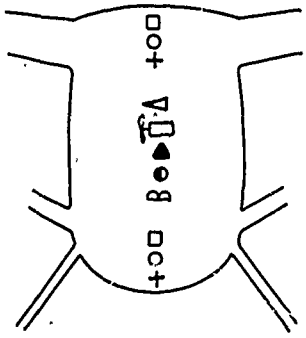


LEGEND

- ▲ Gas Sampling
- □ Skin Temperature Sensor
- o Radiant Temperature Sensor
- + Ambient Air Temperature Sensor
- ◁ Single Direction Lamp
- Airspeed Recorder
- ◐ Optical Smoke Density Detector
- Camera
- B Smoke Particle Counter

Figure 17. Suggested Test Setup For Small Rotary-Wing Aircraft Burn Studies.





LEGEND

▲ = Gas Sampling

□ = Skin Temperature Sensor

o = Radiant Temperature Sensor

+ = Ambient Air Temperature Sensor

◁ = Single Direction Lamp

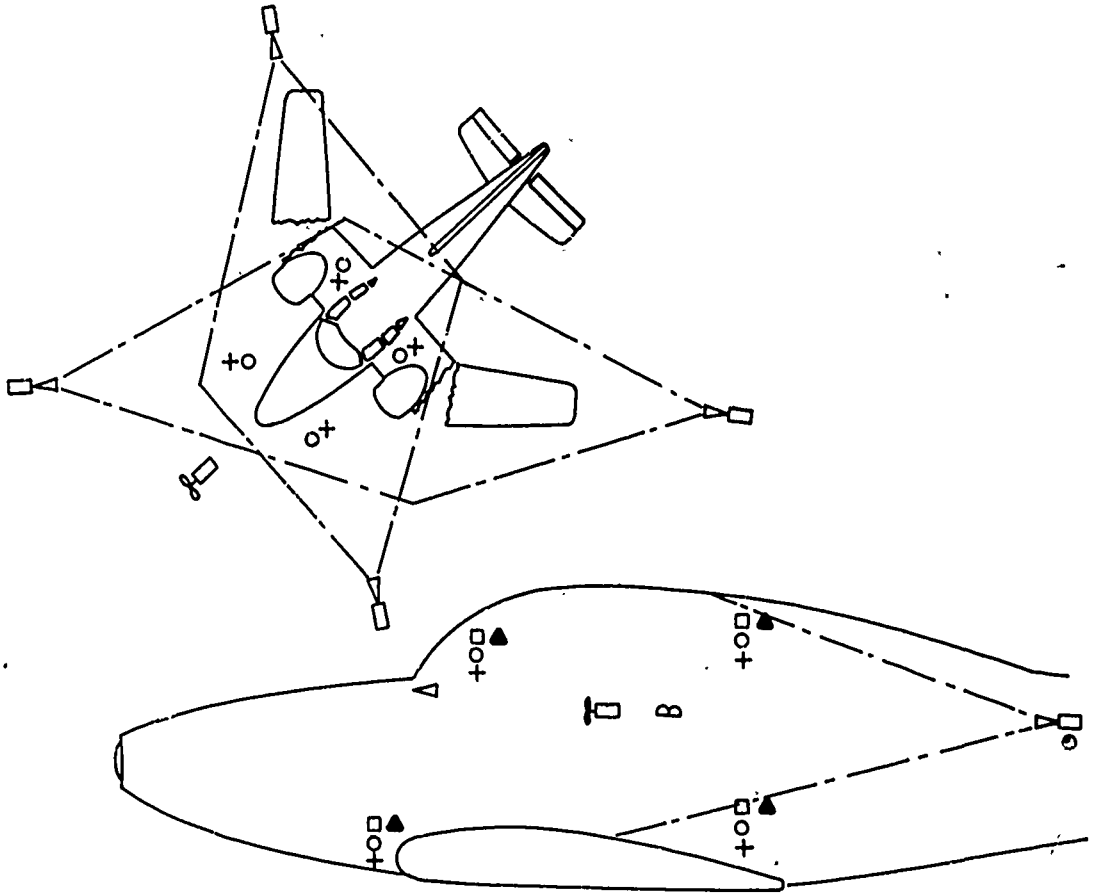
= Airspeed Recorder

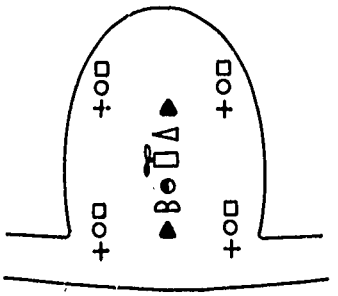
◐ = Optical Smoke Density Detector

= Camera

B = Smoke Particle Counter

Figure 18. Suggested Test Setup For Small Single-Engine, Fixed-Wing Aircraft Burn Studies.





LEGEND

▲ = Gas Sampling

□ = Skin Temperature Sensor

o = Radiant Temperature Sensor

+ = Ambient Air Temperature Sensor

◁ = Single Direction Lamp

= Airspeed Recorder

◐ = Optical Smoke Density Detector

= Camera

= Smoke Particle Counter

Figure 19. Suggested Test Setup For Small Twin-Engine, Fixed-Wing Aircraft Burn Studies.

The test instrumentation required for the actual test aircraft series is denoted in Figures 16, 17, 18, and 19.

D. Human Tolerance Tests

Three areas in need of further investigation were uncovered during this study: (1) the effect on vision of hot, moving air; (2) the correlation between smoke density and particle size versus eye irritation; and (3) the effect of heat on the toxicity of gases. A detailed search of the medical literature might provide some information in these areas. Where no information is available, actual testing must be done using human subjects, where possible, and animal subjects where necessary.

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Dynamic Science A Division of Marshall Industries Phoenix, Arizona	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

AN APPRAISAL OF THE POSTCRASH FIRE ENVIRONMENT

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Preliminary Report, 1952 - 1969

5. AUTHOR(S) *(First name, middle initial, last name)*

Neva B. Johnson, Donald E. Goebel and S. Harry Robertson

6. REPORT DATE September 1969	7a. TOTAL NO. OF PAGES 85	7b. NO. OF REFS 55
8a. CONTRACT OR GRANT NO. DAAG-17-69-C-0115 b. PROJECT NO. 1J662708D504 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* 70-22-CE; C&PLSEL-70	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Natick Laboratories Natick, Massachusetts 01760

13. ABSTRACT

A program was conducted to define the postcrash fire environment for helicopters and light aircraft, and to recommend additional testing, where necessary, to elevate the state of fire knowledge to a useful level.

A thorough literature search indicated that man's survival in an aircraft crash fire is predicated on four main factors: (1) the circumambient heat; (2) circumradiant heat; (3) toxic fumes; and (4) the obstruction to his vision. The magnitude of these factors, however, is dependent upon a variety of circumstances, including the degree of structural breakup, type of airframe structure, interior materials, and type of terrain surrounding the crash site.

A summary of all available data indicates that, while a great deal of knowledge does exist about fires, applying it meaningfully to the aircraft crash fire environment has only begun. Most fire test data found were for large transport-type aircraft. Some data were found for smaller aircraft; however, more data must be accumulated and analyzed before the small aircraft crash-fire environment can be defined.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Fire hazards	8					
Aircraft fires	8,9					
Crash landing	9					
Environments	8					
Aircraft	9					

Unclassified

Security Classification