A Study of the Helicopter Crash-Fire Problem

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A STUDY OF THE HELICOPTER CRASH-FIRE PROBLEM*

FOREWORD

The investigation covered by this report was conducted at the Federal Aviation Agency's Technical Development Center, Indianapolis, Indiana, under U S Army Transportation Research and Engineering Command, Contract 21X2040 709-9062 P 5030-07 S 44-019, Subtask 701, Project 9-38-01-000 dated December 11, 1956

SUMMARY

Helicopter crash accidents resulting in fire have become a serious hazard often destroying the aircraft and causing permanent or fatal injuries to occupants who normally would have survived the impact

Present helicopter design features were analyzed from a crash-fire safety standpoint The physical relocation of some components in helicopter aircraft could greatly reduce the probability of fire occurring in the event of a crash

Published literature concerning fixed- and rotary-wing aircraft accidents and crash-fire research investigations was reviewed and analyzed The need for developing design criteria and determining requirements for helicopter crash-fire protection was clearly indicated The results of this analysis indicated

1 The post-crash-fire accident represents a safety problem of greater magnitude in the larger transport-type helicopter than in the smaller type The development of crash-fire protection for the transport-type helicopter should be given primary consideration over all others

2 Available records of helicopter crash-fire accidents are inadequate for obtaining complete information related to the origin and propagation of fire There is a need for greater emphasis on reporting this type of information in accident reports

3 Abnormal engine displacement, landing-gear failures, and damaged drain cocks during a crash all were interrelated to fuel-cell failures and fuel spillage Fuel cells were damaged by puncture from foreign obstacles or by direct impact rupture from excessive gravity or shear forces during a crash

4 Helicopter crash accidents in which occupants would be expected to survive often originated from a hovering attitude and low-speed maneuvers near the ground, and during normal cruise conditions where control of the aircraft was maintained so that a near-level crash contact attitude with the ground resulted

5 Accidents in which occupants would not survive usually resulted from loss of control of the helicopter at a normal cruise altitude and crash contact with the ground at a steep nose-down or inverted attitude

6 Helicopter design features in many instances increase fire probability and limit passenger survival during a crash Recommended measures for crash-fire safety improvement include (a) engine shutdown during and after a crash, (b) provision of adequate safety exits, where necessary, to prevent entrapment of occupants should the helicopter roll over on one side, (c) relocation of components which contribute to fuel spillage and ignition (this may include landing lights, fuel cells, landing gears, or other accessories), and (d) the construction of undercarriage and forward skin crash contact panels of materials which will not produce sparks and high temperatures as a result of scraping contact with runway surfaces

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7 The chief ignition sources common to all types of jet and reciprocating engine aircraft during a crash are (a) hot surfaces inside and outside the engine, (b) exhaust system or tail-pipe flames, (c) induction system flashback (backfire), (d) electrical arcs and electrically heated filaments, (e) flames from chemical agents, (f) sparks caused by abrading metals, and (g) electrostatic sparks Hot surfaces are present at all times while the engine is operating and may persist for some time after engine shutdown at a temperature above the ignition points of gasoline, oil, and hydraulic fluids

8 Gasoline, kerosene, or JP fuel in the form of mist outside the aircraft or in the form of liquid or vapor within confined areas of the aircraft are considered the most hazardous of all combustibles associated with aircraft crashes

9 Ignition source elimination combined with fuel containment should be the basic objectives in providing crash-fire protection for the helicopter

10 Present crash-fire systems of conventional aircraft do not provide for the elimination of electrostatic and friction sparks

11 The use of aluminum on potential crash contact surfaces would reduce the probability of spilled fuel ignition from friction sparks Aluminum was found superior to all other materials tested while magnesium was found to be unsatisfactory

12 Further investigation by dynamic tests is needed to study certain aspects of crash-fire phenomena as they are specifically related to the helicopter Presently developed fixed-wing, crash-fire protection system concepts should be applied to helicopters and proposed systems evaluated through dynamic tests.

13 The development of new methods for inerting hot-surface ignition sources, looking toward a combined in-flight and crash-fire protection system for helicopters, is needed

INTRODUCTION

The purpose of this report is to establish the scope of the helicopter crash-fire problem by enumerating factors which contribute to the start and propagation of fire, and by presenting applicable information abstracted from reports on crash-fire research and development for fixed-wing aircraft.

The fatalities and injuries resulting from fire following a crash in survivable aircraft accidents constitute a serious safety problem A study of accidents involving fixed-wing air carrier transports has indicated that as high as 30 per cent of the passenger fatalities might be eliminated if fire did not occur during or after the crash [1]

The increased use of large rotary-wing aircraft having heavy payloads has necessitated large powerplants and fuel loads, thereby adding to the already complex fire safety problem In recent years, considerable progress has been accomplished in the development of crash-fire protection for fixed-wing aircraft Research on combustibles and ignition sources together with development of various types of crash-fire prevention systems for fixed-wing aircraft are discussed in available literature It is the intent of the author to apply some of these principles to the helicopter crash-fire problem

Helicopter accident statistics are presented to give the reader background information on the problem and to ascertain in which particular size helicopter the fatalities and accidents are more numerous Summaries of helicopter accident investigation reports are supplied in order that specific physical locations of the damage incurred and details of the fire problem may be analyzed

A general discussion is presented, and possible areas for future development are outlined

ACCIDENT STATISTICS

A recent Technical Development Report[2] containing a summary of accident statistics for rotary-wing aircraft indicated that 8 7 per cent of these accidents resulted in post-crash fire, and of the occupants involved, 42 5 per cent were injured fatally Of the occupants involved in nonfire accidents, only 3 7 per cent were injured fatally Approximately 60 per cent of the total number of fatalities were a result of crashes involving fire No attempt was made to attribute the fatalities specifically to fire because of insufficient information contained in the accident reports

An analysis[1] of the fixed-wing commercial air carrier accidents for the year 1946 concluded that fire followed not more than 15 per cent of all crash accidents Another analysis[3] compiled by the Civil Aeronautics Board (CAB) based on a study of serious fixed-wing commercial air carrier accidents for the period January 1938 to June 1951 showed an 84 6 per cent fatality rate in post-crash fires compared with a 60 8 per cent fatality rate in nonfire accidents

The helicopter has seen comparatively limited commercial service, therefore, in comparing accident and injury rates for the period 1952 to 1957, only military accidents were considered. The two helicopter sizes considered and their designations are presented in Table I The smaller sizes are capable of carrying two to four persons, and the larger sizes are capable of carrying more than four The small craft were involved in 533 major crash accidents of which 7 3 per cent resulted in fire, and the large helicopters were involved in 561 major crash accidents of which 11 6 per cent resulted in fire The fatality rates resulting from the post-crash-fire accidents were approximately 41 per cent for both classes of helicopters A further analysis of helicopter crash-fire accident records indicated that 84 per cent of the helicopters were damaged beyond repair and 16 per cent sustained major damage

TABLE I

SIZE AND DESIGNATIONS OF HELICOPTERS INCLUDED IN ACCIDENT ANALYSIS

Airframe Manufacturer	Designation: Civilian	Navy/Marine	Army/Air Force	Size*
Bell	47	HTL	H-13	Small
	61	HSL	X**	Large
Hiller	12B	HTE	H-23	Small
Kaman	X	HTK	X	Small
	X	HOK	X	Small
Sikorsky	S52	HO5S	H-18	Small
	S55	HO4S, HRS	H-19	Large
	S58	HSS, HUS	H-34	Large
	S51	HO3S	H-5	Small
Vertol	PD18	HUP	H-25	Large
	PD22	HRP	H-21	Large

* Small - Carries two to four occupants.
Large - Carries more than four occupants.

** X - Designation unknown.

HELICOPTER ACCIDENT INVESTIGATION REPORTS

Military helicopter accident reports were reviewed at the Naval Aviation Safety Center, Norfolk, Va., the Army Aviation Safety Board, Fort Rucker, Ala , and the Directorate of Flight Safety Research, Norton Air Force Base, San Bernardino, Calif Accident summaries also were obtained from the CAB and National Fire Protection Association publications A review of this material was directed toward determining the primary causes of post-crash fires, the components that contribute to the fire hazard, and the extent and significance of crash-fire damage However, very little complete information of this type could be found

The absence of reliable witnesses at accident sites, the inability to observe ignition occurring within the aircraft, and the total destruction of the aircraft by fire were factors which made the collection of detailed information very difficult A summary of information abstracted from accident investigation reports was tabulated and is presented in Table II A large number of unknown factors were listed in the reviewed accident investigation publications as shown in

TABLE II

A SUMMARY OF INITIAL FACTORS CAUSING FIRE COMPILED FROM 70 HELICOPTER ACCIDENT REPORTS

Initial Ignition Source	Number of Accidents	Per Cent of Total Accidents
Electrical short circuits	3	4 2
Hot exhaust flames or surfaces	5	7 1
Friction of metal on landing surfaces	2	2 8
Unknown	60	85 9
Initial Flammable Fluid Involved		
Gasoline	13	18 6
Oil	1	1 4
Unknown	56	80 0
Initial Cause of Combustible Spillage		
Fuel cell or fitting rupture	10	14 3
Fuel line or fitting rupture	3	4 3
Oil line or fitting rupture	1	1 4
Unknown	56	80 0

Total accidents - 70

this table. Accident information necessary for determining factors of special interest in this analysis was incomplete Cases in which the initial ignition sources and combustibles involved could not be determined are omitted from this table However, ruptured fuel cells or broken combustible fluid lines were known to be existent in some of these cases

The investigation of one accident involving a Bell Type 47 helicopter, Fig 1, revealed the following information The helicopter had been traveling sideways at approximately two feet altitude when its downwind skid hit the ground and collapsed The helicopter rolled on its right side, causing the main rotor blades to hit the ground and splinter This left only the main supporting metal spars of the blades attached to the rotor head These spars made contact with the ground and reaction forces were transmitted to the engine forcing it to twist and work against its shock mounts As a result, the starter and tachometer generator were dislodged The battery, voltage regulator, relay box, fuel tanks, and fuel lines which were attached to the frame remained intact The forward end of the right saddle fuel tank was punctured by a piece of metal which had been thrown by the rotor spar The released fuel may have been ignited by an electrical short circuit causing a fire The fire, propagated by the flow of fuel and wind, progressed toward the pilot's compartment The forward engine section and the pilot's compartment were burned away The initial impact damage to the craft was minor, however, the resulting fire caused irreparable aircraft damage and severe burns to the two occupants

Accident record reviews and discussions with military accident investigators and helicopter manufacturer representatives revealed the following information

1 Many accidents which result in fire are of such a nature that occupants are able to escape before the aircraft is completely demolished

2. Crash-fire accidents in which occupants frequently survive have occurred while the helicopter was hovering or moving at a very low speed near the ground

3 Crash-fire accidents have resulted from hard landings brought about by engine malfunction at a critical altitude or by pilot misjudgment while simulating emergency procedures and practicing normal autorotations Complete control of the aircraft usually is maintained in this type of accident and crash contact with the ground is made in a near-level attitude Occupants generally survive the impact forces resulting from this type of accident

4. Accidents caused by loss of control of the helicopter at cruising altitudes, resulting in impact at either a steep nose-down or inverted attitude, usually are of a nature where survival of occupants would be doubtful

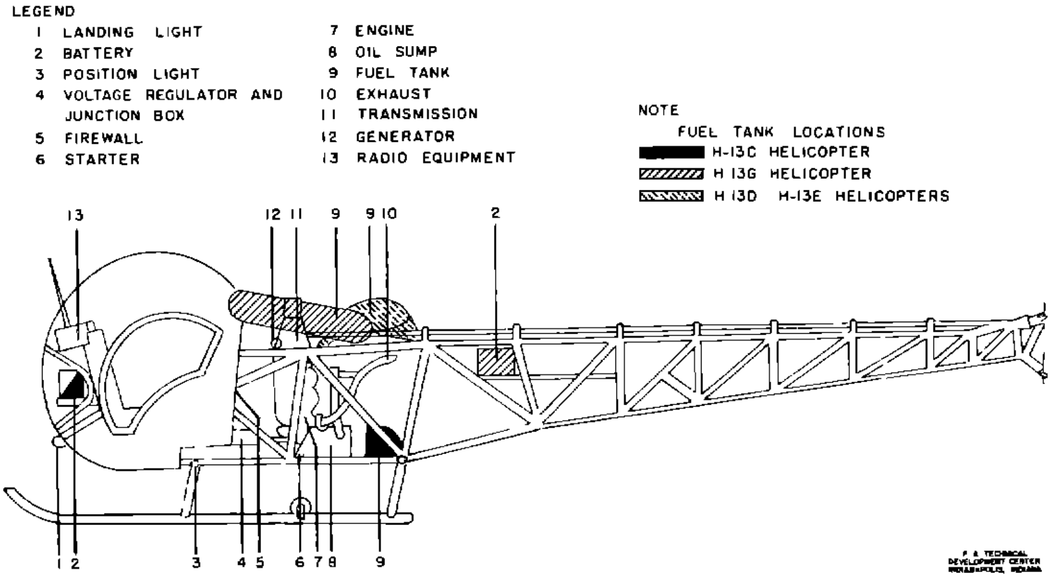

Fig 1 Bell Helicopter Model 47 (HTL, H-13)

5 Fires have occurred during hard landings as a result of landing-gear strut failure and the puncturing of a bottom fuel cell

6 A helicopter may roll on its side as a result of a landing-gear failure and hinder the escape of occupants

7 A landing-gear failure may leave the bottom fuel cells and drain cocks vulnerable to direct impact damage

8 A hard landing can result in the engine breaking loose and severing fuel and oil lines or possibly rupturing fuel cells

9 A large amount of military helicopter operations are over wooded areas and rough terrain Emergency landings in such areas may result in puncture of fuel cells by trees, stumps, and other objects

10 The small single-rotor aircraft such as the H-13, Fig 1, and H-23, Fig 2, have the main rotor clutch unit and gear box attached directly to the engine If this type of helicopter rolls on its side during a crash, the main rotors will contact the ground, imposing intermittent negative torque on the engine itself The resulting engine vibration can be sufficiently severe to cause accessories to separate from the engine, thereby increasing the fire hazard The engine also may continue to run for some time after the crash unless it is shut down by the operator

11 Larger helicopters such as the H-19, H-34, H-25, and H-21, Figs 3, 4, 5, and 6, have main rotor clutch and gear-box assemblies connected to the engine through a drive shaft Failure of main rotors and drive-shaft couplings when the rotor contacts the ground precludes severe engine vibration The engine may continue to run or overspeed after the impact, thereby creating another serious fire hazard

12 Main rotor gear-box tear-out occurs when the rotor system is thrown out of balance by loss of all or part of one blade This type of failure occurs when a main rotor blade makes contact with the tail cone, fuselage, or other obstacles, leaving the helicopter uncontrollable

A summary of accident records, showing causes of accidents, damage incurred, attitude at impact, and probable causes of fire, is given in Table III These data were abstracted from military accident reports, but were grouped for convenience under civil helicopter type designations

TABLE III

SUMMARY OF HELICOPTER ACCIDENT REPORTS

	Type	Cause of Damage	Damage Incurred	Results
1	Bell 47	Collided with ground	Broken gas line.	Gasoline spray ignited by short circuit or hot exhaust Damage irreparable
2	Bell 47	Collided with another helicopter	Landing gear sheared off	Fire Initial cause factors undetermined Damage irreparable
3.	Bell 47	Midair collision	Fuel cell sheared off	Fire Initial cause factors undetermined Damage irreparable
4	Bell 47	Collided with ground	Two main fuel cells ruptured	Fuel ignited on hot exhaust Damage irreparable
5	Bell 47	Collided with ground in level attitude while autorotating at forward airspeed of 50 to 70 mph Aircraft came to rest on side	Ruptured fuel tank	Fuel ignited on hot exhaust Two occupants received major injuries due to impact and fire Damage irreparable
6	Bell 61	While hovering near ground forward rotor hit fuselage Helicopter collided with ground.	Piece of steel rotor spar split open mid-fuselage fuel cell. Forward transmission torn out.	Fuel ignited on hot exhaust One injury and one fatality due to fire Damage irreparable
7	Hiller 12B	Airframe failure Collided with ground	Engine broke loose	Fire Initial factors undetermined Damage irreparable
8.	Kaman HOK	Rotor failure in flight Collided with ground	Fracture of all hold-down nuts on No 6 cylinder.	Gas and oil fire destroyed No 6 cylinder and piston, and part of Nos 5 and 7 Damage irreparable

TABLE III (continued)

SUMMARY OF HELICOPTER ACCIDENT REPORTS

	Type	Cause of Damage	Damage Incurred	Results
9	Sikorsky S51	Restricted cyclic control during takeoff caused collision with ground in nose-down attitude on left wheel from 8-foot altitude Aircraft rolled on left side	Fuel cell ruptured.	Fuel ignited on hot exhaust Three occupants escaped uninjured prior to fire Damage irreparable
10	Sikorsky S51	Loss of control. Collided with ground from 150 feet (inverted attitude)	Fuel cells ruptured	Spilled fuel ignited Initial ignition source unknown Two fatalities Damage irreparable.
11	Sikorsky S55	Engine failure at 20-foot altitude during takeoff Collided with ground on nose and left wheel. Rolled and came to rest on left side	Broken oil line, fuel drain cock damage allowing release of gasoline, and damaged starter	Initially fire started as a result of oil being ignited by arcing caused by damaged starter lead No injuries Damage irreparable.
12	Sikorsky S55	Collided with ground	Ruptured gasoline line and forward fuel cell	Fire with irreparable damage
13	Sikorsky S55	Fuel starvation necessitated autorotation from 600 feet into trees. Contacted ground in level attitude	Rotors sheared off by trees and fuel cells ruptured Engine started again after impact	Fire Initial ignition source undetermined Two occupants received major injuries due to impact and fire One fatality. Helicopter destroyed
14	Sikorsky S55	Collided with ground	Broken fuel pressure fitting. Damaged starter relay	Short circuit ignited spilled fuel Damage irreparable
15	Sikorsky S55	Collided with ground	Intake manifold No 7 cylinder broke loose	Fire and irreparable damage

TABLE III (continued)

SUMMARY OF HELICOPTER ACCIDENT REPORTS

	Type	Cause of Damage	Damage Incurred	Results
16	Sikorsky S55	Rotor blade severed tail cone Collided with water.	Transmission broke loose from fuselage	Fire and irreparable damage
17	Sikorsky S55	Collided with water.	Engine was pushed back under fuselage, rupturing fuel cell	Fire and irreparable damage
18.	Sikorsky S55	Collided with ground	Left rear landing gear failure caused rupture of fuel cell	Short circuit or friction ignited spilled fuel Damage irreparable
19	Sikorsky S55	Transmission failure caused collision with ground	Transmission failure due to oil starvation caused by oil pump failure	Transmission overheated and glowed red Damage irreparable
20	Sikorsky S55	Rotor severed tail cone on landing approach causing collision with ground in nose-down attitude	Fuel cells and fuel lines ruptured	Initial cause of resulting fire undetermined Five fatalities Damage irreparable
21.	Sikorsky S55	Loss of rotor rpm at 100 feet caused collision with ground while in nose-down left turn	Fuel cells ruptured	Initial cause of resulting fire undetermined Two fatalities Damage irreparable
22	Sikorsky S55	Tail rotor hit obstacle while hovering Collision with ground in nose-down attitude on left wheel Rolled on left side	Forward fuel cell ruptured	Fuel ignited on hot exhaust system Four escaped uninjured, one received minor injury due to fire Damage irreparable

TABLE III (continued)

SUMMARY OF HELICOPTER ACCIDENT REPORTS

	Type	Cause of Damage	Damage Incurred	Results
23	Sikorsky S55	Fuel starvation caused hard landing on coral reef and S55 skidded about 45 feet	Collapsed right forward gear Ruptured fuel cell in bottom side	Friction sparks ignited fuel Fire started before helicopter came to a stop Six were uninjured, two received minor injuries due to fire Damage irreparable
24	Sikorsky S55	Main rotor failure at 600 feet caused collision with ground in nose-down attitude	Fuel cells and lines ruptured	Initial cause of resulting fire undetermined Four fatalities Damage irreparable
25	Sikorsky S55	Collided with ground in longitudinal level attitude but in 40° left bank	Fuel cells and lines ruptured	Initial cause of resulting fire undetermined Two major injuries and one fatality due to impact and fire Damage irreparable
26	Vertol PD18	Collided with water	Gasoline line ruptured	Fire in engine compartment Initial cause undetermined Damage irreparable
27	Vertol PD18	Collided with ground	Fuel cell ruptured	Initial cause of fire undetermined Helicopter destroyed
28	Vertol PD22	Rotor failure caused collision with ground in level attitude	Mid-fuselage fuel cell ruptured Mid-transmission oil lines and oil tank ruptured	Fire started forward of fuel compartment and progressed forward Three fatalities due to impact and fire Damage irreparable

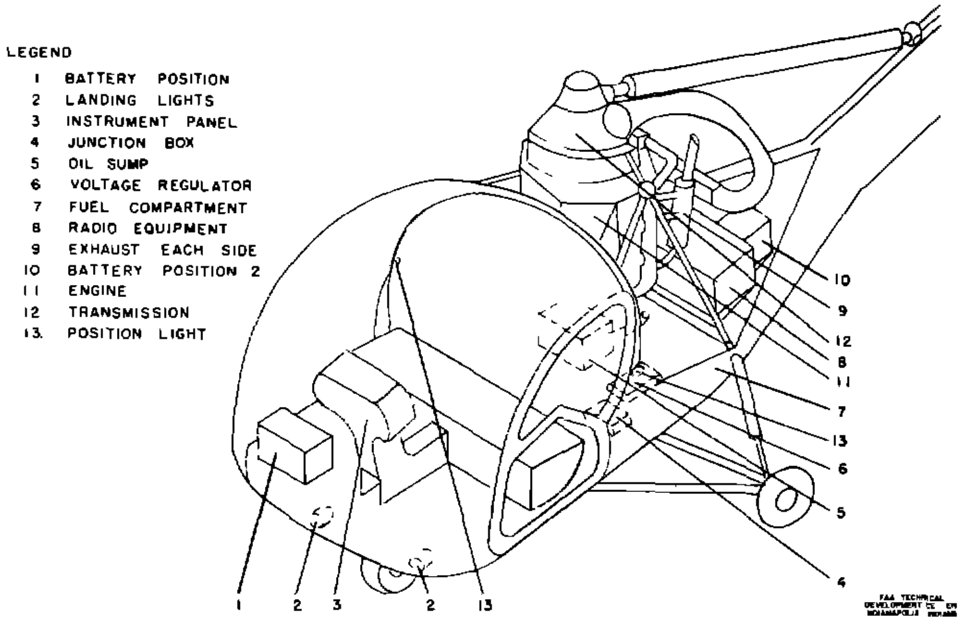

Fig 2 Hiller Helicopter 12B (HTE, H-23)

The close proximity of engine, fuel cells, electrical components, and passenger compartments to each other are shown in the helicopter illustrations, Figs 1 to 6, inclusive

Design features such as locations of items which may add to the crash-fire hazard in helicopters were noted. The following general observations are presented and pertain to helicopters illustrated in Figs 1 to 6, inclusive

1 The small helicopter, Figs 1 and 2, generally has all electrical components within the engine compartment and in close proximity to both fuel cells and fuel lines These components could provide an ignition source if damaged during a crash

2 Electrical components which are not a part of the accessory, but are located in the lower part of the engine compartment, are vulnerable to initial impact damage See Figs 1 and 2

3 In some types of helicopters, Figs 3 and 4, the landing gears are attached to the fuselage structure in areas where failure of the landing gear could lead to fuel-cell puncture

4 Engine accessories are located on the bottom side of upright or angled engines as shown in Figs 1, 2, 3, and 4 These accessories, in some types of helicopter accidents, are immediately susceptible to impact damage Where electrical, oil, and fuel-pump accessories are side by side, ignition and flammable fluid sources are present in very close proximity to one another

5. Oil cells and hydraulic reservoirs of dry sump engines often are located on the engine side of the firewall. See Figs 3, 5, and 6 Oil or hydraulic fluid spilled from a ruptured tank and ignited either on the engine hot surfaces or by electrical sources could provide an additional ignition source for the main fuel supply

6 The engine is located directly over a bottom fuselage fuel cell in one type of helicopter See Fig 2 Impact forces during a crash could cause this engine to be displaced into the cell.

7 Fuel cells located in the bottom of the helicopter fuselage, Figs 2, 3, and 4, are vulnerable to direct-impact damage and rupture when a landing-gear failure occurs These fuel-cell locations are undesirable from a crash-fire prevention standpoint

8 Hot exhaust gases are emitted overboard in some helicopters from ports located in the lower fuselage section The locations of these exhaust ports increase the probability of

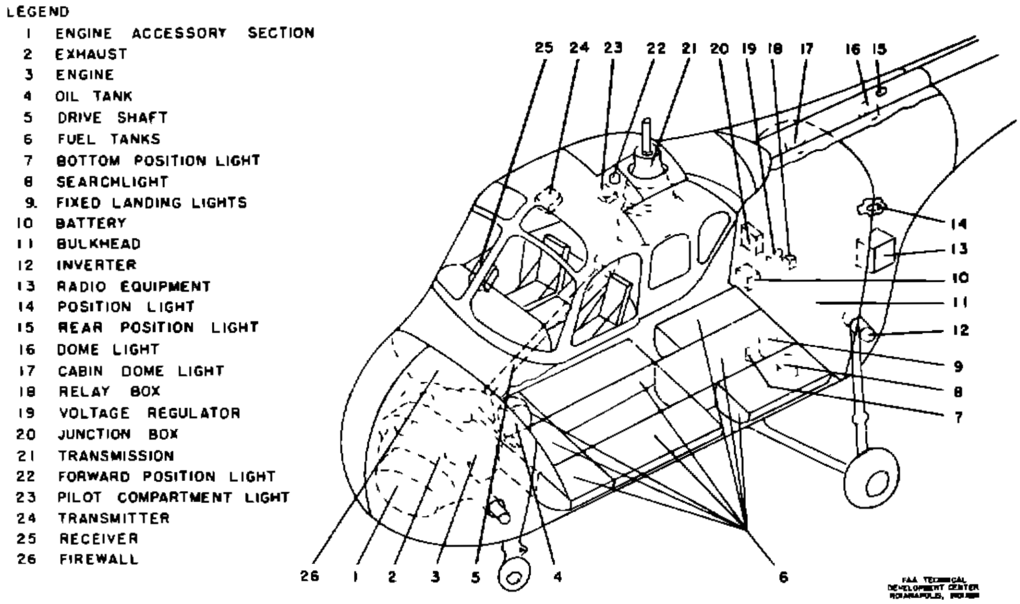

Fig 3 Sikorsky Helicopter S-55(HO4S, HRS, H-19)

spilled fuel ignition from exhaust flames or hot surfaces during a crash The most dangerous conditions occur when the helicopter rolls over on the side where the exhaust port is located

9 The use of magnesium on probable crash contact surfaces of helicopters presents the problem of spilled fuel ignition from friction sparks during a crash Magnesium should not be used on crash contact surfaces

10 External landing lights are sometimes located on the bottom section of the helicopter fuselage as shown in Figs. 3, 5, and 6 These lights are susceptible to damage during a crash when a landing gear fails. The heated lamp filaments have been known to ignite flammable fluids during an aircraft crash.

CRASH-FIRE RESEARCH

Extensive research has been conducted by the National Advisory Committee for Aeronautics (NACA) to determine the interrelationship of combustible ignition, combustible spillage, and ignition sources in fixed-wing aircraft crash-fires Most of the information obtained is directly applicable to the helicopter crash-fire problem The following is a resume touching on only significant information abstracted from NACA reports [4,5,6,7]

Fuel Spillage

The flammable fluid (gasoline, JP fuel, or kerosene) which supplies the prime power source of the aircraft is considered to be the most dangerous fire hazard During crash-fire tests of both reciprocating and gas turbine-powered fixed-wing aircraft, spilled fuel was present as mist, liquid, and vapor Results of these tests indicated that.

1 The hazard of fuel-mist ignition by sources around an engine located forward of the fuel source was greatest during a crash in which a combination of low forward speed and high deceleration of the aircraft occurred

2 The ignition of fuel mist occurred several seconds after initial impact due to the time required for the mist to reach an ignition source around the engine.

3 The use of fuel of low volatility does not reduce the fire hazard in an aircraft crash significantly when the fuel is spilled as a mist

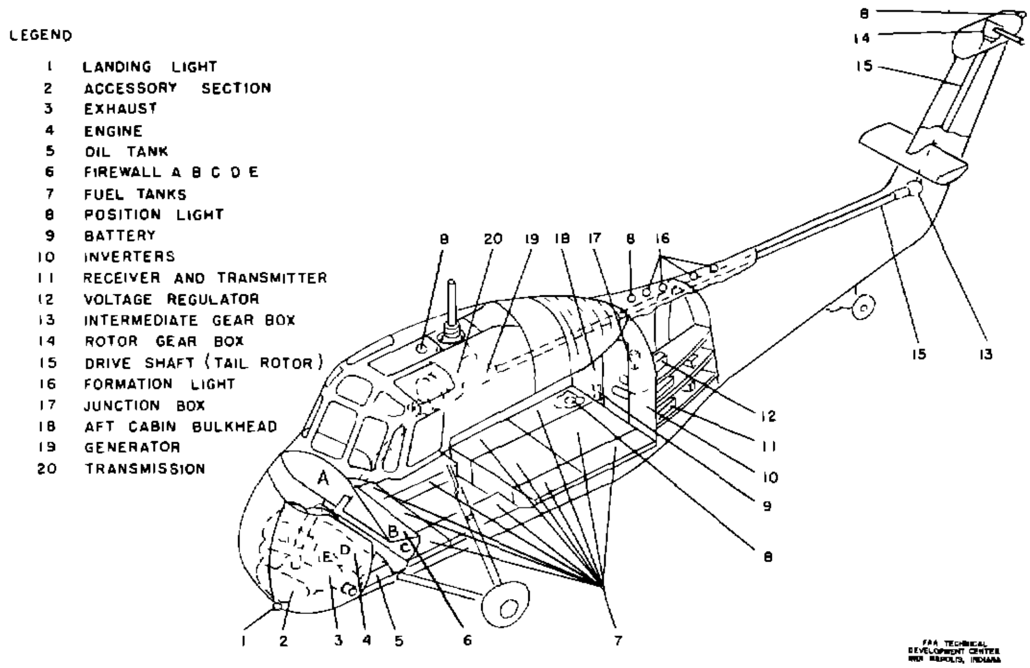

Fig 4 Sikorsky Helicopter S-58(HSS, HUS, H-34A)

4 The fuel mist in ignitible concentrations can be expected to remain in the crash area not more than 17 seconds The length of time for fuel mist to remain in the crash area is inversely proportional to the wind velocity

5 The danger of ignition of fuel vapors in open air from liquid fuel spilled on the ground is remote unless the ignition source is very near and within a few inches of the ground

6 Gasoline spilled within cavities of the aircraft where there is little airflow can vaporize rapidly, presenting a large concentration of ignitible mixture This spillage in liquid or vapor form could move to electrical ignition sources nearby or other sources at some distance, possibly through anti-icing or cabin air-conditioning ducts The former type of fuel movement and ignition can occur directly after impact while the latter would require several seconds

7 Movement of liquid fuel to ignition sources by gravity flow along the outside surfaces of aircraft can occur

8 Ignitible fuel-air mixtures from the engine induction system can be released by impact damage and ignited by sources within the engine nacelle Such quantities are small and would not produce a serious fire unless ignition of other fuel spillage occurred

Ignition of Combustibles

The ignition of fuel mixtures depends upon a number of common variables, including the fuel-air ratio, temperature, pressure, and velocity of flow, together with the fuel chemical composition and diluent gases The following is a summary of information concerning ignition of combustible mixtures by hot surfaces, sparks, and flames

1. The ignition temperature of aviation gasoline on hot metal surfaces increases with stream velocity but decreases as residence time and surface area increase The contact time for ignition of JP-4 fuel, kerosene, and aviation gasoline decreases with an increase of surface temperature and mixture pressure. Minimum ignition temperatures of gasoline, oil, and hydraulic fluid sprayed on an exhaust stack of an operating engine were found to be about 960° F , 760° F , and 600° F , respectively

2 Minimum spark-ignition energies of combustible mixtures increase with increasing size of electrodes and mixture velocity and decrease with increasing electrode spacing

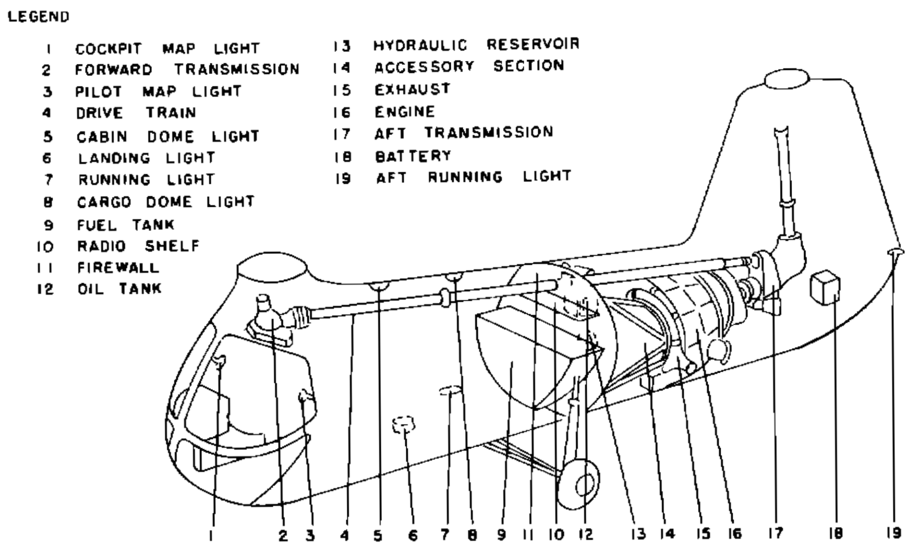

Fig 5 Vertol Helicopter PD18 (HUP, H-25)

Fuel-air mixture ignition from a capacitor discharge (electric spark) was not affected by electrode material. A condition of low humidity and moving dust concentrations was found to be capable of producing electrostatic sparks that would ignite fuel vapor mixtures Tests disclosed that a dust flow rate of 400 grams per second in a 45-mph airstream over a landing gear strut was capable of producing 3,900 electrostatic volts, whose discharge could ignite the proper gasoline-air mixture in 0 75 second High humidity, however, was unfavorable to the production of a high electrostatic charge

3 The minimum energy needed for inductance discharge ignition of inflammable mixtures decreases as the electrode material density decreases This minimum ignition energy of inductance sparks also decreases as the inductance potential increases and is unaffected by alternating or direct currents Energies required for spark ignition vary with the stoichiometric mixture of the combustible in air The energy required for ignition of some constituents of gasoline decreases from 0 9 to 0 1 millejoule as the stoichiometric mixture ratio increases from 1 0 to 1 8 and then reverses and increases as the ratio increases

4 Ignition of a stoichiometric mixture by flame contact was found to occur instantaneously

Ignition Sources

A number of ignition sources were found to be present during full-scale crash tests on fixed-wing aircraft The following is a summary of information concerning these ignition sources in both gas turbine and reciprocating engine powered aircraft

1 The exhaust disposal system, heat exchangers, combustion heaters, and the interior of the cylinder heads in reciprocating engines were found to be the most critical hot surfaces Time-temperature studies on a C-82 aircraft exhaust system indicated that normal cooling after engine shutdown from a maximum temperature of 1,200° F at takeoff power to 950° F (the minimum ignition temperature of gasoline) required 30 seconds, and 84 seconds were required to cool to 760° F (the minimum ignition temperature of oil) The critical areas in a gas turbine engine were found to be the combustion liner, transition liner, turbine inner cone, tail cone, and tailpipe Tests indicated that ignition of fuel by those parts in the main gas stream is not probable because of the high velocity of the gases Ignition may occur from either hot surfaces within the engine downstream of the compressor (not in the main gas stream) or from the outside surfaces of the tailpipe

2 Friction and chemical sparks from abraded airplane metals depend upon the type of metal which is abraded, the bearing force, bearing surface, and the contact time Ignition occurs most frequently when the aircraft moves over a very hard surface, such as concrete

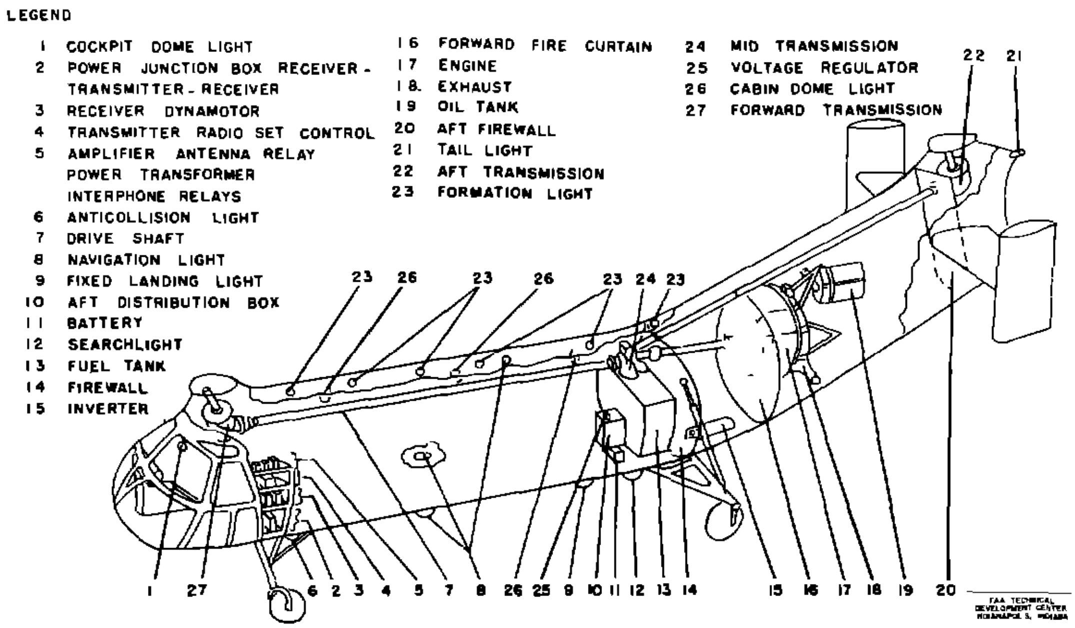

Fig 6 Vertol Helicopter PD22 (H-21A)

and asphalt runways or rock-filled terrain. Tests indicated that aluminum bearing on asphalt and concrete runways would not ignite combustible mixtures of gasoline, JP-4 fuel, kerosene, or preheated oil up to bearing pressures of 1,455 psi and at a maximum sliding speed of 40 mph However, titanium, magnesium, chrome-molybdenum steel, and stainless steel would produce friction sparks that would ignite combustible mixtures at bearing pressures and sliding speeds well below those that would be expected in an aircraft crash landing

3 Exhaust flames occur in a reciprocating engine when an unburned fuel-air mixture is expelled from a combustion chamber and is ignited on the interior surface of the hot exhaust. Disruption of normal engine operation by impact or ignition shutoff prior to impact may set up conditions for this type of ignition Flames are exhausted from the tailpipe in the jet engine when ingested fuel is mixed with the compressor air and directed into the combustor, or when the ingested fuel is bled off with cooling air to the turbine section and ignited

4 Induction flames in a reciprocating engine occur during abnormal operation of the engine, that is, when ignition of the fuel-air mixture in the cylinder causes backfire through the intake port and intake system by either preignition or faulty valve operation. This source of ignition may be present several minutes after engine stoppage during a crash Flames from a jet engine intake usually occur when the ignition downstream backfires or explodes through the engine during a surge or other abnormal conditions

5 Electrical arcs and electrically heated wiring and filaments are ignition sources which may appear in either gas turbine or reciprocating engine aircraft when the electrical system is disrupted by impact Severed wiring may produce arcing, short-circuited wiring may become incandescent, and broken lamp filaments may remain hot for a short time These conditions could result in the ignition of combustibles

6 Flames from chemical agents may occur in gas turbine or reciprocating-engine powered aircraft during a crash when oil, hydraulic fluid, or deicing fluid are ignited. These flames often occur initially and provide the ignition source for the main body of spilled fuel

7 Parts which are torn from the aircraft in a crash and propelled through dust and air can accumulate enough electrostatic charge to cause a spark to jump between the parts or to ground The electrostatic sparks may be of sufficient intensity to ignite fuel vapor or vaporized mist left in the aircraft's wake.

Development of Crash-Fire Prevention Systems

A number of systems developed to provide aircraft fire protection are listed and discussed briefly for their possible application to the helicopter crash-fire problem

1 A fuel-tank inerting system developed by the Cornell Aeronautical Laboratory utilizes the aircraft engine exhaust gases for inerting fuel tanks Hot exhaust gases are cooled and directed into fuel tanks to replace continuously the fuel vapor remaining in the top of the tank until the entire fuel supply is exhausted This inerting system was developed originally for military aircraft as a protection against fire caused by tracer bullets entering the fuel tanks Fuel-cell rupture during a crash or exhaust-gas leakage into passenger and pilot compartments in flight would render the application of this system undesirable for crash-fire prevention in a helicopter

2 An engine fire zone inerting system developed by the Cornell Aeronautical Laboratory for fixed-wing aircraft utilizes engine exhaust gases to inert confined powerplant zones The confined zones near the wing and the wing itself were protected by restricting the fire to the forward engine nacelle zones Present helicopter engine installations generally are not divided into confined fire zones similar to fixed-wing multiengine transport-category aircraft

3 A fuel-tank explosion suppression system has been developed by the Graviner Manufacturing Co Ltd of England for use in military aircraft to suppress explosions of fuel tanks hit by tracer bullets The detection of explosive flame triggers a detonator enclosed in a capsule containing a mixture of fuel and extinguishing agent The capsule in turn explodes, discharging its contents of fuel and extinguishing agent to enrich the explosive mixture to a degree that suppresses explosion For crash-fire protection, Graviner suggests that an extinguishing agent only be used The possibility of crash damage causing fuel-tank rupture or puncture also limits the use of this type of protection However, the use of a capsule system within the engine compartment may be feasible for inerting purposes during a crash

4 The containment of fuel during a crash would be of great value in preventing or reducing the magnitude and intensity of any resulting fire Bladder-type fuel cells to resist the fluid pressure built up by the high decelerations experienced during a crash have been under development at this Center It has not been determined whether this type of fuel cell could withstand point penetration as caused by fragments of a propeller, rotor blade, landing gear, or any obstacle which might be encountered during a crash accident

5 An ignition source inerting system was developed by the National Advisory Committee for Aeronautics[6,8] containing a number of components, each of which inerts a certain type of ignition source The following is a brief description of this inerting system

a The external hot surfaces in the reciprocating engine are cooled by application of a liquid with a high latent heat of vaporization Water was used during initial testing but a salt solution with a low freezing temperature was used in a production model[9] manufactured by Walter Kidde and Co , Inc The original hot surface cooling system, consisting of a pressurized bottle of coolant, a release valve, distribution lines, and nozzles, sprayed coolant to the inside and outside of the hot exhaust surfaces A water nozzle spray system utilized for cooling the engine exhaust system of a C-82 airplane was tested and found to be inadequate because the nacelle airflow disrupted the spray The coolant container was attached to the exhaust system to remain intact during a crash. A further development produced an arrangement of mesh screen wrapped around and welded to the stack and entwined by perforated tubing to to distribute and retain the coolant. This provided more effective cooling than the spray system. Stack interior-surface cooling also was integrated into this system The hot outside surfaces of the jet engine were cooled in a similar manner

b The combustion chamber interior was inerted by discharging CO_2 into the intake or induction system The CO_2 discharge shut down the engine and eliminated exhaust and induction system flames A quick-operating fuel shutoff valve at the carburetor was made a part of this system Hot interior sections in the jet engine were cooled by a water spray.

c The electrical system was inerted in both types of aircraft by removal of the power from the main bus and by grounding all circuits Special consideration was given to grounding the fields of electric motors and generators d Main fuel and oil-supply lines were shut off in the reciprocating engine by quick-operating valves located at the firewall Fuel was shut off in the jet engine prior to entering the combustor by a quick-operating valve All residual fuel between the shutoff valve and combustor was vented and drained overboard

Full-scale crash tests to evaluate the original type of inerting equipment on reciprocating engine aircraft were successful with three exceptions (1) the impact forces during one test caused separation of the engine from the exhaust system and the spray ring manifold which was attached to the engine and rendered the cooling system ineffective, (2) gasoline vapor which flowed through a wing heating duct to the heat exchanger was ignited during another test, and (3) electrostatic discharge from a landing gear strut which had been propelled by impact forces into the air provided a spark of sufficient intensity when it approached the ground to ignite the fuel spilled in the wake of the aircraft during a previous test.

These full-scale crash tests also indicated that ignition of the spilled engine fuel by hot exhaust surfaces, exhaust flames, hot gases, electrical sources, induction system flames, chemical agents, and electrostatic sparks occurred in 0.7, 1.3, 0 1, 0 6, 2 2, 3 5, and 2 4 seconds minimum, respectively, after initial impact The components to inert the hot surfaces, exhaust flames, exhaust gas, electrical system, and induction system flames functioned in 0 19, 0.34, 0 34, 0 10, and 0 06 second, respectively, after initial impact Chemical-agent ignition sources were inerted by all system components Electrostatic discharges and sparks caused by sliding friction were two sources of ignition not provided for in this system

6 Many types of triggering switches are used to initiate the inerting system including reaction, cable-type deformation, pressure contact, and inertia switches Each switch is used to detect certain damage that might result in flammable fuel spillage or otherwise create a hazardous fire situation. The following recommendations[10] have been made regarding the installation of triggering devices in fixed-wing aircraft

a. The initiating system should not operate inadvertently or under minor damage conditions.
b The system should have selective inerting which would leave the aircraft flyable while nonessential electrical components in a wing area are inerted when a wing tank is breached
c Reaction switches should be used to detect either engine tear-out or abnormal vibration which occurs when the propeller contacts the ground or other objects
d Cable-type deformation switches should be placed in the leading edge of each wing to detect structural damage that might cause fuel-cell failure
e A reaction-type switch should be used to detect excessive forces which might cause landing-gear failure leading to fuel-cell rupture.
f Pressure contact switches should be placed in various locations at the bottom of the fuselage and the engine nacelles to detect initial ground contact of these surfaces during a wheels-up or crash landing
g Provision for manual operation of the inerting components should be made so that if a crash is foreseen, maximum protection can be afforded prior to impact

7. Graviner Manufacturing Co Ltd has developed a combined in-flight and crash-fire protection system using methyl bromide as an extinguishing, cooling, and inerting agent In the event of a crash, the system is initiated by a combination of contact and inertia-type triggering switches. The methyl bromide* is directed into hot surface areas and the engine induction system to stop the engine and inert the combustion chambers An electrical system shutoff also is provided in this system The methyl bromide containers usually are located aft of the firewall with plumbing used to distribute the agent to the vital locations The possibility of engine or distribution system tear-out during a crash might render this system useless

*Since methyl bromide is extremely toxic, its use should be confined to the engine nacelle and kept away from passenger compartments.

DISCUSSION AND CONCLUSIONS

The statistics show that the crash-fire problem is of a serious magnitude for all types of helicopters, and that remedial steps should be taken to minimize it Primary consideration for crash-fire protection should be given to the large helicopters from an economic standpoint and because of the greater number of passengers involved

The review of crash-fire accident records and the investigation of one helicopter accident were inconclusive regarding the indication of exact primary sources and causes of helicopter crash fires Crash-fire records indicated the type of accident in which occupants would or would not survive Accidents resulting in fire which occur during hovering or slow maneuvers near the ground, and those where control of the aircraft is maintained so that a near-level crash contact attitude at impact occurs, would result in the survival of occupants in most cases.

Another consideration for simulating maximum adverse flight conditions, especially in military helicopter operations, is that combination of critical altitudes and airspeeds at which the design landing gear sink rate will be exceeded on contact with the ground should complete engine failure occur According to Katzenberger and Rich,[11] the most critical flight condition for an S-55 helicopter of 6,835 pounds gross weight, is zero airspeed at approximately 140 feet altitude The minimum sink rate at impact for this helicopter, which could be expected under the aforementioned conditions if the engine failed and blade stall occurred, would be approximately 44 feet per second The maximum vertical contact rate considered noninjurious to passengers was 25 feet per second, and the design ground contact vertical deflection rate for the S-55 helicopter landing gear was 8 feet per second

Helicopter engines continue operating after impact in many accidents, presenting a serious fire hazard. The operator should shut down the engine prior to impact by shutting off the fuel flow when an accident is foreseen and when time allows Residual fuel in the lines will be consumed, the engine will be purged with air, and the ignition hazards of exhaust and induction system flames will be reduced Automatic engine shutdown and inerting of combustion chambers would be very desirable for accidents which are not foreseen.

Design characteristics of helicopters, including the location of electrical components, wiring, landing and position lights, landing gear, engine accessories, engines, fuel and oil cells, hydraulic reservoirs, and fuel drain cocks, create potential ignition and flammable fluid-spillage hazards which may be directly responsible for fire following accidents Apparent hazards should be studied by helicopter design groups and steps taken to minimize potential ignition sources and causes of fuel spillage Relocation of engines, fuel cells, and landing gear is sometimes impractical on present machines, however, electrical components, wiring, external lights, oil cells, hydraulic reservoirs, and fuel drain cocks could be relocated or otherwise protected in many cases to minimize the fire hazard Also, the undesirable fire-hazard features of present helicopters should be studied to establish criteria for future helicopter designs to minimize crash-fires.

Many of the previously discussed results of research work accomplished on fixed-wing aircraft concerning combustibles and ignition hazards are applicable to the helicopter The helicopter usually has its prime mover, fuel supply, passenger compartment, electrical components, and so forth, in close proximity with each other in a fuselage of limited space. The fuel tanks, electrical components, passenger compartments, and so forth, in the fixed-wing aircraft may be separated by some distance. The time required for combustibles to move to the ignition sources and propagate fire to passenger compartments in a helicopter may be found to be shorter than that experienced in fixed-wing crash-fire accidents. In fixed-wing aircraft accidents (usually on takeoff or landing) in which occupants would be expected to survive, the aircraft has a high forward speed and low rate of descent as compared to the helicopter's low forward speed and high rate of descent. Hence, in a crash where each operator would maintain aerodynamic control until the moment of impact, the fixed-wing aircraft would tend to slide further forward than the helicopter on the same terrain. These characteristics could alter the fuel-spillage patterns, time in which ignition sources and combustibles unite, and fire propagation patterns from those found in fixed-wing aircraft crash fires Limited full-scale crash-fire tests should be conducted on helicopters to determine if differences occur

An ignition inerting system combined with a fuel containment system probably would give the maximum protection to any type of aircraft under crash situations in which occupants would survive It would be advantageous to combine both an in-flight and crash-fire system from an economic and operational standpoint

Present means of eliminating electrical ignition sources, exhaust and intake flame ignition sources, and stopping flammable fluid flow by using valves between the engine and fluid supply can be adapted to the helicopter readily The main problem is to provide protection against flammable fluid ignition by hot external surfaces of the reciprocating engine and by internal and external hot surfaces of the gas turbine engine This could be accomplished by cooling and/or inerting with agents that would be effective crash or in-flight fire extinguishants. Testing of such agents and means of application are necessary and could be accomplished through static tests

Ignition of combustibles brought about by electrostatic and friction sparks are not provided for in present crash-fire protection systems Electrostatic spark ignition of spilled fuel probably would not occur frequently in helicopter accidents The crash area generally would be limited, therefore limiting the fuel-spillage area Debris propelled by impact could very well land outside the fuel spillage area Sparks generated by friction of the aircraft metal, especially from steel (landing gear) and magnesium parts of the fuselage, would be present if the accident occurred on concrete, asphalt, or rocky landing surfaces. To reduce this source of ignition, the use of aluminum on probable helicopter contact surfaces would be beneficial From an operational standpoint, avoiding hard surface areas insofar as possible during emergencies, simulated emergencies, practice autorotations, and normal landings would reduce the occasion of this type of fuel ignition in the event of a crash

Criteria used to establish the location and type of triggering device required for initiating an inerting system for fixed-wing aircraft were based on failures that resulted in fuel spillage. The same criteria should be used for the helicopter Evaluation of available triggering devices to indicate helicopter engine tear-out, landing-gear failure, transmission tear-out, and fuselage deformation should be made during simulated crash tests

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