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AIRCRAFT FIRE SAFETY RESEARCH

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INTRODUCTION

Aircraft systems inherently possess a variety of potential fire and explosion hazards, which from time to time contribute to equipment and property damage and/or personnel injuries and fatalities. Historically, aircraft mishaps have frequently triggered intense research and engineering efforts directed at improving selected aspects of the overall fire protection problem. For military aircraft, the fire and explosion damage and loss experiences in combat, such as in southeast Asia in the late 1960's and early 1970's, provided additional impetus for the enhancement of survivability under various hostile threat operational environments. Today's civil and military aircraft are exemplary both in performance capability and overall system safety, of which fire safety is a key ingredient. Although aircraft fire safety problems are largely more diversified than those anticipated with spacecraft, per se, it is intended that by reviewing key aspects of recent aircraft fire safety research activities, the general philosophy of approach, if not the specific results, could contribute to the identification and resolution of spacecraft fire hazard concerns.

NATURE OF THE PROBLEM

The aircraft fire and explosion threat is complex and diversified, involving a variety of materials (fuel, engine and hydraulic oils, interior cabin materials, metals, etc.), which are subjected to a broad span of natural and induced operating environment conditions and potential exposure to a number of ignition sources. The latter, for example, can include electrical arcs and sparks, friction sparks, hot surfaces, and open flames. In the case of military aircraft, combat operations introduce significant additional means for fire/explosion initiation. Achievement of an effective fire protection posture necessitates "early" and "heavy" emphasis on fire prevention, supplemented as necessary by fire hardening, detection, extinguishment/suppression, and control measures.

AVIATION FUELS

In addressing the aircraft fire safety issue, priority attention must be given to the fuel onboard because of its large quantity, widely dispersed distribution, and relatively high fire/explosion hazards. Table I summarizes typical properties of military jet fuels that are deployed operationally or are undergoing research and development (R&D). A low flash point, volatile fuel, JP-4, is still largely utilized by the military because of worldwide availability and performance considerations. A kerosene fuel similar to commercial Jet A-1 fuel, JP-8, is utilized in the United Kingdom and is being considered for NATO-wide use in the very near future. The JP-8 fuel, like

JP-5, which is utilized by the Navy for safer aircraft operations off of carriers because of its higher flash point, offers considerable safety advantage. Air Force fuel R&D activities have recently focused on the use of (1) alternate sources such as oil shale, tar sands, and coal liquids as a means for assuring future, secure, domestic supply of acceptable quality jet fuels; as well as (2) the development of a high density, naphthenic-based fuel (referred to as JP-8X) offering a volumetric energy density up to 15 percent greater than JP-4.

For military aircraft, gunfire/projectile impacts can induce both ullage explosions and dry bay fires. The generation of flammable fuel-air mists within the fuel tank as a result of projectile penetration also renders low-volatility fuels vulnerable to ignition; although, in general, the fire hazard is considered to be less with the higher flash point fuels. During aircraft crash situations, similar external dispersion of fuel in air can occur as a result of fuel tank rupture and structural failure. The latter renders low-volatility fuels susceptible to ignition and a rapid fireball-flame spread response, thereby compromising crew and passenger safety under what in some instances would have been an impact-survivable situation. Over the years, various approaches have been investigated to render jet fuels safe. Most recently, the major effort in this area has been through a cooperative program between the United States and the United Kingdom to determine the feasibility of developing antimisting fuels using a British-developed antimisting kerosene (AMK) additive in a Jet A, low-volatility, fuel. This program progressed to the full-scale testing stage involving a controlled impact demonstration with a Boeing 720 at Edwards AFB, California in 1984. The Boeing 720 flew successfully using the treated fuel; however, the degree of fire protection provided by the AMK fuel was judged to be inadequate for the Federal Aviation Administration (FAA) to proceed with rule making at the present time. The FAA sponsored a Fuel Safety Workshop in the fall of 1985 to help shape a future program of activity in this area. The details of the planned future program have not been officially announced.

Air Force fuel R&D activities are currently also focusing on the needs of future supersonic and hypersonic vehicles. For these applications, in addition to the usual desired performance properties, a fuel will need to provide a high heat-sink capability. A typical fuel heat-sink requirement trend for high-Mach flight vehicles is depicted in figure 1. Current operational hydrocarbon fuels offer only a half MJ/kg (several hundred Btu/lb) heat-sink capability. One approach being considered is to use an endothermic fuel. A typical scheme is represented by the dehydrogenation of methylcyclohexane (fig. 2), resulting in the formation of toluene and hydrogen and offering a total heat sink of approximately 4.4 MJ/kg (1900 Btu/lb). Actually, the Air Force sponsored much research in this area in the 1960's and is moving ahead with this technology opportunity once again. Obviously, a number of other candidate fuels exists, as shown in table II, including cryogenic hydrogen. Various system safety issues, including fire safety, will need to be addressed as progress towards the actual system application of these fuels is made.

AIRCRAFT FUEL SYSTEM EXPLOSION PROTECTION

In aircraft fuel systems, by and large, through the application of appropriate fire/explosion prevention measures, normal operation mishap possibilities have been adequately minimized. In the case of military systems, the combat scenario has necessitated incorporation of additional fire and explosion protection measures. Current practice includes the use of reticulated plastic foam explosion suppressants (i.e., polyester and polyether polyurethane foams); bromotrifluoromethane (CF_3Br, Halon 1301) inerting on a part-time basis; and liquid nitrogen inerting for full-time protection. Major current R&D effort is directed towards the development of an onboard inert gas generation system (OBIGGS) with first likely application to be on the C-17 aircraft currently under development for the Air Force by McDonnell-Douglas. Research is continuing by the Air Force for the development of more efficient air separation membranes for OBIGGS to enable application to fighter aircraft, as well as to reduce subsystem weight penalty for the larger aircraft. Actually, the current OBIGGS technology is very competitive with other state-of-the-art, full-time fuel tank explosion protection systems, and compared to LN_2, it offers considerable advantage in worldwide logistical independence. References 102 to 111 provide additional information on the above approaches as well as on some of the electrostatic hazard problems encountered operationally with reticulated foams. With respect to the latter, industry efforts are underway to develop a more conductive reticulated baffle foam, with an acceptable product likely to be available very soon.

HYDRAULIC FLUIDS

In the area of aircraft hydraulic systems, the preponderance of fire problems has been experienced with military aircraft, which for years employed a petroleum-base hydraulic fluid (MIL-H-5606). By comparison, civil experience with the more fire-resistant phosphate-ester-type hydraulic fluid has been very favorable. Because of performance and materials compatibility reasons, the phosphate-ester-type fluid is not acceptable for military aircraft. Recently, military aircraft have been converting to MIL-H-83282, a synthetic hydrocarbon with a much higher flash point temperature, which is totally acceptable in existing operational aircraft systems. Since the mid-1970's, technology effort has also been focusing on the development of a nonflammable hydraulic fluid for future advanced military aircraft applications. This technology (refs. 112 to 119) has progressed to the selection of a CTFE (chlorotrifluoroethylene) fluid for use in a 55-MPa (8000-psi) system, and the fluid is scheduled for demonstration/validation in the near future. Table III summarizes selected properties of current and candidate nonflammable hydraulic fluids as well as the fire properties goals that were established in 1975 for the screening of candidate materials.

PROPULSION INSTALLATIONS

Propulsion installations have inherently been treated as high fire-threat areas; consequently, a well established fire protection engineering capability exists. Much of this capability evolved from the earlier days when full-scale engine/nacelle fire tests were conducted by the CAA in Indianapolis, Indiana, and subsequently by the FAA at the Atlantic City, New Jersey test facilities. Testing was conducted in support of both military and civil applications. To my knowledge, the only ongoing testing of this type is at the FAA facility for the Air Force utilizing a surplus F-111 aircraft fuselage/TF30 engine as the test article. This testing is focusing on jet fuel ignition fire detection and fire extinguishing agent considerations under a broad range of air mass-flow ventilation rates and temperature conditions representative of today's turbofan engine installations in military aircraft. At the same time, at the Aero Propulsion Laboratory, similar tests are being performed in an engine nacelle fire-test simulator for the purpose of establishing comparative fire protection performance trends. The engine nacelle simulator was developed a few years ago as a planned alternative to full-scale testing because of the high cost and future general nonavailability of actual advanced engines for conduct of potentially destructive fire testing.

With regard to engine compartment fire and overheat detection, modern aircraft are largely equipped with continuous-element, heat-sensitive-type systems (i.e., pneumatic and electrical resistance types). These systems provide line coverage and require 5 to 15 sec for response. Dual loop coverage has been incorporated in certain instances to reduce past false-warning problems. For advanced flight vehicles, detection systems will require high reliability, quick response, and the ability to discriminate more clearly between fire and overheat conditions. The latter will necessitate more emphasis on optical sensors (ultraviolet, infrared types) integrated with continuous element systems. It should be pointed out that very little R&D is currently in progress in this area. A few years ago, an advanced ultraviolet aircraft fire detection system was developed for the Air Force (ref. 120) and installed in an F-111 aircraft at the Sacramento Air Logistics Center, McClellan AFB, California, for flight test evaluation. The planned evaluation was successfully accomplished; the system still remains installed and is performing satisfactorily.

Extinguishment of engine compartment fires is presently accomplished by means of fixed systems employing halogenated hydrocarbon agents. No major technological advancement has been made in this area in recent years. Halogenated fire extinguishing agents that were researched mainly in the 1940's to early 1960's and used on aircraft are indicated in table IV. Present day preference is for Halons 1301 and 1211, which offer the best combination of performance, low toxicity hazard, and reasonable availability/cost. The Boeing Company has recently completed a favorable investigation of the fire extinguishing performance potential offered by various nitrogen-enriched air (NEA) mixtures as an ancillary function of OBIGGS (ref. 102). Use of NEA for continuous purging of electronic cabinets and fire control onboard spacecraft would also appear to merit consideration.

AIRCRAFT POST-CRASH/INTERIOR CABIN FIRES

The aircraft survivable impact, post-crash fire scenario and the closely intertwined interior cabin fire problem have received considerable attention in recent years, both on a national and international basis (refs. 121 to 127). The post-crash fire scenario is a difficult one to contend with. The environment rapidly deteriorates from thermal, chemical, and visibility viewpoints. Toxic and irritant products generated have rapid debilitating effects. The traumatic situation makes breath-holding essentially impossible and pain thresholds are rapidly reached. The cabin can become a totally lethal environment. This also is true of ramp and in-flight fires if the fire source is large enough. Time, measured in seconds, is a key factor in survival.

Approaches for enhancing the crash worthiness of the aircraft include the use of crash-resistant fuel tanks where feasible, protection of fuel system components, development of fire-safe fuels, increasing the fire worthiness of interior materials, improving interior emergency lighting, and providing more fire-resistant escape slides. The bulk of the activity in these areas has been pursued by the FAA and NASA. Sarkos (ref. 127) provides an excellent summary of efforts directed toward improving aircraft interior safety. The work in the latter area obviously should have direct applicability to the spacecraft fire safety problem, particularly where use of a normal-air habitable atmosphere is planned.

With regard to extinguishment of fires within aircraft interior compartment areas, first-aid fire extinguishers employing Halon 1211 (CF_2BrCl) fire extinguishant are now being utilized by both military and civilian aircraft because of its suitability, to some degree, for all classes of combustibles, excluding metal fires. Selected higher hazard areas, such as galleys and refuse bins within lavatories, in certain cases have been equipped with fixed fire extinguishing systems usually of the Halon 1301 (CF_3Br) type. Use of Halon fire extinguishants in oxygen-enriched and hyperbaric chambers depends in part on the extent of oxygen enrichment and should be carefully and independently assessed for each application. Depending on the rapidity of fire extinguishment action, different degrees of agent pyrolysis can be experienced. Consequently, in assessing the overall toxicity hazard, consideration must be given to both the byproducts formed by the fire and the extinguishant utilized. Removal of potentially toxic byproducts from the spacecraft atmosphere after effecting fire control will also require special attention in order to resume safe, normal operations.

CONCLUDING REMARKS

In summary, during the past 15 years, very significant progress has been made toward enhancing aircraft fire safety in both normal and hostile (combat) operational environments. I have attempted to touch on most of the major aspects of the aircraft fire safety problem and necessarily have had to limit the depth of coverage. The technology of aircraft fire protection, although not directly applicable in all cases to the potential spacecraft fire scenarios, nevertheless does provide a solid foundation to build upon. This is particularly true of the extensive research and testing pertaining to aircraft interiors' fire safety and to OBIGGS, both of which are still active areas of investigation.

TABLE I. - TYPICAL PROPERTIES OF MILITARY TURBINE ENGINE FUELS

	JP-4	JP-5	JP-8	JP-8X
Density, kg/m^3	764	818	800	872
Boiling range, °C	65 to 250	190 to 260	175 to 270	175 to 270
Heat of combustion				
MJ/kg	43.5	42.8	43.0	42.6
Btu/lb	18 700	18 400	18 500	18 300
Btu/gal	120 000	126 000	124 000	135 000
Hydrogen content, wt %	14.4	13.7	13.8	13.3
Viscosity, cS, at				
-40 °C	2.8	11.0	10.0	14.0
-18 °C	1.9	4.2	3.8	4.4
4.4 °C	1.4	2.2	2.0	2.4
Flash point, °C	-30	60	53	53
Freezing point, °C	-59	-46	-50	-62

TABLE II. - HIGH-MACH PROPULSION FUEL CANDIDATES

	Methyl-cyclohexane	Decalin[a]	Methane	Ethane	Hydrogen
Density, kg/m^3, at 16 °C	772	882	[b]424	[b]574	[b]70.7
Boiling point, °C	101	194/185	-161	-89	-252
Freezing point, °C	-126	-43/-31	-183	-172	-259
Base fuel					
Heat of combustion, MJ/kg	43.4	42.6	50.0	47.5	120.0
Heat of combustion, Btu/lb	18 650	18 320	21 500	20 420	51 600
Heat of combustion, Btu/gal	120 106	134 926	76 110	97 811	30 444
Products (100 percent conversion)					
Heat of combustion, MJ/kg	45.4	44.6	------	52.1	------
Heat of combustion, Btu/lb	19 530	19 160	------	22 384	------
Heat of combustion, Btu/gal	125 773	141 017	------	107 219	------
Heat sink, MJ/kg (100 percent conversion, 15 to 725 °C)	4.43	3.91	[c]2.69	[c]6.98	[c]14.7
Ratio of heat sink/heat of combustion	0.098	0.088	0.054	0.13	0.122

[a]Double values for decalin boiling and freezing points are for the cis and trans varieties, respectively.
[b]At boiling point.
[c]From boiling point to 725 °C.

TABLE III. - TEST PROPERTIES OF AIRCRAFT HYDRAULIC FLUIDS

Test parameter	Goal	MIL-H-5606	MIL-H-83282	Phosphate esters Skydrol 500B	Navy MS-6 silicone	Halo-carbon A-08	Dupont E-6.5	Brayco 814Z
Heat of combustion, MJ/kg	<11.6	42.1	41.2	29.8	22.7	5.56	4.14	0
Autoignition temperature, °C	>700	224	340	510	410	640	670	920
Hot manifold ignition								
Stream, °C	>930	430	315	780	480	930	>930	>930
Spray, °C	>930	760	700	820	540	>930	>930	>930
Atomized spray, open flame	Nonreactive	Sustains	Sustains	Extinguishes	Extinguishes	Nonreactive	Nonreactive	Nonreactive
Flash point, °C	N/A	100	224	180	280	-----------	-----------	-----------

TABLE IV. - PROPERTIES OF HALON FIRE EXTINGUISHANTS

Formula	Halon number	Molecular weight	Freezing point, °C	Boiling point, °C	Density (liquid) at 21 °C, kg/m^3	Storage stability, °C
CCl_4	104	154	-13	77	1580	200
CH_3Br	1001	95	-93	3	1730	----
CH_2BrCl	1011	129	-87	67	1930	120
CF_2Br_2	1202	210	-142	23	2280	180
CF_3Br	1301	149	-174	-58	1570	>260
CF_2BrCF_2Br	2402	260	-111	47	2160	>260
CF_2BrCl	1211	165	-161	-4	1830	200

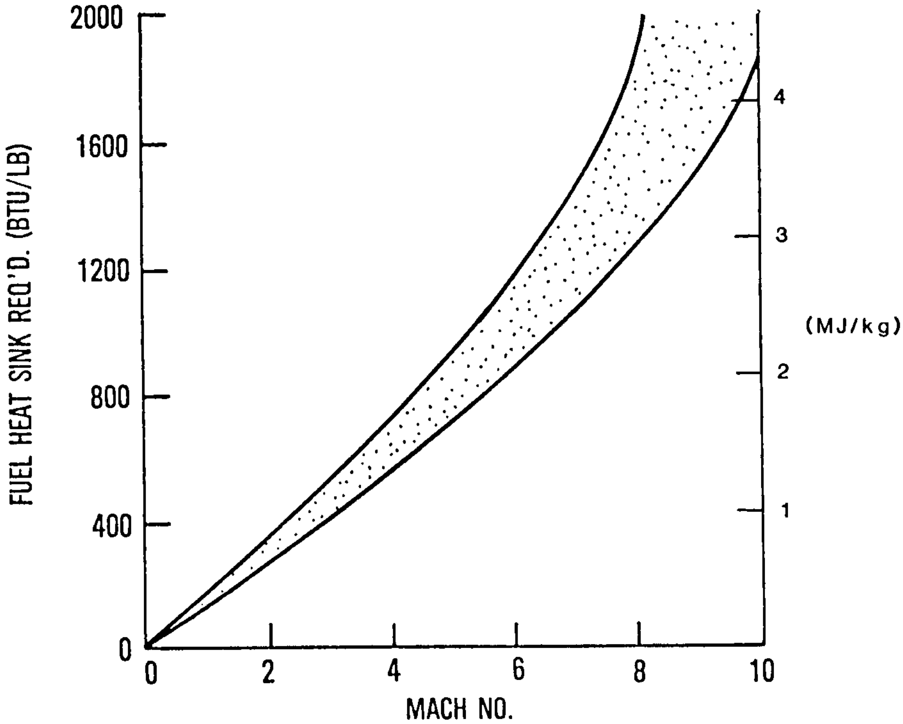
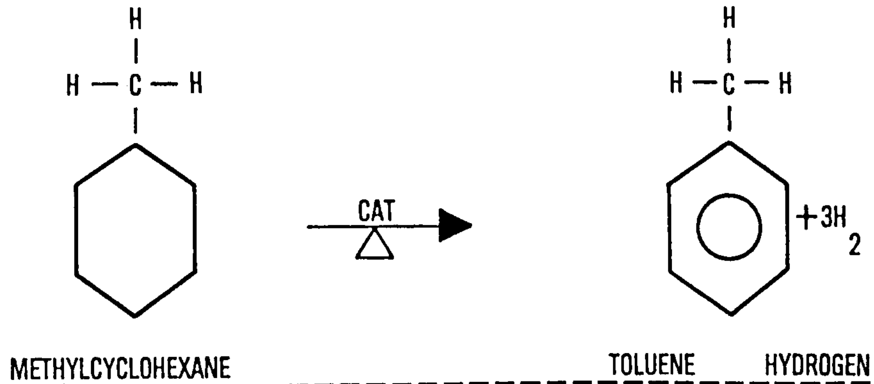


Figure 1. - Typical fuel heat-sink requirement trend for high-Mach-number flight vehicles.



COOLING CAPABILITY	MJ/kg OF FUEL
SENSIBLE HEAT (MCH, 15-540°C)	1.73
HEAT OF REACTION AT 540°C	2.05
SENSIBLE HEAT (PRODUCTS, 540-730°C)	.65
TOTAL	4.43

Figure 2. - Endothermic dehydrogenation of methylcyclohexane (MCH).