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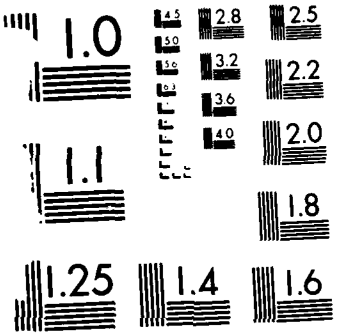

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CRC Report No. 546

FLAMMABILITY OF AIRCRAFT HYDRAULIC FLUIDS — A BIBLIOGRAPHY

Contract No. DAAK-70-86-C-0011

January 1986

COORDINATING RESEARCH COUNCIL, INC.
219 PERIMETER CENTER PARKWAY, ATLANTA, GEORGIA 30346

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FLAMMABILITY OF AIRCRAFT HYDRAULIC FLUIDS - A BIBLIOGRAPHY

(CRC PROJECT NO. CA-49-71)

Prepared by the

Aviation Fluids Flammability Group

January 1986

Aviation Fuel, Lubricant, and Equipment Research Committee

of the

Coordinating Research Council, Inc.

ABSTRACT

As part of an overall effort to collect flammability data on aircraft fluids, a critical survey was made of the aircraft hydraulic oil literature, with particular emphasis on flammability testing and flammability characteristics of existing and projected aircraft hydraulic fluids. Commercial aviation and military aviation fluids are treated separately, in view of their divergent development. Flammability test procedures are described. Flammability test results and other inspection tests are given for a variety of current and proposed aircraft hydraulic fluids.

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I. BACKGROUND AND HISTORY

As part of an overall effort to collect flammability data on aircraft fluids, a critical survey of the aircraft hydraulic oil literature was made by the Aviation Fluids Flammability Group of Coordinating Research Council, Inc. (CRC). Membership of the Group is detailed in Appendix A. Particular emphasis has been placed on flammability testing and flammability characteristics of existing and projected aircraft hydraulic fluids. Commercial aviation and military aviation fluids have been treated separately in the survey, in view of their divergent development.

For many years, hydraulic fluid power has been used effectively and efficiently to provide power transfer in complex hydraulic systems due to the extremely high efficiency, compact size, and light weight of hydraulic systems when compared with alternative methods including mechanical or electrical devices. Typical aircraft systems utilizing hydraulic power include primary flight controls and utility systems such as landing gears, brakes, accessory doors, and many others. The most widely used fluid in military aircraft over the last thirty-five years has been a light mineral-oil base meeting specification MIL-H-5606(1). This fluid or its preservative version, MIL-H-6083(2), has provided excellent service over a temperature range of -54 to 135°C. The primary deficiency of this oil has been its high degree of flammability.

The flammability of MIL-H-5606 has prompted many government and private research programs to develop fluids of improved flammability characteristics. The most successful program of these years was the development and adoption of phosphate ester-based, fire-resistant hydraulic oils generally employed in today's jet-powered commercial aircraft(3,4). The phosphate esters have significantly improved resistance to ignition and flame propagation over the petroleum-based fluid; however, the different chemical characteristics of the phosphate esters make them incompatible with the elastomeric seals, wiring insulation, and various coatings developed for petroleum-based oils. Different materials for these purposes are thus required for compatibility with the phosphate esters. In addition, phosphate ester fluids are not capable of operating at the higher temperatures found in some military aircraft hydraulic systems. Silicate esters, another fluid type having better high-temperature oxidation stability than the phosphate esters, but also incompatible with petroleum oil systems, are employed in the supersonic Concorde(5). Silicate esters meeting MIL-H-8446(6) have also been employed in some military aircraft, but are no longer utilized because of hydrolytic stability problems.

While commercial aviation was able to adopt fluids requiring new system materials because of wholesale fleet replacements, the military, with a large inventory of existing aircraft, was unable to go the same route(7). One special high-temperature mineral oil, MIL-H-27601(8), was developed for high-speed, high-temperature applications, but its poor low-temperature properties prevented its general adoption. In the early 1970's, a hydraulic fluid based on poly-alpha olefins with suitable additives, MIL-H-83282(9), was developed by the US Air Force and private industry and flight tested by the US Navy to replace the more flammable MIL-H-5606 oil. The US Army developed a rust-inhibited version, MIL-H-46170(10), to replace the corresponding MIL-H-6083 oil. Both fluids are completely compatible with systems currently serviced with petroleum-based fluids, and can be used in all mixture ratios with the petroleum fluids. The poly-alpha olefin based fluids are replacing the MIL-H-5606 type fluids in many military applications.

II. FLAMMABILITY HAZARD ASSESSMENT

Flammability testing of aircraft fluids continues to be empirical, because no single fundamental property adequately describes the flammability characteristics of a fluid. It is, therefore, necessary to analyze the hazard environment, and then to relate the results of various tests to that environment. The assessment of flammability hazards should address at least the following parameters:

Fluid Exposure

- Fluid system pressures and temperatures
- Environmental air temperature, pressure, and velocity
- Possible modes of fluid exposure such as misting, pooling, or wick material absorbancy

Ignition Sources

- Type of source such as open flame, hot surface, or electric spark
- Energy level of the ignition source
- Location of ignition source
- Size and shape of ignition source

Extreme temperatures in some modern military systems are illustrated in Table I which lists maximum bulk and surface temperatures experienced in different locations of various aircraft(11,12). The extreme temperatures of modern braking systems are obvious.

In addition to analyzing the above parameters during the design and testing of hydraulic systems, reductions in flammability hazards depend heavily upon investigations of accidents caused by hydraulic fluids. Such investigations pinpoint the most frequent sources of problems and can serve to prioritize changes. Sometimes, hazards can be reduced by parts redesign or relocation; however, performance requirements or material limitations often mitigate against such changes, and highlight the need for fluids with improved flammability characteristics.

The results of accident investigations by various branches of the US Government have thus pointed out the need for better flammability features than exist in hydraulic oils meeting MIL-H-5606.(12) US Air Force and US Navy(13) studies of non-combat fires between 1965 and 1975 are summarized in Table II. More detailed results of the studies are given in Appendix B. Out of some 3600 US Air Force and 2500 US Navy fires over the eleven-year period, 101 US Air Force and 101 US Navy fires were directly attributed to hydraulic fluid (MIL-H-5606), and another 184 US Air Force and 33 US Navy indicated hydraulic fluid involvement. The uncertainty arises from the fact that, depending upon the severity of the accident, pinpointing the exact cause may be very difficult, particularly since more than one combustible fluid is often involved in a fire. A further breakdown of data in Table III shows the wheel-well area to be very susceptible to hydraulic oil fires. These tend to occur during landings or aborted takeoffs, due to maximum hydraulic system pressures and the very high temperatures reached on the braking surfaces. When hot engine surfaces in the nacelle are included in the analysis, some 80 percent US Air Force and 68 percent US Navy hydraulic fluid fires were the result of a hot surface acting as the ignition source. This is the type of information vital to giving direction to hydraulic fluid development and flammability test design. It also becomes reasonable to conclude that sprays on hot surfaces are an important test parameter to be addressed in hydraulic-fluid flammability abatement studies.

On the other hand, a survey(14) of FAA Service Difficulty Reports, covering commercial jet transports operating in the US over the period 1975 to March 1984, disclosed a total of four reported "fires" involving hydraulic systems. (All such transports used phosphate ester fluids in the time period.) In two incidents, electrical sparks apparently ignited hydraulic fluid, one in a rear stairs compartment, the other in the wheel-well area. In another incident, smoke evolved from a hot engine surface; while in the fourth case, a hydraulic leak was involved, along with an overheat alarm, with no evidence of fire.

III. FLAMMABILITY TESTING

Aircraft accident investigations have indicated hydraulic oil fires usually are complex events, with the possibility of several release modes and several ignition sources. Quite often, hydraulic fluid is sprayed at high pressure, followed by leaking or seeping, forming pools of liquid. Liquid may be absorbed by porous materials such as insulation. The sprays, as well as the pools, may be exposed to hot surfaces, sparks, or open flames. Accurate assessment of a hydraulic fluid's flammability, therefore, cannot be established with a single test procedure, although testing may be simplified once major hazards have been identified. Flammability tests are often designed to incorporate specific parameters such as fluid pressure, hot surface temperature, and a specific ignition source, because these variables are intended to duplicate or closely relate to a field problem situation. On the other hand, fluid specifications usually include simpler, standardized flammability tests used primarily for manufacturing control. To better understand flammability characteristics of hydraulic fluids, a brief description of various flammability test methods follows, along with the significance of the method.

A. Flash Point and Fire Point

The flash point is the minimum temperature which a fluid must attain to generate sufficient vapor to ignite in the application of a small flame in a specific apparatus under closely controlled conditions. The fire point is the minimum temperature (usually higher than the flash point) at which ignition and continued burning take place. The most commonly specified flash and fire tester for hydraulic fluid is the Cleveland Open Cup, ASTM Test Method D 92(15); however, MIL-H-5606E requires the Pensky Martens Closed Tester, ASTM Test Method D 93(15).

The usefulness of flash point/fire point data is limited by the fact that they are based entirely upon vapor evolution, and are obtained under quiescent conditions at a fixed vapor-to-liquid volume ratio. Investigations(16) have shown, however, that the flash point temperatures of petroleum products, particularly those of fuels, mark a relatively narrow transition region above which the flame speed over a pool of the fluid increases by several orders of magnitude. The flash test is also useful in the detection of hydraulic oil contamination by more flammable fluids.

B. Autoignition

Spontaneous ignition of a flammable fluid in the presence of an oxidant occurs only when the temperature is at or above that required to generate heat by oxidation at a rate which is greater than the rate of dissipation of this heat to the surroundings(17). Autoignition has been defined as the ignition of a material commonly in air as the result of heat liberation due to an exothermic oxidation reaction in the absence of an external ignition source such as a spark or a flame(18). The autoignition temperature (or AIT) is the temperature at which autoignition occurs under the specified conditions of the procedure. In the test, a small quantity of liquid is injected and vaporized in a quiescent, uniformly heated, air-filled container. Time delays between injection and ignition are recorded as part of the results, and maximum ignition delays are specified in the procedure. If no reaction occurs, the unit is purged, the temperature is raised, and fluid is again injected. This process is repeated until ignition is observed. Cool flame reactions are also noted on occurrence. Standard AIT tests were formerly conducted per ASTM Test Method D 2155, which was replaced in 1980 by the revised procedure ASTM Test Method E 659(18).

Test results obtained by this procedure should be used with caution because of apparatus and test condition effects(19). Results are influenced by apparatus size (larger vessels give lower results) and by the vessel material which may have catalytic effects. Vessel pressure and oxygen concentration have major effects on AIT, with pressures above atmospheric resulting in the lowering of AIT. Also, the test measures only vapor ignitability. The primary usefulness of the test is to furnish a relative rating scale, rather than produce absolute values which can be directly applied to problem solutions.

C. Hot Surface Ignition

To overcome some of the AIT test shortcomings, a number of "dynamic" tests have been developed. All include a heated metal surface and a method of delivering fluid to the hot surface. In some procedures, air is swept over the hot surface at controlled velocity and pressure. In the Hot Manifold Test per modified Federal Test Method 791B, Method 6053(20), illustrated in Figure 1, 10 ml of fluid is dripped with a buret at a flow rate of 10-15 ml/min on a 3-inch diameter stainless-steel tube heated to 704°C. This method has been modified by one researcher(21) to include sprays at varying pressure and a variety of atomizing nozzles. In a facility illustrated in Figure 2, another investigator(22) has used differing hot surface shapes, as well as varying air flows, to obtain differing residence times and differing test results. The same investigator has also examined the effect of two different metal compositions. Still others(23) have designed equipment to reach surface temperatures as high as 1649°C with induction-heated graphite specimens.

It can be argued that the closer the test equipment and operation approaches the real-life situation, the higher the reliability of the results. Such an approach may have to be taken in the early investigation of a major problem, and full-scale high-temperature brake tests have been conducted(11,24). Other investigators simulated fluid leakage into a closed, high-temperature compartment(24), studied pressure and volume effects in an actual aircraft compartment(26), or used a small wind tunnel to relate laboratory tests to design factors(28). High experimental costs tend to curb such approaches, however, and they are not necessarily feasible for engines or aircraft still in the design stage. Attempts to relate large-scale test results to small-scale laboratory procedures are limited by the heterogeneity of the air/fluid mixtures in all these experiments. Several investigators(22,23,27) point out that it is the temperature of a critical air/fluid vapor mixture which determines ignition, rather than the temperature of the igniting surface; however, very few of the tests are able to measure temperatures in these vapor zones which are seldom stationary.

D. Flame Propagation

In fluid flammability safety studies, flame propagation often refers to "pool burning," or burning above a liquid layer typical of a spill. The propagation of a flame, after ignition, can be very slow or fast enough to cause detonation depending upon a number of factors, including the composition of the fluid, bulk fluid temperature, air velocity, and other factors. The speed with which the flame front travels above the quiescent liquid is directly related to the vaporization characteristics of the fluid, with drastic increases of flame speed when fluid temperatures are above the fluid's flash point(29,30). This phenomenon is illustrated in Figure 3 for several fuels. Because only vaporized fluid can be ignited and burned, the low volatility of most hydraulic fluids usually tends to prevent pool burning.

Under certain conditions, however, even very low volatility fluids will maintain a steady flame once ignited. In one such test, the liquid is absorbed on a porous substrate or wicking material and ignited. A schematic of the apparatus is shown in Figure 4. The procedure takes advantage of the decrease in fluid viscosity adjacent to the flame to promote wicking and reduce the required ignition source intensity. This type of test, of course, is the equivalent of a wax candle. Several variations of this approach are being used to measure comparative propagation rates of fluids with a variety of non-combustible substrates, including ceramic fiber cord(9), or asbestos string wicks(7). Results from these tests can rate the relative ability of hydraulic fluids to sustain a flame when insulation or some other porous material has become soaked with the fluid and is ignited by a flame or fire.

In a different evaluation of flame propagation, hydraulic fluid is sprayed from a nozzle under designated conditions. A flame, usually fed by oxy-acetylene, is moved into the spray a prescribed distance away from the nozzle, and the tendency of the spray to ignite and maintain a flame after removal of the ignition source is measured. Such a procedure is described in Federal Test Method 791B, Method 6052(31). A recent study(32) systematically investigated the parameters of this procedure and noted that air velocity, fluid temperature, and nozzle pressure all required close control. Spray nozzles should be standardized and preselected for improved test precision. Ambient air temperature appeared to have little effect on test results.

A test which measures the effect of evaporation on flammability is described in Federal Test Method Standard 791B, Method 352(33). An absorbent wick, soaked in the test fluid, is repeatedly passed through a flame. The test criterion is the average number of cycles necessary for a self-sustaining flame to be established.

E. Ignition Sources

Aside from the above-mentioned hot surfaces and oxy-acetylene flames, one author(19) summarizes the effect of hot wire and hot gas ignition sources in terms of heat-source diameter, in that ignition temperatures decrease with increasing heat-source diameter. Ignition temperature differences between these ignition sources were noted below source diameters of 2.5 mm. Other ignition sources used to evaluate military fluids include ballistic rounds of various types(24).

F. Heat of Combustion

The heat of combustion or specific energy is not directly related to a potential hazard, and is not a measure of flammability. It is a measure of the heat generated during combustion after ignition and is, therefore, considered a significant factor in the overall flammability characteristics of a fluid. The higher the heat of combustion, the greater the energy releases into the bulk fluid while it is burning. Heat of combustion is normally determined by ASTM Test Method D 240(34).

IV. FLAMMABILITY CHARACTERISTICS OF HYDRAULIC FLUIDS

As pointed out earlier, the flammability of hydraulic oils is checked by a battery of tests, not all of which are fully standardized. Table IV presents such a listing for hydraulic fluids in current use. The results reflect that, for a given fluid, an improvement in one test does not necessarily cause similar improvements in other flammability characteristics. Thus, while the alpha-olefin fluid meeting MIL-H-83282 had an AIT some 80°C higher than the MIL-H-5606 oil, its hot manifold ignition temperature was 66°C below that of the MIL-H-5606 product. These results follow earlier findings(19) that more volatile products tend to have higher hot surface ignition temperatures than less volatile fluids of similar chemical composition. On the other hand, careful control of test parameters in the spray/oxy-acetylene test showed a significant difference between these two fluids in favor of the alpha-olefins(32). AIT and hot manifold minimum ignition temperatures on a wide variety of fluids are given in Appendix C.

As a result of the findings with the alpha-olefin type products, the Air Force has issued the flammability criteria for new technology hydraulic fluids shown in Table V.(24,25) Criterion A was developed to insure nonignition of the hydraulic fluid when exposed to all anticipated ignition sources aboard current and future aircraft. Criterion B covers all anticipated ignition sources except overheated carbon brakes resulting from an emergency rejected takeoff. Test results for two experimental materials are compared with the near term goals of Criterion B in Table VI. The two fluids are a tetrachlorophenylmethyl siloxane (Nadraul MS-6)(13) and a chlorotrifluoroethylene oligomer (CTFE)(25). The reduction in flammability over existing fluids is noteworthy.

The performance of differing fluids in a dynamic hot surface test(22) is illustrated in Figure 5. In this procedure, the fluid is sprayed on the heated surface from a high-pressure nozzle, while air velocity is varied from 0.8 to about 40 meters per second. The marked effect of air velocity on ignition temperature is noteworthy, as are the significant differences among the fluids tested. Changing metal composition from stainless steel (Figure 5) to titanium decreased ignition temperatures 25 to 75°C in the same test, as illustrated in Figure 6.

The American Standards Institute (ANSI) and the International Standards Organization (ISO) have developed a classification system of fire-resistant hydraulic oils. Except for one category, these "oils" contain water and/or glycol, and are not suitable for aircraft. A description of the classification system can be found in Appendix D.

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TABLES

AND

FIGURES

TABLE I

TYPICAL MAXIMUM OPERATIONAL TEMPERATURES IN MILITARY AIRCRAFT*

(All Temperatures in °C)

Oil Bulk Temperatures

Aircraft			Temperatures
F-104	F-111	AWACS	Between 107 and 135
F-105	A-7	HH-53B	
F-106	F-15	B-1	

Brake Temperatures

Aircraft	Normal	Rejected Takeoff
F-15 and C5A (Beryllium)	200 - 260	650
F-16 (steel brakes)	370 - 430	1260
B-1 (carbon brakes)	600 - 650	1650

Engine Temperatures

Aircraft	Forward of Firewall	Aft of Firewall	Accessory
F-4, F-5, F-105, A-10		700	
B-1, F-15, F-16	260 max.		
C-5		700	400
C-141		650	410

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* Taken from Reference 12.

TABLE II

MILITARY HYDRAULIC FIRE SUMMARY

NON-COMBAT EXPERIENCE*

Fire History	1965 - 1975		1970 - 1975
	USAF	USN	USAF
Total Non-Combat Fires	3634	2500	1807
Hydraulic Fluid Related	101	101	46
Other (fuel, tires, electrical, etc.	3533**	2399***	1761****

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* Taken from Reference 12.

** 184 may have been hydraulic fluid related.

*** 33 may have been hydraulic fluid related.

**** 25 may have been hydraulic fluid related.

TABLE III

MILITARY HYDRAULIC FLUID IGNITION SOURCE HISTORY

NON-COMBAT EXPERIENCE*

	1965 - 1975		1970-1975	1975-March 1978
	USAF	USN	USAF	USAF
Hot Surface Ignition				
Engine	39	33	13	3
Brakes	36	20	21	11
Bleed Air Ducts	2	0	0	0
Other	3	15	12	2
Runway Friction Sparks	9	0	-	2
Engine Ingestion	3	0	-	0
Electrical Arcing	2	16	-	4
Combustor Burn-Through	1	0	-	0
Unknown	6	15	-	4
Incendiary	0	2	-	-

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* Taken from Reference 12.

TABLE IV

FLAMMABILITY OF CURRENT HYDRAULIC FLUIDS*

(All Temperatures in °C)

Test	Test Method	MIL-H-5606	MIL-H-83282	Phosphate Esters**	Silicate Esters***
Flash Point, Open Cup	ASTM D 92	99	224	182	215
Auto-Ign. Temp.	ASTM D 2155	241	371	510	404
Linear Flame Propagation Rate, cm/sec	MIL-H-83282	0.76	0.33	-	-
Hot Manifold Ign.					
Drip	FS 791-6053	430	315	780	-
High Press Spray	FS 791-6053#	816*	816*	-	-
High Press Spray	FS 791-6053	760**	700**	815**	-
Spray Ign. Temp.	AMS 315°C (SAE)				
Low Pressure		increases flame	carries flame	extinguishes flame	-
High Pressure		ignites & continues to burn	ignites, self-extinguishing	-	-
Heat of Combus., kJ/kg	ASTM D 240	4.2×10^4	4.2×10^4	3.0×10^4	-

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* Taken from Reference 13.

** Taken from Reference 24.

*** Taken from Reference 5.

\# Same spray conditions as used in AMS 3150C, high pressure spray.

TABLE V

US AIR FORCE FLAMMABILITY CRITERIA FOR NONFLAMMABLE HYDRAULIC FLUID*

Requirement	Test Method	Criterion A (Rejected Takeoff)	Criterion B (Minimum Acceptable)
Heat of Combustion	ASTM D 240	0 kJ/kg	1.16×10^4 kJ/kg
Hot Manifold Ign.	Modified Fed. Method Std. 791, Method 6053**	1650°C (3000°F)	930°C (1700°F)
Min. Autogenous Ignition Temp.	ASTM E 659 Modified to include air circulation	1430°C (2600°F)	700°C (1300°F)
Atomized Fluid Flammability Test	@20.7×10^5 Pa and 17 ± 6°C		
(a) Arc/Spark	6 J and 20 kV	Fluids may flash but must self-extinguish	
(b) Propane/Air Flame	15-1/4 cm high flame premixed stoichiometric propane air flame from 1.9 cm ID burner	Flame front must not propagate back to nozzle flame. Self-extinguishing when ignition source removed.	
(c) Incendiary Ignition	-	Fluids may flash but must self-extinguish	

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* Taken from References 24 and 25.

** Taken from Reference 21.

TABLE VI

FLAMMABILITY OF CANDIDATE AIRCRAFT HYDRAULIC FLUIDS*

Test	Near Term Goal	Siloxane (Nadraul MS-6)	CTFE
Heat of Combustion	<2.78 cal/g	5.41	1.33
Auto Ignition Temperature, °C	>705	410	643
Hot Manifold Ignition, °C			
Stream	>927	482	927
Spray	>927	538	>927
Atomized Spray, Open Flame, °C	non-reactive	extinguishes	non-reactive

---

* Taken from Reference 24.

TABLE VII

TYPICAL TESTS FOR COMMERCIAL AIRCRAFT HYDRAULIC FLUIDS

	Phosphate Esters			Silicate Ester
Test	Skydrol LD-4*	Skydrol 500B-4*	Hyjet IV**	Hydaulic Fluid M2-V***
Viscosity, cs				
-54°C	1158	2765	1375	2450
-38°C	11.42	11.51	10.58	16.9
100°C	3.93	3.78	3.57	5.25
232°C	-	-	-	-
Pour Point, °C	<-62	<-62	<-62	<-79
Relative Density, 25/25°C	1.009	1.057	0.999	0.946
Coeff. Expansion, x 10^{-4}/°C	9.18	8.46	8.28	9.0
Moisture, wt %	0.1-0.3	0.1-0.3	0.2	<0.01
Acidity	0.10 max	0.10 max	0.07	0.04
Bulk Modulus, MPa @38°C, 435 kPa	1738	1944	1631	1282****
Specific Heat, Cal/g/°C				
38°C	0.437	0.418	-	0.44
149°C	0.507	0.487	-	0.54
260°C	-	-	-	0.64
Thermal Conduct, W/m/°C				
38°C	0.132	0.132	-	0.145
149°C	0.116	0.116	-	0.121
260°C	-	-	-	0.097
Electr. Conduct, pS/m	43	42	130	-

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* Taken from Reference 3.
** Taken from Reference 4.
*** Taken from Reference 5.
**** Isothermal secant bulk modulus taken from Reference 38.

NOTE: Test procedures used for these determinations were not identified in the referenced documents.

TABLE VIII

MILITARY HYDRAULIC FLUID SPECIFICATIONS

Specification Military Symbol NATO Code Inspection Requirements	Test Method	MIL-H-5606 OHA H-515	MIL-H-6083 OHT C-635	MIL-H-46170 FRH H-544	MIL-H-83282 - H-537
Kinematic Viscosity, cSt.	ASTM D 445				
@ 100°C (212°F)		5.0 max	--	3.4 min	3.4 min
@ 40°C (100°F)		13.0 min	13.0 min	19.5 max	14.0 min (@37.8°C)
@ -40°C (-40°F)		500 max	800 min	2600 max	2200 max
@ -54°C (-65°F)		3000 max	3500 max	REPORT	--
Pour Point, max	ASTM D 97	-59.4°C(-75°F)	-59.4°C(-75°F)	-54°C(-65°F)	-54°C(-65°F)
Flash Point, min	ASTM D 92	93.3°C(200°F)*	93.3°C(200°F)*	218°C(425°F)	204°C(400°F)
Swelling with Syn L	FS 791-3603	19-30%	19-28%	15-25%	18-30%
Water, % (PPM)	ASTM D 1744	0.01 max	0.05 max	0.05 max	(100 max)
Total Acid No. max	ASTM D 664	0.20	0.20	0.20	0.10
Lubricity, Scar Diam: mm	ASTM D 2266				
@ 40 KG Load		1.0 max	1.0 max	0.65 max	0.65 max
Copper Strip Rating, max	ASTM D 130	2e	3a	--	--
Corr. & Oxidation Stability:	FS 791-5908				
168 Hrs @ 121°C (250°F)		--	PASS	PASS	--
168 Hrs @ (275°F)		PASS	--	--	PASS
Galvanic Corrosion	FS 791-5322.2	--	PASS	PASS	--
Corrosion Protection:	ASTM D 1748				
Hrs in Humd. Cabinet		--	100 min	100 min	--
Salt-Water Immersion		--	--	--	--
Bulk Modulus, Isoth. Secant	MIL-H-83282				
@ 3000 psi & 100°F		--	--	200,000 min	200,000 min
Flammability:					
High Temp/High Pressure	FS 791-6052	--	--	PASS	PASS
Flame Propagation	MIL-H-83282	--	--	PASS	PASS
Wick Ignition	MIL-H-83282	--	--	--	10 cycles, min
Autoignition Temp, min	ASTM E 659	--	--	343°C(650°F)	343°C(650°F)
Storage Stability, 12 months	FS 791-3465	CLEAR	CLEAR	CLEAR	CLEAR
Low Temperature Stability	FS 791-3458	--	PASS	PASS	PASS
High Temperature Stability	MIL-H-83282	--	--	--	5% max change
Evaporation Loss, max:	FS 791-350				
6 Hrs @ 71°C		2% max	70% @ 99°C	5% @ 300°F	--

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* by ASTM D 93

TABLE IX

NONFLAMMABLE FLUID REQUIREMENTS AND CHARACTERISTICS*

Test	Test Method	Target Requirements*	MIL-H-5606**	CTFE*
Kin. Viscosity, cs	ASTM D 445			
-54°C		2500 max	2000	2231
135°C		1.5 min	3.0	1.5
Pour Point, °C	ASTM D 97	-62 min	<-65	<-65
Four Ball Wear Scar, mm	ASTM D 2260			
10 kg		0.5 max	-	-
40 kg		1.0 max	-	0.55#
Specific Heat, KCal/kg/°C	ASTM D 2766			
@38°C		-	0.47	0.23
@93°C		-	0.52	0.24
Thermal Conduct., W/m/°C	ASTM D 2717			
@38°C		-	0.135	0.074
@93°C		-	0.131	0.067
Bulk Modulus, Isoth. Secant, Pa x 10^8 @38°C & 2.09 x 10^7Pa	MIL-H-23282	>14	14.5	12.1
Vapor Pressure, mm Hg @ 149°C	ASTM D 2879	-	56***	71***
Coeff. Expansion, x 10^{-4}/°C	-	-	7.2***	9.0***
Density @ 25°C, g/cc	ASTM D 287	1.7 max	0.84	1.836

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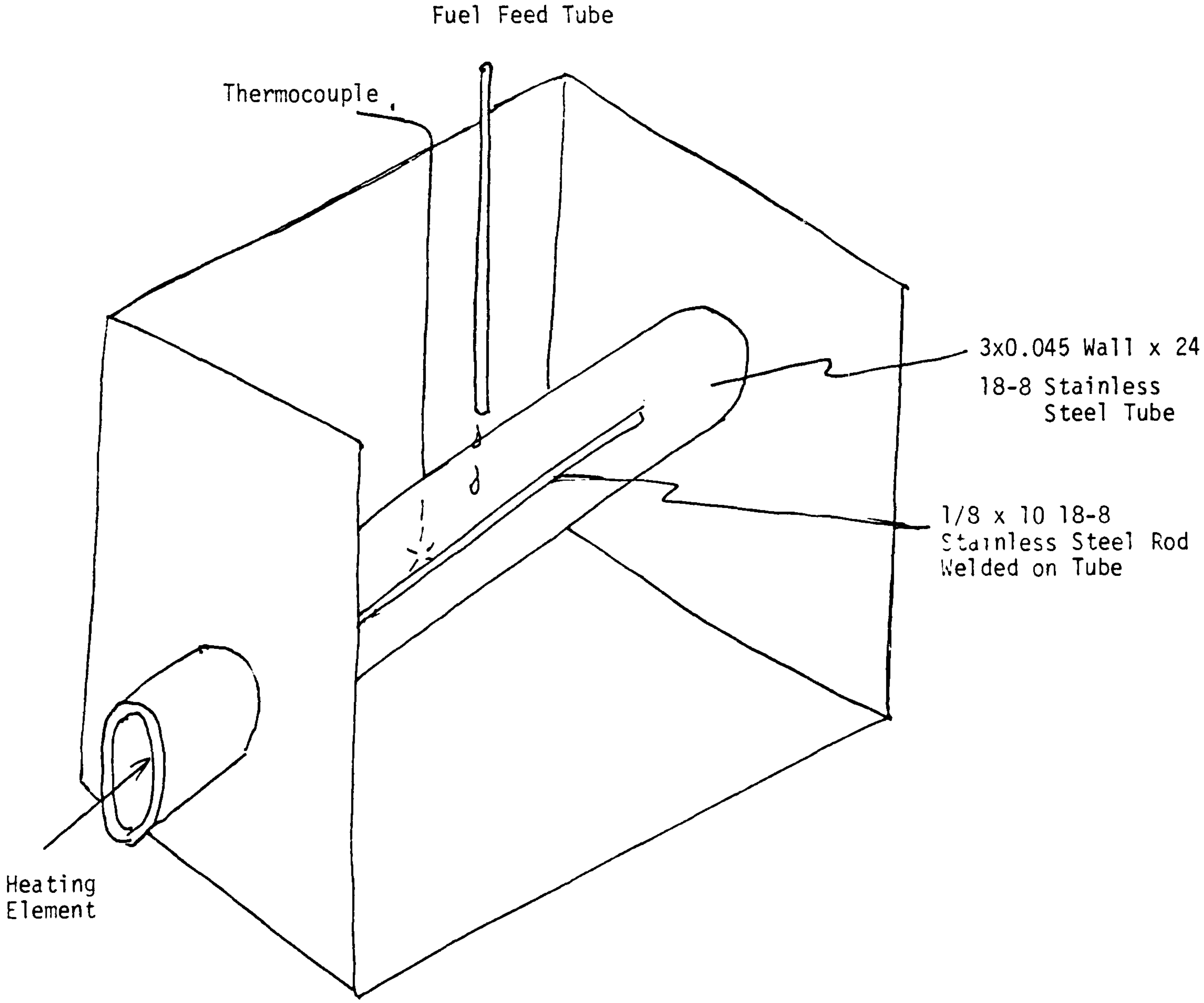
* Taken from References 24 and 25.

** Taken from Reference 13.

*** Taken from Reference 36.

FIGURE 1

HOT MANIFOLD TEST*



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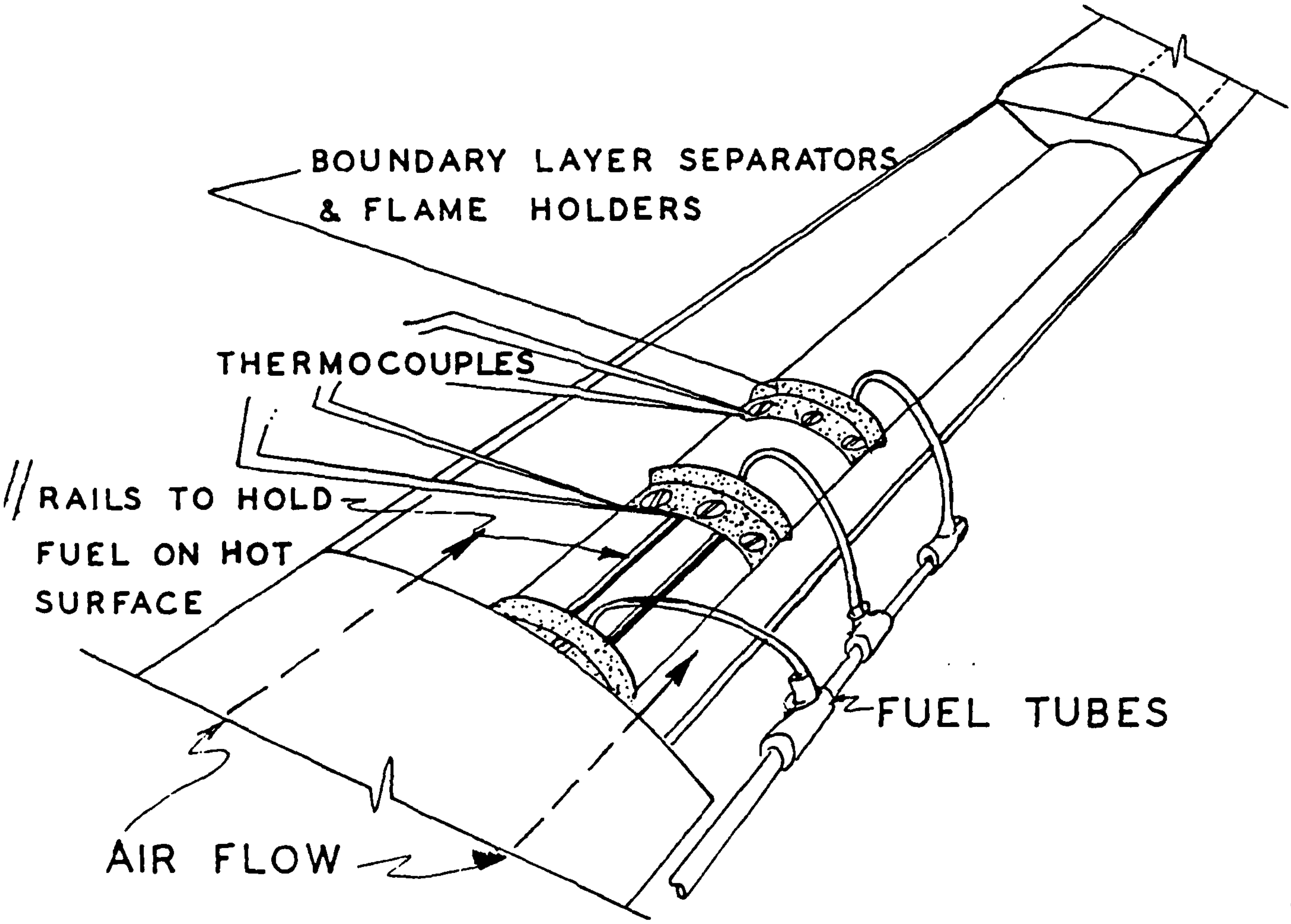
* Adopted from Reference 20.

FIGURE 2

FIRE SIMULATION FACILITY *



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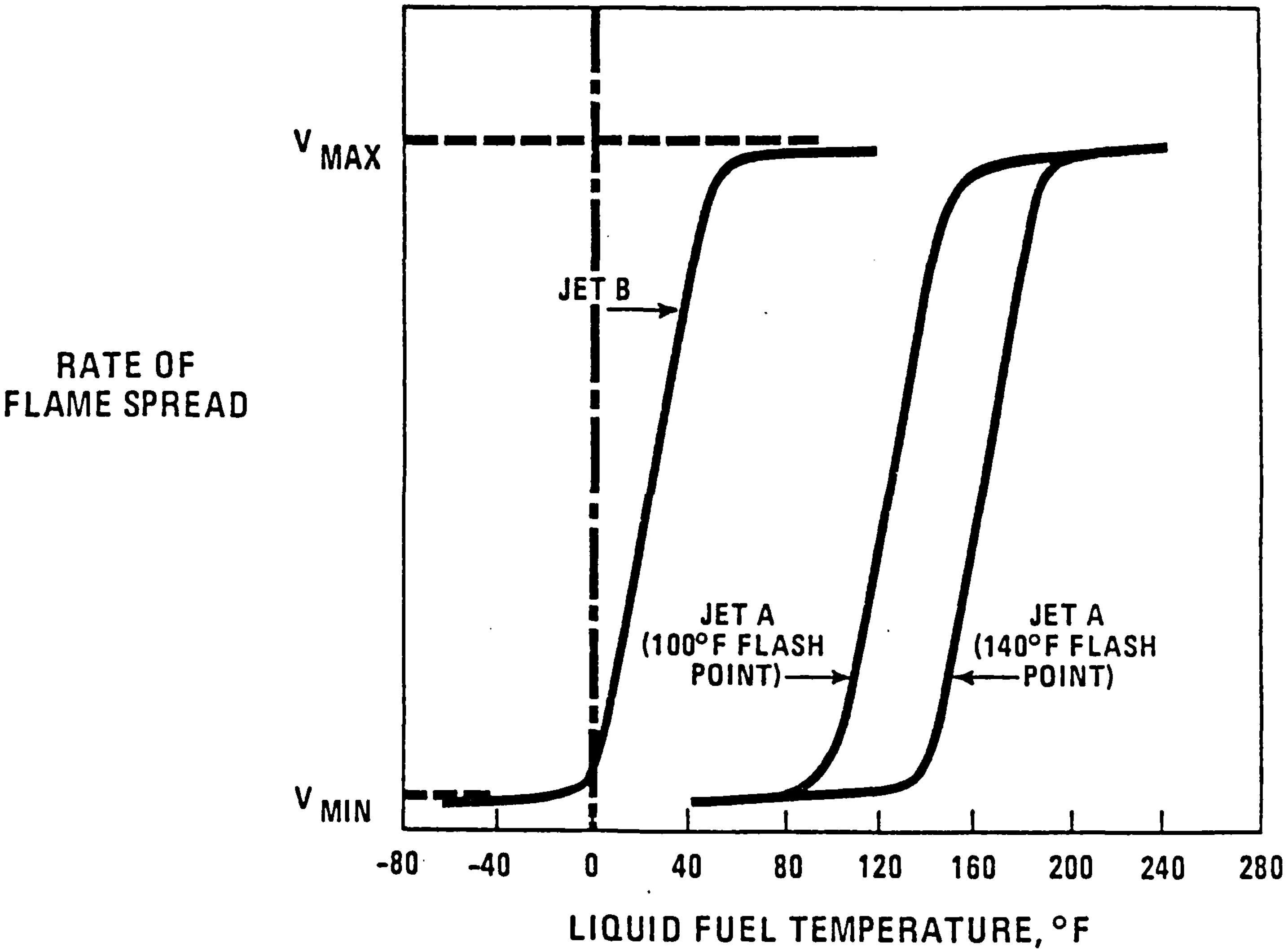
* Taken from Reference 22.

FIGURE 3

RATE OF FLAME SPREAD VS. LIQUID FUEL TEMPERATURE FOR JET A AND JET B TYPE FUELS IN AIR AT ATMOSPHERIC PRESSURE*



Reference	Fuel	Flame Spread Rate Ft./Min.	
		V MIN ($T < T_{f.p.}$)	V MAX ($T > T_{f.p.}$)
Weatherford and Schaekel (29)	JET A JET B	3.5	248 ± 10
Kuchta Et Al (30)	JET A JET B	0.6	438 ± 30

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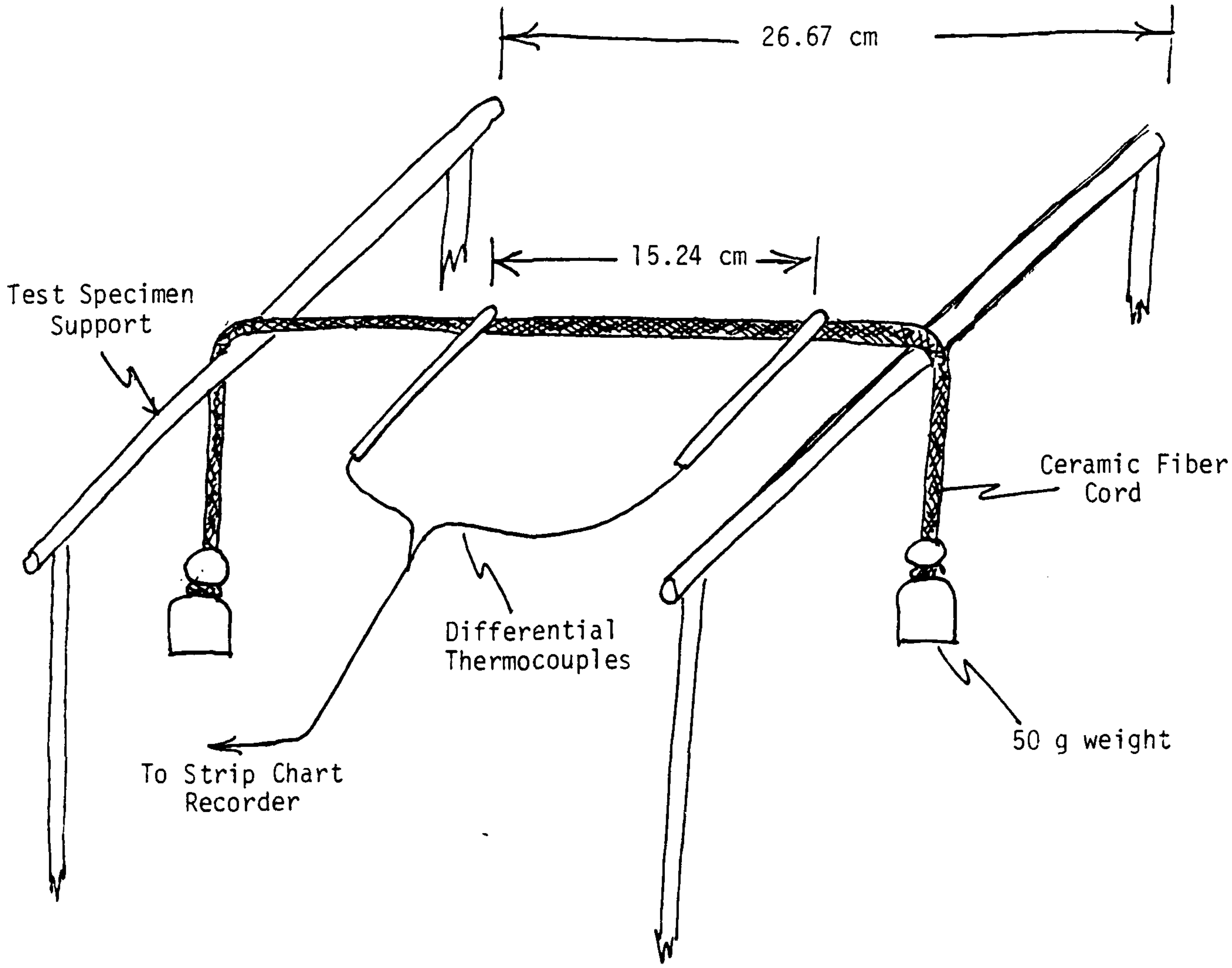
* Taken from Reference 16.

FIGURE 4

APPARATUS FOR DETERMINATION OF LINEAR FLAME PROPAGATION RATE*



Thermocouple junctions are held 2 mm above ceramic fiber cord.

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* Taken from References 7 and 9.

FIGURE 5

EFFECT OF AIR VELOCITY ON FLUID AUTOIGNITION TEMPERATURES

Stainless Steel Surface

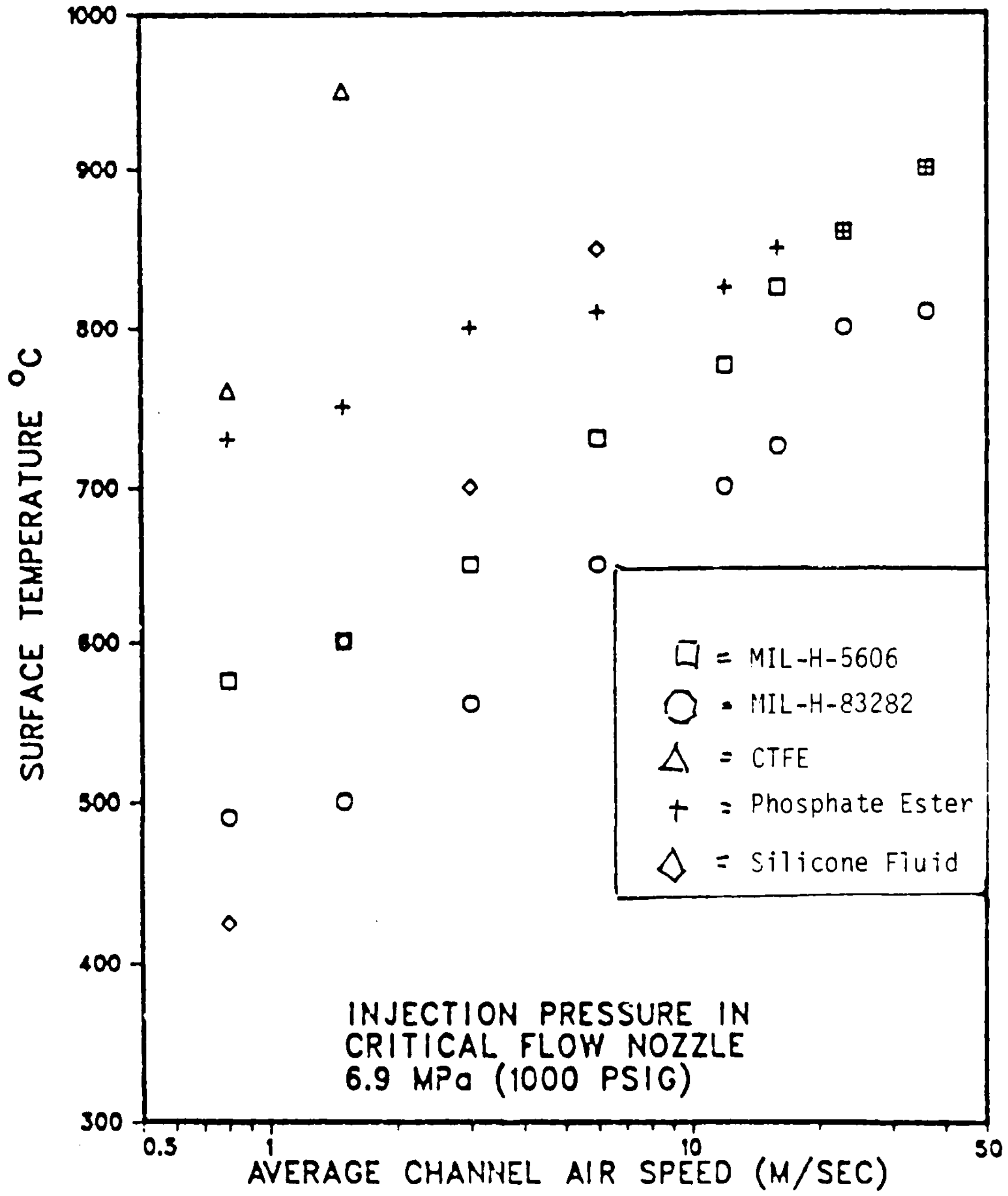
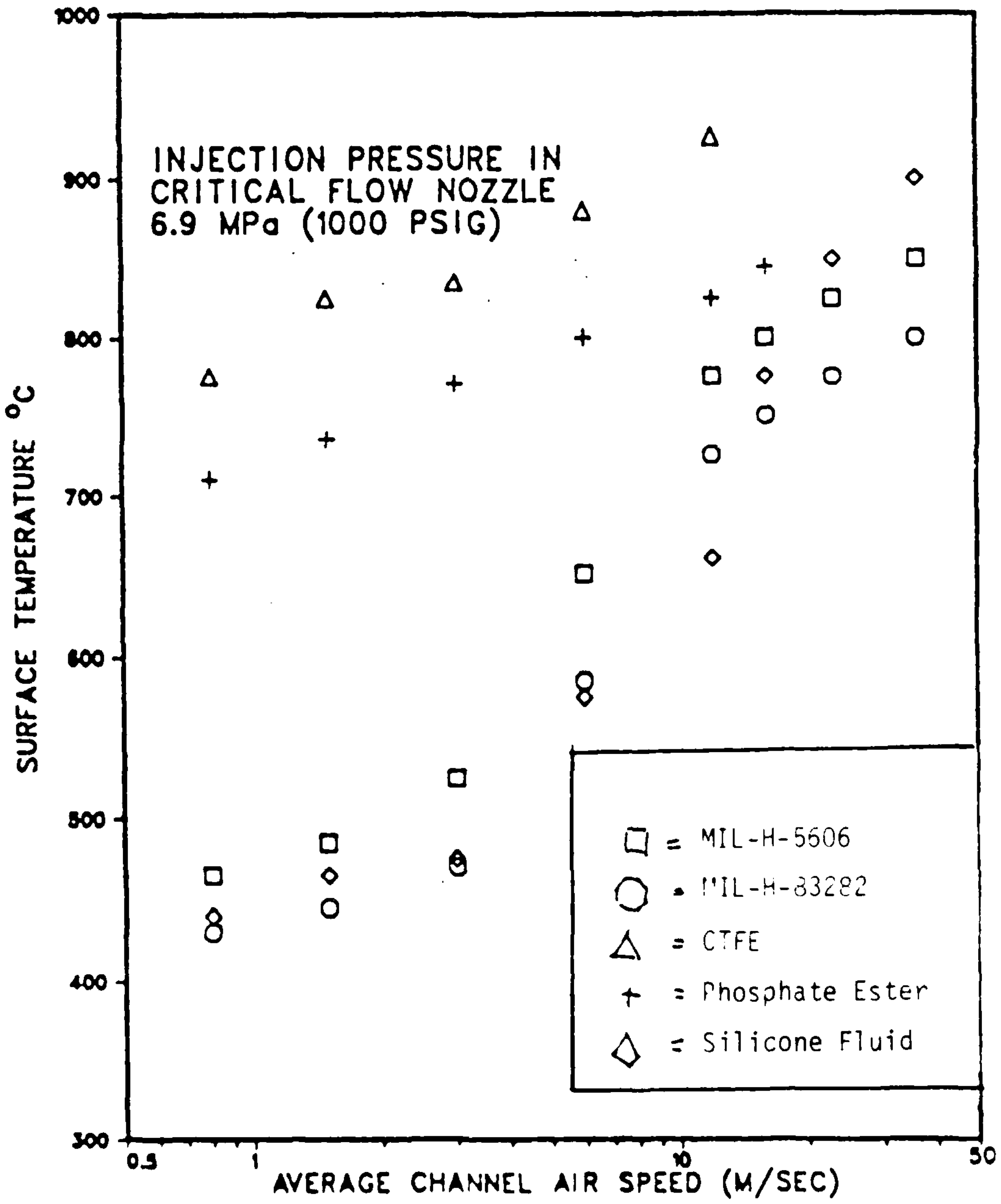


FIGURE 6

EFFECT OF AIR VELOCITY ON FLUID AUTOIGNITION TEMPERATURES

Titanium Surface



APPENDIX A

MEMBERSHIP OF THE
CRC AVIATION FLUIDS FLAMMABILITY GROUP

MEMBERSHIP OF THE
CRC AVIATION FLUIDS FLAMMABILITY GROUP

Name	Affiliation
B. R. Wright, Leader	Southwest Research Institute
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D. F. Mearns	Naval Air Systems Command
C. J. Nowack	Naval Air Propulsion Center
E. L. Richardson	General Electric Company
C. E. Snyder	U.S. Air Force - AFML
H. F. Sullivan	University of Waterloo
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Name	Affiliation
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APPENDIX B

DETAILED US AIR FORCE AND US NAVY ACCIDENT FINDINGS

TABLE B-1

AIRCRAFT HYDRAULIC FIRE PHASE OF OPERATION HISTORY

	1965 - 1975		1970-1975
	USAF	USN	USAF
Parked	10	31	5
Taxi (to takeoff & from landing)	26	10	20 (7/13)
Takeoff Roll	5	2	2
Initial Climb	16	11	8
Inflight	15	18	4
Final Approach	1	0	0
Landing Roll	17	11	7
Ground Run	11	18	0
TOTAL	101	101	46

TABLE B-2

HYDRAULIC COMPONENT FAILURE FIRE HISTORY

	1965 - 1975		1970-1975
	USAF	USN	USAF
Lines & Fittings	43	66	14
Brakes	16	0	15
Seals	12	16	5
Pump	3	6	2
Valve	3	0	3
Other	24	13	7
TOTAL	101	101	46

APPENDIX C

FLAMMABILITY DATA ON VARIOUS FLUIDS

TABLE C-1

PHYSICAL AND OTHER PROPERTIES OF LUBRICATING OILS, ENGINE OILS, AND HYDRAULIC FLUIDS*

Fluid	Compound or Chemical Class	Viscosity, cs 100 F	Viscosity, cs 210 F	Specific Gravity (Water=1)	Flash Point, F	Fire Point, F	Autoignition[b] Temperature, F	Decomposition Temperature, F
Mineral Oils								
MIL-2190	Mineral oil	32.2	5.8	0.86	~450	--	665 (5)	--
Harmony 44 (Gulf)	Mineral oil	87.6	9.8	0.88	~460	--	680 (5)	--
MLO-5731	Mineral Oil - naphthenic	--	--	--	--	--	--	640 (29)
MLO-7277	Mineral oil - naphthenic	--	--	--	--	--	464 (40)	725 (31)
MLO-60-294	Mineral oil - paraffinic, deep dewaxed	14	3.15	0.88	385	430	700 (28)	~620 (31)
Mobil DTE-103	Mineral oil	124	8.74-10.2	0.92	390	--	702,675 (40)	--
MIL-H-6083B	Mineral oil	--	--	--	255	--	470 (40)	--
MIL-H-5606A	Mineral oil	--	--	--	--	--	437 (4)	--
MIL-O-5606 (Esso Univis J-43)	Mineral oil	--	--	--	195	225	437 (2)	--
Glycols and Water Glycols								
Ethylene Glycol	Glycol	8.7	--	--	240	--	856 (36)	--
Propylene Glycol	Glycol	19.6	--	--	230	235	835 (36)	--
Ethylene Glycol + 50 % Water	Water-glycol	2.2	--	--	--	--	9903 (36)	--
Houghto-Safe 271	Water-glycol	~43	~16 (150F)	1.045	--	--	767 (5)	--
Houghto-Safe 520	Water-glycol	43.2	25.1 (130F)	1.075	--	--	--	--
Houghto-Safe 620	Water-glycol	43.2	29.8 (150F)	1.055	--	--	--	--
Nyvac 20 (Mobil)	Water-glycol and additives	41	--	1.07	--	--	750 (41)	--
Irus 902 (Shell)	Water-oil emulsion	97.4	51	0.93	--	--	709 (41)	--
Ucon 50HB-260	Polyalkylene glycol	56	--	--	455	500	743 (36)	--
Ucon 50HB-280-X	Polyalkylene glycol	--	--	--	500	600	743 (20)	--
Ucon LB-60	*Polyalkylene glycol*	10.7	--	--	310	325	653 (36)	--
Ucon LB-400-X	Polyalkylene glycol	--	--	--	--	--	752 (20)	--
Phosphate Esters								
Houghto-Safe 1010	Triaryl phosphate ester	18.2	3.9	1.20	505	670	>1200 (41)	--
Houghto-Safe 1055	Triaryl phosphate ester	130	8.0	1.145	505	680	1020,830 (40)	--
Houghto-Safe 1115	Triaryl phosphate ester	32.2	4.1	1.165	--	680	>1200 (41)	--
Houghto-Safe 1120	*Triaryl phosphate ester*	49.8	5.0	1.15	485	690	1020 (5)	--
Houghto-Safe 1130	Triaryl phosphate ester	62.8	6.0	1.145	490	680	>1200 (41)	--
MIL-H-19457 (Type 1)	Triaryl phosphate ester	--	--	--	--	--	1040 (19)	--
Tricresyl Phosphate	Triaryl phosphate ester	38.3	4.48	1.17	470	--	1110 (12)	680 (37)
Trioctyl Phosphate	Trialkyl phosphate ester	--	--	0.926	405	--	545 (13)	~380 (29)
Trihexyl Phosphate	Trialkyl phosphate ester	--	--	--	--	--	549 (12)	--
Pydraul AC	Phosphate ester-chlorinated hydrocarbon	88.8	5.0	1.36	450	745	1148 (5)	--
Pydraul F-9	Phosphate ester-chlorinated hydrocarbon	50.9	5.9	1.285	430	675	1100 (41)	--
Cellulube 220 (Shell S.F.R.)	Phosphate ester	43.4	4.9	1.145	455	665	1038 (5)	--
Pydraul 150 (Monsanto)	Phosphate ester	30.5	7.9	1.125	380	470	975 (41)	--
Skydrol	Phosphate ester	--	--	--	360	470	>1300 (41)	--
Mono- and Dibasic Acid Esters								
Plexol 201	Di-2-hexyl sebacate	12.7	3.31	0.912	420	450	--	--
Plexol 244	Di-isooctyl adipate	9.64	2.77	0.926	400	445	712 (12)	--
Plexol 273	Di-isodecyl adipate	14.5	3.56	0.920	425	460	--	--
Plexol 79	Polyester	1250	108	1.023	540	620	--	--
MIL-L-7808 (0-60-18, Esso 4040)	Sebacate-adipate diester	12.1	3.1	--	437	460	728,486 (7)	490 (27)
MIL-L-7808 (H-1026)	Di-2-ethylhexyl sebacate	12.58	3.3	--	--	--	755 (40)	575 (15)
MIL-L-9236B (0-60-7, TP-653B)	*Trimethylol propane ester*	15.1	3.4	--	430	475	738,431 (7)	~650 (24)
MIL-L-9236 (0-60-27)	Trimethylol propane ester	14.8	3.45	--	435	485	--	--
MIL-L-9236 (0-60-23)	Trimethylol propane ester	15.99	3.62	--	470	525	--	--
MIL-L-9236 (0-61-17)	Trimethylol propane ester	15.78	3.59	--	490	535	--	--
MIL-L-9236B	Trimethylol propane ester	16	3.2	0.97	425	510	>800 (41)	~650 (24)
MLO-54-581 (Texaco, TL-2456)	Diester	--	--	--	435	475	743 (2)	--
TP 653B (Hey. Newport)	Trimethylol propane ester	--	--	~0.97	--	--	705,507 (40)	--
P/O (Esso 4275)	Polyester	--	8.04	0.951	510	--	711,500 (40)	--
MLO-60-50	Trimethylol propane ester	--	--	--	--	--	--	748 (31)
Trimethyolpropane Tri-pelargonate	Trimethylol propane ester	--	--	--	--	--	--	606 (27)
Silanes								
MLO-54-408C	Tetra dodecyl silane	34.58	6.37	--	555	625	775 (17)	658 (15)
MLO-56-280	Diphenyl di-n-dodecyl silane	37.2	6.2	--	530	580	690 (17)	>680 (15)
MLO-56-578	Octadecyl trioctyl silane	27.5	5.76	--	520	590	790 (17)	--
MLO-56-582	Octadecyl tridecyl silane	33.9	6.8	--	545	595	750 (17)	--
MLO-56-610	Dodecyl tridecyl silane	26.4	5.6	--	535	575	750 (17)	--
MLO-56-611	Didodecyl dioctyl silane	23.1	5.0	--	520	565	750 (17)	--
MLO-57-9	Tetra undecyl silane	29.26	6.11	--	545	600	760 (17)	--

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* Taken from Reference 19.

TABLE C-1 (Continued)

Fluid	Compound or Chemical Class	Viscosity, cs 100 F	Viscosity, cs 200 F	Specific Gravity (Water=1)	Flash Point F	Fire Point, F	Autoignition[b] Temperature, F	Decomposition Temperature, F
Silicates and Silicones								
Tetra (2-ethylhexyl) Silicate	Ethyl hexyl silicate	--	--	--	--	--	--	638 (29)
Onsil 8.F.1	(2-ethylhexyl) silicate	--	--	--	--	--	~570 (12)	--
Oronite 8200	Silicate ester	31.75	11.14	--	385	440	716 (2)	--
Oronite 8515	Silicate ester	24.3	8.11	--	390	450	710 (40)	--
MLO-54-645	85% oronite and 15% plexol	--	--	--	340	455	716 (2)	--
MLO-54-540 (Monsanto OS-45)	Silicate ester	--	--	--	325	430	703 (2)	--
MLO-54-856 (Hollingshead, 72073C)	Silicate ester	--	--	--	315	440	716 (2)	--
Versilube F-50	Silicone	52	16	1.045	550			
Versilube F-44	Silicone	55	17	1.045	550	640	900 (40)	>600 (41)
Dow Corning 190	Polymethyl siloxane	22.6	--	--	240	640	900 (40)	>600 (41)
Dow Corning 400	Polymethyl siloxane	10.9	--	--	255	--	860 (36)	--
Dow Corning 500	Polyethyl siloxane	44.9	--	--	470	280	610 (36)	--
Dow Corning 550	Silicone	65 – 87	--	1.065	600	--	900 (36)	--
Dow Corning 700	Poly (methyl, phenyl) siloxane	2.8	--	--	305	--	--	740 (29)
Dow Corning 710	Methyl phenyl silicone	220	--	1.112	520	325	940 (36)	--
MLO-59-98	50% methyl phenyl silicone (DC 258) plus 50% TMP adipate tetracoproate	61.8	13.5	--	--	-- --	-- --	588 (15) 625 (31)
Halogenated Silicones and Hydrocarbons								
MLO-53-446 (GE 81406)	Chlorinated silicone	--	--	--	560	710	786 (2)	514 (15)
MLO-59-287 (GE F-50)	Chlorophenyl methyl silicone	--	--	--	--	--	--	630 (31)
Fluorolube F-S	Polytrifluoroch loroethylene	5	--	1.86	--	--	~1205 (12)	>620 (41)
Pydraul A-200	Chlorinated hydrocarbon	49.8	5.0	1.42	350	680	1200 (41)	--
Arochlor-1248	Tetrachlorodiphenyl	43.0	3.2	1.41	380	None	~1185 (12)	--
Arochlor-1242	Trichlorodiphenyl	17.7	--	--	350	633	1230 (36)	--
Arochlor-1254	Chlorinated hydrocarbon	--	--	--	--	--	~1085 (12)	--
Aromatic Ethers								
OS-124 (Monsanto, 5P4E)	5 ring polyphenyl ether	363	13.1	1.20	550	660	1112 (40)	>830 (31)
MCS-293 (Monsanto)	Aromatic ether	25.2	4.13	1.19	428	518	914 (40)	675
MLO-59-692 (Monsants)	Bis (phenoxyphenoxy) benzene	--	--	--	--	--	--	942 (31)
mm-4P4E	Bis(m-phenoxyphenyl) ether	60.9	5.98	--	465	--	1095 (17)	~835 (17)
pp-4P3E	Bis(p-phenoxyphenyl) ether	2.83(300F)	1.51(400F)	--	516	585	1040 (17)	~835 (15)
mmm-5P4E	m-Bis(m-phenoxyphenoxy) benzene	332	12.7	--	540	660	1050 (17)	870 (17)
5P4E	Bis(phenoxyphenoxy) benzene	380	13.4	--	560	660	1130.1030 (7)	870 (27)
pppp-6P5E	Bis [p-(p-phenoxyphenoxy)phenyl] ether	4.20(400F)	1.55 (600F)	--	635	--	1030 (17)	773 (15)
Phosphonitriles								
MLO-63-24	Hexaphenyltriphosphonitrile	--	--	--	--	--	--	810 (31)
MLO-63-25	Phenoxy base triphosphonitrile	--	--	--	--	--	--	905 (31)
K488 (Olin Mathieson)	Tetrameric octylfluoroamyl phosphonitrilate	--	--	--	--	--	900 (19)	--
Miscellaneous Oils								
Lard oil		--	--	<1	395	--	833 (38)	--
Linseed oil		--	--	0.95	435	535	820 (38)	--
Lube oil, cylinder		--	--	<1	--	535	783 (38)	--
Lube oil, light machine		--	--	<1	318	370	--	--
Lube oil, spindle		--	--	<1	169	200	--	--
Menhaden oil		--	--	0.927	435	--	828 (38)	--
Mineral seal oil		--	--	--	170	255	--	--
Olive oil		--	--	0.91	437	--	826 (38)	--
Palm oil		--	--	0.92	421	--	650 (38)	--
Pine oil		--	--	0.86	172	175	--	--
Rapeseed oil		--	--	0.915	325	550	836 (38)	--
Rosin oil		--	--	0.98-1.1	266	--	648 (38)	--
Soybean oil		--	--	0.925	540	--	833 (38)	--
Tung oil		--	--	0.94	552	--	855 (38)	--
Turkey-red oil		--	--	--	476	--	833 (38)	--
SAE No. 10 lube oil		--	--	--	340	380	720 (20)	--
SAE No. 60 lube oil		--	--	--	480	620	770 (20)	--

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[a] Autoignition and decomposition temperature data from references cited in parentheses. Viscosity, specific gravity, flash point, and fire point data mainly from vendor's literature.

[b] Ignition evidenced by visible flame except for underlined values where sudden pressure rise was used. Bureau of Mines data (Refs. 2, 4, 5, 7, and 40) were obtained using reaction vessels >200 cc. Values listed for other references were determined in reaction vessels <12

APPENDIX D

INTERNATIONAL STANDARDS

CATEGORIES FOR FIRE-RESISTANT HYDRAULIC FLUIDS

ISO Standard 6743/4, 1982

Class L Classification

Family H (Hydraulic Systems)

(Note: This family does not include automotive brake fluids or aircraft hydraulic fluids.)

General classification of fire-resistant fluid types:

Fluid Category HFA: Solution or emulsions containing more than 80 percent water. Service temperature +5° to +50°C (+41° to +122°F).

Fluid Category HFB: Water in oil emulsion. Service temperature +5° to +60°C (+41° to +140°F).

Fluid Category HFC: Water polymer solutions or water-glycol containing less than 80 percent water. Service temperature -20° to +60°C (-4° to+140°F).

Fluid Category HFD: Synthetic fluids containing no water. Service temperature -20° to +150°C (-4° to +302°F).

Category HFA: Two major subdivisions of this class are: HFAS-Solutions and HFAE-Emulsions with continuous water phase.

HFA fluids are generally unsuitable for use in highly rated systems due to their low viscosity and poor lubricity. Suitable paints and coatings are necessary to prevent rust and corrosion of components above the liquid level.

Most HFA fluids have a viscosity level comparable to that of water. For such fluid systems, changes in water content will not be accompanied by a significant change in viscosity, and viscosity control is not required. Where solution-type fluids containing thickeners are used, the viscosity will vary in service with water content and thickener integrity. The viscosity of these fluids should be monitored and maintained in accordance with pump manufacturer's and fluid supplier's recommendations. Consult supplier for recommended procedures for adding make-up water.

Category HFB: HFB fluids are dispersions of finely divided water droplets in a continuous phase of mineral oil with special emulsifiers, stabilizers, and inhibitors. They normally contain approximately 40 percent water. Changes in water content will change viscosity, stability, and/or fire resistance.

HFB fluids have viscosity grades similar to normal mineral hydraulic oil and exhibit quite good lubricating and anticorrosive properties. The fluid is non-Newtonion, and the operational viscosity may vary from one part of a system to another according to the shear forces applied (stated viscosity may be higher than effective viscosity). Because of this viscosity characteristic and high vapor pressure, pump inlet conditions have to be carefully designed so as to avoid cavitation.

Since viscosity and fire resistance vary with water content, fluid viscosity should be measured at regular intervals during the initial period of operation to determine the water content. Fluid viscosities should be selected and maintained in accordance with pump manufacturer's and fluid supplier's recommendations. Excessive loss of water should be avoided since this reduces fire resistance and causes a decrease in viscosity. Adding excessive amounts of water should be avoided as this will increase the fluid viscosity and may cause operating problems.

Avoid contamination by acids, alkalis, hard water, inorganic salts, solvents, HFC fluids, or HFD fluids since emulsion stability (phase separation) may occur.

Category HFC: HFC fluids are true solutions, derive their fire resistance from the presence of approximately 45 percent water, and have viscosity characteristics similar to mineral oil. Because viscosity and fire resistance vary with water content, measure fluid viscosity at regular intervals during the initial period of operation to determine the water content. Select and maintain fluid viscosities in accordance with pump manufacturer's and fluid supplier's recommendations.

Avoid excessive loss of water since this reduces fire resistance and causes an abnormally high viscosity.

Category HFD: The water-free HFD fluids such as phosphate esters are fire-resistant by virtue of their chemical composition, are available in viscosity grades similar to mineral hydraulic oils, and are suitable for higher operating temperatures than HFA, HFB, and HFC fluids. The various HFD fluids differ in low-temperature capability; elastomer, paint, and metal compatibility; specific gravity; and toxicity. The two major subdivisions of these fluids are distinguished by the nature of the synthetic products and are designated by HFD-R (phosphate esters) and HFD-U (other compositions). Manufacturers should be consulted regarding these characteristics.

It is readily apparent from reviewing the classifications that the fluids used by aircraft manufacturers and users as well as other military applications are almost exclusively the HFD fluids. It should be noted, however, that many of the same flammability procedures are applicable both to water containing fluids and also nonwater-containing fluids.

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