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(R) Importance of Physical and Chemical Properties of Aircraft Hydraulic Fluids

RATIONALE

The update implements multifold revisions to the document. The title was changed to describe better the content of the document, which discusses the significance and relevance of aircraft hydraulic fluid properties, rather than being an compilation of typical fluid properties. Scope was extended to include phosphate ester hydraulic fluids used in commercial aircraft. Referenced test methods and property descriptions were updated, where appropriate. Sections that did not relate to physical and chemical properties of aircraft hydraulic fluids were deleted.

FOREWORD

This document discusses in qualitative terms the properties of a fluid relevant to use for aerospace hydraulic systems. Further, it discusses the effect of the fluid properties on the design of aerospace hydraulic systems and components. AIR1362 and AIR1116 (Noncurrent) also are concerned with fluid properties, but contain specific data on current fluids.

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1. SCOPE

This document discusses the relative merits of the physical and chemical properties of hydraulic fluids in relation to the aerospace hydraulic system design, and the related materials compatibility. The discussion in this report applies both to hydrocarbon and phosphate ester based aircraft hydraulic fluids. In some cases, numerical limits are suggested, but, in general, the significance and effect of a property is noted qualitatively.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP598 The Determination of Particle Contamination in Liquids by the Particle Count Method.

AIR810 Degradation Limits of Hydrocarbon-Based Hydraulic Fluids, MIL-H-5606, MIL-PRF-6083, MIL-PRF-83282 and MIL-H-46170 Used in Hydraulic Test Stands

AIR1116 Fluid Properties (Noncurrent)

AS1241 Fire Resistant Phosphate Ester Hydraulic Fluid for Aircraft

AIR1362 Aerospace Hydraulic Fluids Physical Properties

AIR4713 Aerospace - Chlorinated Solvent Contamination of MIL-H-5606/ MIL-PRF-83282 Vehicle Hydraulic Systems

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428- 2959, Tel: 610-832-9585, www.astm.org.

ASTM D 92 Flash and Fire Points by Cleveland Open Cup Tester

ASTM D 93 Flash Point by Pensky-Martens Closed Cup Tester

ASTM D 97 Pour Point of Petroleum Products

ASTM D 445 Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)

ASTM D 471 Rubber Property-Effect of Liquids

ASTM E 659 Autoignition Temperature of Liquid Chemicals

ASTM D 892 Foaming Characteristics of Lubricating Oils

ASTM D 972 Evaporation Loss of Lubricating Greases and Oils

ASTM D 2619 Hydrolytic Stability of Hydraulic Fluids (Beverage Bottle Method)

ASTM D 2603 Sonic Shear Stability of Polymer-Containing Oils

ASTM D 2624 Electrical Conductivity of Aviation and Distillate Fuels

ASTM D 2717 Thermal Conductivity of Liquids

ASTM D 2766 Specific Heat of Solids and Liquids

ASTM D 2780 Solubility of Fixed Gases in Liquids (Ostwald Coefficient)

ASTM D 2879 Vapor Pressure-Temperature Relationship by Isoteniscope

ASTM D 3427 Air release properties of Petroleum Oils

ASTM D 3825 Dynamic Surface Tension by the Fast-Bubble Technique

ASTM D 4052 Density and Relative Density of Liquids by Digital Density Meter

ASTM D 4172 Wear Prevention Characteristics of Lubricating Fluids (Four-Ball Method)

ASTM D 4289 Elastomer Compatibility of Lubricating Greases and Fluids

ASTM D 4308 Electrical Conductivity of Liquid Hydrocarbons by Precision Meter

ASTM D 4636 Corrosiveness and Oxidation Stability of Hydraulic Oils, Aircraft Turbine Engine Lubricants and Other Highly Refined Oils

ASTM D 5306 Linear Flame Propagation Rate of Lubricating Oils and Hydraulic Fluids

ASTM D 6304 Water in Petroleum Products, Lubricatiing Oils, and Additives by Coulometric Karl Fischer Titration

ASTM D 6793 Isothermal Secant and Isothermal Tangent Bulk Modulus

2.1.3 U.S. Government Publications

Available from Document Automation and Production Service (DAPS), Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

FED-STD-313 Material Safety Data Sheets, Preparation and Submission of

FED-STD-791 Lubricants, Liquid Fuels, and Related Products; Methods of Testing

Method 3458 and 3459 Low Temperature Stability

Method 3603 and 3604 Rubber Swelling

MIL-PRF-5606 Hydraulic Fluid, Petroleum Base; Aircraft, Missile, and Ordnance

MIL-PRF-83282 Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base

MIL-PRF-87257 Hydraulic Fluid, Fire Resistant; Low Temperature, Synthetic Hydrocarbon Base, Aircraft and Missile

3. HYDRAULIC FLUID PROPERTIES

The properties of the fluid must be considered in the design of a hydraulic system, but it is possible to design a system to be less sensitive, or more robust, to a particular fluid property. For this reason, the property of the hydraulic fluid must be weighed for each individual hydraulic system, taking into account the system's basic design, function and environment, as well as the fluid toxicity and disposal issues. Besides the hydraulic system itself, ground handling and servicing needs of the system must also be considered.

The only absolute characteristic of a hydraulic fluid is that it be a liquid throughout the range of use. All other fluid properties must be considered in hydraulic system design.

Hydrocarbon-based aviation hydraulic fluid normally meet one of the applicable US Military specifications (See MIL-PRF-5606, MIL-PRF-83282, MIL-PRF-87287). Phosphate ester-based hydraulic fluids used in commercial aircraft typically meet SAE specifications (See AS1241).

A commonly used test method is listed below, although other acceptable methods may be used in many cases. Care must be used comparing data from the different methods for different fluids.

3.1 General

The sequence of fluid property listing has no bearing on the relative importance. Moreover, strength in one characteristic can often compensate for weakness in another.

3.2 Viscosity

Viscosity describes the resistance created from the relative motion of fluid molecules when a shear force is applied. See ASTM D 445. It is one of the most important properties defining the fluid's usable temperature range. Dynamic (absolute) viscosity is the ratio between the applied shear stress and rate of shear of the fluid. Kinematic viscosity is the resistance to flow of a fluid under gravity. Generally, kinematic viscosity data is provided for a fluid [centistoke (cSt) or mm^2/sec] which must be multiplied by the density of the fluid at that temperature to yield Dynamic viscosity [centipoise (cP)]. Dynamic viscosity is the parameter required for pressure drop equations in a hydraulic system. It is also desirable that pressure-viscosity curves at various temperatures be furnished.

Viscosity/temperature curves should be provided in the fluid descriptive data. The viscosity temperature relationship is sometimes referred to as the viscosity index. A fluid thickened (made more viscous) by a viscosity index improving polymer, such as polymethylmethacrylate, generally has a good viscosity index or exhibits smaller changes in viscosity with temperature changes. The disadvantage of viscosity index improved (polymer-thickened) fluids is they suffer both temporary and permanent viscosity loss under shear strain conditions experienced in hydraulic systems. The actual viscosity under shear conditions is somewhere between the measured viscosity of the fluid at low shear conditions and the viscosity of the base oil. This behavior, viscosity loss under shear conditions, is called shear instability. If a fluid is not thickened with a viscosity index improver it is more likely to be shear stable and does not have a permanent viscosity loss in applications. It is therefore important to know if a fluid is shear stable or not.

3.2.1 Maximum Viscosity Requirement

The maximum viscosity allowed for hydraulic equipment sets the minimum usable temperature of a fluid. For a system, two levels of maximum viscosity are important in establishing the usability of a fluid and the design criteria to be used. These two maximum viscosities are first, the maximum starting viscosity, and second, the maximum operating viscosity. The generally accepted maximum starting viscosity level is typically around 2200 cP . This viscosity can be tolerated only briefly and may cause filters to go into bypass mode. While fluids with higher viscosities can be pumped by using larger pumps and increased diameter line sizes, the significant weight penalty associated with those design changes are usually unacceptable for aerospace applications. Therefore, the true maximum viscosity level for a hydraulic system designed by ignoring the aforementioned weight penalties, could be several times this 2200 cP value.

The pump, system friction, engine and/or aerodynamic heating rapidly increase the fluid temperature once a system has been started. This increase in temperature rapidly decreases the viscosity to the maximum operating viscosity level, the viscosity at which full system operation can be expected. This viscosity level is one of the basic system design criteria and is on the order of 450 cP. Acceptable low temperature performance is, however, designated in the specification of an aircraft or by analysis and may correspond to a higher or lower viscosity. The wording may be that a system operates without detrimental effect at a specific temperature and meets full performance at another specific temperature. A higher maximum operating viscosity increases the system design problems, whereas a lower operating viscosity decreases them and results in system weight saving.

3.2.2 Minimum Viscosity Requirement

As with maximum viscosity, two levels of minimum viscosity are important in establishing usability of a fluid and the design criteria to be used. The first level of 1.5 to 2.0 cP is generally accepted as a tolerable minimum for efficient pump operation. The second level viscosity, as low as 0.5 cP (or less), is the minimum viscosity of the fluid that can be pumped. With some types of pumps, the efficiency will be reduced at these very low viscosities. Extremely low viscosity may cause reduced lubricity, with resulting reduced component life. Low viscosity increases internal and external leakage in slide, servo and similar valves and in actuator packings causing reduced system efficiency and design penalties.

3.2.3 Shear Stability of Viscosity

Viscosity index improved (polymer thickened) fluids “lose” viscosity by two mechanisms:

a. Alignment of the polymer with the high shear field, which reduces the thickening efficiency of the polymer and causes the effective viscosity under the shear conditions to become lower than dynamic viscosity under low shear conditions. This viscosity loss is temporary. Once the shear field is removed, the fluid returns to its original low shear dynamic viscosity

b. Breakdown of the polymer into lower molecular species, which results in a permanent loss in dynamic viscosity. Some level of viscosity decrease as a result of shearing will occur in service with any polymeric viscosity index improved fluid. The viscosity may plateau at an acceptable level and the fluid perform as desired for many hours. See ASTM D 2603.

The ability of a fluid formulation to withstand the shearing action of pumping and valve operation, without permanent viscosity loss, is considerably important to the life of a fluid. The maximum allowable shear induced viscosity loss in viscosity index improved fluids is very system dependent and long term component and system testing is required to determine that the fluid is suitable for the application. Therefore, the minimum viscosity guidelines described in 3.2.2 may not be suitable in cases of viscosity index improved fluids. Nonviscosity index improved fluids do not usually experience temporary or permanent viscosity loss as a result of mechanical shearing.

3.2.4 Pressure Effect on Viscosity

The increase in viscosity with pressure is significant and can be as much as 30% (or even higher at low temperatures) for aerospace hydraulic fluids at pressures of 345 bar (5000 psi). Generally, fluids whose viscosity changes more with temperature are also fluids whose viscosity changes more with pressure. While this viscosity increase results in higher pressure losses in lines, the most significant effect is on sizing of filters in the high pressure side of hydraulic systems.

3.3 Pour Point

Normally this property is of no importance to the hydraulic system or component designer. It does, however, indicate an absolute low temperature limit to retain fluidity of the fluid and it is advisable to operate at least 10 °C above a fluid pour point. See ASTM D 97.

3.4 Low Temperature Stability

This is not generally a design consideration, but describes a fluid's resistance to separation, gelling, solidification, decomposition and other forms of degradation during storage at extremely low temperature. Unless the effects of low temperature reverse themselves when the temperature is increased, a fluid is either unusable or will require special storage and handling. This irreversibility also affects the usability of the fluid in an aerospace vehicle resulting in undesirable ground handling requirements. See FED-STD-791 Method 3458 and 3459.

3.5 Storage Stability

This property is of considerable importance in field logistics. A fluid which requires special storage procedures and storage degradation checks is undesirable.

3.6 Lubricity

Most, if not all, hydraulic fluids consist of a base fluid and performance improving additives, including a lubricity additive. The presence of an additive, the type of additive and the concentration all significantly affect the results of lubricity tests and system performances. Care must be taken in comparing test results to use the same test conditions and to compare formulated fluids to formulated fluids and base stocks to base stocks. The four ball wear test is valuable for preliminary screening of a fluid. It is quick, low cost, uses small fluid samples and has satisfactory repeatability and reproducibility. See ASTM D 4172. The piston pump wear test is a much more reliable indication of the hydraulic system usability of a fluid. It is generally performed at the maximum use bulk oil temperature of the fluid or of the pump. For specification purposes, it is desirable to run the test on a pump which is representative of the general type of pumps expected to be used with the fluid. Good indication of lubricity in one pump will not mean similar indication in pumps of different manufacturers. Lubricity is not only necessary for the pumps, but also for the slide, servo and similar valves and for the effect on packing life. However, in general, a fluid which has good lubricity in a piston pump will also have the necessary lubricity for such valves.

In the development of new fluids, poor pump lubricity does not necessarily indicate an unusable fluid, but may rather indicate need for further pump development or the use of a different type of pump. Adjustments may also be possible in the fluid formulation to improve lubricity.

3.7 Combustion Indices

3.7.1 Flash Point, Fire Point and String Propagation Rate

These properties are primarily related to system safety and not to hydraulic system design as such. See ASTM D 92, ASTM D 93, and ASTM D 5306.

Certain fluids can be used at temperatures greatly in excess of their flash and fire points, although system and personnel safety must be kept in mind. These properties also serve as a good index of volatility and vapor pressure. For system design volatility and vapor pressure should be considered for possible build-up of combustible fumes.

3.7.2 Autoignition Temperature

This property is important to establish a top usable temperature limit of the hydraulic system environment without the use of special design precautions. If the temperature in the area surrounding hydraulic lines or components is greater than the autoignition temperature, the lines or components may need to be either rerouted or shielded for safety. See ASTM E 659.

3.8 Vapor Pressure

Vapor pressure is a necessary design property generally provided in fluid descriptive data as a function of temperature. High vapor pressure can limit the usable maximum temperature of a fluid, by causing pump cavitation and sponginess in the entire hydraulic system if vapor pockets are formed. See ASTM D 2879.

3.9 Power Transmission

3.9.1 Bulk Modulus

Bulk modulus is the reciprocal of compressibility and is a function of pressure and temperature. Both secant and tangent bulk moduli under isothermal and adiabatic conditions should be provided. Equipment functions that occur rapidly require knowledge of adiabatic bulk moduli, which are of great importance in dynamic considerations of hydraulic system design. The adiabatic secant bulk modulus enters into the design calculations for hydraulic pumps and motors. The adiabatic tangent bulk modulus is used in the design of servomechanisms. Isothermal bulk moduli are typically easier to measure (See ASTM D 6793) and can be used for estimating adiabatic bulk moduli.

Pressure transients in a hydraulic system, including pressure spikes and actuator response time, are affected by the bulk modulus of the fluid. Pressure spikes increase with bulk modulus. The response time for a hydraulic system is a function of the velocity of sound in the hydraulic fluid, and depends on the sonic bulk modulus which is related to adiabatic-reversible (isentropic) tangent bulk modulus.

Since bulk modulus is basically base stock related, great care must be used selecting desirable high bulk modulus base stocks. Within a class base stock type, bulk modulus varies proportionally with density, meaning the higher the density, the higher the bulk moduli. (Because no standard test method exists, data from different sources should not be considered comparable. However, data from the same source on different fluids should be comparable.) See AIR1362.

It should be noted that that the effective fluid bulk modulus in a typical hydraulic system is much less than that of pure fluids because of the inevitable presence of minute amounts of free (undissolved) air in the fluid.

3.9.2 Gas Solubility

The percent of soluble gas versus pressure and temperature of a fluid should be stated in the fluid descriptive data and is a necessary factor in hydraulic system design. Release of dissolved gas in a hydraulic system can cause pump cavitation and system sponginess (low bulk modulus). See ASTM D 2780.

3.10 Density

Density of hydraulic fluid is important for weight calculation in the design of a system and, therefore, is desired to be low. Density is also a key parameter for inlet line sizing, for fluid acceleration, for pump response requirements, for laminar/turbulent flow characteristics, etc. If a fluid specification is being prepared to cover fluids of a known class of base material, the permissible range of density versus temperature can be specified. Density is generally base stock related. In any case, the density-temperature relationship of a fluid should be stated in the fluid descriptive data. See ASTM D 4052.

3.11 Rubber Swell

This test is run on specially compounded rubber standards, representative of the type of elastomers to be used. However, since the standards are specific published formulas, they may not be precisely the formulations used in commercial seals. By the use of these standards, it is possible to compare the relative effects of various hydraulic fluids on the different types of standard elastomers. The behavior, e.g. rubber swell, shrinkage or degradation, of a specific rubber compound in a given fluid is of considerable value in the design and installation of seals of that elastomer-fluid combination. Moreover, the free elastomer swell or shrinkage in a given fluid cannot be taken as the same as with the installed seal confined rubber swell or shrinkage in a system, but merely as a guide for design precautions. While specially compounded rubber can be used for fluid development, final fluid testing should involve commercially available elastomers of probable use. The fluid descriptive data should state free swell and engineering property change data for the commercial elastomer and fluid at conditions meaningful to designers. See FED-STD-791 Method 3603 and 3604, ASTM D 471, and ASTM D 4289.

3.12 Thermal Characteristics

3.12.1 Thermal Stability

The reported maximum thermal stability of a fluid may be either a bulk oil temperature or a hot spot temperature. The exact conditions of a hydraulic fluid thermal or thermal- oxidative test must be provided to ensure a fair comparison of fluids. Conditions to specify include time, temperature, metallurgy present, absence/presence of oxygen, gas flow rate, etc. Posttest analyses conducted in thermal or thermal-oxidative tests provide insight into fluid degradation and potential fluid/system problems. These analyses may include viscosity change, acid number change, metal aggressiveness and notation of the formation of particles. Means of eliminating undesirable breakdown products must be provided when a fluid is used at the thermal breakdown temperature. See AIR810.