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DEVELOPMENT OF A HIGH TEMPERATURE SILICONE BASE FIRE-RESISTANT FLUID FOR APPLICATION IN FUTURE MILITARY AIRCRAFT HYDRAULIC SYSTEM DESIGNS

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SUMMARY

INTRODUCTION

The development of a superior fire-resistant hydraulic fluid for use in current military aircraft without requiring retrofit modifications has been shown to be a formidable task. In order to achieve superior fireresistance properties in a candidate fluid, other critical properties such as viscosity, density and bulk modulus will probably be quite different when compared to the currently used petroleum fluid (MIL-H-5606). Because of these differences, the new fluid will not function properly in current hydraulic system designs. New fluids which are similar to 5606 in basic physical properties usually offer only slight improvements in fire-resistance characteristics. Accordingly, the major thrust of this program has been directed toward the development of a military aircraft hydraulic fluid with excellent fire-resistance capabilities suitable for use at operating temperatures as high as 478°K (400°F) in future aircraft hydraulic system designs. Our intent is to provide such a fluid with completely characterized chemical and physical properties so that future aircraft hydraulic systems can be designed around this fluid and take advantage of its fire-resistant nature.

CONCLUSIONS

1. A candidate high temperature $(478^{\circ}K (400^{\circ}F))$ fire-resistant hydraulic fluid designated Nadraul MS-6 has been developed. This formulation consists of a tetrachlorophenylmethyl siloxane fluid containing 4 wt. % dibutyl chlorendate as an antiwear additive. It was developed for future aircraft hydraulic system designs.

2. A hydraulic pump-loop circuit evaluation conducted at 20.7 MPa (3000 PSI) and 422° K (300°F) average fluid temperature for 500 hours was completed. No unusual wear or fluid deterioration was observed. Some of the pump components were found to have deposits or corrosion products on their surfaces, the exact nature or origin of which has yet to be determined.

FUTURE PLANS

Efforts in this program will center on developing design guide data on a 30 dm³ (8 gallon) batch of Nadraul MS-6. In addition to evaluation for specification type properties, this batch of fluid will be used to generate data which are not usually found in specifications for hydraulic fluids but are essential for the design and analysis work involved on developing new hydraulic systems. These properties will include heat transfer characteristics, bulk modulus, viscosity-pressure curves, density-temperature curves among others. Also an evaluation of fluid performance in a 55 MPa (8000 PSI) hydraulic system test stand is planned in addition to a 478° K (400° F) pump test.

Further investigations into the corrosion of steel in the presence of water in the MS-6 fluid will be made in an effort to determine its nature and origin. In addition, effective inhibitors will be sought if indeed they are required.

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BACKGROUND

The susceptibility of military aircraft to fire hazards under combat or operational conditions greatly diminishes an effective strike force. A particularly vulnerable area can be found in aircraft hydraulic systems in which the operating fluid (MIL-H-5606) has a flash point of 372° K (210° F) which is only 39° K (70° F) higher than jet fuel. The exposure of this fluid to an ignition source as a result of enemy ground fire, accidents or system malfunctions represents a real threat to the safe operation of military aircraft.

Hydraulic fluid induced aircraft fires have occurred and are documented by the Naval Safety Center for naval aircraft. In many cases total aircraft and crew have been lost as a result of such incidents. This loss of weapons systems and personnel could have been eliminated if suitable fire-resistant fluids were developed for use in military aircraft hydraulic systems.

The search for a nonflammable hydraulic fluid has been going on for at least 25 years. Since 1958, commercial aircraft have been using a phosphate ester hydraulic fluid which is fire-resistant. This fluid, however, is not suitable for military aircraft applications. Hydraulic fluids based on super refined mineral oil and synthetic hydrocarbon (MIL-H-83282) base oils have been developed and are commercially available. However, although these fluids are less flammable than MIL-H-5606, they are not fire-resistant.

A major breakthrough in the search for a fire-resistant military aircraft hydraulic fluid occurred in 1968 with discovery of suitable antiwear additives for silicone fluids. This resulted from a NAVAIRDEVCEN in-house independent research program. Silicone fluids had been considered for military aircraft hydraulic system applications because of their superior fire-resistance properties. However, one shortcoming was their inability to lubricate metal components, especially under boundary lubricating conditions. A patent was issued in 1971 (reference (1)) covering the use of NAVAIRDEVCEN developed antiwear additives (polysulfides) in silicone fluids.

Based on these findings NAVAIRSYSCOM tasked NAVAIRDEVCEN in FY-69 to develop a fire-resistant hydraulic fluid suitable for future military aircraft. During FY-72, the program was redirected to provide a fluid for present aircraft usage. In FY-73, a candidate silicone base fire-resistant aircraft hydraulic fluid was developed and was designated NADRAUL MS-5, references 2 and 3. In order to obtain superior fire-resistance properties certain "trade-offs" had to be considered. Basically MS-5 fluid differs from MIL-H-5606 in that the viscosity and density are higher and the bulk modulus is lower. Because of these differences, a flight control simulator evaluation was performed to assess the effect of MS-5 on critical flight control parameters. The results of this investigation have led to the following conclusions. Because of viscosity, density and bulk modulus differences relative to MIL-H-5606, the use of MS-5 in current military aircraft hydraulic systems is not considered feasible without major modifications to

the hydraulic system. In January of FY-74, this program reverted to its original goal of developing a high temperature fire-resistant fluid for future aircraft hydraulic system designs.

RESULTS AND DISCUSSION

TETRACHLOROPHENYLMETHYL SILOXANE BASE FLUID

The Nadraul MS-5 silicone fluid formulation, although possessing improved fire-resistance and antiwear properties, was limited to application temperatures not greater than 408°K (275°F) due to the thermal instability of the sulfur containing thiadiozole antiwear additive. Therefore, MS-5 could not be considered as a high temperature (478°K (400°F)) fluid. In addition, it was determined that the supplier of the base fluid in MS-5, a dichlorophenylmethyl siloxane fluid, had taken this product off the market because of low volume usage. Faced with these obstacles, it was decided to investigate the use of a tetrachlorophenylmethyl siloxane fluid which had previously been considered in the retrofit program but was rejected because it would immediately precipitate the viscosity-index improver found in MIL-H-5606 when admixed. This fluid, which is used in the constant speed drives on the A-4 aircraft, is covered by Military Specification MIL-S-81087A. Because of the increased chlorine content relative to the dichloro fluid, the inherent antiwear properties are improved; however, the use of an antiwear additive was still required. Dibutylchlorendate, formerly designated "CCD", was found to provide the desired antiwear qualities even at temperatures as high as 478°K (400°F) (Table I). The optimum formulation resulting from this investigation contained 4 wt. % dibutylchlorendate in the tetrachlorophenylmethyl siloxane fluid and is designated Nadraul MS-6. The chemical structures of the base silicone fluid and antiwear additive are given in Figures 1 and 2, respectively.

Having established a suitable formulation based on antiwear properties, additional property determinations were made and these are listed in Table II. As can be seen in this Table, the MS-6 formulation appears to be quite suitable for continuous operating temperatures as high as 478° K (400° F) in addition to offering superior fire-resistance properties. In regard to fireresistance evaluations, some of the tests performed on MS-5 have not been done for MS-6. However, it is not unreasonable to assume that the MS-6 fluid will be equivalent to MS-5 in these tests, i.e., linear flame propagation, oxygen index, hot manifold drip and high pressure spray ignition, mist flash back and gun fire testing (reference (2)). Also, the bulk modulus and streaming potential characteristics are expected to be substantially equivalent to MS-5 (reference (2)). The MS-6 fluid is not miscible with small quantities of MIL-H-5606, however, it is miscible with MIL-H-83282 fluid in all proportions.

ALKYL-ESTER SILOXANE BASE FLUID

Another siloxane fluid which has been under investigation is an alkylester modified siloxane, the chemical structure of which is given in Figure 3. Because of the highly organic nature of this molecule, its solubility

characteristics are appreciably better than conventional siloxanes and it has been found to be completely miscible with MIL-H-5606 fluid. By controlling the amount of ester units in the siloxane chain, distinct viscosity and fire-resistance properties can be obtained as shown in Table III. The viscosity can be observed to increase with increasing ester content as does its fire-resistance properties.

Initial investigations have centered on the 18% ester base fluid containing 2.5% wt. of an additive package consisting of 4 parts trioctyl phosphate and 1 part tris (2-chloroethyl) phosphite. The properties of this formulation which is designated "750" are listed in Table IV. Comparing the properties of 750 with MS-6, it can be observed that the 750 formulation is not as good as MS-6 in the following tests:

- 1. Steel on steel wear at higher temperatures
- 2. Flammability (high pressure spray and wick test)
- 3. Oxidation corrosion
- 4. Hydrolytic stability

Because of these deficiencies relative to MS-6, no further work was performed on this fluid.

HYDRAULIC PUMP-LOOP CIRCUIT EVALUATION OF NADRAUL MS-6

A major criteria for determining the capability of a fluid to function as a hydraulic fluid is its ability to lubricate hydraulic pump components. Laboratory screening techniques designed to determine the antiwear properties of fluids have shown that the MS-6 formulation possesses significantly improved antiwear properties in comparison to other silicone fluids. Based on these results, a performance evaluation was initiated to determine the lubricating properties of Nadraul MS-6 in an aircraft hydraulic pump under simulated service conditions. The hydraulic pump-loop circuit evaluation was performed on a system simulating the basic functions of the A-4E aircraft hydraulic system. Details concerning the operation of this system along with photographs and schematic diagrams of the test stand have previously been reported (reference (3)). A new Vickers Model PV3-044-3A Variable Displacement "In-Line" Pump was used in this evaluation. Fluorocarbon elastomeric seals were used throughout the pump, actuators and other critical components. An exploded view of the pump assembly is shown in Figure 4. Target operating conditions were as follows:

1.	Pump Discharge Flow Rate	0.250 dm ³ /s (4 gpm)
2.	Reservoir Pressure	206.8 kPa (30 PSI)
3.	Pump Discharge Pressure	20.68 MPa (3000 PSI)
4.	Reservoir Temperature	422 [°] K (300 [°] F)
5.	Actuator Temperature	422°K (300°F)

6. Actuator Cycle

> Extend Retract

OFF 60s **ON 240s** 10s 10s

7. System Operation ON 7.5h OFF 16.5h (shutdown on weekends)

A daily log of the performance evaluation was maintained at hourly intervals. The following operating conditions were monitored throughout the test:

- 1. System Operating Time
- 2. Actuator Cycles
- 3. Pump Speed
- 4. Pump Inlet Pressure

5. Pump Discharge Pressure

6. Actuator Cylinder Pressure, Extended and Retracted

7. Pump Case Drain Pressure

8. Pump Case Drain Flow

9. Pump Discharge Flow

10. System Return Pressure, Before and After Filter

11. Temperature at

- a. Pump Inlet

- b. Pump Dischargec. Systemd. Pump Case Drain
- e. Return Line
- f. Reservoir

12. Pump Shaft Seal Leakage

13. Actuator Seal Leakage

14. Pressure Drop Across Filters

Samples of fluid were taken periodically to determine changes, if any, in viscosity, antiwear properties, acid number and wick flammability.

Prior to starting the evaluation, the pump was calibrated by measuring the pump discharge flow and case drain flow at various pump speeds and pressures. After the completion of the 500 hour test, this calibration procedure was repeated.

After accumulating 500 hours of performance under the target conditions previously outlined, the test stand was arbitrarily shut down in order to examine the internal pump components. A summary of the operating conditions which resulted during this test is shown in Table V. No abnormal pump operating conditions were noted during this period. The pretest and post-test pump calibration data shown in Table VI indicated that the pump performance was essentially equivalent to that which was observed at the beginning of this test.

Seal Leakage

Seal leakage rates were monitored on the pump shaft and the three actuators, all of which contained fluoroelastomer packings. The pump shaft seal was noted to be only wetted with fluid during the daily operating period. A record of actuator seal leakage is shown in Table VII. Leakage rates ranged from 1 to 5 ml during the same period. The observed leakage rates were well within acceptable limits.

Filters

A record of the pressure drop across the return line and case drain filters is presented in Table VIII. The case drain filter element was replaced only once during the test at 134.5 hours. This was done not because of pressure buildup but to examine the filter for particulate matter. The pressure drop across this element remained low throughout the entire test. The return line element had to be replaced several times due to high pressure buildup. This element was replaced at 17.5, 45.0, 81.0, 164.0, 236.5, 284.5, 289.5 hours. After the 289.5 hours replacement, this filter element remained in the system until the end of the test (500 hours). Analysis of the debris retained on the filters indicated that approximately half of the material was organic while the other half was inorganic. The inorganic fraction was found to be either metallic iron or iron oxide while the organic fraction was not identified. During the period when the filters had to be frequently replaced a problem occurred in the four-way directional control valve. This valve is fabricated from two dissimilar metals (aluminum and steel) and was not designed to operate at 422° K (300°F). Because of differences in the coefficient of thermal expansion of the two metals, the elastomeric seal would severely abrade. This is attributed to a design problem associated with the test stand and not the result of fluid action. The organic material found in the filter elements was considered to originate from this valve. After the four-way valve was replaced at 290 hours, no further problems developed.

Fluid Properties

During the course of this investigation, fluid samples were obtained to determine if any degradation was occurring. Table IX shows the results of the analyses which were performed on the fluid samples. The viscosity of the fluid was observed to be within +4.1 mm²/s of the original viscosity. The wear scar diameter exhibited in the Four Ball Wear Test was observed to be not greater than 0.08 mm from the valve obtained at the start of the test. The acid number was observed to be within +0.036 to -.003 of the original value. No change in wick flammability properties occurred.

After the test was completed, property determinations were made on the bulk fluid after it was drained from the system and compared to the values obtained prior to the test (Table X). Based on these results, it is concluded that no gross degradation of the fluid has occurred.

Pump Inspection

After 500 hours of performance, the pump was disassembled, photographed and dimensions and weights taken on critical friction elements. Table XI summarizes the dimensional and weight changes obtained where they could be measured. Minimal changes were observed on all components with the exception of the cylinder block which increased in weight by 8.3 grams. Figures 5 through 14 show the condition of the pump components before the test while Figures 15 through 21 show most of the same components after the test. The piston shoes shown in Figure 8 had many score lines on each assembly before the test. The other components were found to be in excellent condition. In general, after the test, many of the components had a coating or deposits on them. The exact nature and origin of these deposits is not known. The deposit on the pump housing (Figure 17) could be easily wiped off while the coating on the other components had to be mechanically abraded.

System Inspection

After 295 hours, the actuators were disassembled and inspected. One actuator was found to have an oxide coating inside the cylinder barrel. The barrel was cleaned using glass bead blasting. When the oxide was removed, pit marks were found in the area of piston travel only and followed a certain pattern. The second actuator was found to have an oxide coating but no pit marks. The third actuator had no oxide coating or pit marks. An oxide coating was also found on the fluid side of the accumulator. On the air side the fluid was found to contain small particles of seal material. These components are part of the test stand which have been in service during several different evaluations. The condition of these components prior to the test was not carefully monitored.

CORROSION ASPECTS

The corrosion experienced on some of the components from the pump test prompted an initial investigation into this area based on information reported in reference 4. This paper is concerned with corrosion problems experienced in aircraft systems when halocarbons used as cleaning solvents are trapped in the hydraulic system and hydrolyze in the small amount of water present in MIL-H-5606 hydraulic fluid. Essentially, 100 ml of hydraulic fluid is placed in a jar and 10,000 PPM halocarbon or 10,000 PPM water or both are added and exposed to thermal cycling (room temperature to $377^{\circ}K$ ($270^{\circ}F$)). Indeed when both halocarbon and water are present a steel strip immersed in the fluid will severely corrode. Similar tests were performed using Nadraul MS-6 as the test hydraulic fluid and the source of halogen (no halocarbon was added). At 10,000 PPM water the steel strip was observed to corrode after the first cycle (16 hours at room temperature, 8 hours at $377^{\circ}K$ ($220^{\circ}F$)). With no added water present the strip did not corrode even after 10 cycles. The water content of the MS-6 fluid from the pump test averaged about 300 PPM before and

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after the test. Further structural testing is in progress to determine if this amount of water is critical and also to determine whether the hydrolysis of the chlorine is coming from the base fluid, the antiwear additive or both.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance of Mr. Henry Lee who performed various chemical and physical property determinations and Mr. Paul Ceban who performed the pump test evaluation.

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FIGURE 1 - Structure of Tetrachlorophenylmethyl Siloxane



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1. Mounting Screw 2. Washer 3. Sleeve 4. Coupling Shaft 5. Shaft Packing 6. Inlet Plate 7. Outlet Plate 8. Mounting Screw 9. Sealing Screw 10. Screw Packing 11. Locking Nut 12. Adjusting Screw 13. Packing 14. Spacer 15. Spring Guide 16. Control Spring 17. Washer 18. Spring Guide 19. Pilot Valve 20. Needle Bearing 21. Valve Plate 22. Packing 23. Packing

24. Locating Pin 25. Mounting Screw 26. Washer 27. Name Plate 28. Insert 29. Housing 30. Control Piston 31. Retaining Ring 32. Retainer 33. Spring 34. Spring Spacer 35. Cylinder Block 36. Mounting Screw 37. Washer 38. Plate Retainer 39. Hold Down Plate 40. Piston and Shoe Subassembly 41. Shoe Wear Plate 42. Pintle Bearing 43. Locating Pin 44. Yoke 45. Spring Guide 46. Control Spring

47. Control Spring 48. Spring Seat 49. Carbon Seal 50. Seal grommet 51. Garter Spring 52. Spacer 53. Wave Spring 54. Retainer 55. Shaft Bearing 56. Insert 57. Drive Shaft 58. Packing 59. Thrust Ring 60. Retaining Pin 61. Mating Ring 62. Packing 63. Locating Pin 64. Mounting Screw 65. Instruction Plate 66. Mounting Screw 67. Rotation Plate 68. Insert 69. Mounting Flange

FIGURE 4 - Continued





FIGURE 6 - Rear View of Cylinder Block Before Test



FIGURE 7 - Drive Shaft and Yoke Assembly Before Test



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FIGURE 10 - Piston Hold Down Plate Before Test





FIGURE 12 - Pump Valve Plate with Needle Bearing Before Test





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F'GURE 14 - Plate Retainer Before Test















TABLE I. ANTIWEAR PROPERTIES OF TETRACHLOROPHENYLMETHYL SILOXANE FLUID

W+ 7	Wea	r Scar Diameter	(mm)*
Dibutyl Chlorendate	348°K (167°F)	450°K (350°F)	478°K (400°F)
0	1.30	**	**
1	1.10	**	**
2	0.69	1.38	**
3	0.76	1.02	1.01
4	0.82	0.98	1.05
5	0.96	1.01	1.06

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* Shell Four Ball Wear Test: ASTM Method D 2266, 40 kg Load, 1200 rpm, 1h, 52100 steel balls

** Could not be determined due to excessive vibration of test apparatus indicating extremely poor antiwear properties

TABLE II. PROPERTIES OF EXPERIMENTAL FIRE-RESISTANT HYDRAULIC FLUID NADRAUL MS-6

Property	Test Method		Value
Composition			
Base Fluid		96 wt % te	etrachloropheny1-
		methyl sil	loxane
Antiwear Additive		4 wt % dit	outyl chlorendate
Density, 298 [°] K (77 [°] F)	ASTM D287	1.04 g/cm	3
	10001 5 115		
Viscosity	ASTM D-445	50-2/2	15 0)
4/6 K (400 F)		5.0 mm / s	(5.0 cs)
$3/2 \times (210 \text{ F})$		19.3 mm^{-18}	(17.3 cs)
$232^{\circ}v$ (-(0) F)		1 200 mm2	(1290 cc)
219° (-40 F)		2 780 mm ²	(12)0 cs)
21) K (05 1)		2,,, co mm ,	0 (2/00 00)
Steel on Steel Wear (40kg)	ASTM D-2266		
(52100 steel)			
348°K (167°F)		0.82 mm	
450 K (350 F)		0.98 mm	
(M=10 steel)		1.05	
348° K (167°F)		0.85 mm	
478°K (400°F)		0.85 mm	
Flammability			
Flash point	ASTM D-92	550°K (530	O ^o F)
Fire point	ASTM D-92	616 [°] K (650	0°F)
Wick test	AMS-3150C	100+ cycle	es
Autoignition	ASTM-D2155	672 [°] K (750) [°] F)
High pressure spray	FTS-791-6052	No ignitio	on
Low pressure spray	AMS-3150C	Extinguish	nes fire
Flame propagation	MIL-H-83282	No ignitio	on
Oxidation-Corrosion	FTS-791-5308		
168h		478 K (400	<u>) F) 450 K (350 F)</u>
▲Viscosity, 311 K (100 F)		+13.2%	+0.02%
Acid No. Change mgKOH/g		+0.08	+0.03
Metal Wt. Change			
mg/cm-		-1.0	-0 33
A1		+0.02	-0.03
Mg		-0.02	-0.04
Fe		+0.01	-0.02
Ag		+0.04	
Insolubles or gum		None	None

• • •

TABLE II (Continued)

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Property	Test Method	Value		
Thermal Stability 168h, 478°K (400°F) OViscosity , 311°K (100°F) Acid No. Change mgKOH/g Insolubles or gum	FTS-791-5308 Modified to use N2 instead of O2	Metals No metals +4.7% +7.1% +0.08 +0.18 None None		
Rubber Swell, 168h STD "L", 394°K (250°F) Viton, 343°K (158°F) 408°K (275°F) 450°K (350°F)	FTS-791-3603	+5.0% +0.7% +0.8% +1.3%		
Copper Corrosion, 478 [°] K (400 [°] F) 100h	ASTM D130	Pass		
Shear Stability AViscosity @ 311°K (100°F) Acid No Increase mgKOH/g	MIL-H-5606	+2.0% 0.00		
Pour Point	ASTM D97	<211 [°] K (<-80 [°] F)		
Low Temp Stability 72h, 219°K (-65°F)	FTS-791-3459	Pass		
Foaming Tendency 298°K (77°F), 5 min. Collapse time 372°K (210°F), 5 min. Collapse time 298°K (77°F), 5 min. Collapse time	ASTM D892	0.400 dm ³ (400 ml) 10 min. 0.380 dm ³ (380 ml) 10 min. 0.350 dm ³ (350 ml) 9 min.		
Hydrolytic Stability 48h, 380°K (225°F) Awt. of Cu AViscosity, 311°K (100°F) Total acidity H ₂ 0 layer Acid No. organic layer	ASTM D2619	0.00 mg -0.017% 1.94 mgKOH 0.03 mg KOH/g		

TABLE III. EFFECT OF ESTER CONTENT ON PROPERTIES OF ALKYL-ESTER SILOXANE FLUID

Property	Test Method	10% Ester	18% Ester
Density, 298 ⁰ K (77 ⁰ F)	ASTM D287	0.876 g/cm ³	0.891 g/cm ³
Viscosity, mm ² /s (CS) 311°K (100°F) 233°K (-40°F) 219°K (-65°F)	ASTM D445	17.4 1010 4055	33.2 3040 14,000
Flash Point Fire Point	ASTM D92 ASTM D92	512 [°] K (480 [°] F) 544 [°] K (520 [°] F)	564 [°] K (555 [°] F) 597 [°] K (615 [°] F)
Wick Test, Cycles	AMS-3150C	17	100+
Steel on Steel Wear, mm 40kg, 1200 RPM, 1h 348°K (167°F) 422°K (300°F) 450°K (350°F) 478°K (400°F)	ASTM D2266	0.90 1.04 1.86 2.0	0.77 1.04 1.20 1.74

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TABLE IV. PROPERTIES OF EXPERIMENTAL FLUID "750"

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ALL AND A

Property	Test Method		Value
Composition			
Base Fluid		97.5 wt % Alkyl	-Ester Siloxane
		(18% Ester)	1 74
Additives		2.0 wt % Trioct	yl Phosphate
		0.5% Tris (2-Ch	loroethyl) Phosphite
Density, $298^{\circ}K$ (77°F)	ASTM D287	0.890 g/cm ³	
Viscosity, mm ² /s (CS)	ASTM D445		
372°K (210°F)		6.8	
311 [°] K (100 [°] F)		32.4	
233°_{K} (-40°F)		2900	
219 [°] K (-65 [°] F)		12,700	
Steel on Steel Wear mm	ASTM D2266		
40 kg, 1200 kPM, 1h			
348°K (16/°F)		0.65	
422 K (300 F)		0.80	
450 K (350 F)		1.09	
478°K (400°F)		1.30	
Flammability			
Flash Point	ASTM D92	561°K (550°F)	
Fire Point	ASTM D92	589°K (600°F)	
Autoignition	ASTM D2155	672°K (750°F)	
High Pressure Spray	FTS-791-6052	Ignites, Self F	rtinguishes
Wick Test, Cycles	AMS-3150C	Erratic Test Ren	sults 30 to 100+
Oxidation-Corrosion	FTS-791-5308	408°K (275°F)	450°K (350°F)
168h			
▲Viscosity, 311°K		+1.2%	+818%
(100°K)			
Acid No Change		-0.21	+11.1
Metal Wt Change			
(mg/cm ²)			
Cu		-0.08	+1.68
A1		+0.02	-0.03
Mg		+0.09	+0.08
Fe		+0.02	-0.02
Cđ		0.0	

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TABLE IV (Continued)

Property	Test	Method			lue	
Rubber Swell 168h	FTS-79	91-3603	+2.17			
Fluereelectomer 3/3°K						
(1580E)			+0 57			
$(13c^{-}r)$ $(00^{0}r)(275^{0}r)$			+0.5%			
450°K (350°F)			+0.6%			
Copper Corrosion, 450°K	ASTM I	0130				
(350°F) 100h			Pass			
Shear Stability	MIL-H-	-5606				
△Viscosity, 311°K ('00°F)			+12.3%			
Acid No Change	-		0.00			
Pour Point	ASTM (97	< 211°K	(-80°F)		
					Amount after	600s
Foaming Characteristics	ASTM I	0892	300s Ae	ration	Collapse	
298°K (77°F)			130 m1		0 ml	
372° K (210°F)			100 m1		0 ml	
298°K (77°F)			125 ml		0 m1	
Hydrolytic Stability 48b, 380°K (225°F)	ASTM I	02619				
AWE of Cu					-0.009 mg	
S Viscosity, 311°K					-3.2%	
					20/ 1 - 2 200	
Layer					204.1 mg KOH	
Acid No. Organic Layer					1.4 mg KOH/g	

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TABLE V. HYDRAULIC PUMP-LOOP CIRCUIT OPERATING DATA

AVERAGE FLUID TEMPERATURE

412 K (282 F)
414 [°] K (286 [°] F)
422°K (299°F)
405°K (270°F)
429°K (313°F)
412 [°] K (282 [°] F)

FLOW RATE

.

-

Pump	Disch	arge	
Pump	Case	Drain	

0.250 dm³/s (4 gpm) 0.0025 dm³/s (0.04 gpm)

AVERAGE FLUID PRESSURE

19.99 MPa (2900 PSI)
193.0 kPa (28 PSI)
386.1 kPa (56 PSI)
18.23 MPa (2650 PSI)

PUMP SPEED

TOTAL PUMP TEST TIME

NUMBER OF ACTUATION CYCLES

FLUID QUANTITY

Initia	1		
Total	Added	During	Test

4050 rpm

500h

81,341

12.20 dm³ (12,200 ml) 4.35 dm³ (4350 ml)

TABLE VI. PRETEST AND POST-TEST PUMP CALIBRATION DATA

. ..

			P	Pump Discharge Flow		
Dune Case	Bump B		Pret	test	Post-	ſest
(rpm)	<u>MPa</u>	(PSI)	$\frac{dm^3/s}{s}$	(gpm)	dm ³ /s	(gpm)
1000	5.17	(750)	0.12	(1.9)	0.11	(1.8)
	10.34	(1500)	0.11	(1.7)	0.11	(1.8)
	15.51	(2250)	0.11	(1.7)	0.11	(1.8)
	19.30	(2800)	0.10	(1.6)	0.11	(1.7)
2000	5 17	(750)	0.23	(3.6)	0 22	(3.5)
2000	10.24	(1500)	0.23	(3.5)	0.22	(3.5)
	10.34	(1300)	0.22	(3.5)	0.22	(3.3)
	10.01	(2250)	0.23	(3.5)	0.22	(3.3)
	19.30	(2000)	0.21	(3.4)	0.21	(3.4)
3000	5.17	(750)	0.31	(5.0)	0.31	(4.9)
	10.34	(1500)	0.31	(5.0)	0.31	(4.9)
	15.51	(2250)	0.30	(4.8)	0.30	(4.8)
	19.30	(2800)	0.30	(4.8)	0.30	(4.8)
4000	5.17	(750)	0.41	(6.6)	0.41	(6.5)
4000	10.24	(1500)	0.41	(6.5)	0.41	(6.5)
	10.34	(1300)	0.41	(6.5)	0.41	(6.3)
	15.51	(2250)	0.40	(0.4)	0.40	(0.4)
	19.30	(2800)	0.40	(0.4)	0.40	(0.4)

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Amount of Leakage Pump Leakage (m1) 405°K (270°F) -414°K (285°F) Operating Measurement Time Period Actuator Douglas Douglas Douglas (h) (h) Cycles No. 1 No. 2 No. 3 15.5 7.5 ---* 2,855 Trace Trace 3,705 21.0 5.5 ---Trace Trace 4.5 25.5 4,320 Trace Trace ---33.0 7.5 5,560 ---Trace Trace 34.5 1.5 5,744 ---Trace Trace 42.0 7.5 6,990 ---Trace Trace 48.5 6.5 8,083 ---Trace Trace 51.0 2.5 9,009 ---1 1 53.5 2.5 9,295 1 1 ---7.5 61.0 10,588 2 2 ---68.0 7.0 11,820 2.5 2.5 ---75.0 12,990 7.0 3 2.5 ---5.5 80.0 13,946 ---5 2.5 86.0 5.5 14,840 5 ---2.5 93.0 7.0 16,016 5 2.5 ---99.0 6.0 17,008 3.5 ---2 7.5 106.5 18,220 ---4.5 2 109.0 2.5 18,595 ---2 1 112.0 3.0 19,015 ---3 1 119.5 7.5 20,280 5 ---1.5 7.5 127.0 21,520 5 ---2 134.5 7.5 22,685 5 2 ---142.0 7.5 23,875 4 2 ---3 149.0 7.0 24,980 4.5 1.5 156.5 7.5 26,275 2 5 1.5 27,440 164.0 7.5 4 4 1.5 170.0 6.0 28,425 4 3 1.5 5 177.5 7.5 29,720 3.5 1 5.0 182.5 30,545 5 3 1 5 189.5 7.0 31,720 3.5 1.5 196.5 7.0 32,915 5.5 4 1.5 203.5 7.0 34,140 5 4 1.5 211.0 7.5 35,440 5 4 1.5 218.5 7.5 36,715 5 4 1.5 226.0 7.5 37,935 5 4 1.5 3 2 229.0 3.0 38,450 ---6 5 236.5 7.5 39,705 1.5 243.5 7.0 40,920 6 5 1.5 251.0 7.5 42,210 5 3 1.5 7.5 258.5 5 43,525 3 1.5 262.0 3.5 44,080 2 3 ---

TABLE VII. RECORD OF ACTUATOR SEAL LEAKAGE

44

4

5

1.5

45,295

269.5

7.5

TABLE VII (Continued)

			Am	ount of Leak	age
Pump	Leakage		(m1) 405 ⁰ K	(270°F) -41	4°K (285°F)
Time	Period	Actuator	Douglas	Douglas	Douglas
(h)	(h)	Cycles	No. 1	No. 2	No. 3
277.0	7.5	46.550	4	5	1.5
284.5	7.5	47.785	4	5.5	1.5
289.5	5.0	48.630	4	*	1.5
294.5	5.0	49.485	4		1.5
300.5	6.0	50,500	4		1.5
308.0	7.5	51,730	4		1.5
315.5	7.5	52,945	4		1.5
323.0	7.5	54.130	4.5		1.5
329.0	6.0	55,110	4.5		1.5
336.5	7.5	56,310	4.5		1.5
343.5	7.0	57,460	4.5		1.5
351 0	7.5	58,720	4.5		1.5
358 5	7.5	59,900	4.5		1.5
366 0	7.5	61,080	4		1
373 5	7.5	62 275	4		1
381 0	7 5	63 430	4		ī
385	7 5	64 630	4		ī
396.0	7 5	65 820	4		î
403.5	7.5	66 905	Ä		ī
403.5	3 5	67 385	2		0.5
407.0	7 5	68 520	Ā		1
414.5	7.5	69 660	4		1
422.0	5.5	70 234	4		i
427.5	7.5	71 540	4		i
433.0	7.5	72 720	Å		i
442.5	7.5	73 813	4		-
450.0	7.5	74 960	4		;
457.5	7.0	76,015	7		;
404.5	7.5	77, 107	7		
472.0	7.5	78 220	4		;
4/9.5	1.5	70,230	0.5		ò
401.0	7.5	70,510	6.5		1
400.0	7.5	20 765	4		-
490.0	1.5	00,703	*		0.5
500.0	4.0	81,341	2		0.5

* Actuator removed from system due to malfunction

••••

TABLE VIII. RECORD OF PRESSURE DROP ACROSS FILTERS AFTER EACH START UP

(PUMP SPEED 1500 RPM; FLOW RATE MAIN (Y-PASS 0.19 dm³/s (3 gpm))

Pump								
Operating	Syst	em	Pump Di	scharge		ΔP		A P
Time	Temper	ature	Presi	sure	Retur	n Line	Case	Drain
(h)	F	K	PSI	MPa	PSI	kPa	PSI	kPa
•	100	201	1500	1	10	102	•	•
5.0	100	210	1900	10.34	15	105	0	0
5.0	115	319	1800	12.41	20	130	0	0
12.5	104	313	2450	10.09	20	193	0	0
17.5	120	322	2/50	18.96	30*	20/*	0	0
22.0	128	326	2850	19.65	10	00.9	0	0
29.5	100	301	2975	20.51	11	/5.0	0	0
31.0	195	304	2975	20.51	20	41.4	0	0
38.5	100	301	2700	18.61	20	137.9	0	0
45.0	1/5	352	2750	18.96	22*	151./*	0	0
51.5	205	369	2900	19.99	2	13.8	0.5	3.5
54.0	210	372	2890	19.92	2	13.8	0.5	3.5
61.5	205	369	2900	19.99	5	34.5	0.5	3.5
68.5	208	371	2900	19.99	10	68.9	1	6.9
75.5	218	376	2925	20.17	12	82.7	0.5	3.5
81.0	190	361	2900	19.99	45*	310*	2	13.8
81.0	210	372	2940	20.27	1	6.9	1	6.9
86.5	210	372	2940	20.27	2	13.8	1	6.9
93.5	200	366	2950	20.34	1	6.9	1	6.9
99.0	210	372	2925	20.17	2	13.8	1	6.9
106.5	208	371	2925	20.17	2	13.8	1	6.9
109.0	230	383	2875	19.82	3	20.7	1	6.9
112.0	225	380	2875	19.82	3	20.7	1	6.9
129.5	220	377	2900	19.99	3	20.7	1	6.9
127.0	220	377	2900	19.99	4	27.6	1	6.9
134.5	210	372	2975	20.51	5	34.5	1**	6.9**
142.0	210	372	2950	20.34	0	0	0	0
149.0	210	372	2975	20.51	7	48.3	1	6.9
156.5	230	383	2950	20.34	11	75.8	1	6.9
164.0	150	339	2900	19.99	50*	345*	1	6.9
164.0	155	341	3000	20.68	3	20.7	1	6.9
170.0	158	343	2925	20.17	3	20.7	1	6.9
177.5	158	343	2925	20.17	3	20.7	1	6.9
182.5	145	336	2925	20.17	4	27.6	1	6.9
189.5	158	336	3000	20.68	5	34.5	1	6.9
196.5	120	322	3000	20.68	15	103	1	6.9
203.5	130	327	3025	20.85	15	103	1	6.9
211.0	130	327	3050	21.03	18	124	1	6.9
218.5	130	327	3025	20.85	23	159	1	6.9
226.0	130	327	3025	20.85	23	159	1	6.9

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TABLE VIII (Continued)

(PUMP SPEED 1500 RPM; FLOW RATE MAIN BY-PASS 0.19 dm³/s (3 gpm))

Pump								
Operating	Syst	tem	Pump Di	ischarge		Δp		ΔP
Time	Temper	rature	Pres	ssure	Retu	rn Line	Case	Drain
(h)	F	K	PSI	MPa	PSI	kPa	PSI	kPa
229.0	125	325	3025	20.85	40	276	1	6.9
236.5	125	325	3050	21.03	50*	345*	1	6.9
236.5	145	336	3000	20.68	3	20.7	1	6.9
243.5	135	330	3025	20.85	5	345	1	6.9
251.5	125	325	3025	20.85	8	55.2	1	6.9
258.5	230	383	2950	20.34	9	62.1	1	6.9
262.0	200	366	3025	20.85	8	55.2	0.5	3.5
269.5	180	355	3000	20.68	14	96.5	1	6.9
277.0	215	375	2950	20.34	16	110	0.5	3.5
284.5	286	414	2925	20.17	23*	159*	0.5	3.5
284.5	170	350	2950	20.34	4	27.6	1	6.9
289.5	290	416	2950	20.34	12*	82.7*	1	6.9
289.5	215	375	2925	20.17	1	6.9	0.5	3.5
294.5	180	355	2925	20.17	1	6.9	1	6.9
300.5	185	358	2950	20.34	2	13.8	0.5	3.5
308.0	190	361	2950	20.34	2	13.8	1	6.9
315.5	225	380	2950	20.34	2	13.8	1	6.9
323.0	220	377	2950	20.34	2	13.8	1	6.9
329.0	205	369	2950	20.34	2	13.8	1	6.9
336.5	165	347	2950	20.34	2	13.8	0	0
343.5	205	369	2950	20.34	2	13.8	0	0
351.0	170	350	2975	20.51	2	13.8	0	0
358.5	205	369	2950	20.34	2	13.8	0	0
366.0	215	375	2950	20.34	2	13.8	0	0
373.5	218	376	2950	20.34	2	13.8	0	0
381.0	170	350	2950	20.34	3	20.7	0	0
288.5	215	375	2950	20.34	2	13.8	0	0
396.0	166	347	2950	20.34	4	27.6	0	0
413.5	183	357	2950	20.34	3	20.7	0	0
407.0	188	360	2950	20.34	3	20.7	0	0
414.5	168	349	2950	20.34	4	27.6	0	0
422.0	245	391	2925	20.17	2	13.8	0	0
427.5	225	380	2950	20.34	2	13.8	0	0
435.0	218	376	2925	20.17	3	20.7	0	0
442.5	218	376	2925	20.17	4	27.6	1	6.9
450.0	160	344	2975	20.51	8	55.2	0	0
457.5	178	351	2950	20.34	9	62.1	0	0
464.5	225	380	2925	20.17	?	48.3	0	0
472.0	198	365	2925	20.17	9	62.1	0	0
479.5	215	375	2900	19.99	15	103	0	0
481.0	232	384	2900	19.99	14	96.5	1	6.9
488.5	232	384	2900	19.99	19	131	0	0
496.0	215	375	2925	20.17	22	152	0	0

*Filter element replaced due to high pressure build-up **Filter element check for metallic particles and replaced

Sample Test Hours	Viscosity ⁽¹⁾ 311 [°] K (100 [°] F) mm ² /s or (cs)	Wear Scar ⁽²⁾ mm <u>478[°]K (400[°]F)</u>	Acid Number(3) mg KOH/g	Wick ⁽⁴⁾ Flammability <u>Cycles</u>
0	54.4	1.00	0.062	100+
5	54.6	1.02	0.087	
10	54.4	1.08	0.073	
25	54.4	1.01	0.059	
50	58.5	1.06	0.071	
75	57.3	1.04	0.059	100+
100	55.0	1.03	0.071	
150	54.4	1.02	0.098	
200	55.2	1.00	0.076	
250	54.5	0.99	0.071	100+
300	55.8	0.98	0.073	
350	57.0	0.97	0.069	
400	55.5	0.99	0.067	
450	55.2	0.99	0.069	
500	54.8	1.02	0.071	100+

TABLE IX. PUMP TEST FLUID SAMPLE PROPERTIES

1. ASTM Method D445

2. ASTM Method D2266 40 kg, 1200 rpm, 1h, 52100 Steel Balls

3. ASTM Method D664

4. FTS-791-352

TABLE X. MS-6 FLUID PROPERTIES BEFORE AND AFTER PUMP TEST EVALUATION

Property	Test Method	Before Test	After Test
Density 298 [°] K (77 [°] F)	ASTM D287	1.035 g/cm ³	1.034 g/cm ³
Viscosity 372°K (210°F) 311°K (100°F) 233°K (-40°F) 219°K (-65°F)	ASTM D445	$18.6 \text{ mm}^2/\text{s}$ 54.4 mm ² /s 1023 mm ² /s 2722 mm ² /s	7- 55.3 1002 2831
Pour Point	ASTM D97	211 [°] K (-80 [°] F)	211 ⁰ K (-80 ⁰ F)
Fire Resistance Wick Test, Cycles Flash Point Fire Point Autoignition High Pressure-Spray Ignitia	AMS 3150C ASTM D92 ASTM D92 ASTM D2155 on FTS-791-6052	100+ 550°K (530°F) 616°K (650°F) 672°K (750°F) No ignition	100+ 552°K (535°F) 616°K (650°F) 616°K (730°F) No ignition
Steel on Steel Wear 52100 Steel, 40 Kg 348°K (167°F) 450°K (350°F) 478°K (400°F)	ASTM D2266	0.71 mm 0.99 1.02	0.70 mm 0.98 1.02
Acid Number	ASTM D974	0.062 <u>mg KOH</u> g	0.067 <u>mg KOH</u> g
Oxidation-Corrosion 168h, 478°K (400°F)	FTS-791-5308	+18.9%	+12.8%
ACIO NO. Change		TU.IU mg KUH	+0.21 mg KOH

•

	Weight Change	Dimensional Change
Element	mg	mm (in.)
Piston	* **	
1	-20.0 -23.8	
2	-23.8 -28.6	N. 11
3	+16.5 -29.7	No dimensional
4	+ 5.1 -24.3	change when measured
5	-23.7 -29.0	to fourth decimal
6	-23.0 -26.2	place in inches
7	-21.5 -26.0	
Cylinder Block	+8.300	
Bore No.		
1		(+0.0001)
2		(+0.0002)
3		(0.0000)
4		(+0.0001)
5		(+0.0000)
6		(0.0000)
7		(+0.0001)
Shoe Wear Plate	-1.4	(0.0000)
Shoe Held-Down Plate	-3.8	(-0.0002)
Shoe Hold-Down Plate	* **	
Retainer	-3.4 -25.2	(0.0000)
Pilot Valve		(0.0000)
Control Piston		(-0.0001)

TABLE XI. PUMP FRICTION ELEMENT DIMENSIONAL AND WEIGHT CHANGES

*Weight taken on element on disassembly from pump *Weight taken on element after cleaning

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NAVATR (ATR-954) 12	opres
(2 for retention) (1 for AIR-53031)	
$(1 \text{ for AIR-320A}) \qquad (1 \text{ for AIR-530312A})$	
(1 for AIR-5203) (1 for AIR-340C)	
(1 for AIR-52032) $(1 for AIR-340D)$	
(1 for AIR-52032F) (1 for AIR-4117)	
$(1 \text{ for AIR-JUSTE}) \qquad (1 \text{ for AIR-JII}) $	
NAVAIRFWORKFAC North Island (Code 343)	
NAVAIREWORKFAC (borry Doint (Code 332)	
NAVATREWORKFAG CHEFTY FOILT (Gode 320)	
NAVAIREWORKFAC PERSACOIA (Code 340)	
NAVAIREWORKAG JECKSONVIILE (Code 540)	
NAVAIREWUKKFAC NOTIOIK (Code 332)	
NAVAIRSYSCOMREPLANT	
NAVAIRSYSCOMREPAC	
COMNAVAIRLANT	
COMNAVAIRPAC	
NAVAIRTESTFAC (Code 4220)	
NAVAIRPROPTESTCEN	
NAVAIRENGCEN	
NAVWPNSCEN (3014)	
NAVSAFCEN	
NAVSHIPSYSCOM	
NAVSHIPRANDCEN (2831)	
NAVSHIPTECHREP	
ONR (Code 470)	
NRL	
(1 for Code 6170)	
(1 for Code 6434)	
NAVSEC	
U. S. ARMY MERDC (SMEFB-CLF)	
U. S. ARMY MSAA	
(1 for AMXSY)	
(1 for AMXSY-CM)	
II S ARMY BRI. 2	
(1 for VL)	
(1 for TRL-W)	
IT S ARMY FRANKFORD ARSENAL (SARFA-PDC)	
II C ADMY TANK AITOMOTIVE COMMAND	
IL C ADWY MATERIAL COMMAND	
U. S. ANNI PALENTAL COPPAND	
U. S. ANNI AVIATION SISTERS CONTAIND	
U. O. ANTI AIR FUDILIII KOU LAD	
U. S. ARTI FUELS AND LUDKIGANIS LAD	
U. S. AKMI NAIIUK DEV CENIEK	
AFML, WFAFD	
(1 FOR AFML/LAE)	
(1 IOT AFML/LNL)	
(I TOT ASD)	
NAVAIRENGCEN (ESSD-9322)	