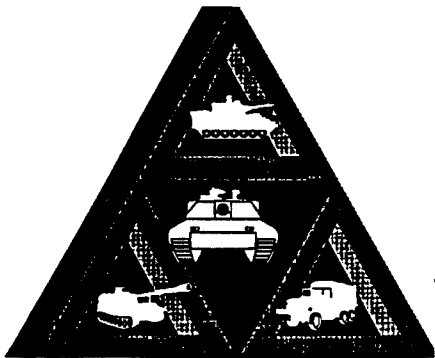


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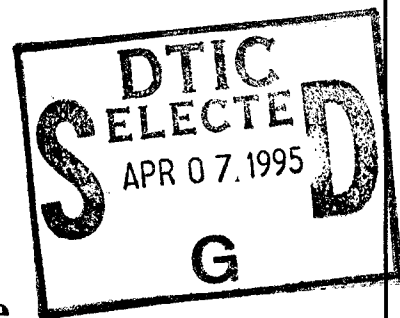


Technical Report

No. 13640

Evaluation of Environmentally Acceptable Hydraulic Fluids

March 1995



By **In-Sik Rhee**
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Section 1 Background/Objective

In recent years there has been an increasing interest in Environmentally Acceptable (EA) Hydraulic Fluids, especially among agricultural, construction, forestry, lumber, and mining industries where involuntary or accidental fluids leakage or spillage is detrimental to the environment. In response to the demand for EA hydraulic fluids, a number of lubricant suppliers have developed EA hydraulic fluids which are less toxic and more biodegradable than currently used hydraulic fluids. Although there are many military applications for which the current EA hydraulic fluids are not useable, it is possible that some of these products can be used for some military applications. Technical evaluation is needed to determine how they perform according to current military requirements.

Most EA hydraulic fluids were formulated with vegetable oils (rapeseed, sun flower, corn, canola) and synthetic ester, such as the polyol ester. The vegetable oils are becoming more important than synthetic ester based oils because of their availability and low cost. Typically, rapeseed oil based fluids have excellent lubricating properties and biodegradability.¹ The potential benefits for use of EA hydraulic fluids are to reduce the quantity of hazardous waste being generated and to lower disposal costs although current EPA rulings no longer classify used oils as hazardous waste. However, a demand for biodegradable oils is coming from California, Texas and Florida, because of their more stringent state regulatory requirements. A pressing need to use biodegradable oils is to eliminate the hazardous pollution caused by accidental oil spillage, which is especially important in environmentally sensitive applications. Another good reason to use biodegradable, vegetable/synthetic ester based oils is to develop a market for US grown agricultural feedstocks and to reduce reliance on overseas petroleum crude oil.

The following hydraulic fluids were identified as having some potential for biodegradable basestocks application since their requirements for low temperature operability and long-term storage stability are not critical.

VV-C-850 ²	<i>Cutting Fluids, Sulfurized Fatty and Mineral Oils</i>
MIL-H-17672 ³	<i>Hydraulic Fluid, Petroleum, Inhibited</i>
MIL-H-46001 ⁴	<i>Hydraulic Fluid, Petroleum Base, for Machine Tools</i>

To determine whether EA hydraulic fluids would be suitable in military applications, a market study was initiated by the Fuels and Lubricants Division of the U.S. Army's Mobility Technology Center, Fort Belvoir VA with funding provided by the Defense Environmental Restoration Account (DERA), managed by the HAZMIN Office of the Defense Logistics Agency (DLA) located at Defense General Supply Center (DGSC), Richmond, Virginia.

The objective of this project is to evaluate currently available EA hydraulic fluids to determine their performance according to current military specifications. If test results indicate that the EA hydraulic fluids meet current military specification requirements, recommendations for specification amendments will be provided to the appropriate preparing activities. If they do not meet any current military specifications, suppliers will be queried as to the possibility of developing EA hydraulic fluids which could meet military requirements.

Section 2 Approach

A market survey for EA hydraulic fluids was conducted within the United States. The approach used in this survey was to review technical data sheets and current technology used in EA hydraulic fluids, and to determine availability of EA hydraulic fluids including manufacturers. For evaluation, the samples of EA hydraulic fluids were collected and a test plan was developed based on the requirements of military hydraulic fluids. Typical tests performed on all samples were viscosities, pour point, flash point, corrosion protection, corrosiveness and oxidation stability, thermal stability, lubricity, accelerated storage stability and elastomer swell. Hydraulic pump testing and environmental tests (i.e., biodegradability, toxicity) were not included under this testing program due to the unavailability of test equipment. The test protocol is listed in Table 1.

Table 1. Test Protocol for EA Hydraulic Fluid Evaluation

Test	Method
Viscosity, Kinematic	ASTM D 445
Viscosity index	ASTM D 2270
Pour point	ASTM D 97
Flash point	ASTM D 92
Fire point	ASTM D 92
Neutralization number	ASTM D 664
Galvanic corrosion	FED-STD 7915,#5322
Rust prevention	ASTM D 665
Foaming	ASTM D 892
Thermal stability	Cincinnati Milacron
Elastomer compatibility, NBR-L	FED-STD 791,#3603
API, Specific Gravity	ASTM D 287
Water content	ASTM D 1744
Evaporation @ 100 °C, 1 hr	Thermogravimetric Analysis (TGA)
Copper corrosion @ 100°C, 3 days	ASTM D 130
Corrosiveness & Oxidative Stability, 100 °C	ASTM D 4636
Low temperature stability, -15 °C, 72 hrs	FED-STD 791,#3458
Humidity Cabinet corrosion, 720 hrs	ASTM D 1748
Lubricity	ASTM D 4172
Oxidation stability, Pressure Differential Scanning Calorimeter (PDSC)	Modified ASTM D 5483
Storage stability @ 100 °C, One month	Army method

To compare with military hydraulic fluids, MIL-H-46001 was selected as a reference sample because most samples received have been designed as industrial hydraulic fluids. For this reason, MIL-H-46001 hydraulic fluid was also tested to provide baseline comparison data. The VV-C-850 cutting oil and MIL-H-17672 hydraulic fluids were not selected as a reference sample because of their initial design criteria. In fact, VV-C-850 oil was originally formulated to use as cutting fluid in the machining of metals, while MIL-H-17672 fluids was designed to use in shipboard hydraulic systems.

Section 3 Market Survey

Environmental safety and compliance has become the most significant worldwide issue in oil industry in recent years. The use of EA hydraulic fluids in mobile and industrial hydraulic systems is becoming the first among many to resolve environmental pollution problems. For this reason, the lubricants industry and equipment manufacturers have shown increased interest in the development of EA hydraulic fluids because of high demand and government legislation. In the United States, market potential for EA hydraulic fluids is expected to grow with the increase of environmental regulations. Table 2 lists EA hydraulic fluids that are commercially available. Currently, there are three types of EA hydraulic fluids available. These types of fluids are either vegetable oil based, synthetic polyglycol based or synthetic ester based. Each of these fluids has characteristics that differ from conventional mineral oil.

Table 2. Domestic Environmental Acceptable Hydraulic Fluids

Product Name	Basestock	Description	Company Name	Address
EL 146	Seed oil + mineral oil	Readily biodegradable and non-toxic ISO 46 hydraulic oil for use in heavy duty hydraulic systems.	EarthRight Technologies	33307 Curtis Blvd. Eastlake, OH 44095
Plantohyd 40	Rapeseed + sulfurized fatty vegetable oil	Universal, multigrade hydraulic oil for agricultural, forestry, and construction machinery	Fuchs Metal Lubricants Company	Metal Lubricants Co., 17050 Lathrop Avenue, Harvey, IL 60426
Functional 9403071	Rapeseed	Biodegradable, corrosion inhibited, antiwear hydraulic oils for mobile, industrial & marine hydraulic systems	Greenoco, Functional Products, Inc.	Functional Products, Inc., 24000 Merchante Road, Unit 5, Cleveland, OH 44122
Greenwood Hydraulic Fluids	Vegetable; rapeseed	Biodegradable, corrosion inhibited, antiwear hydraulic oils for mobile, industrial & marine hydraulic systems	Greenoco, Inc.	The Green Oil Company Company, P.O. Box 577, Blue Bell, PA 19422
HYD271, 272	Vegetable; canola	Biodegradable, corrosion, antiwear and oxidation inhibited hydraulic oils for industrial hydraulic systems	International Lubricants, Inc.	International Lubricants, Inc., 7930 Occidental South, Seattle, WA 98108
Mobil EAL 224H	Vegetable; rapeseed	Biodegradable, antiwear, corrosion protective hydraulic oil for moderate or severe operating conditions.	Mobil Oil	Mobil Oil Corporation 3225 Gallows Road Room 5W806, Fairfax, VA 22037-0001
Mobil XRL 1711-78	Synthetic ester	Antiwear, corrosion protective hydraulic oil.	Mobil Oil	Mobil Oil Corporation 3225 Gallows Road Room 5W806, Fairfax, VA 22037-0001
Quintolubric 822-220,330, 450	Polyol ester	Fire resistant hydraulic fluid to replace phosphate esters	Quaker Chemical Corp.	Quaker Chemical Corp Conshohocken, PA 19428-0809
HVO-46 Hydraulic Vegetable Oil	Vegetable	For hydraulic systems that require both antiwear and rust and oxidation properties	Renewable Lubricants, Inc.	476 Griggy Road P.O. Box 474 Hartville, OH 44632

Table 2. Domestic Environmental Acceptable Hydraulic Fluids (continued)

Product Name	Basestock	Description	Company Name	Address
Royco 3100, 3046, RTJ 27, RTJ 41	Polyol ester	Biodegradable, antiwear hydraulic fluids	Royal Lubricants	Royal Lubricants Company, Inc., P.O. Box 518, Merry Lane, E. Hanover, NJ 07936
OS 107086	Sunflower oil	Based on Sunyl PF 311; Sunflower oil with alkylated phenol	SVO Specialty Products, Inc.	SVO Specialty Products, Inc., 35585-B Curtis Blvd., Eastlake, OH 44095
OS 106575	Sunflower oil	Based on SUNYL PF 311; Sunflower oil	SVO Specialty Products, Inc.	SVO Specialty Products, Inc., 35585-B Curtis Blvd., Eastlake, OH 44095
Biostar Hydraulic 46, Code 1616	Rapeseed; Ethyl hexyl oleate, c18 fatty acids	Environmentally friendly, zinc free, antiwear oil for high pressure hydraulic equipment	Texaco	Texaco Lubricants Company, North America, P.O. Box 4427, Houston, TX 77210-4427
Synstar Hydraulic 46, Code 2073	Trimethyl-propane (TMP) & Penta-erythritol ester blend, BHT	Environmentally friendly, zinc free, antiwear oil for high pressure hydraulic equipment	Texaco	Texaco Lubricants Company, North America, P.O. Box 4427, Houston, TX 77210-4427
Terra-Lube ECO 2000	Natural esters, Triglycerides	Biodegradable and non-toxic natural ester based universal hydraulic fluid designed for use in all equipment	CoChem, Inc.	CoChem, Inc. 7555 Bessemer Ave. Cleveland, OH 44127
Calgene Q1093, 1094, 1095	Rapeseed, Canola oil	Vegetable oils based VI Index, wear and oxidation additives	Calgene Chemical, Inc.	Calgene Chemical, Inc. 7247 N. Central Park Ave. Skokie, IL 60076-4093
Clark Cone oil	Cone oil	Environmentally friendly product	CoChem, Inc.	CoChem, Inc. 7555 Bessemer Avenue Cleveland, OH 44127

Vegetable oils have excellent lubrication qualities and are nontoxic and biodegradable. They are made from renewable resources such as rapeseed, sunflower, corn, canola and are much less expensive than synthetic fluids. Their chemical structure are triglycerides in which a variety of saturated, monounsaturated or poly unsaturated fatty acids are esterified to a glycerol backbone. The physical properties of a vegetable oil depend on the nature of its fatty acid composition. The disadvantages of these oils are well known, two of which are poor low temperature fluidity and rapid oxidation at elevated temperatures.⁶

Polyglycol oils are the oldest biodegradable fluids and have been used in construction machinery, the vicinity of ground water, and the food processing industry. Currently, the usage of these fluids tend to decline due to the tendency to be aquatically toxic when admixed with lubricating additives and the incompatibility with mineral oils and other materials such as elastomers.⁷

Synthetic esters, mainly based on trimethylolpropane, polyol ester and pentaerythritol, are regarded as the best among the biodegradable base fluids. The biodegradability of these oils is comparable to vegetable oils and their lubrication properties are very similar to mineral oils. The advantages of these oils are excellent fluidity, and low temperature and aging stabilities. On the other hand, the cost of synthetic esters are much higher than those of mineral oils.⁸ Their differences are summarized in Table 3.

Table 3. Comparison of Base Fluids

	Mineral Oils	Vegetable Oils	Synthetic Esters	Poly-Glycol
Biodegradability CEC-L33-T82, %	10-40	70-100	10-100	10-90
Viscosity Index	90-100	100-250	120-220	100-200
Pour Point, °C	-54 to -15	-20 to 10	-60 to -20	-40 to 20
Compatibility with Mineral Oils	-	Good	Good	Not miscible
Oxidation Stability	Good	Poor to Good	Poor to Good	Poor
Relative Cost	1	2 to 3	5 to 20	2 to 4

EA Hydraulic fluids also require additive to enhance performance. The lubrication properties of some vegetable oils such as rapeseed oil and synthetic esters can be improved by antioxidants, corrosion inhibitors and pour point stabilizers. However, the use of conventional additives in EA hydraulic fluids may pose potential problems on the fluid's biodegradability and ecotoxicological properties due to the toxicity of chemicals. Thus, the domestic additive manufacturers are also investing in developing the EA additives which are compatible with EA hydraulic fluids. Some EA additives such as sulphur-carriers have been developed and are currently available in the domestic market.

Section 4 Test Results

A total twenty-six samples were received from fourteen oil companies. Most fluids were designed as industrial hydraulic fluids, and were formulated with vegetable oils (rapeseed, sunflower, corn, canola) and synthetic ester such as polyol ester. These types of base oils are currently used in EA hydraulic fluids because of their biodegradable characteristics. To assess EA fluids, all samples were tested according to the limited testing program. Table 4 summarized the results of tests which were conducted through in-house laboratory testing which included accelerated storage stability test. Code letters have been used to protect the identities of the samples submitted.

Viscosity is the most important property in selecting hydraulic fluids. This property directly affects flow characteristics, heat generation within system, pumping operation, sealing, leaking characteristics. Currently, military hydraulic systems use four different types of viscosity grades (ISO VG 32,46,68 and 150). The viscosity of most samples were measured within ISO viscosity grades 32 and 46 ranges. Based on these results, the availability of other types of viscosity grades seems to be no problem. Viscosity Index (VI) is used for measure of how viscosity changes with temperatures. All samples had very high VI indexes which exceeded the minimum VI index limit (90) of MIL-H-46001 specification. Generally, a high VI indicates that the viscosity of fluids undergo less change with temperature variations. In the low temperature (-15 °C) viscosity tests, most EA hydraulic fluids flowed in capillary tubes while some vegetable fluids had difficulty to flow due to their poor low temperature properties.

Pour point is defined as the lowest temperature at which oil flows when chilled under specified test condition and is used for determining low temperature operation limits of hydraulic fluids. The MIL-H-46001 specification requires a minimum of -12 °C pour point in grades 1, 2 and 3 and a minimum of -6 °C for grade 4. These types of industrial hydraulic fluids were originally formulated to use in machine shops which are not sensible to cold environment. The test results showed that all samples met the specification requirements. To verify these results, the low temperature stability tests were conducted at -15 °C for 72 hours. Nineteen samples were clear and remained as liquid while some vegetable oils froze. It appeared that the low temperature stability of vegetable based fluids are poor compared to mineral oils because they consist of a wide range of fatty acid ester. However, the synthetic ester based fluids did not have any low temperature stability problems at this test temperature.

Lubricity is the degree to which fluids lubricate moving parts and minimize wear within a system. Most hydraulic fluids often contain anti-wear additives to improve wear prevention properties. This property is usually evaluated in the Four Ball Wear test. To assess the effectiveness of anti-wear additives in EA hydraulic fluids, the four ball wear tests were performed according to ASTM D2266, Wear Preventive Characteristics of Hydraulic Fluids. The test results indicated that all samples tested provided good wear properties which can be compared with that of MIL-H-46001 fluid.

Flash and fire points of hydraulic fluids do provide a rough characterization relative to their flammable nature. Almost all samples exceeded to the MIL-H-46001 specification requirements and provided a much lower flammability than that of MIL-H-46001 fluid. Also, the evaporation tests showed that EA fluids did not have a volatility problem. It appeared that EA fluids exhibit excellent inherent fire resistance characteristics over the conventional petroleum based hydraulic fluids.

To assess the corrosion properties of EA fluids, five different types of corrosion tests were performed: copper corrosion test, galvanic corrosion test, rust prevention test in synthetic seawater, humidity cabinet test, and corrosiveness and oxidation stability test. These corrosion tests were originally designed to evaluate specific corrosion characteristics of fluids in different applications and environments. The galvanic corrosion and rust prevention tests are currently used in industrial hydraulic fluid specifications such as MIL-H-46001 while other three corrosion tests are used for evaluating mobile hydraulic fluids such as military tactical hydraulic fluids. The test results showed that most EA samples failed in galvanic corrosion tests while two-third of samples passed the rust prevention tests. In copper corrosion tests, most samples provided excellent corrosion protection against copper metal and showed a comparable performance to that of MIL-H-46001 fluid. Humidity cabinet tests showed that a majority of EA fluids tested provide better corrosion protection than MIL-H-46001 fluid. The ASTM D4636 test method measures corrosiveness and oxidation stability of fluids. In this test, most EA fluids failed in corrosion tests and some vegetable fluids became polymerized during tests due to their poor thermal stability.

The oxidation stability of EA hydraulic fluids are one of the important operational parameters in military hydraulic systems. To evaluate this property, Pressure Differential Scanning Calorimetry (PDSC) tests were conducted. This method is currently being developed to assess oxidation stability of lubricating oils in service and storage conditions. The test results showed that vegetable oil based fluids give poor oxidation stability while synthetic ester fluids provide the same quality of oxidation stability of petroleum based fluids. It appeared that vegetable based fluids are applicable to use in moderate operation temperatures (below 90 °C).

Measurement of water content is also important in relation to corrosion prevention and oxidation resistance properties of fluids. The test results showed that most samples had a higher water content than MIL-H-46001 fluid. A high water content in fluids may affect to fluid life and cause corrosion problems in hydraulic systems.

The thermal stability of industrial hydraulic fluids is currently comprehensively evaluated based on the changes in appearance, neutralization number, and viscosity of the fluid. In the Cincinnati Milacon thermal stability test,⁹ vegetable oils showed a poor thermal stability. These results also agreed with those of corrosiveness and oxidation stability tests.

Foaming is attributed to mechanical operating conditions producing turbulence in the presence of air or water. Excessive foaming of fluids result in decreasing lubrication effectiveness and create maintenance problems in hydraulic system. The test results indicated that most EA fluids do not have foaming problems.

Seals have sometimes failed to perform their designed function of retaining hydraulic fluids and excluding contaminants because of incompatibility between the seal elastomer and the hydraulic fluid. The deterioration of elastomer seals results in the failure of hydraulic power and causes leaking of fluids. To prevent this problem, elastomer compatibility tests were performed using the reference elastomer (NBR-L). Most EA fluids provided an abnormal behavior when compared to the MIL-H-46001 product.

Hydraulic fluids generally change in prolonged storage. If the change results in product falling out of specification range or causes performance to be below standard, that change is noteworthy and can be disturbing. Prior to use, this property must be determined. To evaluate this property, an accelerated storage stability test was conducted at 100 °C for one month duration. The evaluation method used in this test was to compare MIL-H-46001 requirements with fluid based on viscosity, acid number and oxidation induction time changes. The test results showed that some vegetable oils have a short storage life due to their poor oxidation and thermal stability at elevated temperatures.

Table 4. Environmental Acceptable (EA) Hydraulic Fluids - Physical Property Data

EA HYDRAULIC FLUIDS - VISCOSITY, GRAVITY, WEAR PREVENTION

Product Code	Viscosity, 100°C, cSt	Viscosity, 40 °C, cSt	Viscosity, -15°C, cSt	Viscosity Index	Pour Point, °C	API Gravity	Specific Gravity	Lubricity, 40kg, Scar Diam, mm
MIL-H-46001 Specification Requirements	Report	Grade 1:28.8-35.2 Grade 2:41.4-50.6 Grade 3:61.2-74.8 Grade 4:135-165	NR ¹	90 (min)	-12 (max) -12 -12 -6	30-33 28-32 29-31 27-30	NR	NR
A	8.45	39.50	3204.3	155	-18	22.3	0.92	0.34
B	9.82	46.15	819.4	155	-30	21.47	0.925	0.51
C	10.6	50.46	1829.7	154	-30	22.3	0.92	0.44
D	8.34	37.08	2230.5	160	-27	25.72	0.9	0.46
E	7.97	35.87	951.5	161	-30	22.3	0.92	0.5
F	8.97	41.55	1298.3	155	-24	22.3	0.92	0.47
G	8.23	39.17	649.8	154	-18	22.0	0.922	0.55
H	6.27	33.08	878.6	135	-17	24.0	0.910	0.39
I	10.8	50.6	758.1	155	-26	24.17	0.9088	0.67
J	14.28	66.1	1136.0	155	-26	23.82	0.9107	0.66
K	19.3	94.6	2084.3	150	-26	21.97	0.9220	0.53
L	9.58	49.13	1103.9	148	-36	24.0	0.910	0.4
M	13.62	96.55	4456.0	128	-54	7.2	1.02	0.42
N	7.61	43.49	1256.7	132	-57	10.0	1.0	0.45
O	3.44	12.24	145.6	169	-58	24.0	0.91	0.87
P	9.92	48.48	1035.1	152	-36	22.3	0.92	0.44
Q	9.52	38.08	988.9	167	-36	24.0	0.910	0.39
R	10.54	48.8	911.1	156	-29	21.47	0.925	0.43
S	9.67	50.43	1125.0	147	-45	22.0	0.922	0.49
T	9.76	45.05	817.4	157	-34	22.3	0.92	0.81
U	9.41	44.48	1340.1	155	-24	22.3	0.92	0.6
V	9.66	46.68	2309.4	153	-24	22.3	0.92	0.57
W	9.69	44.88	1463.0	147	-15	22.3	0.92	0.73
X	2.56	8.13	77.0	151	-65	27.4	0.89	0.85
Y	8.08	35.24	1359.0	161	-18	22.3	0.92	0.73
MIL-H-46001	5.29	31.43	1543.7	99	-39	31.1	0.87	0.43

1. Not required

Table 4. Environmental Acceptable (EA) Hydraulic Fluids - Physical Property Data (continued)

EA HYDRAULIC FLUIDS - OTHER BASIC PROPERTIES

Product Code	Oxidation Stability ² , min	Low Temp Stability, 72 hrs, -15°C	Evaporation Loss ³ , % (100°C, 1 hr)	Flash Point, °C	Fire Point, °C	Water Content, ppm	Swell of Synthetic NBR-L Rubber, %	Foaming, Seq. I, II, III	Neutralization Number mg KOH/g
MIL-H-46001 Specification Requirements	NR	NR	NR	Grade 1: 188 Grade 2: 196 Grade 3: 196 Grade 4: 221 (min)	216 218 218 246	NR	NR	Pass	1.5 (max)
A	29.0 (155 °C)	white solid	0.18	310	362 (min)	238	9.16	pass	0.43
B	45.45 (130 °C)	cloudy, crystals, flowing	0.78	200	320	248	11.34	fail	0.33
C	9.31 (130 °C)	flowing, clear	0.01	264	352	183	11.29	pass	0.80
D	4.65 (130 °C)	flowing, clear	0.06	260	358	257	11.86	pass	0.79
E	12.1 (155 °C)	flowing, clear	0.03	310	340	202	10.8	pass	0.13
F	31.96 (130 °C)	flowing, clear	0.25 (gain)	294	340	232	14.07	fail	3.04
G	14.3 (155 °C)	flowing, clear	1.15	316	362	309	34.18	pass	1.32
H	15.43 (180 °C)	flowing, clear	1.2	260	272	125	33.06	pass	0.96
I	17.9 (180 °C)	flowing, clear	0.2	268	320	347	26.46	pass	2.04
J	20.6 (180 °C)	flowing, clear	0.23	270	320	392	25.46	pass	2.43
K	14.84 (180 °C)	flowing	0.17	270	366	380	17.74	pass	3.09
L	13.34 (180 °C)	milky, solid	0.78	278	335	124	10.35	pass	1.35
M	60.9 (210 °C)	flowing, clear	0.3	278	282	463	35.99	pass	0.42
N	43.3 (210 °C)	flowing, clear	0.13	264	288	330	42.42	pass	0.42
O	38.6 (180 °C)	flowing, clear	4.51	186	190	543	39.4	fail	0.22
P	13.85 (180 °C)	milky, solid	1.0	294	334	217	10.27	pass	1.08
Q	30.57 (155 °C)	milky, solid	0.4	296	344	356	11.8	pass	1.47
R	25.08 (155 °C)	flowing	0.86	276	302	151	14.28	pass	1.21
S	28.7 (155 °C)	flowing, clear	1.48	260	340	175	16.07	pass	2.14
T	30.73 (155 °C)	flowing, crystal forming	1.3	264	348	212	12.6	pass	0.24
U	4.62 (130 °C)	flowing, clear	0.01 (gain)	314	358	304	20.42	pass	2.82
V	3.09 (130 °C)	flowing	0.14 (gain)	318	352	272	18.07	pass	1.49
W	6.75 (130 °C)	milky, solid	0.23	338	364	335	8.56	pass	0.4
X	43.6 (180 °C)	flowing, clear	7.5	180	185	480	41.19	ND	0.27
Y	9.0 (155 °C)	milky, solid	0.13 (gain)	316	360	178	10.85	ND	0.07
MIL-H-46001	24.2 (180 °C)	flowing, clear	0.75	212	234	125	7.78	fail	0.58

2. Pressure Differential Scanning Calorimeter (PDSC)

3. Thermogravimetric Analysis (TGA)

Table 4. Environmental Acceptable (EA) Hydraulic Fluids - Physical Property Data (continued)

EA HYDRAULIC FLUIDS - CORROSION TESTS

Product Code	Copper Corrosion (3 days, 100°C)	Galvanic Corrosion	Rust Prevention, Synthetic Seawater (ASTM D665)	Humidity Cabinet, Hrs. to Fail	Corrosiveness and Oxidation stability (ASTM D4636, 100°C)
MIL-H-4001 Specification Requirements	NR	Pass	Pass	NR	NR
A	1a	fail, pitting	pass	203	fail
B	4c	fail, slight pitting	pass	>720	fail
C	1b	fail, pitting	fail w/polymerization	187	fail
D	2c	fail, pitting	fail, severe rust	96	fail
E	1a	fail, pitting	fail, rust	>720	fail
F	1b	fail, pitting	fail, rust	>720	fail
G	1a	fail, slight pitting	pass	66	fail
H	1a	fail, slight pitting	pass with discoloration	66	fail
I	1a	pass	pass	>720	fail (121°C)
J	1a	pass	pass	>720	fail (121 °C)
K	1a	fail, slight pitting	pass	>720	fail (121 °C)
L	1b	pass	pass with polymerization	230	pass
M	1b	fail, pitting	ND	240	pass
N	1b	fail, pitting	pass	104	pass
O	1b	pass	pass	232	fail
P	1b	fail, pitting	pass	>720	pass
Q	1b	fail, pitting	pass	>720	fail
R	1a	fail, slight pitting	pass	>720	fail
S	2c	fail, slight pitting	pass	>720	fail
T	1b	pass	pass	>720	pass
U	2c	fail, pitting	fail, rust	>720	fail
V	1a	pass	fail, rust	>720	fail
W	2c	fail, pitting	fail, rust	252	fail
X	1b	pass	pass	504	pass
Y	3a	fail, pitting	ND	21	fail
MIL-H-46001	1a	pass	pass	48	pass

Table 4. Environmental Acceptable (EA) Hydraulic Fluids - Physical Property Data (continued)

EA HYDRAULIC FLUIDS - CINCINNATI MILACRON THERMAL STABILITY TEST, PROCEDURE A

Product Code Steel Rod	% Vis Change Copper Rod	Neutralization # Change, mg KOH/g	Precipitate or sludge, mg/100 mL	Steel Rod		Copper Rod		
				Visual Condition	Deposit, mg 3.5 (max)	Metal Removed, mg/200 mL 1.0 (max)	Visual Condition	Deposit, mg 10 (max)
MIL-H-46001 Spec Requirements	+5 (max)	Grade 1,2,3: +0.75 Grade 4: 0.15	25 (max)	Report	3.5 (max)	1.0 (max)	5	
A	+5.27	1.9	8.6	like new	5.5	1.9	2c	1.2
B	+46.8	1.29	49.2	slight tarnish	0.3	nil	1a, sludge	nil
C	+19.02	1.44	12.25	slight tarnish	0.4	nil	4b	2.4
D	+14.9	1.19	11.45	slight tarnish	0.9	nil	4a	0.6
E	+11.12	6.27	10.85	slight tarnish	nil	nil	1a	0.6
F	+13.76	4.72	17.75	slight tarnish	nil	nil	1a	2.1
G	+9.79	2.49	3.6	slight tarnish	0.4	nil	1a	nil
H	+2.75	1.61	1.2	slight tarnish	0.5	nil	1b	nil
I	-4.73	0.05	32.35	medium tarnish	0.5	nil	3a	0.3
J	-1.97	0.39	17.35	medium tarnish	0.7	nil	2c	0.7
K	-0.35	1.08	10.3	medium tarnish	0.2	nil	3b	6.9
L	+4.38	0.15	15.65	slight tarnish	1.5	nil	2c	7.4
M	-37.39	1.74	22.15	slight tarnish	1.8	nil	2e	1.1
N	-0.39	3.38	10.95	slight tarnish	1.8	0.3	3a	0.4
O	+16.91	0.82	3.95	slight tarnish	1.0	0.4	3a	0.7
P	+7.65	0.7	12.20	medium tarnish	2.5	0.3	4a	1.1
Q	+30	0.38	9.6	medium tarnish	0.4	nil	1b	0.9
R	+0.10	3.61	11.45	slight tarnish	0.6	0.9	2c	nil
S	+5.39	0.93	11.85	slight tarnish	0.4	0.3	3a	nil
T	+10.41	3.65	27.15	slight tarnish	0.7	nil	4a	2.2
U	+172.57	0.39	18.95	slight tarnish	2.3	nil	1a	2.4
V	+175.86	2.09	37.3	slight tarnish	1.7	0.6	1a	1.8
W	+82.22	0.9	28.35	slight tarnish	2.0	nil	1b	1.2
X	+6.77	2.04	5.6	slight tarnish	1.5	nil	1b	1.0
Y	+50.17	0.35	192.15	slight tarnish	1.7	nil	1b	1.7
MIL-H-46001	+7.45	0.49	8.75	medium tarnish	nil	nil	4b	5.6

**Table 4. Environmental Acceptable (EA) Hydraulic Fluids - Physical Property Data
(continued)**

EA HYDRAULIC FLUIDS - ACCELERATED STORAGE STABILITY (100 °C, ONE MONTH)

Product Code	Viscosity Changes, %, 40 °C	Acid Number Changes, mg	PDSC, Induction Time Changes, %
A	+0.9	0.29	-5.0
B	+16.2	1.67	-27.66
C	+25.0	2.74	-16.0
D	+2.3	1.85	-8.0
E	+18.9	2.7	-48.1
F	+21.1	1.55	0
G	-3.0	2.4	0
H	-0.4	1.08	0
I	-8.3	1.76	0
J	-4.5	1.43	-12.6
K	-3.3	1.62	0
L	+0.83	0.1	0
M	-0.85	1.94	-9.6
N	-2.64	2.09	-16.75
O	-0.25	0.45	-22.0
P	-0.6	1.53	0
Q	-0.8	1.69	0
R	-2.3	2.46	-11.56
S	-0.9	2.31	0
T	+19.93	0.98	-9.5
U	+19.72	1.41	-68.0
V	+50.28	0.05	0
W	+76.6	0.69	-73.48
X	-0.62	0.36	-51.83
Y	+74.4	0.98	-87.55
MIL-H-46001	+1.43	0.03	-25.58

Section 5 Conclusions/Recommendations

On the basis of the work completed to date, EA hydraulic fluids can be used in selected military industrial applications. Most fluids tested were very close to meeting requirements of MIL-H-46001 specification and are promising as the candidate EA military hydraulic fluids. The results of this study are summarized in the following finding:

- Numerous EA hydraulic fluids are currently available in domestic market and new products are being developed.
- EA hydraulic fluids are biodegradable and less toxic products, and were formulated using vegetable oils (rapeseed, sunflower, corn, canola) and synthetic esters.
- Vegetable based EA hydraulic fluids were limited in operational temperature ranges (-10 °C to 90 °C) due to poor thermal and low temperature stabilities. On the other hand, synthetic ester based fluids showed a wide operational capability (-40 °C to 150 °C) which can meet the requirements of military mobile hydraulic fluids.
- Humidity cabinet test results showed that EA hydraulic fluids provide better corrosion protection than current military hydraulic fluids. EA fluids also showed good performance in the copper corrosion test and rust prevention test using synthetic sea water. In the corrosiveness and oxidation stability tests, most EA fluids failed due to their poor oxidation stability.
- PDSC tests showed that vegetable oil based fluids give poor oxidation stability while synthetic ester based fluids provide the same quality of oxidation stability of petroleum based fluids.
- EA fluids provided high flash and fire points over petroleum based fluid. Also, they did not show any evaporation and foaming problems.
- Elastomer compatibility tests showed that EA fluids might be incompatible with certain types of elastomers.
- EA fluids provided good wear properties which can be compared with petroleum based fluid.
- Accelerated storage stability tests showed that some vegetable based fluids had a short storage life due to their poor oxidation and thermal stability at elevated temperatures.

Although EA hydraulic fluids did not meet the current military specification requirements, they are potentially good candidate fluids for the replacement of some current petroleum based military hydraulic fluids which create environmental problems. Based on the market survey, further development of EA fluid is highly recommended.

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