Extreme-Pressure Lubricant Tests on Jojoba and Sperm Whale Oils

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ABSTRACT

Laboratory and simulated in-use lubricant tests were performed on sulfurized jojoba oil and on reference sulfurized sperm whale oil. Data from these comprehensive tests indicated sulfurized jojoba oil prepared from heat-treated filtered oil to be comparable or superior to sulfurized sperm whale oil as an extreme-pressure additive for motor oils, gear lubricants, and automotive transmission fluids.

INTRODUCTION

The protected but still endangered sperm whale (*Physeter macrocephalus* or *P. catodon*) and desert-grown nuts from jojoba [*Buxus chinensis* (Link 1822), *Simmondsia californica* (Nuttall 1844), *Simmondsia chinensis* (Schneider 1907)] are the only major sources of natural liquid waxes (1,2). The search for oils to replace sperm whale oil in extreme-pressure lubricants has led the U.S. Department of Agriculture to conduct in-depth evaluations on several selected agricultural research products including jojoba oil and other ester-type candidates. Refined jojoba oil performed very well in preliminary screening tests and was selected for evaluation of simulated in-use performance in engine, automatic transmission, and differential gear lubrication. Data summarized and reported here from tests comparing jojoba and sperm whale oils indicate the feasibility of utilizing sulfurized jojoba oil as an extreme-pressure lubricant additive in place of sulfurized sperm whale oil.

MATERIALS

Jojoba Oil

Nuts were harvested and dried at the San Carlos Apache Indian Reservation in Arizona. Six oil samples were prepared in this manner:

Sample I was clear supernatant oil obtained by expeller-pressing dried nuts and allowing the turbid oil to stand for one week before the clear supernatant was decanted from sedimented fine particles.

Sample II was hexane-extracted oil that had been washed with methanol, heated to 300 C, cooled, and filtered.

Sample III was II that had been heated to 300 C two additional times in the presence of activated charcoal and filtered each time.

Sample IV was I heated to 250 C, cooled and filtered.

Sample V was I heated rapidly to 300 C with 8 g of activated charcoal (Darco G-60, ICI United States, Inc., Wilmington, DE) per 500 ml of oil and filtered while hot (250 C) through Celite Filter Aid (Johns-Manville, New York).

Sample VI was V prepared in larger quantity. Working with 500 ml batches, preparation of this sample required 8 hr per gallon.

Surfurized Jojoba and Sperm Whale Oils

All samples, including two gallons of refined jojoba oil, were sulfurized by the same general procedure. Oil was mixed with elemental sulfur (11.0 ± 0.5% by weight) under reduced pressure (208 mm), and the mixture was heated slowly to 121 C (250 F). After 30 min, the mixture was heated slowly to 182 C (360 F) and allowed to react at that temperature for 4 hr with constant stirring. The mixture was cooled to 93 C (200 F) and blown free of hydrogen sulfide and other sulfur-containing volatiles by drawing air through the oil until entrained air gave a negative test with lead acetate paper. Sulfurized sperm whale oil was purchased from Mayco Oil & Chemical Co., Bristol, PA.

Base Oils for Lubricant Tests

Five base oils used in lubricant tests were:

A. Mid-continent 30W crankcase oil (Southwest Research Institute, San Antonio, Texas).

B. Transmission fluid containing 6.5% by volume of Lubrizol 3140 as viscosity index improver (Southwest Research Institute).

C. RGO-100 reference gear lubricant oil (Southwest Research Institute).

D. Commercial 100/100 vis solvent-extracted neutral oil (Mayco Oil & Chemical Co., Bristol, Pennsylvania).

E. Topaz S105 oil, similar to 102 paraffin oil (Atlantic Richfield Co., Philadelphia, PA).

TEST METHODS

Preliminary Laboratory Tests

Preliminary tests that provided the basis for selection of candidates for the simulated in-use lubricant evaluation were:

Solubility. Compatibility of candidate oil with base oil after 24 hr at 1.7 C (35 F), 24 hr at room temperature, 24 hr at 1.7 C (35 F), and 30 days at room temperature.

Viscosity. American Society for Testing and Materials (3) ASTM D-445.

Viscosity Index. ASTM D-2270.

Pour and Freezing Points. ASTM D-97.

Flash and Fire Points. ASTM D-92

Neutralization Number. ASTM D-974.

API Gravity. ASTM D-287.

Copper Corrosion. ASTM D-130.

Lead Compatibility. Federal Test Method (4) FTM-

TABLE I

Wax Ester Composition of Untreated, Refined, and Boiled Jojoba Oils (GLC Area %)

Number of Carbon atoms in wax ester	Untreated	Refined (300 C)	Boiled (420 C)
C 34	0.1	0.1	0.3
C36	2	2	4
C38	7	7	9
C40	30	30	33
C42	50	50	39
C44	10	10	10
C46	1	1	4
C48	0.1	0.1	0.5

TABLE II

Properties of Sulfurized Jojoba and Sperm Whale Oils and of Base Oils[a]

Property	Jojoba		Sperm whale	A	B	C	D
	Sample I	Sample VI					
Sulfur, % by weight	11	11	11	0.17	0.33	0.16	0.15
Viscosity @ 38 C, SUS[b]	---	---	---	534	2687	1051	103
Viscosity @ 99 C, SUS	834	---	260	66	170	95	40
Viscosity Index	---	---	---	100	104	103	112
Pour point, C	12	17	18	---	---	---	
Freezing point, C	9	15	15	---	---	---	
Flash point, C	223	248	240	243	277	227	192
Fire point, C	293	262	280	---	---	---	---
Aniline point, C	---		---	119	125	116	102
Saponification number	81	118	167	---	---	---	---
Neutralization number	7.0	3.5	3.0	---	---	---	---
Gravity, degrees API[c]	---	---		29	27	27	33

[a]Base Oils: A = Mid-continent 30W crankcase lubricant oil (Southwest Research Institute, San Antonio, Texas); B = Transmission fluid containing 6.5% by volume of Lubrizol 3140 as viscosity index improver (Southwest Research Institute); C = RGO-100 reference gear lubricant oil (Southwest Research Institute); D = Commercial 100/100 vis solvent-extracted neutral oil (Mayco Oil & Chemical Co., Bristol, Pennsylvania).

[b]Saybolt Universal Seconds.

[c]American Petroleum Institute.

5321.1.

Emulsifiability. ASTM D-1401.

Foaming. ASTM D-892.

Wear Test (Scar). ASTM D-2267-67.

Extreme-Pressure Test (Weld). ASTM D-2783.

Thermal Oxidation Stability. FTM-2504.

Simulated In-Use Performance Tests

This part of the evaluation was designed to obtain comparative performance data between sulfurized sperm whale oil and its replacement candidate. Most tests were conducted with reference base lubricants containing only 10% by weight of sulfurized oil. Exception to that was the 1970 Oldsmobile "MS" Sequence III C Test, which was conducted using the General Motors Reference Lubricant 72 A and 1% by weight sulfurized sperm whale oil or its replacement candidate. Procedures used in these simulated in-use performance evaluations are described briefly below.

L-37D High-Torque Gear Lubricant Test (FTM-6506.1). This evaluation is required under the Military Specifications for Multipurpose Gear Lubricant MIL-L-2105 (5) to establish a lubricant's load-carrying wear and extreme-pressure characteristics under conditions of high-speed low-torque and low-speed high-torque. The procedure employs a 3/4 ton truck hypoid rear axle in the familiar T-shaped equipment layout with an engine driving the pinion gear. Load is provided by dynamometers coupled to each end of the axle. The test involves two sequences: Sequence I high-speed low-torque operation; 100 min at 440 rpm 1060 N·m (9460 lb-inch) torque, 146–149 C (295–300 F); Sequence II –low-speed high-torque operation; 24 hr at 80 rpm, 4723 N·m (41,800 lb-inch) torque, 135 C (275 F).

Performance is assessed by a critical examination of the contact surfaces of the gear teeth for any distress characterized by wear, ridging, rippling, pitting, or spalling. Base oil C was used in this test.

L-42 High-Speed Gear Lubricant Test (FTM-6507.1). This is a high-speed shock bump test required under the MIL-L-2105 specification to establish the minimum antiscore quality of hypoid lubricants. Performed on the same installation as the L-37 Test, but with a different model axle assembly, the L-42 Test follows a four-sequence protocol.

Sequence I–break-in; 10 min at 600 rpm, 54 N·m (480 lb-inch torque), 107 C (225 F); 4 cycles of 600-400-600 rpm, same torque and temperature; 20 min at 850 rpm, 71 N·m (624 lb-inch) torque, 107 C; and 4 cycles of 850-700-850 rpm, same torque and temperature; Sequence II–high speed operation; 5 cycles of 550-1100-550 rpm, inertial torque only, start at 93 C; Sequence III–visual inspection (optional); Sequence IV–shock operation; 10 cycles of 550-650-550 rpm, 178 N·m (1572 lb-inch) torque, start at 138 C (280 F) or near final temperature of Sequence II.

Lubricant performance meets test requirements if the area scored on the gear teeth during the sequences of acceleration/deceleration cycles is less than that produced during reference tests with a borderline-pass oil, such as RGO 10-90. Test samples were formulated in base oil C.

Dexron-II Automatic Transmission Fluid Specification Tests (GM-6137-M). This specification (6) requires candidate fluids to pass a series of chemical and bench tests analogous to our preliminary tests and to perform satisfactorily under simulated in-use and in-use conditions. Generally, candidate automatic transmission fluids are fully formulated with performance-improving additives; e.g., extreme-pressure agents, antioxidants, antisquawk agents, corrosion inhibitors, dispersants, viscosity index improvers, pour point depressants, and antifoam agents. Our comparisons were conducted with sulfurized jojoba oil or sulfurized sperm whale oil in base oil B.

Performance testing included the Turbo Hydramatic Cycling Text (THCT) to measure shift performance and friction retention as affected by oxidation of the fluid and the High Energy Friction Characteristics and Durability Test (HEFCAD) to measure friction retention of the fluid. These tests, conducted according to GM-6137-M, served as a minimum requirement for comparison of sulfurized jojoba oil with sulfurized sperm whale oil. Other tests of the DEXRON-II protocol would normally be completed before accepting a candidate for commercial use in automatic transmission fluids.

1970 Oldsmobile "MS" Sequence III C Test (ASTM STP 315F). This method describes an engine test procedure for evaluating high temperature performance characteristics of motor oils, such as oil-thickening characteristics, sludge, and varnish deposits, as well as engine wear. It is designed to relate particularly to high speed turnpike operation under relatively high ambient conditions typical of the Southwestern and Southern United States, and it is most useful in evaluating the thickening characteristics of motor oils under the above conditions. The test engine is operated for 64 hr at 3000 rpm under a load of 100 bhp. Cooling jacket outlet and oil gallery temperatures are 118 C (245 F) and 149 C (300 F), respectively.

TABLE III

Properties of Sulfurized Jojoba and Sperm Whale Oils in Four Base Oils[a] (10% by Weight in Base Oil). Values for Jojoba are Averages of Samples I to V, Except Where Specified

Test	A	B	C	D
Solubility				
Jojoba	OK	OK	OK	OK
Sperm whale	OK	OK	OK	OK
Viscosity, SUS[b]				
Jojoba, 38 C	760	2985	1278	166
Sperm whale, 38 C	608	2491	1115	132
Jojoba, 99 C	84	197	116	47
Sperm whale, 99 C	72	170	102	43
Viscosity Index				
Jojoba	112	119	116	138
Sperm whale	101	113	110	122
Gravity, degrees API[c]				
Jojoba	28	26	26	32
Sperm whale	28	26	26	31
Copper corrosion[d] (classification by ASTM D-130)				
Jojoba, Sample I	3 a	3 b	2 c	2 d
Sample II	1 b/2 a	1 b/2 a	2 a	2 a
Sample III	1 b	1 b	1 b	1 b
Sample IV	1 a/b	1 b	1 b	1 b
Sample V	1 a/b	1 b	1 a/b	1 a/b
Sperm whale	2 a	2 a	2 b	2 a
Lead corrosion (weight loss, mg/inch^2)				
Jojoba, Sample I	0.3	6.0	10.4	9.8
Sample II	0.2	4.1	3.2	1.4
Sample III	11.9	25.6	30.7	9.1
Sample IV	8.3	18.6	22.8	11.0
Sample V	13.2	21.4	27.6	18.9
Sperm whale	22.5	12.7	19.0	12.9

[a]Base oils, see Table II, footnote a.

[b]Saybolt Universal Seconds.

[c]American Petroleum Institute.

[d]Corrosion: 1 a<1 b<2 a<2 d< 3a<3 b.

RESULTS AND DISCUSSION

Properties of Sulfurized Jojoba and Sperm Whale Oils

Properties and chemical composition of natural jojoba oil have been reported earlier (1,7,8). Refinement of jojoba oil prior to sulfurization brought no changes upon the wax ester composition and the viscosity of the oil. However, when the oil was heated to its boiling point and percolated for 15 min, a slight randomization of the alcohol/acid combinations was observed, as indicated in Table I. Properties of sulfurized jojoba and sperm whale oils and those for four of the five base oils are listed in Table II.

Preliminary Laboratory Lubrication Tests

Results from the preliminary tests on sulfurized jojoba and sperm whale oils are listed in Table III. Both samples remained soluble in every base oil, even after standing for 30 days. Sulfurized jojoba oil imparted a slightly greater increase in viscosity to the base oils than did sulfurized sperm whale oil, although the original nonsulfurized oils had identical viscosities; i.e., 35 ± 1 cp at 25 C. Gravity values, which are useful in calculations involving storage and shipping operations, were essentially the same. Jojoba caused slightly less copper corrosion than did sperm whale, and both, at 10% by weight in base oil, performed within the criteria set for allowable corrosion. Both corroded lead within the range commonly experienced with lubrication oils. They would, nevertheless, require antilead corrosion additives to meet the standard for excellent performance; i.e., less than 0.16 mg/cm^2 (one mg/inch^2). The purification treatment that lessened copper corrosion instead tended to increase lead corrosion. The change responsible for this increased lead affinity has not been identified, but purification had no other obvious deleterious effects on the lubricant properties of sulfurized jojoba oil.

TABLE IV

Emulsion Properties of Sulfurized Jojoba and Sperm Whale Oils in Various Lubricant Base Oils (ASTM D-1401)[a]

Phases	A	B	C	D
Jojoba oil (Sample V)	1	10	1	1
Water	10	20	15	17
Oil/Water Emulsion	69	50	64	62
Sperm Whale Oil	1	9	8	12
Water	0	24	11	2
Oil/Water Emulsion	79	47	61	66

[a]10% by weight in base oil. Starting with 40 ml each of oil and water, measurements are expressed as phase volumes in milliliters. Test time is 60 min. Base oils are described in Table II, footnote a.

TABLE V

Foaming Characteristics of Sulfurized Jojoba and Sperm Whale Oils in Various Lubricant Base Oils (ASTM D-892)[a]

Oil	Temperature C	A	B[b]	C	D
Jojoba, Sample V	24	5/0	0/0	0/0	5/0
	93	20/0	0/0	0/0	15/0
	24	5/0	0/0	0/0	5/0
Sperm whale	24	0/0	0/0	510/20	250/0
	93	40/0	0/0	150/0	20/0
	24	20/0	0/0	180/0	80/0

[a]10% by weight in base oil. Measurements expressed as ratios of milliliters of foam after 5 min bubbling vs. milliliters of foam after 10 min settling. Maximum allowed at 5 min bubbling, 300 ml at 24 C and 50 ml at 93 C. Base oils described in Table II, footnote a.

[b]Base oil B contains antifoam agent.

Both oils were also very similar in emulsifiability, as seen in Table IV. Normally, a good emulsion is required for lubricants used in marine and industrial applications, whereas a good de-emulsification property is necessary for lubricants used in engine gears and transmissions.

Foaming characteristics of sulfurized jojoba oil were slightly superior to those of sulfurized sperm whale oil (Table V). Excessive foaming is undesirable. MIL-L-2105 for gear lubricants specifies foam limits after 5 min of bubbling as: Sequence I at 24 C (75 C)–300 ml; Sequence II at 93 C (200 F)–50 ml; Sequence III at 24 C–300 ml. Sulfurized sperm whale oil failed to meet these standards in oil C, but both oils performed excellently in the transmission fluid base (oil B). In every base oil, sulfurized jojoba oil was totally defoamed in less than 10 min, whereas sulfurized sperm whale oil failed in one (oil C) of its twelve tests.

Wear and extreme-pressure test results indicated the equivalency of sulfurized jojoba and sperm whale oils. The values from conventional 4-ball wear scar and load weld determinations are given in Table VI. Scars of less than 0.7 mm and extreme-pressure welds approaching three hundred kilograms are desired when 10% by weight of the additive is used.

Unrefined sulfurized jojoba oil (Sample I) at 5% concentration carried to a 260-Kg weld load, but it also produced large wear scar (0.620 mm). Refining the oil generally improved wear performances ca. 20–25% while reducing load carrying capability only 5–10%.

The final step in our preliminary testing approached in-use conditions. Lubricant stability and effectiveness were assessed simultaneously in a heated (163 C or 325 F)

TABLE VI

Four-Ball Lubrication Tests on Sulfurized Jojoba and Sperm Whale Oils in Topaz S105 Base Oil (E)

Test	% by weight in base oil	Jojoba oil samples I-V[a]	Jojoba oil samples VI	Sperm whale oil	Topaz S105
Wear Test, ASTM D-2266-67					
Scar in mm	0				0.803
	5	0.465–0.650	0.505	0.558	
	10	0.565–0.705	0.590	0.623	
Extreme-pressure weld point, ASTM D-2783					
Weld load in Kg	0				120
	5	240–260	240	230	
	10	280	280	300	

[a]Range of data for Samples I through V.

TABLE VII

Thermal Oxidation Stability of Sulfurized Jojoba and Sperm Whale Oils in Gear Lubricant Test (FTM-2504)[a]

Tests	Jojoba oil samples I	II	III	IV	V	VI	Sperm whale oil
Viscosity at 99 C, centistokes							
0 Hr	25	25	22	21	23	21	21
10 Hr	26	26	22	22	24	22	25
20 Hr	28	30	24	22	25	24	29
30 Hr	32	39	24	23	27	28	34
40 Hr	43	63	26	24	30	32	43
50 Hr	138	67	30	29	39	36	44
% Increase, 50 Hr	457	169	34	36	68	71	108
Analysis of 50 hr sample							
Acid number						4.3	10.2
n-Pentane insolubles, % weight						4.3	0.2
Benzene insolubles, % weight						1.7	0.1
Catalyst weight loss or gain, gram						−0.0047 (−0.051%)	+0.0051 (+0.059%)
Bearing clearance increase, mm						0.010	0.002
Gear backlash increase, mm						0.005	0.002

[a]10% by weight in base oil C (RGO-100 reference gear lubricant).

gearcase with two spur gears operating under load and with air bubbled through the lubricant. Under these conditions (FTM-2504), sulfurized refined jojoba oil (Sample VI) easily met the MIL-L-2105 criterion of not more than 100% viscosity increase at 50 hr, whereas sulfurized sperm whale oil performed at the borderline of approval (Table VII). Pentane insolubles from jojoba exceeded the MIL-L-2105 Limit (3%) slightly, but benzene insolubles were better than specification (2%).

In the preliminary tests with the first five jojoba samples, the viscosity of unrefined sulfurized jojoba oil (Sample I) increased 460% while that of two purified samples increased only 35% at 50 hr. Refining is thus beneficial to thermal stability as well as to wear-reducing properties. Pentane and benzene insolubles were also drastically reduced by purification, while increases in gear backlash and bearing clearance were insignificant and obviously not related to purification.

Simulated In-Use Performance Tests

Only summaries of the data on conditions and results from these comprehensive tests are reported here because of their extensive and detailed nature. A few of the observations are listed in Table VIII.

L-37D High Torque Axle Test. Medium to heavy wear was observed with both sulfurized jojoba and sperm whale oils, but it was not excessive and was within the limits of the evaluation criteria for the test. Details of the test showed sulfurized jojoba oil to be slightly better than sulfurized sperm whale oil.

L-42 High-Speed Axle Test. In order to pass this test, which simulates speeds as high as 160 kph (100 mph), scoring on the coast side gear tooth surface must be less than 18%; whereas on the drive side, scoring in excess of 2% may constitute failure. Sulfurized jojoba and sperm whale oils both failed the test when formulated in base oil RGO-100 without other additives. Sperm whale results were less satisfactory than those for jojoba; it operated at a much higher temperature, and its test had to be terminated at the end of Sequence 2 instead of Sequence 4 because a loud noise developed at the rear axle unit. In a fully formulated test, both oils should perform satisfactorily because the margin of failure was small, despite the 90 to 100% scoring of gear surfaces.

Turbo Hydramatic Transmission Cycling Test. In this test, sulfurized jojoba oil also proved superior over sulfurized sperm whale oil. With the latter, the test lasted for only 850 cycles before termination due to excessive foaming. Examination of the sulfurized sperm whale oil test parts indicated some wear and some deposit formation. In contrast, sulfurized jojoba oil lasted four times longer and gave lower wear and less deposits. Changes in transmission shift times at various test cycle intervals were less for jojoba thanfor sperm whale.

Fully formulated transmission fluids that pass the THCT complete 20,000 shift cycles and perform according to the following test limits:

1–2 Shift time	0.35–0.70 sec
2–3 Shift time	0.25–0.50 sec
Viscosity at 99 C (210 F)	5.5 cSt minimum

TABLE VIII

Simulated In-Use Evaluations of Sulfurized Jojoba and Sperm Whale Oils as Extreme Pressure Lubricant Additives

Evaluations	Sulfurized jojoba oil (Sample VI)	Sulfurized sperm whale oil
L-37D High torque axle test (FTM-6506.1)		
Sequence I. High speed, low torque		
Gear tooth surface condition	Satisfactory	Satisfactory
Sequence II. Low speed, high torque		
Gear tooth surface wear	Medium heavy	Heavy
Rippling on pinion gear	80% of tooth surface	90% of contact area
Scratches, pitting, spalling	Nil	Nil
Ridging	Nil	50% of teeth, 90% of contact area
Scoring, discoloration, corrosion, deposits	None	None
Backlash increase, mm	0.064	0.089
Stability of pinion shaft		
Torque before and after test, lb-in.		
to break:	45, 15	45, 15
to turn:	40, 10	40, 10
L-42 High speed axle test (FTM-6507.1)		
Scoring on ring and pinion gears	90-100%	100%
Axle backlash increase, mm	0.140	Not measured[a]
Lubrication temperature, C		
Sequence 2	126	179
Sequence 4	140	Not measured[a]
Turbo hydramatic transmission cycling test (GM-6137-M)		
Cycles completed	3,780	850
Shift time, sec.; 1-2 shift at 250 cycles	0.70	0.67
850 cycles	(0.70)	0.74
2000 cycles	0.70	—
3780 cycles	0.79	—
2-3 shift at 250 cycles	0.45	0.52
850 cycles	—	0.62
2000 cycles	0.62	—
3780 cycles	0.89	—
Viscosity, cSt, 38 C; at 0 cycle	59	47
850 cycles	—	53
3780 cycles	55	—
Viscosity, cSt, 99C; at 0 cycle	9.6	7.5
850 cycles	—	9.0
3780 cycles	8.8	—
Acid number increase	1.34	1.10
Carbonyl group absorbance increase, OD	0.16	0.72
Copper content at end of test, ppm	56	115
High energy friction characteristics and durability test (GM-6137-M)		
Engagement time, sec.: 0 hr, 10 cycles	0.70	0.67
24 hr, 4,375 cycles	0.83	0.82
50 hr, 9,000 cycles	0.89	0.81
100 hr, 18,000 cycles	0.88	1.61
Dynamic torque, N°m; 0 hr, 10 cycles	125	132
24 hr, 4,375 cycles	106	99
50 hr, 9,000 cycles	96	108
100 hr, 18,000 cycles	94	58
Clutch plate condition, composition	Light glazing Light flaking	Heavy glazing Heavy flaking Moderate pitting
1970 Oldsmobile "MS" sequence III C test (ASTM-STP-315F)		
Viscosity change: original, cSt, at 0 hr	144.94	141.32
% increase at 8 hr	+ 21	+ 21
16 hr	+ 34	+ 34
40 hr	+ 110	+ 114
56 hr	+ 806	+ 889
64 hr	+ 3971	+ 5218
Piston varnish (no varnish = 10.00)	9.32	9.27
Oil ring land deposit (no deposit = 10.00)	6.28	6.41
Sludge (no sludge = 10.00)	9.54	9.47
Ring and lifter sticking	None	None
No. of parts[b] scuffed and/or worn	13	28
Lifter plus cam wear, mm: average	0.010	0.010
maximum	0.018	0.020
Rod bearing weight loss, mg.; average	116.1	36.4

[a]Test terminated at end of Sequence 2.

[b]Parts include cam lobes, lifters, valve stems, rocker arm pads, and/or rocker arm pivots.

Acid number increase	6.0 maximum
Carbonyl absorbance increase	0.70 OD maximum

Shift times for sulfurized jojoba oil without full formulation deteriorated beyond these limits by the time the test was terminated at 3780 cycles due to foaming, but on a comparative basis, sulfurized jojoba oil performed significantly better than sulfurized sperm whale oil. At termination of the tests, carbonyl group absorbance was still within limits for jojoba but not for sperm whale. There was no viscosity increase with sulfurized jojoba oil at 3780 cycles, whereas the viscosity of sulfurized sperm whale oil increased 19% after only 850 cycles.

High Energy Friction Characteristics and Durability Test. Proper formulation with other transmission fluid additives, particularly a foam suppressor, would have allowed a more thorough comparison of extended performance via the THCT. Such formulation, however, was beyond the scope of these studies. Instead, extended performance in transmission use was estimated by determining high energy friction characteristics and durability in a sealed clutch pack during 24 100 hr of testing as follows:

Engagement time	0.45–0.75 sec
Dynamic torque	115–183 N·m (85–135 lb-ft)
Static torque–dynamic torque	≤14 N·m (10 lb-ft)
Clutch plate condition	≤ light glaze, flaking, and/or discoloration

Neither fluid met these specifications, but test results indicate that sulfurized refined jojoba oil outperforms sulfurized sperm whale oil. For example, whereas the engagement time in the sperm whale test increased 100% from the 9,000 cycle check to the 18,000 cycle check, there was no significant change (+12%) in the jojoba test. Furthermore, the dynamic torque at 18,000 cycle dropped to half that at 9,000 cycles in the sperm whale test, but there was essentially no change (−3%) between the two points in the jojoba test. The clutch plate conditions at the end of the tests also indicated the superiority of sulfurized jojoba oil over sulfurized sperm whale oil.

1970 Oldsmobile "MS" Sequence III C Test. The General Motors Reference Engine Lubricant 72-A gives results that are borderline-fail in terms of viscosity increase at 38 C (100 F) and 40 test hours. The same is true in tests for varnish development, sludge, ring and lifter sticking, scuffing, and wear. Average results from four trials with this reference lubricant compare as follows with criteria for the III C test:

	72-A Performance	Pass Limits
Viscosity increase at 38 C and 40 test hours		
Maximum	381%	400%
Average engine ratings at 64 test hr (Maximum score = 10)		
Piston varnish, minimum	9.2	
CRC Manual No. 1		9.5
CRC Manual No. 9		9.3
Oil ring land deposit, minimum	6.7	6.0
Sludge, minimum	9.2	9.0
Ring and lifter sticking	None	None
Valve lifter and camshaft lobe combined wear		
Average, mm	0.018	0.025
Maximum, mm	0.030	0.051

As shown in Table VIII, addition of 1% by weight of sulfurized jojoba oil to the 72-A reference oil dropped the latter's viscosity increase at 40 hr to 141%, and sulfurized sperm whale oil dropped it to 146%. Beyond 40 hr, the unsupplemented reference oil usually thickens too much for viscosity measurements. Yet both sulfurized oils kept viscosity within measurable limits. Both oils were essentially equal in terms of sludge and deposit formation. The jojoba test engine contained fewer scuffed and/or worn parts, but it sustained relatively high rod bearing weight loss. This weight loss is difficult to explain in the absence of other signs of wear. It may be related to the negative effect of refining on the compatibility of sulfurized jojoba oil with lead (Table III).

ACKNOWLEDGMENT

Measurements for pour, freezing, flash, and fire points, saponification and neutralization numbers, and four-ball wear and weld point tests were conducted at the Eastern Regional Research Center, U.S. Department of Agriculture, Philadelphia, PA.

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