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ENGINE LUBRICANT REQUIREMENTS FOR REMOTELY PILOTED VEHICLES (RP--ETC(U)
SEP 77 H W MARBACH, J A RUSSELL DAAK02-73-C-0221

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ENGINE LUBRICANT REQUIREMENTS FOR REMOTELY PILOTED VEHICLES (RPV)

Final Report
AFLRL No. 85

by

H. W. Marbach, Jr.
John A. Russell

Prepared by

U. S. Army Fuels and Lubricants Research Laboratory
Southwest Research Institute
San Antonio, Texas

for

U. S. Army Air Mobility Research and Development Laboratory
Fort Eustis, Virginia

Under contract to

U. S. Army Mobility Equipment Research and Development Center
Petroleum and Materials Department
Fort Belvoir, Virginia

Contract No. DAAK-02-73-C-0221

September 1977

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFLRL No. 85
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*): ENGINE LUBRICANT REQUIREMENTS FOR REMOTELY PILOTED VEHICLES (RPV)
5. TYPE OF REPORT & PERIOD COVERED: Final Report
6. PERFORMING ORG. REPORT NUMBER: AFLRL No. 85
7. AUTHOR(s): H. W. Marbach, Jr.; John A. Russell
8. CONTRACT OR GRANT NUMBER(s): DAAK 02-73-C-0221
9. PERFORMING ORGANIZATION NAME AND ADDRESSES: U.S. Army Fuels and Lubricants Research Laboratory, P.O. Drawer 28510, San Antonio, Texas 78284
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 24p.
11. CONTROLLING OFFICE NAME AND ADDRESS: U. S. Army Air Mobility R&D Laboratory, Eustis Directorate, Fort Eustis, Virginia 23604
12. REPORT DATE: Sept[redacted]977
13. NUMBER OF PAGES: 21
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*): U. S. Army Air Mobility Research and Development Center, Petroleum and Materials Department, Fort Belvoir, Virginia 22060
15. SECURITY CLASS. (*of this report*): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Remotely Piloted Vehicle, 2-Stroke Lubrication, Engine Deposits, MIL-SPEC Lubricants, Engine Test, Spark Plug Fouling, Capacitive Discharge Ignition.

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

The Army is exploring the feasibility of using Remotely Piloted Vehicles (RPV's) in a multi-mission role. Powerplants for these RPV's are to be small, two-stroke, air-cooled, reciprocating engines which require a fuel/oil mix for operation. As no federal or military specification lubricant exists for this application, this report details results of an analytical/experimental investigation to evaluate the suitability of existing MIL SPEC lubricant classes for Army RPV use. Performance of a limited sampling of military specification lubricants was evaluated by cyclic testing with a small two-stroke, air-cooled piston engine currently used in the

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ACKNOWLEDGEMENT

The authors wish to express their deepest thanks to Messrs. Jim McKay and Zack Bishop, SwRI Engines, Fuels and Lubricants Division, who provided invaluable assistance in adapting engine merit rating techniques to this program. Also, the efforts of Messrs. Lyle Sievers, Leonard Ackermann, and Ed Owens, AFLRL, in adapting a capacitive discharge ignition system to the McCulloch MC101 engine are gratefully appreciated.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

In recent years, the US Army has perceived the distinct advantages of a field weapons system built around numbers of small, unmanned remotely piloted vehicles (RPV's). Today's electronic miniaturization provides the means to efficiently package fairly sophisticated battlefield surveillance/target designation systems. The Army platform aboard which these systems will be carried appears to be evolving into a 150-300 pound gross weight vehicle capable of being launched, controlled, and recovered from a location behind the forward edge of battle area (FEBA). Though some RPV's are conceived as expendable, the expense of the Army's envisioned payload package mandates a reliable (but cost effective) vehicle capable of precise guidance and recovery.

The power class of 20-25 HP was selected to give the required vehicle performance. An air-cooled, two-stroke reciprocating engine was particularly attractive because of its simplicity, good power-to-weight ratio, and relative low cost. A market survey, however, showed a distinct void in the 20-25 HP range for acceptable engines. The Army's demonstrator RPV, the Aquila, is powered by a single-cylinder, 9.6-HP McCulloch MC101 go-kart racing engine. For the increased horsepower requirement and for additional smoothness, a twin-cylinder opposed configuration was selected. Cost effectiveness could be achieved by maximizing the use of off-the-shelf, high-production engine components. To demonstrate this capability, the Eustis Directorate, US Army Air Mobility Research and Development Laboratory, Ft Eustis, VA awarded two Mini-RPV Engine Demonstrator contracts* in February 1977. By March 1978 each contractor is to deliver five engines for Government test and evaluation. The introduction of Army RPV's into the battlefield presented a problem requiring immediate analytical and experimental investigation: there is no federal or military specification for two-stroke air-cooled engine lubricants. In the absence of such a specification, three alternative plans of attack were open:

a. Undertake a program to develop a specification for the class of lubricant.

b. Determine the suitability of other military specification and Government-procured lubricant families in this application.

c. Consider the application of a family of existing commercial two-stroke engine lubricants.

The first of these options would require a research and development effort of a sizable scope and time frame. The second approach would be aimed at identifying promising MIL-Spec lubricant classes to satisfy RPV requirements, but would eventually require evaluation of each individual product on Qualified Products Lists (QPL). The third option would be a straightforward approach, but would still introduce a unique lubricant into the Army's supply system. It was felt that the second approach was a good starting point in determining the necessity for a separate two-stroke lubricant specification.

Under supervision of the Eustis Directorate, USAAMRDL, Ft Eustis, VA and USAMERADCOM, Ft Belvoir, VA, the US Army Fuels and Lubricants Research Laboratory (AFLRL) initiated a program involving the following sequential tasks:

a. Obtain and analyze representative samples of a reference lubricant known to be operating satisfactorily in the McCulloch MC101B engine.

*Contract No. DAAJ02-77-C-0014 to Bennett Aerotechnical, Auburn, AL and Contract No. DAAJ02-77-C-0015 to Teledyne Continental Motors, Mobile, AL.

b. Compare compositional analyses from Task "a" with known composition and properties of specification lubricants (e.g., MIL-L-2104C, MIL-L-46152, MIL-L-23699B, and MIL-L-22851B).

c. Identify representative MIL-Spec oils most comparable to the reference lubricants selected under Task "a". In addition, select oils with contrasting performance and composition.

d. Obtain baseline engine test data for the Task "a" reference lubricant with the MC101B engine, using a test cycle designed to be representative of the RPV mission profile.

e. Evaluate candidate MIL-Spec lubricants and compare performance to data developed in Task "d" for the reference lubricant.

f. From performance of lubricants in Task "e", identify those most promising MIL-specifications and perform engine tests on as many qualified lubricants as possible for a given specification. (This last task was, of course, limited by economic considerations since a large number of qualified products exist for most military specification lubricants).

Based upon the above approach, recommendations were to be made regarding the necessity for development of a separate specification or for the applicability of existing specifications to the RPV mission. A further goal of this investigation was to monitor progress of the two "second generation" multi-cylinder Mini-RPV Demonstrator Engine designs to ascertain those design parameters which might influence the two-stroke lubricant selection. In this regard, two parameters are identified: (1) cylinder head temperatures will most likely be allowed to rise to the 500°F range as opposed to more common McCulloch MC101 operating temperatures in the 250°F range, (2) a capacitive discharge ignition system with surface gap spark plug is planned to replace the conventional magneto system and standard electrode spark plug.

Since the lubricant investigation was well into Task "e" when these design considerations were known, a decision was made to modify the test engines for a limited test series at AFLRL so that more meaningful data might be acquired. Testing of these modified configurations comprises the final phase of this lubricant investigation and has been segregated and detailed in the final section of this report.

II. TEST FUEL AND LUBRICANTS

It should be emphasized that this program was designed to evaluate lubricants rather than fuels. To determine which fuel class would best serve this purpose, initial performance testing was accomplished using two fuels, a normally leaded automotive gasoline[1]* and an aviation gasoline.[2] Engine performance characteristics were compared at sea level conditions, using the MC101B reference oil with both fuels, and it was found that there were no significant performance differences regardless of the fuel used. It was decided to use the automotive gasoline due to availability at AFLRL and project cost, plus the fact that candidate RPV engine evaluations in a parallel program at MERADCOM were using this fuel. This gasoline was procured in drummed batches under the VV-G-76b specification and was used in evaluation of all lubricants. Typical fuel properties of the gasoline (AFLRL code AL-6544-G) can be seen in Table 1.

TABLE 1. TYPICAL FUEL PROPERTIES

Properties	VV-G-76b AL-6544-G Normally Leaded
Gravity, API	56.7
RON	93.5
MON	82.7
RVP	8.4
Distillation	
10%	130
50%	222
90%	338
EP	387
F.I.A.	
% Aromatics	30
% Olefins	5
% Saturates	65
Lamp Sulfur, %	0.104
Lead, g/gal.	2.03
Gum Washed, mg/100 ml	0.6
Gum Unwashed, mg/100 ml	1.2

The selected reference lubricant, AL-6408-L, is recommended by the McCulloch Corporation for its family of chain saw and Go-Kart racing engines. As [illegible] seen in Table 2, it is an ashless dispersant, [illegible]-diluted mineral oil and is certified by the [illegible]g Industry of America for service in two-cycle, water-cooled engines[3] (BIA/TC-W). Both viscosity and flash point of this lubricant are dramatically affected by the properties of the diluent. This lubricant had shown excellent performance in both static engine tests at MERADCOM and flight tests with the Lockheed Aquila RPV, but is not qualified to any federal or military lubricant specification. Because of its demonstrated performance in the MC101 engine, this oil was selected as baseline reference for this program.

The class of MIL-spec lubricants closest in composition to the above BIA/TC-W reference lubricant are those ashless dispersant oils qualified under MIL-L-22851B[4] for aircraft piston engines.† These are considerably higher in viscosity and flash point than the BIA/TC-W lubricant, but, as can be seen in Table 2, have no metallo-organic additives and low sulfur content. In MIL-L-22851B, there are Type II (large aircraft engines) and Type III (small aircraft engines) lubricant classes. Each oil class is identified in Table 2. All commercially available oils qualified under this specification were tested.

The two classes of lubricants most prevalent in the Army inventory are those automotive crankcase oils qualified under MIL-L-46152[5] for administrative vehicles and MIL-L-2104C[6] for tactical and combat vehicles. Both classes contain metallo-organic (ash-forming) additives with the tactical/combat oils generally having higher concentrations than the administrative oils. Two typical qualified products from MIL-L-46152 (one mineral base, and one synthetic base) and one from MIL-L-2104C were tested, plus AL-4591-L, a lubricant qualified under both of these specifications.

*Numbered superscripts refer to "Fuels and Lubricants Specifications References" at end of this report. This list provides exact descriptive nomenclature for each specification discussed in the text.

†NAVAIR Instruction 10350.1A, 8 July 1976, permits MIL-L-22851B Type II or III oils for use in fuel-oil mixture applications in two-cycle air-cooled drone aircraft powerplants.

The final lubricant selected was a qualified product under MIL-L-23699B[7], the specification for synthetic-base gas turbine lubricants such as used in Army helicopters. This lubricant class is designed for high-temperature operation and is therefore attractive for two-stroke applications: such lubricants frequently contain tricresyl phosphate as a load-bearing additive.

Due to the large number of qualified products existing for most military specification lubricants, the selection of the lubricants used was governed by:

- Economic considerations
- Oil composition
- Engine lubricant experience, and
- General availability for RPV applications.

Those lubricants selected satisfy the criteria stated for the six sequential tasks described previously.

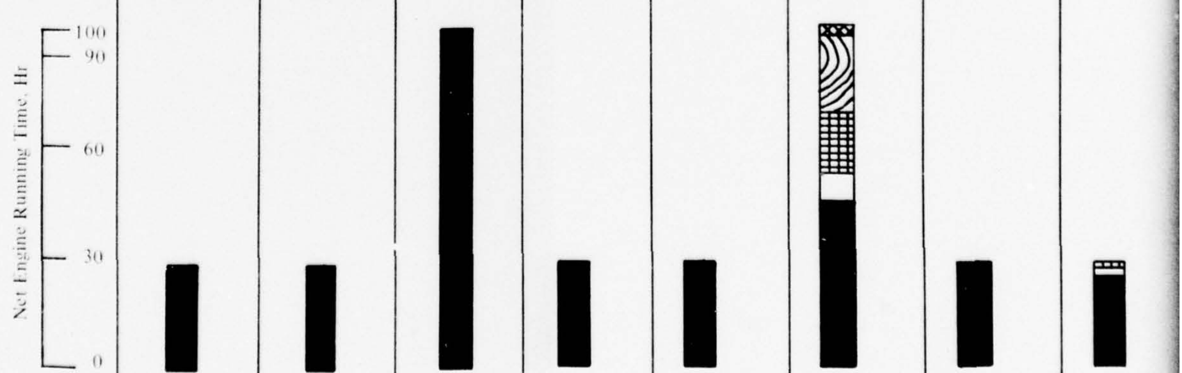
TABLE 2. LUBRICANT

Specification	Reference Oil Two-Stroke Engine-Ashless Dispersant (BIA/TC-W Qualified)			MIL-L-22851B Four-Stroke Aircraft Piston Engine - Ash				
Test No.*	1	11	19	5	7	18	10	14
AFLRL Code **	AL-6408-L	AL-6408-L	AL-6408-L	Type II AL-6535-L	Type III AL-6534-L	Type III AL-6534-L	Type II AL-6535-L	Type III AL-6674-L
Properties								
Viscosity, cSt @ 210° F	6.47	6.47	6.47	20.42	15.15	15.15	25.93	15.17
Viscosity, cSt @ 100° F	38.70	38.70	38.70	261.8	143.3	143.3	327.8	137.8
Viscosity Index	133	133	133	124	113	113	112	122
Flash Point, ° F	160	160	160	530	470	470	520	460
Additive Composition, wt %								
Sulfur	0.12	0.12	0.12	0.41	0.15	0.15	0.14	0.14
Phosphorus	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01
Barium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sulfated Ash	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001

TABLE 3. MERIT R

Piston Skirt	7.6	9.0	8.5	3.5	3.8	2.9	2.8	2.1
Ring Lands, Crown	7.1	7.2	5.3	3.5	2.9	2.5	2.4	2.2
Ring Lands, Second	7.4	8.7	6.3	3.0	2.5	2.6	2.5	2.3
Ring Freedom, Top	10.0	10.0	10.0	10.0	9.3	9.4	9.0	9.5
Ring Freedom, Second	10.0	10.0	10.0	10.0	10.0	7.9	9.2	8.3
Piston Scuffing	10.0	9.9	10.0	9.9	9.7	10.0	10.0	10.0
Cylinder Head Deposit	9.7	9.7	9.8	8.5	8.4	8.4	8.1	7.9
Piston Top Deposit	8.6	8.9	8.5	7.9	6.9	7.5	6.0	8.2
Top Grove Fill	10.0	9.9	9.9	10.0	9.9	9.6	9.9	9.7
Second Grove Fill	10.0	10.0	10.0	10.0	10.0	9.8	9.9	9.6
Exhaust Port Crossing	9.2	9.0	9.7	9.5	9.0	7.0	8.2	9.0
Total Merits	99.6	108.3	98.0	84.8	82.4	77.6	78.0	78.8

TABLE 4. SPARK PLUG



(No. of Plugs Fouled)	(0)	(0)	(0)	(0)	(0)	(4)	(0)	(2)
Fuel/Oil Ratio	16:1	16:1	16:1	16:1	16:1	16:1	16:1	16:1
Engine No.	1	3	5	2	3	6	2	6

*Tests 2, 4, and 6 were aborts.

**AL - series code system used at AFLRL to avoid revealing proprietary data.

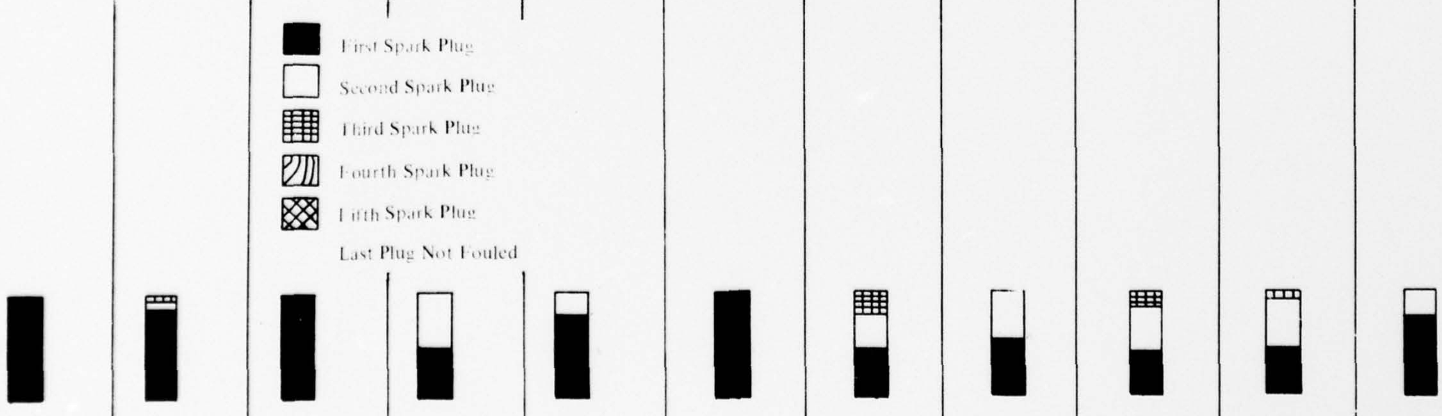
TABLE 2. LUBRICANT DESCRIPTION

	MIL-L-22851B ur-Stroke Aircraft Piston Engine - Ashless Dispersant					MIL-L-46152 Administrative Vehicle Crankcase		MIL-L 2104-C/ 46152	MIL-L-2104C Tactical & Combat Crankcase		MIL-L-23699B Synthetic Gas Turbine
8	10	14	17	8	9	3	13	15	12	20	16
e III 534-L	Type II AL-6535-L	Type III AL-6674-L	Type III AL-6674-L	Type II AL-6536-L	Type II AL-6539-L	AL-6358-L	AL-5680-L	AL-4591-L	AL-5185-L	AL-5185-L	AL-6682-L
.15	25.93	15.17	15.17	25.48	25.24	14.44	11.53	12.71	12.65	12.65	5.06
.3	327.8	137.8	137.8	367.3	303.6	123.6	71.91	128.81	131.5	131.5	27.46
	112	122	122	100	116	126	183	99	96	96	125
	520	460	460	550	540	445	466	470	455	455	480
.15	0.14	0.14	0.14	0.25	0.39	0.44	0.26	0.39	0.41	0.41	0.03
.01	<0.01	<0.01	<0.01	0.02	0.03	0.15	0.10	0.07	0.09	0.09	0.09
.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.11	0.04	0.04	<0.01
.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.19	0.26	0.14	0.44	0.44	<0.01
.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.15	0.11	0.08	0.08	0.08	<0.01
.001	0.001	0.001	0.001	0.001	0.001	0.99	1.05	0.87	1.37	1.37	0.01

TABLE 3. MERIT RATING

.9	2.8	2.1	3.5	2.2	2.8	8.2	9.2	7.7	8.6	7.9	4.2
.5	2.4	2.2	2.8	2.3	2.2	9.0	9.6	8.8	9.8	9.7	7.3
.6	2.5	2.3	2.1	2.1	2.2	8.5	8.5	9.2	10.0	9.1	7.0
.4	9.0	9.5	9.5	9.7	9.8	10.0	9.8	9.5	10.0	9.5	9.8
.9	9.2	8.3	8.9	8.9	9.8	10.0	9.6	9.6	10.0	10.0	9.6
.0	10.0	10.0	10.0	9.9	10.0	9.8	10.0	10.0	10.0	10.0	10.0
.4	8.1	7.9	8.2	8.1	8.5	9.4	8.7	8.5	8.4	8.1	8.2
.5	6.0	8.2	8.1	8.0	8.2	8.8	8.1	7.9	8.2	8.2	8.1
.6	9.9	9.7	9.8	9.8	9.9	10.0	9.9	9.9	9.8	9.8	9.8
.8	9.9	9.6	9.8	9.8	10.0	10.0	10.0	9.9	10.0	10.0	9.8
.0	8.2	9.0	8.6	8.7	9.0	9.8	9.2	8.8	8.0	9.0	9.3
.6	78.0	78.8	81.3	79.3	82.4	103.5	102.6	99.8	102.2	101.3	93.1

TABLE 4. SPARK PLUG FOULING



(0)	(2)	(0)	(1)	(1)	(0)	(2)	(1)	(2)	(2)	(1)
16:1	16:1	32:1	16:1	16:1	16:1	16:1	16:1	16:1	32:1	16:1
2	6	2	4	1	3	5	1	4	6	5

2

III. EXPERIMENTAL PROCEDURE

A. Test Stand Set-up

The McCulloch MC101B engine (see Figure 1) is a small air-cooled, two-stroke cycle spark ignition engine, which develops between 8-10 horsepower at 7,000 to 8,000 RPM (see Table 5). A standard production model was used with a Walboro SDC-43 high-speed carburetor having the main jet drilled out to 0.035 inches. This carburetor has an adjustable jet for idle and mid-range mixtures, permitting more precise fuel-flow control. Six individual engines were used for testing; the same carburetor was used throughout. Test engine components were cleaned and inspected, and questionable or out-of-tolerance parts replaced prior to assembly. New piston rings and gaskets were used for each test. Manufacturer's allowable tolerances and recommended procedures were used throughout the program with the exception of fuel/oil ratios which were run at either 16:1 or 32:1. The engine was mounted on a test stand using rubber insulators between the engine mount and test stand to absorb engine vibration. A DSI 28-46-1014-1-1 fixed-pitch wooden propeller was adapted to the engine for load absorption, and a safety guard screen was mounted on the test stand.

TABLE 5. MC101B ENGINE SPECIFICATION

Engine	Single Cylinder, 2-stroke, air-cooled, loop-scavenged.
Displacement	7.5 cu. in. (122.7 cc)
Bore	2.280 in. (58 mm)
Stroke	1.835 in. (46.6 mm)
Compression Ratio	9.4:1
Weight	12 lbs. 4 oz. (4.7 kg)
Spark Plug	L-78 Champion
Spark Plug Gap	0.025 in. (0.64 mm)
Carburetor	WALBORO SDC-43
Power	9 H.P. @ 7000 RPM
Timing	22° BTDC
Breaker Point Gap	0.015 in. (0.38 mm)

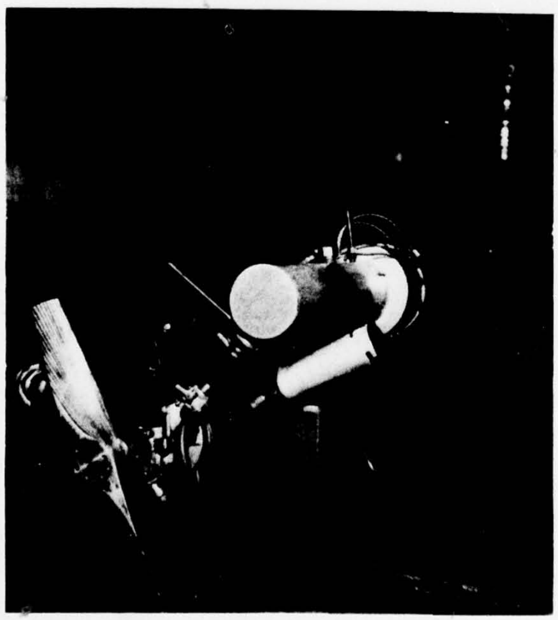


FIGURE 1. TEST STAND SET-UP

Fuel flow was measured by means of a flowmeter and controlled at 25 ml/min at 5000 RPM. Leaning procedure was as follows:

1. Open low-speed jet 3/4 turns from full closed.
2. Stabilize engine (5-10 minutes) at 5,000 RPM.
3. Adjust low speed jet to achieve 25 ml/min fuel flow.

Intake, exhaust, and spark plug temperatures, intake air flow, ambient air, RPM, and barometric pressure were recorded after stabilization in each cycle mode (see below). Inlet air temperature was controlled at 105 ± 5°F.

B. Test Procedure

A test cycle developed by the Electrical Power Laboratory, USAMERADCOM, Fort Belvoir, Virginia, simulating a typical RPV mission profile was employed for all testing. This cycle consisted of nine modes: warmup, takeoff, climb-out, cruise, letdown, go-around, level-off, landing, and turnaround (engine-off heat soak) which totaled 120 minutes (90 minutes running and 30 minutes turnaround). A slight modification of the original 112-minute MERADCOM profile to include an additional eight minutes in the cruise mode was made at AFLRL (see Figure 2) in order to accommodate timing devices. This is considered to be a negligible modification for the purpose of lubricant evaluation. The initial cycle for each test was preceded by a 15-minute break-in and fuel flow adjustment at 5000 RPM, after which the cylinder head was retorqued to prevent leaks. After each test the engine was disassembled and visually rated (see next section). Engine components were then color photographed for further rating and recording. Typical instrumentation readings are given in Table 6.

TABLE 6. TYPICAL ENGINE OPERATING DATA

Mode	Warm-Up	Take-Off	Climb-Out	Cruise	Let-Down	Go Around	Level Off	Landing	Turn-Around
Minutes	1	3	10	68	2	2	2	2	30
RPM	2500	7000	6000	5000	2500	7000	5000	2500	–
Intake Temp, °F	78	89	98	104	105	102	101	105	–
Exhaust Temp, °F	417	981	1073	978	550	1080	1036	540	–
Spark Plug Temp, °F	150	265	268	248	208	260	258	212	–
Ambient Air, °F	70	70	72	72	75	75	75	75	–
Fuel lb/Hr	0.8	5.9	4.4	2.7	0.9	6.0	2.7	0.9	–
Air lb/Hr	–	93.0	68.0	38.0	–	92.0	38.0	–	–

C. Merit Rating Method

It was desirable to provide means for quantitative comparison of lubricant performance. In the absence of any standardized, widely accepted method for air-cooled, two-cycle engines, a rating technique developed at SwRI was used to evaluate those characteristics deemed critical for good lubricant performance. This system makes use of Coordinating Research Council (CRC), Boating Industry of America (BIA) and SwRI-developed rating systems and is based on a merit rating wherein all rating points are from 0-10 (10 = clean). Merit rating data for each component are given in Table 3. Ring lands and piston skirt deposits are rated by using CRC Manual No. 9 color standards, while ring grooves are rated by percent of carbon fill. Piston scuffing is rated as percent of area scuffed. Ring freedom rating is accomplished by using the BIA Ring Rating Chart. The piston and cylinder head deposits are rated by using the SwRI system which evaluates the carbon deposit quantity and lacquer intensity while the exhaust port is rated by percent of area filled with carbon. A totally clean engine would have a combined total merit rating of 110 points. Not enough tests have been run to derive a "fail rating limit" for lubricants. Therefore, the merit ratings are used only to differentiate between degrees of deposition.

Mode	RPM	Duration, min	Clock Time
Warm-Up*	2500	1	0
Take-Off	7000	3	1
Climb-Out	6000	10	4
Cruise	5000	68	14
Let-Down	2500	2	82
Go-Around	7000	2	84
Level-Off	5000	2	86
Landing	2500	2	88
Turn-Around	0	30	90

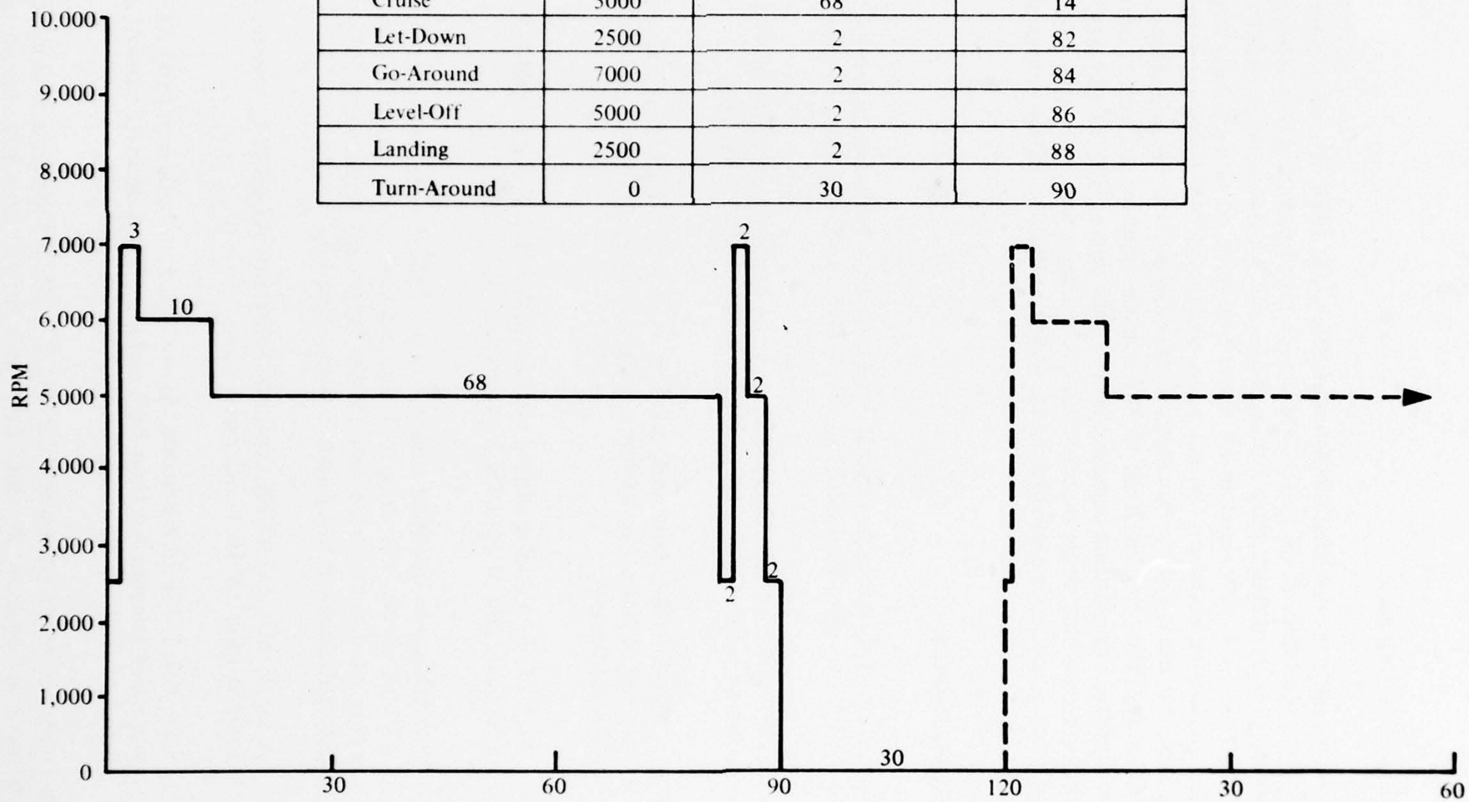


FIGURE 2. AFLRL RPV 2-STROKE OIL TEST CYCLE

IV. EXPERIMENTAL RESULTS

A. Engine Performance

Engine performance characteristics (RPM, CHT, EGT, Knock, etc.) were essentially identical for all tests regardless of oil concentrations or test duration. The single engine operating problem encountered involved spark plug fouling which will be discussed in detail below. Fuel/oil ratios of either 16:1 or 32:1 were used in all tests. Durations of either 30 net engine running hours (not counting shutdown mode) or 100 net hours were used. No significant wear was observed regardless of the lubricant used, but two small scuff areas appeared at the same location on the piston skirt of Test No. 3 and Test No. 11. Both of these areas appeared to have restored themselves to a low-friction surface. This scuffing occurred on the same engine (No. 3) and may have been characteristic of components of this single machine since these tests were run with two different lubricants. At the end of each test, all engine dimensions were found to be within engine manufacturer's allowable tolerances.

B. Engine Deposits

Significant differences in deposit ratings were observed between lubricant classes. These are reflected in the overall rating (merit) system (see Table 3) and can be summarized as follows:

- The reference oil, AL-6408-L, was run at a fuel/oil ratio of 16:1 for 30 and 100 hours. Overall rating for this lubricant ranged between 99 and 108.

- A MIL-L-2104C lubricant, AL-5185-L, selected for high metallo-organic additive content was tested twice for 30 hours using fuel/oil ratios of 16:1 and 32:1. These rated 102 and 101, respectively.

- AL-4591-L, a dual qualified product under MIL-L-2104C and MIL-L-46152, was tested at a fuel/oil ratio of 16:1 for 30 hours and rated 100.

- Six lubricants qualified under MIL-L-22851B were tested at fuel/oil ratios of 16:1 or 32:1 (Test No. 17) using test durations of 30 or 100 hours (Test No. 18). These lubricants rated between 78 and 85. No significant total rating differences attributable to oil concentrations or test duration were observed.

- A single MIL-L-23699B synthetic lubricant, AL-6682-L, was tested for 30 hours with a fuel/oil ratio of 16:1 and rated 93.

- Two MIL-L-46152 lubricants, AL-5680-L (synthetic base) and AL-6358-L (mineral base), were also selected for their high metallo-organic additive content and were run at fuel/oil ratios of 16:1 for 30 hours. These rated 103 and 104.

The range of merit ratings for the MIL-L-22851B lubricants is considered to be significantly lower in merit rating than all other lubricants tested, primarily due to heavier engine deposits. However, this entire collection of lubricants operated satisfactorily under the stated test conditions with the single exception of spark plug fouling.

C. Spark Plug Fouling

Spark plug fouling results can be seen in Table 4. These can be summarized as:

- The reference oil operated in two cases for 30 hours (Tests Nos. 1 and 11) with no fouled plugs. In a third case (Test No. 19) it was operated for 100 hours, again with no fouled plugs. These three tests were run with 16:1 fuel/oil ratios. Piston and plug for Test 19 are shown in Figure 3(a).

- Three tests (Nos. 12, 15 and 20) using MIL-L-2104C lubricants (metallo-organic additives) resulted in at least one fouled plug prior to 30 hours. Test Nos. 12 and 15 were run at 16:1 fuel/oil ratio, but in Test No. 20 the same lubricant as in Test No. 12 was used with concentration decreased to 32:1. Plug fouling still occurred.

- Three of the six MIL-L-22851B lubricants tested for 30 hours at 16:1 fuel/oil ratio, operated for the entire 30 hours without spark plug fouling (Tests Nos. 5, 7, and 10). The three other lubricants (Tests Nos. 8, 9 and 14) fouled at least one plug during that time. One of the three former oils (Test No. 7) which had showed no plug fouling to 30 hours, was operated in a subsequent test for 100 hours. In this test (No. 18) no plug fouling was observed until the 50th hour, but four plugs were required from 50 to 100 hours. Piston and a typical fouled plug are shown in Figure 3(b). In another case (Test No. 14) with a lubricant which had fouled plugs at 16:1 fuel/oil ratio, a second test (No. 17) was run with lubricant concentration decreased to 32:1. This particular oil (AL-6674-L) had required three spark plugs to complete 30 hours at 16:1. Changing to 32:1 resulted in a 30-hour test with no fouled plugs.

- The single MIL-L-23699B synthetic lubricant fouled two plugs within the 30-hour duration at 16:1 fuel/oil ratio.

Deposit scrapings were taken from representative plugs and analyzed for metals content using X-ray fluorescence. Results can be generalized as:

- Spark plugs which fouled with ashless lubricants (MIL-L-22851B) were coated with deposits of a carbonaceous nature (i.e., sooty), and having no metallic content other than insignificant traces of lead.

- Those plugs which fouled with lubricants having metallo-organic additive packages (MIL-L-2104C, MIL-L-46152, MIL-L-23699B) showed, in addition to lead, significant metallic deposits corresponding to those in a lubricants additive package (i.e., Zn, Ca, P, Ba).

The *number of plugs* fouled for a given test may *possibly* be a relative index of problems to be anticipated for RPV engine ignition systems, but no extrapolations or correlations should be attempted regarding spark plug endurance in a true field environment because repeatability of spark plug endurance has not been well enough defined in this program.

(a) Test 19: Reference Oil (AL-6408-L)
100 hours
16:1 fuel/oil ratio
265°F CHT @ 7,000 RPM
98.0 Merit Rating
No Fouled Plugs

(b) Test 18: MIL-L-22851B, Type III Oil (AL-6534-L)
100 hours
16:1 fuel/oil ratio
265° CHT @ 7,000 RPM
77.6 Merit Rating
4 Fouled Plugs

FIGURE 3. ENGINE COMPONENTS FOR LOW-CHT TESTS

V. HIGH TEMPERATURE TESTS WITH CD IGNITION

As mentioned previously, the McCulloch MC101 engine in modified form has been used quite successfully as the powerplant for the Aquila RPV. In the course of this present program, certain design parameters for second-generation RPV powerplants were identified by cognizant Army engineering agencies. Among these were:

- Use of a capacitive discharge ignition system
- Anticipated cylinder head temperatures in excess of 450°F.

In an effort to simulate these parameters, MC101B engines at AFLRL were adapted to a capacitive discharge system* and cooling air was restricted to achieve a 450°F CHT at 7000 rpm as measured by a thermocouple embedded in the cylinder head. It was hoped that capacitive discharge ignition might eliminate the spark plug fouling problem discussed above, and that operation at higher temperatures would provide preliminary information on any other lubrication problems to be expected in second-generation RPV engines. Three tests were run using the same test cycle as discussed previously. Results are presented in Table 7. Test 21 utilized AL-5185-L, the MIL-L-2104C lubricant described in Table 2. This oil was selected because its particular additive package makeup was formulated to withstand the higher temperatures typical of diesel engine operation. Engine operation for this test was routine for 15 hours at which point a spark plug was fouled. A new spark plug was installed, and the engine operated satisfactorily until the 26th hour at which time power was lost and could not be restored. It should be

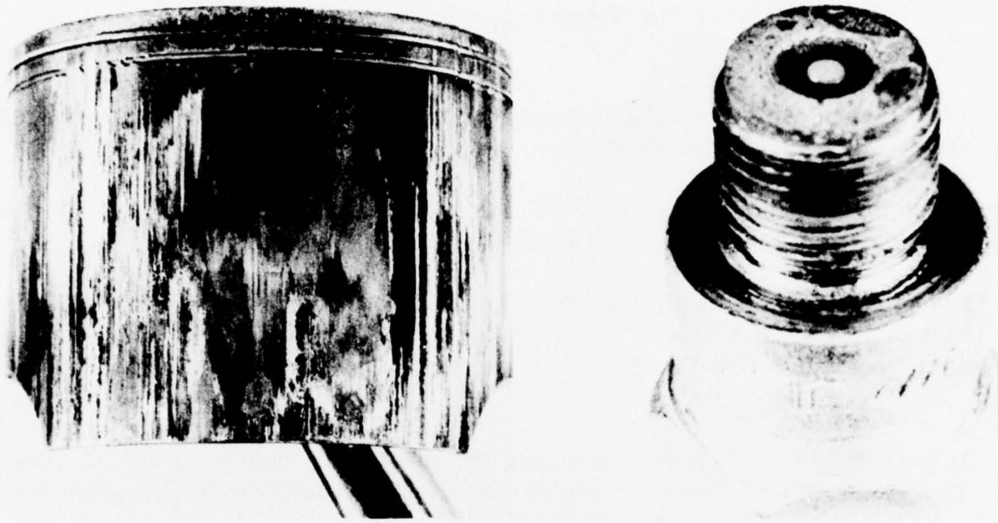
TABLE 7. TESTS RUN WITH C.D. IGNITION AT INCREASED CYLINDER HEAD TEMPERATURE

Specification	MIL-L-2104C	Ref. Oil	
Test No.	21	22	23
AFLRL	AL-5185-L	AL-6408-L	AL-6408-L
Lubricant Description			
Properties			
Viscosity, cSt @ 210°F	12.65	6.47	6.47
Viscosity, cSt @ 100°F	131.5	38.70	38.70
Viscosity Index	96	133	133
Flash Point, °F	455	160	160
Additive Composition, wt %			
Sulfur	0.41	0.12	0.12
Phosphorus	0.09	<0.01	<0.01
Barium	0.04	<0.01	<0.01
Calcium	0.44	<0.01	<0.01
Zinc	0.08	<0.01	<0.01
Sulfated Ash	1.37	0.002	0.002
Merit Rating			
Piston Skirt	4.5	5.5	–
Ring Lands, Crown	6.0	1.8	2.5
Ring Lands, Second	7.0	3.0	2.5
Ring Freedom, Top	9.0	0	1.0
Ring Freedom, Second	8.7	8.5	0
Piston Scuffing	8.0	8.5	5.0
Cylinder Head Deposit	5.2	8.5	8.7
Piston Top Deposit	5.8	7.2	7.6
Top Grove Fill	9.5	–	–
Second Grove Fill	9.5	–	–
Exhaust Port Crossing	7.5	8.5	8.5
Total Merits	*	*	*
Spark Plug Fouling			
(No. of Plugs Fouled)	(1)	(0)	(0)
Fuel/Oil Ratio	32:1	32:1	32:1
Engine No.	2	3	1

*Not meaningful due to catastrophic seizure.

*Delta Products, Inc. – Mark Ten 30KV Capacitive Discharge Ignition System With a Champion UL-77V Spark Plug mentioned that engine operation to this point was normal but that subsequent disassembly of the engine revealed severe cylinder, piston skirt, and ring scoring. Piston and plug for Test 21 are shown in Figure 4(b).

Tests 22 and 23 were duplicates utilizing the BIA/TC-W reference oil (AL-6408-L) used in Tests 1, 11, and 19 as described in Table 2. Here, a different failure mode was encountered: catastrophic seizure. Although no spark plug fouling was identified with this lubricant in either test 22 or 23, engine seizure occurred at 53 hours in Test 22 and 13 hours in Test 23. Subsequent engine disassembly in both cases revealed severely scored cylinder liners, completely seized piston rings, gross evidence of piston skirt/cylinder metal-to-metal contact, and for Test 22 abrupt disintegration of the wrist pin roller bearing. Piston and plug for Test 23 are shown in Figure 4(a). This BIA/TC-W reference oil (AL-6408-L) was utilized in an effort to eliminate spark plug fouling since it had shown excellent performance in Tests 1, 11, and 19 at lower operating temperatures. Although this excellent characteristic was again exhibited even at the higher engine operating temperatures, the ashless dispersant additive package characteristic of this class of oils is apparently not able to operate satisfactorily in this severe environment. It might be noted that a similar experience(1R) occurred at AFLRL in 1974 when evaluating an air-cooled rotary combustion (Wankel) engine with a different (but virtually identical) BIA/TC-W reference lubricant. In this case, catastrophic failure in an extreme high temperature situation occurred repeatedly within a few hours of test initiation.



(a) Test 23: Reference Oil (AL-6408-L)
13 hours
32:1 fuel/oil ratio
450°F CHT @ 7,000 RPM
Merit Rating–not meaningful
No fouled plugs

(b) Test 21: MIL-L-2104C Oil (AL-5185-L)
26 hours
32:1 fuel/oil ratio
450°F CHT @ 7,000 RPM
Merit Rating–not meaningful
1 Fouled Plug

FIGURE 4. ENGINE COMPONENTS FOR HIGH-CHT TESTS

VI. CONCLUSIONS

(1) No class or classes of MIL-specification lubricants are satisfactory for RPV applications on the basis of the data generated in this investigation.

(2) The reference oil used was outstanding in all aspects of the low-CHT phase of this investigation, particularly in engine cleanliness and the total absence of plug fouling.

(3) Spark plug fouling occurred with virtually all military specification lubricants tested. This could result in RPV mission failure, and is of fundamental importance. The observed plug failure rate is considered to be far above that normally acceptable for an Army field weapons system.

(4) Those MIL-specification lubricants containing metallo-organic additives provided cleaner engines than ashless oils; both classes provided adequate lubrication. The heavier deposit levels observed for the ashless oils in the low-CHT testing did not affect *engine* performance. Whether this conclusion would hold for test durations approaching design life of the RPV engine is not known.

(5) Simulation of second-generation RPV engine CHT's of 450°F with capacitive discharge ignition resulted in lubricant failure and consequent severe engine wear or seizure for two lubricants.

VII. RECOMMENDATIONS

(1) If future RPV engine temperatures can be limited to 200°-300°F, serious consideration should be given to utilization of the BIA/TC-W class of lubricants in the RPV program. This would, of course, entail more comprehensive experimental evaluation of this lubricant class. Such a study, however, would seem warranted based upon the excellent performance of the reference lubricant employed in the low-CHT phase of this present program.

(2) Any subsequent experimental lubricant evaluation program should employ both the test cycle and merit rating system employed in this present program. The merit rating system should be further refined to include a *plug fouling index* such as addition of one merit point per hour of running time on the initial plug[1R], or subtraction of 5-10 points from the engine merit rating for each plug replaced in a given test.

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20 October 1977
Contract DAAK-02-73-C-0221