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WADC TECHNICAL REPORT 53-180
AD 016911



# STUDY OF MINIATURE ENGINE-GENERATOR SETS

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*MAY 1953*



**WRIGHT AIR DEVELOPMENT CENTER**

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2159

ERRATA - May 1957

The following addition is applicable to WADC Technical Report 53-180, entitled "Study of Miniature Engine - Generator Sets" and dated May 1953:

FOREWARD

Add the following paragraph "This report is Part I of a series of five parts. The remaining four parts are as follows:

Part II - "Investigation of Engines, Fuels and Lubricants," December 1954

Part III - "Design Procedure for Small, High-Speed DC Generators," March 1956

Part IV - "Investigation of Altitude and Low Temperature Performance; Starting, Cooling Carburetion, Controls Systems; Noise Reduction", October 1956

Part V - "Summary Report: Feasibility" October 1956

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

# FOREWORD

This report was prepared in the Mechanical Engineering Department of The Ohio State University under Contract No. AF 18(600)-192 "Study of Miniature Engine-Generator Sets" with The Ohio State University Research Foundation. The project was initiated, administered, and directed by the equipment laboratory, with Dr. Erwin Naumann acting as project engineer.

Research and Development Order R656-2112-1, "Aircraft Electrical Systems Evaluation - Supplementary Project #1 - Study and Research On Miniature Engine Generator Sets" is applicable to this report.

The report covers work performed during the first contract year. In most cases design and test work discussed herein has not been completed, but the report discusses work in progress.

## ABSTRACT

Progress in the study of the feasibility and the practicability of miniature engine-generator sets as power sources for special applications is discussed and a development program for such equipment is presented. A discussion is included of the test apparatus and instrumentation necessary for evaluating the performance of miniature engine-generator sets and components. Performance curves, design features, and the results of endurance tests are given for typical commercially available miniature two-cycle engines. The design of special experimental engines and components necessary for the fundamental test program is discussed. A comparison is made between the weights and volumes of batteries and engine-generator sets for equal periods of service.

## PUBLICATION REVIEW



FOR THE COMMANDER:

W. T. Harding for
Richard Stolle, Colonel, USAF
Chief, Equipment Laboratory
Directorate of Laboratories.

CONTENTS



ILLUSTRATIONS

Figure



Table

# INTRODUCTION

During the past few years a need has developed for miniature, self-sustained electrical power sources for a wide variety of applications. USAF applications could include power sources for radio and radar sets, paratroop and crash beacons, emergency power sets, remote weather observation stations, etc. The power requirements of interest range from 35 watts to 400 watts, while conceivable applications would necessitate both alternating and direct current with a wide variety of characteristics. Necessary and desirable features of such power sources should include reliability, consistency of performance under extreme environmental conditions, and high power output per unit weight and volume.

Miniature internal combustion engine-generator sets, similar to those of larger capacities now widely used by the armed forces, might be a logical solution for these requirements. There are, however, no such engine-generator sets commercially available at the present time and little design and performance data are available for miniature engines, generators, and components.

The purpose of this study is to determine the present state of development of the components of miniature engine-generator sets and to develop procedures and techniques of design, analysis, and performance testing which will be useful in establishing the feasibility and limitations of such units for certain applications.

The culmination of effort in this study will be the preparation of information concerning the design and performance of miniature engine-generator sets in the form of a manual which will indicate optimum design characteristics for the component parts for a wide variety of design and operating conditions. For given output requirements and range of operating conditions, this manual would be useful in determining not only the relative merits of an engine-generator set in preference to some other power source, but, should it be deemed feasible, the specifications for designing, manufacturing, installing, and operating such a unit.

This report covers the first year of study on this project. It is presented only as an introduction to the problems involved, since no conclusions have been reached yet concerning feasibility or optimum design. Due to the general lack of scientific data and previous work in this field, considerable time during the year was spent in developing test apparatus and instrumentation, as well as in surveying the related literature.

# SECTION I

## SUMMARY

The preliminary phases of the study of miniature engine-generator sets have been completed with the development of the necessary test equipment and techniques, the evaluation of commercial apparatus, and the design of special fundamental test vehicles.

### Test Equipment

An investigation was made to determine the necessary test apparatus and instrumentation for complete evaluation and development of the components of miniature engine-generator sets. Certain commercial equipment was found to be useful and applicable, but the majority of the apparatus required had to be designed specifically for testing the miniature units. Testing techniques were evolved specifically for the high-speed, low-torque components involved.

### Commercial Equipment

A literature survey was made of design, test, and performance data available on miniature engine-generator sets or their components. It was found that a very meager amount of information was available.

Fifteen commercial, miniature, 2-cycle engines were procured for test evaluation. Since these engines were built to power model airplanes, racers, etc., the specific power output was found to be very high, whereas the economy was very poor. The maximum specific power output obtained was 2-1/4 bhp per cu in. displacement and the specific fuel consumption ranged from 2-3/4 to 5 lb per bhp-hr. The speed range of the engines tested was 7,000 rpm to 18,500 rpm. The engines were found to be structurally inadequate for engine-generator applications. Numerous failures of structural components were encountered during dynamometer tests; bearing and other component failures occurred under all test conditions.

Five commercial generators have been procured for evaluation purposes. Two of these generators are three-phase tachometer generators, on which overspeed no-load tests have been made up to 12,000 rpm. The three other units are 115 volt universal motors rated from 1/20 to 1/6 hp. No tests of these units have been performed as yet.

Experimental Designs

It was obvious from the results of tests on commercial engines that special test vehicles and components would have to be developed. A two-cycle test engine has been designed and construction of the first assembly is completed. This unique engine is designed to permit variation of all of the engine design characteristics so that their effect on performance may be studied. Additional components which have been designed are an independent spark ignition breaker system and an experimental airbleed carburetor assembly.

# SECTION II

# TEST APPARATUS AND INSTRUMENTATION

Of primary importance to the investigation of the potentialities of miniature engine-generator sets was the development of adequate test apparatus and instrumentation necessary for complete testing of the components involved. A preliminary survey of the requirements for such a test program, and of the commercial availability of the required apparatus, indicated that many special items would have to be developed and that the standard test equipment which could be used would have to be modified to meet the unique conditions of this project.

## Equipment for Atmospheric Testing

Tests of components under normal laboratory conditions of temperature and pressure required development of the following equipment.

1. Power Measurement

The first major item of apparatus considered was a dynamometer for measuring the power output of miniature engines as well as the power absorbed by miniature generators. Many different types of designs and principles for torque measurement were considered (see references 1, 2, 5, 6, 10, 13, 14, 16 and 27). However, the cradled direct-current electric dynamometer was considered sensitive enough for the torque measurements required. This type of unit is capable of operation as a generator for power absorption as well as a motor for driving other machines. Since no such unit of the required size was available commercially, a special dynamometer was designed, constructed, and tested, using a Westinghouse Universal Motor #172162-E (rated at 1/3 hp at 8000 rpm, 115 volts). One of three such dynamometers built is shown in Figure 1. It has been operated successfully at speeds greater than 20,000 rpm and has been used to absorb up to 1-1/3 hp as a generator and to deliver 2/3 hp as a motor. The dynamometer was operated from a 250-volt dc source through a standard type of speed and load control circuit.

Important components of the power-measuring equipment include speed- and torque-indicating systems. The torque values are relatively low because of the small power outputs and the high rotative speeds needed to keep the engine and generator sizes to a minimum. A hydraulically balanced torque measuring system was selected which maintained a constant positioning of

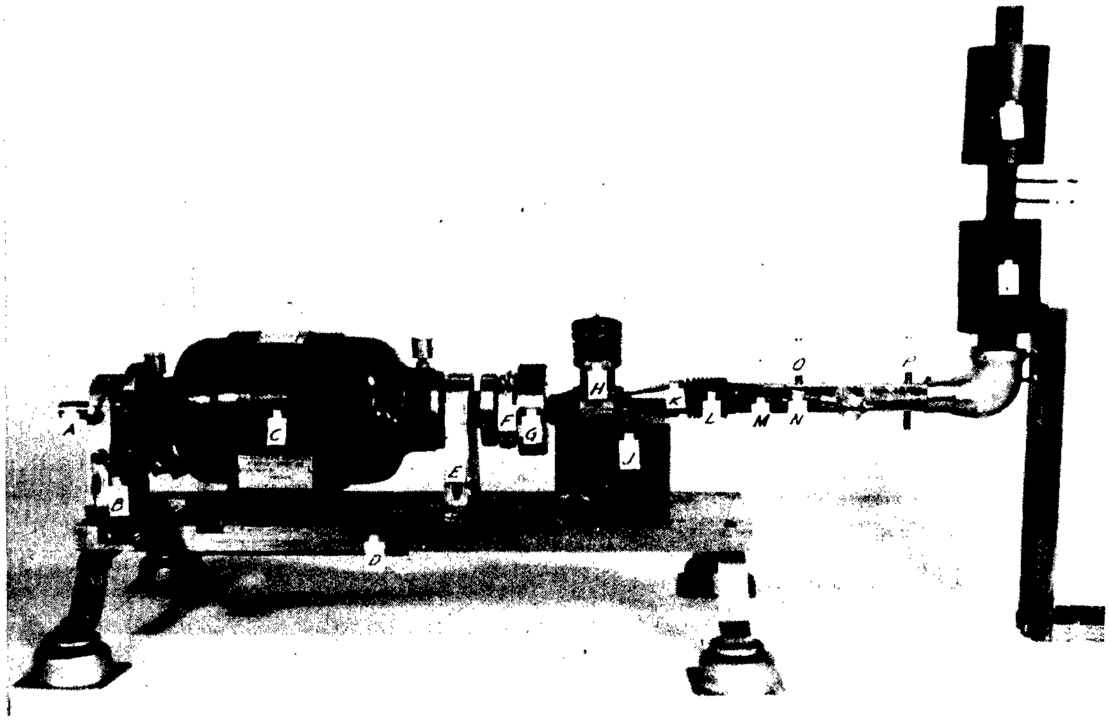



Figure 1. Dynamometer and Engine E with Experimental Carburetor

A. Mount for Spark Ignition Breaker System
B. Electrical Contact Board
C. Motor Housing
D. Bed Plate
E. Cradle Support
F. Morflex Flexible Coupling - Floating Center
G. Flywheel
H. Engine E
J. Engine Mounting Block
K. Carburetor Adaptor
L. Flexible Metal Bellows
M. Carburetor Body
N. Fuel Control Needle Valve
O. Throttle Valve
P. Choke Valve
Q. Balance Chamber
R. Total and Static Pressure Probes
S. Silencer

the dynamometer housing. The torque measurement was indicated on a manometer connected to the hydraulic balance pressure. The system was calibrated by applying known static torques to the motor casing. This system permits a wide range of torque measuring capacities and sensitivities, depending on the length of dynamometer lever arm, the hydraulic piston area, and the specific gravity of the indicating fluid. Static torques were reproducible within 2 per cent and were sensitive to torque changes of less than 2 per cent. It is felt that dynamic torque measurements were at least as accurate as for static conditions, because when the equipment was in operation the vibrations tended to make the hydraulic torque scale less sluggish in seeking equilibrium.

The speed-measuring device cannot be coupled to the dynamometer shaft because of the low torques involved. For this reason a Hewlett-Packard Model 505A electronic tachometer was employed. The engine flywheel, Figure 1-G, was used to cycle the photoelectric tachometer head. One half of the periphery of the flywheel was chrome plated to reflect light and the other half was painted a dull black; however, the reading accuracy of the instrument in the higher speed ranges used, estimated to be ±5 per cent, was not as good as desired. A much greater sensitivity and accuracy could be obtained with a Berkeley Model 554 EPUT meter, actuated by the impulse from a similar photoelectric tachometer head.

2. Temperature Measurement

Numerous and varied engine and generator temperature measurements were required during tests. Both a Brown "Electronic", indicating, automatic-balancing potentiometer and a Leeds and Northrup Micromax six-channel recording potentiometer were used for temperature measurements, using standard copper-constantan, iron-constantan, and chromel-alumel thermocouples. The accuracy of these instruments was within the desired 2 per cent limits, and the temperature ranges encountered were well within the ranges of the thermocouples used.

3. Miscellaneous Engine Test Apparatus

Certain test apparatus and instrumentation peculiar to miniature engine testing was required. As the need arose this equipment was developed to expedite the test program and to improve the accuracy and reproducibility of the results.

A fuel-measuring system which would supply clean fuel at any desired constant head to the needle valve was necessary. The fuel was supplied through a strainer-equipped float chamber, which could be raised or lowered to control the fuel head. The

float chamber was supplied either from a large capacity tank or from a calibrated burette which was used for measuring flow per unit of time. Calibration of this apparatus indicated that a constant fuel head was maintained over the range of flow rates required.

It was necessary to measure engine air consumption in order to compute volumetric efficiencies, fuel-air ratios, etc. Accurate air measurement is difficult to achieve if excessive pressure losses preceding the engine air intake are to be avoided. Several methods were investigated, and the most satisfactory were found to be either a direct-connected rotometer or a velocity head measurement obtained with total and static pressure probes in the intake passage.

Since the engines tested were designed for air cooling, equipment was developed for measuring the cooling air which was supplied to a cooling shroud placed around the engine cylinder. The quantity of cooling air was controlled by means of a pressure reducing valve and the flow rate was measured using a calibrated orifice. The air flow was controlled so as to maintain constant cylinder head temperature throughout a particular test.

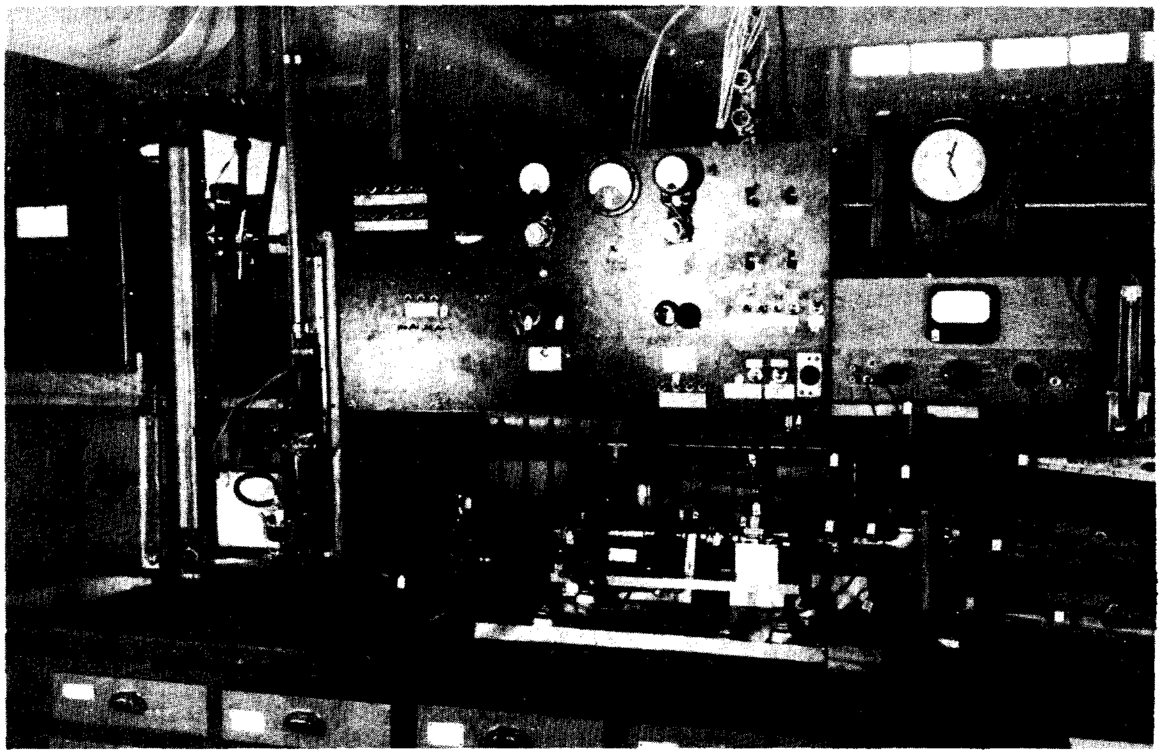


Figure 2. Dynamometer Test Installation

Figure 2 shows the installation of the engine test apparatus. A more complete description of the design considerations, construction details, and calibration techniques applicable to the test apparatus is available in Reference 18, which was prepared in collaboration with this study.

4. Propeller Loading

In some cases it was found desirable to load and test the engines with propellers rather than a dynamometer. The power absorption at various speeds for different size propellers was obtained by driving the propellers with a dynamometer. A series of propellers was calibrated so that different engine speeds could be attained when operating at full throttle by switching from one propeller to another. Power absorption of a given propeller was found to be reproducible within about 10 per cent for the variations in atmospheric conditions encountered in the laboratory from day to day.

5. Generator Test Instruments

Instruments required for measuring the electrical output of the generators were available on the commercial market. They include dc voltmeters and ammeters and 60-cycle, 400-cycle, and 800-cycle ac voltmeters, ammeters, and wattmeters.

## Testing at Low Temperatures and Pressures

An altitude- and cold-cabinet has been selected which will permit testing of engine-generator sets and all components at widely varying temperatures and pressures. The test chamber will be large enough that the entire engine-generator set or the engine and dynamometer, and all necessary instrumentation can be placed inside. Tests from -65°F to 150°F may be required, at altitudes from sea level to 40,000 ft. Fresh air will be admitted to the chamber continually to replace the air consumed by the engine and withdrawn from the chamber as exhaust gases. General performance of component parts at low pressures and temperatures will be studied, and special emphasis will be placed on starting problems.

# SECTION III

# COMMERCIAL EQUIPMENT

A survey of the present commercial equipment which might be applicable to or modified for miniature engine-generator sets was made. A discussion of the evaluation testing thus far performed with some of this equipment is given in this section.

## Commercial Engines

### 1. General Description

The only miniature engines found on the commercial market in the size range desired were model airplane engines. These engines were air-cooled, three- or four-port, cross-scavenged, crankcase-compression, two-cycle engines. Ignition systems employed were either hot point (glow plug) or spark.

### 2. Engine Design Features

Fifteen different makes and models of engines were purchased for evaluation. Table I lists the design features employed on these engines, together with the manufacturer's ratings. The displacements ranged from 0.29 cu in. to 1.0 cu in., with speeds from 7000 rpm to 18,500 rpm, and power ratings up to 1-1/2 hp. The stroke-to-bore ratio ranged from 0.74 to 1.06, and the connecting rod length-to-crank radius (l/r) from 2.9 to 4.1. Crankcase breathing was controlled by either a rotary valve driven by the crank pin or by a hollow crankshaft port, with the exception of engine I, which used a piston controlled crankcase port. The computed brake mean effective pressures corresponding to the manufacturer's ratings ranged from 35 psi to 62 psi. The weight-to-power ratio of the engines ranged from 0.58 to 1.39 lb per rated hp.

### 3. Construction Details

Before criticizing construction of these engines, it should be noted that they were built to sell on the model airplane hobby market. Considering this restricted application and the retail price range of $8 to $35, they were found to be of surprisingly good quality. However, every engine tested fell far short, in nearly every detail, of even the minimum requirements for engine-generator applications.

In most cases the major components of the engines were made of aluminum die-castings, which allows very low cost pro-

TABLE I. COMMERCIAL ENGINE DESIGN FEATURES AND RATINGS

| Engine | Ignition | Displacement cu in. | Stroke/Bore | l/r | Piston Rings | Main Bearing | Crank Bearing | Crankcase Breathing | Timing: Exhaust Deg.Atc. | Timing: Transfer Deg.Atc. | Timing: Crankcase Open Deg. Btc. | Timing: Crankcase Close Deg. Atc. | Manufacturer's Rating: H.P. | Manufacturer's Rating: RPM | Manufacturer's Rating: BMEP | Weight, oz. | Weight, lb/hp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | G | 0.296 | 0.854 | 3.46 | None | R | P | HCS | 112 | 117 | 120 | 34 | 0.40 | 10,200 | 52.5 | 5.5 | 0.85 |
| B | G | 0.287 | 0.867 | 4.08 | 2 | B | P | RV | 110 | 122 | 145 | 45 | 0.40 | 13,500 | 40.9 | 6.6 | 1.02 |
| C | S | 0.310 | 0.900 | 3.98 | None | B | P | RV | 115 | 124 | 160 | 34 | 0.39 | 13,000 | 37.8 | 7.2 | 1.17 |
| D | G | 0.297 | 0.996 | 3.82 | None | P | P | HCS | 110 | 117 | 163 | 46 | 0.32 | 11,500 | 36.5 | 7.0 | 1.39 |
| E | G | 0.295 | 0.909 | 3.69 | 2 | 2-B | P | RV | 109 | 123 | 117 | 48 | 0.75 | 18,500 | 54.4 | 7.5 | 0.62 |
| F | G | 0.296 | 0.900 | 3.73 | 2 | B | P | HCS | 108 | 119 | 118 | 47 | 0.50 | 13,500 | 49.6 | 7.6 | 0.95 |
| G | G | 0.299 | 0.950 | 3.57 | None | P | P | HCS | 110 | 126 | 125 | 38 | 0.50 | 11,000 | 60.2 | 5.8 | 0.72 |
| H | G | 0.602 | 0.986 | 3.29 | None | 2-B | P | RV | 110 | 120 | 130 | 70 | 1.12 | 12,000 | 61.7 | 10.5 | 0.58 |
| I | S | 0.998 | 1.058 | 3.83 | 2 | B | P | PP | 120 | 129 | 47 | 47 | 0.69 | 7,750 | 35.2 | 14.0 | 1.27 |
| J | S-G | 0.600 | 0.918 | 3.73 | 2 | 2-B | P | RV | 115 | 120 | 125 | 75 | 1.32 | 17,000 | 51.2 | 13.8 | 0.65 |
| K | S-G | 0.621 | 0.949 | 3.36 | None | R | P | HCS | 110 | 120 | 150 | 55 | 0.50 | 9,000 | 35.4 | 9.6 | 1.20 |
| N | G | 0.298 | 0.743 | | 2 | 2-B | P | RV | 109 | 121 | 235 | 57 | 0.75 | 17,500 | 57.0 | 6.5 | 1.17 |
| O | S-G | 0.607 | 0.739 | 3.66 | 2 | 2-B | N | RV | 106 | 118 | 127 | 58 | 1.50 | 16,500 | 59.3 | 14.0 | 0.58 |
| P | S-G | 0.607 | 0.931 | 2.86 | 2 | B | P | RV | 110 | 122 | 115 | 39 | | | | 14.0 | |
| Q | G | 0.292 | 0.919 | 3.61 | None | P | P | HCS | 107 | 144 | 149 | 34 | 0.50 | 15,000 | 45.2 | 7.0 | 0.87 |

Key to Symbols:

Crankcase Breathing
- HCS - Hollow Crankshaft
- RV - Rotary Valve
- PP - Piston Port

Crank Bearing
- P - Plain
- N - Needle

Main Bearing
- R - Roller
- B - Ball
- P - Plain

Ignition
- G - Glow
- S - Spark

duction of intricate parts. The strength and endurance of these parts, though, were found to be inadequate, particularly at the elevated temperatures occurring in some parts during prolonged engine operation. The material, machining, and heat-treatment employed on the steel parts, such as the crankshaft, cylinder liner, and piston pin, were found to be considerably better. Machining tolerances were, in most cases, found to be just tolerable, and occasionally they were very poor. The mounting flanges usually were poorly aligned. The center lines of the crankshaft and the cylinder bore were not always perpendicular, and some of them did not intersect. In some cases alignment of the fuel control needle valve assemblies was so poor that rework was required before fuel control could be attained. The arrangement of the engines was, in general, good from a maintenance accessibility standpoint, but no means were provided for positive locking of fastenings. The sealing of joints against leakage was in some cases not adequate.

The machining of plain bearings employed as connecting rod or main bearings was with few exceptions extremely poor. Clearances were excessive even before the engines were operated. In some designs provision was made for taking thrust on the crankshaft only in one direction.

4. Description of Tests

Engine tests were conducted using either dynamometer or propeller loading. Figure 2 shows a typical dynamometer test installation. The dynamometer was used as a motor to start the engine and then was switched to function as a generator to provide the necessary load. All tests were made at full throttle, so that engine speed was controlled by the load on the dynamometer. A standard type of field and armature circuit speed control was used, which permitted regulation of the speed and load while maintaining carburetor adjustments for optimum speed and torque. An iron-constantan thermocouple attached to the spark or glow plug gasket was used during all tests to indicate the cylinder head temperature. This temperature was maintained constant during each test run by controlling the airflow through the cylinder cooling shroud.

After the engine speed and temperatures were stabilized at each setting, a series of simultaneous speed and torque readings were taken while the various engine and exhaust gas temperatures were observed, fuel consumption taken and all data recorded. Immediately following the performance test, the engine was motored to obtain the friction horsepower over the desired speed range, using the same carburetion settings. It should be noted that with the air-cooled, crankcase-scavenged, two-cycle engine it is impossible to maintain normal operating tempera-

tures during friction horsepower tests because it is necessary to maintain fuel flow to provide adequate engine lubrication.

For most endurance tests and for performance testing of engines which were not sufficiently rugged to withstand the more rigorous dynamometer tests, it was convenient to use a propeller to load the engine. Figure 3 shows a typical propeller test installation. A safety shield around the propeller was used during tests but is not shown in the photograph. The tests were conducted in a manner similar to the dynamometer tests, except that the engines were started by means of an electric starting motor equipped with a flexible shaft and a dog to engage the propeller or the speed measuring disc mounted in front of the propeller.

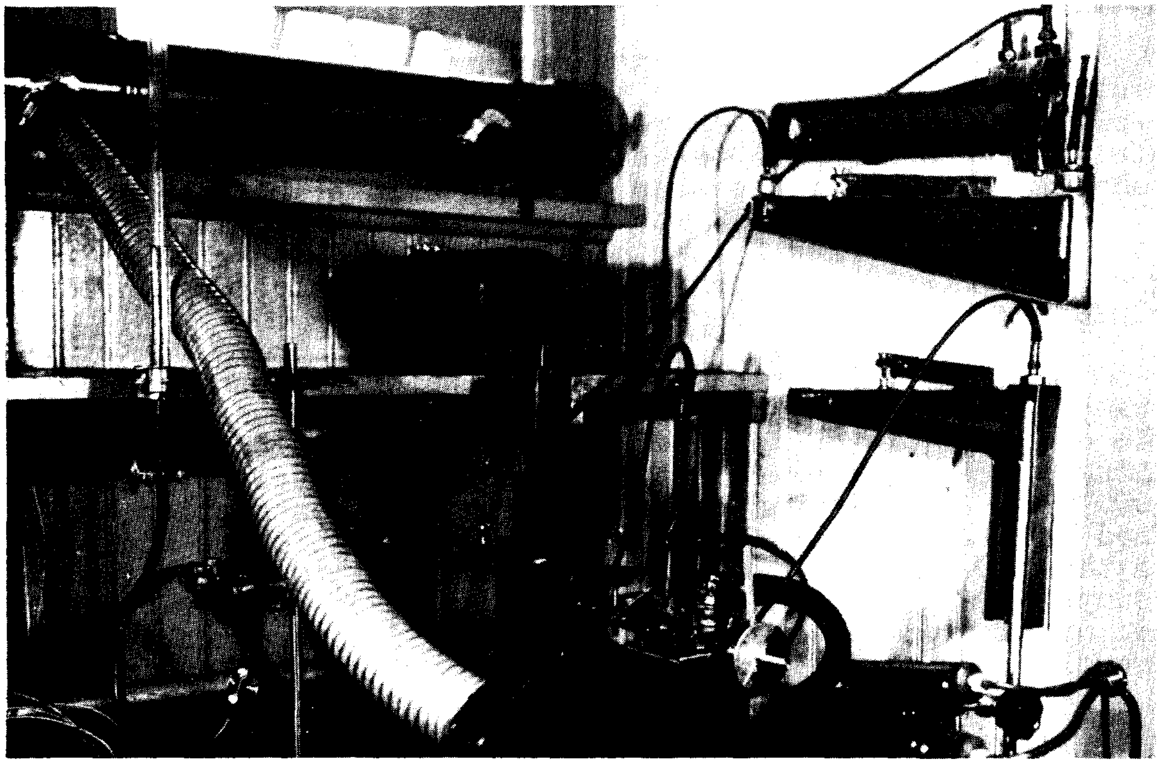


Figure 3. Propeller Test Installation Showing Engine E and Experimental Carburetor

5. Engine Performance

Figures 4 through 10 are the results of the performance tests of commercial engines to date. On performance curves, data points are plotted for brake horsepower, friction horsepower, and brake specific fuel consumption; whereas curves for torque, me-

chanical efficiency, and brake mean effective pressure are computed from the above curves. With the exception of the brake specific fuel consumption data, all data are corrected to standard conditions of dry air at 14.7 psia and 59°F. Standard SAE Gasoline Engine Test Code practices were used for all computations.

The performance curves are useful primarily to establish the general order of magnitude of the various performance parameters, since insufficient data have been obtained to permit evaluation of the numerous design features. This lack of experimental data results from the fact that very limited tests could be performed with the engines before failures occurred. Certain types of engines and replacement parts were difficult to acquire because of limited production. This was particularly true for the larger and better constructed engines.

The length of test runs required to obtain performance curves varied from 20 minutes to 1 hour. All engines were run-in for 60 to 100 minutes prior to performance testing. Only two fuels were used in these tests. Fuel #1 was 80 per cent methyl alcohol and 20 per cent castor oil with a lower heating value of 11,243 Btu per lb; fuel #2 was 67 per cent methyl alcohol, 8 per cent nitromethane, and 25 per cent castor oil with a lower heating value of 11,109 Btu per lb. The heating values of the fuels include the heating value of castor oil.

Figure 4 illustrates the results of the performance tests on Engine J. Further tests of this engine were not possible due to a piston failure, discussed in Section III 6. The maximum brake horsepower obtained was approximately 0.9 at 13,000 rpm. The minimum brake specific fuel consumption obtained was 3.75 lb per bhp-hr at 13,500 rpm, which is equivalent to a thermal efficiency of 5.45 per cent. Minimum specific fuel consumption was achieved at speeds equal to or greater than the speed of maximum power with all engines. A discussion of the extremely high values for specific fuel consumption and means for increasing efficiency is presented later in this report.

Figure 5 depicts the performance of Engine O, before failure of the crankcase. This engine produced the highest power output of all engines tested, 1.35 hp at 15,000 rpm. As with all other engines tested, however, this model never produced the manufacturer's rated power. Either the manufacturers overrate their products, or the ratings are quoted for unusual fuels and operating conditions.

Figures 6 through 9 are performance data obtained from test of Engine P, which proved to be one of the most durable models. It accumulated considerable running time before the

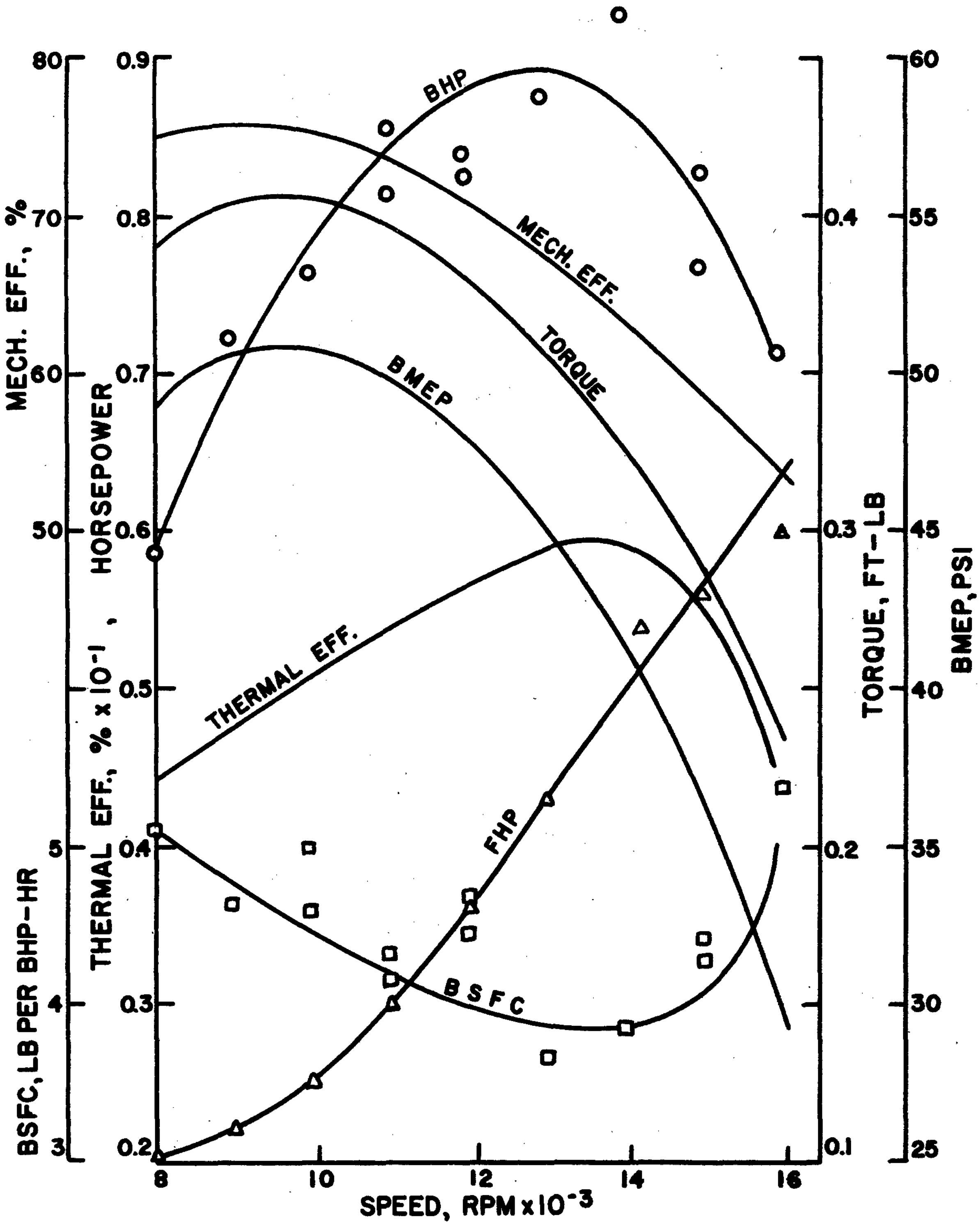



Figure 4. Performance Curves for Engine J; 400° F Cylinder Head Temperature, No. 1 Fuel.

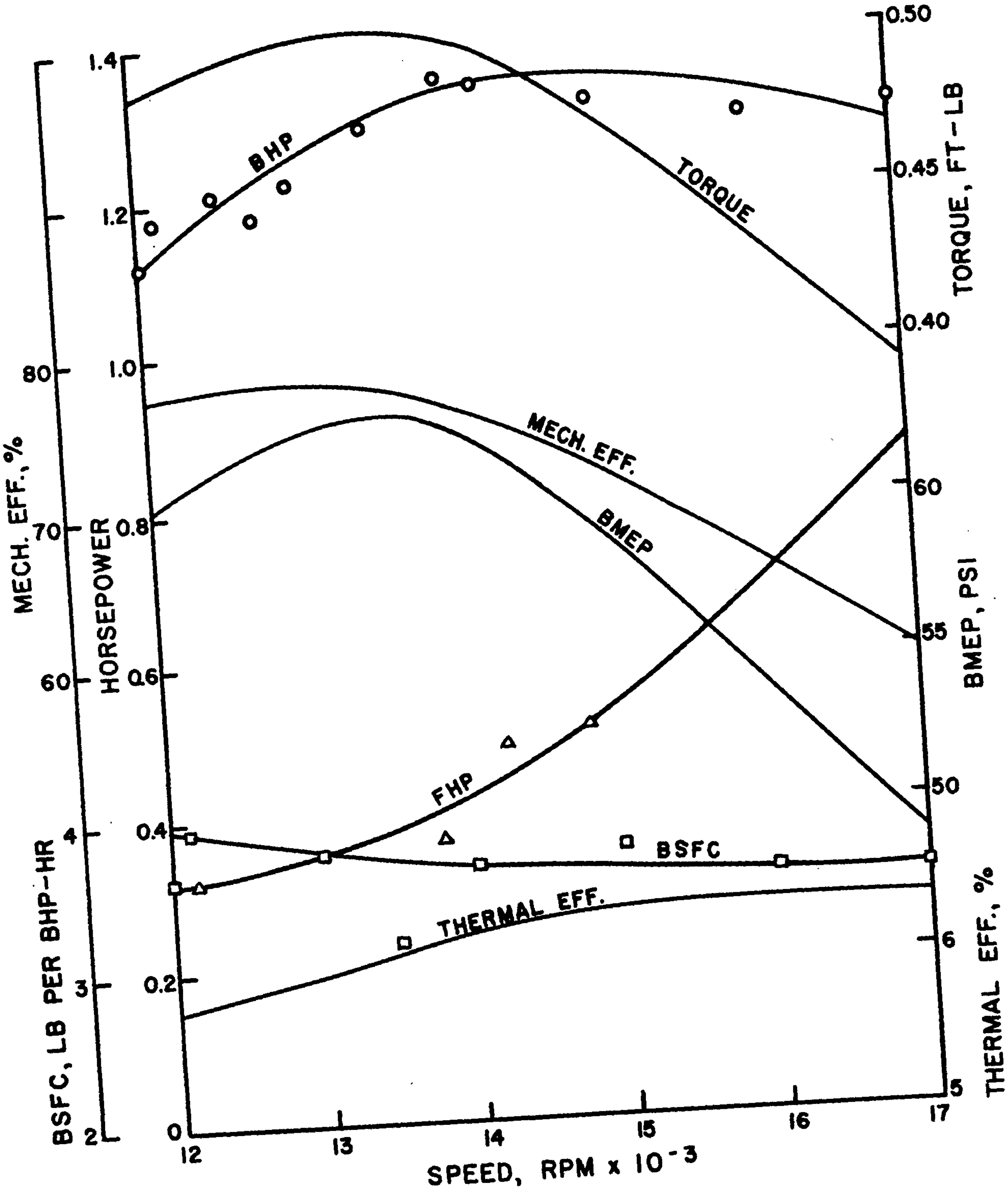



Figure 5. Performance Curves for Engine O; 400° F Cylinder Head Temperature, No. 1 Fuel.

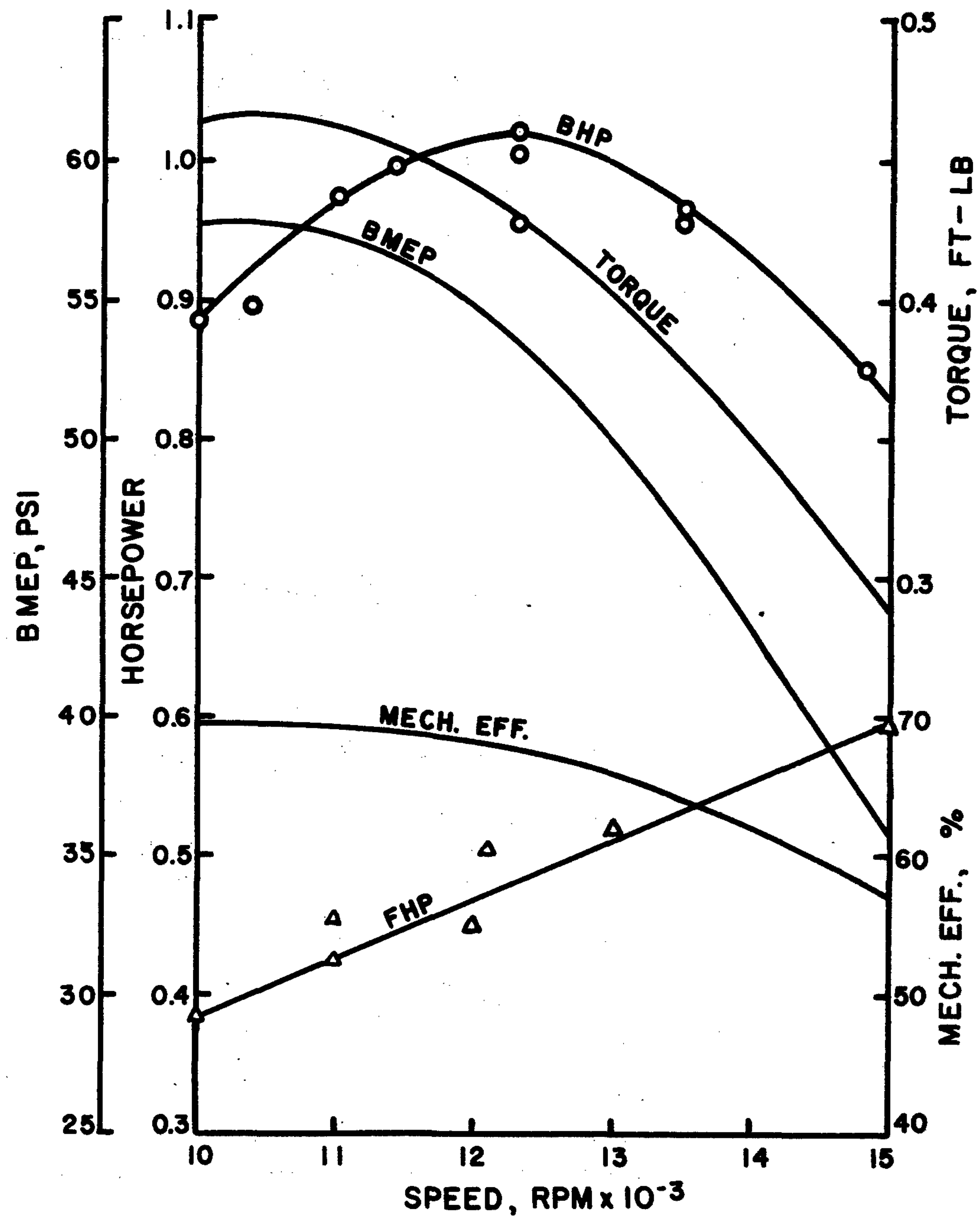



Figure 6. Performance Curves for Engine P; 400° F Cylinder Head Temperature, No. 2 Fuel.

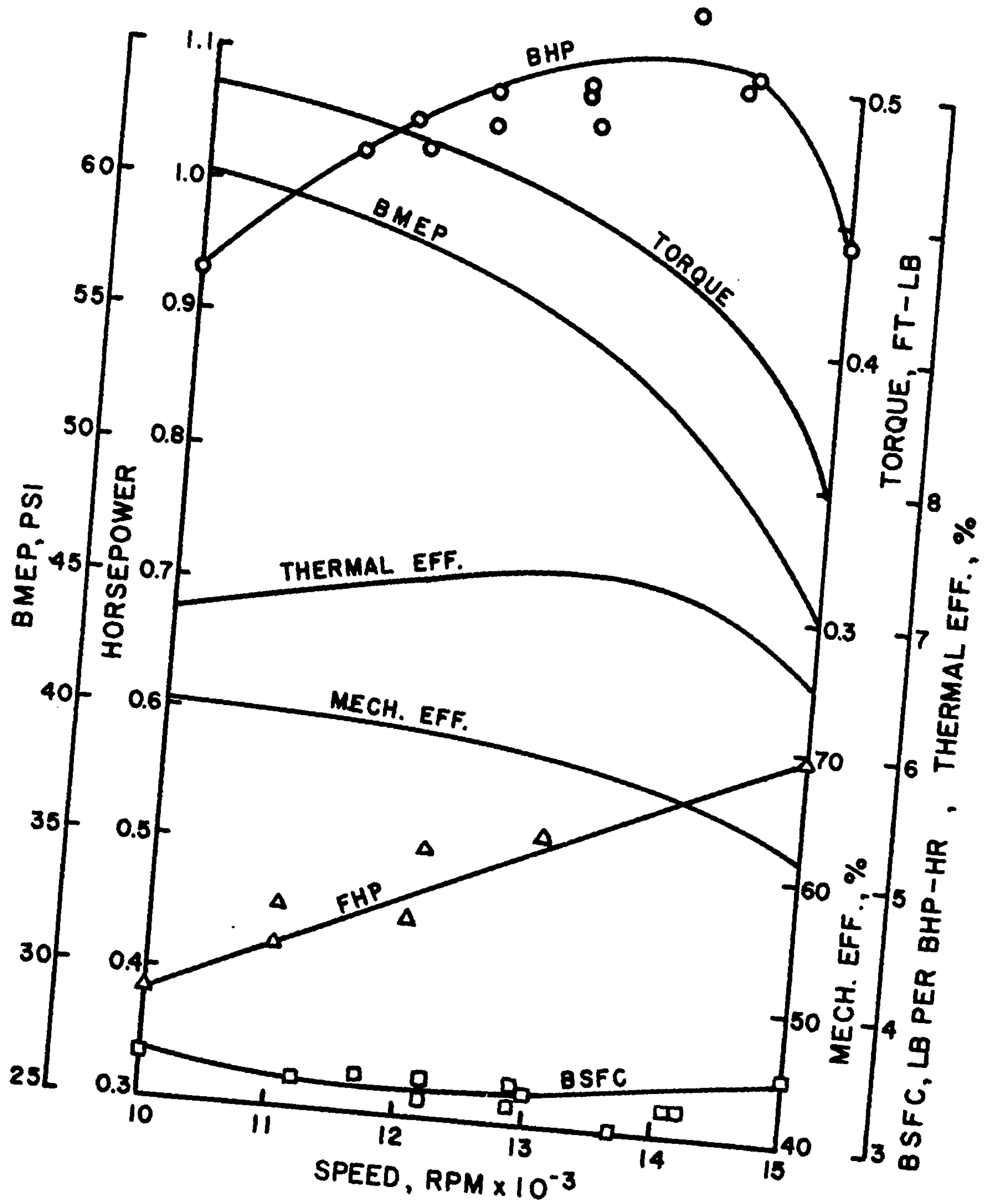



Figure 7. Performance Curves for Engine P; 400° F Cylinder Head Temperature, No. 2 Fuel.

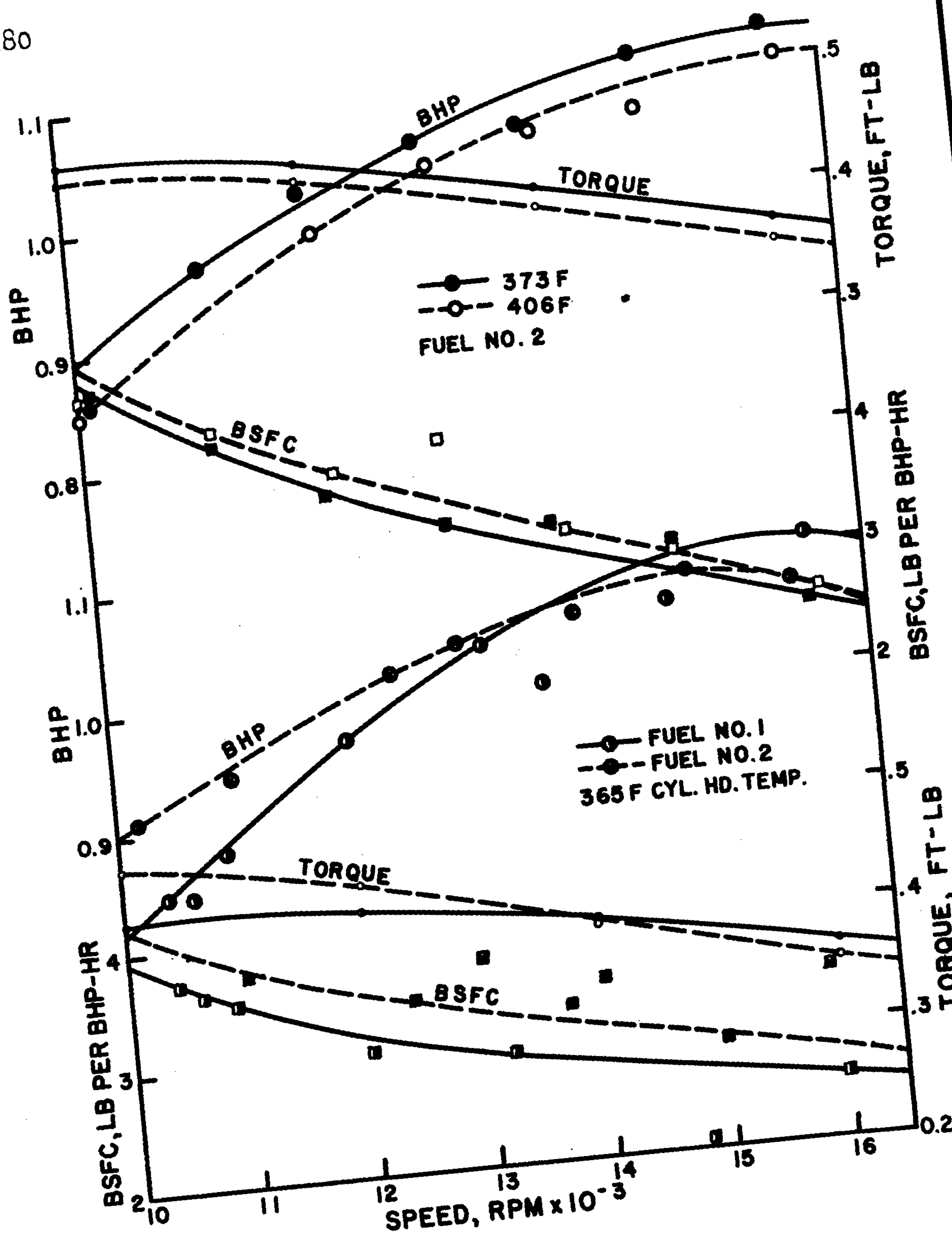



Figure 8. Performance Curves for Engine P; Effects of Cylinder Head Temperature and Fuels.

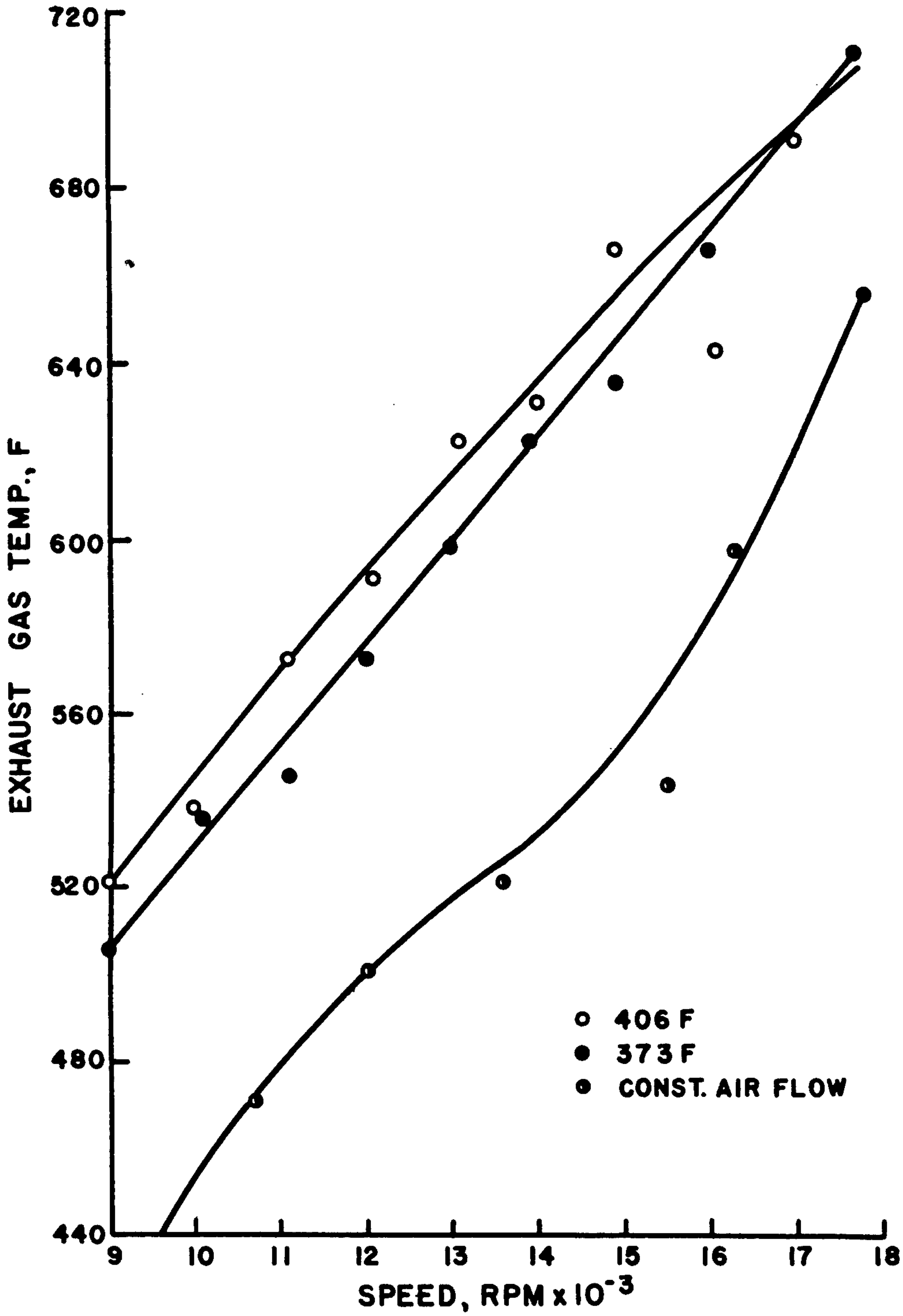



Figure 9. Effect of Engine Speed on Exhaust Gas Temperatures for Engine P.

connecting rod broke at 17,000 rpm. A comparison of the test results of this engine with the operating conditions illustrates graphically one of the major difficulties encountered to date with the tests, namely, erratic performance. For example, a comparison of Figures 6 and 7 illustrates this. These tests were performed on successive days with a total running time for both days of one hour. All conditions were duplicated as closely as possible, except barometric pressure and humidity. In the data for Figure 6, the barometer reading was 28.81 in. Hg, and the relative humidity was 17 per cent; and for Figure 7, the barometer reading was 29.17 in. Hg, and the relative humidity was 25 per cent. The room temperature was the same both days. The reason for the difference in performance for the two days is not explained, but there are numerous factors which could contribute to the difference in performance. Since the data are corrected to dry air conditions at standard pressure and temperature, the differences in humidity and pressure on the two days should not affect the corrected power. However, accuracy of the humidity correction is questionable, since it is known that expert operators of engines of this type at competitive racing events mix different fuels for optimum performance under different humidity conditions. Unfortunately a friction horsepower test was obtained only on the first of the two test days, thus making a comparison of the friction horsepower for the two days impossible. Differences in piston ring "seating" and therefore compression could, however, contribute to different performance characteristics. Another item to consider is carburetor adjustment technique. Throughout the testing of all engines carburetion adjustment proved to be the most critical and erratic factor in the tests. It was shown time and again that minute changes in carburetor adjustment could produce greater changes in results than the total of all other variables. For example, it was found that after deliberately changing the carburetor setting from an optimum point, the optimum could not necessarily be re-established by readjustment of the carburetor.

The foregoing discussion casts doubt then as to the validity of the curves shown in Figure 8. These curves show variations in performance of Engine P for two different cylinder head temperatures and the two different fuels. It was found, however, that operation at cylinder head temperatures of 450°F and above led to a progressive tendency toward seizure in this particular engine, which was undoubtedly caused by inadequate piston cooling and lubrication at the higher temperatures.

Figure 9 illustrates the variation of exhaust gas temperature with engine speed for different cylinder head temperatures. The exhaust gas temperature increased with speed, since there was less time for complete burning in the cylinder and the burning continued later in the cycle; thus making it impos-

sible to extract as great a percentage of work from the expanding gases.

Figure 10 shows the only dynamometer performance curve thus far obtained for a 0.29 cu in. displacement engine. Other engines of this size on which dynamometer tests were attempted failed structurally before a complete test could be achieved. This engine showed the same general type of results and trends as discussed for the 0.6 cu in. displacement engines.

A preliminary study of engine air consumption on 0.29 cu in. displacement engines indicated that: (a) at the lowest engine operating speeds possible (9,000 to 10,000 rpm), the volumetric air consumption per revolution equaled approximately 150 per cent of the "full stroke" piston displacement; (b) the volumetric efficiency dropped to a minimum value of around 88 per cent between 11,000 and 13,000 rpm; and (c) as the engine speed continued to increase the volumetric efficiency increased to approximately 110 per cent between 18,000 and 19,000 rpm. Since the crankcase breathing, which determines the air consumption of the engine, is controlled by the "full stroke" piston displacement, the values for volumetric efficiency greater than 100 per cent can be due only to (1) the dynamic resonance of the intake- engine- and exhaust system, and (2) the inaccuracies of air measurement resulting from the pulsating character of the air flow. The intake system consisted of a 20 in. Rotometer and a 24 in. long entrance duct from the rotometer to the engine. The exhaust system, on the other hand, consisted only of a short stack, 1/2 in. in length. These results indicate that a large percentage of the mixture was being lost directly out the exhaust port without entering into the combustion cycle. This loss of unburned mixture explained the relatively low exhaust gas temperatures and was an important factor in the exorbitantly high specific fuel consumptions. A large engine breathing capacity is necessary to attain complete scavenging of the cylinder for maximum power output per unit displacement volume, which probably is justifiable for model aircraft applications where the penalty of high fuel consumption is not important.

It should be possible to reduce the specific fuel consumption of miniature engines considerably, possibly to values less than 1.0 lb per bhp-hr for hydrocarbon fuels (References 1 and 17). With cross-scavenged engines a considerable portion of the fuel will always be lost through the exhaust port, but by better proportioning of the crankcase volume, porting arrangement, and port timing a significant decrease in the fuel waste could be obtained. Improvements in scavenging methods, however, should result in an even greater improvement in the efficiency. Poor carburetion, another major factor in the poor

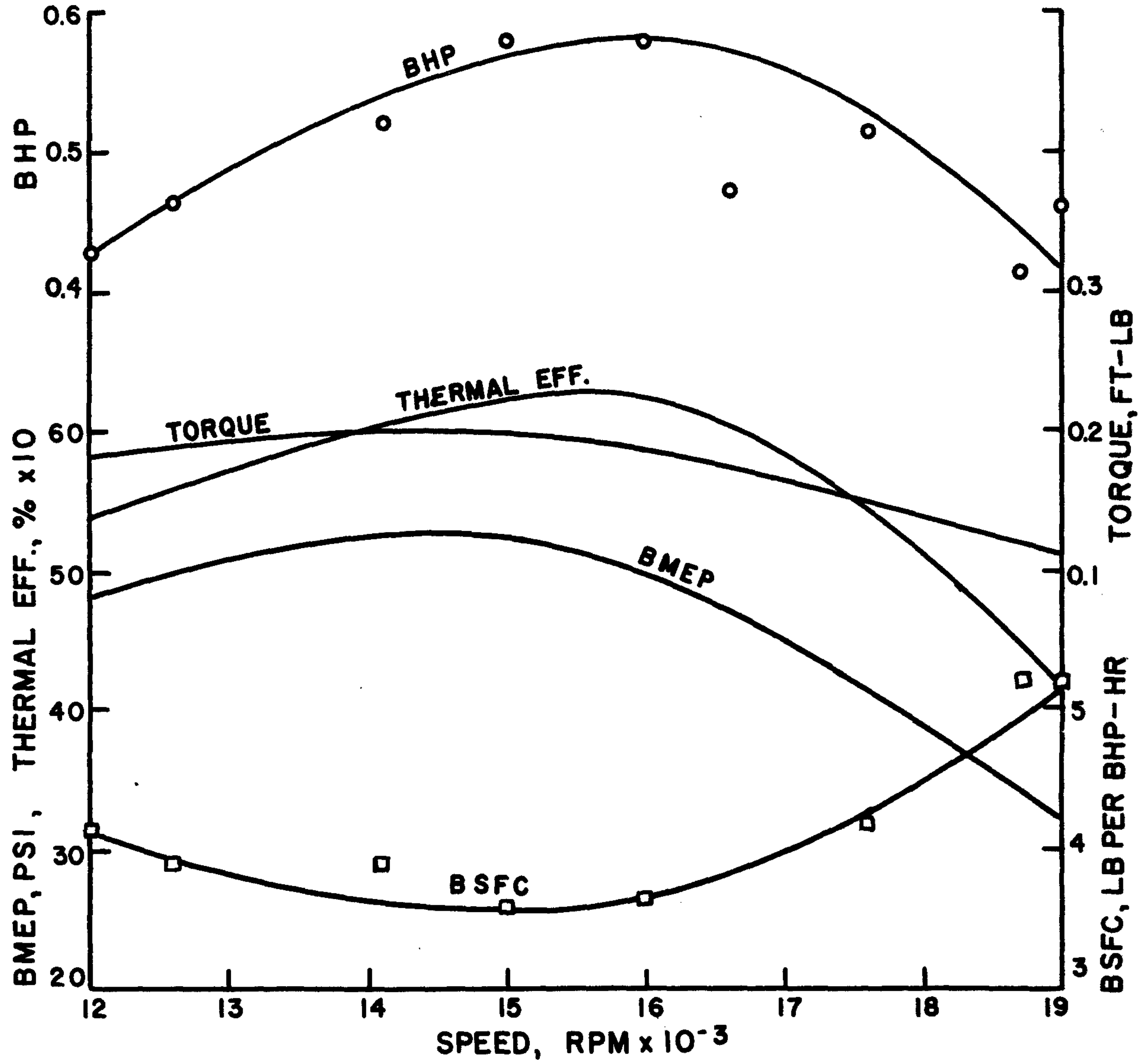



Figure 10. Performance Curves for Engine E; 400° F Cylinder Head Temperature, No. 1 Fuel.

fuel economy, appears at this time to be the most difficult technical problem demanding a solution. It is felt, however, that marked improvement in carburetion can be achieved.

It should be noted that surprisingly high values of mechanical efficiencies were achieved and would seem to indicate that small engines should be capable of operating with a respectable specific fuel consumption. The high specific power output (2.2 bhp per cu in. piston displacement for Engine O) is, to a large degree, responsible for the high mechanical efficiency. Several factors to consider in connection with the engine power output and mechanical efficiency are as follows: (a) the dynamometer brake horsepower values do not include the windage and hysteresis losses in the flexible coupling (these losses appear to be less than 0.1 hp); (b) the friction horsepower values do include the flexible coupling losses; (c) the friction horsepower tests were conducted with engine temperatures lower than for normal operation which would ordinarily increase the friction. These factors would indicate that the actual brake horsepower and mechanical efficiency are higher than those reported and thus tend to substantiate the assumption of good potential fuel economy for the miniature engine.

6. Engine Durability

The poor durability of the engines tested again reflected the techniques and materials employed in their construction and the intended market for the engines. Dynamometer tests of the engines revealed a lack of the structural rigidity required for reliable prime movers. The most frequent failures were crankcases, bearing housings and mounting flanges. Endurance data on the other components were obtained primarily from tests using propeller loading.

The following is a list of general observations concerning the durability of the engines tested.

(a) The maximum total running time accumulated on any engine was 29.5 hours, which was accomplished only by frequent disassembly to clear varnish deposits from the internal parts of the engine and by frequent removal of deposits from the outside surfaces which impeded cooling. The longest continuous run for any engine was 8 hours.

(b) After several hours of operation the center electrodes of both spark plugs and glow plugs broke loose from the porcelain insulator, causing compression leakage and in most cases ignition failure.

(c) The electrical elements in the glow plugs burned

out after a relatively short period of operation. The element, however, continued to operate as a hot spot for many hours thereafter, as long as the engine was kept running.

(d) The two most critical bearings were the wrist pin bearings in the piston bosses and the crank-end connecting rod bearings. These bearings showed a decided tendency to pound out of shape and become sloppy after relatively short running times. Larger, stronger bearings with closer tolerances should be used.

(e) The location of the ignition breaker points on most of the engines led to frequent shorting of the ignition systems. The breaker points rode on a cam ground on the propeller shaft between the two main bearings. Oil for the main bearings eventually contaminated the points causing the ignition to fail.

(f) Considerable difficulty was encountered in keeping fastenings tight during high speed running where considerable vibration was present. Positive locking devices should be incorporated on all fastenings.

(g) Threads in the soft aluminum have a tendency to strip and should be bushed wherever possible.

Figure 11 shows the piston for Engine J which failed during dynamometer tests. This type of piston is inherently weakened somewhat by the transfer ports in the side. The failure appeared to be caused by fatigue rather than by lack of lubrication or overheating. The entire pin boss on one side cracked away from the piston shell. Damage of the cut-off edge of the piston apparently resulted from shearing action after the fatigue failure.

Figure 12 shows a failure of the driving pilot hole of the rotary valve for Engine E, resulting from the soft, low strength metal and excessive bearing stresses on the driving pilot. Failure of the mounting flange was caused by a crankcase failure in which the lower half of the crankcase was wrenched off.

Figures 13 and 14 show the results of a connecting rod failure on Engine P while it was running at 17,000 rpm. Most of the damage resulted from wedging of the broken rod and the impact of sudden stoppage. The bent crank journal resulting from the failure can be seen in Figure 14.

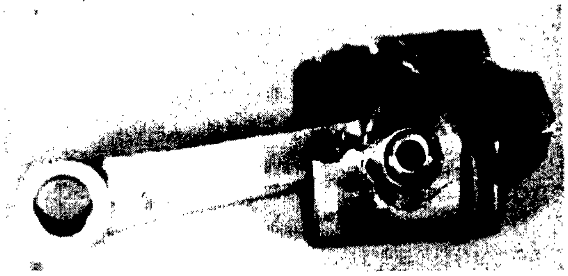


Figure 11. Piston Failure Engine J

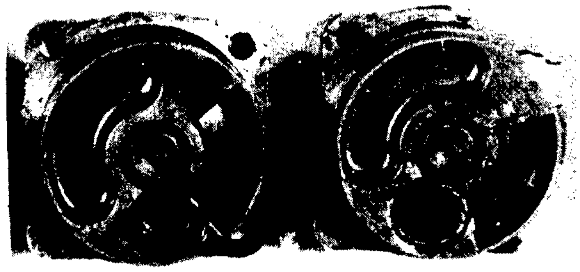


Figure 12. Rotary Valve Failure Engine E

Figure 13. Damaged Parts of Engine P after Connecting Rod Failure

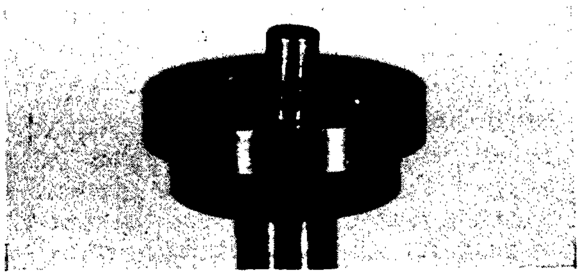


Figure 14. Bent Crank Journal of Engine P after Connecting Rod Failure

Commercial Generators

1. General Description

A survey is being made of all major concerns known to manufacture small generators. The results of this survey to date indicate that very few miniature generators approaching the requirements of the project are in existence. Machines have been obtained from two conerns which appear to have some possibility whereas the other companies contacted had nothing to offer.

The machines obtained were as follows:

a. One three-phase, two-pole permanent-magnet tachometer generator
b. One three-phase, four-pole permanent-magnet tachometer generator

c. Two 1/20 hp, 115-volt, 5000-rpm Universal (Series) Motors
d. Two 1/12 hp, 115-volt, 5000-rpm Universal (Series) Motors
e. Two 1/6 hp, 115-volt, 10,000-rpm Universal (Series) Motors

The Universal Motors can be used as dc generators. A four-pole propeller-synchronizing generator should be available for tests in the near future.

2. Test Results

Tests have been performed only on the two- and four-pole tachometer generators. These tests were preliminary in nature and consisted of determining line-to-line, no-load output voltage and required input horsepower as functions of generator speed. The results of these tests are shown in Figure 15. The four-pole unit (A of Fig. 15) appears to have greater possibility for adaptation to project requirements than does the two-pole. Under the no-load conditions, the units operate very satisfactorily at speeds up to 12,000 rpm, which is approximately 4 times the intended maximum operational speed. Complete tests of these generators under various load conditions will be made when modifications to the windings can be effected.

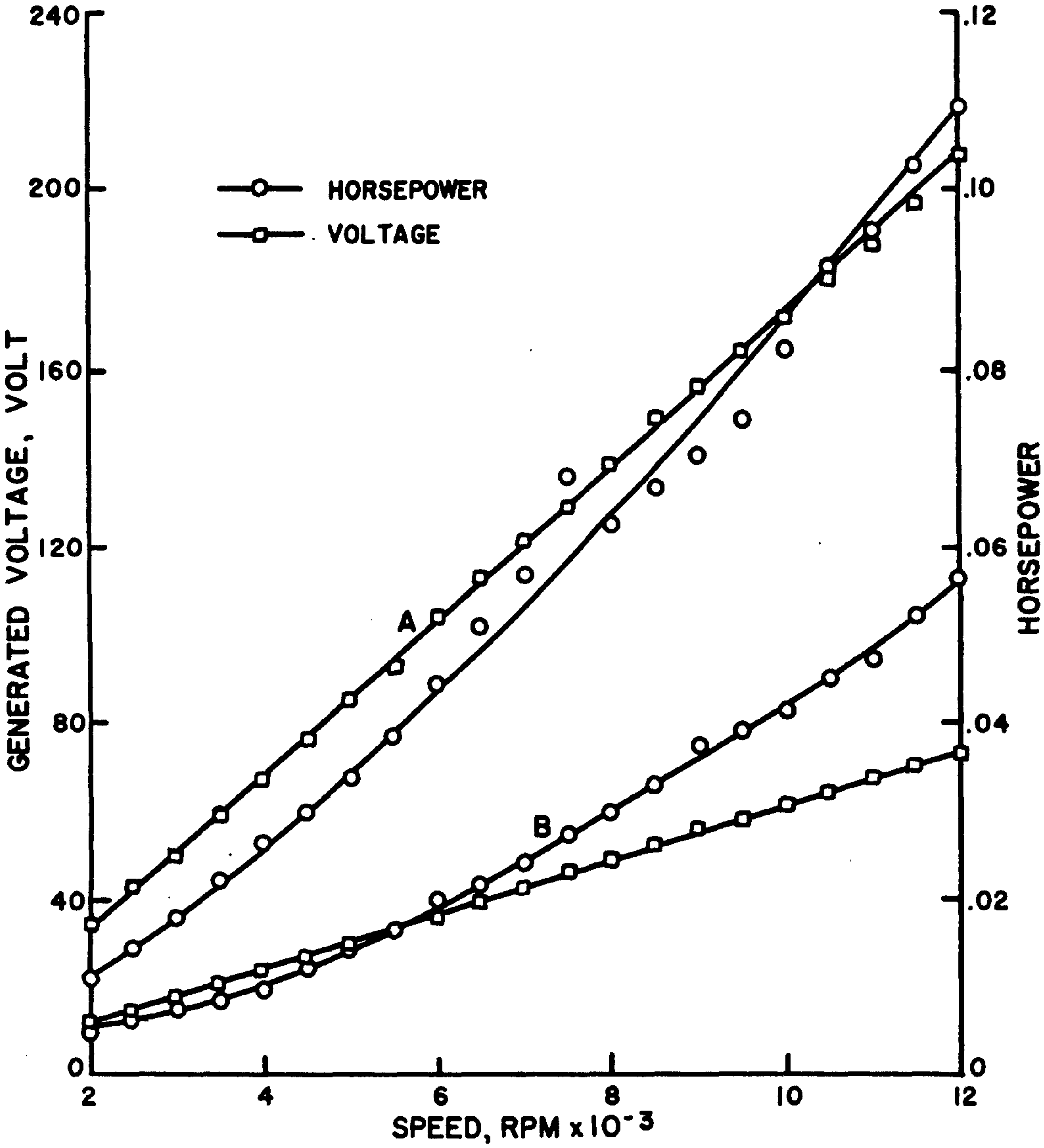



Figure 15. Variation of Line-to-Line Voltage and Input Horsepower with Speed under No-Load Conditions for Three-Phase Tachometer Generators; A, four-pole; B, two-pole.

# SECTION IV

# EXPERIMENTAL DESIGNS

A number of specially constructed experimental prototype components of miniature engine-generator sets must be designed and constructed to investigate thoroughly the optimum design and performance features. The following are several such items on which work has been essentially completed.

## Two-Cycle Test Engine

There are many engine configurations currently used in the two-cycle field. The major differences in design occur in the scavenging systems, porting arrangements and timing, bearing types, combustion chamber shapes, etc. The configuration chosen for the first experimental model permits varying many of these design characteristics individually, with only simple modifications to the engine, so that their effects on performance can be established. A piston displacement of 0.6 cu in. was chosen for the first test engine. The maximum sea-level power potential of this engine might be expected to approach 1.5 hp at speeds in the vicinity of 16,000 rpm. This power is considerably in excess of that required for an engine-generator set rated at 35 watts to 400 watts; however, modifications for improved economy, greater endurance, or operation at higher altitudes should reduce the power potential to the right order of magnitude.

### 1. Design Requirements

A major requirement of a test engine design is the ability of the structure to withstand the vibration loads imposed on the engine at high speeds. As stated previously, the commercial model aircraft engines tested could operate only a few hours before failure. An experimental engine also must be repeatedly disassembled and assembled as components are interchanged. The primary consideration in the design was to provide for the variation of as many as possible of the engine design parameters, such as compression ratio; combustion chamber shape; exhaust, intake, and transfer port timing; porting and scavenging arrangements; methods of ignition; ignition system location and timing; crankcase compression volume; etc. In addition, the effects on performance of the usual operating variables can be investigated, such as ambient pressure and temperature, different fuels, engine operating temperatures, cooling air requirements, etc.

Changes in the design parameters will be effected by modifying parts and by substituting new parts built to different specifications. The first assembly of the engine incorporates a cross-scavenging, free-breathing cylinder and cylinder liner. This arrangement, shown in Figure 16, should approach the maximum power output attainable for this displacement, but at a sacrifice in fuel economy. Subsequent assemblies will incorporate a "loop" scavenged cylinder and liner, which should decrease specific fuel consumption but probably at the expense of the maximum power attainable.

Figure 17 shows most of the components of the first experimental engine. This assembly employs ball bearings at the main bearings, a needle bearing on the crank end of the connecting rod, and an Oilite rotary valve bearing. Two standard commercial cast-iron piston rings are used. The materials used throughout are 24S-T4 Aluminum Alloy and SAE 3140 Alloy Steel. All threaded holes into the aluminum parts are fitted with Rosan Ring-Locked Steel Inserts or Stainless Steel Helicoil Inserts, and screws will be lock-wired to prevent lossening with vibration. Complete detail drawings and design analyses of this two-cycle experimental engine are presented in Reference 15, which was prepared in collaboration with this project.

## Spark Ignition System

An experimental spark ignition breaker system was devised to be mounted on the outboard end of the dynamometer. This unit facilitates the variation of the ignition timing during engine operation, and prevents contamination of the points with fuel and lubricant, as happens so frequently when the breaker points are operated from an exposed section of the engine crankshaft. The breaker system is mounted on an extension of the dynamometer motor housing so that the torque required to drive the breaker system is included in the measured engine torque. Possible variations in timing caused by movement of the dynamometer housing will be less than $1/4^{\circ}$, with the stabilizing effect of the torque-measuring system.

## Experimental Airbleed Carburetor

As stated previously, the major factor which contributes to erratic test results and inefficient operation is the needle-valve carburetor used on commercial engines. To improve the carburetion system, an experimental airbleed type carburetor was constructed which incorporates an airbleed mixing chamber with a needle-valve controlled fuel orifice. The mixing cham-

1. CRANKCASE
2. CONNECTING ROD
3. EXHAUST PASSAGE
4. PISTON
5. PISTON PIN
6. CYLINDER SLEEVE
7. NEE
8. CRA
9. MAI
10. CRA
11. ROT
12. RET

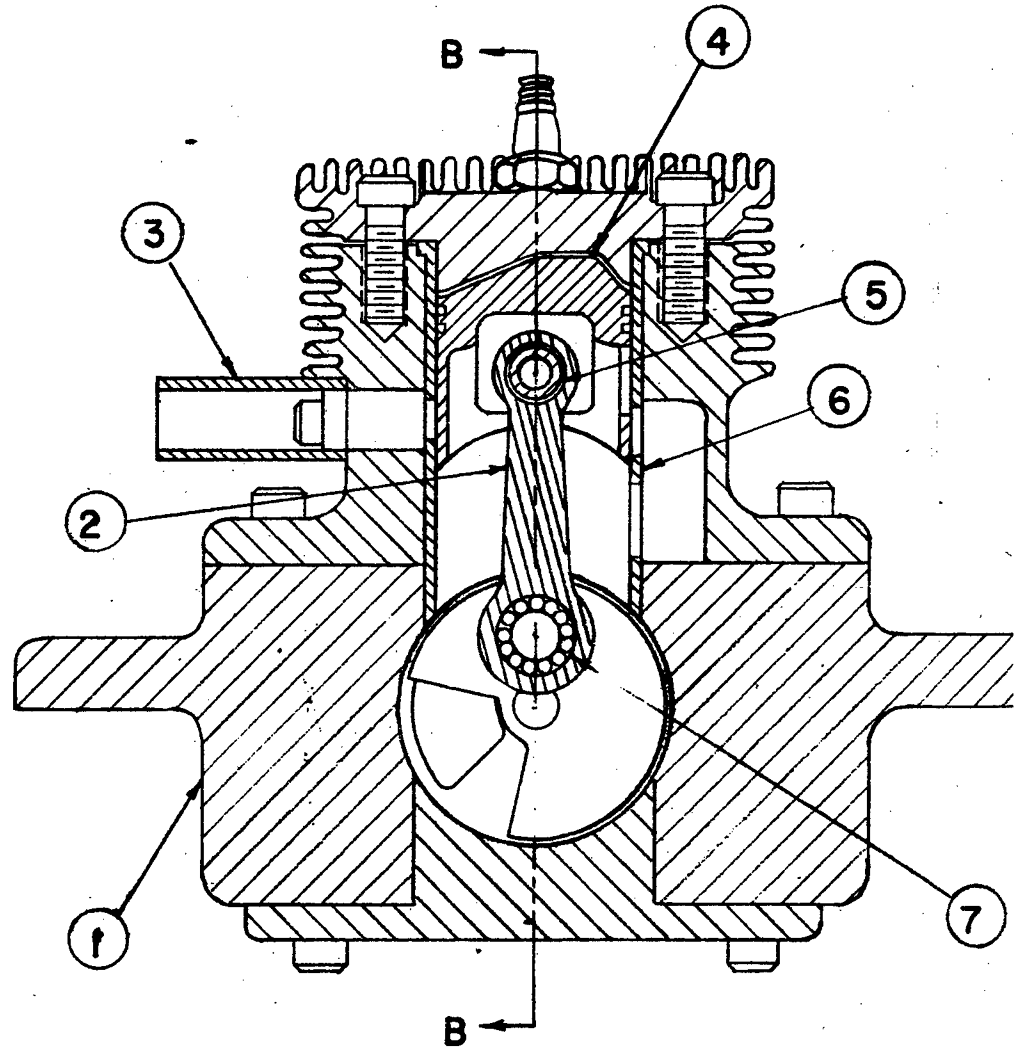
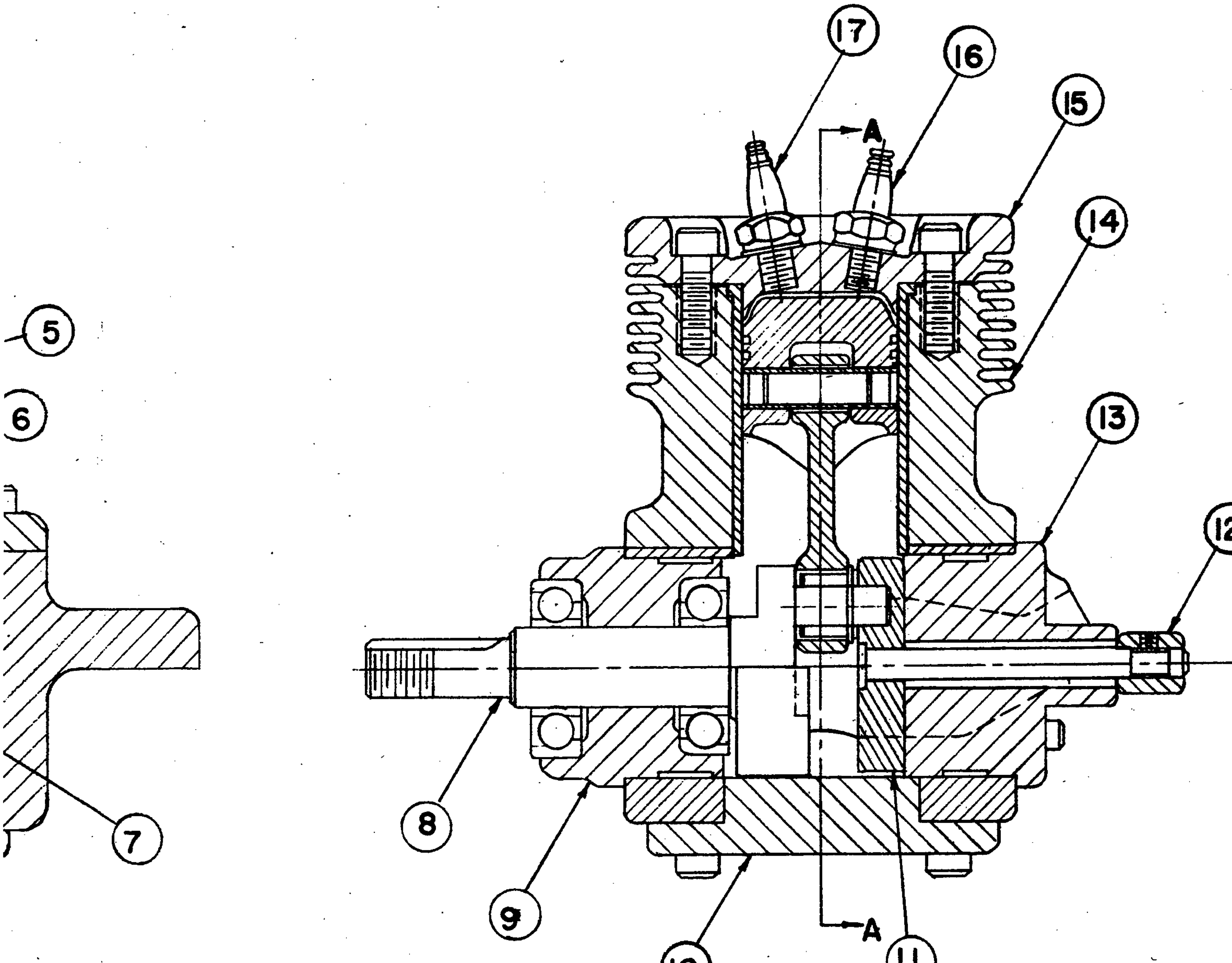



FIGURE 16 T

7. NEEDLE BEARING
8. CRANKSHAFT
9. MAIN BEARING HOUSING
10. CRANKCASE VOLUME ADAPTER
11. ROTARY VALVE
12. RETAINER
13. INTAKE HOUSING
14. CYLINDER
15. CYLINDER HEAD
16. GLOW PLUG
17. SPARK PLUG




URE 16 TWO-CYCLE TEST ENGINE

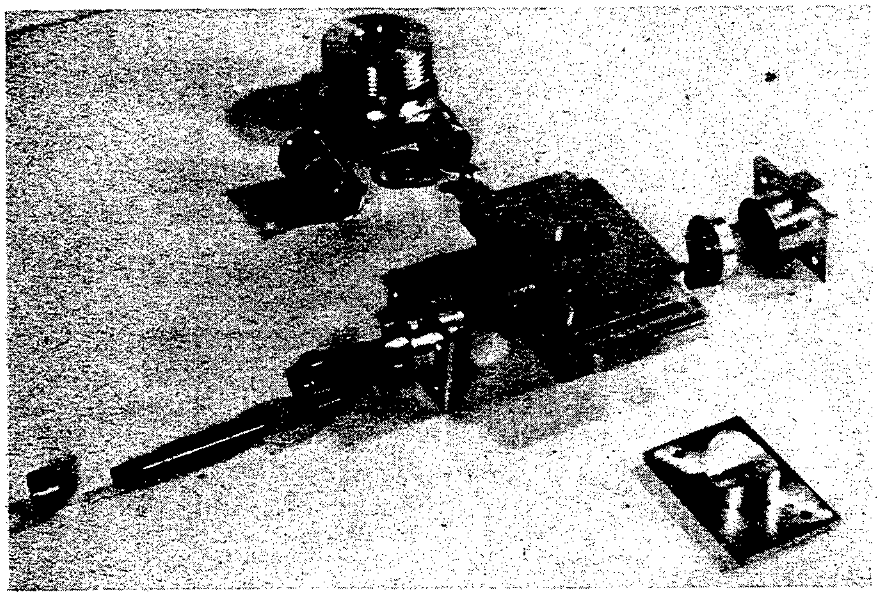


Figure 17. Experimental Two-Cycle Engine for Use in Investigation of Various Design Parameters

ber is mounted on the carburetor body, which contains throttle and choke valves and a removable venturi. Air coming into the carburetor entered through a silencing chamber, a duct containing total and static pressure taps, and a balance chamber. This carburetor assembly appears in Figures 1 and 3. Preliminary tests indicate that the carburetor gives improved mixture control and that it will be satisfactory for studies of the parameters which affect vaporization and mixing.

# SECTION V

## DEVELOPMENT PROGRAM

Early in the study of miniature engine-generator sets it became evident that such units would be much lighter and more compact than any other power source for many types of service. Likewise, as the scarcity of factual information on these units was established, it became obvious that considerable experimental data on small engines and generators would be required before decisions concerning feasibility and practicability of such power sources for certain applications could be made intelligently. Accordingly, the following program was formulated to guide the development of miniature engine-generator sets and to evaluate their potentialities. In addition, evaluation tests of special equipment in intermediate states of development will be performed at the request of the contracting agency.

### Long Range Program

I. Engine Investigation Program

A. Evaluation of existing equipment

1. Procurement and evaluation testing of present commercial engines. (Based on the test results and experience presented in this report, it is felt that little more fundamental information can be gained from such testing, and that this phase of the program should be terminated.)

2. Use of commercial engines for special tests to study endurance, effects of different type fuels, lubrication, cooling, etc.

3. Use of commercial engines for test apparatus and instrumentation development. (Test instrumentation to meet anticipated needs has been built.)

4. Evaluation of new commercial engine designs and modifications as they become available on the market. (All new products and developments which seem promising will be investigated immediately.)

B. Special Test Engine and Component Development

1. Preliminary design studies of various engine cycles; limitations and advantages of different engine lay-

outs and arrangements, methods of breathing, scavenging, carburetion, ignition, lubrication, cooling, etc. (The work already in progress in this phase will be expanded, especially the carburetion studies.)

2. Design and construction of experimental models - incorporating where possible standard commercial components. (At least two more experimental engines will be built soon. One of these will be of a four-cycle design.)

3. Test and development program on prototype engines to ascertain the effects of all primary design parameters and operating variables on economy, performance, and endurance at laboratory temperature and pressure. (This phase of the program is now starting. It will receive the major attention in the second year of the project.)

4. Special tests of engines: starting, warm up, and general performance at widely varying conditions of temperature and pressure. (The altitude and cold test-facilities will be completed soon. A minor portion of the research effort will be directed toward this phase during the coming year.)

C. Engine Analysis and Evaluation of Optimum Designs

1. Compilation and analysis of all test and analytical data, showing the effects on economy, performance, endurance, size, and weight of the various design features, cycles, fuels, ambient conditions, carburetion and ignition systems, etc. (Significant work in this phase must follow IB3 and IB4, and might be expected in the third contract year.)

II. Generator Investigation Program

A. Evaluation of existing equipment

1. Study of all available commercial equipment and literature on generators, voltage controls, transformers and rectifiers. (This work is nearly completed.)

2. Tests of commercial and, if available, military equipment: capacity, control, efficiency, operating temperature, weight, speed, and durability. (These tests are now started and will continue for several months.)

B. New Equipment Development

1. Preliminary studies: optimum weight and capacities, generator speed characteristics for various applications.

2. Design and construction of selected models.

3. Test and development of experimental designs.

4. Performance tests in altitude and cold chamber.

5. Endurance tests.
(Preliminary design studies and work in the successive phases will be initiated this year.)

III. Miscellaneous Investigations

A. Engine and Generator Cooling

1. Heat transfer characteristics of components. (Some preliminary analysis of engine heat transfer parameters has been started.)

2. Cooling blower analysis.

3. Over-all system analysis and design.

B. Noise Suppression: Silencing capabilities for intake and exhaust silencers, and their effects on performance.

C. Automatic Starting Systems

D. Supercharger investigation for high altitude operation

E. Shock resistance of equipment

F. Suppression of radio and radar interference

G. Speed and voltage regulation

H. Installation design, to achieve a compact, reliable, light weight power source which can be produced at an acceptable cost.

I. Writing of adequate specifications for design and acceptance testing of complete installations and individual component parts.

Emphasis for Next Contract Year

The following is an outline of several major programs to be emphasized during the next contract year.

I. Experimental Engine Development

A. Study of First Basic Test Engine

1. Cylinder compression ratio

2. Ignition, type of system, location of plug, and timing

3. Crankcase compression ratio

B. Modify engine, to determine effects of:

1, Combustion chamber shape

2. Port timing

3. Crankcase timing

4. Loop and cross scavenging systems

5. Pressure actuated crankcase valves

II. Carburetion Development

A. Development of gaseous and vapor fuel mixing system. (To be used in lieu of liquid fuel carburetion for much of the test work of item I.)

B. Investigation of parameters affecting vaporization, mixing, and combustion of liquid fuels.

C. Design of test apparatus and experimentation to study the above parameters.

D. Development of a miniature carburetion system.

III. Fuel and Lubricant Studies

A. Operating characteristics of various fuels and addatives.

B. Starting characteristics of various fuels and addatives at various ambient conditions.

IV. Experimental Engine Design

A. Modified components for existing test engine (for item IB).

B. Design studies of other two-cycle engine arrangements and sizes; Construction of additional two-cycle test engines.

C. Four-cycle engine design studies - construction of one four-cycle test engine.

V. Generator Development

A. Tests of commercial and military equipment available.

B. Design, construction and testing of experimental ac and dc generators.

C. Design studies of rectifying and control equipment.

VI. Special Evaluation Tests

A. Evaluation of starting and performance characteristics at varying ambient temperatures and pressures of a 100-watt engine-generator set to be supplied by the WADC.

Completion of this program should conclude the major portion of the fundamental engine and generator studies and optimization. Most of the miscellaneous studies, listed in section III of the long range program, can be pursued more advantageously after the optimum design characteristics are established. Hence, little effort will be devoted to the miscellaneous investigations during the coming year.

## APPENDIX I

## COMPARISON OF BATTERIES AND ENGINE-GENERATOR SETS ON A WEIGHT AND VOLUME BASIS

While many factors must be considered when choosing a primary power source for a particular application, the weight and volume are two important considerations for aircraft service. Figure 18 presents fundamental data which facilitate rapid general comparisons between the weights of batteries and engine-generator sets. These data apply to all types of engine-generator sets and to primary and secondary batteries of 25 to 500 watt capacity, 1.5 to 120 volts, for continuous or over-all service from 1/4 hour to 4000 hours. Battery performance is presented for the most favorable temperatures, i.e., 70° to 75°F. Weights for the magnesium-silver chloride batteries and for the zinc-type dry cells are based on continuous discharge to a cutoff voltage of 1.25 volts per cell. It is recognized that a 1,25 volt per cell cutoff voltage is high for dry cells but it was selected for this study because it is consistent with voltage regulation requirements of most aircraft equipment. The voltage of the air-depolarized battery would vary from 2.45 to 2.25 volts per cell. The variation in voltage for the lead-acid storage cells would be from a nominal 2 to about 1.75 volts per cell, while the silver peroxide-zinc storage cells are considered for a cutoff voltage of 1.0. These voltage variations are comparable, since the silver peroxide cells in particular maintain a nearly constant voltage of 1.3 to 1.5 volts per cell for 80 to 95 per cent of the discharge period. No effects of battery deterioration with storage or extremes of temperature are included. No allowance has been made in the battery data for the weight of auxiliary equipment to convert direct to alternating current. In summary, Figure 18 is a comparison of the pounds per watt of batteries used as dc sources under the most ideal conditions to total weight per watt of engine-generator sets which could be developed.

The thin, solid curves indicate the total weight of equipment and fuel in pounds per watt of generator capacity for engine-generator sets having an over-all fuel consumption rate of 1.5 lb. per kwh and respective gross equipment weights of 0.2, 0.1, 0.05, and 0.025 lb per watt. The gross equipment weight includes the weights of all components, such as engine, generator, fuel tank, silencers, controls, rectifiers, etc., but does not include the weight of the fuel. The dashed lines represent total weight in pounds per watt for a fuel consumption rate of 2.5 lb per kwh and are given for

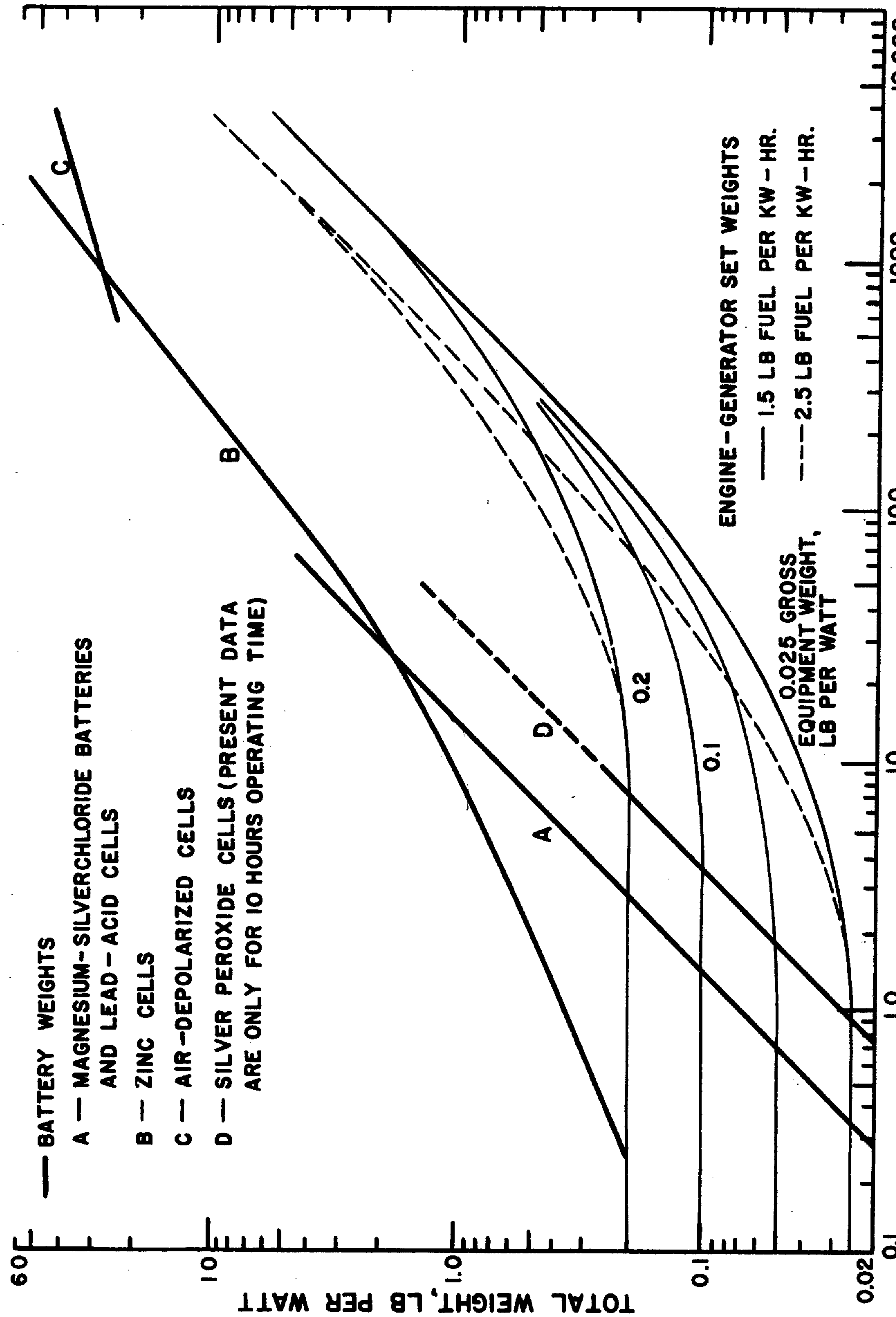



Figure 18. Comparative Weights of Batteries and Engine-Generator Sets.

equipment weights of 0.2 and 0.025 lb per watt only. As expected, these curves show that for less than about 10 hours of operation the equipment weight is the dominant factor, while fuel weight is nearly insignificant; from 10 hours to 100 hours, both weights are significant, and after 100 hours the fuel contributes such a large fraction of the total weight that the equipment weight has little effect on the total pounds per watt. Hence, for less than about 10 hours operating time, equipment should be very light weight, even if it is quite inefficient. For more than 100 hours of operation, power sources must be efficient, regardless of the weight penalty that may be imposed, to gain efficiency and reliability.

Small engines and generators of 35 to 500 watt capacity which have been tested to date indicate that fuel consumption rates of 1.25 to 2.0 lb per kwh should be attainable. In addition, it appears that equipment weights of 0.05 to 0.15 lb per watt could be obtained in relatively sturdy, reliable units. For sets having very low capacity and refined controls, the equipment weight may exceed the above estimates; but for large, simple systems it is conceivable that it might be even less. For instance, a 400-watt engine-generator set built for relatively short term usage might weigh less than 20 pounds, which would be less than 0.05 lb per watt. At high altitudes, larger and heavier engines would be required to deliver a given capacity, hence the weight per watt would be increased considerably over conditions for ground level operation. Batteries would be affected little by the low pressures at high altitudes, but engine-generator sets should operate satisfactorily at temperatures of 150° to 300°F which might be encountered in high speed flight, while batteries would deteriorate rapidly at these higher temperatures.

The following example illustrates a method for using the chart to compare the weights of batteries and engine-generator sets for a particular application. Suppose a power source of 200 watts for 50 hours of continuous or successive operation is desired. Figure 18 shows that the lightest battery would be composed of silver peroxide cells and would have a weight of 1.35 lb per watt, or a total battery weight of 1.35 x 200 = 270 lb., assuming that the 50 hour discharge would be obtainable. If a battery of zinc dry cells were used the total weight would be 540 lb. These weights would be for the battery alone, and would not include any control equipment, or converter if alternating current were desired. In contrast to this, suppose experience showed that a 200 watt engine-generator set, complete with controls, silencers, etc., weighed 20 lb, or 0.1 lb per watt, and operated at 1.5 lb fuel per kwh. Figure 18 shows the total weight of equipment plus fuel is 0.175 lb per watt, or 35 lb total. Thus,

there would be a saving in weight of 235 lb if an engine-generator set were used as the power source in preference to the battery. Figure 18 also permits a comparison with a heavier and less efficient engine-generator set. If the equipment weight were 40 lb and the fuel consumption rate were 2.5 lb per kwh, the total weight would be 0.325 lb per watt, or 65 lb, which would still be a saving of 205 lb over the battery weight. It might be pointed out that a 200 watt engine-generator set having good performance characteristics and weighing only 19 lb complete has already been developed by the U.S. Army Signal Corps. Another engine-generator set in an advanced state of development has been produced by the Ruckstell-Hayward Engine Company for the USAF. This unit is rated at 100 watts and weighs only 19 pounds with all accessories, including an automatic self-starting system. Six pounds of fuel is sufficient to run the unit for 24 hours, with an average fuel consumption of about 2.5 lb per kwh. If a concentrated attempt were made to decrease weight per unit power, undoubtedly further gains would be possible.

## Basis for Battery Data

Battery weights are presented in simple units, such as pounds per watt, irrespective of total capacity or voltage, because for a given nominal voltage and time of discharge to a certain cutoff voltage (final voltage), the number of cells required is proportional to the capacity, If the nominal voltage is doubled, twice as many cells must be placed in series to deliver the prescribed voltage; but, for the same capacity, the number of amperes per bank of cells connected in series is reduced and only half as many banks need be placed in parallel. Hence, the number of cells per watt of capacity is essentially independent of the battery voltage. The number of cells per watt is a function of discharge time, since for longer periods of discharge fewer amperes per cell can be drawn (if the cutoff voltage is to remain constant) and more banks of cells must be placed in parallel. This presentation is open to criticism because of insufficient consideration of individual operating conditions which cannot be generalized, but should be acceptable for the purpose of this weight study.

The weights of the silver peroxide cell batteries (curve D) were based upon technical data supplied by the Yardney Electric Corporation showing performance of their "Silvercel" storage batteries. An average watt-hr per lb for several of the high output sizes was selected. While these high energy per pound rates were applicable for operating times of about 1 to 10 hours with low voltage batteries of various capacities, it is doubtful if low amperage, higher voltage batteries (30

to 120 volts) could be assembled which could maintain the same capacity per lb.

The data for zinc type dry cells were computed from basic performance data supplied by the Ray-O-Vac Corporation for their formula Q cells used for continuous discharge at 75°F to a terminal voltage of 1.25 volts per cell. The weight per watt obtained for these batteries was found to be comparable with weights per unit capacity for zinc dry cells manufactured by the Burgess Battery Company and for the average of five leading brands of cells tested by the U.S Bureau of Standards.[25] Also, it was established that flat-cell batteries have about the same weight per unit capacity as standard zinc dry cells. Curve B represents the minimum weight per watt for zinc cell batteries and is based on batteries composed of cell sizes yielding the minimum weight per watt for the length of discharge considered. In other words, for 10 hours of service, a battery composed of many very small cells with several banks of cells in parallel gives the lightest battery, whereas for 200 hours of service a battery made up of larger cells is lightest. In computing the total battery weight, 10 per cent was added to the aggregate of the individual cell weights to allow for binding and packaging. This figure usually runs between 5 and 15 per cent of the total battery weight.[25]

To keep the battery capacities comparable with those of the engine-generator sets, the weights are based on an average capacity for the discharge period. Thus, when a load is first applied, the battery capacity would exceed the average capacity, but by the time the cutoff voltage is reached the actual capacity would be less. The average voltage per cell was established from an arithmetic mean voltage of $(1.5 + 1.25)/2 = 1.375$ for the zinc dry cells, assuming a constant battery and load resistance. Actually the true mean voltage for zinc cells is less than the arithmetic average voltage, so the method used here is slightly optimistic of zinc cell performance. The approximate variation of weight with cutoff voltage for batteries of zinc cells is:

| Cutoff voltage/cell | Fraction of weight for cutoff voltage of 1.25 |
|---|---|
| 1.25 | 1.00 |
| 1.20 | 0.92 |
| 1.10 | 0.86 |
| 1.00 | 0.83 |
| 0.90 | 0.81 |

The Burgess AM power units are water-activated, silver chloride - magnesium cell batteries. For this type of battery the average voltage used was an integrated mean voltage for the discharge period based on performance data supplied by the Burgess Battery Company. For these units, the cutoff voltage has little effect on the weight per watt, since throughout most of the battery life these cells maintain a nearly constant voltage, regardless of discharge rate, then the voltage falls off rapidly. Flash current or voltage is of no value in comparing battery performance for continued service.

The curves for battery performance are presented for operating temperatures of 70° to 75°F. Performance of zinc dry cell batteries reduces with temperature, until at 0°F the capacity is only about 27 per cent of the capacity at 70°F; and at -20°F, only 6 per cent. In addition there is an appreciable deterioration of zinc cells at high temperatures. The magnesium - silver chloride batteries are not affected similarly by temperature and are reported to perform satisfactorily from -60° to 150°F. Silver peroxide cells show the following variation in capacity with temperature, in per cent of capacity at 75°F -- 75°F, 100 per cent; 122°F, 90 per cent; 32°F, 83 per cent; -4°F, 59 per cent. Lead-acid batteries at -60°F produce only 10 per cent of their rated capacity at 70°F. It must be recognized that the above figures are subject to variation as operating conditions change (i.e., current drains, cutoff voltages, etc.) and they are presented only to provide an idea of the order of magnitude of temperature effects on battery performance. No shelf or storage deterioration was considered, again to permit battery performance to be reported at its best.

Air depolarized cells of the Edison and LeCarbone types are advantageous for low capacities over a discharge period of several months. Such batteries operate with a nearly constant voltage, 2.45 to 2.25 volts per cell, throughout the discharge period. They are normally filled with water at the time of use, and even after two years normal storage a capacity of 90 per cent of rating is guaranteed.

Various high-output lead-acid storage batteries were considered, including the U.S. Air Force Type K-1 battery and many types listed as standard by the U.S. Army Signal Corps. It was found that these lead storage batteries gave weights per watt almost exactly equal to the values shown for magnesium - silver chloride batteries. In no case did the lead-acid storage batteries have a lower weight per watt than the primary batteries. Even for a long-term discharge, the air-depolarized type primary battery was found to be lighter and smaller than lead-acid storage batteries for similar applications. Other types of batteries suitable for short term aircraft applications were considered. In the interests of simplifying the curve,

the magnesium - silver chloride and zinc - silver peroxide batteries were selected as being representative of the various possible battery systems.

Comparisons of several types and sizes of cells showed the following approximate volume and weight relationships:

Silver peroxide cells, 16 to 19 cu in. per lb
Zinc cells, 15 to 19 cu.in. per lb
Magnesium - silver chloride batteries, 12 cu in. per lb
Air-depolarized cells, 20 cu in. per lb
Lead acid, 10 to 20 cu in. per lb

Too few data are at present available to permit an accurate estimate of weight and over-all outside volume relationship for engine-generator sets.

Conclusions

From Figure 18 and the preceding discussion, it may be concluded that:

1. Engine-generator sets have a tremendous weight advantage over batteries for constant load and continuous or over-all service beyond 10 hours.

2. Between 3 and 10 hours the weight of engine-generators could range from 10 per cent to 80 per cent of the weight of the batteries. Intermittent or variable load requirements might favor batteries.

3. Between 1 and 3 hours, operation with dc probably favors the batteries, whereas for ac service the engine-generators are probably preferable because of the additional equipment necessary to convert the battery current to ac.

4. Batteries appear to be most advantageous for discharge periods of about 1 hour or less.

5. An intermittent or cyclic load would make the battery position more favorable than it is shown in Figure 18, since some batteries have an appreciably longer life with intermittent service while the engine-generator sets likely would not have a favorable part-load or idling efficiency and would have to be designed for the maximum load requirements.

6. For operating time in excess of 20 hours, it is

evident that the use of slightly heavier, but more efficient and rugged, engines is desirable, since the advantages of better efficiency increases with time while the penalty for increased equipment weight becomes less important.

It is recognized that many other considerations such as ease of operation, reliability, availability, cost, adaptability, flexibility, etc., are important in a primary power source, but the preceding study presents the relative merits of batteries versus engine-generator sets so far as over-all weight and volume are concerned. From present knowledge of existing small engines and generators, it is apparent that, potentially, engine-generator sets could show tremendous weight advantages over batteries. However, a design and development program will be necessary to make reliable engine-generator sets of these capacities available.

# APPENDIX II

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