Recent Developments in Aircraft Engines

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The Society of Automotive Engineers, Inc.
29 West Thirty-ninth Street
New York City

Reprinted from THE JOURNAL OF THE SOCIETY OF AUTOMOTIVE ENGINEERS *for March,* 1925.

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By L. M. WOOLSON[1]

ANNUAL MEETING PAPER

Illustrated with PHOTOGRAPHS AND DRAWINGS

ABSTRACT

ADVANCES in airplane performance during the last few years may be ascribed mainly to advances in aerodynamics and to improvements in powerplants. The latter have resulted in producing more power for the same weight of engine and smaller overall dimensions for engines of the same power-rating. The accompanying paper describes two engines of 500 and 800 hp. respectively that have been recently developed by the Packard Motor Car Co. for aircraft service. When these engines are compared with previous types they are found to be more compact and to produce more power per pound of weight. When each is operated at its rated speed, the Model 1500 engine develops 100 hp. more than the Liberty while weighing 140 lb. less, and the Model 2500 engine develops 250 hp. more than its predecessor, the Model 2025, with a decrease in weight of 75 lb.

In applying these facts to commercial aviation, these comparative performances mean that the new engines can carry double the pay-load over the same distance or the same pay-load 2¼ times as far as could their progenitors.

These improvements have been made possible largely because of a new type of cylinder construction, original studies with regard to the loads that can be carried by bearings, reduction of the weight of the crankshaft while at the same time strengthening it, and the compacting and lightening of the timing and accessory-drive layout. Other improvements were made in the lubricating system and in the design of the valve-gear and springs.

Nothing was taken for granted and every detail was given the closest scrutiny. It was decided that if a distinct advance in the art was to be made, it could be accomplished only by disregarding precedent and starting at the ground. As a result of investigating the relation of bearing materials to allowable speeds and loads, it was ascertained that failures of aircraft bearings rarely occur because of lack of lubrication or of wear but are caused by fatigue of the babbitt lining produced by minute flexing of the back of the bearing. Tests showed that the limitations of the bearings could be raised provided they could be prevented from flexing under load and ample force-feed lubrication were provided. The *PV* values of the bearing loads adopted, as compared with those of the Liberty engine, are: for the crankpin, 18,520 lb. per sq. in. as against 13,200; for the center bearing, 35,000 as against 22,650; and for the intermediate bearing, 27,000 as against 14,000.

The critical speed of vibration of the Packard crankshaft is 64 per cent higher than that of the Liberty; it is also twice as stiff as well as weighing 30 per cent less, a feature accomplished by the use of journals having comparatively large outside diameters but bored out through their centers.

Novel cylinder construction enables the cylinders to be spaced closely together and the weight of the whole engine to be diminished. Other advantages incorporated into the design include water circulation in close contact with the heated surfaces, the use of a steel cylinder-barrel as a wearing surface that carries the explosion loads down to the crankcase, the locating of the hold-down flange some distance from the end of the cylinder barrel so that the ends of the barrels of the cylinders of the two banks can practically be allowed to touch inside the crankcase and the engine can be run in an inverted position.

Still other features comprise improved types of valve-housing and valve-gear layout; positive cooling of the exhaust-valve by oil pumped through it; a special type of multiple-cluster small-diameter piano-wire valve-spring; simplicity in the grouping of the accessories; a special type of magneto having a single magnetic circuit and two independent electrical circuits, either one of which will fire all 12 cylinders; the possibility of replacing magneto ignition with battery ignition by substituting a generator for the magneto but without other change to the engine or to the wiring between the distributors and the spark-plugs; the use of very short comparatively light rugged slipper-type pistons; and the ability to use either direct drive or gear reductions.

As each improvement in engine design means an immediate improvement in airplane design, recent developments in engine design have already made possible maneuvers that would have been impossible a few years ago. Although experimental work is continually being directed along conventional lines, such as the barrel and cam types of engine and those of the Diesel or the semi-Diesel type, the most important advances, in the opinion of the author, are to be made by conventional 12-cylinder water-cooled engines and by 9-cylinder fixed-radial air-cooled engines.

When the weight of airplane engines is reduced to 1 lb. per hp., as seems likely in the near future, the engine will consume its weight of fuel every 2 hr. It is important, therefore, that, as the carrying capacity of the airplane is reduced by the amount of fuel that must be carried, efforts to reduce the fuel consumption should run concurrently with those to improve the engine.

THE wonderful improvement in airplane performance that has taken place during the last 6 or 7 years has been mainly due to two factors, (*a*) advances in aerodynamics that have improved the structure of the airplane and have decreased the parasitic resistances so that less power is required to fly at a given speed with a given load, and (*b*) improvements in powerplants that have resulted in producing more power for the same weight of engine, and smaller overall dimensions for engines of the same power-rating.

As an example of these powerplant improvements, I would call your attention, in Fig. 1, to a comparison of the Liberty engine with one of the new Packard engines that will be described later. It will be noted that the new engine is somewhat more compact than the Liberty,

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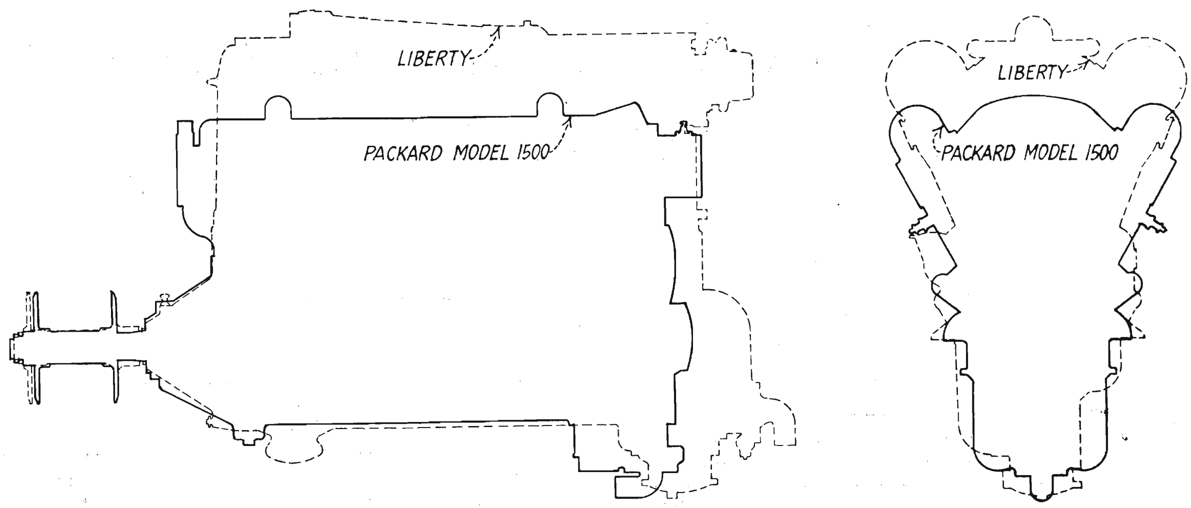

Fig. 1—Profiles of Liberty and Model 1500 Engines
The New Engine Is Somewhat More Compact, Particularly with Regard to Height and Length

particularly with regard to height and length. Bearing this in mind and examining Fig. 2, we find that the new engine develops about 100 hp. more than does the Liberty, when each is operated at its rated speed, and that the new 500-hp. engine weighs about 140 lb. less than the Liberty. A similar comparison in Fig. 3 shows the relative performance of the new 800-hp. engine and its predecessor, the Packard Model 2025 engine.

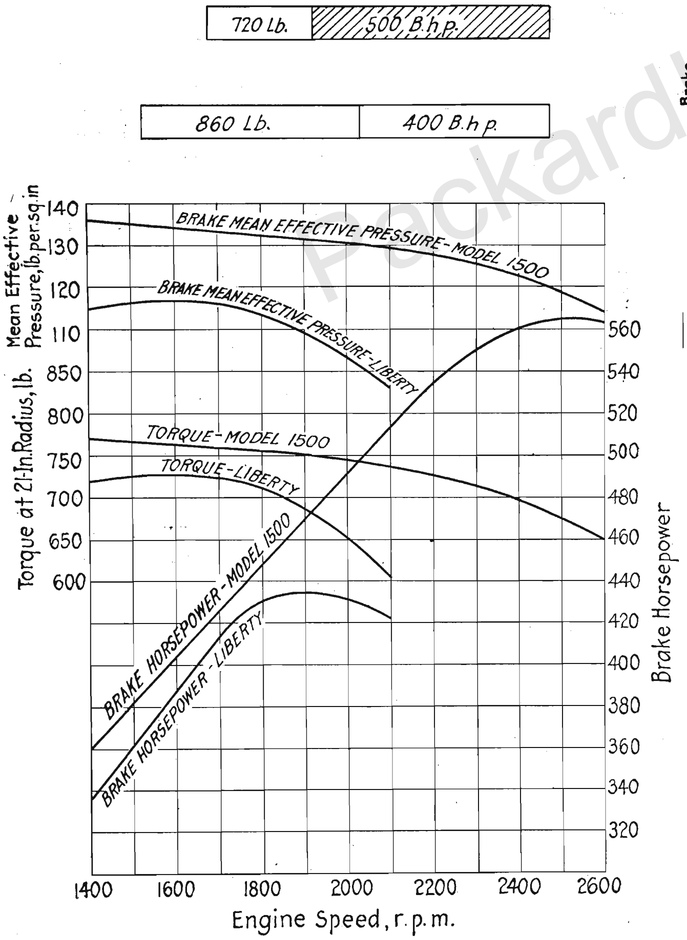

Fig. 2—Comparison of Weights and Horsepowers of the Liberty and the Model 1500 Engine

When Both Engines Are Operated at Their Rated Speeds, the Model 1500 Engine Develops about 100 Hp. More and Weighs about 140 Lb. Less than the Liberty

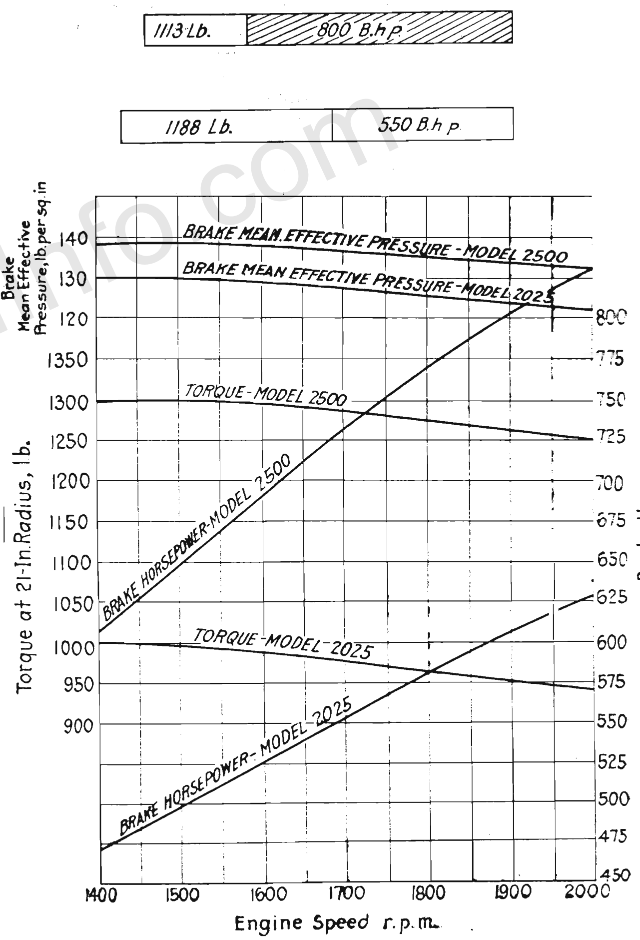

Fig. 3—Comparison of Weights and Horsepowers of the Model 2025 and the Model 2500 Engine

The Model 2500 Develops 250 Hp. More than the Model 2500 Although Weighing 75 Lb. Less

It will be of interest to translate these superiorities into airplane performance so that we may obtain a concrete impression of the advantages accruing to airplanes from the use of lighter and more compact engines. Actual flight tests with the new engines have so far been limited to some new military airplanes, the performance of which I am not at liberty to disclose. But, as we all are working toward the development of commercial aviation as the ultimate goal, it will to a certain extent be even more interesting to examine the influence of lightweight powerplants on airplanes that have been designed for strictly commercial purposes.

With this in mind, I have prevailed on W. B. Stout, who is undoubtedly the foremost exponent of commercial aviation in this country if not in the world, to allow me to present comparative data on the performance of his Air Pullman when equipped with a Liberty and with a Packard Model 1500 engine. The data prepared by Mr. Stout's engineer, Mr. Prudden, are shown in Table 1 and, I am sure, will be of more than passing interest to students of commercial aviation. The comparison has been arranged in two ways: (*a*) on the assumption that the increased power and decreased weight of the new engine would be utilized to increase the pay-load without increasing the cruising radius, and (*b*) an alternative basis, that the improved performance of the new engine would allow the carrying of a greater fuel-supply to allow a greater cruising-range with the same pay-load as formerly.

TABLE 1—ESTIMATED COMPARATIVE PERFORMANCES OF THE STOUT AIR PULLMAN WHEN EQUIPPED WITH LIBERTY AND WITH PACKARD MODEL 1500 ENGINES RESPECTIVELY

	Liberty	*Model* 1500
Pay-Load, lb.	1,000	2,000
Useful Load, lb.	2,000	3,000
Cruising Radius with 1,000-Lb. Pay-Load, hr.	4	8½
Cruising Radius with 1,000-Lb. Pay-Load, miles	420	960
Cruising Radius with 2,000-Lb. Pay-Load, hr.	....	4
Cruising Radius with 2,000-Lb. Pay-Load, miles	....	440
Maximum Speed, m.p.h.	116	124
Cruising Speed, m.p.h.	105	112
Minimum Speed, m.p.h.	54	59
Climb from Sea Level, ft. per min.	600	700
Service Ceiling, ft.	10,000	11,000
Absolute Ceiling, ft.	12,000	12,700

COMMERCIAL APPLICATION

The first comparison shows that it is possible to transport double the pay-load over the same distance at a higher speed with the new engine than with the Liberty, and the second, that it is possible to transport the same pay-load over 2¼ times the distance at a higher speed.

The importance of these conclusions cannot be overestimated in the face of the oft-repeated statements to the effect that, although the development of lightweight aircraft engines is highly important for military aircraft, commercial aircraft can get along with comparatively heavy engines.

Here is an example of a 100-per cent increase in payload, or a possible 100-per cent increase in revenue, accomplished by substituting the new engine for the Liberty engine, itself as light as any aircraft engine used in commercial service today. And it should be remembered that aircraft-engine development of the present type has by no means reached the limit of its possibilities, nor are lightweight engines, when properly designed, more expensive to manufacture, less reliable, or shorter lived than so excellent an engine as the Liberty. The reverse is actually the case, for Government testing requirements for new engines are continually becoming more arduous, a highly commendable condition.

Before designing the new Packard engines, a definite program was laid down that differed somewhat from the course generally pursued in such cases. It had been decided that the new engines were to represent a distinct advance in the art, and the Packard organization had a background of experience in building aircraft engines that warranted setting a very high standard. The result could not be accomplished merely by making changes and improvements in an existing design; it was necessary to start at the ground and to disregard precedent when precedent was based on so-called common practice unsupported by well recognized and proved engineering limitations.

STUDY OF DETAILS

In other words, practically nothing was taken for granted. Even relatively unimportant parts of the en-

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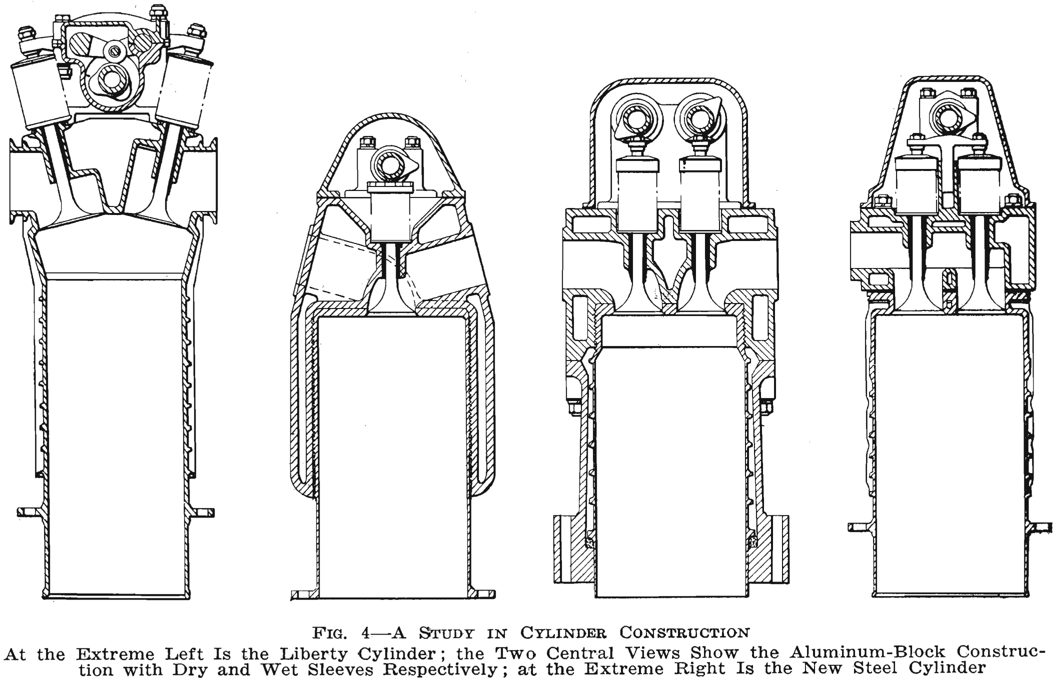

FIG. 4—A STUDY IN CYLINDER CONSTRUCTION
At the Extreme Left Is the Liberty Cylinder; the Two Central Views Show the Aluminum-Block Construction with Dry and Wet Sleeves Respectively; at the Extreme Right Is the New Steel Cylinder

gine received the closest possible scrutiny in an effort to obtain the maximum possible power-output with the least possible weight and the greatest possible dependability. Time will not allow an explanation of the methods employed in all cases but, in general, it may be stated that when a problem involved stresses that would yield to sound engineering methods, such a solution would be acceptable, but, when the design had been dictated merely by so-called good engineering practice, a more or less thorough investigation was made either by theoretical analysis, or by practical experimentation, or by a combination of the two, in an endeavor to ascertain the actual limitations.

A case in point is the matter of the relation of bearing materials to allowable loads and speeds. This, of course, represents one of the oldest studies in the world of mechanics; volumes have been written on it. The arrival of aircraft engines, however, has thrown an entirely new light on the possibility of increasing the permissible speeds and loads, provided that certain essential requirements that have been uncovered by long experience with aircraft engines are observed. At this point it might be well to inject the statement that the foundation of any engine design is represented by its bearing layout, that the structure cannot proceed until this foundation has been laid, and that the structure will not be satisfactory if the foundation is poor. In other words, a fundamental principle of good engine-design is, to begin with exact knowledge of the loads to which the engine bearings are to be subjected and to design accordingly.

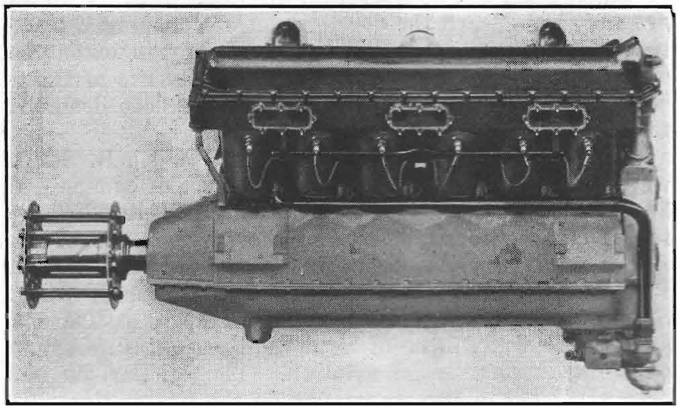

Fig. 6—Right Side View of the Model 1500 Direct-Drive Engine
The Cylinders Are Placed Very Close Together and the Valve-Housing Is Very Compact and Clean

In aircraft engines, the life of the connecting-rod and the main bearings are the most important influences controlling the period between overhauls and should receive first consideration. On the other hand, if past practice is merely followed and a so-called generous bearing-area is provided, we shall be overlooking two important considerations. One is that past practice in aircraft-engine bearings has not given altogether satisfactory results, the other, that we shall be prevented from using an im-

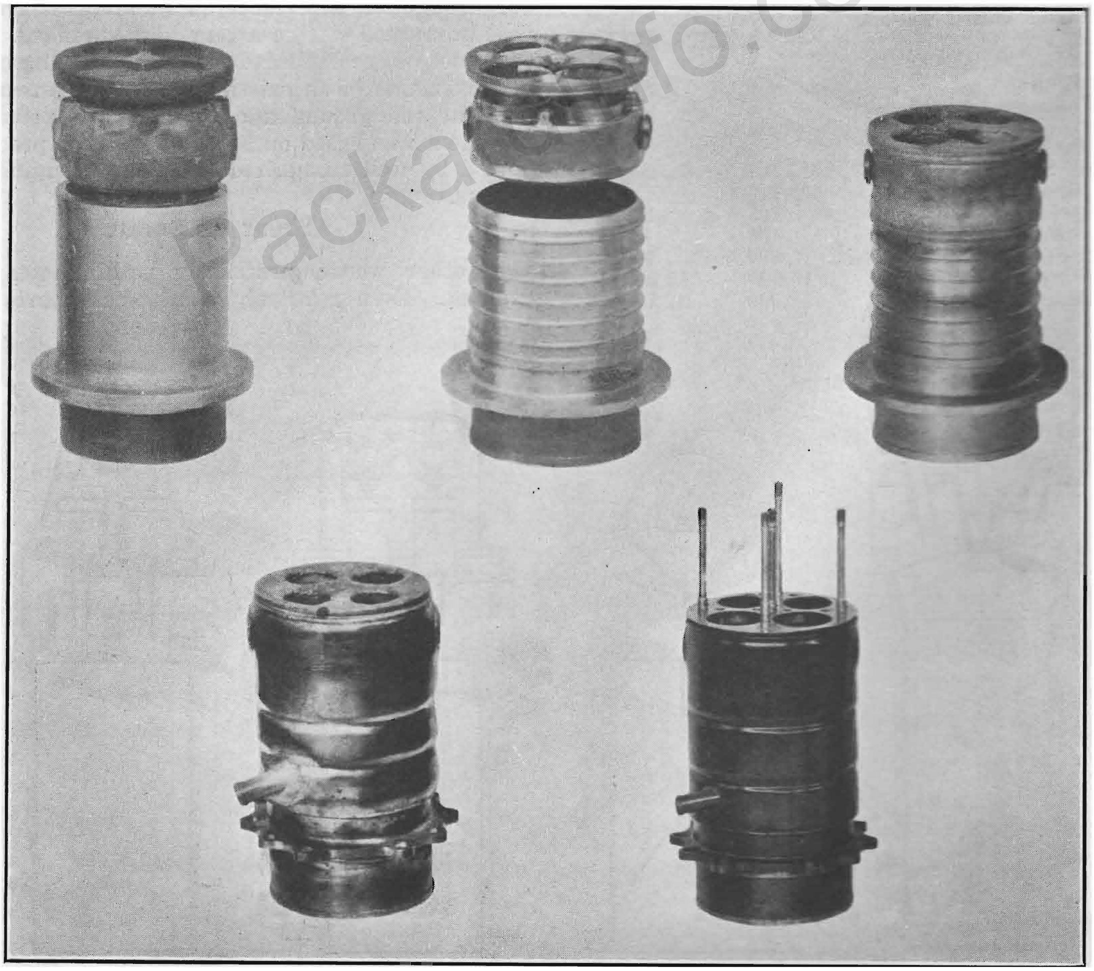

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Fig. 5—Five Stages of Steel Cylinder Construction
The Weight of the Model 1500 Cylinder Is 9.5 Lb. and It Develops 50 Hp.; the Weight of the Model 2500 Cylinder Is 15.2 Lb. and It Develops Nearly 70 Hp.

TABLE 2—SUMMARY OF BEARING-MACHINE TEST RESULTS

Shaft Material	Bearing Material	Bearing Size Diameter, In.	Bearing Size Width, In.	Total Load, Lb.	Load, Lb. per Sq. In.	Speed Without Seizure, R.P.M.	*PV* Value Without Seizure, Lb-Ft. per Sec.
40-Point Carbon	Babbitt-Lined, Steel-Backed	1¾	¾	6,050	2,300	2,750	48,500
40-Point Carbon	Babbitt-Lined, Steel-Backed	1¾	1¾	12,100	1,975	2,950	44,500
40-Point Carbon	Half and Half Solder, Bronze-Backed	1¾	1¾	9,625	1,570	2,500	30,000
Hardened Steel	Phosphor Bronze	1¾	1¾	11,000	1,800	2,000	27,400
40-Point Carbon	71½ per cent Copper, 23 per cent Lead, 5½ per cent. Tin	1¾	1¾	8,030	1,310	2,000	20,000
40-Point Carbon	87 per cent Magnesium, 13 per cent Copper	1¾	1¾	6,050	990	2,000	15,000

Comparison of Loads and Bearing-Values
of Liberty and Packard Model 1500 Engines

Ratings
Liberty......................420 b. hp. at 1700 r.p.m.
Packard Model 1500...........500 b. hp. at 2100 r.p.m.

	Bearing Loads					
	Crankpin		Center		Intermediate	
	Liberty	Model 1500	Liberty	Model 1500	Liberty	Model 1500
Maximum Unit Load, lb. per sq. in.	1,035	1,191	1,580	1,692	1,150	1,685
Mean Unit Load, lb. per sq. in.	750	808	1,365	1,274	720	983
PV, lb-ft. per sec.	13,200	18,520	22,650	35,000	14,000	27,000

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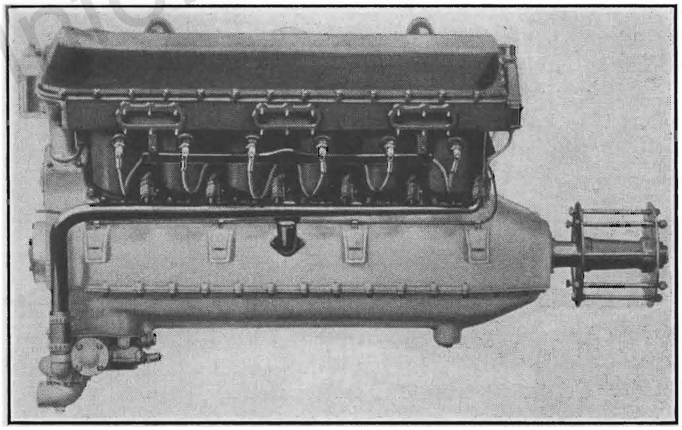

FIG. 7—LEFT SIDE VIEW OF MODEL 2500 DIRECT-DRIVE ENGINE
Its Similarity to the Model 1500 Engine Is Apparent. All the Features Described Are Common to Both Engines and in Some Instances the Parts Are Interchangeable

portant means of reducing the weight, namely, reducing the length of the bearings and, consequently, the length of the engine. It will be necessary to digress for a moment to state that the length of an aircraft engine has not always been limited by bearing considerations for, in many cases, the closest spacing of cylinder centers possible with certain types of cylinder construction, rather than the length to be allotted to the bearings, has dictated the design.

FAILURE OF BEARINGS

This limitation of close cylinder-spacing, however, was removed in the new Packard engines by a new type of cylinder construction and assembly that will be described later, hence, the necessity arose for a thorough investigation into the possibility of shorter crankshaft and connecting-rod bearings than had hitherto been customary.

Reverting now to the discussion of bearings, bearing failures had been observed in practically all makes and types of aircraft engine. These failures, however, were rarely caused by lack of lubrication, nor was the wear of the bearings measurable. Cracking and crushing of the babbitt was the major difficulty; and this occurred after from 30 to 150 hr. of operation, depending on the severity of the service.

Failures were finally found to be caused by fatigue

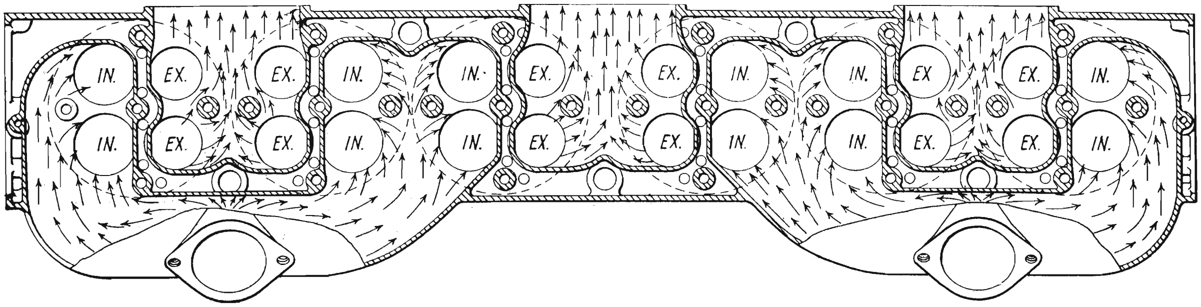

FIG. 8—CROSS-SECTION OF VALVE-HOUSING, SHOWING INTAKE, EXHAUST AND WATER PASSAGES
The Large and Free Passages Are Obtained by Siamesing the Four Valves into One Port

of the babbitt lining that was produced by minute flexing of the backing of the bearing. The importance of more rigid bearing-backing was thus emphasized and it became evident that, if the babbitt were prevented from flexing under load, far greater loads could be carried without distress. It was then determined to run a series of tests on a bearing-testing machine, using various types of bearing-metals, and in each case gradually increasing the speed and the load in an endeavor to ascertain what the bearing limitations actually were, granted that the two well-recognized requirements were complied with.

REQUIREMENTS OF BEARINGS

The first of these was, that the bearing must not flex appreciably under load, and the second was, that ample force-feed lubrication must be provided, not only to produce a continuous oil-film, but also to circulate a quantity of oil sufficient to ensure the proper viscosity of the oil that maintains the requisite thickness of the oil-film.

It was realized that, in the engines to be built, both these requirements could be controlled in the design and, once the comparative information had been obtained from the bearing-machine tests, the data could be translated into the engine design. It was recognized, of course, that conditions in the bearing-testing machine were very different from those obtaining in an engine running under its own power, in that the loads on the machine were concentrated uniformly in a fixed direction, whereas those on the engine are constantly changing, both in intensity and in direction. It is not claimed that the results of these tests throw any particularly new light on the subject of bearings. What was accomplished was the acquiring of definite knowledge along the desired lines without having to rely on the reported work of various investigators, each of whom conducted his tests with other apparatus, other materials and other test-conditions of speed, load and lubrication.

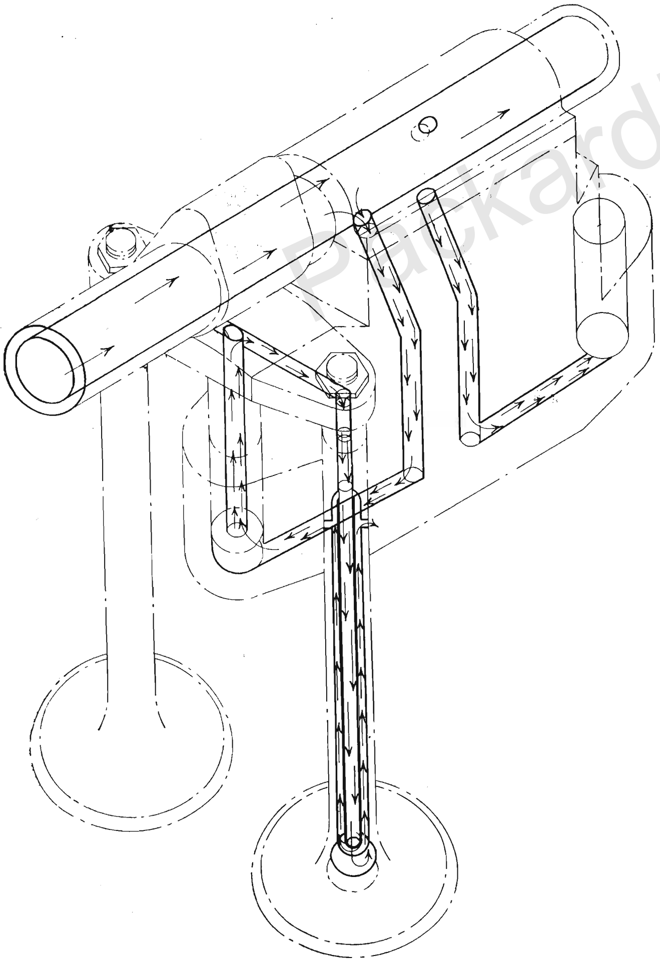

FIG. 9—METHOD OF COOLING THE EXHAUST-VALVES BY CIRCULATION OF OIL
The Camshaft Is Hollow and Is Supplied with Oil under Pressure through a Continuous-Metering Groove in the Rear Bearing

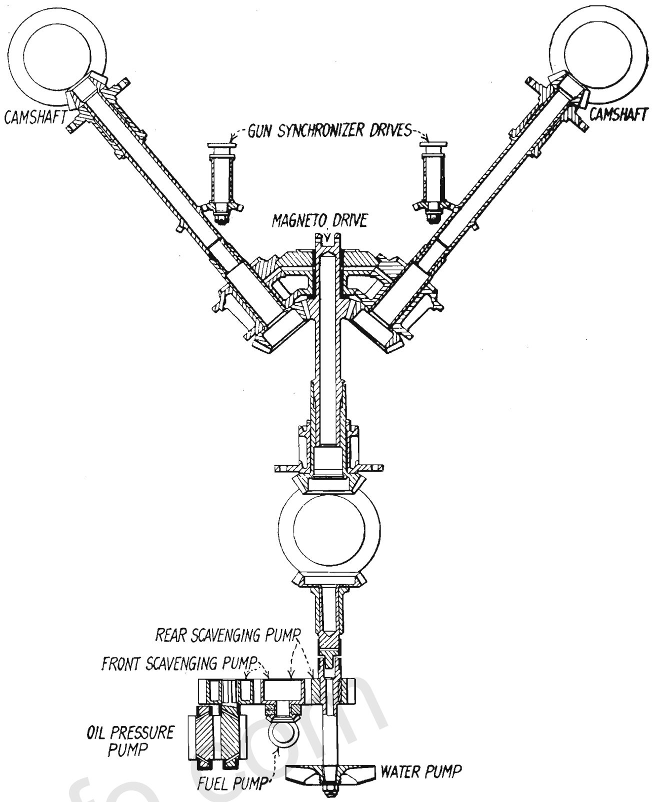

FIG. 10—DIAGRAM OF TIMING-GEAR AND ACCESSORY-DRIVE LAYOUT
Note Simplicity, Integral Construction of Shaft and Gear, and Pressure-Lubricated Chilled-Aluminum Plain Bearings

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A summary of the more interesting tests is shown in Table 2. It should be explained that the last column indicates a *PV* value that could be maintained for a period of not less than 1 hr. without seizure and does not necessarily mean that the bearing would not withstand higher loads and higher speeds for a shorter interval, or with more clearance or still higher oil-pressure. A complete investigation, in which all the different variables were altered a fraction at a time, would necessitate years of work, but the tests described accomplished what was desired in the time available.

COMPARISON OF *PV* VALUES

In the same table is presented a comparison of the *PV* values employed in the Liberty and in the new Packard engine. In spite of the fact that in some cases the values of the new engine exceed those of the Liberty by more than 50 per cent, tests to date have indicated that the new bearings will have at least double the life of the corresponding Liberty bearings. This could never have been accomplished had we been content to follow so-called good engineering practice that stipulated some arbitrary maximum *PV* value with no relation to what limited the life of aircraft-engine bearings in actual service.

The permissible rubbing factors in the new crankshafts having been determined and these rubbing factors being recognized as independent of the diameter of the journals, the problem of designing the shaft itself remained. It was desired to keep the weight of the shaft down to the minimum, Liberty engine experience having shown that additional rigidity in the shaft is highly desirable, not so much from the standpoint of avoiding crankshaft failure, for such was extremely rare with the Liberty, as of avoiding persistent troubles with the timing-gear train that are induced by torsional vibrations of the crankshaft.

The new shafts, therefore, were designed so that the primary critical speed would occur far beyond the operating range of the engine. The factors entering into the determination of the critical speed are, mainly, the rigidity of the crankshaft and the mass inertia of the crankshaft and of the parts in any way connected with the crankshaft, such as the connecting-rods, the pistons and the propeller.

W. R. Griswold is responsible for this phase of the design. Under the action of the harmonic forces of the rotating and the reciprocating parts, an originally straight element of the crankshaft is deflected at the critical speed. The portion of the shaft to the right of the node is displaced in a direction opposite to the section of the shaft to the left of the node, the vertical distance measured from the axis of the crankshaft representing the amplitude at the various sections. The critical speed of vibration varies as the square root of the inverse ratio of amplitudes; the critical speed of the Packard Model 1500 crankshaft is 64 per cent higher than the critical speed of the Liberty.

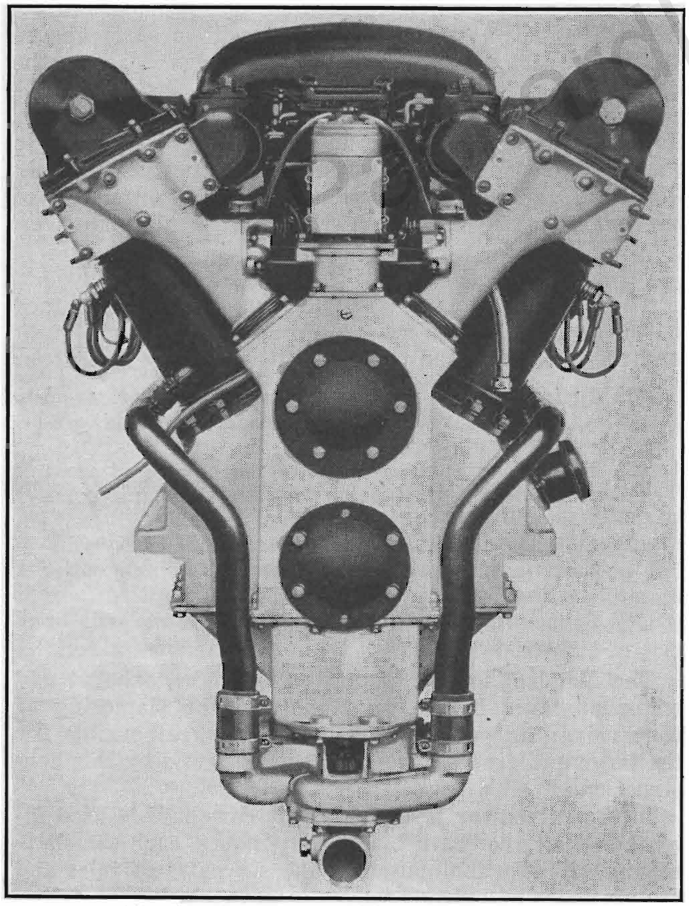

FIG. 11—REAR VIEW OF MODEL 2500 ENGINE
Maintenance Is Facilitated by the Simplicity of the Accessory-Drive Layout and the Absence of Engine Accessories Projecting to the Rear of the Engine

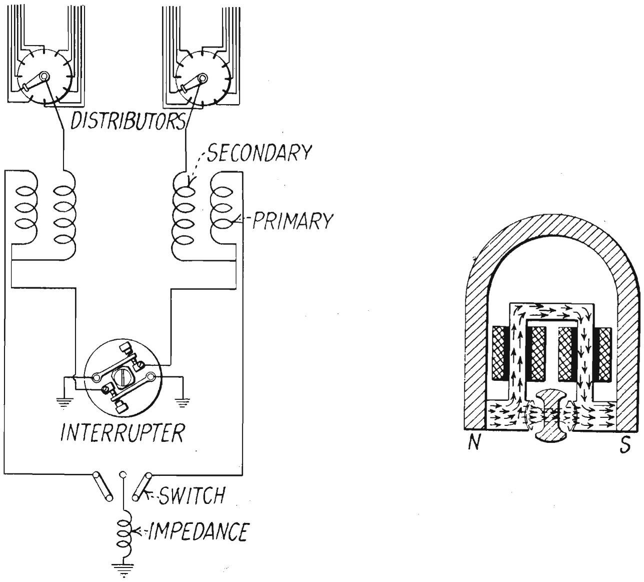

FIG. 12—DIAGRAM OF MAGNETO CIRCUITS AND WIRING
The Magneto Comprises One Magnetic and Two Independent Electrical Circuits

CRANKSHAFTS

The Packard crankshaft is about twice as stiff as the Liberty shaft, although the weight is approximately 30 per cent less. This was sought and accomplished by the use of journals having comparatively large outside diameters but bored out through their centers, so that relatively great stiffness accompanied by light weight is provided. The practical result in the finished engine has been a marked improvement in smoothness of operation and in freedom from wear in the timing-gear train. In the Liberty and other aircraft engines with fairly limber crankshafts, it has been noted that the non-driving faces of the gear teeth showed fully as much wear as did the driving faces. That this characteristic is entirely absent in the new Packard engines offers practical proof of the attainment of a satisfactory degree of rigidity in the crankshaft design.

As no precedent, that it was necessary to follow, existed in cylinder construction, a very careful analysis was made of all the existing types. Generally speaking, three types of construction that are worthy of serious consideration are in use and these are shown in Fig. 4. At the extreme left is shown the well-known Liberty design, used also in post-war types of Packard aircraft engines. The left central view shows the aluminum-block construction with dry sleeve, and the right central, the aluminum-block construction with wet sleeve. An analysis of the requirements indicated that two major considerations would dictate the choice of cylinder design for the new engine. One was, that adjacent cylinders should be spaced as closely together as possible, so that the bulk and weight of the engine as a whole would be diminished; and the other was, that the cylinder-assembly should be as light as possible.

CYLINDER CONSTRUCTION

The cylinder construction evolved as a result of this study is shown at the extreme right of Fig. 4. Each block is composed of six individual cylinders attached to a single aluminum casting that is termed the valve-housing. The individual cylinder is composed of a drawn-steel sleeve welded to a forged combustion-chamber head machined completely, and having a head-plate and a sheet-metal water-jacket welded into place. Each cylinder is provided with four valves, short valve-ports being formed integral with the cylinder. These valve-ports are accurately hollow-milled on their outer surfaces; and the head-plate is bored so as to form a press-fit over the valve-ports, the plate seating on shoulders so as to provide about $\frac{3}{8}$ in. water-space above the combustion-chamber. The cylinder-head is provided with five bosses into which are screwed long studs for supporting the valve-housing. The spark-plug bosses are formed integral with the combustion-chamber. Steps in the manufacture of these cylinders are shown in Fig. 5. The weight of the complete Model 1500 cylinder is 9.5 lb. and the cylinder develops nearly 50 hp.; the weight of the complete Model 2500 cylinder is 15.2 lb. and the cylinder develops nearly 70 hp.

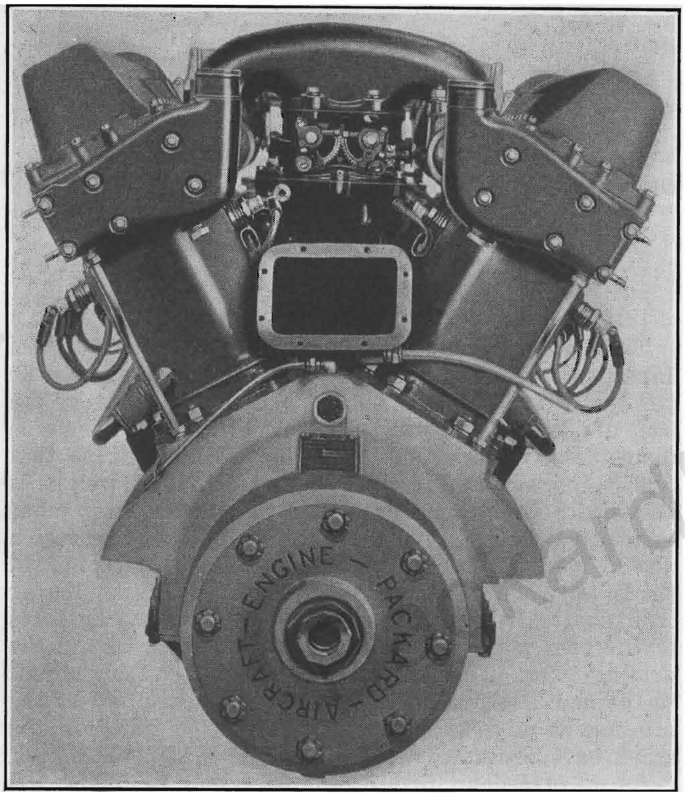

Fig. 13—Front View of Model 1500 Direct-Drive Engine
The Propeller-Hub Is of the Taper-Fit Type and Carries a Forged-Aluminum Loose Flange, Which Is Not Keyed or Otherwise Located on the Propeller-Hub

The advantages of the new cylinder-construction may best be studied by comparing it with the other designs shown. The first point in its favor is that it provides water circulation in close contact with all the heated surfaces, which is not the case with the closed-type sleeves shown in the two central views in Fig. 4. Another point in common with the first two designs is, that the steel cylinder-barrel is used as a wearing-surface and carries the explosion loads down to the crankcase, which is not done by the dry-sleeve cylinder, in which the aluminum water-jacket assists in withstanding the heavy loads.

Location of Hold-Down Flange

Another advantage that also applies to the Liberty cylinder is that the hold-down flange is located some distance from the end of the cylinder barrel and allows a very compact construction, as the ends of the barrels of the cylinders of the two banks can practically be allowed to touch inside the crankcase; this method of construction also serves to add depth to the crankcase with a considerable gain in rigidity. Another incidental advantage accruing from this construction is that the engine can be run successfully in an inverted position. Inverted engines, when used in airplanes, have three major points in their favor: (*a*) greatly improved vision for the pilot; (*b*) a higher line of thrust; and (*c*) greater propeller-tip clearance. Other advantages of individual-cylinder construction are ease of manufacture, ability to install the largest possible valves while maintaining adequate water-circulation around all the valve-seats and, finally, a cylinder-spacing arrangement closer, it is believed, than is possible with any other construction.

The aluminum valve-housing is bolted to the six cylinders to form a cylinder-block; and this block remains assembled in this fashion throughout all the usual assembling and disassembling operations, although, if necessary, an individual cylinder can be replaced at any time with the minimum of delay.

Fig. 6 shows the right side of the Model 1500 engine. It will be noted that the cylinders are placed very close together and that the valve-housing design results in a compact and clean construction. Fig. 7 shows the left side of the Model 2500 engine. The similarity in design of the 500 and the 800-hp. engines is apparent, all the features described in this paper being common to both engines and, in a few instances, the actual parts being interchangeable.

Water is led into the individual cylinders from a manifold connected to short pipes welded to the jacket at the lower end. The water delivery from the cylinder is through a series of holes drilled in the top plate and arranged radially about the exhaust-ports so as to ensure that local steam-pockets will not be formed above the exhaust-valve seats. A single copper-asbestos gasket is used between the individual cylinders and the valve-housing, this gasket, of course, not being subjected to gas pressure as is the conventional automobile detachable-head gasket, but merely serving as a water-seal to prevent leaks between the inlet and the exhaust passages.

Valve-Housing

The valve-housing is an aluminum casting machined on all surfaces. It is used interchangeably on the right and the left banks and performs the following functions:

(1) Distributes the mixture to the six cylinders from the two carbureter cross-header manifold connections
(2) Forms the exhaust-passages, each two adjacent cylinders having their two pairs of exhaust ports siamesed into a single exhaust outlet
(3) Collects the water circulated through each cylinder-jacket and delivers it through a single outlet at the front of the engine
(4) Supports the camshaft-bearing pedestals and the valve-stem guides

The diagram in Fig. 8 shows the intake, exhaust and water passages in the valve-housing, the siamesing of four valves into one port being largely responsible for the large and free passages that are allowed by this construction.

In the valve-gear layout, a single camshaft is used interchangeably for each block of cylinders, each camshaft having 12 cams for operating the six pairs of inlet and the six pairs of exhaust-valves in each block. The camshaft is mounted in seven heat-treated cast-aluminum split bearings that are held down to the valve-housing by long cylinder hold-down studs. Hollow dowels locate the bearings accurately in line. Each bearing-pedestal carries integral guides for the adjacent cam-followers, the alignment of which transversely to the camshaft is maintained by engagement with the flat faces above the guides. Means for cooling the exhaust-valves by the circulation of oil are provided by suitably drilled passages in the camshaft-bearings adjacent to the exhaust-cams, this feature of the construction being shown diagrammatically in Fig. 9. The camshaft is hollow and is supplied with oil under pressure through a continuous-metering groove in the rear bearing.

COOLING OF EXHAUST-VALVE

In the camshaft journal next to each exhaust-cam is drilled a hole opposite to the nose of the corresponding exhaust-cam. This hole registers with a vertical passage in the camshaft-bearing pedestal when the cam is at its highest point and the exhaust-valves consequently are closed. The oil flows through this passage to the bottom of the cam-follower guide, which forms a closed-end cylinder, and the space underneath the cam-follower is thus filled with oil. The camshaft in revolving cuts off communication with this passage and, when the cam-follower is depressed by the cam, the oil can escape only by being forced through the hollow cam-follower stem and the horizontally drilled passages leading out through the drilled tappets into the exhaust-valve stems. The latter are drilled throughout their entire length, the lower end of the hole in the valve-head being closed by a screwed-in plug. A small steel tube is welded to this plug and is centered in a counterbore at the upper end of the valve-stem. The oil is forced down through the tube and out at the bottom through horizontal holes, thus cooling the head of the valve. The oil is then discharged through the annular space between the tube and the inner wall of the valve and out into the valve-housing through horizontal holes drilled through the upper end of the valve-stem just below the counterbore. With this system, a positive means of cooling is provided by which a fixed quantity of oil is pumped through each exhaust-valve whenever it is opened. As a result, the exhaust-valves operate at a very low temperature and the valve-seat is preserved in excellent operating condition for long periods.

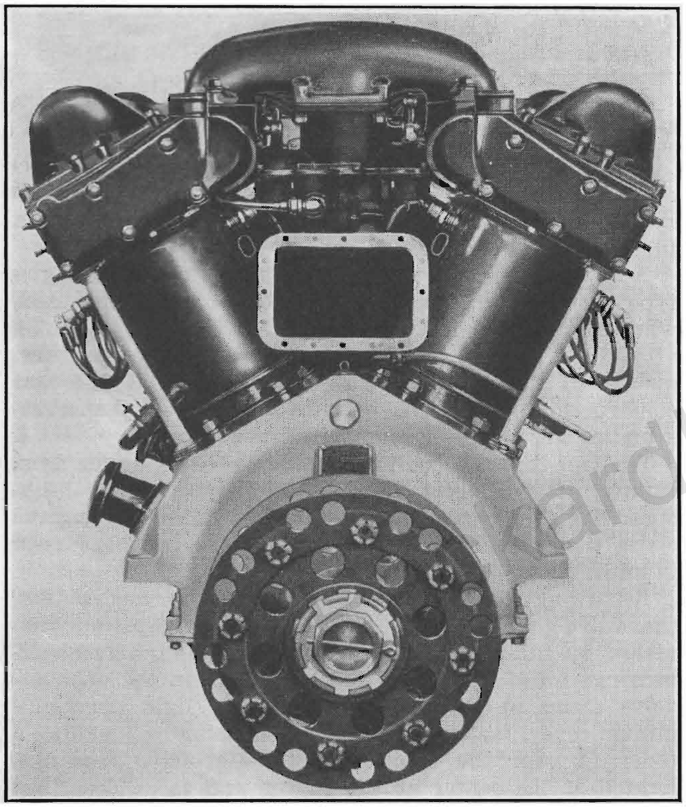

FIG. 14—FRONT VIEW OF MODEL 2500 DIRECT-DRIVE ENGINE
A Splined Hub with Split Centering-Cones Is Used To Prevent the Galling and Freezing of the Propeller-Hub that Sometimes Occurs in Large Sizes of Engines Having the Taper Construction

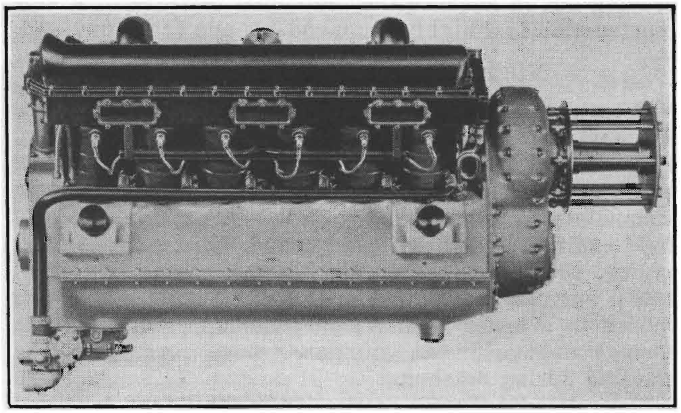

FIG. 15—RIGHT SIDE OF MODEL 2500 GEARED ENGINE
The Gears Are of the Spur-Gear Single-Reduction Type and Are Entirely Self-Contained

The rate of oil-flow, the size of the oil passages, and other pertinent data were all obtained by a bench set-up of a single valve heated by a Bunsen burner, this study resulting in a final design from which all experimental features had been removed long before the engine had been tested in its entirety. Incidentally, this method of

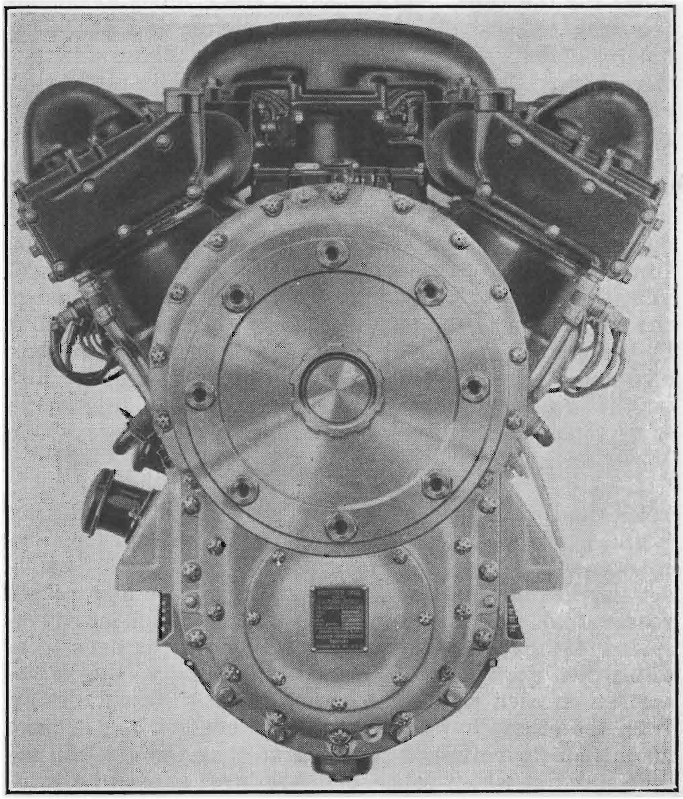

FIG. 16—FRONT VIEW OF MODEL 2500 GEARED ENGINE
A Two-to-One Reduction to the Propeller-Shaft Has Been Found Particularly Desirable for Load-Carrying Airplanes of Moderate Speed

proving out in advance the individual features of a new construction is a highly commendable one to follow.

MULTIPLE-CLUSTER VALVE-SPRINGS

Returning to a description of the valve-gear in these new engines, the valve-springs are worthy of special note. These are of the multiple-cluster type and consist of a group of small-diameter piano-wire springs arranged in a planetary fashion around the valve-stem. In the Model 1500 engine, 7 of these springs and, in the Model 2500 engine, 10 springs are used with each valve. The individual springs are located over tubular guides that are welded to a lower fixed washer; the upper ends of the springs engage in an annular groove formed in the movable spring washer.

Several advantages accrue from this construction, which may justifiably be termed indestructible. The most important point, perhaps, is the least obvious, namely, that which relates to the natural period of vibration of the small springs. This phase of the problem is discussed at length below. Other advantages result from the increased factor of safety in numbers, so to speak, since any valve will continue to function even though several of the springs may be broken. Furthermore, the reciprocating weight, represented by the upper washer and one-half the weight of the springs, is reduced, as compared with the conventional construction, and, finally, the physical properties of the small-gage piano-wire are generally superior to those of springs heat-treated after forming. Considerable effort was devoted to arriving at this valve-spring construction, which, it is believed, is of sufficient general engineering interest that the history of its development should be traced.

Valve-spring failures have always been prevalent to a certain extent in aircraft engines; and these failures at times lead to disastrous results with overhead-valve engines for the valve may drop into the combustion-chamber and, consequently, wreck the piston and the combustion-chamber head. For some time, these failures were regarded as not being preventable, the cause being attributed to fatigue and to minute imperfections in the material. The first serious consideration of this very important subject appears on record in the British Advisory Committee for Aeronautics' Report No. 241, issued in March, 1916, in which the whole matter is very ably discussed. It is clearly proved that the basic seat of the trouble lies in a resonance effect between the natural vibrations of the spring and the forced oscillations of the engine. These latter oscillations are brought about by the firing impulses. It is of interest to note that our own experience with various types of multi-cylinder aircraft engine has led us by an independent route to the same conclusions as those of the British.

CAUSES OF VALVE-SPRING BREAKAGE

We had noted that, in very high-speed six-cylinder engines, valve-spring breakages were frequently encountered at speeds in excess of 4000 r.p.m.; in 12-cylinder engines the limiting speed appeared to be above 2000 r.p.m.; and in some 18-cylinder engines frequent valve-spring failures occurred at very moderate speeds, certainly not exceeding 1600 r.p.m. Naturally, the valve-springs in each case were of somewhat different design from the others but the variations were not of sufficient magnitude to refute the statement that the critical engine-speed at which valve-spring-failures assumed alarming proportions was inversely proportional to the number of cylinders or of the firing impulses. It was apparent, then, that, if valve-spring breakages were to be avoided in 12-cylinder engines running at speeds greater than 2000 r.p.m., the characteristics of the spring with respect to its natural period of vibration must be altered.

TABLE 3—CHARACTERISTICS OF SPRINGS

	Single Valve	Multiple Type
Diameter of wire, in.	0.120	0.055
Mean diameter of coil, in.	1.453	0.336
Number of effective coils	11	28
Rate of build-up, lb. per ft.	104	152

Examining a simplified expression for the periodic vibrations of valve-springs, we find that

$$t = 2\sqrt{(WL/Sg)} \tag{1}$$

where

g = equals acceleration due to gravity

L = length, in inches, of the wire in the active coils of the spring

S = stiffness, or rate of build-up, in lb. per ft.

t = time, in seconds, of one complete vibration

W = weight, in lb. per in. of length, of the wire in the spring

In Table 3 are given the corresponding dimensions and characteristics of a conventional or single valve-spring, as compared with those of the multiple type used in the new construction.

Applying formula (1) it will be found that the single-type spring has a frequency of 72 vibrations per sec., whereas, in the multiple-type, the frequency is 250 vibrations per sec. In other words, the natural frequency of the small-diameter springs used in the new construction is about 3½ times as high as the corresponding frequency of the conventional spring.

The fact that the small springs have been immune from failure, after a great many prolonged tests with high-speed engines, goes a long way toward substantiating the claim that valve-spring breakage in the past has been brought about by synchronized vibrations.

Returning to a description of the engine construction, the valve-gear operates with copious lubrication furnished by full-pressure feed to the individual camshaft-bearings aided by the oil discharged from the exhaust-valve stems at each opening. A very light sheet-aluminum cover, fastened to the valve-housing and making a taper fit over the ignition distributor-drive housings, located at the center of the engine and to be described later, prevents external leakage of oil. Oil from the valve-housing is returned to the crankcase through liberal drains, placed at both ends of the engine and provided with oil traps to prevent crankcase vapors from accumulating in the valve-gear compartment.

TIMING-GEAR AND ACCESSORY-DRIVE LAYOUT

The timing-gear and accessory-drive layout is shown in Fig. 10 and is worthy of note, (*a*) for its simplicity, the minimum number of gears being employed; (*b*) for the integral construction of the shaft and the gear, wherever permissible; and (*c*) for the use of pressure-lubricated chilled-aluminum plain bearings throughout, these three features combining to save considerable weight while preserving the utmost dependability.

The simplicity of the drives was accomplished by grouping the accessories in a manner that produced an important additional saving of weight. All fuel, oil and water pumps were combined into a single unit that is used interchangeably on both the Model 1500 and the Model 2500 engines. This unit is driven through an Oldham coupling from a short shaft journaled in the rear bearing-cap. This shaft carries an integral bevel-

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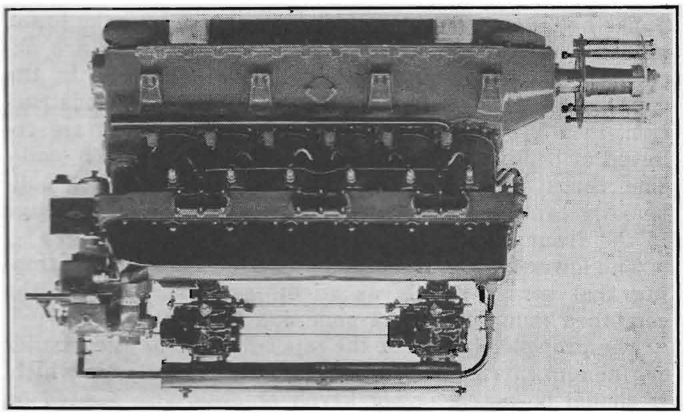

Fig. 17—Right Side of Model 1500 Inverted Engine
The Inverted Type Has Four Major Advantages: (*a*) Improved Visibility, (*b*) High Center of Thrust, (*c*) Accessibility for Maintenance and (*d*) Gravity Fuel-Feed

gear at its upper end that meshes with a bevel-gear mounted on an extension of the crankshaft.

The rear view of the Model 2500 engine, shown in Fig. 11, illustrates the simplicity of the accessory-drive layout as compared with those of previous types of aircraft engine; and the absence of engine accessories that project to the rear of the engine will be appreciated by those who have had maintenance experience with aircraft engines installed in a crowded position against the fire-wall or the front bulkhead of an airplane.

The pump unit contains three spur-gears that are housed-in to form the two oil-scavenging pumps; and these gears, in turn, each drive another unit, the first driving the water-pump, the second, the fuel-pump, and the third, the oil-pressure pump. The whole pump-unit is very compact and weighs only 16 lb., including the oil-strainer and the oil-pressure-relief valve.

Magneto

The camshaft central drive-shaft is also formed with its gears integral and is continued through the top of the crankcase to drive the special magneto by a laminated spring-coupling. This magneto is based on a principle invented by Packard engineers and developed by the Splitdorf Company, and may be briefly described as a single mechanical instrument with all the electrical parts duplicated and independent throughout. That is to say, there are only one set of magnets, one set of pole-pieces, one rotor, one driving-shaft, one coupling, one cam and one set of rotor bearings.

On the other hand, there are two primary and two secondary coils, two condensers, two interrupter-arms, and two sets of contacts, as well as double external binding-posts leading to the two separate distributors, either one of which will fire all 12 cylinders and each having its separate drive from one of the camshafts. The magneto employs but one magnetic circuit; and the two electrical circuits are independent of one another throughout. The inductive effect between the two primary windings is eliminated through the use of an impedance coil in the switch-to-ground circuit.

In Fig. 12 is shown a simplified diagram of the magnetic and electric circuits employed in this magneto. It will be noted that this instrument differs radically from the two-spark magneto used formerly to a considerable extent. In the older type, it was customary to utilize both ends of the secondary winding, the high-tension circuit being to one spark-plug to ground and from ground back through the other spark-plug. In this type, practically all electrical failures result in both sets of spark-plugs being simultaneously affected, whereas in the new magneto the two electrical systems are completely isolated from one another and, should one system fail, the operation of the other will not be appreciably affected.

Timing of both the magneto and the distributors has been facilitated in these new engines by specially developed mountings, the magneto being furnished with a slotted flange at the driving end and the accurate timing being accomplished by swinging the magneto bodily on this mounting, two 5/16-in. nuts serving to lock the magneto in its desired position. Similarly, the distributors can be rotated bodily by loosening a clamp-bolt, the final adjustment being made with the assistance of an inspection opening located over the No. 1 left cylinder terminal.

Magneto or Battery Ignition

A recently developed advantage of this ignition-system lies in the fact that by substituting a generator for the magneto and by providing a suitable contact-breaker on the end of the generator shaft, battery ignition can replace the magneto ignition when desirable, without any changes to the engine itself nor to the wiring between the distributors and the spark-plugs, the same distributors being used regardless of whether magneto or battery ignition is employed.

Because of this interchangeable ignition arrangement,

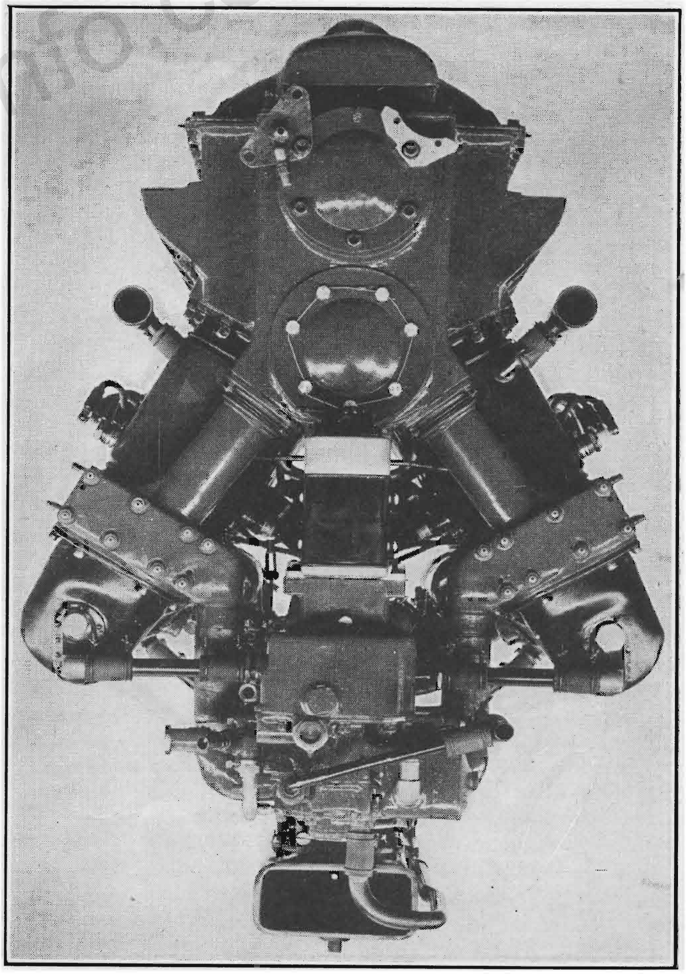

Fig. 18—Rear View of Model 1500 Inverted Engine
Fire Risk Is Diminished Somewhat, for the Gasoline Tanks Are Confined to the Extreme Bottom of the Installation

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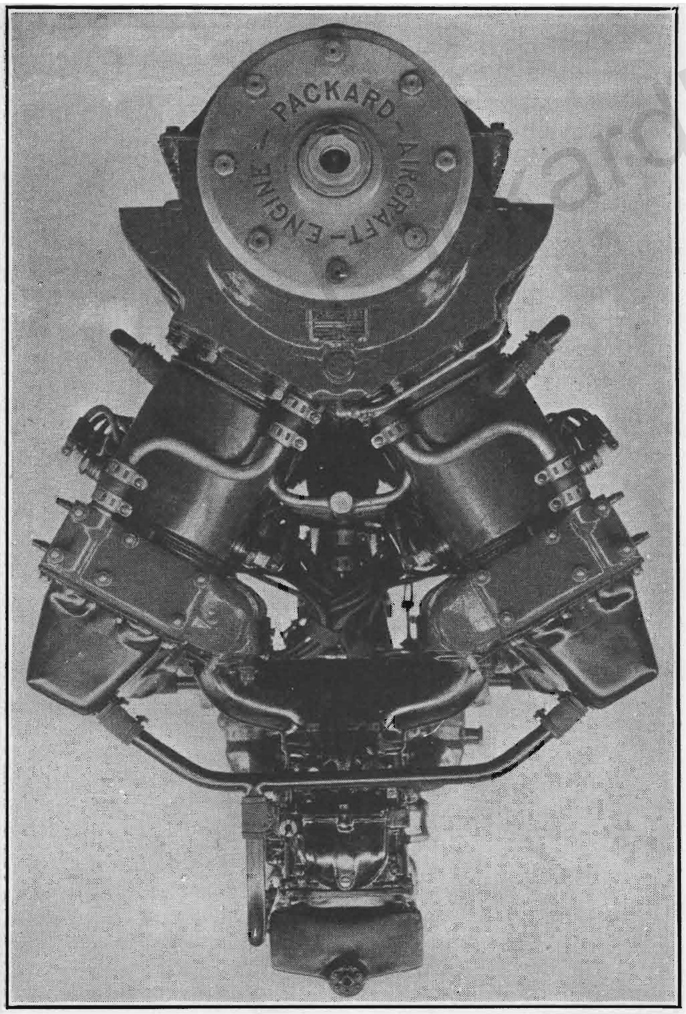
the engines used in airplanes having little demand for electric current can be equipped with magnetos, and those in airplanes requiring a considerable amount of current, for wireless, lighting, and the like, can be supplied with battery ignition. The result is, that the weight of the engine for each class of service will be kept at the minimum and an engine can very easily be transformed from one service to another.

The pistons of both the Model 1500 and the Model 2500 engines are of special interest in that they are of the slipper type and are very short and comparatively light, although of rugged construction. The Model 1500 piston is 3 11/32 in. long and weighs 2.94 lb.; the Model 2500 piston is 3 15/16 in. long and weighs 4.47 lb., bare. The smaller piston is 5⅜ in. in diameter and has only 90 per cent of the weight of the Liberty piston although having 15 per cent more area; the larger piston is 6⅜ in. in diameter and has 63 per cent of the weight of the Shenandoah engine piston although having only 9 per cent less area than the latter. The lengths of these new pistons were established after a series of tests in which the length of the skirt was gradually diminished.

CRANKCASE

The crankcases of both engines are of particularly rugged design, great depth being obtained partly because of the design of the cylinder and partly because of the arrangement of the main bearings. The eight main-bearings are of steel-backed babbitt construction, the upper half being doweled to the crankcase and the lower half to the forged duralumin bearing-caps that are accurately fitted in longitudinally machined ways in the transverse webs of the crankcase. With this construction, in a V-type engine, the main-bearing bolts are relieved of bending stresses imposed by the explosion loads. The thrust-bearing is of the deep-groove radial ball-bearing type and is located between two plain bearings in the front bearing-cap.



Gravity Fuel-Feed Avoids the Use of Complicated Piping and Pumping Arrangements

The lower half of the crankcase is an aluminum stamping that serves merely as an oil-pan and supports the combined pump-unit by a generous flange.

The propeller hub is of the taper-fit type on the smaller engine and carries a forged-duralumin loose flange which, it should be noted, is not keyed or otherwise located on the propeller hub, a construction that has proved perfectly satisfactory in flight tests as well as in overload propeller-whirling tests. This feature is shown in Fig. 13. On the larger engine, a splined hub with split centering-cones is used, as is shown in Fig. 14. This construction follows precedent and is desirable in larger engines because galling and freezing of the propeller hub are experienced with the taper construction in these sizes.

THE DRIVE

Although both the 500 and the 800-hp. engines were originally intended for direct-drive service, both have been built for use with gears, the gear-reduction forming a separate unit bolted to a special crankcase flange.

The gear reductions have been designed and built by the Allison Engineering Co., of Indianapolis. They are of the spur-gear single-reduction type and are entirely self-contained. A noteworthy feature is the employment of a shock-absorbing drive between the crankshaft and the pinion that has proved very successful in eliminating the gear trouble resulting from impact loading. Fig. 15 shows the side view and Fig. 16 the front view of the 800-hp. geared engine. These gear reductions give a two-to-one reduction to the propeller-shaft that has been found to be particularly desirable for load-carrying airplanes of moderate speed.

In addition to providing improved propeller efficiency, these geared engines lend themselves particularly well to a streamline installation; and, in this manner, improved propeller efficiency and decreased resistance combine to offer important advantages in airplane performance.

The 500-hp. engine has also been built in the inverted type and, as mentioned previously, an inverted engine has many advantages for aircraft use. It is entirely possible that the future will see the inverted engine as one of the standard types. A side view of the inverted Model 1500 engine is shown in Fig. 17, a rear view in Fig. 18, and a front view in Fig. 19.

ADVANTAGES OF INVERTED ENGINES

An inverted engine when used in airplanes, possesses four major advantages. First, in the usual type of single-engine tractor airplane, the pilot's vision straight ahead is seriously obscured by the cylinders and cowling of either a V-type or a large radial-type engine. He is practically compelled to swing the airplane from its true course to obtain a view along the normal line of flight. It is unthinkable that poor vision dead-ahead, such as this, will be tolerated when the air is as full of airplanes as we expect it to be in the future. Collisions in the air, even today, are far more numerous than would be the case if poor visibility conditions did not exist. With an inverted engine, as shown in Fig. 17, the cowling in front of the pilot can be made to slope to meet the line of the propeller-hub spinner; in this way, favorable vision can be secured.

The second major advantage of the inverted engine lies in the high center of thrust that ensures better flying qualities, in that it offsets the tendency of the airplane to climb when full power is on. The additional propeller-tip clearance is also desirable from a consideration of taxying over rough ground and, in some cases, removes the limitation on the diameter of the propeller that would otherwise exist.

A third point in favor of the inverted engine is its accessibility to a mechanic working on the ground. If the engine mounting is properly designed and the cowling suitably arranged, the engine can be readily worked on from the ground without the necessity for stepladders and other equipment. Furthermore, the crankcase covers can be removed and the bearings examined, should this be desirable.

The fourth point in favor of the inverted engine has regard to the location of the carbureters that, in many installations, will allow gravity fuel-feed and will avoid the use of complicated piping and pumping arrangements. The fire risk is also diminished to a certain extent with this arrangement, for gasoline leaks are confined to the extreme bottom of the installation, and covering the whole exterior of the engine with gasoline, as is normally the case, is not possible.

Taking everything into consideration, we must bear in mind that commercial aviation practice at present is in a very fluid state and sentiment with reference to the ideal powerplant may be expected to crystallize along any one of several different lines; among these possibilities the inverted V-type engine stands out with some attractive features.

CONCLUSIONS

This discussion would be far from complete were we not to attempt to draw some conclusions from the accomplishments described. At the outset, stress should be laid on the statement that the advance made by reducing the weight of aircraft engines to approximately 1.4 lb. per hp. represents but one of the infinitely small steps that must be taken before the commercial possibilities of aviation can be adequately realized.

It is encouraging, however, to note that, with each advance in engine design, important improvements in airplane design immediately follow; and these alternate steps typify the sound progress that is being made in aviation. Incidentally, the interrelated advances in the design of the airplane and of the engine result in continual improvements in airplane performance that, from a military standpoint, result in maneuvering qualities of a highly sensational nature.

As an example, the daring and highly skilled pilots composing the First Pursuit Group at Selfridge Field are engaged daily in maneuvers that would have been impossible a few years ago.

With airplanes that weigh complete little more than an engine of corresponding horsepower would have weighed several years ago, most astonishing performances are possible. For instance, such maneuvers included what amounts to a climbing tail-spin, that is, a vertical barrel-roll, and several barrel-rolls at the top of a loop, with practically vertical zooms for hundreds of feet. Needless to say, maneuvers such as these and the terrific acceleration that results from catapulting airplanes from battleships produce difficult problems in engine operation, particularly with reference to carburetion; in this way, progress in engine and airplane evolution adds new problems to be solved.

THE FUTURE

Turning now to the future, it may be of interest to speculate toward what direction progress in aircraft engines will lead. Contemporary problems in this field are well defined and consist largely of detailed improvements calculated to yield lighter and more reliable engines that will be more economical with respect both to first cost and to operation and maintenance. Although experimental effort in engine development is being continually directed along unconventional lines, such as the barrel and cam types and engines employing the Diesel or semi-Diesel cycle, reasons exist for believing that during the next few years important advances will be made by conventional 12-cylinder water-cooled engines and by 9-cylinder fixed-radial air-cooled engines, the two types that offer the best possibilities for immediate engineering advance.

We may look forward to having available in the near future engines that will weigh about 1 lb. per hp.; and, concurrently with this development, considerable effort will undoubtedly be devoted toward reducing the specific fuel-consumption. For it should be borne in mind that an engine weighing 1 lb. per hp. will, at the present rate of fuel consumption, consume its own weight of fuel every 2 hr. So far as performance is concerned, the useful carrying-capacity of the airplane is reduced by the amount of fuel with which it is necessary to leave the ground, although, of course, the fuel load may be distributed in a more economical manner from a structural standpoint than is possible with units of passenger or freight load.

In closing, I would like to pay hearty tribute to the men in charge of our Army and Navy aircraft-engine development work who have been largely responsible for the success of the new engines described in this paper. In the first place, they have had the foresight and the courage to demand results considered impossible of attainment but a relatively short time ago and, in the second place, they have offered valuable assistance in the way of constructive criticism at various stages in the development work. With so admirable cooperation between Government and industry, we may look forward to a period of intensive aircraft development that will result primarily in an air force for National defense that will be second to none and will form the foundation for a transportation system by air on a scale that will defy our present-day imagination.

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