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By Eugen Vohrer

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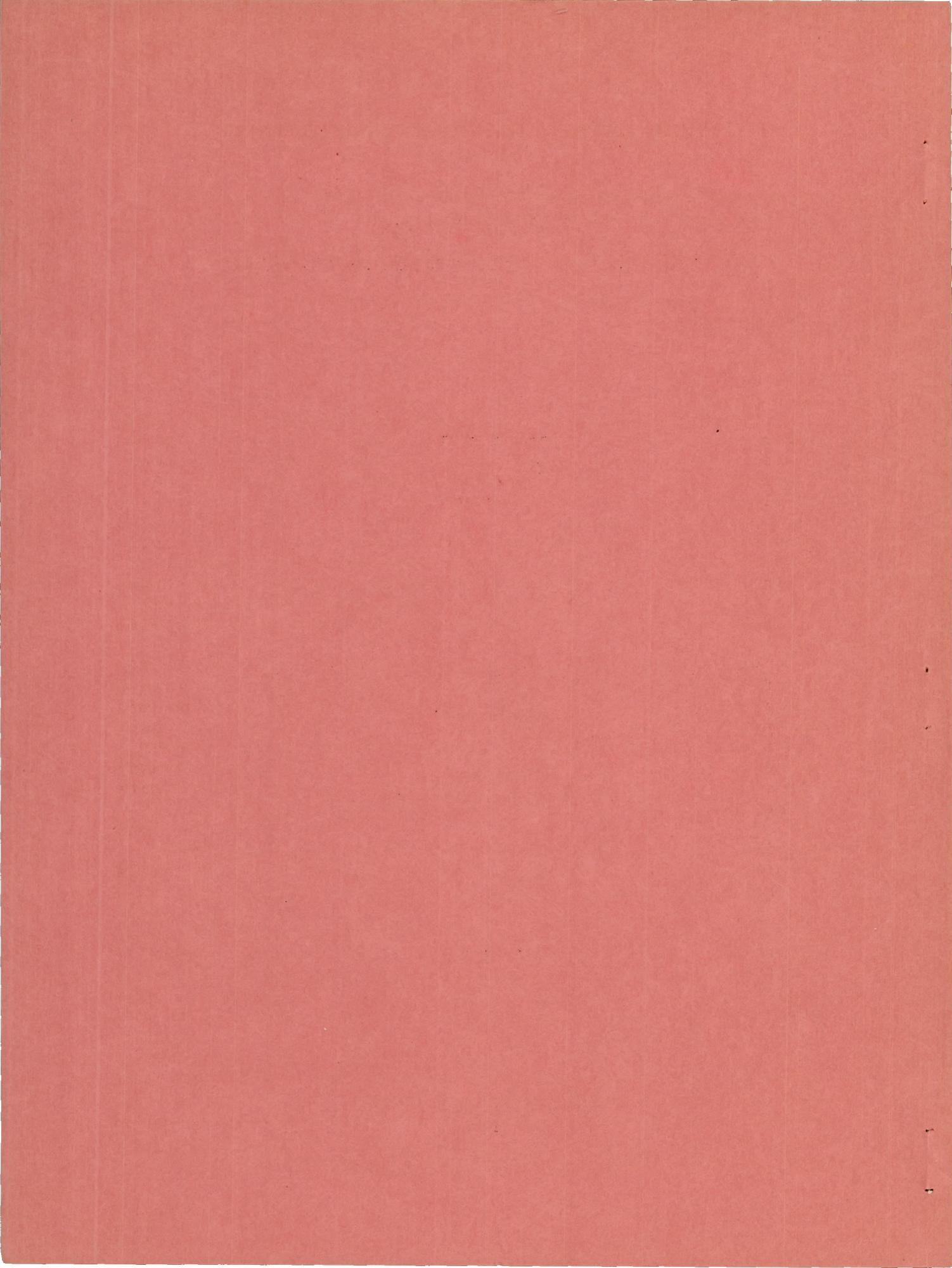Washington
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INTRODUCTION

The steadily increasing demands made on present-day
power plants due to the continued development of the air-
plane raise more and more difficult design and production
problems. Nevertheless, advances have been made in the
development of the airplane engines such as would have
been considered impossible a few years ago. Several en-
gine manufacturers (Wright, Pratt & Whitney, and Bristol)
were able in one decade to more than double the output of
their engine types (Cyclone, Hornet, and Pegasus) for the
same displacement volume and to reduce the weight/power
ratio by almost half. How was this progress made possible?

The present-day high-power engines are the result of
careful design making use of the laboriously won data on
the application of higher speeds, greater mean and intake
pressures, higher compression ratios and smaller fuel con-
sumptions. A particular impulse was given by the use of
higher knock-rating fuels and better lubrication oils, and
the mechanical problems - reduced wear of the engine parts,
increased useful life and improvement in over-all operat-
ing characteristics - are now solved to such an extent that
the intervals between overhaulings have been lengthened
from 250 hours to 500 to 600 hours and that the total life
of the engine extended to more than 3,000 hours.

This rapid development in the airplane engine is re-
sponsible for the present-day flight performance. High
short-period power performance reduces the take-off dis-
tance and makes possible favorable take-off characteristics
also for high-speed aircraft. There is an increase in the
rate of climb and at the higher altitudes high cruising
speeds are attainable. The lowered fuel consumption re-
sults in considerably greater economy, pay load, and range,
particularly for long-distance flights.

Since 1934 there has been observed a strong increase in engine performance and, in almost every country with its own aviation industry, the center of interest is the large power unit capable of generating over 2,000 horsepower. Various papers have been published in recent times on the possibilities and problems arising in connection with the creation of suitable structural forms, cylinder size and arrangement, head resistance, cooling, etc. Our purpose in the present paper is to give an outline of the present state of development and point out the possibilities available for the further increase in the power/displacement ratio, the economy, and the reliability of the engine.

HIGH-OUTPUT ENGINES

In 1936, Nutt, chief designer of the Wright Aeronautical Corporation, denoted engines of 25 or more horsepower per liter as high-power engines. Today, after two years, we can already raise this number to about 30 horsepower per liter (0.41 hp./cu. in.) for engines of over 2 liters cylinder displacement and for the smaller cylinder dimensions to 35 horsepower per liter (0.57 hp./cu. in.). The present peak values (referred to power in take-off) for the large radial engines lie at 37 horsepower per liter (Wright Cyclone G 102, fig. 1), for the air-cooled in-line engines at 57 horsepower per liter (0.93 hp./cu. in.) Napier Dagger VIII, fig. 2), and for the liquid-cooled engine between 34 and 36 horsepower per liter (0.67 hp./cu. in.) (Rolls-Royce Merlin II, Allison V 1710-C6, fig. 3).

For the development of more than average-size airplanes there are available at present principally two types of engine construction; namely, the single-row, 9-cylinder, radial engine or the 14- and 18-cylinder, double-row, radial engine with 1,000 to 1,500 horsepower and the liquid-cooled, 2×6 cylinder, in-line, V engine with 1,000 horsepower output. In addition to the high-power, air-cooled, in-line H-type engine with 4×6 cylinders introduced in England some years ago, there has been an increase in the power of air-cooled, in-line, V engines (reference 1). The original problems of providing adequate cooling of the in-line engine have given rise to bold plans for the future with the object of developing engines that will be able to enter into serious competition with the liquid-cooled power plants.

Wood (reference 2) sees the trend of development of the

liquid-cooled, in-line power plant in a 24-cylinder, X engine and points out that the engine and oil radiators could be built into the aircraft in such a manner that the total frontal cross section is only slightly greater than that of the engine alone. Actually for present-day aircraft with nozzle radiators, the power expenditure for cooling still amounts to about 5 to 10 percent of the engine power output (reference 3).

In the medium power outputs between 300 and 800 horsepower, the air-cooled, two-row engine predominates, followed by the single-row, radial engine, and only in individual cases is this performance given by the liquid-cooled engine. Engines of this output range of the air-cooled type at present attain power/displacement ratios of up to 38 horsepower/liter (Argus As 410, fig. 4; Renault 12 S) and the water-cooled type, 34 horsepower per liter (Jumo 210).

Since at large forward speeds the reduction of the frontal drag is often of greater effect than that of the weight, the large representation of the in-line engines in all power ranges is in no small measure due to their great success in the races of recent years and the victory of an air-cooled, in-line engine over the more than 50 percent stronger radial engines in the air races in the United States in 1936 (reference 1).

DEVELOPMENT OF PRESENT-DAY ENGINES

FOR HIGHER POWER OUTPUT

The continuous power developed by an engine determines in general the size of the swept volume. From the familiar power formula

$$N = \frac{1}{900} \, V_H \, n \, p_m$$

for equal displacement V_H, there are given the two possibilities of raising the power, namely, by application of higher rotational speeds (n), and by higher mean effective pressures (p_m). The maximum rotational speed of an engine is limited, however, by the restricted speed of the valve mechanism and by the maximum valve cross sections permitted by the cylinder head. For the engine with direct

intake the maximum speed limit is characterized on the power diagram by the highest point on the power curve. More recent engines at standard conditions on a normal day attain at this point a mean indicated pressure of between 12 and 13 atmospheres (177 to 191 lb./sq. in.). Investigations have shown that this mean effective pressure can be attained for a gas speed at the inlet port of about 80 meters per second (262 ft./sec.) if the latter is computed from the ratio of piston area to the maximum free port area and mean piston speed (fig. 5). If the swept volume and size of port are held fixed, the maximum values of the speed and the power to be expected may be predicted from them. Since within wide limits the free inlet cross section determines the power developed by a cylinder further improvements in the flow relations, having regard to high rotational speeds and mean pressures, are particularly promising.

For the supercharged engine the increase in the size of the valve cross sections on account of the reduced flow losses in the ports means a lowering of the supercharge pressure, supercharge temperature, and supercharge power.

According to figure 6, the flow losses amount to about 45 percent of the total power losses. In the attempt further to reduce these throttle losses, there has been an increase, in the course of development, in the ratio of intake valve diameter/cylinder diameter to about 0.5 for the two-valve cylinder and to about 0.35 for the four-valve cylinder. Exhaust valves are in general 6 to 11 percent smaller in diameter than the intake valves. The question arises as to what shape of combustion chamber makes possible the application of maximum valve areas. The most favorable conditions appear to be for the case of the spherical-shape combustion chamber with two obliquely arranged valves. Large valves require, however, correspondingly large lifts to which especial attention must be paid, particularly with regard to the durability of the valve springs at the higher valve gear speeds. The smaller lift of the four-valve arrangement is more favorable in this respect, though not providing the possibilities for maximum valve cross section.

In many cases the choice of more favorable valve timing, taking account of the rotational speed and supercharge pressure, leads to a further improvement in the mean effective pressure. From 4 to 8 percent higher values, according to the initial conditions are attainable (reference 4),

(fig. 7) and these may be raised still further by an increase in the volumetric efficiency through the scavenging of the burned gases remaining behind (ref. 8).

Undoubtedly, the most effective means for raising the useful pressure lie in increasing the air flow through the cylinder. Care must be taken, however, that the weight of air drawn in is converted into power at high efficiency. According to Ricardo, the effectiveness of a combustion chamber may be expressed by the factor

$$\eta = \frac{\text{indicated power (hp}_i)}{\text{air consumption (kg/h)}} C$$

where C is a constant which for 87 octane aviation gasoline may be set equal to 87.8. According to tests, the spherical combustion chamber has the advantage over the roof-shaped or cylindrical chambers (fig. 8). For operation with direct air intake, high-power mixtures, and well-shaped combustion chambers, there are at present attainable 1,500 indicated horsepower per kilogram air per second (595 bhp./cu. in.). The dependence of this ratio on the supercharge pressure and the fuel-air ratio is shown in figure 9. The effect of the rotational speed is insignificant.

The effect of the compression ratio on the mean pressure is relatively small but on the ignition pressure it is considerable (fig. 10). For a given fuel the mean pressure may be increased more by supercharging than by the application of a higher compression ratio. On the other hand, the higher thermal efficiency of the high-pressure engine leads to lower fuel consumption, so that for purposes of greater economy, range, and power a compromise must be made between the degree of supercharge and the compression ratio, the limits being drawn by the knock rating of the fuel. For an economical ratio between the power and weight of a power plant, Ricardo suggests for the immediate future a rise in the ignition pressure to 80 kg/cm² (1,150 lb./sq. in.). With the application of 87 octane fuel, greater compression ratios than 7:1 for the air-cooled engine and 8:1 for the liquid-cooled engine do not appear to be of any further advantage, since beyond this limit the thermal efficiency no longer increases proportionately with the compression ratio ϵ, although the maximum pressure continues to rise. At $\epsilon = 7$ the maximum pressure of 80 kg/cm² will be attained at about 1.5 atmospheres supercharge and for $\epsilon = 8$ at about 1.23 atmospheres supercharge.

The effect of the supercharge temperature on the power, according to tests thus far made, is a function of the type of construction of the cylinder. Figure 11 shows that high supercharge pressures may lead to considerable power losses. Here too, possibilities appear for the effective reduction of these losses by the improvement of the supercharger, utilization of the cooling effect of the fuel evaporation, and the lowered atmospheric temperatures at high altitude and, finally, by the cooling of the charge by means of alcohol or water.

With present airplane-engine superchargers there are now attainable adiabatic efficiencies of 70 to 75 percent. Test laboratory results give values lying above 80 percent which will probably be practically utilized in the near future. The importance of improvement in the efficiency may be seen in the fact that a 10 percent increase, for example, in the efficiency of a supercharger with 7,000 meters critical altitude gives an increase in power of 4.5 percent or for equal temperature an increase in the rated altitude by about 1,000 meters. Figure 12 shows the attainable cooling effect through the fuel evaporation as a function of the fuel-air ratio. The temperature of the supercharge air and the efficiency of the fuel preparation determine the proportion of the fuel evaporated. With good atomization approximately half the fuel will evaporate at 20° C. and above 50° C. the total fuel will evaporate. Complete utilization of this advantage will be mainly the result of the fuel and mixture preparation ahead of the cylinders while in the case of direct fuel injection into the cylinder the shorter time available for the mixture preparation will result in a lowered mixture cooling. The utilization of the decreasing air temperature with altitude is possible, however, where the mixture is allowed to form directly in the cylinder or at a position between the supercharger and inlet valve by means of a carburetor and where the supercharge air temperature is already so high on account of the compression that intake air preheating is not required to take care of icing danger or to improve the mixture preparation. At the rated altitude of 4.5 kilometers the difference in power between preheating the intake air to $+15^\circ$ C. and utilization of the cold air already amounts to 8 percent. The most effective mixture cooling through fuel evaporation and elimination of preheating are therefore possessed by engines with pressure carburetors. The possibility of supercharge cooling by means of the addition of water or alcohol will be discussed below in connection with the increase in take-off power.

If the rated altitude of a power plant is 4.5 kilometers about 80 percent of the cruising power will be available at 6 kilometers altitude. These relations will be sufficient, except for some particular cases, for practical purposes in the near future. At 7,000 meters critical altitude of the supercharger, 1.3 atmospheres supercharge are still available at 4.5 kilometers (15,000 ft.) with a supercharge temperature which is still sufficiently far below the knock limit. The required peripheral wheel speed of about 325 meters per second is still far removed from the limiting output of single-stage superchargers, which limit is at present determined by the strong lowering in the supercharger characteristics after attaining the speed of sound corresponding to a peripheral speed of about 500 meters per second and a delivery head of 12,700 meters. Further possibilities for raising the altitude are offered by the improvement of the gas-flow process. Earlier valve opening time and later closing of the outlet valve lead to greater power with increasing altitude through scavenging. A compromise will have to be effected between the valve timing overlap and the present requirements of safe idling and good starting of the engine. In many cases, the determination of the most favorable ignition timing is of importance for the power and fuel consumption at high-altitude operation. From the increase in the air-flow discharge and the decrease in the pumping and exhaust power for a constant supercharge pressure of 1.033 atmospheres and constant supercharge temperature with normal valve timing, the following increases in power with altitude are to be expected:

Altitude in km	0	2	4	6	8
Increase in indicated power in percent	0	4	7	9.25	10.5

The problem of cooling is one of the most serious of the airplane-engine designer. Development and research have given him a wide field and the problems are so numerous that they can be sketched only briefly in the following. Since there is little promise for an appreciable improvement in the present thermal efficiency of about 31 percent, referred to indicated-power and high-power mixture, each increase in the power/displacement ratio leads inevitably to an increase in the heat losses by almost the same percent as the increase in power. Fundamental methods had to be found to conduct away this waste heat in order to obtain moderate temperature rises in the struc-

tural elements as cylinder head, piston, and other parts.
Thus, for example, Wright has increased the cooling-fin
area of the cylinder head and cylinders of the Cyclone by
120 percent while the power has increased by only 62.5 per-
cent (reference 5). In the case of the Pegasus, Bristol
has obtained a 113-percent power increase by increasing the
total fin area by 164 percent (reference 6). The fin spac-
ing for the cylinder head now amounts to 5 to 5.5 milli-
meters (.216 in.) for a maximum fin depth of about 40 milli-
meters (1.56 in.). If, as in the case of the Pegasus XVIII,
the cooling fins are milled from the complete cylinder, the
fin spacing may be chosen from 4.5 to 5 millimeters and the
fin depth up to 55 millimeters (2.16 in.). Table I shows
some cooling surface characteristics of airplane engines.

By proper cowling of the cylinder and shaping of the
cooling-air inlet, it is possible to lower the cylinder
temperatures and cooling losses. Regulation of the cooling-
air cross sections at the exit of the engine cowling im-
proves the cooling action at small speeds and at high speeds
reduces the cooling which without cross-section regulation
would increase with the third power of the flight speed.
The cooling-air requirement of present-day engines lies
between 15 and 30 kilograms per horsepower-hour (6.83 lb.
and 13.66 lb.) and the internal cooling-power expenditure
between 1.5 and 3 percent of the engine output. The most
difficult cooling conditions occur in climb on account of
the high engine power required and the low flight speeds.
The high fuel consumption of 300 grams per horsepower-hour
in take-off is due to the fact that the insufficient air
cooling must be assisted here by the "fuel cooling." Con-
siderable improvement may be expected by the application
of forced cooling (reference 7).

By means of liquid cooling, it may be easier to main-
tain the combustion space and the portion of the cylinder
covered by the piston travel at a uniform temperature.
The problems here are less those of the engine than those
of the radiator since with a liquid-cooled engine it is
always possible, on the assumption of sufficient mechani-
cal strength, to attain increased power for special pur-
poses by changing only the amount of fuel, supercharging
pressure, and size of radiator. In further development
it will again be striven to eliminate the heat stresses
of the cylinder and to improve the heat transfer from the
external surfaces to the cooling medium and the operating
conditions of the piston. According to most recent re-
sults obtained, it is possible to reduce the interference

drag by lowering the radiator into the fuselage or wing and through the application of nozzle cooling (cooling with small speeds) to reduce greatly the internal cooling drag (reference 7). The wing-surface radiator will lose more and more in importance with the continually decreasing wing areas required for the high speeds. There are, moreover, indications that the profile drag increases on account of the increased viscosity of the heated boundary layer (reference 3). It appears to be possible both for the liquid- and air-cooled engines to attain a cooling power expenditure which makes up only a small portion of the engine propulsive power.

METHODS OF INCREASING TAKE-OFF POWER

The trend of airplane design has been such that the engine is called upon to deliver continually increasing power at take-off. At first a 10-percent-higher-than-rated power was considered satisfactory. At the present time, however, engines are known which have a 25 percent increase of short-period output. Competitive races and performance records also contribute to the ever increasing demand on the engine power. The limit for the supercharge pressure required for these powers is determined by the occurrence of knocking. Fortunately, fuel chemists have succeeded in improving the knock rating of the fuels to such an extent that it is rather the cooling and maximum pressure that may be looked upon as the limits of power increase.

For supercharged engines 87 octane fuel is at present employed almost without exception. Recent tests have shown, for example, that for favorably shaped combustion chambers knocking is set up at a supercharge pressure of 1.4 atmospheres and a supercharge temperature of 110° C. (fig. 11). Such temperatures occur in operation near the ground with a supercharger designed for 4,500 meters rated altitude and 1.3 atmospheres supercharge pressure. In such a case between the rated and the take-off power there would be possible a supercharge-pressure increase of only 7.5 percent. Under the assumption that the maximum mean indicated pressure (p_i = 12.5 atm.) occurs for a gas velocity of 80 meters per second at the intake and for the most usual stroke-bore ratio H:D = 1.1, figure 13 shows the maximum speeds and the attainable powers for the various cylinder sizes. The unfavorable effect of high supercharge temper-

atures on the engine power here comes plainly into evi-
dence. Investigations having for their object the lower-
ing of the temperature and the raising of the supercharge
pressure are concerned with the application of high octane
fuels, speed regulation of the supercharger, and super-
charger cooling by injection of water or alcohol.

The improved fuel efficiency makes possible the appli-
cation of higher temperatures, supercharge pressures, and
compression ratios without the fear of knocking. The ad-
vantages gained in power in raising the octane number from
70 to 87 to 100 are very great. Thus, according to Ricardo,
for a compression ratio $\epsilon = 6.5$ in passing from 87 to 100
octane there is an increase in the mean effective pressure
by 52 percent if the power in each case is limited by
knocking (reference 8). Of this power increase available
only about 15 percent is at present utilized. Thus, for
example, the 30-liter Pratt & Whitney 14-cylinder double-
row radial engine Twin Wasp gives 1,065 horsepower take-off
power at 87 octane and 1,215 horsepower at 100 octane.
With this fuel the supercharger with no regulation would be
utilized better near the ground without lowering of the
supercharge temperature and the power required for driving
the supercharger. The possibility of raising the compres-
sion ratio through the use of high octane fuel up to the
maximum compression limit imposed by the engine construc-
tion would be a means of lowering the supercharger power
requirement and the specific fuel consumption. In addition
to the fuels of 100 octane number, there also deserves to
be mentioned the favorable characteristics pointed out by
O. Kurtz of a three-component mixture Bi-Bo-Alc with 90
octane (reference 4).

In connection with the lowered atmospheric temperature
with increasing altitude, the end temperature of the super-
charge air for the supercharger with fixed gear ratio and
constant efficiency decreases somewhat faster than the in-
take temperature with the altitude and the required super-
charger power increases. As regards the effect of the de-
creasing exhaust back pressure on the gas flow, there is
an increase in engine power with altitude for constant su-
percharge pressure. In the ideal case of no losses and
continuous regulation, the gear ratio between engine and
supercharger will be varied so that the presecribed super-
charge pressure will just be attained. Power requirement
and compression end temperature thereby decrease to such
an extent on the ground that for a 4.5 kilometer supercharg-
er and 1.3 atmospheres supercharge pressure, there may be
an increase in the take-off power of about 25 percent.

With increasing altitude, the engine power falls off by
the increase in the power taken by the supercharger and the
end temperature until at 4.5 kilometers rated altitude it
reaches the power of the engine with unregulated super-
charger. Without supercharger regulation there would be
required in the case of the example given an increase to
about 1.5 atmosphere for a 25-percent take-off power in-
crease. The advantages of the centrifugal supercharger
with speed regulation are maintained not only for the
take-off and climb but its application leads to greater
rated altitudes such as were not considered possible on
account of insufficient take-off power. The question as
to what supercharge processes approach the "ideal case"
most closely and what speed regulation possibilities
possess any promise of success for the airplane engine
supercharger was considered by A. Nutt in his paper before
the Lilienthal-Gesellschaft in 1936 (reference 5). The
two-stage supercharger already in use to some extent may
be considered as the first step to speed regulation. Ac-
cording to the favorable results of a test design of the
D.V.L. (reference 11), the no-losses, stageless supercharge
regulation is no longer to be considered as an unsolved
problem. The application of the exhaust turbine super-
charger is hindered by the high exhaust temperatures
(1,000° C. to 1,150° C.) of internal combustion engines.
Their practical application will depend on the further im-
provement of heat-resisting materials and the production
of an economic cooling method of the gases before imping-
ing on the blades without the usual disadvantages for the
turbine and the propulsive power, or through sufficient
cooling of the endangered structural parts themselves (ref-
erence 10). The exhaust turbosupercharger will have the
advantage over the mechanically driven supercharger, partic-
ularly in fuel consumption and in range at high-altitude
flight.

The requirement of effectively lowering the large
loss in power at high supercharge temperatures has suggest-
ed the utilization of the high heat of evaporation of water
and alcohol, since surface radiators, on account of their
size and weight, their uneffectiveness in take-off, and
their additional propulsive loss in flight are eliminated
as far as economical installation is concerned. The re-
sults of present D.V.L. tests (reference 4) indicate that
through the injection of water or alcohol into the cylinder
a considerable lowering in the charging and combustion
temperatures amy be attained with small expenditure. Since
cooling of the charge appears necessary only for the case

of the short-period power output, the weight expenditure for
cooling remains within tolerable limits. If the advantages
of charge-cooling are combined with the possibilities of a
100 octane fuel, we may obtain power/displacement ratios
which with present-day means we shall hardly be able to ex-
ceed. The way leads step by step to those peak outputs of
70 to 100 horsepower per liter which can now be attained
only in the laboratories on test engines.

On the way to these performances the further develop-
ment of the two most highly stressed structural parts,
namely, the piston and the exhaust valve must lead to spe-
cial progress. Improvement in the heat flow, sufficient
resistance to increased maximum pressures, decrease in car-
bon deposit, fractures and wear on the piston rings, and,
finally, piston cooling are the problems of design and in-
vestigation for the near future. Sticking piston rings and
piston seizing are the most common of engine disturbances.
We can no longer restrict ourselves to the piston rings
alone in conducting the heat away to the cylinder walls,
but must also, in the view of Ricardo, strive to attain ef-
fective cooling of the piston rings by heat transfer to the
oil. This requires the use of a very large number of deep
cooling fins on the under side of the piston as well as an
increase in the distance of the first piston ring from the
piston bottom, in order to remove the latter farther from
the direct effect of the combustion gases. The lack of
uniformity in the quantity and direction of flow of the oil
to be injected on the inner side of the piston is to be
replaced by a carefully regulated flow of cooling oil and,
finally, we may expect improvements also in the piston ma-
terial.

With the increasing heat to be disposed of by the cyl-
inder and the higher mechanical stresses through the rising
rotational speeds, the structural shape and material of the
exhaust valve have changed considerably. Chemical cooling
of the exhaust valve has been improved by keeping the en-
tire valve head hollow so that it can be cooled in the
same manner as the valve stem. Pye announces a new material
for the valves which should be an improvement over stellite
(reference 9).

THE VARIOUS METHODS OF PREPARATION OF THE FUEL MIXTURE

AND THEIR EFFECT ON POWER, ECONOMY, AND SAFETY

The carburetor method still occupies the chief place
in mixture preparation before injection. The progress
made in power, fuel consumption, and safety are to a large
extent the result of the efficiency of our present carbu-
retor installations. Foreign engine manufacturers often
guarantee fuel consumptions for cruising of 195 grams per
horsepower-hour, and only recently in a test of the Argus
As 410 (fig. 4) a fuel consumption of only 186 grams per
horsepower-hour could be obtained. Ice and condensation
deposits, sensitivity to position, and danger of fire ap-
pear as disadvantages of the carburetor for the elimina-
tion of which various methods are suggested: carburetor-
heating, air-preheating, addition of alcohol, elimination
of the float-type carburetor. Ice formation is the most
serious problem. After it was found that warming the car-
buretor by the engine-lubricating oil was inadequate, an
attempt was made to warm the intake air by means of the
exhaust gases. Space and weight requirements are too great,
however, for a sufficiently large preheater and, moreover,
preheated air leads to considerable loss in power. A more
favorable method, according to the English tests, appears
to be the addition to the fuel of 3 to 5 percent alcohol
which, whenever there is a tendency to ice formation, is
independently supplied by a simple apparatus from a small
tank and is atomized together together with the fuel.
Pressure carburetors connected between supercharger and
cylinder eliminate any necessity for a deicing method and
make possible for high altitude operation the utilization
of the decreasing atmospheric temperature. With regard to
uniform mixture distribution in the case of a large number
of cylinders, pressure carburetors offer considerably
greater difficulty than suction carburetors arranged ahead
of the supercharger. Carefully serviced carburetors at
present attain a time interval between overhaulings of 500
to 600 hours.

A fundamental means of elimination of the disadvan-
tages of operation with a carburetor is found in the me-
chanical preparation and distribution of the fuel. It is
known that an engine with fuel injection into the cylinder
gives a higher power output than an equally large carbu-
retor engine. The reasons for the increase in power are,
according to Ricardo, to be found in the greater air flow

due to the elimination of the carburetor throttle losses
and in the possibility of the dead air scavenging without
loss in fuel. For large overlap of the valve timing an
increase of 15 to 20 percent in power may be expected
through dead-air scavenging. On the other hand, it is not
to be expected that with direct injection merely the fuel
preparation will be as good as with the carburetor, but
by means of intensive atomization of the fuel adjustment
of the fuel jet to the shape of the combustion space and
good turbulence of the fuel-air mixture in the cylinder,
care must be taken to see that even the last fuel drops
reaching the cylinder do not escape combustion.

Under certain conditions, it may even be necessary
to make use of the Diesel engine methods to attain an ef-
fective mixing. As regards fuel consumption, there is no
essential difference between the injection and carburetor
engine. The application of high-boiling-point gasoline
which, on account of the low volatility cannot be consid-
ered for the carburetor engine, is promising for the di-
rect fuel injection into the cylinder.

Of equal importance for all mixture preparation proc-
esses is the proper choice of fuel-air ratio and its regu-
lation. Lowering of the fuel consumption is of utmost
significance for economy over long ranges. One of the
means of attaining it is the operation with excess air.
The progress attained in the improvement in the mixture
preparation and distribution have made possible the appli-
cation of higher excess air ratios with lower fuel con-
sumption. The lowest consumptions today lie within the
range of an excess air coefficient of 1.10 to 1.25, cor-
responding to a decrease in power, for constant super-
charge pressure, of 10 to 20 percent based on the maximum
power mixture ($\lambda = 0.8$ to 0.9, fig. 14). As a result of
the lowered combustion speed in the case of excess air,
there is a retardation in the pressure rise and the com-
bustion continues far into the expansion stroke with the
consequences of after-burning and high exhaust tempera-
tures. By advancing the ignition, these disadvantages may
be eliminated and conditions obtained which are suitable
for continuous operation. The utilization of this knowl-
edge means a fuel-saving in cruising flight of about 20
percent.

The requirements for increased power, economy, and
safety of recent high-performance engines have made it
necessary that the pilot be relieved as far as possible

from regulating the engine and this function be trans-
ferred to regulating devices. The methods of regulating
themselves have in the course of development become more
numerous and complicated. The power is regulated by the
supercharge-pressure regulator operated through oil pres-
sure by changing the throttle-valve setting. In most
cases the supercharge-pressure regulators are no longer
designed as simple final pressure regulators for a single
adjustable maximum pressure but as single or several-
stage regulators for variable supercharge pressures. It
has the function of always maintaining constant the pres-
sure selected by the pilot's throttle lever and of being
continuously variable up to the take-off supercharge pres-
sure so that at all altitudes there remains no range of
dead motion of the throttle lever. A similar effect may
be attained with a simple final pressure regulator by put-
ting a throttle valve ahead of and behind the supercharger.
The application of the excess-air method and flight at
high altitudes require, in order to remove the difference
in fuel consumption and avoid engine injury due to the
inaccurate setting, an independent mixture and ignition-
point regulation. The importance of this regulation be-
comes clear when it is considered that before its intro-
duction differences in fuel consumption of 25 percent were
found for the same engine and airplane design. The mix-
ture regulators have in general two fundamental settings,
one for full load, denoted as "rich mixture" and one for
reduced load, denoted as "poor." Whereas, in the case of
the carburetor engine, the mixture regulator only regulates
the mixture for altitude in the case of direct-injection
engines, the fuel regulator must properly adjust the fuel
to the intake air. This explains the fundamental differ-
ence in the construction of the two types of regulators.

SPECIAL PROBLEMS

The above considerations have been restricted to the
development of the type of airplane-engine construction
that is practically the only one in use, namely, the valve-
operated, four-stroke, spark-ignition engine. The years
of research and development have brought this standard air-
plane engine to such a high stage of maturity that engines
of a newer type of construction may not be expected to
surpass its performance in a short time. There are no
limits, however, set to the spirit of technical progress
and therefore the question arises whether unusual changes
in airplane-engine construction might have any chance for

success.   In the center of these special problems stands
the sleeve-valve engine.   Interest in the Diesel engine
seems in recent years to have fallen off in view of the
hardly attainable weight requirement and the continuous
decrease in the fuel consumption of the spark-ignition
engines.   The tendency toward ever-increasing flight
speeds further restricts its range of applicability, and
only in long-range flight will it remain for the present
of advantage over the spark-ignition engine.

The way to sleeve-valve-driven airplane engines was
pointed out by Ricardo and the Bristol firm in England.
The two engine types, Perseus and Hercules, that are put
out in series production are a proof of the practicability
of the sleeve-valve engine.   The 9-cylinder, radial
Perseus XII with 24.8 liters displacement (fig. 15) has a
maximum power output of 918 horsepower at 1980 meters al-
titude and the 14-cylinder, double-row Hercules (fig. 16)
with 38.7 liters displacement has an output of 1,375
horsepower at 1,220 meters.   These four-stroke sleeve-
valve engines already attain the peak values of 36 to 37
horsepower per liter of the poppet-valve engines.   The
numerous advantages - higher volumetric efficiency, ability
to assume a greater load through high knock rating, lower
fuel consumption, better mean effective pressures by util-
izing stratified charge, and turbulence obtained by Ricardo
with Burt-McCollum sleeve-valve mechanism are not to be
overlooked.   It is not to be supposed that development will
stop there.

To the problems of future engine development belongs
also that of the two-stroke-cycle engine.   For serious at-
tempts seem up the the present to have been made to develop
a two-stroke engine for operation with gasoline.   The im-
perfect cylinder scavenging and the difficulty of the heat
transfer seriously obstruct the way to success.   The
straight flow scavenging seems to be the one most closely
approaching the ideal case of uncontracted laminar flow
and the most successful.   The advantage of slots on the
cylinder periphery of the opposing piston engine has al-
ready been pointed out by O. Kurtz (reference 4).   Nothing
seems more suitable here than the application of the
sleeve-valve already used in the four-stroke engine which
is also known to give low head resistance.   It is hardly
to be supposed that with such sleeve valve gear difficul-
ties will arise in obtaining the proper time areas for
the cross section for the scavenging and expansion of the
gases.   The power expended in scavenging will in this case

not exceed 7 to 8 percent of the engine power. In doubling the working strokes, we must take into account the considerable increase in the specific flow heat. For equal mean piston pressures and rotational speeds, two-stroke engines show a 40 to 60 percent higher heat stressing of the cooling surfaces than the four-stroke engines. It is therefore to be assumed that liquid cooling will be the only type of cooling applied to the two-stroke spark-ignition engines for the present, particularly since with four-stroke sleeve engines it is already difficult to cool the cylinder head effectively by air. For the protection of the piston and piston rings against seizing, there are to be used the methods already familiar from the two-stroke Diesel engines and the object will be attained more quickly if it is decided to make use of forced oil-cooling of the piston. The advantages to be expected from the two-stroke engine may briefly be summarized as follows.

Low pressures of the charge due to large scavenging cross sections, lower stressing of engine through the action of the ignition pressures which in each rotation counteract the inertia pressures, and more uniform rotational torque that are all favorable to high speeds with adequate volumetric efficiency and high power to weight ratio; large cylinder outputs that require fewer cylinders or cylinders with smaller displacement volumes as compared with the four-stroke engine; and lower exhaust temperatures that are favorable to the application of the exhaust turbine.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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TABLE I

Cooling Area Characteristics of Airplane Engines

	Displacement Number of cylinders	Take-off power	Cooling area Displacement			Cooling area Cylinder power
			Cylinder head $m^2/liter$	Piston travel $m^2/liter$	Total $m^2/liter$	
	liters	hp.				$m^2/hp.$
Wright Cyclone G 100	29.85/ 9	1100	0.435	0.168	0.603	0.0164
Wright Cyclone GR 1820	29.85/ 9	850	.370	.155	.525	.0184
Bristol Pegasus XVIII	29.1 / 9	980	.387	.195	.582	.01725
Bramo Fafnir	26.8 / 9	950	–	–	.661	.0187
BMW 132	27.7 / 9	880	–	–	.602	.0190
Napier Rapier	8.86/16	340	.272	.203	.475	.01235
Argus As 410	12 /12	450	.389	.264	.653	.0175

Figure 1.- Wright "Cyclone G 102". Bore 156 mm, stroke 174 mm, V=29.88 liters, take-off power 1115 hp. n=2300 r.p.m., rated power at 1830 m altitude 913 hp. at 2200 r.p.m. octane number of fuel 90, ϵ = 6.7 , outside diameter 1400m , length 1412 mm ,weight 578 kg, propeller reduction gear 16:11 . Fuel consumption in cruising 193 g/hp.hr. Wright also makes a similar design of a 14 cylinder double row radial engine(V = 42.1 liters) for 1520 hp. take-off and 1217 hp. rated load near the ground.
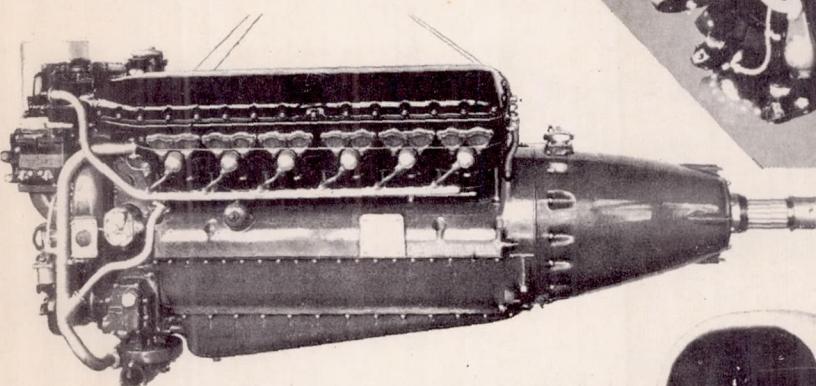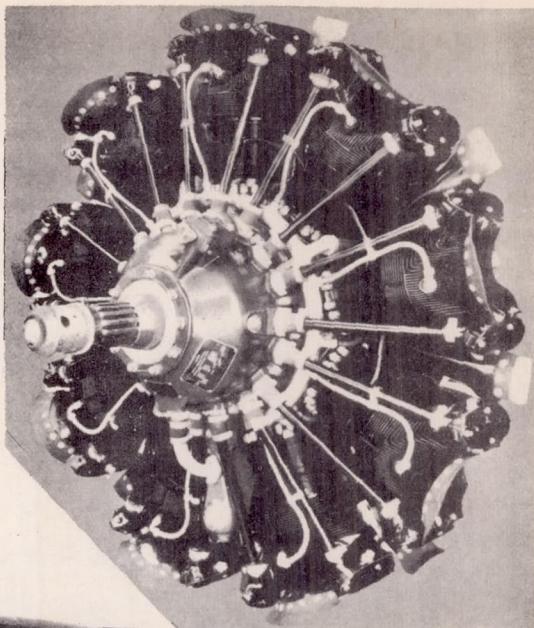
Figure 3.- Allison "V 1710-C 6". 12 cyl., liquid cooled, bore 139.7 mm, stroke 152.4 mm. V = 28 liters , take-off power 1014 hp., n = 2600 r.p.m., 1.205 at. supercharge, cruising power 700 hp., n = 2300 r.p.m., fuel octane number 87 , ϵ = 6 , length 2.4 m. Width 0.778 m , height 1.07 m , propeller reduction gear ratio 2.1 , weight 580 kg.
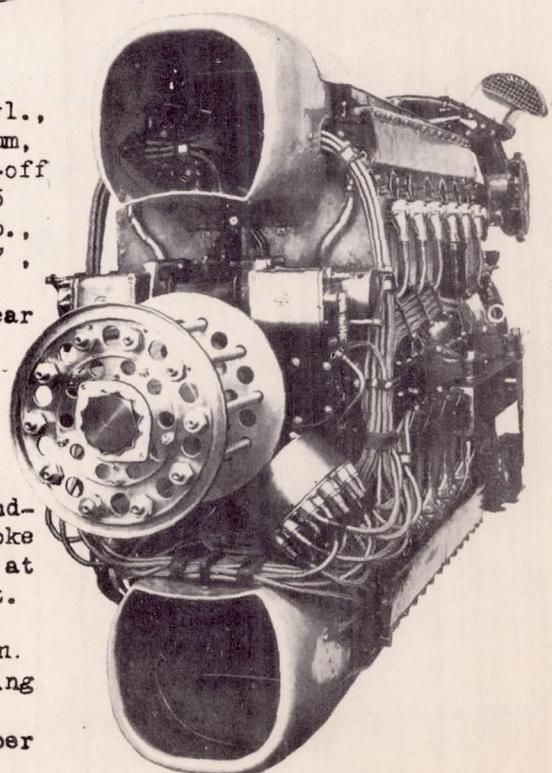
Figure 2.- Napier Dagger VIII. 24 cylinder H type , bore 97 mm, stroke 95 mm, V = 16.85 liters, maximum power at ground 969 hp. at 4200 r.p.m., 1.455 at. supercharge pressure, maximum power at 2.67 km. altitude 1014 hp. at 4200 r.p.m. 1.385 at. supercharge pressure , cruising power (max.) 781 hp. at 3600 r.p.m., 1.279 at. supercharge, fuel octane number 87, ϵ = 7.75 , weight (dry) 592 kg.
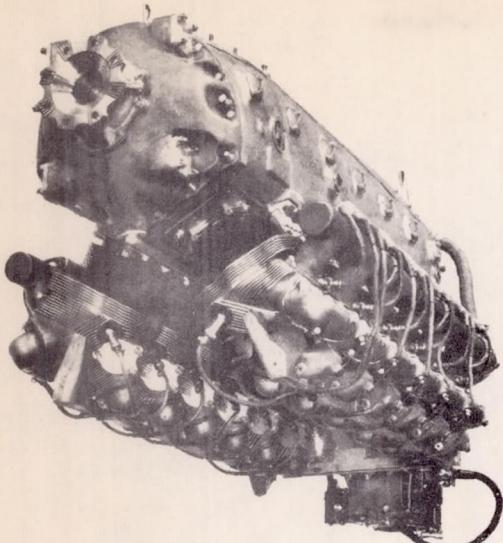
Figure 4.- Argus, As 410. 12 cyl., stroke 115 mm, bore 105 mm, V = 12 liters, take-off power 450 hp. at n = 3200 r.p.m., rated power 360 hp. at n = 3000 r.p.m., cruising power = 300 hp. at n = 2820 r.p.m., fuel octane number 87 , ϵ = 6.4, length 1595 mm, width 655 mm, height 875 mm, weight 300 kg. propeller reduction gear ratio 3.2 , fuel consumption 190 g/hp. hr.
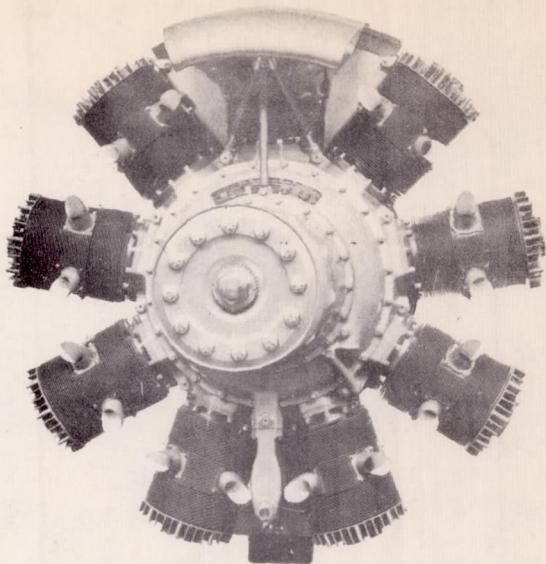
Figure 15.- Bristol, "Perseus XII". 9 cyl. sleeve valve engine, bore 146 mm, stroke 165 mm, V = 24.9 liters, maximum power at ground 840 hp. at n = 2650 r.p.m., maximum power at 2 km altitude 918 hp. at n = 2750 r.p.m. rated power at 2 km. altitude 755 hp., outside diameter 1320 mm.
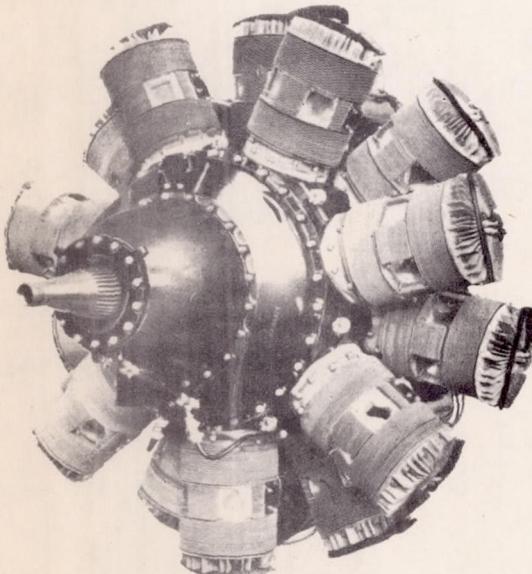
Figure 16.- Bristol "Hercules". 14 cyl. double row radial engine with sleeve valve gear, bore 146 mm, stroke 165 mm, V = 38.7 liters, maximum power at ground 1290 hp. at n = 2650 r.p.m., maximum power at 1220 m altitude 1375 hp. at n = 2750 r.p.m.
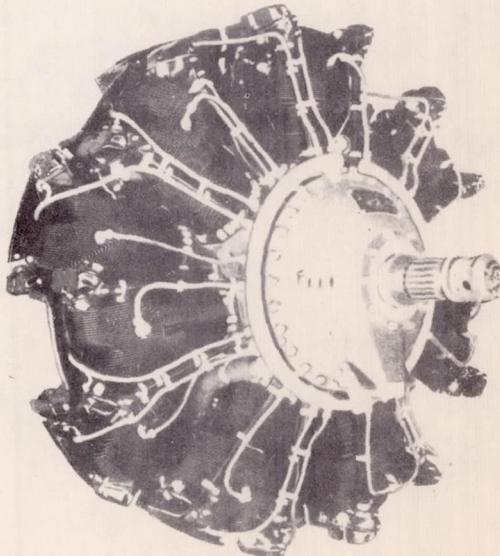
Figure 17.- Wright Cyclone 14 cyl. double row radial engine (see figure 1).
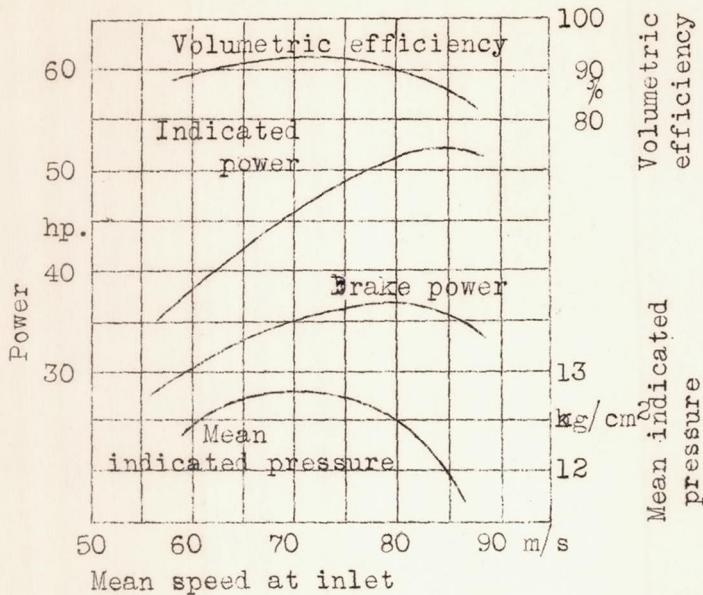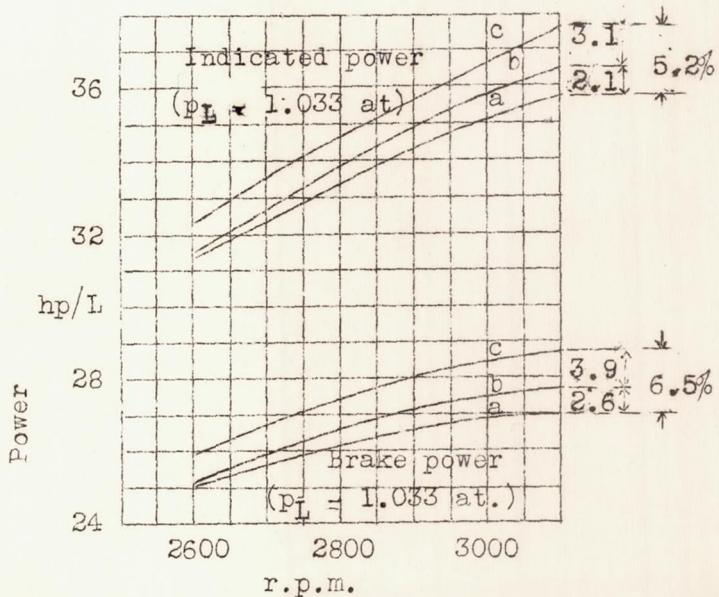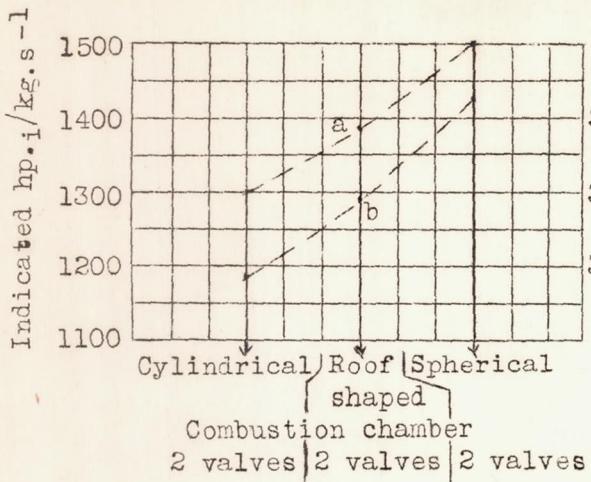
Figure 5. - Power, volumetric efficiency, mean indicated pressure as functions of the velocity at intake. Single-cylinder tests with a 1 liter cylinder, supercharge pressure 1.033 at., $\epsilon = 6.5$, supercharge air temperature $t = 20^\circ$.

Figure 7.- Increase in power through improved valve timing. a) power curve with outlet cam, b) power curve with more favorable valve timing, c) power curve with more favorable timing and greater opening times of the valves.

Indicated hp.$_i$/kg.s^{-1}

1500
1400
1300
1200
1100

a
b

Cylindrical│Roof │Spherical
          │shaped│
       Combustion chamber
     2 valves│2 valves│2 valves

Efficiency of combustion chamber

36 %
34
32

Figure 8.- Efficiency of
          combustion chambers.
a) indicated power per kg. air
per second, b) efficiency of
the combustion chamber η =
indicated power÷ air
comsumption (kg/hr) x 87.8,
ε = 6.5, supercharge pressure
1.033 at. supercharge air
temperature 20°, λ = 0.8 - 0.9.

(a) 6 x N$_i$ of single
    cylinder
(b) Uneven mixture
    distribution
(c) Flow losses
(d) Auxiliary drive and
    valve gear
(e) Piston rings
(f) Connecting rod and
    piston
(g) Crankshaft
(h) Supercharger

Figure 6.- Internal losses
           of a six
cylinder in-line engine.

Power hp.

300
280
260
240
220
200

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

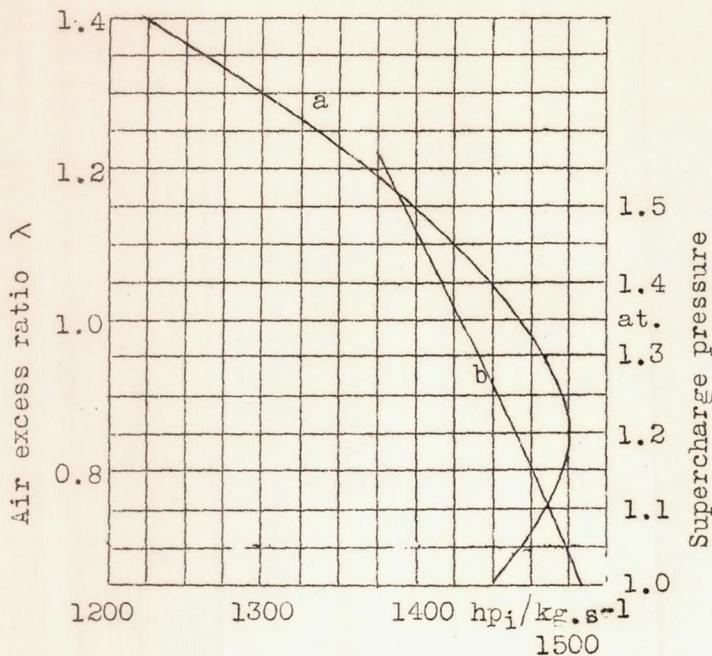2400   2600   2800   3000
           r.p.m.
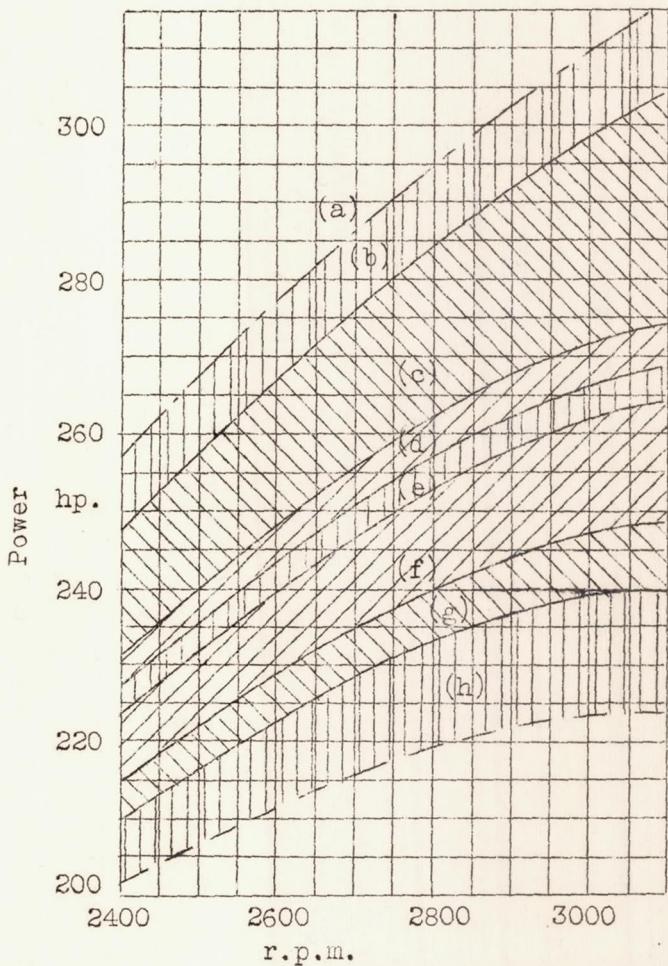
Figure 9.- Indicated horsepower per kg. air per second. a) as a function of the air excess ratio, b) as a function of the supercharge pressure at maximum power mixture (supercharge air temperature 20°, $\epsilon = 6.5$)
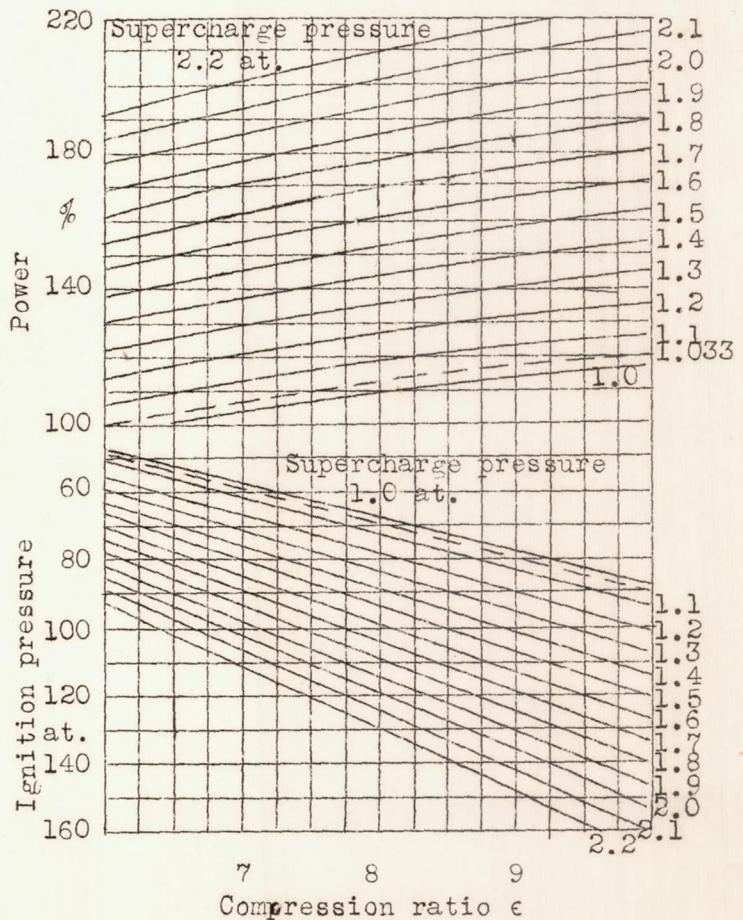

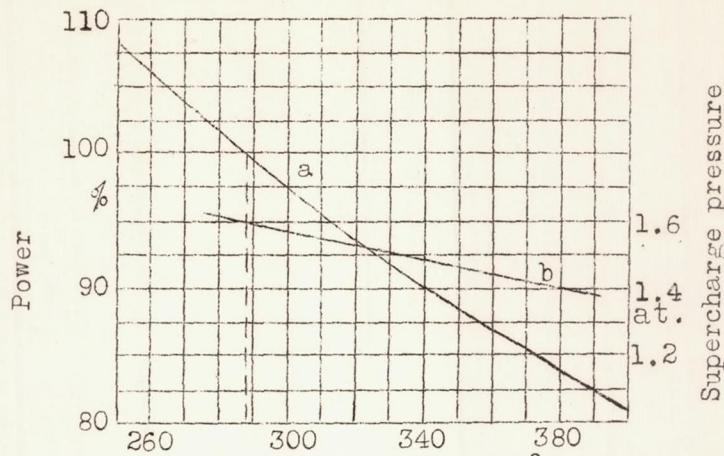Figure 10. - Power and ignition pressure for various compression ratios and supercharge pressures.

Figure 11.- Effect of supercharge temperature on the
power. a) change in power with supercharge
air temperature , b) maximum supercharge pressures
determined by the knocking limit as a function of the
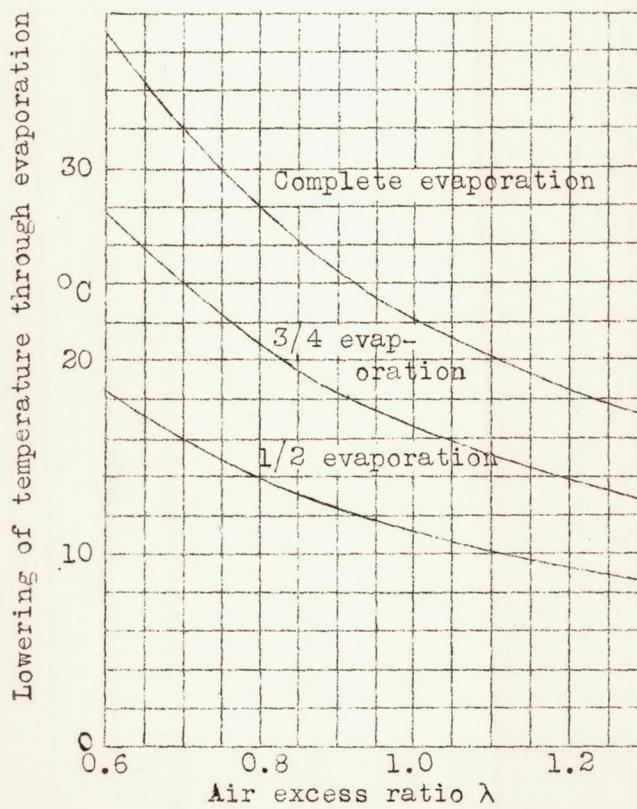temperature ($\epsilon = 6.5$, fuel octane number = 87).

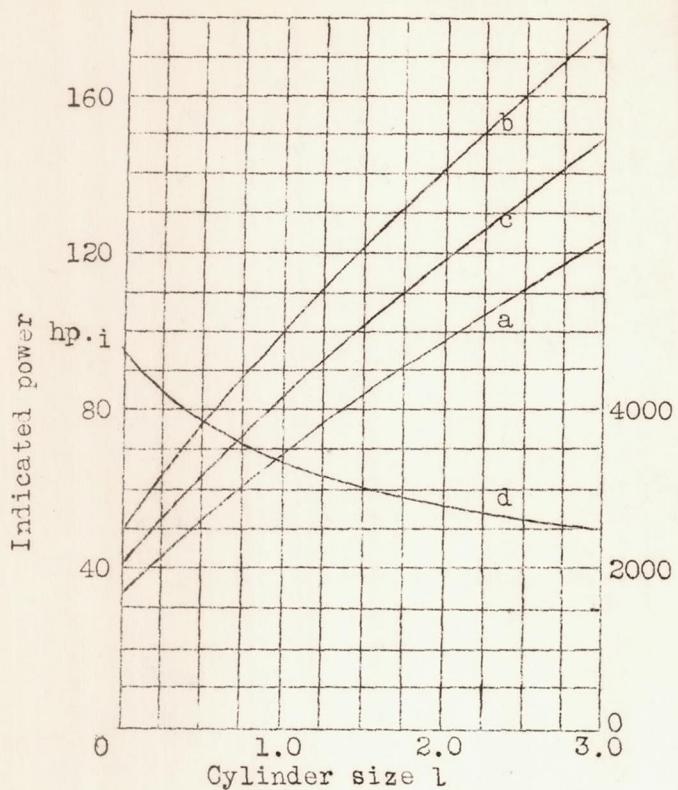Figure 12.- Effect of fuel evaporation on the supercharge
temperature.

Figure 13.- Cylinder power and speed as a function of the cylinder size. a) maximum indicated power of direct intake engine b) maximum indicated power at 1.4 at. supercharge and 25° intake air temperature c) maximum indicated power at 1.4 at. supercharge and 110° intake air temperature (knock limit), d) maximum rotational speeds. Pm_i = 12,5 at 80 m/s gas velocity at inlet. Stroke – bore ratio H/D = 1.1, inlet area F_e = 0.1445 D^2 ϵ = 6.5, fuel octane number 87.

Figure 14.- Effect of excess air on power and fuel consumption.