POSSIBLE DEVELOPMENTS OF AIRPLANE POWER PLANTS

by

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PREFACE

Aviation captures the interest of most engineers and the development of power plants for airplanes is a subject of particular interest to the mechanical engineer. In view of this, this thesis attempts to point out the possible lines of development of airplane power plants. The principal value of the work contained herein lies in the fact that the problems and difficulties of development along each line are pointed out. Conclusions are drawn as to the possible future design features of each type of prime mover which may be used in aircraft. Many engineers will probably not agree as to the feasibility of these conclusions but in the opinion of the author these possible design features and resulting performance characteristics will come as a direct result of futher experimental and development work.

The data from which the included curves and diagrams were drawn and the discussion of the design features from which the conclusions were drawn was taken from various technical publications as listed in the bibliography.

The writer wishes to express his appreciation to Prof. F.L.Wilkinson,Jr. for his suggestions and the use his publications used in writing this thesis.

POSSIBLE DEVELOPMENTS OF AIRPLANE POWER PLANTS

II. INTRODUCTION

The development of airplanes since the first flight in 1903 has been remarkably rapid. During the last decade tremendous strides have been made in the improvement of the performance and reliability of aircraft. Cruising speeds and range have been approximately doubled. The engine manufacturer has contributed engines of greater power and increased reliability,but the aircraft manufacturer has contributed the improvement in efficiency which has accounted for a major part of the better performance. The parasitic drag of the best airplane has been reduced to a figure so low that its entire elimination would produce an increase in performance of but a few per cent. Apparently, then any futher improvement in performance of aircraft must come as a result of improved engine operating characteristics.

The development of aircraft has been primarily due to two things, the increased popularity of air travel and the importance of airplanes for military purposes. To meet the ever increasing demands of the air-line operators and the military personnel, aircraft and aircraft engines have been built larger and larger. The engines used in these planes have had a more favourable weight-power ratio,greater fuel economy, and increased aerodynamic efficiency.These factors have been partially responsible for the increased range and weight carrying capacity of these larger planes.

The margin of possible improvement along this line has by no means been reached and in a favourable economic situation it seems that futher startling gains may actually be realized.

The development of power plants for these planes of tomorrow is a problem of special interest and importance to the mechanical engineer. To venture precise predictions as to what these developments will be for any long period of time is certain folly. However, from a study of the trends of development and a study of the desirable operating characteristics of airplane engines this paper proposes to point out and to discuss possible engine developments. Due to the scope of the subject, the discussion and the conclusions drawn will apply only to the engines of planes designed for limited-stop, main-line transport, and transoceanic service for commercial purposes, and for the bombers and observation planes as applied to the military needs.

No limit can yet be placed on the size of engine which might usefully be employed. In responsible quarters discussion has taken place regarding the possibility of building a flying boat with a total weight of two hundred tons. Such a plane would require six or eight airscrews, each driven by an engine or engines developing about five thousand horsepower. There is some controversy as to whether it would be better to have a single engine developing all the power required for each airscrew or to have a num-

ber of engines geared to a single airscrew shaft. This controversial point is outside the scope of this paper but the point is that an engine developing five thousand hp. may be needed. It is generally conceded by eminent aeronautical authorities that there is a definate need for an aircraft engine developing between 1000 hp. and 2000 hp. Possibilities of meeting this need are herein discussed.

III. OPERATING CHARACTERISTICS

An analysis of the desirable performance characteristics of an airplane engine will serve as a method of judging an engine's suitability for airplane use.

First, and above all, an engine must be reliable or dependable in its operation. Flying can never be safe until engines become absolutely dependable. This seems almost too much to expect but when one looks at the great strides made in this direction since the war, it is safe to anticipate a time when motor failure will be extremely rare. One method of measuring development in this line is in the hours of service in the air between overhauls. It was once necessary to overhaul an engine after ten or twelve hours in the air. Now it is common to extend this time to four or five hundred hours, depending on the service experience with the engine in question.

Good airplane engines should have a low specific weight. This is important for all types and sizes of engines as the weight any given plane can carry is constant, depending on the air-foil section and the effictive wing area. Therefore, the less the weight of the engine the more passengers or pay-load the plane can carry.

The specific fuel consumption, lbs. of fuel per hp. hr., is particularly important in planes designed for long range operations. For example consider the sample case shown

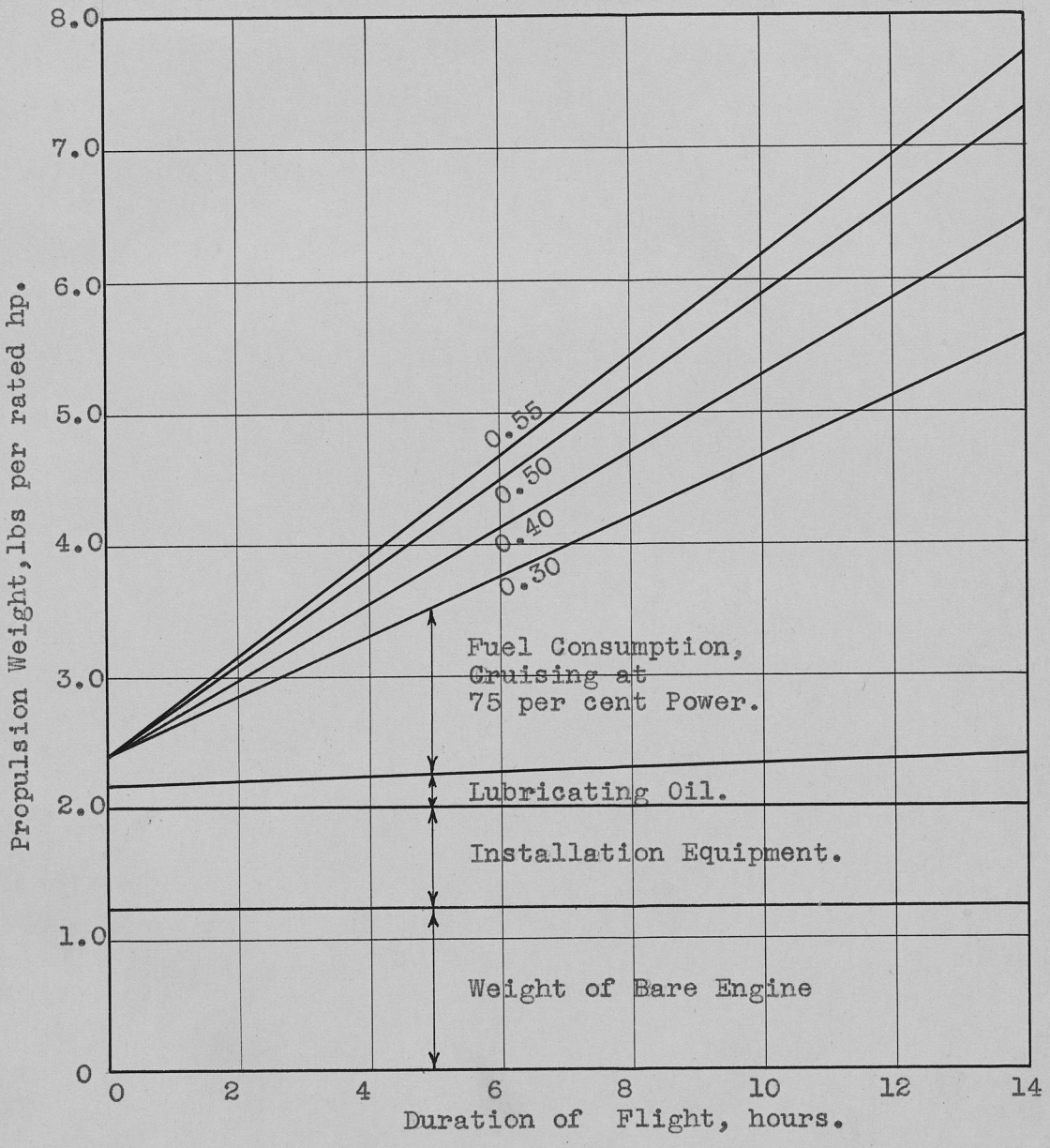


Fig.2 - The Important Effect of Specific-Fuel-Consumption Value as Illustrated for a Sample Case.

in Fig. 1. Here the propulsion weight, which is the weight of the bare motor, installation equipment, lubricating oil, and fuel, has been plotted as a function of flight duration. The propulsion weight has beennplotted for power plants having specific fuel consumptions of 0.30, 0.40, 0.50, and 0.55 pounds. It will be observed that a fifteen per cent increase in the basic weight of the engine is of less importance than an increase in the fuel consumption of o.10 lb. per hp. hr. for a flight of no more than three hours. For a flight of ten hours or more the increase in basic weight is almost insignificant. From this it is apparent that the governing consideration of net pay-loads for long flights with an engine of given size and power is the fuel consumption while cruising.

The good airplane engine should be easily accesible for repairs both in flight and on the ground. The modren air-cooled engine is easy to get to for repairs on the ground but it is impossible to reach it during flight. The advantage of having an engine accesible during flight is that many small troubles or faulty adjustments can be corrected before they have a chance to do any damage.

The frontal area of an engine is a factor in the parasitic drag and the effictive wing area. Thus if the frontal area is reduced, the drag is reduced and the effictive wing area is increased. This would increase the lifting power of any given plane and therefore the operating range.

The ideal aircraft engine should have little loss of power with increase in altitude. Without supercharging this loss is large for the present spark-ignition engines. The normal operating altitude of the engines considered here is between 8000 ft. and 15,000 ft.,and if the cruising power output drops to about 75 per cent of that at sea-level, the size of the engine required is increased by a proportional amount. This fact decreases the pay load of the plane and the operating efficiency of the engine.

The modren cabin transport planes are very effectively insulated from engine and propeller noises but high frequency vibrations of the engine are readily transmitted through the insulating materials and these vibrations have proved to be a source of discomfort to the passengers. Engine vibrations also necessitate the use of heavy engine settings and stronger wing bracing than if the engine were free from vibrations. Therefore, it is considered desirable to have an engine free from vibrations.

Other characteristics of less importance but which should be considered are; the fire hazard should be low and the engine should not interfer with radio communication.

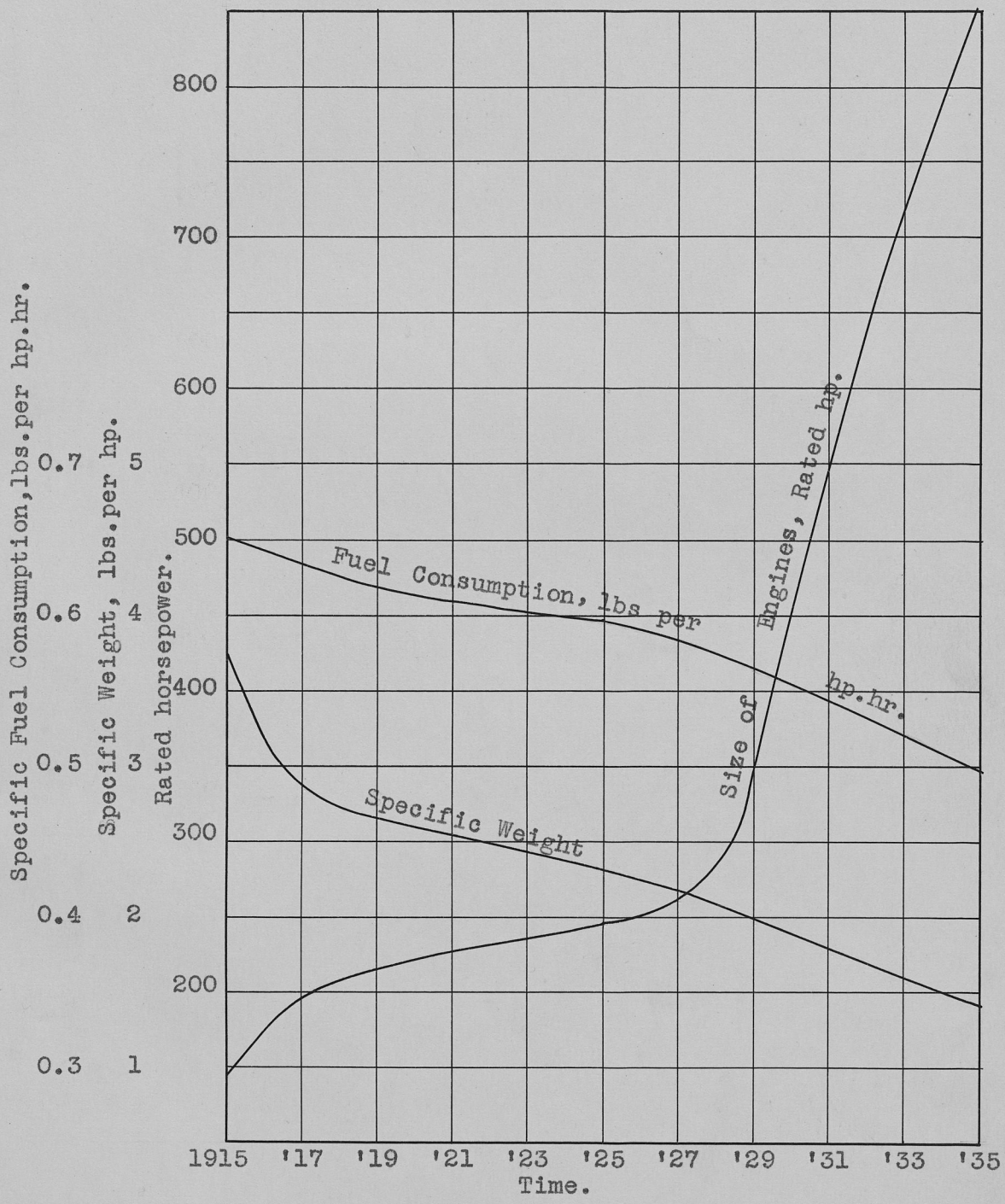


Fig.1. Trends of Engine Size, Specific Weight, and Specific Fuel Consumption since 1915.

IV. SPARK-IGNITION ENGINES

No type of engine can hope to supercede the present engines unless it excells in the afore-mentioned operating characteristics. An analysis of the development and design features of the present engines will serve as a criterion of measurement and at the same time disclose possibilities of futher development.

Up until after the war the majority of airplane engines were of the in-line water-cooled type. This type has largely been displaced by the radial air-cooled engine due to the decreased specific weight and the elimination of a plumbing system. The development of airplane engines is roughly shown in Fig. 2. Here the maximum rated power output of the engines in production each year has been plotted against time. It will be noticed that the size increased from one hundred hp. to about two hundred hp. during the war. Then followed a period of the next ten years when there was very little increase in the size of engines. Beginning in 1927 the size has increased rapidly at the rate of about one hundred hp. per year. Unfortunately the rate of development is not a direct function of time and it does not necessarily follow that the present rate of development will continue.

Fig. 2 also shows how the specific weight,unit weight per hp.,has decreased from four lbs. per hp. at the beginning of the war to an average of approximately one and one-half lbs. per hp. now. It appears that the specific weight

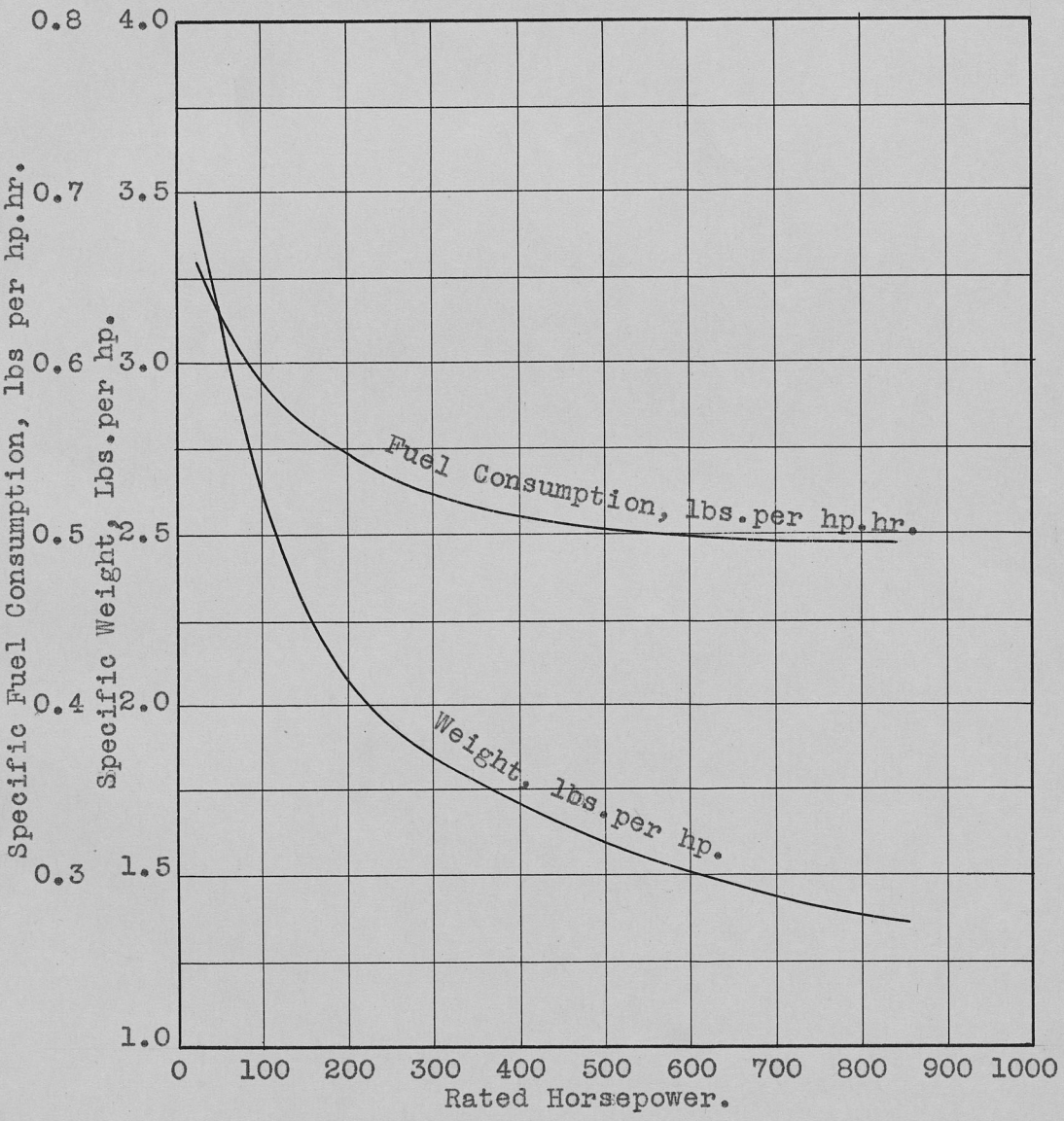


Fig.3 - Variations of Specific Weight and Fuel Consumption for 1935 Engines.

is a direct function of engine size as will be shown more clearly in the next graph.

The other curve in Fig. 2 shows that the specific fuel consumption,fuel consumption per hp. hr., has been lowered from 0.65 lbs. in 1917 to an average of approximately 0.50 lbs. per hp. hr. at present. This decrease is neither a function of time or engine size but rather is the result of refinements in carburation and ignition.

At present there are ninty-eight types and sizes of engines being built in the U.S. Eighty-five per cent of these engines are of the radial air-cooled type. Fig. 3 is a graphic representation of the operating characteristics of all of these engines based on builders rating.In this figure the specific weight and specific fuel consumption have been plotted against rated hp. output. The specific weight is seen to decrease with the increase of rating and it may be considered as a direct function of engine size. The specific fuel consumption is also lower in the larger engines but it cannot be assumed to be only a function of size. It is largely due to good fuel distribution and to the control methods employed on the larger engines where fuel consumption is particularly important. The values of specific weight,1.35 lbs., and of specific fuel consumption, 0.50 lbs. will serve as a definate measurement with which to compare these characteristics of any proposed engine.

There is little possibility of developing the present

type of radial air-cooled engine, which doninates the field today, into an engine of from 1000 hp. th 2000 hp. The National Advisory Committee for Aeronautics has stated that according to what is now known the limit of power output is about twelve hundred hp. This limitation is due to the fact that sufficient heat cannot be dissipated to the air from cylinders of more than six inches in diameter. The number of cylinders that may be used in a single row radial is limited by mechanical details of construction to fourteen. It is of course possible to use two or more tows of radial cylinders but considerable difficulty has been experienced in cooling the second row sufficiently. Another difficulty in using this type of engine is the problem of mounting. From this then it is apparent that the limit in size of an air-cooled engine is fourteen six inch cylinders which with the maximum crank throw and boosting of the inlet pressure would deliver about twelve hundred hp. Since this output is below the specifications previously established, the air-cooled radial cannot be considered as a possibility in the 1000 hp. to 2000 hp. class.

Since the engine cannot be air-cooled it follows that fluid cooling must be used and as radial cylinders are not easily jacketed for fluid cooling,the future engine of more than 1200 hp. will probably be the in-line type. The fluid used may be water or some chemical which will allow the engine to operate at higher temperatures with no more danger of over heating.

An in-line engine with a single bank of cylinders operating on the crankshaft would necessitate a very heavy and long crankshaft. In order to eliminate this two or more banks of cylinders operating on the same crankshaft could be used. The banks could be arranged in the conventional V, X, or W manner. There is a possibility of eliminating the crank by employing a cam or swash plate to convert the motion of the pistons into rotative power,however, the low mechanical efficiency of a mechanism of this sort would probably off-set any advantage. The crank has withstood the attact of inventive genius for more than a century and there is no indication that any superior mechanism for converting reciprocating motion into rotative power will be introduced in the near future, Therefore, the engine will probably be the in-lined fluid-cooled V, X, or W type.

The hypothetical engine being developed must have a high output per cubic inch displacement or per pound of weight. This brings up the question of two-stroke or four-stroke cycle operation. All of the gasoline engines now in use work on the four-stroke cycle but if the number of power strokes could be doubled as in the two-stroke cycle the specific weight could be greatly reduced. The two-stroke cycle could not compete with the four-stroke cycle if carburetion of the fuel is considered necessary. The high fuel consumption and the danger of pre-ignition of the charge eliminates it from the picture. However, if the fuel may be injected directly into the cylinder these disadvantages are obviated.

Yet on the other hand the installation of an injector system would tend to futher complicate the engine mechanism and increase the specific weight. A careful analysis of these factors seems to indicate the fact that the four-stroke cycle would be definately superior and that the low specific weight must be obtained by high rotative speeds and high brake mean effictive pressure.

The ratios of bore to stroke, bore to crank throw, bore to connecting rod length, etc. have become pretty well standardized for this type of engine and need not be discussed herein.

Since the engine under development is to be used for long flights, the choice of compression ratio is worthy of much study because of its effect on fuel consumption. The ideal or air standard efficiency of the Otto cycle is given by the formula

$$e = 1 - r^{1-k}$$

in which r is the compression ratio and k is a constant for air equal to 1.4. Actual operation of an engine does not follow this equation exactly in that the value of k is not the correct exponent for the compression and expansion of the gases, but the equation does indicate the fact that the compression ratio is the controlling factor. The point to which the compression may be raised is limited by the ignition temperature of the fuel. In other words if the compression ratio is so high that the temperature of the charge is raised above the ignition temperature of the fuel, auto-ignition

or detonation will take place. Other factors affecting the temperature rise are; supercharger characteristics as fixed by the flight requirements, the combustion air intake temperature limits, and the power requirements while cruising. Assuming that these factors are known the compression ratio should be selected to give minimum fuel consumption without detonation in normal cruising operation. With the high octane number fuels now obtainable this compression ratio should be from 6 or 8 to 1.

Supercharging will be necessary to prevent a great loss of power with increase in altitude and to increase the power available for take-off. Supercharging may best be accomplished at sea-level and up to altitudes of about 8000 ft. with a multi-speed geared blower. At altitudes above this an exhaust-turbo compressor becomes more efficient than the geared blower and the engine should be equipped with both.

Carburetion of the fuel could be carried on in a conventional type carburetor but means of accurately controlling the mixture strength should be provided. This is important as the spedific fuel consumption increases with the fuel-air ratio. During the last year a device has been developed by Pratt and Whitney to automatically control this ratio. Another alternative is the installation of an instrument which by an approximate exhaust gas analysis serves to give an indirect measurement of the fuel-air ratio. By observation of the instrument dial it is possible to manuelly control the ratio.

The formation of ice in a carburetor can be prevented by the addition of a little alcohol to the gasoline. The continuous addition of alcohol whether the circumstances require it or not is, however, objectionable because it introduces corrosion and other difficulties. To overcome this disadvantage an automatic device has been produced by the Royal Aircraft Establishment which causes alcohol to be introduced into the float chamber only when freezing conditions are encountered.

The currently accepted type of spark plugs operate at a temperature at which the electrode materials oxidize and burn away at a rapid rate and the electrodes are frequently subject to corrosion when using highly leaded fuels. This results in faulty ignition of the fuel-air charge and a subsequent loss of power. A plug should be developed with high thermal conductivity as a governing consideration.Such a spark plug would greatly increase the reliability and power output of an engine.

The valves used in the future large engine may be the poppet type with some means of internal cooling. There are valves of this type now available which have operated satisfactorily at extremely high output per cubic inch with speeds as high as 3400 r.p.m. Another possibility is the use of sleeve valves. Recent experiments conducted by a commercial organization have proved the reliability of the sleeve valve operating under high thermal stresses without internal cooling. This fact that the sleeve valve does not have to be

cooled may cause it to replace the poppet valve.

From this analysis of the design features, plausible specifications of a 1000 hp, to 2000 hp. spark-ignition engine may be drawn.

(1) Fluid cooled.

(2) cylinders in-line with several banks of cylinders operating on a common crankshaft.

(3) Four-stroke-cycle operation.

(4) General design ratios as are used at present.

(5) Supercharged with a multi-speed geared blower and an exhaust-turbo compressor.

(6) Compression ratio from 7:1 to 8:1.

(7) Carburetor fitted with accurate automatic fuel-air mixture control device and equipped with means of preventing the formation of ice.

(8) Spark plugs either liquid cooled or fitted with fins for air cooling.

(9) Top cylinder pressure limited to 1400 lbs. per. sq. inch.

(10) Internally cooled poppet valves or sleeve valves.

(11) Weight of bare engine, 1.0 lb. per hp. at maximum rating.

(12) Fuel consumption, 0.45 lbs. per hp.hr. at cruising.

(13) Free from the operating vibrations common in the present type of engines.

(14) Reduction gearing to the propeller.

(15) Installed in the wing in such a manner that the engine could be inspected during flight.

The resulting engine is entirely possible according to present knowledge and it has most of the desirabel operating characteristics.

Several engines of this general type and size have actually been built and operated in racing aircraft. Rolls Royce built a 2300 hp. engine in 1930 and Packard followed soon thereafter with a 2400 hp. engine. Both of these engines performed satisfactorily but their consumption of fuel and lubricating oil made their use for commercial purposes prohibitive. However, their performance indicates the possibility or rather the probability of development along this line.

V. DIESEL ENGINES

In consideration of the recent advances made in the field of aircraft Diesel engine research it is next fitting to analyze its advantages, disadvantages, development, and possibilities of further development.

The chief advantage of the Diesel engine over the spark-ignition engine is its high thermal efficiency. This is true because it is possible to employ higher compression ratios in the compression-ignition engine. If the spark-ignition engine could use as high a compression ratio as the Diesel engine it would have a higher thermal efficiency than the Diesel engine, but for reasons explained in the previous chapter it is impossible to use compression ratios of more than 8:1 in the spark-ignition engine while compression ratios of 16 or 18 to 1 are common in the diesel engine.

In Figure 4, the thermal efficiencies of the ideal Otto and Diesel cycles have been plotted on a semi-lograthmic scale as a function of compression ratio. In both cases the efficiency varies inversely with the fuel-air ratio or directly as the per cent theoretical air required for complete combustion. Spark-ignition engines usually operate using between 89% and 111% theoretical air and between compression ratios of 5 and 8 to one. This shows ideal efficiencies between 32% and 48% but in actual service the efficiency usually runs between 25% and 30%. As there is less danger of detonation in the Diesel cycle it is possible to employ higher compression ratios and higher per cent theoretical air. For this reason the Diesel cycle is inherently

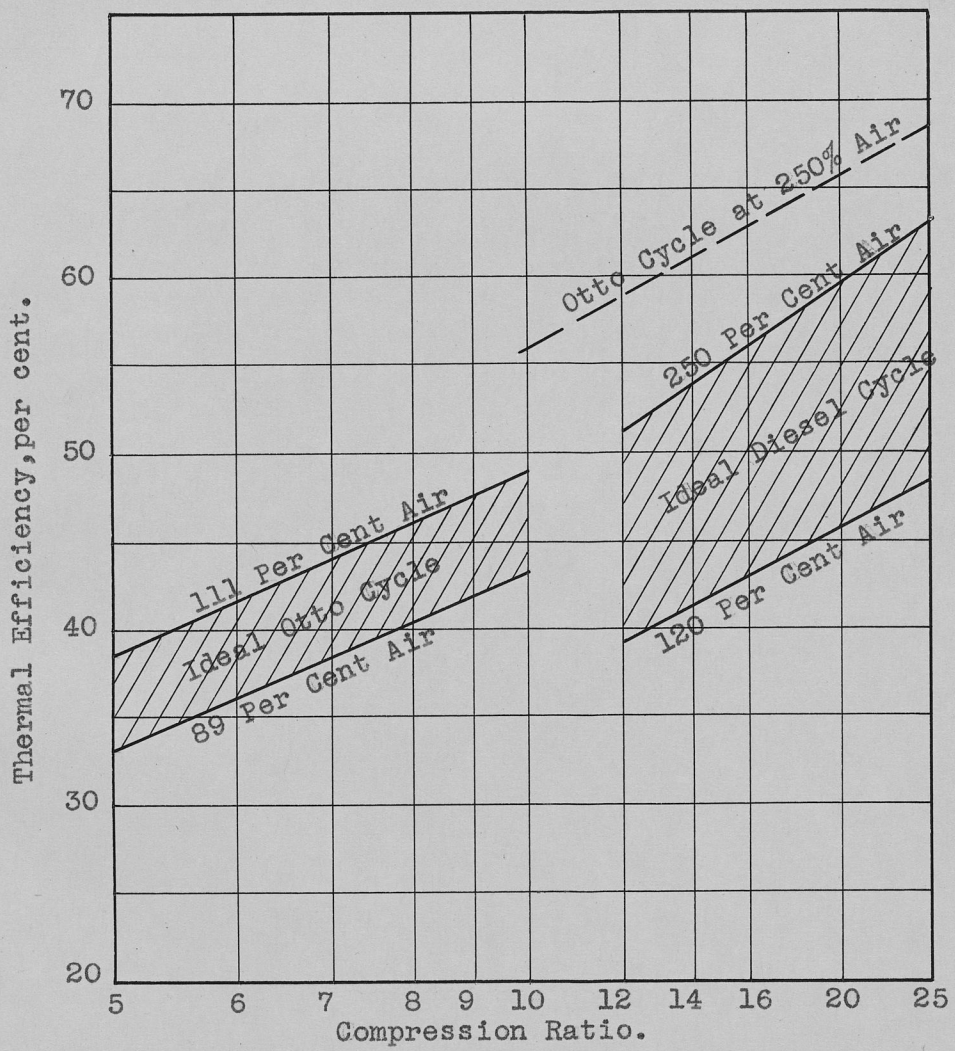


Fig.4 - Ideal Effects of Compression Ratio on Thermal Efficiency for Otto and Diesel Cycles.

more efficient with ideal efficiencies ranging between 40% and 63% using 120 and 250 per cent air. Actual operating efficiencies lie between 30% and 40%.

According to figures released by the Wright Aeronautical Corporation the cost of fuel for transport planes in 1935 was 1.52 cents per passenger mile and the fare per passenger mile was about 6 cents, which places the fuel cost at 25 per cent of the total passenger revenue. As passenger traffic on the airlines increases, schedules speed up, and fares reduce, the fuel bill will become still more important item. If the airlines had been equipped with compression-ignition engines operating at average efficiencies and with fuel oil based on an average cost, the cost per passenger mile would have been 0.32 cents instead of 1.52 cents. Further indulgence in this assumption shows a saving in operating cost of 20 per cent of the passenger revenue, and a total economy to the airlines in the neighborhood of $4,000,000 which is by no means an insignificant figure.

The Diesel cycle is much more applicable to the two-stroke-cycle than the spark-ignition engine as only air is used for scavenging in the Diesel while the S-I engine must use a mixture of fuel and air unless an injection system is employed. For this reason the fuel economy of which would further complicate the system, the two-stroke spartk-ignition engine is very poor and it is not used commercially. The two-stroke-cycle engine develops more power for a given displacement and runs smoother due to the power impulse in each

cylinder revolution. It can also be built to weigh less than the four-stroke-cycle engine, as the latter has to withstand higher peak pressures. Supercharging is essential for the present-day engines and in the case of the two cycle engine, there is no additional weight for the supercharger as the bolwer for scavenging can readily be used for supercharging by increasing the pressure.

The Diesel engine has many other advantages over the gasoline aircraft engine, and these will become more pronounced as development work is done on Diesel aircraft engines and fuel for them. Some of the advantages claimed for the Diesel engine over the present type of engines are:

1. Fire hazards are greatly reduced on account of the lower volatility of Diesel fuel and by the fact that there is no explosive mixture outside of the engine cylinders. The fuel tanks can be filled with the motor running, if necessary.

2. Weight of the fuel and fuel tanks is reduced as the bulk of Diesel fuel is less than that of gasoline.

3. Produces no electrical interference which could affect the radio transmission and reception on aircraft, and since it has no electrical ignition system, it is not vulnerable to the action enemy "rays" or "beams".

4. Starts easier in cold weather and requires less time for take-off, as it does not have to be warmed up before flight, depending upon its own cylinder pressure for the necessary heat.

5. Has higher thermal efficiency at all loads, due to more complete combustion of the fuel inside the engine cylinder, which makes the exhaust cooler, quieter and flameless.

6. Requires smaller cooling surfaces, as less heat has to be dissipated on account of its higher thermal efficiency; the fins or radiator can be reduced in area by 30 to 35 per cent with a considerable saving in frontal area, drag and weight.

7. Simpler in construction and has fewer parts which can be made more robust, thereby, increasing the reliability of the engine.

8. Does not require elaborated controls and instruments, which reduces the engine-installation cost and also reduces the strain on the pilot while flying.

9. Is unaffected by heavy rains, as there are no carburators, magnetos, or ignition cables to be affected.

10. Fouling of the ignition system by excess lubrication is impossible as any excess oil on the cylinder walls is burned as fuel.

11. There is no danger of the ice formation at the air intakes, nor danger of vapor lock in the fuel lines.

12. Much larger engines in fewer units are feasible, improving any distribution of load on the wings of large aircraft.

13. No great loss of power with increase in altitude.

At present there are several disadvantages in using an aircraft Diesel engine. The initial cost is too high as

with any new product, the introductory price will be high because extensive development expense has to be amortized. On a production basis there should be little difference in the cost of the basic Diesel engine and a comparable spark-ignition engine. What price difference does exist will result from accessory cost and this difference should favor the Diesel.

Another disadvantage of the Diesel is its high weight-power ratio. There is little justification of this fact since the top pressure of the Diesel cycle is not as high, or certainly no higher, than that of the Otto cycle. It is only when the injection characteristics allow the combustion to proceed in the direction of the Otto cycle that the top pressure is any higher. Thus with the increase knowledge of combustion the weight-power ratio of the four-stroke-cycle Diesel should approach that of the present gasoline engine and should be considerably less if the two-stroke-cycle is used. This assumption is substantiated by test data from the Massachusetts Institute of Technology where excellent mean effective pressures have been obtained with top pressures of less than 800 lbs., per square inch. According to Kenneth A. Browne of the Wright Aeronautical Corporation unpublished results of some commercial experiments are still more encouraging in this respect.

The Diesel engine requires greater crank torque and higher rotative speeds for starting than an equivalent gasoline engine. It is obvious that with higher compression ratios and the tighter piston fits employed a greater torque will be necessary. Since the Diesel engine fires by the heat

of compression, it is necessary to crank it at a much higher speed than the equivalent size of gasoline engine. At the end of the compression stroke, the actual heat which is available for firing the Diesel fuel is, of course, dependent upon the rate of heat dissipation to the surrounding metal parts and, obviously, the higher the cranking speeds the less time available for such dissipation. Likewise, the piston clearance, and, therefore, the blowby which occurs in cranking is a very material factor. The greater the blowly and consequent loss of heat of compression, the higher the cranking speed must be to offset the heat drop. Thus the greater horse power required for starting is a disadvantage of the Diesel engine.

DEVELOPMENT

The Diesel engine for aircraft had its inception in Germany towards the end of the war. The pioneering work was done by the late Dr. Hugo Junkers, and the first engine produced to his designs was a 5-cylinder, two-cycle, water-cooled engine of the horizontal type intended for installation in the wing of an airplane. Further development was curtailed in 1918 when Germany was limited to engines of 200 h.p. and it was not until 1926 that Germany again produced an aircraft Diesel. Germany is now building an engine known as the Jumo-4 which develops 750 h.p. at 1720 r.p.m. and weighs 2.20 lbs., per h.p. and an engine called the Jumo-5 developing 550 h.p. at 2104 r.p.m. and weighing 2.04 lbs. per h.p. Certain German companies are working on aircraft Diesel engines of 1000 h.p. and up, both for commercial and military purposes, but no details have been released for publication.

Great Britain has done considerable research work in aircraft Diesels and they have developed several engines which have performed satisfactorily. One of these engines is the Bristol Phoenix, a four-cycle, air-cooled, radial, 9-cylinder engine developing 415 h.p. at 1900 r.p.m., and weighing 2.63 lbs., per h.p. Another is the Napier Culverin, manufactured under the Junkers patent and developing 720 h.p. at 1700 r.p.m. and weighing 2.48 lbs., per h.p.

Recently, the French Air Ministry has done considerable development work on The Clerget engine and has produced a 14-cylinder, radial, air-cooled, four-cycle engine deliver-

ing 700 h.p. at 1950 r.p.m., and weighing 1.89 lbs., per h.p.

In the United States the development of Diesel aircraft has not been as progressive as in Europe. However, this condition of affairs will soon be changed as a number of Diesel aircraft engines are under development at the present time. No data is available as they are still in the experimental stage, but it can be assumed that they will probably be in the 1000 h.p. class.

In 1930, Packard built the first Diesel aircraft engine in this country. It was a 9-cylinder, radial, air-cooled, four-cycle engine rated at 225 h.p. at 1950 r.p.m. and weighing 2.26 lbs., per h.p. In 1931, Guiberson built an engine of the same type developing 230 h.p. at 2000 r.p.m., and weighing 2.30 lbs., per h.p. Due to the economic condition in 1932 and 1933 the manufacture of both of these engines was discontinued until recently. The interest in Diesel engines was revived in 1934 when the Lambert Engine Company built an engine to the designs of D. L. Deschamps, formerly of Belgium. This engine was a 12-cylinder, two-cycle, inverted V-type, liquid-cooled engine delivering 1200 h.p. at 1600 r.p.m., with a weight of 2.00 lbs., per h.p.

POSSIBLE DESIGN FEATURES

A review of the advantages and disadvantages of the Diesel aircraft engine shows clearly that it would be desirable to have a Diesel engine in the 1000 hp. to 2000 hp. class. The research and development already done as manifest in the engines listed above indicates a definate probability of futher development of this type of internal combustion engine. From a study of the operating characteristics and design features of the above engines and a study of the results of recent experiments, conclusions may be drawn as to the probable design features of the large future engine of this class.

The heat loss from the cylinder walls of the Diesel is about 30% less than that of the conventional gasoline engine, and for this reason it is possible to build an air-cooled Diesel of about 1500 hp. and still have adequate cooling of the valves and cylinder walls. However, since the assumption is made that engines of up to 2000 hp. will eventually be needed, it will be necessary to use fluid cooling in this theoretical engine. For reasons previously discussed the cylinder arrangement will probably be the in-line type with two or more banks of cylinders arranged in the V, W, or X type and operating on a common crankshaft.

The four-stroke-cycle may be used but indications are that the two-stroke-cycle would be far superior for two reasons. First, since low specific weight is desirable the output of a given engine could be practically doubled by doubl-

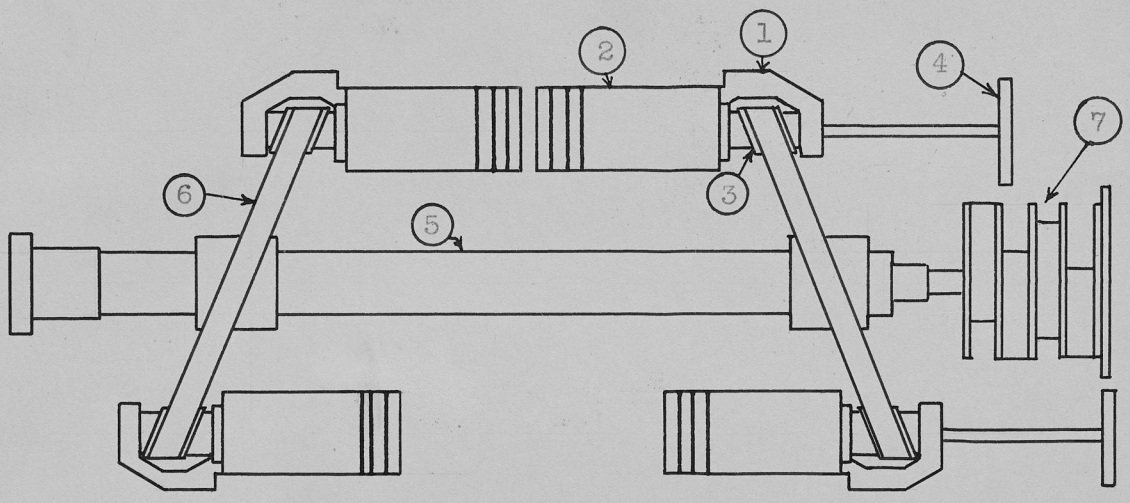


Figure 5. Stirling Crankless Opposed Piston Diesel

1. Bridge 2. Piston 3. Slipper Bearing

4. Air Pump Piston 5. Shaft 6. Inclined Disc

7. Air Distributing Valve

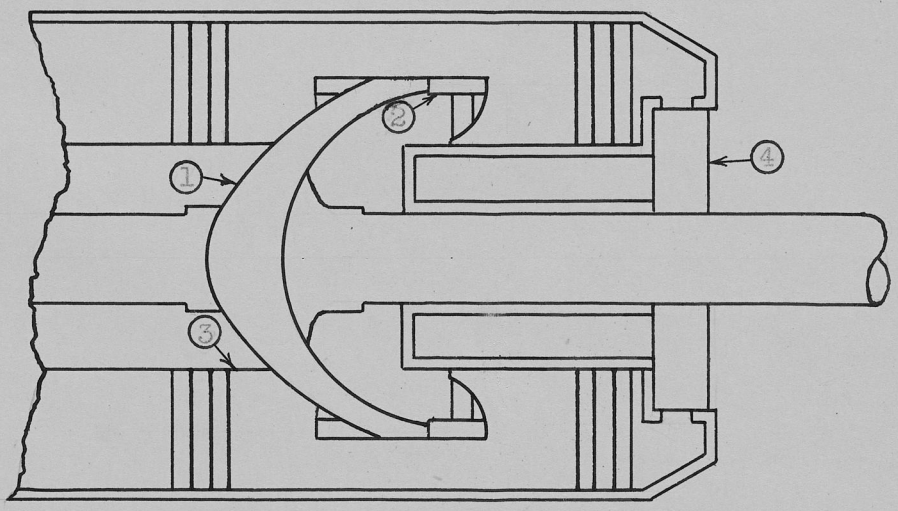


Figure 6. Bleser Double-Ended Piston Engine

1. Cam 2. Roller Bearing 3. Piston

4. Air Inlet Valve

ing the number of power strokes as would be the case with the two-stroke-cycle. Second, the weight of the given engine would probably be less since the whole construction could be lighter due to the lower top pressures and the more even flow of power to the crankshaft. With either cycle it would be necessary to use a supercharger and it would not materially increase the total weight to increase the capacity of the supercharger to a point where it could take care of the scavenging. Thus, the two-stroke-cycle would be eminently superior to the four-stroke-cycle for aircraft use.

The two-stroke-cycle can be used with the in-line arrangement of cylinders but the opposed piston type offers greater facility for scavenging. For this reason it is quite possible that it would be advantageous to employ some type of opposed piston setting. The inlet and exhaust ports could be set in the cylinder walls at such a point that they would be operated automatically by the piston movement. Fig. 5 shows an engine of this type. It is being built by the Stirling Engine Co. primarily for marine work but there is no reason why the idea could not be applied to an aircraft engine. The engine shown employes a scavenging pump for each cylinder and the reciprocating motion of the pistons is translated into rotative power by means of slippers on the pistons operating in contact with an inclined disc.

Annother possible cylinder arrangement is shown in Fig. 6. An engine of this type is in the experimental stage

at the Bleser Motors, Ltd. in Springfield, Ill. This is a cam or swash plate engine utalizing six double ended pistons with roller bearings in the pistons operating in contact with the cam. The cylinders are arranged in a circle around the main shaft and are parallel to the main shaft. The cam is so constructed that each piston goes thru four strokes in each main shaft revolution. In other words there are twelve power strokes per revolution. This engine is said to have a high thermal and mechanical efficiency and to be almost entirely free from vibrations. This engine has a comparatively small frontal area and this type of cylinder arrangement would be desirable in an aircraft engine.

The importance of fuel economy has been stressed. The two factors governing fuel economy or thermal efficiency are the compression ratio and the fuel-air ratio of the ideal cycle. This ideal cycle is known as the air-standard efficiency and has been used for years as a reference in analyzing engines; primarily because of its simplicity of mathematical expression. The equation for efficiency is

$$e = 1 - \left(\frac{1}{r}\right)^{n}$$

in which r is the compression ratio and n is the average value of the exponent of the compression and expansion lines. This formual is ralatively simple and takes into account the varying composition of the mixtures of actual working gases thru the cycle, the variation in their specific heats, the equilibrium conditions of dissociation at high temperatures

and the effect of continued combustion during the expansion stroke in the exponent,n. Fortunately Goodenough and Baker have as a result of much experimental work developed an empirical formula for the determination of the exponent which takes into account the factors listed above. The formual is

$$n = 0.434 - \frac{19.5}{a-r} - \frac{0.7}{r}$$

in which a is the percentage of air supplied, based on 100% for the chemically correct amount for complete combustion. Since r is small as compared to a and since r is fixed for any given engine the controlling factor in the evaluation of the exponent is the percentage of air. As the maximum percentage of air is found at no-load the logical conclusion is that the maximum efficiency will occur at no-load and it will steadily decrease with the increase of load. This fact is apparent from an examination of a Diesel engine indicator card. As the value of a decreases there is a less complete expansion of the combustion gases with a subsequent drop in thermal efficiency. Since the value of a largely determines the mean effective pressure for any given engine the conclusion is that the thermal efficiency decreases with the increase of mean effective pressure.

The mean effective pressure determines the torque of an engine and as it is very desirable to have a high torque per unit of displacement, the Diesel aircraft designer is faced with the task of maintaning the proper relation between specific output and fuel economy. As has been shown the specific fuel consumption is largely dependent on the compression

ratio and the per cent theoretical air. The compression ratio may of course be arbitrarily chosen with a minimum value which is sufficient to bring the temperature of the compressed gases above the temperature of the fuel flash point and a maximum value depending on the strength of the cylinder, piston, and crank. The compression ratio usually used in aircraft Diesels is between 14:1 and 18:1.

The fuel injection system of the Diesel engine is the only complicated or delicate mechanism of the engine and as the operating dependability of the engine depends largely on this mechanism it cannot be given too much consideration. Mixing of the fuel and air and combustion of the mixture must take place in the Diesel cylinder between the time of fuel injection and the time the piston starts its downward motion. The time interval must necessarily be short, especially in the high speed Diesels where the interval is measured in hundredths of a second. As a result a great many designs have been developed in the effort to insure thorough mixing of the fuel and air. Fuel injection systems may be divided into two classes, air-injection and mechanical injection.

Air injection of the fuel embodies the employment of high pressure air, at about 900 lbs. per square inch, to force the oil charge into the cylinder when the spray-valve has been opened by a cam or otherwise. This system necessitates the use of a two-stage or three-stage compressor which complicates the system and makes this type too heavy, too

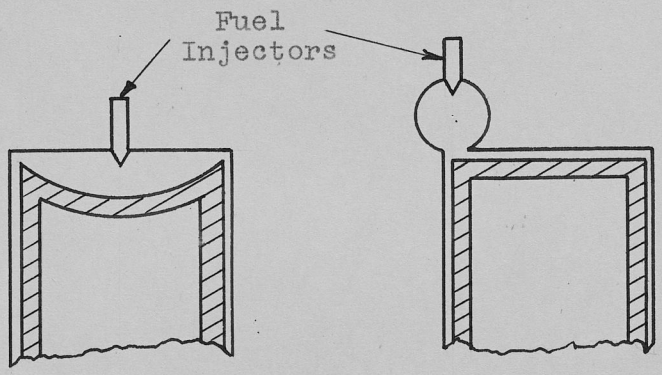
expensive, and too unreliable for use in an aircraft Diesel.

Mechanical injection methods may be subdivided into three types, common rail, individual pump for each cylinder, and the distributor system. The common rail system embodies the use of a mechanically operated needle valve and a pumping device which maintains the pressure on the fuel line leading to the spray valve at about 4000 lbs. per sq. in. A relief valve bypasses that part of the oil discharged by the pump which does not enter the cylinder. The amount of oil entering is determined by the time the needle valve is held off of the seat. In the individual pump type the measured charge of fuel is forced through the pipe leading to the injection valve by the pump plunger action. The spray valve is usually fitted with a spring loaded differential needle which is lifted as soon as the pump plunger starts its delivery stroke. The distributor system embodies the use of a single pump delivering a measured quantity of fuel to each cylinder through a casing in which rotates some type of disk, or distributor, which places each cylinder fuel valve in communication with the fuelpump in sequence. An examination of these three types of mechanical injectors seems to indicate that the distributor typewould probably serve best in an aircraft Diesel engine because of its simplicity, compactness, low weight, reliability,and application to a high speed engine. In addition to these advantages the distributor system insures that,provided the load does not change, each cylinder will do exactly its pro rata share of work

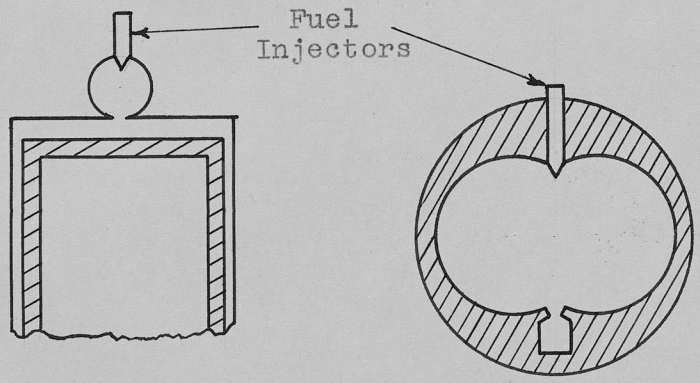
since the fuel delivered to each cylinder is measured by the same device. This equal division of load maintains the desired mechanical balance and prevents unequal shaft strains.

The aircraft Diesel must necessarily have relatively small cylinders with high rotative speeds of the shaft in order to get a high specific output. This fact makes the combustion problem rather difficult as the fuel and air must be mixed in a very short interval of time. This mixing is generally accomplished by piston and cylinder head design. There are four general types of design of pistons and cylinder heads. These types are illustrated in Fig.7. A is usually termed direct injection, B turbulence chamber, C pre-combustion, and D air-cell. In the direct injection type the mixing is accomplished by using multiple-hole injection spray valves and by the air motion set up by the piston motion. The top of the piston is usually concave in order to crowd the air into the center of the clearance space, so that the oil penetration need not be so extreme to insure complete diffusion. This method provides very poor mixing in small bore high speed engines and is therefore unsuitable for aircraft purposes.

The turbulence chamber type confines practically all the clearance volume to the small cylindrical chamber as shown in the included diagram. The upward motion of the piston forces the air into the chamber with a swirling motion and as the fuel is injected this rotation of the air continues and the mixing is comparatively good.



A. Direct Injection B. Turbulence Chamber



C. Pre-Combustion Chamber D. Lanova Air-Cell

Figure 7.

Combustion Methods.

The pre-combustion chamber type confines about 30% of the clearance volume to a small chamber in the cylinder head. The heat vaporizes the fuel and mixes it with the available air, whereupon ignition occurs. Since there is insufficient air in the chamber for complete combustion the pressure rise is not excessive and on the expansion stroke the fuel in the chamber is forced out into the main chamber where combustion is completed. This type of combustion control has the advantage of keeping the top pressure lower than in either of the other two types discussed and as a result the piston wall construction neednnot be as heavy. However, in both the turbulence chamber and the pre-combustion chamber types the cylinder head design is somewhat complicated and must be comparatively heavy.

The air-cell type combines the effective combustion control of the pre-combustion type with the simplicity of the direct injection type. D in Fig. 7 shows a conventional arrangement of this type. Here a small cavity is provided in the piston in which air is trapped and compressed to a high pressure by the combustion in the main chamber. When the piston starts on its power stroke the cylinder pressure drops which permits the air trapped in the air-cell to stream out, mix with the unburnt fuel and so complete combustion. This design is particularly successful in clearing the fuel nozzle of carbon by means of the high velocity air jet. This type as shown was developed and is used by the Cummins Diesel Engine Co.

Various combinations of turbulence chamber, pre-combustion chamber and air-cell have been tried and several have been very successful in securing combustion control. One of these known as the Lanova is shown in Fig. 8. Here the cylinder head is provided with two circular cavities. At one side of the head is the air-cell,B. Oil is injected through the nozzle,A, and some of it passes across the head and enters the cell along with a slight amount of air. The fuel-air mixture in the cell experiences a partial combustion which creates a high pressure in the cell. The gases blow out of the cell and set the air and fuel in the cylinder in motion in two separate circuits which fill the two cavities and insure mixing of the air and fuel. Altho this system gives high fuel economy it does not materially decrease the top pressure and it complicated the design of the cylinder head.

From this review of the possible mithods of combustion control it seems that the Cummins of the Lanova systems would be preferable on a Diesel aircraft engine. Of these two systems the Cummins system seems to offer the simpler, lighter,and more reliable method of burning the fuel.

The starting problem could be solved for planes in regular scheduled service by having a portable electric motor which could be attached to the crankshaft by a suitable gear arrangement. For other planes some method of decompressing could be devised which with a powerful inertia starter would provide adequate means of starting.

The general design of oil engines has reached some form of standardization and a study of the design of the existing Diesel engines shows the following approximate ratios to be true: Crankshaft, 65% to 70% of cylinder bore; crankpins, 60% to 67% of cylinder bore; piston pins, 30% to 40% of cylinder bore; length of connecting rods, 2 to 2¼ times stroke; length of piston, 1½ times piston bore.

From this analysis of the design features and a consideration of the problems involved, plausible specifications of a 1000 h.p. to 2000 h.p. Diesel engine may be drawn.

1. Cylinder arrangement will be in-line of possibly as in the Stirling or Bleser engines.

2. Fluid cooling.

3. Two-stroke-cycle operation.

4. General ratios as listed above.

5. Combustion control by the air-cell method.

6. Injection system of the distributor type.

7. Top cylinder pressure limited to 800 lbs. per sq. in.

8. Weight of bare engine, 0.8 lbs. to 1.0 lb. per maximum h.p. with four-stroke operation and from 0.6 lbs. to 0.8 lbs. with the two-stroke-cycle operation.

9. Maximum fuel consumption.

	lbs. per b.h.p.hr.
Clear exhaust, rated b.h.p.	0.40
75 per cent rated b.h.p.	0.35
Take-off, 125% rated b.h.p.	0.50

10. Starting by portable electric of compressed air unit or by decompression and an inertia starter.

11. Minimum service intervals at normal operation:

50 hrs.,routine inspection of nozzles,etc.;

350 hrs., top overhaul;

1000 hrs., major overhaul of bearings,pistons.

12. Must have sufficient scavenging and supercharging capacity to develop rated h.p. at 15,000 ft.altitude.

13. Balance of reciprocating parts must be such that the engine is free from torsional vibrations in the operating range.

14. Installation should be in the wing in such a manner to facilitate inspection both during flight and on the ground.

15. Reduction gearing to the propeller to be arranged for most efficient operation at cruising speed.

If such an engine could be built, and at present the high cost of research and development seems to be the only obstacle, it would have all the advantages previously listed over the present type of gasoline engime. As a result of these advantages, air travel would become safer and cheaper and larger aircraft with greater flying range than now possible could be built.

STEAM POWER PLANTS

The reliability of steam power has caused engineers and inventors to revert to it again and again as a possible means of powering aircraft. It has probably been considered more than any other type which has not been given any practical application until recently. Aside from the fact that steam power would be dependable, steam power units could be built in sizes much larger than that now possible with the spark-ignition engine. The overall operating efficiency of a steam power plant using turbines or a turbine and economizers and pre-heaters would compare favorably with the efficiencies of the gasoline engine. The system would be free from vibrations, the fire hazard low, no interference with radio communication, and there would be very little loss of power with increase in altitude.

The principal difficulty has been to develop a system of boiler, turbine, reduction, gearing and condenser with a high thermal efficiency and a low specific weight. The boiler problem could be solved by using forced draft and forced circulation in a flash type boiler. Suitable turbines are already on the market. The conventional type of reduction gearing using spur gears would be too heavy as the rotative speed of the turbine would be high and it would be necessary to have a considerable reduction to the propeller in order not to have low propeller efficiencies. The condenser design is rather difficult due to the fact that an enormous amount of latent heat must be dissipated to the air. The use of metal covered wings with the surface acting as a

condenser seems to be the logical solution, but this offers many mechanical difficulties and would be rather hard to accomplish. The NACA investigated the possibility and after considerable study took an unfavorable view.

Regardless of these difficulties several steam power plants have been designed. In 1930, several engineers collaborated on a huge steam power plant and designed a system developing a maximum of 6,000 h.p. The boiler was to be bullet shaped, being surrounded with steam and superheater coils and using forced draft and forced circulation. Two turbines of 3,000 maxium shaft h.p. each and using reduction gearing to the propeller were to be used. The water recovery was to be almost perfect so that only 300 lbs., need be carried. The weight per maximum h.p. output was 2.8 lbs.; another system developing 2,500 h.p. has been designed by a German inventor and it is in the process of being built but no further data on it is available, although the Germans have built a high speed turbine weighing 6 oz.per h.p.

Several smaller steam power plants have been designed, built and put into active operation. One by Besler Brothers in California, developing 150 h.p; and one by the Johnson Company in Ackron, Ohio, developing 50 h.p. These smaller units are interesting but little knowledge is to be gained from their use and their possibilities of development are slim.

A consideration of steam power in aircraft seems to indicate that it would necessarily follow the general design of the system outlined above. That is, flash boiler using

forced draft and circulation, high rotative speed turbine, hydraulic reduction gearing, and wing surface condenser. Such a system is certainly a possibility but much research and development must take place before it can seriously challenge the predominance of the internal combustion engine.

VII. THE INTERNAL COMBUSTION TURBINE

The gas turbine may be said to possess certain inherent advantages over the reciprocating type of internal combustion engines, chief among them being large power output per unit; a potential gain in overall operating efficiency due to the more complete expansion of the combustion gases, simplified lubricating system,, and the attainment of high rotative speeds.

The primary difficulty which has retarded the efforts to convert the gas turbine into a practical prime mover has been the inability of existing construction materials to to retain their physical properties when subjected to the temperatures encountered in its cycle of operation. The temperatures of the casing and rotor blades must stand extremely high and at present, there is no material which will stand up under the thermal stresses. The development of some new construction material with the necessary physical properties or some method of cooling might overcome this difficulty. Lionel S. Marks and M. Danilov have shown by extensive study and experiment that the thermal efficiency to be expected from a gas turbine is not high. This fact would have to be balanced by an equivalent decrease in specific weight, or some method of utilizing the heat energy available in the exhaust gases.

Gas turbines may be of two types, the intermittent or explosion type and the constant pressure type. At present, the explosion type is apparently more applicable to aircraft, since it requires lower compression pressures for satisfac-

tory operation and it offers greater facility for cooling. However, due to its intermittent operation it does not exert a constant torque as the constant pressure type does. With either type it would be necessary to employ some method of utilizing the heat energy available in the exhaust gases in order to obtain good thermal efficiencies. This fact rather complicates the system and limits its application to the larger sizes. This available heat could be used to generate steam which might be used in the combustion turbine for cooling or in a separate steam turbine on the same shaft, or it could be used to run an air compressor supplying the main turbine.

No internal combustion turbine has ever been built which can approach the performance characteristics of the present engines and very little is known regarding their possibilities. It is doubtful whether the gas turbine can ever challenge the internal combustion reciprocating engine and certainly its development is not eminent within the next decade.

VIII. JET PROPULSION

It has been said that when motors reach a high degree of perfection some entirely new development will come along and make motors and propellers unnecessary. Such a possibility is jet or rocket propulsion. This type of propulsion utilizes the reaction of high velocity gases escaping through a nozzle or orifice with the air. There are several methods of obtaining the high velocity gases but the general idea is the same in all types of jet propulsion.

The advantages of such a system are: the complete elimination of any mechanical equipment, high output per pound weight, the attainment of speeds heretofore unapproached, and the possibility of inter-planetary travel.

The obstacles involved in propulsion by this method are obviously much the same as those encountered in the internal combustion turbine. The temperatures are high, the fire hazard is great, and control of combustion is difficult.

There are a number of experimenters in this field meeting with various degrees of success. Professor R. H. Goddard working under a grant from the Smithsonian Institute has developed a rocked which in test flights attained a speed of 700 m.p.h., an altitude of 7,500 ft. and traveled several miles. This rocket is of the constant pressure type rather than the usual explosion type. A liquid fuel and a combustion supporting fluid are fed into combustion chamber provided with a conical nozzle through which the

the products of combustion are discharged. The advantages of this type over the explosion type are that the propellent materials passes several times the energy of powders per unit weight, and that moderate pressures may be employed, thus, avoiding the weight of strong combustion chambers that would be required if propulsion took place by successive explosions. The combustion chamber, which is considered as the motor, weighed five lbs., and the mechanical output at the jet was 1030 h.p. This gave an output of 206 h.p. per pound of motor. This can hardly considered as a fair comparison with other types of propulsion as the fuel and combustion supporting fluid were fed to the combustion chamber by compressed gas and the work of this gas should be subtracted from the work of the combustion. This type of propulsion offers absolutely no possibilities of being applied to the needs as considered herein.

Another jet type propulsion of greater possibilities has been developed by an inventor in Paris, France. His method is to boil equal parts of water and gasoline in a crude oil boiler up to about 2,000 lbs., per square inch. The gases escape through a very fine slot arranged under the leading edge of the main wing where by swirling around and up they create a vacuum over the forward part of the wing. Atmospheric pressure forces the plane into the vacuum. A speed of 600 m.p.h. has been attained on a rotating arm and a speed of 60 m.p.h. was attained on a boat using only one third the fuel required on an equivalent gasoline motor. Further work on this idea is necessary before it can be tried on an airplane but if it should prove successful

it would probably revolutionize the aircraft industry.

At present jet propulsion of any type is nothing more than an interesting experiment and cannot be anticipated to displace the aircraft engine.

IX. CONCLUSION

The possibility of jet propulsion and the use of the internal combustion turbine having been eliminated because of the stated disadvantages and apparently unsurmountable obstacles. There are three possible paths of development of a 1,000 to 2,000 h.p. aircraft engine. First, the spark-ignition engine may revert to the in-line fluid-cooled type as discussed in chapter three. In the opinion of the author the compression-ignition engine will eventually prove to be the best engine for this purpose and will completely dominate the aircraft engine field in this power range. The steam power plant offers some inherent advantages but much development must take place before it can challenge the supremancy of the internal combustion engine, and futhermore, indications are that steam power will not be pratical in units of less than 2000 h.p.

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APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrent its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not necessarily endorse or approve any statements made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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