THE DEVELOPMENT OF AIRCRAFT ENGINES

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TABLE OF CONTENTS

	Page
Preface	1
Purpose	2
Early Aircraft Engines	3
Wartime Engines	8
Later Development	19
Steam Power For Aircraft Engines	31
Novel Designs	40
Recent Development	51
Conclusion	61
Bibliography	63
Appendix	66
Approval Sheet	70

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Preface

The preparation of this topic has consisted entirely of library research work. The results herewith stated are taken from magazines, pamphlets, and text books devoted to aircraft development. They are the results of experimentation and conclusions drawn by experts on the subject.

The author has attempted by this writing to present a continous story of the advancements made in aircraft developments from the time of the first significant beginning up to the present time. In so far as possible, a chronological arrangement according to years has been maintained.

Finally the author wishes to extend acknowledgement to Professor F. L. Wilkinson for valuable data supplied.

Purpose

In this discussion, it is intended to present the performances and characteristics of the engines within themselves. It is obvious that the qualities of the engines have an almost direct bearing upon every other feature of the plane design. The weight of the engine affects the wing design and area and consequently its drag. The frontal area of the engine not only determines the drag at that point but also affects the fuselage design; but these influences are so many and varied that, if any direct and definite conclusions are to be drawn upon the engines themselves, these other factors cannot be discussed in detail by such a limited paper. In turn, the plane design, not to be attributed to the engine design, will also affect the engine performances. So, especially in the earlier types, the reader should not place the entire blame upon the engine when certain of its characteristics appear faulty, although they will necessarily be presented here in such light. The author will, in extreme cases, attempt to bring such considerations to the attention of the reader.

Chapter 1

EARLY AIRCRAFT ENGINES

Disregarding such early attempts at flight by mechanical power as preformed by Leonardo da Vinci about 1500, who attempted to get the required power from previously wound springs, and W.H. Phillips of Great Britain, who was the first to actually attempt the application of heat in power flying around the year 1842, the discussion shall begin just before the first successful human flight in 1903.

The first successfully controlled heavier-than-air flight was made in 1903 by the Wright brothers, and although they have been acclaimed for their results, an engine vastly superior to the one used was designed and built two years earlier. Manly was the designer and builder. The engine was a five cylinder air-cooled radial with a five inch bore and five and one-half inch stroke. It weighed 187.5 pounds fully equipped and developed fifty-two and four tenths horsepower at 950 revolutions per minute for an average specific weight of three and six tenths pounds per horsepower, which is not bad as we shall see, in comparison with some of our almost modern engines. After a thirty hour test, the engine was taken apart and found to be in good condition. Just how remarkable this performance was can be seen by refering to table number 1, appendix. It was nine

years ahead of its time in weight per horsepower, in addition to its design and construction.

The employment of automatically operated inlet valves is its only obsolete feature. The cylinders were made of one sixteenth inch steel, lined with one sixteenth inch of cast iron. The pistons were of steel construction. Its chief drawbacks were frequent carburetor troubles and a bad ignition construction.[1] Ironically enough, this engine never participated in a successful flight. Manly also built a smaller engine developing three and two tenths horsepower running at 1800 revolutions per minute and weighing about ten pounds. It was of the same design as the other engine with a smaller bore and stroke. It suffered the same fate as the previously built engine.[2]

When the Wright brothers gave out specifications for their plane, they desired an engine to develop at least eight horsepower and one not to weigh over 800 pounds, which shows that they were not too optimistic. Supposedly regarding the title at stake, they finally decided to build their own engine. In its final form it was a four cylinder in-line water cooled engine with a four inch bore and four inch stroke. It,

1. History of the Aeronautical Engine, Aviation August,1926.
2. Evolution of Aircraft Engine, Scientific Am. Oct. 1918.

too, had automatic inlet valves. The fuel was sprayed into the inlet manifold with a pump, and ignition was supplied by a single magneto. It developed steadily twelve horsepower, although when first started before it became too hot, it would develop sixteen horsepower. The bare engine weighed 200 pounds for a specific weight of sixteen and seven tenths pounds per horsepower and without any auxiliaries. This engine was not nearly so advanced as was Manly's engine, but still it was the first engine to fly a humanly controlled plane. The flight only lasted for the duration of a few minutes, desirably so because of the unreliability of the engine and its inability to carry a load of fuel.

Naturally, with its initiation aviation developed two extreme factions- those who did see a great future for heavier-than-air craft and a large host of disbelievers. The development in the following years was steady if slow. The Wrights built four, six, and eight cylinder engines developing as high as seventy horsepower, some of them being as light as five pounds per horsepower. The trend in this country was for water cooled vertical and "V" types, while in Europe the air cooled radial predominated. Notably among this type was the Anzani three cylinder, air cooled radial operating on a single crank. It developed twenty-four and one half horsepower at 1600 revolutions per minute and had a specific

weight of six pounds per horsepower. This engine gained its fame by making the first heavier-than-air flight across the English Channel under the guidance of the Frenchman Bleriot. With this famous flight in 1909, the general skepticism about airplane flight began to waver. Some of the big balloon manufacturers began turning their efforts toward heavier-than-air craft.[1]

Even at this period, eight years later, there is still hardly an approach to the engine built by Manly, showing the slow development necessarily in harmony with the dark rule of thumb methods used. The materials were crude and of a great many unknown properties. Research was a matter of hit and miss because the art had not yet become an exact engineering science.[2]

Between the years 1908 and 1912 the French produced more in aviation than all of the other countries combined. During this time the Gnome engine was made and put on the market. It was a startling revision from previous types, and perhaps for its period of time was not falsely priaised. It is the most mechanically refined and exact engine built so far. It had to be so, for it was designed upon the rotary principle, that is, the crank remained stationary while the entire engine revolved. The only satisfactory way for such an engine to be designed

1. "Airplanes and Aero Engines", Engineering, May 3, 1935.
2. "Evolution of Aircraft Engines, Sci. Am., Oct. 5, 1918.

was of the air-cooled radial type. The Gnome was a few years ahead of its time when it was first placed on the market, and almost every believer in air-cooled engines followed it closely. In spite of its popularity, however, it had numerous shortcomings, chief among these being low efficiency, very short life, and a huge consumption of lubricant. The latter of these is particularly undesirable because the engine used castor oil for lubrication purposes. In addition to the above, large amounts of power were absorbed in revolving the cylinders through comparatively stationary air at high speeds, and the motor had to be demounted every eight working hours to clean out the oil and soot.

Chapter II

WAR TIME ENGINES

At the beginning of the war, few engines were being manufactured, and comparatively few of these were performing with any degree of reliability. Germany, who had been preparing for the war, had a head start on the other countries both in the matter of engines and craft. Their motors generally were much higher powered than those of other countries, and although they were comparatively advanced, the better motors were not the high powered ones, nor were the performances of these suprisingly good.

The Imperial government, in order to stimulate the production of more efficient engines, held a national contest among all engines which might be available for government use. Out of forty-five engines which competed for the prize given, only nineteen completed the test. The most reliable one of these ran for fifty hours and was equipped with the then advanced feature of reduction gearing. The ratio was two to one. It was not uncommon at this time for an engine to fail after having been run at full throttle for five minutes. A great deal of this was caused by the spark plugs which cracked through the insulation due to excessive vibration and heat. The worst feature of this early failure was that the plane had not risen to a sufficiently high altitude to allow the pilot a chance of getting back to the airport or seek out some other landing place. This practice

of early failure was not confined to the first test of the engine, but even after four or five flights some of the engines would fail in the take-off of the succeeding flight. It is easy to see how this was made doubly bad in time of war where long periods of warming up the engine were not always available.

The motor, which won the German contest mentioned above, developed 100 horsepower weighing 431 pounds. Its fuel consumption was exceedingly low --0.45 pounds per horsepower hour. The construction of pressed steel cylinder jackets and cylinders of special iron alloy were new features. In another contest in Germany during 1913, sixty-six engines were entered of which fourteen were air cooled. None of the air cooled engines were selected as the ten finalists showing a definite trend in their country to the water cooled engine which they believed superior. The most notable German engine of this type was a vertical six cylinder, 300 horsepower engine with weights as low as three pounds per horsepower and a remarkable low fuel consumption.[1]

But this superiority by Germany was not to be held long. The war caused a sudden and rapid development, especially in size, power, and revolutions per minute. The French had the Gnome which was till considered a good engine. Several other rotary engines were being built with specific weights as low as three pounds per horsepower. By 1914 Great

1. History of the Aeronautical Engine, Aviation Feb. 22, 1926.

Britain had 272 planes. They boasted the fastest and most efficient fighter having a top speed of about ninety-five miles per hour powered with a fifty horsepower motor. Intake valves were still automatically operated, and up until this time few engines were giving satisfactory results, the Gnome remaining the only really practical engine, but with the development of the new engines, the inherent drawbacks of the rotary type were even more outstanding. Its excessive consumption of castor oil lubricant was beginning to be a large problem. The gyroscopic action which it produced on a plane during difficult maneuvers was taking the lives of well-trained pilots. Its future development was limited to 200 horsepower or less, and so a great deal of experimentation was done on the air-cooled static radial engine. It ultimately developed that all of the engines developing more than 200 horsepower were air-cooled static radial engines. Their success, however, was not immediate, and the rotary engine did not completely pass from the picture until 1917.[1]

The Rhone engine came forth with mechanically operated intake valves. This was a forward step, but it was found that it used too much fuel. The eighteen cylinder Rhone had a notably small weight per horsepower - 160 horsepower and 367 pounds. Other modifications were being made in the valve gears of engines, the general belief at that time being that a great many of the problems could be solved by simplification

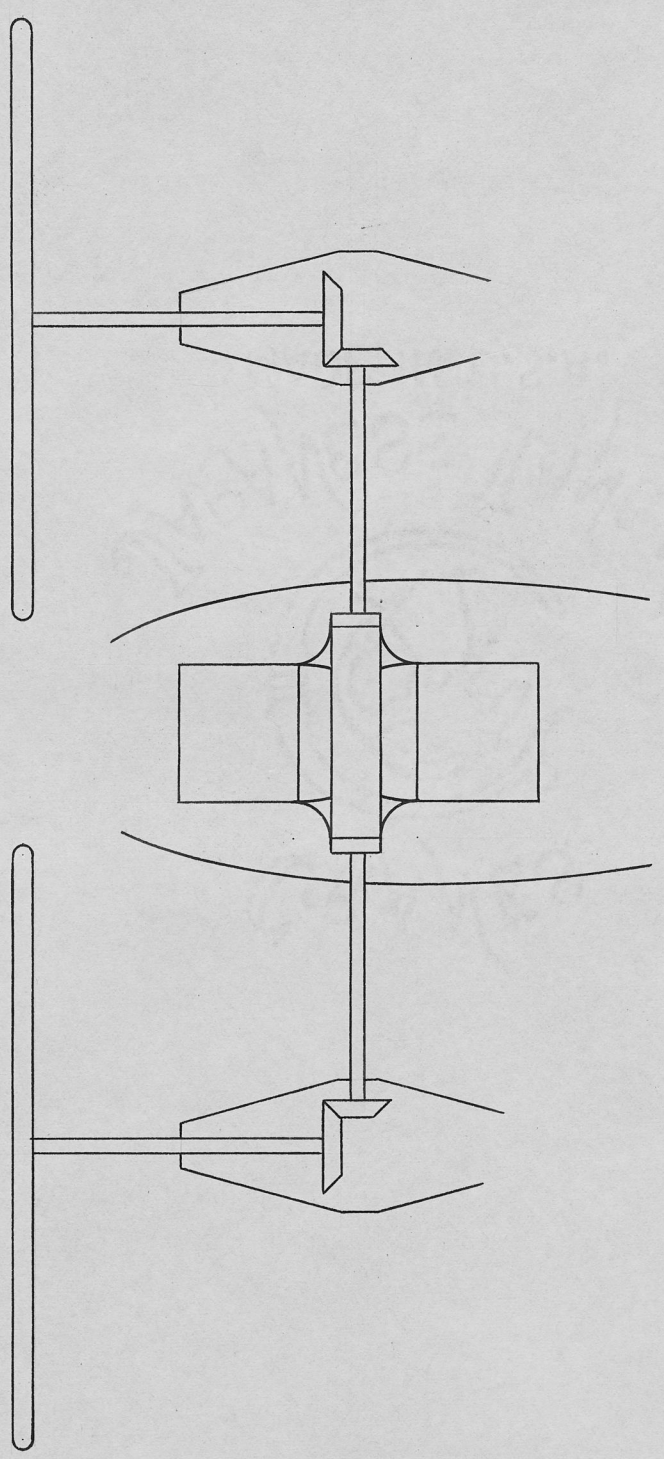
1. Aviation, "History of the Aeronautical Engine," Aug. 16,1926.

of valve gears. In some engines, the intake valves were being placed in the pistons.

A number of different types were being built. The Burlat motor produced their lightest engine of four and one half pounds per horsepower. The Fatava motor was constructed so that varying degrees of power were obtained by cutting out combustion in any number of the cylinders. Others had slots cut in the cylinder walls and were designed to utilize a cross head. Suprisingly, there were still hopes in some minds that man would be able to lift himself by his own power, and prizes were given for development along this line. The Mercedes with a specific weight of four and one fourth pounds per horsepower hour was fast becoming the most efficient and respected engine in Europe.[1] The Hispano-Suiza was becoming well established with its 150 horsepower engine.

By the end of 1914, there were a dozen recognized types of aero engines, but engine failures were still the cause for the most accidents. Considerations of duplicate power plants were being considered both for increases in total power and for safety. Although Sikorsky had designed an engine approaching 600 horsepower, it was still in its infancy, and so the construction of two 300 horsepower units each was proposed. It was fixed so that either motor may drive both propellers (see fig. 1, page 12) and the other used as a standby. A change gear mounted between the motors allowed either or both engines to drive either or both propellers.

1. Internal Combustion Engines in Aviation, Sci. Am. July 11, 1914.



DUAL AERO MOTOR

FIG NO.1

Each motor was complete with all auxiliaries. The propellers were to turn at 900 revolutions per minute, and the total weight of the device was 2700 pounds.[1] The duplication of engines for safety appeared to be a last resort from a desperate position. The carrying of an idle unreliable engine to replace an equally unreliable one was, however, a temporary solution. The development of the airplane had overtaken the development of the engine.[2]

The rotary under severe criticism was still being used in planes under 100 horsepower. The present trend, however, in the higher powered engines was toward the "V" eight cylinder four stroke cycle.[3] Some were constructed with individual cylinders having welded water jackets of monel metal. The splash system of lubrication was done away with to eliminate waste and the possibility of flooding the cylinders with oil during a glide. One of the first of these weighed 950 pounds dry and developed 160 horsepower.[4]

With the demand for more power and speed came the development of the twin-six engine. It had the characteristics of greater power and reliability. Up to the present time no engine had been able to keep an airplane in the air longer than twenty-four hours. This was accomplished by a

1. Sci. Am. S., Dual Aero Engines, Dec. 19, 1914.
2. Sci. Am., Dual Engined Airplanes, Dec. 5, 1914.
3. Sci. Am., Latest Types of Aero Engines, Sept. 19, 1914.
4. Sci. Am., Curtis Motor, March 21, 1914.

German with a stationary water cooled engine. Machines were needed to carry a useful load of one ton, and 100 horsepower engines would not do it. It was hoped that the twin-six would cut down vibration which was the cause of a good many engine failures. The most notable of the early twelve cylinder "V" engines was the Sunbeam. It delivered 225 horsepower and weighed 1080 pounds. Two of these were used to fly a seventy foot plane. Rolls Royce produced a similar motor of 250 horsepower weighing only 800 pounds.[1]

It was in this year, 1915, that the first plans for the famous Liberty Engine were laid. Visions of America entering the great conflict were perceptible to many and the United States did not want to be lacking if the occasion should arise. It was obvious to the designers that there were three prime requisites of a good aviation engine -- reliability, low weight per horseppwer, and low fuel and oil consumption. Since these requirements were conflicting, the best compromise should be reached. The first problem then was to determine which of these were the most important. A twin-six "V" type was adopted for the design, and the first model was ready for the block test in 1916 in February. It had a cast iron block with cast iron cylinders. The second model appeared in April of the same year with forged steel cylinders and pressed steel jackets. By July 1916, the motor weight was reduced to about two pounds per horsepower dry and developed

1. Sci. Am., Twin-Six Engines for Airplanes, Nov. 13, 1915.

400 horsepower.[1] It burned 0,492 pounds of fuel per brake horsepower hour, and had a speed of 1550 revolutions per minute. In this motor, for the first time, a low specific weight was combined with fine endurance capacities. After 160 hours of continuous running,the engine was disassembled and found to be still in good shape. From this it was concluded that the motor could easily be run for 125 to 150 hours in actual flight between overhauls. This motor had surpassed the progress of propeller design, and consequently with the direct drive of the Liberty engine, the thrust efficiency was low. It should have been provided with reduction gearing. It was considered to raise the speed of the engine to 1800 revolutions per minute, therby reducing its specific weight to one and ninety-four hundredths pounds per horsepower.[2] A heat balance test was run on the engine with the following results:[3]

	Hp.	%B.Hp.	%Total
Average B. Hp.	372	100	27.3
Average Absorbed by Jacket H_2O	339	91	24.8
Average absorbed by friction	48	13	3.5
Exhaust	606	163	44.4
Totals --	1365		100.0

The increase in piston speeds to develop higher powers for the same weight began to attract attention. With the conventional designs, this amounted to increasing the rotative speed of the crank and the consequent addition of reduction gearing to give a satisfactory thrust efficiency,

1. Sci. Am., True Story of Liberty Motor, June 1, 1918.
2. Mechanical Engineer, Liberty Engine Tests, March, 1919.
3. Mechanical Engineer, Liberty Motor, Aug., 1919.

but this additional weight would partly compensate for the increase in power, and so little would be gained. It was then decided that the use of a higer piston speed could be utilized with the increase of rotative speed by changing the bore-stroke ratio. If the length of the stroke should be increased in relation to the bore very little weight would be added for the same bore and at the same time the rotative speed could be kept low. This principle was utilized in the Hispano-Suiza, and the engine became well known because of the adoption of this idea. But it was found that the problem could not be solved as easily as it appeared on the surface.

The valves and valve mechanism began to give trouble laboring under the higher powers. Here for the first time a series of long lines of criticisms on the poppet valve began. It was unreliable and small leaks became worse with time. In its stead, the sleeve and rotary valves were introduced; but with present methods of manufacture, it was difficult to keep down leakage as it did not fit as tight as the poppet valve. Aside from the limitations by the valve gear, wear and tear along with vibration held down the engine speed.[1]

Designers began to see the advantages of streamlining, and the craft itself had advanced past enough crude stages to make streamlining a significant refinement. Here, again, there was a clash between the old rotary engine and modern trends. The advantages of conserving space and giving

1. Aeroplane Engines, Science American, Oct. 16, 1915.

better visibility in fighting planes was more than offset by the possibilities of increased speed due to better air flow over the entire plane, and we find the rotary fading rapidly from the picture.[1] There was an immediate demand for an aircooled motor similar to the rotary type but with better streamline qualities. Obiously the static air-cooled radial was the solution to this problem, and intensive work began to refine it, for up to the present time it had not kept pace with other types.[2] This work was concentrated on the production of medium powered radials. In 1918 several were produced; and although usually they showed a more conservative weight per horsepower, they were not always lighter than the water-cooled engines. Generally, a reduction in weight of fifteen percent could be obtained by the air-cooled engine, and this fact alone seemed to predict a bright future. The absence of the radiator and its shortness were good for speed and pwer. Its overhauling facilities were better. It possessed an advantage in tropic maneuvers. At full power in these regions, the air-cooled engine functioned well at 150 degrees Fahrenheit, while such temperatures would cause excessive evaporation of water in the radiators of water-cooled engines. The chief drawback in the air-cooled engine was with localization of excessive heat spots.[3]

1. Scientific Amer., Radial Engine Saves Space, Dec. 7, 1918.
2. Aviation, Advent of Air-cooled Radial, Feb. 22, 1926.

With the close of the war, we find Germany still content to use the heavier water-cooled engines due to their better reliability and the lack of funds for other development. All of their motors were vertical with six cylinders, having a specific weight of three and seventy-five hundredths pounds per horsepower.[1] In the higher powered engines, frequent trouble was had with burning of exhaust valves by preignition arising chiefly from over-heated ignition plugs. Radiator construction was a big problem. Ignition troubles were too frequent, and in general unreliability prevailed in the United States. In an attempt to stop the flooding of cylinders with oil, a smaller crankcase with auxiliary oil tanks was proposed.[2]

In 1918, there were 37,700 engines in use, being produced at the rate of approximately 3,000 per month. There were engines in service of 375 horsepower, and those of 500 horsepower were being developed through their last stages.[3]

1. "German Airplane Engines", Scientific Amer., Jan. 26, 1918.
2. A. S.M.E.J., Aeronautic Engines, Nov., 1918.
3. "Aeroplane and Aero Engines", Engineering, May 3, 1935.

Chapter III

Later Development

Since the war, development has been along the lines of increasing the ceiling and increasing the output without adding weight, both of which amount to supercharging and higher compression ratios; larger engines; the application of the diesel principle; better fuel; and many novel designs which will be discussed separately.

Supercharging actually became a practical subject in 1916 before the end of the war.[1] At this time the common compression ratio was about four and one-half to one. It was thought that the effect of lower pressurers at high altitudes could be partially compensated for varying the compression ratio with increasing or decreasing the space above the piston at top dead center. The curve on sheet number 20 shows the effect of increasing altitudes on the pressure. With this decrease of pressure the weight of the fresh air charge and consequently the weight of the fuel taken in by the cylinder will be greatly lessened causing a reduction in power.[2] The ordinary airplane of the day was limited to an altitude of about 10,000 feet. At a compression pressure of 120 pounds per square inch preignition would occur, so little could be gained by increasing the compression ratio. Seven or eight minutes were required for an airplane to reach an altitude of 10,000 feet.[3]

1. Inc. Power Plant Efficiency", Aviation, Dec., 1931.
2. "Effect of Altitude on Engines", Sci. Am., Nov. 25, 1916.
3. "Development of Aviation Engines", Sci. Am., Oct.,1917.

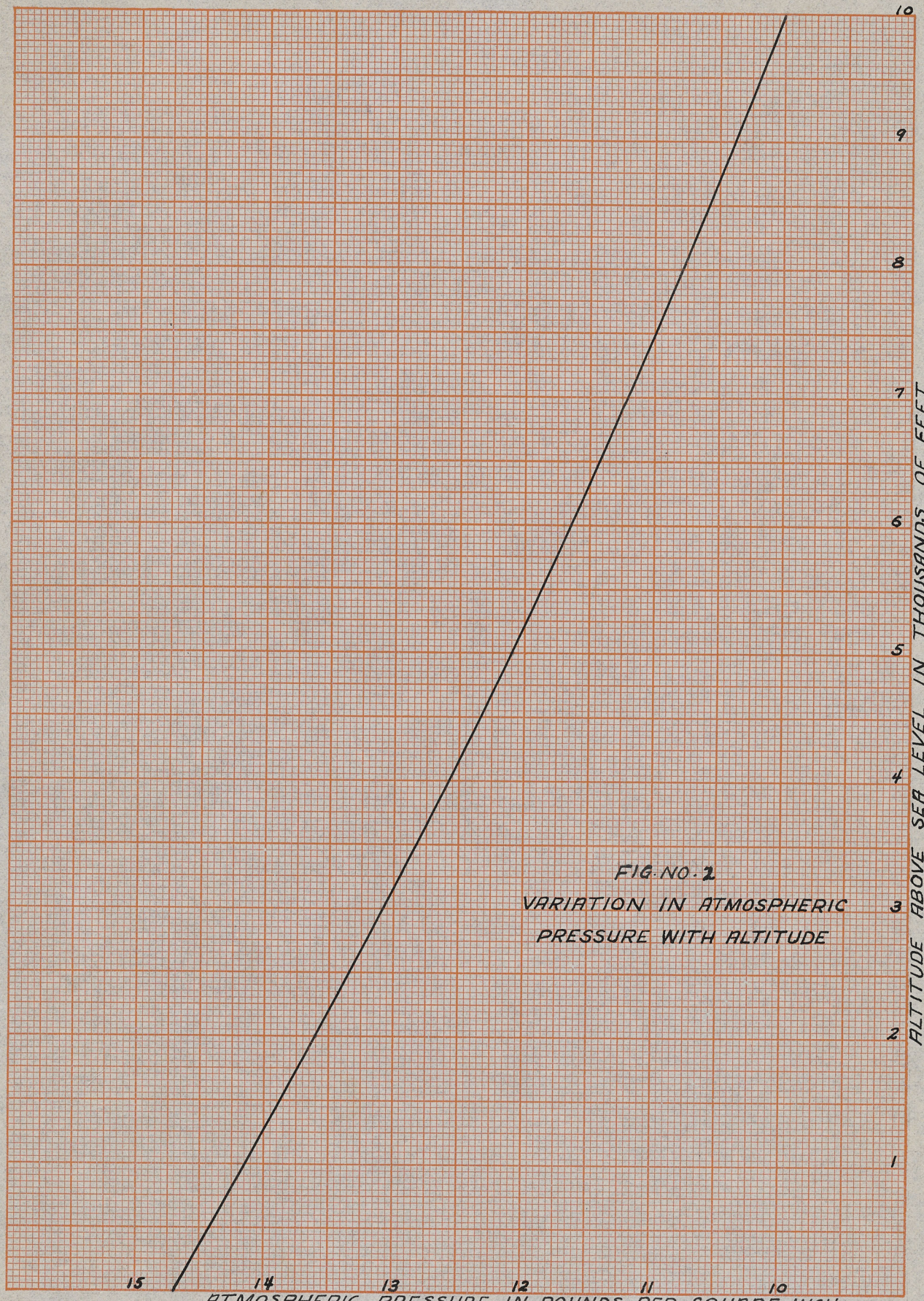


FIG. NO. 2
VARIATION IN ATMOSPHERIC
PRESSURE WITH ALTITUDE

By 1919, planes were flying as high as 25,000 feet with supercharging. By this, a 200 horsepower motor at sea level would be made to develop 100 horsepower at 25,000 feet; whereas before it would have fallen to this value at 8,000 feet, and at 25,000 feet it would have lost seventy-five percent of its original power. The supercharger weighed 100 pounds and was of the gas-turbine centrifugal compressor type. By 1923, it was possible to maintain power up to 30,000 feet. It was found that the back pressure caused by the turbo-compressor was greater than it should be.[1]

Some two stroke cycles had been built, but nome of them had been flown with satisfactory results. Only very few engines of the horizontally opposed type had been built, never with sufficiently good results and never with high powers. The modern "V" type engine had a specific weight of about two pounds per horsepower. Reduction gearing had been difficult to obtain as really good gearing, though it had been used. Up to 1920 some "W" type engines had been built, but the complications were so numerous that it had not found favor. The most prominent example of this kind of an engine was the Sunbeam. It had eighteen cylinders, six carburetors, six magnetos, and six cam shafts with an entirely new complicated valve mechanism. Six carburetors made the job of even air-fuel ratio adjustments difficult.[2]

1. "Aero Engine Supercharging", Engineering, Feb. 9, 1923.
2. "Modern Aviation Engine," American Machinist, Feb., 1920.

A twelve cylinder engine developing 578 horsepower was brought out in the same year having a specific weight of one and ninety-four hundredths pounds per horsepower. It used 0.52 pounds of fuel per horsepower hour for the maximum carburetor setting and 0.45 for the minimum setting. It is obvious that this engine was far in advance of the craft which it flew, for its maximum speed was 120 miles per hour.[1]

In 1921, we see the first successful application of the Diesel principle to airplane flight. The engine was designed by Professor Junkers and installed in a German monoplane. The advantages claimed for this engine are: low weight per horsepower, increased reliability, higher fuel economy, greater simplicity, safety against fire, and perfect balance. It really was not a true Diesel engine but a modification of the type. The compression pressure only went up to 210 pounds per square inch, and a jump spark ignition was used to ignite the charge. It had six cylinders working on the two stroke cycle with two pistons for each cylinder opposed head on. No valve mechanism was needed as the ports were in the cylinder walls. Two separate crankshafts were employed, one on the top and one on the bottom of the engine. One piston uncovered the intake port at the end of its stroke while the other uncovered the exhaust port. The exhaust ports were larger and uncovered first to take care of the expanded charge. This type of port arrangement had a good scavenging

1. "Forward Step in Engines", Sci. Am., Sept. 4, 1920.

affect as the incoming fresh charge at one end swept the burnt gases out at the other. Its specific weight was one and one half pounds per horsepower because of two pistons per cylinder and the fact that it operated on the two stroke cycle. Its balance was unusually good because the in and out movements of the parts in each cylinder exactly balanced each other. Thus, vibration, which was one of the worst qualities of the earlier engines, was eliminated. Gasoline was used as a fuel.[1]

With the demands for higher powered engines increasing, a little later in the year a design for a 1,000 horsepower engine came forth. None of this type had been built yet. It was a combination of series and star arrangement. The designer grouped four stars or four sets each of seven stationary cylinders about a common crankcase, the whole arrangement being strictly symmetrical. The crankshaft rested in five main bearings, and the pistons were made of aluminum. Each cylinder had four valves, two for intake and two for exhaust, making 4 x 7 x 4 = 112 valves needed. The rotative speed of the engine was 2,000 revolutions per minute. No figures are available on its weight or fuel consumption.[2]

Another idea for a high powered unit came forward at almost the same time. Three 400 horsepower Liberty motors were to be clutched together to render a total maximum power of approximately 1200 horsepower, if it should be

1. "New Diesel for Airplane", Sci. Am., Jan., 1921.
2. "1,000 Horsepower Motor for Aircraft", Engineering, Aug., 1921.

needed. This arrangement, however, was for the purpose of obtaining a power of 800 horsepower with one engine left in reserve, and here again is a reoccurance of the old idea back at the beginning of the war. But there was a basic reason for this insurance of reliability, for it was hoped to make a non-stop flight with this unit from New York City to Liverpool, Portugal. The unit was arranged with two engines mounted side by side with one in the rear.[1]

From 1922 to 1925 several significant investigations were made by the National Advisory Committee for Aeronautics. From the investigations in 1922, data on the better engines were published. The Maybach 300 horsepower engine had good performance up to 15,000 feet. Its part load efficiency was good. The specific weight was rather large. The B. M. W. 185 horsepower engine had the low fuel consumption of 0.41 pounds per horsepower hour. Its brake thermal efficiency and indicated thermal efficiency were thirty-three percent and thirty-seven percent respectively. Its performance was good up to 25,000 feet.[2] The Wright E-2 180 horsepower engine first could not be run more than fifty hours without overhaul. The Aeromarine U-6D eight cylinder 220 horsepower was the first engine to successfully complete the 300 hour endurance test required by the Bureau of Aeronautics.[3]

1. "Three Engines in One", Sci. Am., Oct., 1924.
2. "Annual Report", N. A. C. A., 1922.
3. "Investigation", N. A. C. A., 1922.

The 1924 report showed that the power could be increased by changing the fuel injection method. Where fifty-one brake horsepower could be obtained by external injection eighty brake horsepower could be obtained with internal injection. An engine equipped with a Roots type supercharger increased its ceiling from 14,500 feet to 31,000 feet and reduced the time to reach 18,000 feet from fifty-nine minutes to thirty-three minutes. In forty-five minutes, 25,000 feet could be attained, whereas for the same length of time, only 16,000 feet could be formerly reached.[1]

As a result of a great deal of experimental work in 1925 on high compression engines, it was found that before the power could be increased materially by increased compression pressures detonation and preignition took place. It was furthermore found that among many fuels the ability to resist detonation and preignition varied considerably. The investigation is to be carried further and more experimental work to be done on fuels.[2]

The radial air-cooled Bristol Jupiter engine with nine cylinders and developing 400 brake horsepower has been one of England's better motors. Its specific weight has been reduced to two pounds per horsepower according to the rated load and one and eight tenths pounds per horsepower by actual test.[3] Two Packard engines came out at the same time as the Bristol Jupiter engine. One developed 500 horsepower

1. "Report", N. A. C. A,, 1924.
2. "Fuels for High Compression Engines", N. A. C. A., 1925.
3. "Bristol Jupiter Aircraft Engine", Mechanical Engineer, June, 1925.

and the other developed 800 horsepower. The smaller one develops 100 horsepower more than did the Liberty engine and weighs 140 pounds less. An extensive study was made of bearing loads and their affects, and the results incorporated in the design. The engines are characterized by a new type of cylinder construction, a lighter and stronger crankshaft, better timing gears, and a better oil supply.[1]

With the coming of the Schnieder Cup races in 1927, high powered racing engines were being developed. The United States entry was to be represented powered by a Packard "X" engine, so designated because of its shape. It consisted of two twelve cylinder, water-cooled, Packard "V", 1500 horsepower engines mounted on a single crankcase--one inverted and one upright. The unit would develop 1250 horsepower at 2700 revolutions per minute and would weigh one and twelve hundredths pounds for horsepower dry.[2] The Napier "Lion" racing engine which was in the British entry was the first highly powered engine to use reduction gearing.[3]

In 1926 the Nation Advisory Committee for Aeronautics did some experimentation on compression ignition engines using a compression ration of eleven and four tenths. An airless injection system was used having a primary fuel pump, and injection pump, and an automatic injection valve. It

1. "Recent Development in Aircraft Engines", Mechanical Engineer, May, 1925.
2. "New Packard X", Aviation, Aug. 15, 1927.
3. "Napier Lion Racing Engine", Aviation, Oct. 31, 1927.

was found possible to use this on a five by seven inch cylinder up to 1850 revolutions per minute where 0.3 pounds of fuel per horsepower hour were consumed at sixteen brake horsepower. When sixty pounds per square inch brake mean effective pressure was reached, excessive maximum pressures were encountered and the piston life was short. A fixed timing of the injection caused the engine to have poor acceleration qualities.[1] Changes were made in the combustion chamber design to give better turbulence, and the compression ratio was increased to thirteen and one half. The indicated mean effective pressure obtained was 110 pounds per square inch. Forty-seven hundredths pounds of fuel per horsepower hour was consumed with an injection pressure of 1200 pounds per square inch.[2]

Since the fuel consumption of the Diesel cycle is on the ratio of about two to three compared with the Otto cycle, the oil engine begins to compare favorably with the gasoline engine in the matter of weights when a flight of 300 miles or over is to be made. Oil engines have not been made with specific weights as low as three pounds per horsepower. Using a compression pressure up to 420 pounds per square inch, the engine starts readily with one revolution. The speed of the engine varies from 150 to 1700 revolutions

1. "Compression Ignition Engine", N. A. C. A., 1926.
2. Report on Aircraft Engines, N. A. C. A.; 1927.
3. Oil Engines for Aircraft, Aviation, Pg. 18, 1927.

per minute with smooth running, when a cam operated pump is employed.[1]

As burning of the exhaust valves continued to be a source of trouble in the poppet valve engines, a valveless engine and a radial sleeve valve engine were proposed. The valveless engine was of the conventional two stroke cycle, and the power per unit volume of piston displacement was actually seventy to ninety percent more than in the four stroke cycle engine. The main difficulty was had with the loss of unburnt gases in the exhaust which was sometimes as large as twenty per cent. This was due to the fact that the exhaust port was necessarily open when the fresh charge was taken into the cylinder. Improvement in the scavenging of the burnt mixture is obtained by placing large exhaust ports at the bottom of the stroke diametrically on opposite sides of the cylinder while the fresh charge is evenly distributed and prevented from escape by two delector plates on the top of the piston head. The double system of intake and exhaust ports give effective turblulence and good flame propogation throughout the explosion. The starvation characteristics of the ordinary two port two stroke cycle where one side of the cylinder is pocketed with burnt gases is eliminated.

As a result of the escape of unburnt gases, the fuel efficiency is low, but to offset this we have an eveness of crank effort, simplicity of construction, the elimination of grinding valves, and the elimination of the

1. "Oil Engines for Aircraft", Aviation, Apr. 18, 1927.

possibility of failure due to valve gear trouble.[1]

The sleeve valve has the advantages over the poppet valve of less noise, less wear, and consequently more endurance. The engine has the advantage of lessened height due to the absence of an overhead valve gear in the radial type. A sleeve valve radial engine has an overall diameter of thirty-five inches as compared with forty-nine inches for a similar engine of the poppet valve type. The sleeves are lubricated by oil spray from the crankshaft, and it is claimed impossible to assemble the unit without providing correct valve timing.[2]

The air-cooled radial came to the front in 1927 with such famous flights as those made by Lindbergh, CChamberlain, and Byrd. These engines, all 600 horsepower or more, used high compression ratios and had specific weights of about one pound per horsepower.[3]

In 1929 the Packard Automobile Company came forward with a Diesel engine that, for a time, made the world Diesel-minded. They proposed to construct a large plant which would be capable of producing 500 engines per month. After several years of experimentation a 4,200 horsepower unit weighing two pounds per horsepower was built. It then had 200 hours of running behind it and showed no indication of need for overhauling for some time. Besides a saving of twenty per cent in fuel consumption, it is claimed to be

1. "Valveless Aero Engine", Sci. Am., March, 1928.
2. "Slave Valve Aero Engine," Sci. Am., May, 1927.
3. "Progress in Aeronautics", Mechanical Engineer, Jan.,1928.

more in accordance with reliable plane construction. The company indicated that the engine would retail competitively or slightly under the gasoline engine, but since then little has been heard from the engine.[1]

In practice, the use of partial combustion at constant volume results in a greater gain in economy than simple theory indicates. Since higher temperatures are involved, coupled with the slightly increased time available for combustion, there is a reduction in fuel consumption. The amount of constant volume combustion portion of the cycle is limited and chiefly by the engine speed. This at present forbids its use in aircraft engines, but the development of the cycle is being investigated with regard to aircraft possibilities.[2]

The period since the war has been marked chiefly by continued increase in size, power, and speed of the water-cooled "V" type and the advent of the static air-cooled radial engines. Propeller reduction gearing has been used much lately on the larger engines. The exhaust turbine driven supercharger has passed the experimental stage, and progress is being made on the mechanically driven centrifugal and displacement types. There has been much refinement in mechanical details due to the advancement in the materials of constuction.

1. Packard to Begin Building Diesels, Aviation, Nov. 2, 1929.
2. Aircraft Diesel Engine, Mechanical Engineer, Oct., 1929.

Chapter IV

STEAM POWER FOR AIRCRAFT ENGINES

The possibility of powering airplanes with steam engines has received more consideration than any other type which has never been given an application up until recent times. If we disregard several unsuccessful early attempts, the first steam driven airplane to rise from the ground and proceed in continued flight landing successfully took place in 1933 from an Oakland, California airport.

In 1894 a steam driven box kite was launched, but there are doubts that it made a successful ascension and descent. Langley, Stringfellow, and Henson attempted flight by steam, but their attempts all ended in the same discouraging results.[1]

The reliability of steam power in ocean going vessels causes engineers and inventors to revert again to the question of steam power for aircraft. While the internal combustion engine loses power with increasing altitude, the steam power plant gains in power and efficiency with lowering of the exhaust pressure and has everything to gain from altitude flights. It is obvious that the only reason for the development of a steam power plant would be that it possessed enough desirable qualities to warrant the displacement of the internal combustion engine.

1. "Steam Takes to the Air", Aviation, June, 1933.

Up until 1926, experimentation and analysis seemed to indicate that not much hope could be held for steam utilization in flying. Commander E. E. Wilson working with the National Advisory Committee for Aeronautics in 1926 took an unfavorable view after serious study. He said that the modern engine challenges steam with the following figures: "Its weight is less than three pounds per horsepower, and it consumes only one half pound of fuel per horsepower hour. Its reliability is constantly increasing. Failures remain frequent only in the plumbing, water, gasoline and oil lines and systems where reduction of weight has been carried beyond the point where reliability can be maintained. This, however, is being constantly improved; and by the use of the air-cooled engine, one important phase of the plumbing disappears entirely. Now examine the steam power plant. It must compromise a boiler; the engines, auxiliaries; and a condenser, because no aircraft could possibly carry enough water on board to operate a non-condensing engine. To challenge the internal combustion engine, the steam engine must be a high speed turbine with considerable reduction to the propeller; and since the efficiency of a steam turbine is such that the fuel consumption is one pound per horsepower hour instead of the half pound figure found in our modern aircraft engine, it must work at pressures hitherto unemployed to make up for the inherent inefficiency of the steam cycle as compared with the internal combustion engine cycle. Only in very large units and with such pressures could a steam turbine be developed to weigh one pound per horsepower and have a fuel efficiency equal to that of the internal combustion

engine. With the enormous pressure of 1000 pounds per square inch it is likely that the greater reliability of steam will vanish. Damages of steam at this pressure are enormous. On the other hand, the use of a heavy fuel will lessen the operating cost and to some extent the fire hazard.

A boiler must be provided. The flash type is the only type to be considered because of its small weight. Then there is no storage space for either surplus water or steam. Hence, more or less complicated devices will be needed to maintain the proportions of fuel and water supply at desirable values under fluctuations of load. A steam generator could probably be built at a weight of two pounds per horsepower with adequate thermal efficiency. The internal combustion engine needs less cooling equipment. The latent heat of the steam which must be dissapated is enormous. With a turbine to function at the high pressure needed for efficiency, eleven and one-half times the amount of radiator surface required for the internal combustion engine must be provided for the steam plant. With such large surfaces, the weight and drag would be prohibitive. The use of a mercury boiler would reduce the amount of condensing surface required, and a mercury steam plant could probably be built for a weight of five pounds per horsepower, but one of the purposes of a steam plant was to give greater reliability. It is probable that with such elaboration, the quality of reliability would vanish[1]."

1. "Steam Power in Aircraft", Sci. Am., Sept.,1926.

None of the considerations of Commander Wilson can be refuted, but some of them can be modified to such an extent that they lose their critical value adversely to the application of steam power in aircraft. Then, too, it must be remembered that this analysis was made in 1926. Since then, metals and alloys have advanced to the stage where the construction of a steam plant to work with a pressure of 1000 pounds per square inch does not seem to be absurd. At this pressure the efficiency of the steam cycle begins to approach the internal combustion engine cycle so that there is little loss in efficiency. The enormous radiator surface required can be incorporated with the wing surface required for support, and there is no added drag or need for power. It is also conceded that only in the large powered planes would the steam plant have an advantage, and it is only in this respect that it will attempt to be applied. The increasing of power and efficiency is a distinct advantage. Turbines running under these conditions and at 10,000 revolutions per minute can be made suprisingly light and compact. Gear reduction methods have been improved and are of light weight so that only a small amount of power is absorbed in them.[1]

In 1916 data was published on the "feasible considerations" of steam power for aircraft. A boiler capable of 100 brake horsepower could easily be built. It was pro-

1. "Steam Turbines for Airplanes", Sci. Am., April, 1932.

posed to use a uniflow engine working on 750 pounds per square inch and a temperature of 650 degrees Fahrenheit. The boiler would be able to evaporate seventeen pounds of water per 19,890 British Thermal Units applied. It could be made to weigh less than two pounds per square foot of heating surface exclusive of the burners. This represents a weight of one and two-tenths pounds per brake horsepower. Kerosene was to be used as a fuel, and the condenser would exert a twenty-four inch vacuum.[1] These considerations are crude and probably stretched, but they show that people still believe that steam power has its advantages.

In 1926, more data was given out on someone's conception of a steam power plant design. A flash type boiler would be used to generate steam at a pressure of 325 pounds per square inch and at a temperature of 772 degrees Fahrenheit. By burning two pounds of oil per square foot of heating surface 9540 pounds of water per hour could be evaporated assuming an efficiency of eighty per cent for the boiler. The boiler and pumps should not weigh over two pounds per horsepower, and the turbine not over one pound per horsepower making a total of three pounds per horsepower for the entire plant less the condenser. This is about the same as the specific weight of the Liberty engine used in land planes. For the same output as the internal combustion engine, the steam

1. "Steam Power for Airplanes", Sci. Am., May 27, 1916.

engine rejects to the exhaust about two and one-fourth times the jacket loss of the internal combustion engine. The cooling surface will have to be about twice as large and may weigh as much as three pounds per horsepower. This would make a total weight of about six pounds per horsepower, which is about twice that of the modern engine, and it would also burn about twice the amount of fuel. If the steam engine is to compete, it must remedy these things. There are three major reasons why steam should be used; but if it cannot accomplish these, then it is not valuable. (1) Possibility of increase in reliability and life of the plant, (2) possibility of utilizing a cheap heavy fuel and a reduction of the fire hazard, (3) higher powers than are obtainable with an internal combustion engine.[1] In the days when the steam power plant had such strict limitations at every turn, the possibility of steam utilization for flying did seem vague, but with modern methods and materials the future of steam has been brightened. When more funds are available for experimentation along these lines, it will more than likely be found in the higher powered regions that steam possesses enough advantages to warrant its adoption.

In 1930, several engineers collaborated on a huge steam power plant, and produced a design significant enough for the Great Lakes Aircraft Corporation to take an active interest. The boiler was bullet-shaped, being surround-

1. "Steam Power Plant for Aircraft", Power, July 13, 1926.

ed with steam and superheater coils and using forced draft and forced circulation. It would work on the principle of the flash type boiler developing a pressure of about 700 pounds per square inch and a steam temperature of 900 degrees Fahrenheit. It would weigh about two and one-half pounds per horsepower with an efficiency varying according to load between the limits of eighty-two and seventy-five percent with an evaporation at maximum load of about 56,000 pounds of water per hour. The recovery of steam would be almost perfect so that only about 300 pounds of water need be carried. Two turbines of 3,000 maximum shaft horsepower each were to be mounted above and to each side of the boiler. These would weigh 440 pounds each or 880 pounds for both. Due to the high speed of the turbines, elaborate reduction gearing would be installed having a weight of 3400 pounds or almost four times the weight of the turbines supplying the power. The condenser weighed 5200 pounds or about one pound per horsepower.

The total weight of the power plant with all auxiliaries and water supply would weigh about 16,900 pounds. When cruising at 5,000 horsepower, the specific weight would be three and thirty-seven hundredths pounds. At the full power of 6,000 horsepower the specific weight would be two and eight-tenths pounds per horsepower.[1] This is not much in excess of the weight of the internal combustion engine, and such large powers cannot be approached in the internal combus-

1. Data supplied by Professor F. L. Wilkinson.

tion engine without the installation of numerous units. The actual installation of this unit was cut short due to the economic status of 1930; and although no tests were made, the considerations and calculations were conservative enough for the designers to guarantee the figures noted above.

The equipment used to make the flight in 1933 was crude, and the flight itself was without scientific purpose. A reciprocating engine, instead of a turbine, was used weighing 180 pounds. The high pressure cylinders had a bore of three inches, and the low pressure cylinders had a bore of five and one-fourth inches using a stroke of three inches. The boiler and its equipment with water, fuel oil,and other accessories weighed 485 pounds. The engine worked under a pressure of 1200 pounds per square inch and developed 150 horsepower at 1625 revolutions per minute. The steam generator had 500 feet of water tubes built around a crude oil burner designed to release as much as 3,000,000 British Thermal Units per cubic foot of fire box volume per hour. 1500 pounds of water per hour were evaporated. The condenser was most crudely fashioned. It was merely a part of an old automobile radiator. The recovery was about ninety-nine percent so ten gallons of water were enough for an ordinary flight under relatively cool temperature conditions. An electric spark with forced draft was used to start the fire in the boiler. As soon as the fire is started, an automatic control takes place and the pilot only uses the throttle

and reverse mechanism. The ability to reverse is one of the advantages that the steam engine has over the steam turbine and internal combustion engine. The reverse thrust reduces the landing run actually under 100 feet for this plane. If the engine is reversed in the air just before landing, a negative thrust will be built up and greatly increase the gliding angle. Approach angles as great as five to one have been made with successful landings. With steam power, the engine is much quieter in the air which may have its advantages in a war.[1]

With the increase in general business conditions a great deal of experimental work should be done with steam power, and it would not be surprising if we saw huge powered planes performing successfully under steam power in the near future.

1. "Steam Takes to the Air", Aviation, June, 1933.

Chapter V

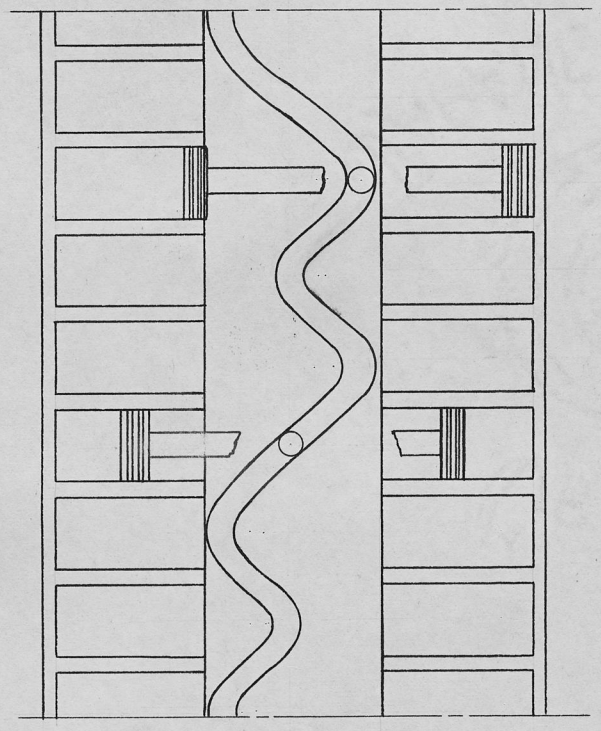
NOVEL DESIGNS

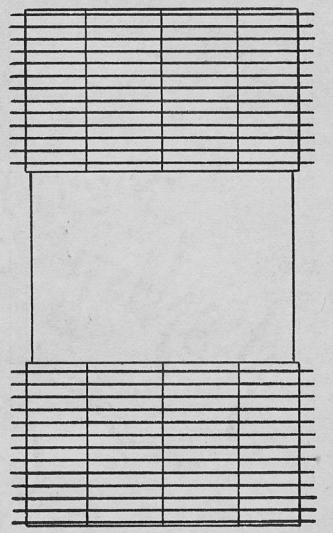
In an endeavor to reduce or eliminate the inherent losses and mechanical difficulties found in the conventional types of aircraft engines, many novel and ingenious methods of propulsion have been designed, the principle ones of which are here included.

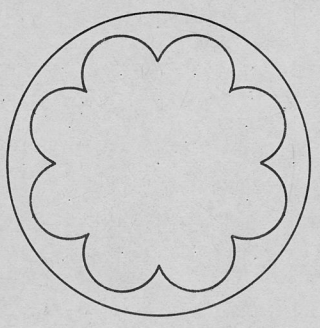
In 1923, a revolver type of engine was constructed. (See fig. 3, page 41) In this design, the end sections containing the pistons could be made to revolve so that the engine would be similar to the rotary type or the end section could be held fast while the center section or ball race revolved. Each ball is acted on by two pistons and can be made to follow any path desired thus giving any motion to the piston, whereas the only variation in the crank and connecting rod engine can be gained by a small offset of the crank. The power stroke is twice as long as the compression and exhaust strokes to allow full expansion of the gases. This phenomena is almost analogous to that found in the compound steam engines.[1]

In the same year, the National Advisory Committee investigated the idea of jet propulsion for airplanes. It was proposed to mix compressed air with the fuel in the combustion chamber and allow it to burn at constant pressure.

1. "Revolver Type Engine", Mechanical Engineer, Nov., 1923.







REVOLVER TYPE ENGINE

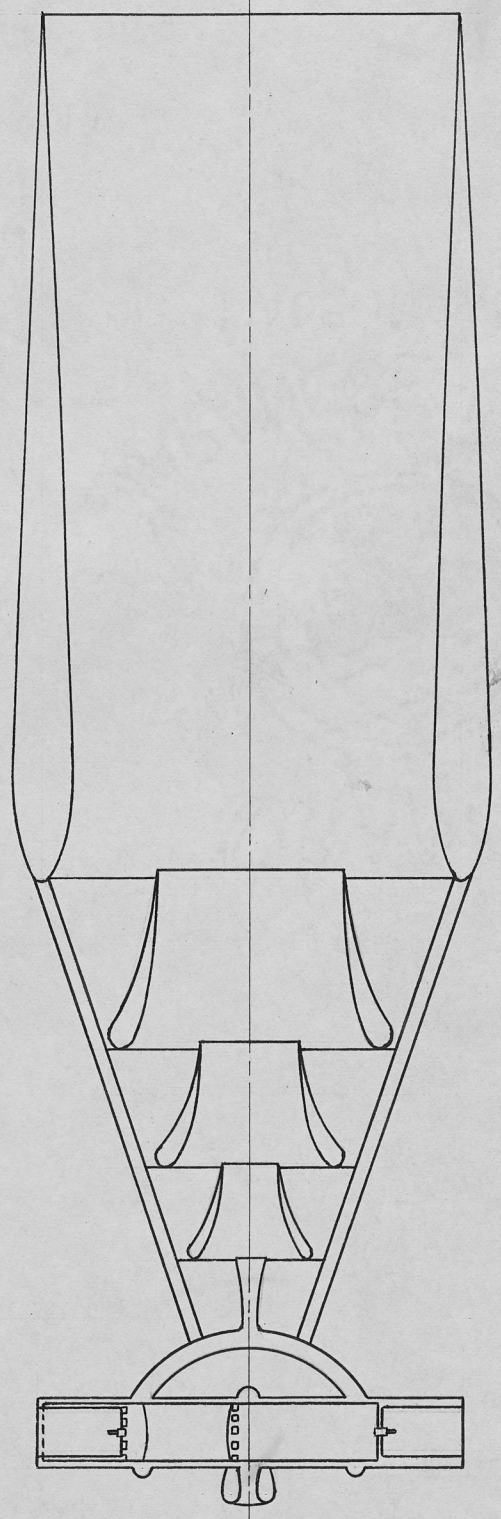
FIG. NO. 3

The products of combustion escaping through a nozzle would cause a thrust. The relative weight and fuel consumption of such a machine decreases as the flying speed increases; but at the high speed of 250 miles per hour, jet propulsion would take about four times the amount of fuel and weigh more per thrust horsepower. It cannot compete with the internal combustion engine at such speeds. By employing thrust augmentors, the efficiency may be greatly increased. The low efficiency is due to the almost total loss of the kinetic energy of the escaping gas. The only energy used is that caused by the inertia of the gas in gaining its high velocity. Larger jets with slower speeds would reduce this loss.[1]

It was not until 1926 that more significant thought was applied to the subject. To improve the efficiency of conversion, the gases of combustion are mixed with large quantities of air inside of the apparatus so that the speed of discharge is decreased while the mass of discharge is increased. This explains the presence of the four air injectors shown in figure 4 page 43. The exhaust gases passing from the combustion chamber meets the four air injectors, each somewhat larger than the preceding one. Each injector draws in a larger mass of air so that finally a mass of air and gas emerges at a relatively slow speed.

This form of reaction engine embodies what is

1. "Jet Propulsion for Airplanes", N. A. C. A., 1923.



JET PROPULSION ENGINE

FIG. NO. 4

really a two cycle internal combustion engine. It consists of a horizontal cylinder inside of which are two walls forming a chamber. Each wall contains a spark plug to be used in starting. The gasoline is injected under pressure and ignited by the spark. There are three series of annular ports, the central orificies placing the carburetor in communication with the chamber, and the end ports place the chamber in communication with the exhaust pipe. Inside, a piston moves freely from one end of the chamber to the other. It has concave faces and a sleeve with ports corresponding to those in the cylinder. After the engine has been started with the pressure injection and spark, the subsequent speed of the piston is sufficient to raise the pressure of the gas to a point of ignition without the use of the spark plugs or compressor. The piston sleeves are arranged so as to open the exhaust ports at such a point as to insure the burnt gases entering the exhaust pipes at the highest velocity. The apparatus could be built for a weight of about two pounds per horsepower.[1]

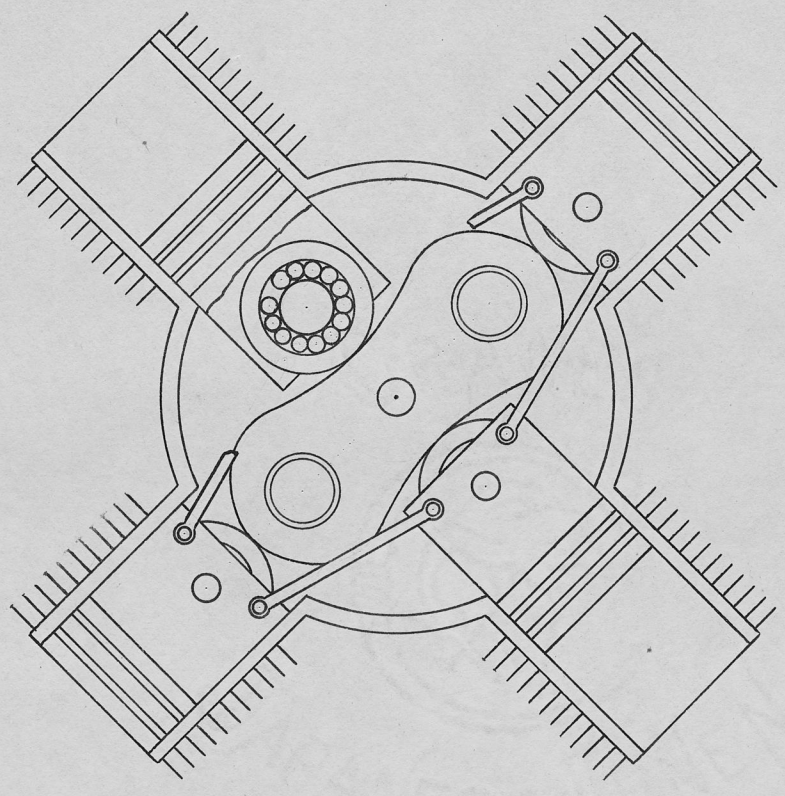
Since high powers are developed in engines by a rotative speed far in excess of that which will give a good thrust efficiency, reduction gearing is conventionally employed. The type of engine about to be described does away with heavy reduction gearing without adding any other form of

1. "Jet Propulsion", Sci. Am., April, 1926.

weight. The actual power output is not a result of the rotative speed but rather one of piston speed. The mechanism connecting the piston to the crank is really responsible for the high rotative speed. If a cam, similar to the one in figure 5, page 46, be designed and substituted for the crank, and the rollers shown be substituted for connecting rods, four strokes of the piston will be required for one complete revolution of the engine. Hence, for the same piston speed as in the conventional type, the rotational speed is one-half. The adjacent pistons are connected by a system of links, and the cam contour is such that continuous contact is maintained. Neither the cam nor rollers show appreciable wear under prolonged running. The motion of the reciprocating parts are identical with the axis and opposite to each other so that the engine is perfectly balanced. Compactness is obtained in the absence of long connecting rods. The valve mechanism can be made much simpler and run directly off of the cam since there is no need of reduction in speed.[1]

In 1932, there was a move to combine the rocket and turbine principles for stratosphere flight. With the speed of escaping gases about 4,000 feet per second, the rocket principle would not become efficient until a plane speed of about 600 miles per hour had been reached. The possibility of attaining such speeds as 600 to 1000 miles per hour lie only in the stratosphere or sub-stratosphere. In order to

1. "An Interesting Engine", Sci. Am., Sept., 1926.



FRENCH ENGINE

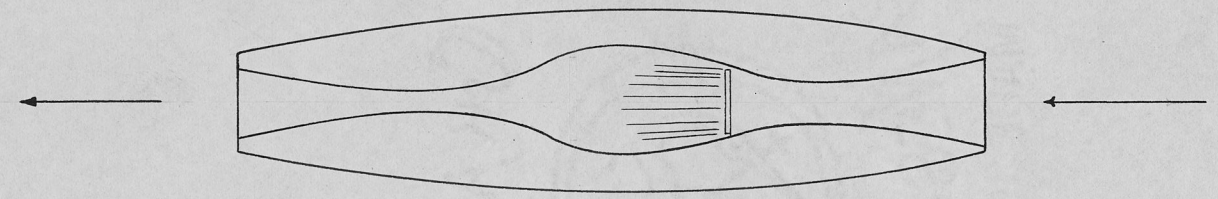
FIG NO. 5

reach these heights, the jet would be allowed to impinge on two series of blades similar to turbine wheels which would turn two propellers. When the height is reached either one or both propellers could be taken from the jet stream and the plane then would function as a rocket. It is hoped someday to fly at heights of 100 miles for long distance trips at which pressure and speed the rocket is more efficient than the internal combustion engine.[1]

Lorin proposed a type of burner which would do away with the necessity of carrying liquid oxygen for combustion in the rare atmosphere, and thus reduce the weight to be carried and simplify the whole apparatus. The air entering a tube shaped similar to that in figure 6, page 48, at such high velocity is compressed to a temperature of ignition, and so the whole apparatus works automatically as long as fuel is supplied.[2]

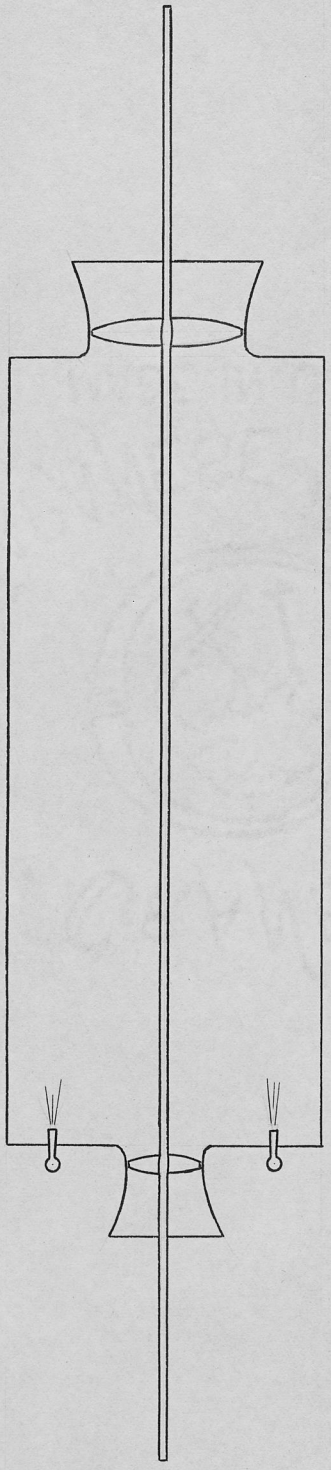
In 1934, an internal combustion turbine was proposed which is of the hot air type rather than the explosion type. The combustion chamber is fitted with orifices in each end, (See figure 7, page 49), and provided with fans to fit each orifice, being mounted on a single shaft. As the cool air is drawn in through the smaller orifice and compressed, fuel is admitted by the nozzles shown. The combustion of the fuel heats and expands the air which escapes through the

1. "Turbine Rocket Plane", Sci. Am., March, 1932.
2. "Super Aviation", Sci. Am., April, 1933.



LORIN JET

FIG. NO. 6



INTERNAL COMBUSTION TURBINE

FIG. NO. 7

large orifice turning the fan. If the temperature of the charge is doubled within the chamber, about one half the work of expansion will be utilized. The weight per unit of power is lower in this type of turbine than in the reciprocating engine.[1]

1. "Internal Combustion Turbine", Mechanical Engineer, July, 1934.

Chapter VI.

RECENT DEVELOPMENTS

A two stroke cycle radial engine was produced in 1930 with a specific weight of less than one pound per horsepower developing 300 horsepower. It was a nine cylinder radial engine turning at 1800 revolutions per minute. Due to the overlapping of the power strokes, it was noticeably absent from vibration. To reduce the overall size, a new type of crank shaft and connecting rod mechanism was designed, the nature of which was not revealed. The fresh charge was forced into the crankcase by a direct drive positive displacement supercharger. Tests show that less than four horsepower is consumed by the supercharger.[1]

Some recent work has been done to increase the thrust efficiency of radial engines. This will be accomplished when: (a) The engine power is increased at suitable propeller speeds; (b) the outside diameter of the engine is decreased; (c) the operating efficiency of the propeller is increased; (d) drag coefficient of the power plant is decreased, or; (e) when the interference between the propeller and the engine is decreased. This has been accomplished to a certain degree by the use of engine cowling as shown in figure 8, page 52. There is a noticeable absence of turbulent flow in the cowled engine.[2]

1. "Two Cycle Radial Engine", Automotive Industry, March 1,1930.
2. "Increasing Thrust Efficiency", S. A. E. Journal, May, 1930.

The Pratt and Whitney Wasp is a 425 horsepower nine cylinder radial and so arranged as to be on the borderline between the conventional gasoline and Diesel engines. It uses either gasoline or fuel oil, and there is no carburetor, but a fuel injection system is employed. The compression is moderate with a spark ignition. The injection take place early in the compression stroke so that there is more time for evaporation than in the Diesel engine, and the pressure and temperature remains below the ignition temperature of the fuel so that combustion is controlled by the spark. It is possible to switch over from one fuel to another without stopping the engine, because it has to be started and warmed up on gasoline. The possibility of retaining low engine weight and avoiding the development work needed for a thorough application of the Diesel principle is probably the major factor in retaining low compression and spark ignition. The fire hazard is not eliminated by such design.[1]

The Packard Diesel aircraft engine developing 225 horsepower has been brought down to the weight of two and twenty-six hundredths pounds per horsepower.[2]

There are unmistakable signs that the limit of the existing types of engines is now being approached; and that, in order to attain any really substantial measure of improvement in the future, some changes in the essential

1. "A Fuel Spray Aero Engine", Mechanical Engineer, Oct.,1930.
2. "The Packard Diesel Engine," Aviation, April 5, 1930.

features of the engine must be looked for. Possibly something may come about by the oil engine. However, both types will have their own sphere of usefulness for years to come. Supercharging offers the greatest scope, but that is limited at sea level pressures to about ten per cent increase, detonation and preignition being caused by overheated exhaust valves and plug points with ordinary fuels.

The principle use of supercharging in aero engines is of course to develop power at high altitudes, and it will be limited to this as long as poppet valves are used for exhaust releases. If, in its stead, we use a single sleeve valve, which has several advantages other than those arising solely from the elimination of the red-hot poppet valve, much higher powers can be obtained even at sea level. An experimental single sleeve valve engine has been run heavily supercharged for several hundred hours on ordinary aviation fuel without overheating of the valve, although a brake mean effective pressure as high as 375 pounds per square inch has been maintained with a specific output nearly three times that of any aero engine now in service. With a special anti-detonating fuel, the engine referred to would maintain a brake mean effective pressure of 550 pounds per square inch and would give a specific output of nearly two and one half horsepower per pound.

The exhaust gases would be discharged from this engine at a pressure of about 300 pounds per square inch, and, therefore, capable of doing a further amount of work

nearly equal to that actually developed in the high pressure cylinder. So far, the attempts to compound in the internal combustion engine have been unsuccessful, and the above mentioned difficulties with the poppet type valve will render it unlikely that this component could be made to function satisfactorily under the severe conditions imposed by a compound fluid. The design of the valve required to transfer the gases from the high pressure to the low pressure cylinder also presents considerable difficulty, which, however, can be avoided by the use of the sleeve valve. The single sleeve of the latter type can conveniently be made to function as the intake and exhaust valve for the high pressure cylinder and also as the intake for the low pressure cylinder. Compounding along these lines would result in a material improvement in economy as well as in reduction of weight, the latter being due to the fact that the cylinder exposed to the high pressures could be made of small dimensions, while the low pressure cylinder could be made light.[1]

The Rolls Royce racing engine of 1931 developed 2300 horsepower, while in 1929, it only developed 1900 horsepower, representing a gain of about twenty-one percent. It only had an increase in weight, however of six and one-half percent. When engines are "pushed" in this manner, the supply of lubricating oil consumed becomes prohibitive for their

1. "Supercharging and Compounding Aero Engines", Engineering, June 6, 1930.

adoption in commercial use. The engine actually used oil while in flight at the rate of fourteen gallons per hour. The increase in performance during the two year period was due to increased speed of the crankshaft, the supercharging gear ratio was raised, and the air intake was enlarged. It was found that a rise of eighteen degrees Fahrenheit in the air intake caused a loss of 100 horsepower. The engine used 0.71 pounds of fuel per horsepower hour in 1929.[1]

The carburetor is not at all satisfactory for use on the new engines. It has not become sufficiently independent of gravity, acceleration, or moisture content of the air.[2] The National Advisory Committee for Aeronautics has developed a fuel injection system to replace the carburetor. It gives better fuel distribution, increased power, and lower fuel consumption.[3]

Although work has been done since 1929, Pratt and Whitney have only recently placed on the market a two row radial. There is a reduction in drag per unit of power. The larger number of cylinders with smaller bores reduces the weights of the reciprocating parts and makes it possible to operate at higher crank speeds with smoother running. The reduced power input per cylinder also makes for longer life.

1. "Airplane Engines", Automotive Industry, Sept. 6, 1930.
2. "Rolls Royce Engine", Automotive Industry, Oct.,31, 1931.
3. "Pratt and Whitney Develops two Row Radial",Aviation, Apr.'33.

It has a specific weight of one and thirty-six hundredths pounds per horsepower.[1]

Superchargers are becoming standard equipment on all of the high powered engines, because the purchase of such an engine is significant of the desire for performance, and a loss of forty-seven percent of the power at 20,000 feet is not good performance. Some experimental work is also being done on the affects of the compression ratio on power at various altitudes. The results of these experiments can be seen from the curves on pages 58 and 59.[2] (figs. 9 and 10)

In a test made on altitude performances of an oil engine versus a gasoline engine, the oil engine was found to be superior. The performance of the Diesel increased to a certain altitude and then gradually fell off. The gasoline engines performance fell continuously with increasing altitude. The planes on which the tests were made were identical except for the engine installation. The Diesel engined plane was somewhat lighter than the gasoline engined plane. For full results of the test see table number three in the appendix.[3]

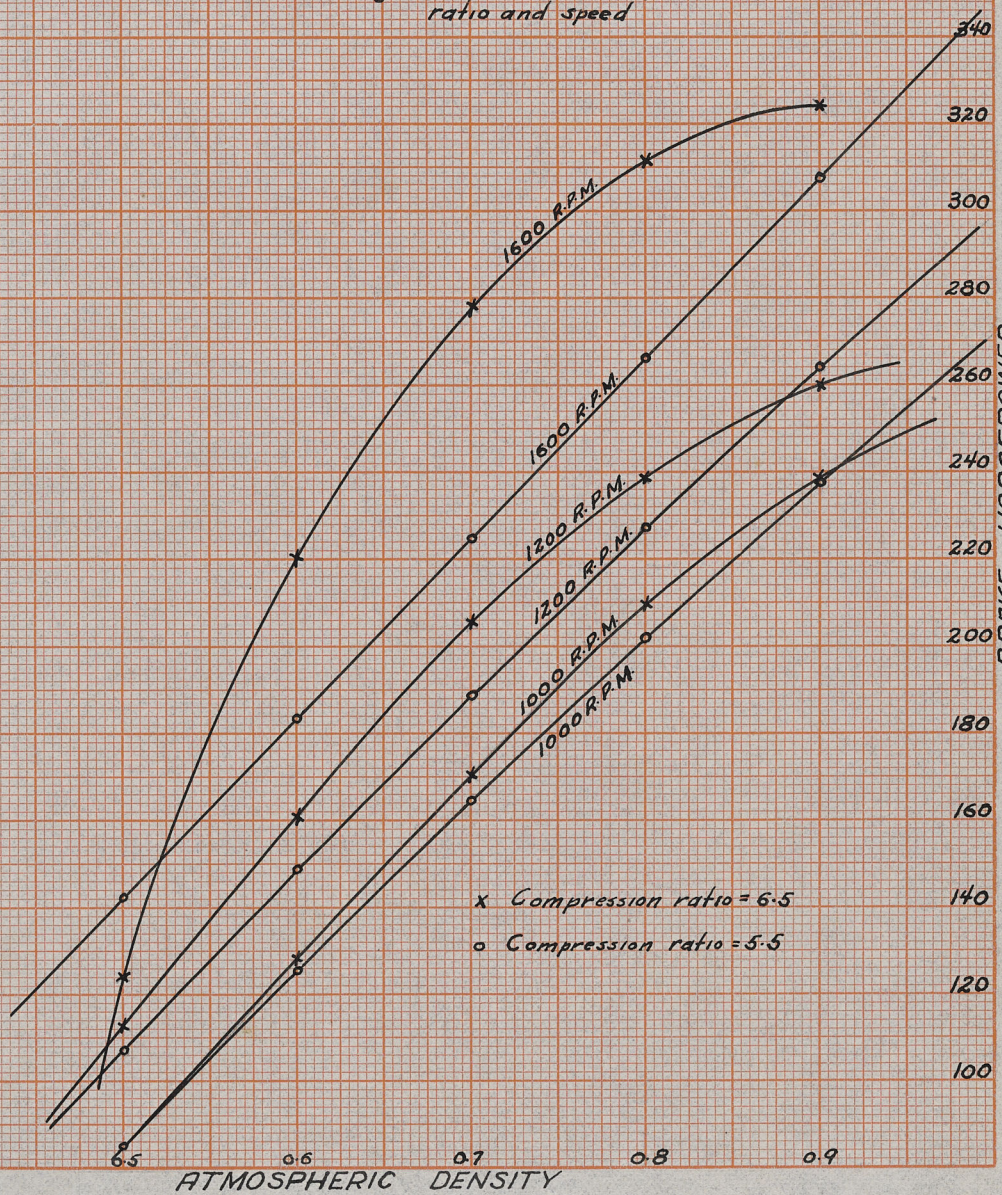
Present development has seen an increase in power capacity per cylinder with compression ratios and rotational speeds. These have become practical because of better

1. "Recent Work of N. A.C.C. A.", N. A. C. A., July, 1932.
2. "Altitude Performance", S. A. E. Journal, June, 1934.
3. "Diesel Versus Gasoline", Sci. Am., June, 1931.

FIG. NO. 8

VARIATION OF HORSEPOWER WITH ALTITUDE

Showing the effects of compression ratio and speed



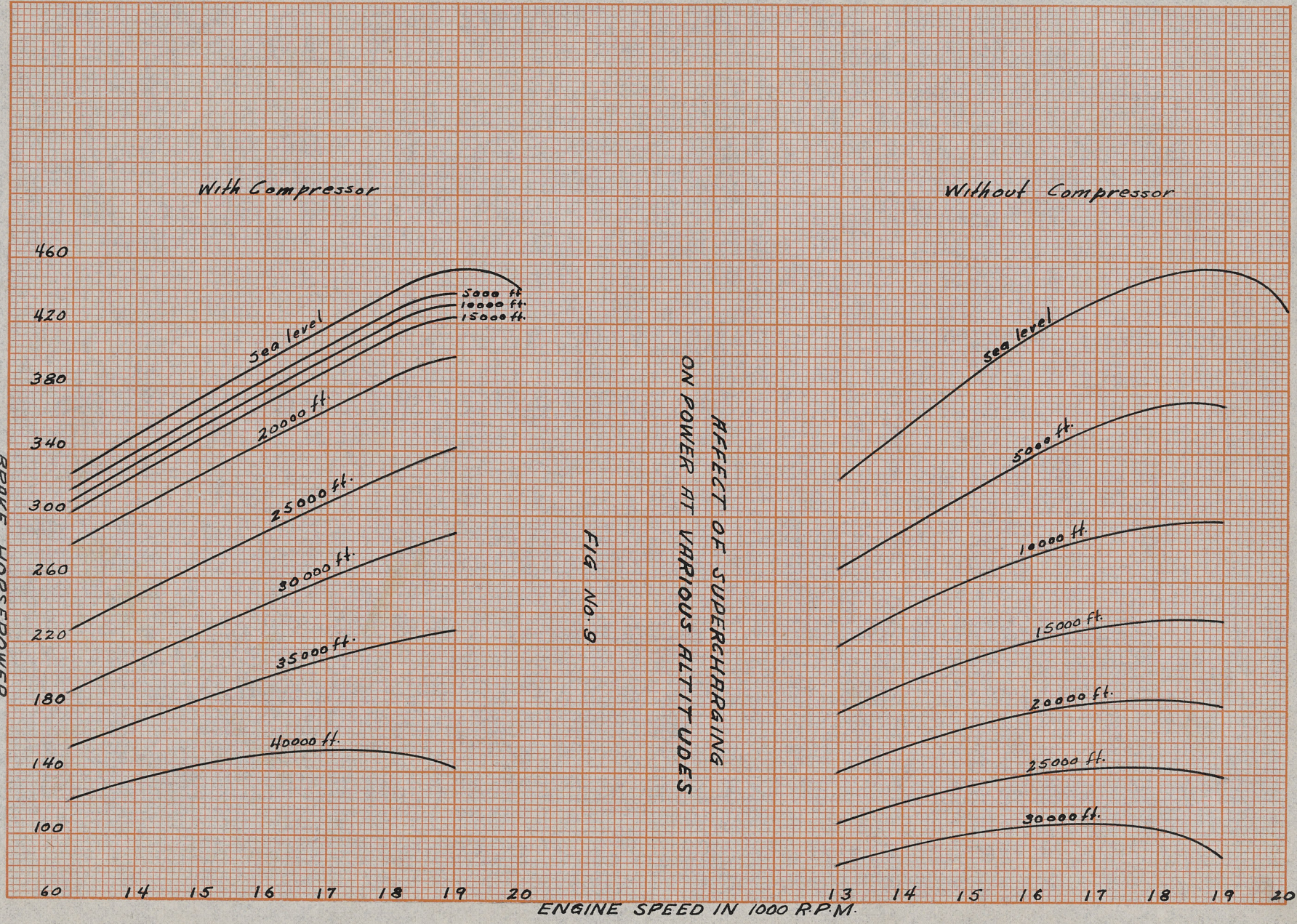


FIG NO. 9

EFFECT OF SUPERCHARGING ON POWER AT VARIOUS ALTITUDES

design and materials. Compactness, as in the two row radial, and cowling have resulted in a reduction in drag.

CONCLUSIONS

As the aircraft engine has developed, its basic features have remained almost unchanged, although there have been variations in type. The supercharger stands out as the only important development outside of more mechanical refinement. The progress made with the Diesel engine threatened to solve many of the problems, but a distinct lack of late development is noticeable. Steam power will undoubtedly make a place for itself in high powered planes of the future, but as yet, it has not been practically applied.

The development of most types of prime movers has proceeded in more or less distinct stages, the invention of each new type having been followed by a period of development which has continued until the limits of that type have been reached when it has been superseded by another type giving higher economy and efficiency.

Chemically-cooled engines, probably with Prestone or similar fluid of high goiling point, will be more extensively used. It allows the engine to run warmer with no more chance of becoming over-heated. Due to the higher temperature differential between the atmosphere and the cooling fluid, the rate of heat transfer will be greater, and the radiator can be made smaller.

Superchargers will be on every engine of the

future for high power. More valve and port areal will be required. Superchargers will be geared to run at different speeds. The constant speed centrifugal blower has proved inadequate. The geared supercharger can be used to give additional power at sea level and low altitudes. When the plane reaches an altitude of about 15,000 feet, the engine can swing back to the exhaust driven turbo-compressor. Higher engine speeds will result in more power per unit weight.

The development of alloys which stand up well under the work for which they are prepared allows the engine to be made light and stand up under higher temperatures and pressures.

The sleeve valve engine built in England has gone through severe tests without the slightest bit of trouble and shows a lower fuel and oil consumption than engines of the poppet valve type. The mean effective pressure has been raised from 160 to 230 pounds per square inch in the air-cooled engines and as high as 575 pounds per square inch in the liquid-cooled engine by heavy supercharging. The pressure on the carburetor was raised to a maximum of thirty-five pounds per square inch.

The use of better fuels is prohibited by cost, but better usage of the present fuels can be made by the substitution of fuel injection for the carburetor.

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APPENDIX

Table No. 1

Showing the characteristics of engines from 1900 to 1919

Engine Name	Year	Hp.	Wt.#	Wt/Hp.#	Fuel #/Hp.Hr.
Langley Manly	1901	52	151	2.9	
Original Wright	1903	12	152	12.7	0.80
Improved Wright	1904	16	180	11.4	
Improved Wright	1905	19	180	9.5	
Redesigned Wright	1908	35	182	5.5	
Average on market	1910	54	309	5.7	
Wolseley	1913	147	720	4.9	
Average on market	1914	112	437	3.9	0.65
Average on market	1915	144	512	3.8	
" " "	1916	185	570	3.1	
" " "	1917	244	694	2.8	
Liberty 12	1917	400	801	2.0	
Liberty 12 (Mr)	1918	432	808	1.9	0.55
Liberty 12 (My)	1918	450	825	1.8	0.50

Table No. 2

Characteristics of American Engines

Motor	No. Cyl.	Type	Rated Hp.	Wt.	Cooling	R.P.M. Crankshaft	#/Hp.Hr.
Curtiss OX-2	8	Vert.	100	425	Water	1400	0.59
Curtiss VX-3	8	Vert.	200	660	Water	1400	0.73
Curtiss V-4	12	Vert.	300	1125	Water	1400	0.61
Duesenberg	4	Rotary	120	455	Air	2100	-
Gen. Veh. Gnome	9	Rotary	100	272	Air	1200	0.72
Hall Scott A-7	4	Vert.	90	410	Water	1370	0.47
Hall Scott A-5	6	Vert.	125	592	Water	1300	0.51
Hispano Suiza	8	V	154	455	Water	1500	-
Sturtevant	8	Vert.	140	600	Water	2000	0.54
Thomas Morse	8	Vert.	135	572	Water	2000	0.59
Wisconsin	6	Vert.	140	637	Water	1380	0.66

Table No. 3

Comparison of Diesel and Gasoline Engines.

Diesel Engine

	Alt. Ft.	Level Speed M.P.H.	Level Speed R.P.M.	Climb Speed M.P.H.	Climb Speed R.P.M.	Rate Ft./min.	Time Min.
	0	116.5	1980	77	1750	730	0
	5000	118.4	2010	79	1795	676	7.06
	8000	118.6	2015	80	1820	617	11.69
	10000	118.0	2010	80.5	1830	567	15.06
	15000	110.6	1950	82	1830	390	25.47
*	19250	92.6	1810	82.3	1775	100	42.90
**	20000	82.0	1750	82	1750	0	-

Gasoline Engine

	Alt. Ft.	Level Speed M.P.H.	Level Speed R.P.M.	Climb Speed M.P.H.	Climb Speed R.P.M.	Rate Ft./min.	Time Min.
	0	103.2	1990	61.2	1790	635	0
	5000	99.4	1970	63.4	1785	412	9.7
	10000	91.3	1905	65.0	1775	190	27.1
*	12000	85.7	1855	65.0	1765	100	100.0
**	14270	64.0	1745	64.4	1745	0	-

* Indicates service ceiling

** Indicates absolute ceiling

APPROVAL SHEET

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

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