VARIABLE COMPRESSION RATIO FOR DIRIGIBLE ENGINES

by

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Professor in Charge

Chairman of Departmental Committee on Graduate Students
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Cambridge, Mass.
May 24, 1933.

Professor A. L. Merrill
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts.

Dear Professor Merrill:

This investigation, on "Variable Compression Ratio for Dirigible Engines", is submitted by the undersigned candidate for the degree of Master of Science in Mechanical Engineering, in fulfillment of thesis requirements.

Sincerely yours,

[Signature redacted]
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INTRODUCTION

The idea of variable compression ratio, first took form in the author's mind while studying the altitude effect on the power of aircraft engines in the course of Advanced Thermodynamics at the University of Michigan in 1931. From then on, the search for material has yielded much information.

The Technical Reports, of the National Advisory Committee for Aeronautics, were used as the principle source of technical data on tests performed.

Prior to the Great War, Practically no research had been done on the altitude effect on internal combustion engines. The early experiments, in this line during the war, consisted of mounting an airplane engine on a truck with the needed apparatus for testing, and then driving to the highest mountain road to be found (Pike's Peak) to carry out the desired tests as far as possible under these limiting conditions.

The idea of a closed chamber, in which the air pressure and temperature could be held at any desired or pre-determined value, was soon conceived. This idea became a reality in 1918, and is now known as the Altitude Laboratory for Testing Aircraft Engines, and is operated by the Bureau of Standards at Washington, D. C. Another one of these chambers have been built in Germany for the same purpose.
Another effective method of testing the altitude effect on aircraft engines has been devised. This method consists of mounting an oil pressure dynamometer between the engine and the propeller hub so that the torque delivered can be measured at all times. The speed of the engine can also be obtained at any instant with an efficient tachometer, and thus the power delivered to the propeller can easily be calculated, which is the brake horsepower of the engine. This method of testing aircraft engines has been most extensively used in England, and has also been used to a limited extent in this country.

The results of the varied tests by both methods check very closely.

The object of this thesis is to link the conclusions regarding the power variation with altitude and the power and efficiency variation with different compression ratios, in such a manner that a graphical picture is presented, showing the advantageous features of the possible higher compression ratios that may be permissible at the higher altitudes.
FUNDAMENTAL PRINCIPLES

Otto Cycle:

In the explanation of the fundamental principles of the Otto Cycle, reference is made to Fig. 1.

In the Otto Cycle a charge of air and gasoline is drawn into the cylinder of the engine and compressed to some desired pressure, as shown by line 1→3. It is then ignited by an electric spark. The heat evolved due to the chemical combination between the carbon and hydrogen of the fuel and the oxygen of the air, causes the temperature to rise to a high value and thus create a much greater pressure in the cylinder, as shown by line 2→3. The piston head is designed and linked up in such a manner as to be the only yielding member under reasonable pressures, and is thus used to permit the high cylinder pressure to exert a force through a distance, producing mechanical work, as shown by line 3→4. The work area, 1→2→3→4, represents an ideal indicator diagram of the Otto cycle. This ideal condition is never reached in practice because of heat flow and non-instantaneous actions.

Decreased Initial Pressure:

If the initial pressure is decreased, all the other respective pressures are decreased. Again referring to Fig. 1, if the intake pressure 1' is reduced by, let us
say, one half (about 18,000 foot altitude), then the compression pressure \( \frac{3'}{2} \) will also be one half of the original compression pressure \( 3 \), and so on with all the other respective points of the cycle; each will have only half the absolute value of the first or original cycle. The result is, that the work area, \( 1'2'3'4' \) will be just one half of the work area, \( 1 2 3 4 \). Providing the temperature remains about the same, the total weight of the second charge is equal to one half the weight of the original charge. If the fuel-air ratio remains constant, we can readily see in this theoretical analysis, that the efficiency of the cycle remains constant. This does not hold true for the final output of the engine as the mechanical efficiency drops off as the density of the charge is decreased, and also the efficiency of burning drops off with a greatly decreased compression pressure.

The drop in mechanical efficiency is explained by the fact that the friction power of an engine does not change with a change in the density of the charge. The indicated horsepower does change with a change in density of the charge; therefore, as the indicated power decreases with a decrease in density, the friction power becomes a larger factor.

Effect of Increasing Compression Ratio:

With the decreased density and pressure of the charge, it is possible to greatly increase the compression
ratio without causing the cylinder pressures to go much beyond those encountered with the higher initial charge density. Also the higher compression ratio can thus be used without the danger of prepignition or detonation becoming troublesome problems.

The theoretical result of utilizing the higher compression ratio is as shown in Fig. 1 by the cycle 1"2"3"4", compared to the cycle 1'2'3'4'. The displacement volume is kept constant, but the clearance volume is decreased to give the higher compression ratio. This is in accord with changing the compression ratio of an engine of given bore and stroke. Providing the volumetric efficiency remains constant, we can readily see that the amount of charge drawn in at 1' is equal to the amount of charge drawn in at 1", as the volume swept out by the piston is the same regardless of the compression ratio employed. The compression stroke of the higher compression ratio is 1"2", which gives a substantially higher compression pressure than 2'. The assumption is made, that the multiplication factor of pressure due to the firing of the charge remains the same. Therefore the maximum pressure 3" will be much higher than the maximum pressure for the lower compression ratio 3'.

The work area 1"2"3"4" is greater than the work area 1'2'3'4', but not in proportion to the increase of the compression pressure and the maximum pressure.
Part II

POWER VARIATION WITH ALTITUDE

Major Variables:

There are three major variables in the performance of an internal combustion engine (4); speed, altitude, and horsepower, as shown in Fig. 12. This plot represents the performance with a constant compression ratio.

Because horsepower is the time rate at which work is being done, it can be readily seen that if the brake mean effective pressure remains constant, the horsepower is directly proportional to the speed of the engine. The mean effective pressure of an internal combustion engine depends upon the density of the charge, or the pressure of the charge, in the cylinder; the density or pressure of the atmosphere varies with the altitude. Therefore, the horsepower developed is some function of the altitude. From this we see that the horsepower developed is a function of both speed and altitude, while speed and altitude are completely independent variables.

In the analysis of this problem the variation in the speed of the engine will be neglected, as we are interested only in the changes of work derived from each individual charge to the cylinder.

Thermodynamics:

From the fundamental facts of thermodynamics, a method has been derived mathematically by which the
work done in one complete theoretical Otto Cycle can be calculated. The formula is as follows:

\[ W = \frac{P_2 V_2 - P_1 V_1}{k-1} - \frac{P_1 V_1 - P_2 V_2}{k-1} \]  

(a)

where:
- \( W \) = work done by the gas.
- \( P \) = pressure (absolute).
- \( V \) = volume.
- \( k \) = constant (1.33 good average value for gasoline engines).

For the point numbers, refer to Fig. 1.

From the above formula it is seen, that if the pressures are changed in some definite proportion, the work will also be changed in the same proportion as \( P \) appears in every term. By the adiabatic change law;

\[ P_1 V_1^k = P_2 V_2^k = C \]  

(b)

we find that the compression pressure is changed in the same proportion as the intake pressure. The actual case in cylinder expansion and compression is not a true adiabatic due to the flow of heat into the cylinder walls. Therefore the value \( k \) has been found by experimental means. If we now assume that the same multiplication factor holds true for the explosion pressure over the compression pressure. The explosion pressure will, therefore, also have the same relationship as the respective intake pressures.

Under these conditions, which are very close to
the real conditions, we can see that, with a given compression ratio, the work derived from one cycle is a function of the initial pressure in the cylinder, or very nearly so.

Test Results:

From the results of the many varied tests performed, both here and abroad, four important formulae have been derived to calculate the power variation with altitude. Two of these formulae are principally empirical while the other two were derived analytically. Of the two important empirical formulae, one is based on the pressure variation and the other is based on the density variation.

The formula for the power variation based on the variation of pressure only (24) is:

\[ \phi = \rho^{0.05} \]  \hspace{1cm} \text{(c)}

where:
\[ \phi = \text{power factor.} \]
\[ \rho = \text{air pressure ratio.} \]

The formula for the power variation based on the variation of the density only (18) is:

\[ B.H.P = B.H.P_0 \left( 1.088 \frac{\Delta}{\Delta_0} - 0.088 \right) \]  \hspace{1cm} \text{(d)}

where:
\[ \Delta = \text{density of the air.} \]

The derived formulae (22) take into account the
two variables of the atmosphere, pressure and temperature. Density is a function of these two variables. The two formulae are:

\[ B.H.P_a = B.H.P_o \left[ \frac{P_a}{P_0} \left( \frac{T_o}{T_a} \right)^{\frac{1}{n}} - \frac{(1-n)}{n} \right] \] (e)

\[ B.H.P_a = B.H.P_o \left[ \frac{P_a}{P_0} \left( \frac{T_o}{T_a} \right)^{\frac{1}{n}} \left( 1 + \frac{\lambda - \lambda n}{n} \right) - \left( \frac{\lambda - \lambda n}{n} \right) \right] \] (f)

where:
- \( P \) = absolute atmospheric pressure.
- \( T \) = absolute temperature.
- \( n \) = mechanical efficiency at sea level.
- \( \lambda \) = ratio of mechanical efficiency to friction horsepower at sea level.

The plot of the calculations of these two theoretical relations of power to altitude, are shown in Fig. 20, as curves D and E, and are compared with the experimental curve A. These curves show good agreement up to about 12,000 feet altitude.

Formulae (e) and (f), in themselves, also agree very closely up to an altitude of about 12,000 feet. From all information to be found, regarding the varied tests, the firmest opinion seems to be that if the power variation is based on only one of the variables, it is better to base it on pressure. Actually the true power law lies somewhere between a pure pressure law and a pure density law, but is certainly nearer the former (24). The experiments show that the engine power is very nearly a function of the pressure only, except for low altitudes,
where it depends, to a certain extent, on the temperature (16).

A vast number of tests have been carried out along this line, both in the Altitude Laboratory (27) and by measuring the power delivered to the propeller while the plane was in flight (16) (18) (232). The results of both types of tests are in close agreement. Absolute and exact conclusions cannot be drawn as the tests vary somewhat, depending upon the conditions under which the experiments were performed.

Fig. 10 gives a reproduction of some of the indicator cards taken with the engine in the Altitude Laboratory. This gives a very good picture of the reduction of the work area at the higher altitudes.

Calculations:

For the calculation of the power variation with altitude, in this thesis, formula (c) was used. The values of the pressures at the different altitudes were read from Table I; the average pressure between the summer and winter values were taken. The calculations, for the various altitudes, were made considering the engine having a constant compression ratio, and then by proportion, calculations could be made for any other compression ratio desired. Table II shows the results of these calculations and Fig. 7 gives a graphical picture of the same.
Part III
EFFECT OF COMPRESSION RATIO ON POWER

The effect of compression ratio on power does not check close enough, in the different experiments, to enable one to draw any particular conclusions or develop any definite formula. The design of the combustion chamber, the valve timing and placement, and other design features may be some contributing factors toward the power change resulting from a compression ratio change. This has not been concluded as a definite fact but studying the results of many different tests of the varied makes of engines, seems to substantiate such an idea.

It is a known fact, however, that the efficiency of an internal combustion engine is greatly increased by an increase in compression ratio. For this reason, the manufacturers of engines, both aeronautical and automotive, are striving to employ higher and higher compression ratios. It is only a matter of about five years ago that a compression ratio of 5:1 was considered rather high; today a compression ratio of 7:1 is not altogether too uncommon.

The major limiting factor in maximum permissible compression ratio is the detonation problem. This seems to be a function of the compression pressure, temperature of the charge after compression, and the nature of the fuel.
Thermodynamics:

From the fundamental thermodynamics we can calculate the theoretical increase in efficiency resulting from an increase in compression ratio, by the following formulae:

\[ E = 1 - \left( \frac{P_1}{P_2} \right)^{\frac{k-1}{k}} \]  
\[ E = 1 - \left( \frac{1}{R} \right)^{k-1} \]

where:
- \( E \) = efficiency.
- \( P \) = absolute pressure.
- \( R \) = compression ratio.
- \( k \) = constant.

This formula was developed from theoretical considerations and, therefore, represents the highest attainable efficiency from the Otto Cycle. The best modern aeronautical engines are actually developing a thermal efficiency within 4 or 5 per cent of the values derived from the use of this formula (9).

A graphical picture of the effect of a change in compression ratio is shown by Fig. 1. On the chart, the area 1'2'3'4', represents the work done during the cycle with a compression ratio of 6:1 and an initial pressure of 7.3 pounds per square inch. The area 1''2''3''4'', represents the work done during the cycle with a compression ratio of 12:1 and an initial pressure of 7.3 pounds per square inch. If we now let the work area 1'2'3'4',
be represented by unity, then by the use of formula (a), we will find that the work area 1"2"3"4" equals 1.43. This figure shows a substantial increase in work from the same amount of fuel. The two necessary assumptions for this calculation are that the value of the constant k is the same for every expansion and compression line, regardless of the compression ratio, and that the pressure increase at ignition has the same multiplication factor. Theoretically the amount of fuel drawn into the cylinder during both of these strokes is exactly the same. Therefore the greater amount of work obtained in the higher compression ratio is due to the greatly increased thermal efficiency. Equations (g) and (h) show that the thermal efficiency is improved by an increase in compression ratio. Fig. 33 shows how closely the results of actual tests check these theoretical values.

Test Results:

The test results obtained in the research of variable compression ratio do not show the same consistency that is shown in the results of the altitude experiments. In the results of some of the tests, as shown by Fig. 22 and 23, we see that the agreement between the theoretical air cycle and the actual test results is very good. Fig. 24 shows the results of a test from which the conclusions were drawn that the gain in power due to an increase in compression ratio does not bear a constant relation to the total power of the
engine, at the different altitudes; being greater at the higher than at the lower altitudes (3).

Fig. 26, 27 and 28 show the results of an interesting experiment in which the carburetor intake pressure was varied and also the compression ratio. The chart of Fig. 26 shows the indicator cards taken with three different compression ratios, and substantiates the theoretical explanation in the thermodynamics division of this part. Fig. 27 gives a good graphical picture as to the greatly decreased fuel consumption resulting from the use of a higher compression ratio; this test also shows the effect of the change in power, the change in fuel consumption, the change in thermal efficiency, and the change in maximum cylinder pressure. Boosting the carburetor pressure (supercharging) results in a large increase in power, a comparatively small increase in maximum cylinder pressures and a slight decrease in fuel economy; whereas, increasing the compression ratio results in a moderate increase in power, a large increase in maximum cylinder pressures, and a marked improvement in fuel economy (23).

Another report (17) shows that an increase in brake horsepower and a decrease in the pounds of fuel used per brake-horsepower-hour usually results from an increase in compression ratio. This holds true at least up to the highest compression ratios investigated, 14:1, provided there is no serious preignition or detonation
at any ratio. The changes in indicated thermal efficiency with changes in compression ratio are in close agreement with what would be anticipated from a consideration of the air cycle efficiencies at the various ratios. In so far as these tests are concerned there is no evidence that a change in compression ratio produces an appreciable consistent change in friction horsepower, volumetric efficiency, or in the range of fuel-air ratios over which the engine can operate. The ratio between the heat loss to the jacket water and the heat converted into brake horsepower or indicated horsepower decreases with an increase in compression ratio. At any compression ratio the indicated mean effective pressure is directly proportional to the volumetric efficiency and at any definite volumetric efficiency, the indicated mean effective pressure is proportional to the air cycle efficiency as determined by the compression ratio.

The conditions inducing detonation in the high compression engine become less severe at high altitudes, therefore a compromise has been sought, in which relatively high compression ratios are employed in conjunction with throttling at the lower altitudes to reduce the density of the charge and thus suppress detonation until sufficient altitude has been gained to permit full-throttle operation (30). This is the nearest attempt to variable compression ratio that has been put into actual use.
Calculations:

For the calculation of the variation in power due to the variation in compression ratio, formula (a) was used. This formula is based on the theoretical air cycle. The value taken for the constant \( k \) was 1.33 which is a very good average for the gases in an internal combustion engine operating under normal conditions (14). This is an average value taken from indicator cards of an engine under test from ground level to an altitude of 35,000 feet, as shown in Fig. 101.

The intake pressure \( P_i \) was taken as the atmospheric pressure at the respective altitude. Then by the formula (b) the pressure for point 2 was calculated. The multiplication factor for the explosion pressure was taken as three in all cases. Because the values are all taken as ratios, they would not be affected by any other particular multiplication factor, however, the chosen value is reasonably close to the results of many experiments. The difference in volume between points 1 and 3 was always taken as a constant (5 in this case) as this would represent the displacement volume of the engine, which is constant for any particular design. The volume of the clearance space was then taken at such a value so as to give the desired compression ratio. These values are shown in Table II.

The values for the respective pressures and volumes were then substituted in equation (a) and the work results all changed into ratios as shown in Table...
II and III.

The results of Table III were plotted as shown in Fig. 7, to give a graphical picture of the performance of an engine employing different compression ratios and operating at various altitudes. The altitudes chosen are: ground level, 1,500 feet, 5,000 feet, 10,000 feet, 15,000 feet, and 20,000 feet. The basis (100%) was taken as ground level and a 6:1 compression ratio.
Part IV

METHODS TO PROVIDE VARIABLE COMPRESSION RATIO

Secondary Chamber:

This method consists of dividing the combustion space into two definite volumes. Any desired volume above the piston, the regular combustion space, with sufficient volumetric capacity to give the maximum compression ratio desired; and a secondary combustion space, connected by a passage containing a manually operated valve, as shown in Fig. 2. The combined volume of the regular combustion space and the secondary combustion space is to be such that the resulting compression would be the lowest compression ratio desired. With this method only the two definite compression ratios can be attained.

Displacer Piston:

Another method of obtaining variable compression is to have a small cylinder fitted with a piston, opening into the combustion space of the engine. The small piston P, Fig. 3, is to be operated by an eccentric E, which in turn can be manually operated. The volume of the ordinary combustion space is to be such as to give the highest compression ratio desired; and the combined volume of the regular combustion space plus the volume of the small cylinder, when the piston P is in the
extreme outward position, is to be such that the resulting compression ratio is the minimum desired. With this system any intermediate compression ratio between the extreme limits can be attained by adjusting the displacer piston to the required position.

Lever Motor:

About the most practicable method for obtaining variable compression ratio in the in-line or V-type engines is the lever motor. Besides variable compression ratio, this type of motor presents other mechanical problems, both advantageous and disadvantageous.

The variable compression ratio is attained without disturbing the continuity of the combustion space. For the use of this method the piston and cylinder are of the regular design now in use, but the connecting rod is, in reality, a three piece rod. The upper part gives a connection between the piston and one end of the lever L, Fig. 4. The lower part of the connecting rod, gives a connection between the crank pin and the middle of the lever. The other end of the lever L acts as a fulcrum, but instead of being pivoted at a permanent point, it is pivoted by an eccentric E. By rotating the eccentric E to its lowest position, the fulcrum end of the lever will then be in its lowest position, thus the stroke of the piston will be at its highest position relative to the cylinder wall. This position will result in the highest possible compression ratio for the engine.
On the contrary, when the eccentric is turned to the uppermost position, the lowest possible compression ratio will result. The engine can be so designed to make these two limiting ratios any values that may be desired, within reasonable limits, and then any intermediate compression ratio, between these extreme limits, can be had by turning the eccentric $E$ to the necessary position.

Other Systems:

There are other methods of obtaining variable compression ratios, but are not likely to be used for commercial purposes. One method used for test engines is a movable cylinder wall and head with respect to the crank shaft and its mounting. This method gives good operation but necessitates heavy construction and requires special and complicated gearing for the valves.
Part V

RESISTANCE OF AIRSHIPS

Factors:

The factors entering into the resistance of an airship are; The total displacement volume, the speed of the ship, the density of the medium through which the ship is being propelled, and the design. After the size of the ship is determined, the last mentioned factor is the one which receives the most attention. There a few points of design that can greatly change the resistance of the ship without changing its general shape. One of the most important points is stream lining of the appendages.

The density of the medium through which the ship is being propelled, is an important factor in the resistance of a ship. There is only one way in which this can be varied, and that is by flying at higher altitudes. The variation of the speed causes the greatest variation in the resistance of a ship as the resistance is proportional to the square of the speed. The time rate of distance covered by the ship is directly proportional to the speed. Therefore, the horsepower required to propel the ship is proportional to the cube of the speed.

Formula:

The formula for calculating the resistance of an airship \( R \) is:
\[ H.P = \frac{V^\frac{2}{3} \rho \nu^3}{550 K} \]  \hspace{1cm} (i)

where:

- \( \nu \) = speed in feet per second.
- \( \rho \) = density of the air in slugs per cubic foot (1 slug = 33.2 pounds).
- \( V \) = total volume or displacement of the ship in cubic feet.
- 550 = the number of foot pounds per second for one horsepower.
- \( K \) = a non-dimensional coefficient depending upon the propeller efficiency and the design of the hull and its appendages.

Calculations:

Using the above formula, the resistance of a ship ("Akron" or "Macon") was calculated. The density of the air was taken as the mean value of the summer and the winter density. Table V shows the results from the calculations and Fig. 8 gives a graphical picture of these results.

The values derived by the use of the formula hold true, to very close limits, in checking actual test results.
Part VI
RESULTS OF INVESTIGATION AND CONCLUSIONS

Performance of the Engine:

From Part II of this thesis we note that the power drops off with an increase in altitude, and if the mechanical efficiency of the engine remained constant, then the pounds of fuel consumed per horsepower hour would remain constant regardless of the altitude. But due to the fact that altitude has no noticeable effect on the friction of an engine, the friction becomes a larger part of the whole output as the higher altitudes are attained. This gives a decreased mechanical efficiency for the higher altitudes and consequently an increase in specific fuel consumption.

Resorting to variable compression ratio the increase in thermal efficiency will offset the loss in mechanical efficiency by a wide margin. It is a known fact that much higher compression ratios can be used at the higher altitudes, for the limiting factors in using higher compression ratios are preignition and detonation. These are both, considering the same fuel, a function of the cylinder pressure and temperature upon completion of the compression stroke. At the higher altitudes, due to the decreased intake pressures and consequently the compression pressures, a higher compression ratio can be used to bring the compression pressure up, equal to or nearly equal to the original compression pressure for which the engine was designed.
The compression ratios for the different altitudes shown in Table IV were calculated on the basis of constant compression pressure. The basis (100%) for these results is a 7:1 compression ratio at an altitude of 1,500 feet. The reason for this basis is that the Maybach dirigible engine employs this ratio and is designed for a flying altitude of 1,500 feet.

Performance of the Ship:

For calculating the performance and the use of an example parallel to actual practice, the Navy dirigible "Akron" was used. These figures would also hold very good for the "Macon" as its design characteristics are practically unchanged in regard to size and resistance. These ships embody the latest designs in rigid airship practice and promise to be of value for future commercial purposes.

Once a ship is completed, the power required to propel it is a function of the speed of the ship and the density of the air through which it is being driven. Therefore, if the speed is held constant, we can see that the resistance is greatly reduced as the flight is carried to higher and higher altitudes. This fact in itself would reduce the amount of fuel required to drive the ship through a certain specified distance. With the additional feature of variable compression ratio for the higher altitudes, the amount of fuel required to drive the ship through the same specified distance would be
further reduced. The percentage of fuel saved would be greater due to the decreased resistance than from the increase in thermal efficiency due to variable compression ratio. A picture of this fact is shown by Fig. 9. The values were calculated and plotted as percentage values, and can therefore be taken for any constant speed.

Example:

The fuel load of the "Akron" is 127,000 pounds for a cruising radius of 10,000 miles at about 55 miles per hour and an altitude of 1,500 feet.

At 5,000 feet and the same ratio of 7:1 the fuel required would be 91%, Fig. 9. Giving a necessary fuel load of 115,400 pounds. 11,600 pounds saving.

At 5,000 feet and a compression ratio of 7.7:1 the fuel required would be 86.5%. Giving a necessary fuel load of 110,000 pounds. 17,000 pounds saving. 5,400 pounds due to variable compression ratio.

At 10,000 feet and a compression ratio of 7:1 the fuel required would be 81%. Giving a necessary fuel load of 103,000 pounds. 24,000 pounds saving.

At 10,000 feet and a compression ratio of 8.9:1 the fuel required would be 71.5%. Giving a necessary fuel load of 90,800 pounds. 36,200 pounds saving. 12,300 pounds due to variable
compression ratio.

In like manner this calculation can be made for any desired altitude.

Disadvantages:

When looking only at the reduced fuel load resulting from flying at the higher altitudes and using the variable compression ratio, it appears to be a much desired feature. However there is one outstanding disadvantage, and this lies in the fact that for a given gas volume the lifting power of a ship is a function of the density of the air. The reduction of lift is on the gross lifting power of the ship and therefore the reduction in pounds is far more rapid for the higher altitudes than the weight of the fuel saved.

Possibilities for Heavier-than-air Craft:

For the long distance heavier-than-air craft, which may come into being for ocean hops, this feature may turn out to be of great value, as this type of craft has a cruising speed much higher than the take-off speed and therefore the reduction of the density of the air will not hamper the lifting power.

For calculating the quite definite advantage of variable compression ratio in this field, a good aerodynamic knowledge of planes is needed. However the advantage is somewhat near that of the dirigible.
Appendix I

TABLES
Table I

STANDARD ATMOSPHERE

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Reference (13).
Table II

POWER VARIATION WITH VARYING COMPRESSION RATIOS

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<th>11:1</th>
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<td>5.625</td>
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</table>
Table III

POWER VARIATION WITH ALTITUDE

power factor (B.HP.).

air pressure ratio.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Ground</th>
<th>1,500 ft.</th>
<th>5,000 ft.</th>
<th>10,000 ft.</th>
<th>15,000 ft.</th>
<th>20,000 ft.</th>
</tr>
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<td>74.7</td>
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<td>67.6</td>
<td>55.3</td>
<td>44.7</td>
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<td>7:1</td>
<td>108.6</td>
<td>102.3</td>
<td>89.6</td>
<td>73.4</td>
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<td>48.6</td>
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<td>109.4</td>
<td>95.9</td>
<td>83.8</td>
<td>64.3</td>
<td>52.0</td>
</tr>
<tr>
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<td>123.5</td>
<td>116.3</td>
<td>102.0</td>
<td>83.6</td>
<td>68.3</td>
<td>55.8</td>
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<tr>
<td>10:1</td>
<td>130.5</td>
<td>123.0</td>
<td>107.6</td>
<td>88.2</td>
<td>72.2</td>
<td>58.4</td>
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<td>11:1</td>
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<td>113.6</td>
<td>93.4</td>
<td>75.5</td>
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<td>12:1</td>
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<td>134.1</td>
<td>117.3</td>
<td>96.3</td>
<td>78.7</td>
<td>63.6</td>
</tr>
</tbody>
</table>

*Pressure 
#/in.² | 14.78 | 13.98 | 13.30 | 10.18 | 8.40 | 6.86 |

*Density 
#/ft³  | 0.0776 | 0.0738 | 0.0658 | 0.0580 | 0.0478 | 0.0406 |

Reference (24)

*Density and pressure taken as the mean between the values for winter and summer given in Table I.
Table IV

COMPRESSION RATIOS TO BE USED TO GIVE THE SAME COMPRESSION PRESSURE AS THE 7:1 RATIO AT AN ALTITUDE OF 1,500 FEET.

<table>
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<th>Altitude Feet</th>
<th>Comp. Ratio</th>
<th>Power*</th>
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<tbody>
<tr>
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<tr>
<td>5,000</td>
<td>7.7:1</td>
<td>94.3</td>
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<td>10,000</td>
<td>8.9:1</td>
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<td>30,000</td>
<td>12.0:1</td>
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</table>

*Values read directly from chart, Fig. 7.

Formula for calculating the above ratios:

Let:
- \( R \) = compression ratio.
- \( P \) = pressure at start of compression stroke.
  \( \text{(atmospheric pressure)} \)
- \( P_c \) = compression pressure.
- \( P_0 \) = pressure at basic altitude.
- \( n \) = constant (1.33 good average value).

The equations for the compression pressures are:

\[
\begin{align*}
P_c &= P \cdot R^n \\
P_0 &= P_0 R_0^n
\end{align*}
\]

Equating the two compression pressures:

\[
P_0 R_0^n = P \cdot R^n
\]

Solving for the new compression ratio:

\[
R_i = R_0 \left( \frac{P_0}{P_i} \right)^{\frac{1}{n}}
\]
Table V

POWER REQUIRED TO PROPEL THE "AKRON" OR "MACON" AT VARIOUS ALTITUDES AND SPEEDS.

<table>
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<tr>
<th>Speed m.p.h.</th>
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<th>10000 ft.</th>
<th>15000 ft.</th>
<th>20000 ft.</th>
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<td>1370</td>
<td>1300</td>
<td>1160</td>
<td>990</td>
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<td>1920</td>
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References (2) and (28).
Appendix II

FIGURES
Fig. 1.

\[ P_a = 14.7 \text{ psi} \quad 6:1 \text{ Ratio.} \]

\[ P_a = 73 \text{ psi} \quad 6:1 \text{ Ratio} \]

\[ P_a = 73 \text{ psi} \quad 12:1 \text{ Ratio} \]
Fig. 7. Horse-power variation at different altitudes with various compression ratios. (Basis: Sea level and 6:1 Ratio.)
Fig. 10 Indicator cards plotted from results of aircraft engine tests @ 1800 R.P.M. and at pressures corresponding to various altitudes. Engine had fixed spark advance. (14)
Figure 15. Average Results of Altitude Tests of Several Aircraft Engines

Fig. 11. (1)

Fig. 12. (4)

Fig. 13. (5)

Fig. 14. (11)

Note: The carburetor air temperature was held at 59°F during the Maybach tests but in testing the other engines it was changed at each density, its value being 32°F at the highest density and 11°F at the lowest density.
POWER VARIATION WITH ALTITUDE

Fig. 15. (11)  
Fig. 16. (11)  
Fig. 17. (18)

Fig. 18. (16)  
Fig. 19. (16)
POWER VARIATION WITH ALTITUDE

Fig. 20. (22)  

Fig. 21. (24)

EFFECT OF COMPRESSION RATIO CHANGE

Fig. 22 (1)  

Fig. 23 (1)
EFFECT OF COMPRESSION RATIO CHANGE

Fig. 24. (3)

Fig. 25. (23)

Fig. 26. (25)

Fig. 27. (25)

Fig. 28. (25)
BIBLIOGRAPHY


