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JET PROPULSION FOR AIRPLANES

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By Edgar Buckingham.

SUMMARY.

This work was undertaken at the Bureau of Standards on the request of the Engineering Division, Air Service, United States Army, and was submitted, with their approval, to the National Advisory Committee for Aeronautics, which authorized its publication as a technical report on recommendation of the Subcommittee on Power Plants for Aircraft.

Air is compressed and mixed with fuel in a combustion chamber, where the mixture burns at constant pressure. The combustion products issue through a nozzle, and the reaction of the jet constitutes the thrust.

Data are available for an approximate comparison of the performance of such a device with that of the motor-driven air screw. The computations are outlined and the results given by tables and curves.

The relative fuel consumption and weight of machinery for the jet, decrease as the flying speed increases; but at 250 miles per hour the jet would still take about four times as much fuel per thrust horsepower-hour as the air screw, and the power plant would be heavier and much more complicated.

Propulsion by the reaction of a simple jet can not compete, in any respect, with air screw propulsion at such flying speeds as are now in prospect.

1. INTRODUCTION.

In the usual method of driving airplanes, air entering the propeller circle from ahead is projected backward in a continuous stream or race, and the reaction of the race against the air screw constitutes the forward driving thrust. This may evidently be regarded as propulsion by means of a jet; but the term "jet propulsion," as commonly understood, implies the use of a smaller and more intense jet, maintained by some other means than an air screw. This is the sense in which the term is employed here.

It is a familiar fact in naval and aeronautical engineering that, other things being equal, it is more economical of power to get a given thrust from a large low-speed race than from a smaller one of higher speed. But when we make a radical change in the method of producing the race, other things are not equal, and the final effect on fuel consumption and weight of machinery can not be predicted without a somewhat detailed analysis of the particular process in question.

A method of propulsion which dispensed with the screw propeller might present some advantages; and since the question whether jet propulsion has any chance of practical success comes up rather often, it has seemed worth while to examine one of the most obvious schemes with regard to the vital points of fuel consumption and weight of machinery.

We shall start by describing the problem and the general method of handling it. The assumptions and the numerical data on which the computations are based will then be given; the processes of computation will be outlined; and the quantitative results will be exhibited by tables and curves. While the computations are somewhat laborious, they are perfectly straightforward, so that it is not necessary to give many details. In conclusion, a few comments will be added on the practical significance of the results obtained.

2. THE PROBLEM.

The plan to be discussed is as follows: The jet is to consist of a continuous stream of combustion products issuing from a nozzle, so that the airplane will be like a rocket with wings, except that a true rocket produces its jet entirely from within itself, without taking in air from outside. The air needed for the jet is to be taken in by a motor-driven compressor and delivered at increased pressure to a receiver which acts as a combustion chamber. The liquid fuel is to be sprayed into the combustion chamber and burned there continuously, at constant pressure, so as to increase the temperature and volume of the gaseous mixture. The resulting combustion products, consisting mainly of nitrogen, steam, and carbon dioxide, are then to expand freely through a suitable nozzle from the receiver pressure to the outside atmospheric pressure at which the air was taken in by the compressor.

For the present we shall consider only a simple nozzle such as is used in steam turbines, and we shall not discuss in detail the possibility of improving the propulsive efficiency of the jet by any of the "aspirator" or "ejector" devices which have been proposed for increasing the momentum and thrust. If such devices are found to be effective, the prospect for jet propulsion will be correspondingly improved; but we wish first to inquire what might be done without them and from what point the improvements must start.

The quantitative results will, of course, depend on the temperature and pressure assumed for the outside air, and on the amount of compression. The outside pressure will be taken as one atmosphere, corresponding to sea level conditions, and the pressure in the combustion chamber as 1.5 to 30 atmospheres absolute or 7.3 to 426 lb./in.^{2} gage. The results of the computations show that this range of compression is much more than wide enough. There would be no advantage in going beyond 15 to 1; and below 7 to 1 the fuel rate increases so fast that it is quite useless to consider such compression ratios as can be obtained with a turbo-booster, and a reciprocating compressor must be used. Most of the computations have been made for atmospheric temperatures of $-30°$, $+30°$, and $+90°$ F., a range which covers nearly all flying conditions.

The general outline of the computations is as follows:

(*a*) By making reasonable assumptions regarding the compressor plant, we compute the temperature of the air as it leaves the compressor, and the weight of fuel used for compressing 1 pound of air from the given initial temperature and pressure to the final pressure in the receiver.

(*b*) From the mixture ratio, the heat of combustion, and other data which are known approximately or may be fairly well estimated, we compute the temperature in the combustion chamber, the final temperature of the expanded gases, and the speed of the jet from the nozzle.

(*c*) From this speed we find the total mass flow needed to give a static thrust of 1 pound; and from the total flow and the mixture ratio we find the rate at which fuel is consumed in the combustion chamber, the rate of air supply, and the rate of fuel consumption by the compressor motor. We thus find the total fuel rate needed to maintain a static thrust of 1 pound.

(*d*) Assuming some particular static thrust, we compute the effective thrust and the thrust horsepower at various flying speeds, and thus find the total fuel rate per thrust horsepower at these speeds for comparison with the known fuel rates obtained with motor-driven air screws.

3. ASSUMPTIONS AND FUNDAMENTAL DATA.

(*a*) *The mixture ratio*, i. e., the ratio, by weight, of air to fuel used in the combustion chamber, is taken to be $m=15$, which is about the value for ordinary gasoline motors. A lower ratio would result in incomplete combustion, while excess air would lower the efficiency of producing the jet more than enough to offset the gain due to the decrease of jet speed.

(*b*) *The heat of combustion.*—The average value for gasoline is about 19,000 B. t. u./lb., while kerosene runs a little higher. We assume the value $h=19{,}000$ B. t. u./lb.

(*c*) *The heat loss from the combustion chamber.*—In ordinary gasoline motors about one-fourth to one-third of the heat developed in the cylinders is lost to the jacket water. In the combustion chamber here contemplated, the temperature will be much higher than the mean temperature in a motor cylinder, and both the chamber and the nozzle will require artificial cooling; but a refractory lining may be used and allowed to run very hot, so that the unavoidable heat loss will probably be a much smaller fraction than in the usual motor cylinder. Nothing more definite can be said in advance of experiment, but we shall assume, provisionally, that one-tenth is a sufficient allowance. The remaining fraction, which is effective in heating the gas mixture, will then be $\epsilon=0.9$. We shall call ϵ the "receiver efficiency."

(*d*) *The speed coefficient of the nozzle*, or the ratio of the actual jet speed to that which would be attained if there were no resistance, is taken as $z=\sqrt{0.92}=0.959$. Experience with steam turbine nozzles shows that values of 0.95 or over could certainly be reached with new nozzles if properly designed. How long such values could be maintained against erosion by the hot gas is a question that only experience can answer; but it may be noted the nozzles would be small and easily replaced.

(*e*) *Efficiency of the compressor plant.*—We suppose the reciprocating compressor and its motor to be a single unit, so that there is no transmission loss. In order to keep down the weight, the compressor must be run as fast as practicable, so that it can not be effectively cooled and the compression will be nearly adiabatic. We assume that the efficiency referred to adiabatic compression is $\eta=0.85$, and that the fuel rate of the motor is 0.5 pound per brake horsepower-hour—a common value for aviation motors. The fuel rate of the whole unit will then be $0.5/0.85=0.588$ pound per air horsepower-hour.

(*f*) *Properties of the gases.*—In calculating the work done and the rise of temperature during compression of the air, the temperature in the combustion chamber, and the temperature and speed of the jet, we have to make certain assumptions regarding the thermodynamic properties of the gases.

We first assume that the gases follow the familiar equation

$$pv=R\Theta \tag{1}$$

Over the range of temperature and pressure to be dealt with, the errors resulting from the inexactness of this assumption are insignificant in comparison with the other uncertainties of the work.

If C_p and C_v denote the specific heats of a gas which follows equation (1), it is easily shown, first, that C_p and C_v are independent of the pressure; and, second, that their difference is equal to the gas constant for unit mass, i. e., that $C_p-C_v=R$, so that their ratio is

$$\frac{C_p}{C_v}\equiv k=\frac{C_p}{C_p-R} \tag{2}$$

From the known density of air and the mechanical equivalent of heat, we find that, for air, $R=C_p-C_v=0.0689$ B. t. u. per pound per degree F., so that by (2) we have, for air,

$$k=\frac{C_p}{C_p-0.0689} \tag{3}$$

where C_p is to be expressed in B. t. u. per pound per degree F.

If C_p is independent of temperature as well as pressure, it is a constant, as is also the value of k, and isentropic changes of pressure and temperature then follow the familiar equations

$$pv^k=const. \qquad \Theta=const.\times p^{\frac{k-1}{k}} \tag{4}$$

In reality, the specific heat of air is not constant. In the first place, it varies slightly with pressure, in accordance with the fact that equation (1) is not exact; but this variation is small and, moreover, it is not accurately known except for temperatures between 20° and 100° C. We shall therefore disregard it and continue to use equations (1), (2), and (3).

In the second place, C_p varies with the temperature, and this variation is too large to be neglected when the temperature range is as wide as in the present problem. To allow for it, we accept the latest data for air published by the Reichsanstalt (Wärmetabellen, Vieweg, 1919) and so obtain the formula

$$C_p=0.2402+0.000'0053\ (t_1+t_2) \tag{5}$$

where C_p is the mean specific heat at one atmosphere between $t°_1$ and $t°_2$ F., expressed in B. t. u. at 59° F., per pound of air, per degree F.

The mean value of k over any interval $t°_1$ to $t°_2$ F. is therefore to be found by computing C_p from equation (5) and substituting the resulting value in equation (3). It is evidently not constant but decreases slowly as the mean temperature $(t_1+t_2)/2$ increases.

Since k is not constant, equations (4) are not exact, but instead of using the more complicated equations which result from setting $C_p=a+bt$, we adopt a middle course. For each computation relating to an adiabatic process, we use equations (4); but instead of always using the same value of k, we use the mean value appropriate to the temperature interval in question, found by computing the mean C_p from equation (5) and substituting it in equation (3). This requires successive approximations, because while the initial temperature and pressure are always known, only the final pressure is given, and the final temperature has to be found in the course of the work.

The foregoing refers specifically only to air, but we use the same methods and the same numerical values for the burning mixture in the combustion chamber and for the combustion products exhausting through the nozzle. With a mixture ratio $m=15$, 1 pound of the mixture in the receiver contains about 0.72 pound of nitrogen, so that nearly three-fourths of the gas is sensibly unaffected by the reaction. The remaining 0.28 pound is converted from oxygen and fuel into carbon dioxide and steam, with small amounts of other gases, and this chemical change affects both the gas constant R and the specific heat of the whole mixture. We have no adequate data for computing the magnitudes of these changes at all accurately, but they are probably quite small; and since we can do no better, we disregard them and follow the common procedure of treating the mixture before, during, and after combustion, as if it were merely so much air, using the numerical data given in equations (5) and (3).

4. NOTATION.

The notation to be used is collected below for reference:

p = absolute pressure.
v = volume.
t = Fahrenheit temperature.
$\Theta=t+460$ = absolute temperature in Fahrenheit degrees.
C_p = specific heat at constant pressure, in B. t. u./lb./deg. F.
k = specific heat ratio.
m = mixture ratio ($m=15$).
h = heat of combustion in B. t. u./lb. ($h=19,000$).
ϵ = receiver efficiency ($\epsilon=0.9$).
z = nozzle speed coefficient ($z=\sqrt{0.92}$).
η = compressor efficiency ($\eta=0.85$).
S = speed of jet, in m. p. h.
S_0 = speed of flight, in m. p. h.
$W(0,1)$ = work of compressing air, in ft. lb./lb.
P_a = horsepower for isentropic compression of 1,000 pound of air per hour.
M_f = total fuel rate in pounds per hour for an air flow of 1,000 pounds per hour.
T_s = static thrust in pounds for an air flow of 1,000 pounds per hour.
T = flying thrust in pounds at speed S_0.
P = thrust horsepower at speed S_0.
P_c = brake horsepower of compressor motor per thrust horsepower.
F = total fuel rate in pounds per thrust horsepower-hour.

5. GRAPHICAL REPRESENTATION OF THE THERMODYNAMIC PROCESS.

Figure 1 serves to represent the separate elements of the process of producing the jet, as well as to show how the subscripts are used with p, v, t, and Θ.

The point O represents the initial state of 1 pound of air at the pressure p_0 and temperature t_0 of the outside atmosphere, the volume being v_0.

The line *OI* represents the compression of the 1 pound of air to the receiver pressure p_1, the temperature rising to t_1 and the volume decreasing to v_1; and the point *I* represents the state of the air as it passes from the compressor to the combustion chamber. We assume that this compression line agrees with equations (4) when the proper value of k is used. The work of compressing 1 pound of air, from which the "air horsepower" is to be found, is represented by the area *OABIO*, the rest of the work done by the motor on the compressor being wasted.

The line *I II* corresponds to the process of injection of the liquid fuel, its evaporation and combination with the oxygen of the air from the compressor, and the heating of the gaseous mixture. The pressure remains constant at the value p_1 given by the compressor, while the temperature increases from the value t_1 of the entering air, to the temperature t_2 of the combustion products which are about to escape through the nozzle. The liquid fuel is injected continuously at the rate of 1 pound to m pounds of air from the compressor, and the increase of volume from *I* to *II* represents the combined effect of increase of mass, change of chemical composition, and thermal expansion at constant pressure. The point *II* represents the state of $(m+1)/m$ pound of the combustion products as they enter the nozzle.

The line *II III* represents the change of state of the $(m+1)/m$ pound of gas as it expands through the nozzle from p_1 to the outside back pressure p_0. The volume increases from v_2 to v_3, the temperature falls from t_2 to t_3, and the gas acquires the speed S, relative to the nozzle and combustion chamber. The point *III* represents the final state of the gases in the jet. On the approximating assumptions we have made regarding the thermodynamic properties of the gases, the expansion *II III* would follow equations (4) if no heat were lost to the nozzle walls and if there were no resistance in the nozzle. The heat loss in the nozzle will probably be negligible, but the resistance will not, and we have assumed that the speed coefficient has the constant value $z=\sqrt{0.92}$. Under these conditions, Zeuner has shown (Techn. Thermodynamik, 2nd ed., 1900, vol. 1 p. 44) that the expansion will take place according to the equations

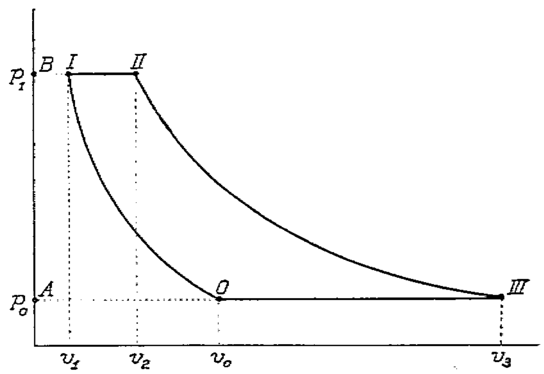

FIG. 1.

$$pv^n = const. \qquad \Theta = const. \times p^{\frac{n-1}{n}} \tag{6}$$

where

$$n = \frac{k}{z^2 + k(1-z^2)} \tag{7}$$

and we shall use these equations in computing the jet speed S and the final temperature t_3.

6. THE TEMPERATURES.

The temperature t_1 of the air delivered by the compressor was computed from the equation

$$t_1 = (t_0 + 460)\left(\frac{p_1}{p_0}\right)^{\frac{k-1}{k}} - 460 \tag{8}$$

by setting $t_0 = -30°$, $+30°$, and $+90°$, and giving p_1/p_0 various values from 1.5 to 30. The values of $(k-1)/k$ needed in the successive approximations were read from an auxiliary curve constructed for the purpose by means of equations (5) and (3). The resulting values of t_1 are given in Table 1, together with the final values of $(k-1)/k$, which are needed later.

The temperature t_2, after combustion, was computed from the equation

$$t_2 = t_1 + \frac{\epsilon h}{(m+1)\,C_p} = t_1 + \frac{1069}{C_p} \tag{9}$$

with the values of t_1 already given in Table 1. The mean values of C_p used in the successive approximations were found from equation (5), and the resulting values of t_2 are given in Table 2, together with the final values of C_p.

The temperature t_3 of the expanded gases in the jet was found from the equation

$$t_3 = (t_2 + 460)\left(\frac{p_0}{p_1}\right)^{\frac{n-1}{n}} - 460 \tag{10}$$

by using, for each value of the pressure ratio, the value of t_2 already found for that ratio and given in Table 2. The values of $(n-1)/n$ were found by using the auxiliary curve already mentioned and a second auxiliary curve giving values of $(k-1)/k-(n-1)/n$ in terms of $(k-1)/k$ for the given value of z. The resulting values of t_3 and the final values of $(n-1)/n$ are given in Table 3.

In each of these three sets of computations the approximations were continued until the last two values agreed within 1 or 2 degrees F.

The temperatures thus obtained are exhibited graphically in Figure 2, plotted from Tables 1, 2, and 3.

7. THE WORK OF COMPRESSING THE AIR.

For continuous isentropic compression of a gas which obeys equations (4), the work $W(0, 1)$ per unit mass is given by the equation

$$W(0,1) = \int_{p_0}^{p_1} v\,dp = p_0 v_0 \frac{k}{k-1}\left[\left(\frac{p_1}{p_0}\right)^{\frac{k-1}{k}} - 1\right] \tag{11}$$

To get W in ft. lb. per lb. of air we take p_0 in lb./ft.^{2}, and v; in ft.^{3}/lb.; and at 1 atmosphere and 32° F. we have

$$p_0 v_0 = \frac{14.696 \times 144}{0.08071} = 26{,}220 \text{ ft. lb.}$$

For any other initial temperature t_0, this is to be multiplied by $(t_0+460)/492$, and we have the following values: at

$t_0 =$	$-30°$	$+30°$	$+90°$ F.
$p_0 v_0 =$	22920	26100	29310 ft. lb./lb.

The values of $W(0,1)$ were obtained by substituting these values of $p_0 v_0$ in equation (11) and using, for each value of p_1/p_0, the value of $(k-1)/k$ already found and given in Table 1. The results are shown in Table 4 and Figure 3.

8. THE SPEED OF THE JET.

It is assumed that the gas obeys the equation $pv/\Theta = const.$ and that the expansion through the nozzle follows equations (6). If S is the linear speed acquired in expanding from p_1, Θ_2 to p_0, we then have

$$S = \sqrt{2\Theta_2 C_p\left[1 - \left(\frac{p_0}{p_1}\right)^{\frac{n-1}{n}}\right]} \tag{12}$$

where if S is to be in ft./sec., Θ_2 C_p must be expressed in foot-poundals per pound.

By using the values: $g = 32.174$ ft./sec.^{2}, 1 mile/hour $= 22/15$ ft./sec., and 1 B. t. u. $= 778$ ft. lb., we may put equation (12) into the form

$$S(M.P.H.) = 152.5\sqrt{(t_2+460)\,C_p\left[1 - \left(\frac{p_0}{p_1}\right)^{\frac{n-1}{n}}\right]} \tag{13}$$

where C_p is expressed, as hitherto, in B. t. u./lb./deg. F.

In using equation (13) to compute values of S, the required mean values of C_p were found by substituting in equation (5) the values of t_2 and t_3 given in Tables 2 and 3; and the values of $(n-1)/n$ were taken from Table 3.

The results are shown in Table 5 and Figure 4.

9. STATIC THRUST T_s AND AIR HORSEPOWER P_a, FOR A FLOW OF 1,000 POUNDS OF AIR PER HOUR IN THE JET.

If the air is supplied at the rate of 1,000 lb./hour, the total mass flow in the jet is

$$M=\frac{16}{15}\times\frac{1000}{3600}=\frac{8}{27}\ lb./sec.$$

And since, in normal units, we have $T_s=MS$, we get the equation

$$32.174\ T_s(lb.)=\frac{8}{27}\times\frac{22}{15}S(M.P.H.)$$

or

$$T_s(lb.)=0.01351\ S(M.P.H.) \tag{14}$$

where values of S are to be taken from Table 5.

The power required for compressing this amount of air isentropically is

$$P_a=1{,}000\ W\ (0,1)/1'980'000$$

or

$$P_a(hp)=5.05\times10^{-4}\ W(0,1)\ \ (ft.\ lb./lb.) \tag{15}$$

where $W\ (0,1)$ is to be taken from Table 4.

The resulting values of T_s and P_a are given in Table 6 and exhibited graphically in Figure 5.

10. TOTAL FUEL RATE FOR A STATIC THRUST OF 1 POUND.

According to the assumption made regarding the compressor plant (section 3, e), when the air flow is 1,000 lb./hour the fuel rate of the compressor motor is 0.588 P_a lb./hour. At the same time 1,000/m or 66.67 lb./hour is being fed into the combustion chamber. Hence the total fuel rate, when the air flow is 1,000 lb./hour, is

$$M_f=66.67+0.588\ P_a\ lb./hour. \tag{16}$$

The static thrust for this flow is T_s lb.; hence the total fuel rate needed to maintain a static thrust of 1 lb. is M_f/T_s lb./hour. In the computation, the values of P_a and T_s were taken from Table 6, and M_f was found from equation (16).

The resulting values of M_f/T_s are given in Table 7, together with values of $58.8\,P_a/M_f$, which is the per cent of the total fuel used in the compressor motor. Figure 6 gives curves for M_f/T_s.

11. RELATION OF THRUST POWER AT VARIOUS SPEEDS OF FLIGHT TO STATIC THRUST AT THE SAME RATE OF DISCHARGE.

When the machine is at rest, the whole mass of gas discharged from the nozzle receives the backward speed S. When the machine is moving forward at the speed S_0, one-sixteenth of the mass still receives the backward speed S, because the fuel starts at rest with respect to the nozzle; but the remaining fifteen-sixteenths receives only the speed $(S-S_0)$, because the air, when it is first taken in by the compressor, has already the backward speed S_0 with respect to the machine. But the thrust is proportional to the rate of production of backward momentum. Hence if T_s is the static thrust for a given jet speed S and mass flow M, and T the thrust at the flying speed S_0, for the same values of S and M, we have the relation

$$\frac{T}{T_s}=\frac{\frac{1}{16}S+\frac{15}{16}(S-S_0)}{S}=1-\frac{15}{16}\frac{S_0}{S} \tag{17}$$

If the thrusts are expressed in pounds and the speeds in miles per hour, the thrust horsepower is

$$P=T\times\frac{22}{15}S_0\div550=\frac{TS_0}{375}$$

whence by equation (17)

$$\frac{P(hp)}{T_s(lb)}=\frac{S_0}{375}\left(1-\frac{15}{16}\frac{S_0}{S}\right) \tag{18}$$

From this equation the values of P/T_s were computed for various values of S and S_0, the results being exhibited in Table 8 and Figure 7.

12. TOTAL FUEL RATE PER THRUST HORSEPOWER.

The fuel rate F in pounds per hour per thrust horsepower is given by the equation

$$F = \frac{M_f}{T_s} \bigg/ \frac{P}{T_s} \tag{19}$$

Table 9 contains values of F computed from this equation. The required values of M_f/T_s were taken from Table 7 and the values of P/T_s were read from Figure 7. The results for $t_0 = +30° F.$ and for flying speeds of *100 to 350 m. p. h.* are shown by the curves in Figure 8.

13. EFFECT OF UTILIZING THE IMPACT PRESSURE DUE TO THE SPEED S_0.

Hitherto, it has been supposed that the pressure of the air in the compressor intake was the same as p_0, to which the jet exhausts, and this corresponds to locating the intake openings at a neutral zone on the side of the fuselage. If the opening is in the nose of the fuselage, so as to receive the full impact due to the flying speed, the pressure in the intake will be $p^1 = p_0 + \Delta p$, where Δp is the impact pressure. Hence the work of compression from p_0 to p^1 or

$$W(p_0\, p^1) = p_0\, v_0 \frac{k}{k-1}\left[\left(\frac{p^1}{p_0}\right)^{\frac{k-1}{k}} - 1\right]$$

will be saved, and the fuel rate for compression diminished.

The fractional saving on the compression will be $W(p_0\, p^1)/W(0,1)$ and the fractional decrease of the total fuel rate will be $[W(p_0\, p^1)/W(0,1)] \times$ that fraction of the total fuel which is used in compressor motor. This latter is the value of the quantity $(0.588\, P_a/M_f)$, which may be found in Table 7. Table 10 contains a few values of the percentage decrease of total fuel rate computed in the manner just described. The saving is small, even at the higher speeds of flight, and Table 9 and Figure 8 do not require any important corrections to adapt them to the more advantageous plan in which the impact pressure is fully utilized.

14. EFFECT OF VARYING THE COMPRESSOR EFFICIENCY.

If the compressor efficiency is not 0.85 but η, the fuel rate will be given by the equation

$$F(\eta) = F(0.85) \times \frac{66.7 + \frac{0.85}{\eta} \times 0.588 P_a}{66.7 + 0.588 P_a} \tag{20}$$

If the compressor efficiency is changed from 0.85 to 0.75, the total fuel rates for $t_0 = +30°$, as given in Table 9 and Figure 8 will be increased by the following percentages:

at $p^1/p_0 =$	*5*	*7*	*10*	*15*
	2.5	*3.0*	*3.7*	*4.3*

It is evident from the curves of Figure 8 that there is nothing to be gained by using a pressure ratio much greater than $p^1/p_0 = 10$, and we may assume that this limit will not be exceeded in practice. If we also assume, as seems quite safe, that a compressor efficiency of 0.75 or better can be obtained, the remaining uncertainty in the compressor efficiency can evidently not affect the fuel rates already computed by more than 3 or 4 per cent. The curves of Figure 8 may therefore be regarded as only slightly affected by the source of error now in question.

15. EFFECT OF VARYING THE RECEIVER EFFICIENCY.

To estimate the effect of an error in the value assumed for the receiver efficiency, we now suppose the heat loss from the combustion chamber to be twice as great as before and set $\epsilon = 0.8$ instead of $\epsilon = 0.9$.

It suffices to examine a single average set of conditions, and we take $t_0 = +30°$, $p_1/p_0 = 10$, and $S_0 = 200$ *m. p. h.* Upon working this case out completely, we find the fuel rate $F = 3.90$, whereas the value previously obtained with $\epsilon = 0.9$ was 3.71 (see Table 9). Doubling the cooling loss has thus increased the total fuel rate for these average conditions by 5 per cent.

It seems very unlikely that the heat loss from the combustion chamber need be as much as 0.2 of the heat developed, and the old value of F seems more probable than this new one, so far as this particular source of uncertainty is concerned.

16. REMARKS.

From the discussion in section 3 of the data and assumptions used in the course of the work, and from the computations in sections 14 and 15 on the two doubtful elements of compressor efficiency and receiver efficiency, it seems probable that the fuel rates shown in Table 9 and Figure 8 give a fair idea of what would actually be obtained if the obvious engineering difficulties could be surmounted and the process of jet formation carried out according to the proposed scheme. A considerable uncertainty remains in regard to the specific heats at high temperatures, but in spite of this, it seems likely that the computed fuel rates are correct to within 20 per cent or better. Relatively, they are much more accurate than this, and they probably give a reliable picture of the effects of variations in the compression ratio, the speed of flight, and the outside air temperature.

The most important point brought out by the curves of Figure 8 is that very high pressure ratios are not advantageous. If it were possible to run the compression in the motor cylinders as high as in the compressor cylinders, there would be a thermodynamic gain and a decrease in fuel rate obtained by increasing the compression. But if we assume, as we have done, that the motor is subject to the same limitations as the standard aviation motor, the advantage of increasing p_1/p_0 soon vanishes.

The minimum fuel rates fall at pressure ratios between 10 to 1 and 20 to 1, and the variation within these limits is so small that there is no appreciable advantage in going beyond 10 to 1, or a maximum pressure of 147 lb./in.² absolute. The design of a suitable compressor would therefore not involve any extraordinary difficulty from the standpoint of the pressures to be handled.

The work of computation might have been considerably shortened by using the rough and ready "air standard" method and ignoring the variation of specific heat with temperature. The errors thus introduced would have been so large, however, that it has seemed better to eliminate them, and leave only unavoidable uncertainties in the final results. We may now turn to a comparison of these results with the performance of the familiar engine-driven air screw.

17. COMPARISON WITH THE FUEL RATE OF AIR-SCREW PROPULSION.

We assume that the air-screw engine has the same efficiency as the engine used for air compression, i. e., that it requires 0.5 pound of fuel per brake horsepower-hour. We also assume that whatever the flying speed may be, an air screw is used which has an efficiency of 0.7. On these assumptions, the fuel rate of the air-screw plant is $0.5/0.7 = 1/1.4$ pound per thrust horsepower-hour, and the ratio of the fuel rate of the jet to that of the screw at the same thrust horsepower is $1.4F$.

Having found that $p_1/p_0 = 10$ is an advantageous value of the pressure ratio, we turn to Figure 8 or Table 9 for the values of F at $p_1/p_0 = 10$, and for $t_0 = +30°$ we get the following results:

at $S_0 =$	100	150	200	250	300	350
$1.4F =$	10.1	6.8	5.2	4.2	3.6	3.1

This does not look very encouraging. At the highest flying speeds yet attained, jet propulsion by the proposed method would require about 5 times as much fuel as ordinary screw propulsion. It is conceivable that under some special circumstances and for short flights such very poor fuel economy might be tolerated if there were nothing else to be said, but we must also consider the probable weight of machinery.

18. SIZE OF THE COMPRESSOR ENGINE.

The compressor engine uses the fraction $0.588\ P_a/M_f$ (Table 7) of the whole amount of fuel consumed; and since the total fuel rate per thrust horsepower is F (Table 9) the fuel rate of the compressor engine is $0.588\ P_a\ F/M_f$ pound per hour per thrust horsepower. This engine has been assumed to take 0.5 pound of fuel per brake horsepower-hour; hence the brake horsepower of the engine is

$$P_c=\frac{0.588\ P_a F}{0.5\ M_f}=1.18\ \frac{P_a}{M_f}\ F \qquad (21)$$

per thrust horsepower developed by the reaction of the jet at the flying speed S_0.

For comparison with the ordinary air-screw plant, we assume, as in section 17, that the efficiency of the air screw is 0.7; and the brake horsepower of the air-screw engine will then be 1/0.7 per thrust horsepower. We therefore have the relation:

$$P \qquad \qquad .7\ P_c \qquad (22)$$

Values of $0.7\ P_c$ are shown in Table 11, and it appears that unless the speed of flight were considerably higher than any yet attained, the compression of the air to feed the jet would require a larger engine than is needed for an ordinary screw propeller drive giving the same thrust at the same speed of flight.

19. REMARKS ON THE WEIGHT OF THE POWER PLANT.

From the curves of Figure 8 we see that pressure ratios between 7 to 1 and 10 to 1 are the only ones worth considering; and upon turning to Table 11 we find that, within this range, the power needed to compress the air for the jet is greater than the power needed to obtain the same thrust power from an air screw of 70 per cent efficiency, until the flying speed is about 250 m. p. h., or somewhat higher than any yet recorded for manned airplanes.

Since the engine does not have to accommodate itself to a screw propeller, it might, perhaps, be run faster and so weigh less per brake horsepower than an air-screw engine; but the air cylinders, etc., add to the weight. Without going into a detailed examination of the question, we may estimate that, at best, the combined engine-compressor unit would be at least 50 per cent heavier than an ordinary aviation engine of the same power, and probably considerably more. Hence before using the figures in Table 11 as ratios of weight of machinery for jet propulsion to weight of machinery for the air screw, we should multiply them by at least 1.5.

Nothing has been said about the weight of the combustion chamber, nozzle, and fuel injection system. This would more than offset the weight of the screw propeller, but the total would not be large, and in view of the uncertainty as to the weight of the compressor unit, it is useless to attempt to form any estimate on this point.

20. CONCLUSIONS REGARDING THE PRACTICABILITY OF THE PROPOSED SCHEME.

It is sometimes supposed, by those who have not considered the matter in detail, that while jet propulsion would probably be rather wasteful of fuel, it might present considerable compensating advantages in the way of lightness and simplicity. We are now in a position to see what these possibilities are with the particular scheme which has been discussed and which is, perhaps, the most obvious one.

In the first place, even at the highest flying speeds now in sight, say 250 m. p. h., the fuel consumption could not be reduced much below 4 times that required by the ordinary air screw (section 17). In the second place, the power plant would be much heavier for jet than for screw propulsion, and the high fuel load would not be offset by any saving of machinery weight. In the third place, the power plant would not be simpler but far more complicated and delicate than the ordinary one. To say nothing of the fuel injection system, the combined compressor and engine would have about twice as many pistons, valves, and other moving parts as a simple engine, and the chances of breakdown and the difficulties of upkeep would be correspondingly increased.

There are, to be sure, a few obvious advantages in the jet scheme. The large, awkward, and fragile propeller would be eliminated, and only the nozzle and not the engine would have to be located with regard to the axis of thrust. Thus the design would be more flexible. The machine might also, if strong enough, be given brilliant maneuvering powers by utilizing the powerful steering effect of swinging the nozzle. On the other hand, a machine which had to start—if it could get off the ground at all—by emitting a jet of flame at 2,500° F. (see Figure 2 for values of t_3) and a speed of 1 mile per second would hardly be a welcome visitor at flying fields.

But to return from such speculations to the quantitative results of the computations, there does not appear to be, at present, any prospect whatever that jet propulsion of the sort here considered will ever be of practical value, even for military purposes.

21. THRUST AUGMENTORS.

Any device or arrangement that would increase the momentum of a jet already formed, without increasing the fuel consumption needed for maintaining the jet or adding seriously to the weight, would diminish the fuel rate and the weight of machinery per thrust horsepower. For example, if some such addition to the apparatus already discussed were capable of increasing the momentum and the thrust 4 times, the fuel rate of the apparatus with this addition, at 250 m. p. h., would be about the same as for an air screw and the machinery would be lighter, so that the whole aspect of affairs would be changed. Instead of concluding that jet propulsion was altogether impracticable, we should have to consider seriously whether it might not have such advantages as to justify an attempt to develop it. Devices of this sort have been proposed, and while nothing definite can be predicted of their probable success, a little qualitative discussion may be in place here.

The maintenance of a constant thrust by the continuous production of backward momentum is necessarily accompanied by a simultaneous production of kinetic energy which trails away and is left behind without contributing to the thrust power. And since momentum is proportional to the first power of speed and kinetic energy to the second power, economy evidently requires that the speed of the race or jet should be kept as low as practicable and the momentum kept up to the required value by increasing the mass flow rather than the speed. The inferiority of the jet to the screw propeller is due to its going to the wrong extreme and combining small mass flow with very high speed. As a means of converting heat of combustion into mechanical energy, the method of jet propulsion which has been discussed would be more efficient than any combination of engine and air screw; but the screw gives a much greater return, per pound of fuel, in the form of thrust work, because the jet carries away so much kinetic energy which is not utilized but dissipated and turned back into heat.

After leaving the nozzle, the jet entrains and mixes with the surrounding air, gradually slowing down and diffusing its momentum over a much greater mass. The total backward momentum is not changed by the mixing, but kinetic energy is dissipated, just as it is in the shock of inelastic solid bodies, and the action is like that of the ballistic pendulum, which conserves the momentum of the projectile but destroys nearly all of its kinetic energy.

To reduce this loss of kinetic energy, it is necessary to decrease the difference of speed between the jet and the initially quiet air with which it mixes; and since the jet speed is already given, the only way to do this is to accelerate that part of the air which is to come in contact with the jet, *before the mixing takes place.* The work required for this acceleration would have to be obtained from the jet; the momentum of the air thus accelerated would augment the thrust, and the useful thrust work would be increased by drawing on the energy of the jet, which would otherwise be wasted.

So far as the writer has seen them described, the devices which have been proposed for accomplishing this purpose consist in surrounding the jet, after it has left the nozzle, by a series of ring shaped guides, of curved profile, after the manner of an ejector or aspirator. If these guides are properly designed, the pressure in the internal free space about the jet falls below atmospheric, air is drawn in, and before it comes into actual contact with the jet, it has already, in its passage through the curved ports between the guides, acquired a considerable component of velocity in the same direction as the jet. The idea seems to be that the shock loss will be reduced and kinetic energy saved; that the backward momentum of the entering air will be added to that already present in the jet so as to increase the thrust; and that the thrust horsepower of the whole combination will be augmented, without any modification of the part of the apparatus originally provided for maintaining the jet or any increase of fuel consumption.

It is hard to see just how this sort of process can be analyzed and referred to the elementary principles of mechanics and thermodynamics so as to permit of forming any definite quantitative opinion of its feasibility. There is no doubt that ejectors and aspirators built on this plan have been very useful and effective for certain purposes; but whether, in the application now in question, they would have the effect hoped for seems very problematical, and the present writer remains skeptical.

22. CONCLUSION.

The method discussed in this paper for propulsion by the reaction of an internal combustion jet is simple and obvious in principle and lends itself to quantitative treatment, but other schemes for producing the jet might give lighter or simpler machinery or present other advantages. For example, one plan, suggested to the writer by Dr. H. C. Dickinson, would combine the separate functions of engine, compressor, and combustion chamber in a single internal combustion engine working on a slight modification of the usual Otto cycle. After the ignition, a valve would open and allow the greater part of the hot compressed mixture to escape through the thrust nozzle, while only enough was retained for the expansion stroke to supply the friction losses and the negative work of the next compression stroke. The engine would run light, so far as shaft horsepower was concerned, the excess power being turned directly into the jet instead of being used to drive a screw propeller.

Without going into any quantitative analysis of this ingenious suggestion, it may safely be predicted that no such method of jet production would have an appreciably higher thermal efficiency than the one we have considered in detail; the fundamental disadvantage of high jet speed and poor ratio of conversion of heat into thrust work would remain as an insuperable obstacle to the use of such jets.

The only hope of success lies in the thrust augmentors, and if any experimental work is to be done, it should be on them. For it would be most unwise to undertake the difficult work of developing apparatus for producing the jet until it had at least been made probable that the jet could be helped out enough to bring its economy within the range of what is tolerable in practice.

BUREAU OF STANDARDS,
March 23, 1922.

TABLE 1 (FIG. 2 AND §6).

TEMPERATURE OF THE AIR AFTER COMPRESSION = t_1 °F.

$\frac{p_1}{p_0}$	$t_0=-30°$		$t_0=+30°$		$t_0=+90°$	
	t_1	$\frac{k-1}{k}$	t_1	$\frac{k-1}{k}$	t_1	$\frac{k-1}{k}$
1.5	23	0.2868	90	0.2860	157	0.2852
2	64	65	137	57	210	49
3	129	61	210	53	291	44
5	221	56	315	46	403	37
7	289	52	392	42	490	32
10	358	47	482	36	594	26
15	468	41	594	30	720	19
20	546	36	682	24	817	13
30	663	29	817	16	967	03

TABLE 2 (FIG. 2 AND §6).

TEMPERATURE IN THE RECEIVER = t_2 °F

$\frac{p_1}{p_0}$	$t_0=-30°$		$t_0=+30°$		$t_0=+90°$	
	t_2	C_p	t_2	C_p	t_2	C_p
1.0	4059	0.2614	4110	0.2620	4161	0.2626
1.5	4103	20	4161	26	4217	33
2	4138	24	4200	31	4262	38
3	4194	30	4262	38	4331	46
5	4272	39	4352	48	4431	57
7	4329	46	4417	56	4500	66
10	4397	53	4493	65	4589	76
15	4482	63	4590	75	4697	88
20	4548	71	4665	84	4781	97
30	4649	82	4781	97	4909	0.2712

TABLE 3 (FIG. 2 AND §6).

EXHAUST TEMPERATURE OF THE JET = t_3° F.

$t_0=$	$-30°$		$+30°$		$+90°$	
$\frac{p_1}{p_0}$	t_3	$\frac{n-1}{n}$	t_3	$\frac{n-1}{n}$	t_3	$\frac{n-1}{n}$
1.5	3705	0.2252	3759	0.2247	3810	0.2243
2	3471	60	3526	55	3580	51
3	3167	70	3221	66	3278	60
5	2816	84	2876	77	2934	70
7	2604	89	2668	82	2725	77
10	2404	94	2465	88	2526	81
15	2191	0.2300	2255	92	2318	85
20	2052	03	2117	95	2181	88
30	1871	07	1938	98	2005	89

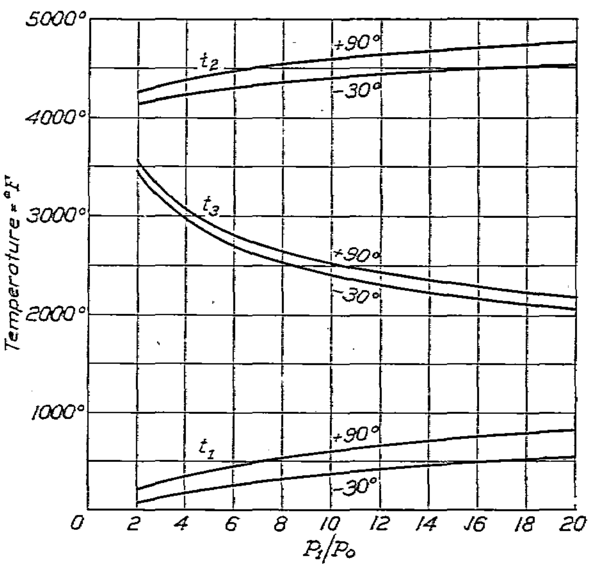

FIG. 2 (Tables 1, 2, 3).—Temperatures

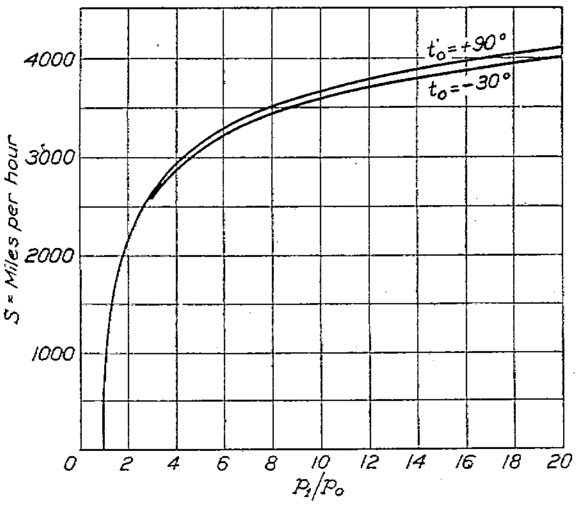

FIG. 4 (Table 5).—Jet speed, S.

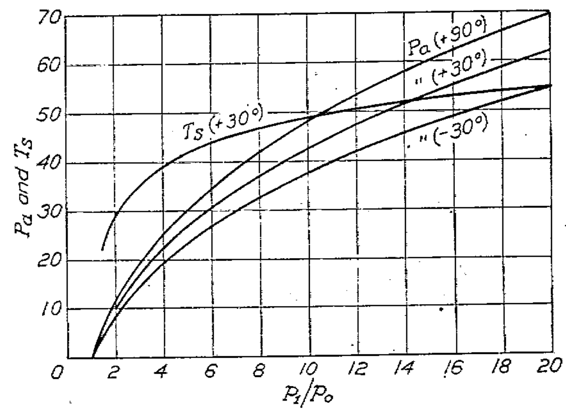

FIG. 5 (Table 6).—Air horsepower, P_a and static thrust, T_s lb for 100 lb. air per hour.

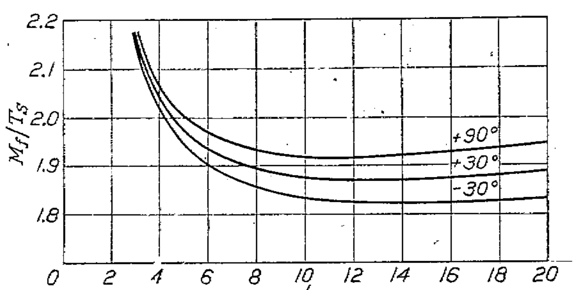

FIG. 6 (Table 7).—Lbs. fuel per hour for static thrust of 1 lb.$=M_f/T_s$.

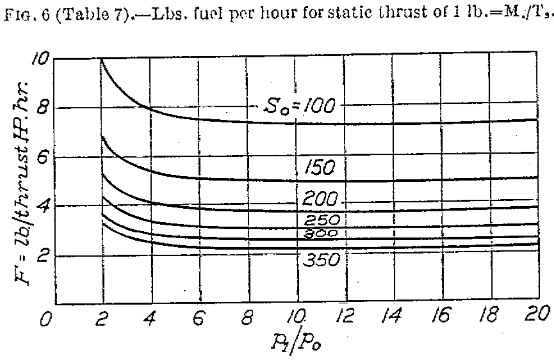

FIG. 8 (Table 9).—Fuel rate, F in lb./thrust H.P. hour.

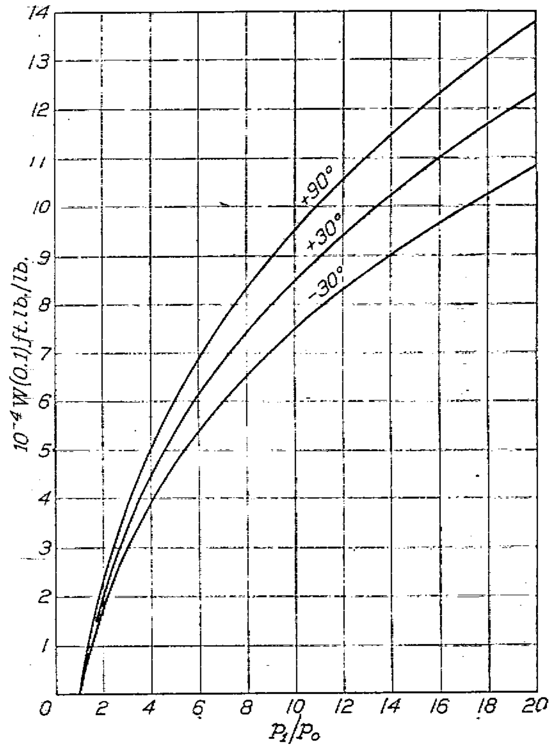

FIG. 3 (Table 4).—Work of compression.

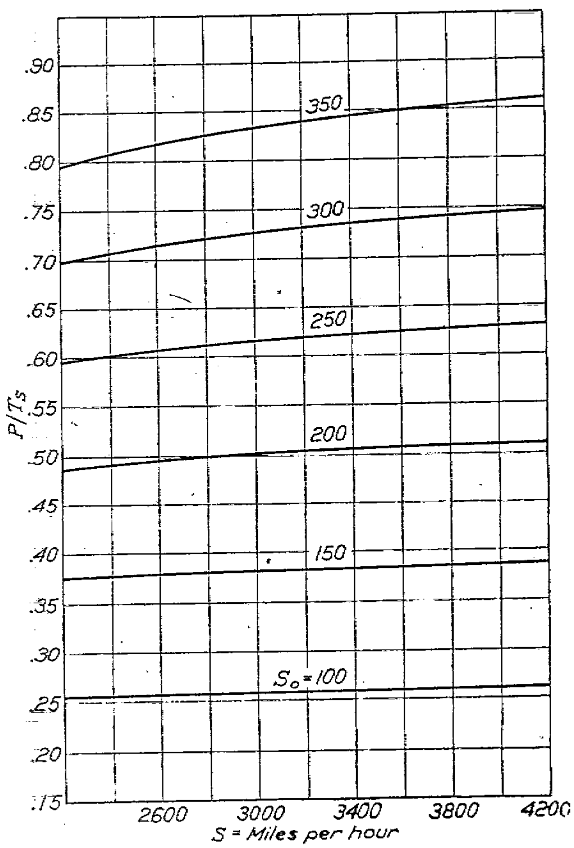

FIG. 7 (Table 8).—Thrust H.P. for 1 lb. static thrust$=P/T$.

TABLE 4 (FIG. 3 AND §7).

WORK OF COMPRESSSION= $W(o, 1)$ FT. LB. PER POUND OF AIR.

$\frac{p_1}{p_0}$	$t_0 = -30°$	$+30°$	$+90$
1.5	9850	11230	12600
2	17570	20020	22450
3	29580	33700	37800
5	46820	53310	59800
7	59620	67860	76090
10	74550	84830	95100
15	93440	106300	119110
20	108170	123020	137820
30	131030	148930	166730

TABLE 5 (FIG. 4 AND §8).

SPEED OF THE JET= S M. P. H.

$\frac{p_1}{p_0}$	$t_0 = -30°$	$+30°$	$+90°$
1.5	1615	1626	1635
2	2086	2100	2115
3	2583	2603	2622
5	3067	3093	3118
7	3331	3362	3392
10	3586	3624	3660
15	3833	3876	3919
20	3998	4046	4095
30	4214	4271	4325

TABLE 6 (FIG. 5 AND §9).

STATIC THRUST= T_s LB. AND AIR HORSEPOWER= P_a FOR 1,000 LB/HOUR OF AIR IN THE JET.

$\frac{p_1}{p_0}$	$t_0 = -30°$		$+30°$		$+90°$	
	T_s	P_a	T_s	P_a	T_s	P_a
1.5	21.8	5.0	22.0	5.7	22.1	6.4
2	28.2	8.9	28.4	10.1	28.6	11.3
3	34.9	14.9	35.2	17.0	35.4	19.1
5	41.4	23.6	41.8	26.9	42.1	30.2
7	45.0	30.1	45.4	34.3	45.8	38.4
10	48.4	37.7	49.0	42.8	49.4	48.0
15	51.8	47.2	52.3	53.7	52.9	60.2
20	54.0	54.6	54.6	62.1	55.3	69.6
30	56.9	66.2	57.7	75.2	58.4	84.2

TABLE 7 (FIG. 6 AND §10).

TOTAL FUEL RATE FOR A STATIC THRUST OF 1 LB.= M_f/T_s LB/HOUR; PER CENT OF TOTAL FUEL USED IN COMPRESSION= $58.8\ P_a/M_f$.

$\frac{p_1}{p_0}$	$t_0 = -30°$		$+30°$		$+90°$	
	$\frac{M_f}{T_s}$	$58.8\frac{P_a}{M_f}$	$\frac{M_f}{T_s}$	$58.8\frac{P_a}{M_f}$	$\frac{M_f}{T_s}$	$58.8\frac{P_a}{M_f}$
1.5	3.19	4.2	3.19	4.7	3.19	5.3
2	2.55	7.3	2.56	8.2	2.57	9.1
3	2.16	11.6	2.18	13.1	2.20	14.4
5	1.94	17.3	1.97	19.2	2.00	21.0
7	1.87	21.0	1.91	23.2	1.95	25.3
10	1.83	24.9	1.88	27.4	1.92	29.8
15	1.82	29.4	1.88	32.2	1.93	34.7
20	1.83	32.5	1.89	35.4	1.95	38.0
30	1.86	36.9	1.92	39.9	1.99	42.6

TABLE 8 (FIG. 7 AND §11).

THRUST HORSEPOWER FOR A STATIC THRUST OF 1 LB.= P/T_s.

S_0 M.P.H.=	100	150	200	250	300	350
S M.P.H.						
1000	0.242	0.344	0.433	0.510	0.575	0.627
1500	0.250	0.362	0.467	0.562	0.650	0.729
2000	0.254	0.372	0.483	0.589	0.688	0.780
2500	0.257	0.377	0.493	0.604	0.710	0.811
3000	0.258	0.381	0.500	0.615	0.725	0.831
3500	0.259	0.384	0.505	0.622	0.736	0.846
4000	0.260	0.386	0.508	0.628	0.744	0.857
4500	0.261	0.387	0.511	0.632	0.750	0.865

TABLE 9 (FIG. 8 AND §12).

TOTAL FUEL RATE IN POUNDS PER THRUST HORSEPOWER-HOUR = *F*.

t_0 °F.	S_0 M.P.H.= p^1/p_0	100	150	200	250	300	350
−30	7	7.22	4.89	3.72	3.02	2.56	....
	10	7.05	4.77	3.63	2.94	2.49	....
	15	7.01	4.73	3.59	2.91	2.46	....
	20	7.03	4.74	3.60	2.92	2.46	....
	30	7.11	4.80	3.64	2.95	2.48	....
+30	1.5	12.63	8.72	6.75	5.59	4.82	4.28
	2	10.00	6.85	5.27	4.32	3.69	3.25
	3	8.48	5.76	4.40	3.63	3.06	2.67
	5	7.63	5.17	3.94	3.20	2.72	2.37
	7	7.37	4.99	3.80	3.08	2.61	2.27
	10	7.22	4.88	3.71	3.01	2.54	2.21
	15	7.21	4.87	3.70	3.00	2.53	2.20
	20	7.25	4.89	3.71	3.01	2.54	2.20
	30	7.37	4.97	3.77	3.05	2.57	2.23
+90	7	7.51	5.08	3.87	3.14	2.66	....
	10	7.38	4.99	3.79	3.08	2.60	....
	15	7.41	5.00	3.80	3.08	2.60	....
	20	7.47	5.04	3.82	3.10	2.61	....
	30	7.62	5.14	3.90	3.16	2.66	....

TABLE 10 (§13).

PER CENT DECREASE OF THE TOTAL FUEL RATE OBTAINABLE BY UTILIZING THE IMPACT PRESSURE, $t_0 = +30°$ F.

S_0 M.P.H.= p^1/p_0=	100 1.013	150 1.029	200 1.052	250 1.084	300 1.121	350 1.168
p_1/p_0 5	0.12	0.27	0.48	0.61	1.09	1.49
7	0.12	0.26	0.46	0.58	1.04	1.42
10	0.11	0.24	0.43	0.55	0.98	1.34

TABLE 11 (§18).

RATIO OF BRAKE HORSEPOWER OF COMPRESSOR MOTOR TO BRAKE HORSEPOWER OF MOTOR DRIVING AN AIR SCREW OF 70 PER CENT EFFICIENCY, FOR THE SAME THRUST POWER, = 0.7 P_c.

t_0	$\frac{p^1}{p_0}$	S_0=100	150	200	250	300	350
−30°	7	2.12	1.44	1.09	0.89	0.75	....
	10	2.46	1.70	1.27	1.03	0.87	....
	15	2.88	1.95	1.48	1.20	1.04	....
+30°	5	2.05	1.39	1.06	0.86	0.73	0.64
	7	2.39	1.62	1.23	1.00	0.85	0.74
	10	2.77	1.87	1.42	1.15	0.97	0.85
	15	3.25	2.20	1.67	1.35	1.14	0.99
	20	3.59	2.42	1.84	1.49	1.26	1.04
+90°	7	2.66	1.80	1.37	1.11	0.94	....
	10	3.08	2.08	1.58	1.28	1.08	....
	15	3.75	2.53	1.92	1.56	1.32	....