REPORT No. 62

EFFECT OF ALTITUDE ON RADIATOR PERFORMANCE

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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By W. S. JAMES AND S. R. PARSONS

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EFFECT OF ALTITUDE ON RADIATOR PERFORMANCE.[1]

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RÉSUMÉ

As an airplane rises to high altitudes the decrease in the density and the temperature of the air have important effects on the performance of the radiator.

The effect of the lower temperature tends to increase the heat transfer in proportion to the increase of the mean temperature difference between the water in the radiator and the air through which the radiator passes.

The decrease in density of the air reduces the mass of air passing through the radiator for a given plane speed, and thus tends to decrease the heat transfer by an amount corresponding (but not proportional) to the decrease in density.

Since head resistance is proportional to density of the air, the effect of decrease in density is to reduce the head resistance by an amount proportional to the decrease of density.

The combined effect of density and temperature changes is to decrease the heat transfer, but head resistance is decreased more rapidly, and for the higher plane speeds the figure of merit is, in general, increased. On the other hand, at the higher altitudes only half (or even less) of the cooling capacity may be required.

If the performance of the radiator at the ground is known (from laboratory tests or otherwise), the density of the air and the temperature difference between air and water at an altitude may be estimated from data contained in the curves of plots 1, 2, and 3 and from the conditions under which the airplane is to be used; and with this information at hand the performance of a radiator at an altitude may be estimated for a particular speed of the airplane at a particular altitude, as follows:

1. To obtain the energy dissipated, first find the mass flow of air through the radiator at the ground and at the desired speed and multiply this value by the ratio of the air density at the altitude to the density at the ground to obtain the mass flow of air at the altitude.
2. Now, from the results of tests at the ground obtain the energy dissipated per 100° F. temperature difference between air and water for the mass flow computed for the altitude, and multiply this value by the estimated temperature difference at the altitude divided by 100 to obtain the energy actually dissipated at the altitude.
3. For head resistance multiply the value at the ground and at the desired speed by the ratio of the density at the altitude to the density at the ground.
4. Horsepower absorbed is computed as at the ground by adding to the head resistance the quotient obtained by dividing the weight per square foot of the radiator filled with water by the lift-drift ratio of the plane and multiplying this sum by the plane speed and the proper conversion factor.
5. Figure of merit, as at the ground, is the ratio of the energy dissipated to the horsepower absorbed.

Plots Nos. 4 to 7 show the effect of altitude on energy dissipated and figure of merit for two typical radiators, and plot No. 8, which shows the ratio of air density at an altitude to density at the ground, indicates the proportional decrease of head resistance with increase of altitude for any type of radiator.

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[1] This report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 29.

INTRODUCTION.

The efficiency of a radiator for airplane engines depends primarily upon two factors: (1) Its capacity for dissipating heat and (2) its absorption of engine power because of the necessity of pushing it through the air (overcoming its head resistance) and of lifting and sustaining its weight.

At high altitudes both the density and the temperature of the air are less than at the ground, and the change in these conditions has an important effect upon the performance of the radiator. The decrease in air temperature tends to increase the cooling capacity, while the decrease in density of the air tends to decrease both the cooling capacity and the absorption of power for any given speed of the airplane. On the other hand, the power of the engine, and consequently the heat to be dissipated, falls off with altitude, so that at high altitudes a given engine may be kept cool by a smaller radiator than that required for the same conditions of speed and climb near the ground.

PURPOSE.

The purpose of this report is, by showing the effect of temperature and density of the air on dissipation of heat and absorption of power, and with the use of available data on atmospheric conditions at altitudes, to present a method for estimating the performance of a radiator under altitude conditions in terms of its performance at the ground. A brief discussion will also be given of the relative cooling capacity required at altitudes and at the ground.

Since atmospheric conditions are continually changing, it will be evident that any estimate of performance at an altitude must be based upon assumed *conditions*, such, for example, as mean summer density and temperature of air, in addition to assumed *requirements* of operation, such as the maximum allowable water temperature. Certain meteorological data have accordingly been included, in order to give such basis as is available for the assumptions that must be made.

DEFINITIONS OF UNITS.

The results of tests at the ground are expressed as follows:

Free air speed (the speed of the airplane), in miles per hour.

Mass flow of air through the radiator, in pounds per second per square foot frontal area.

Energy dissipated (heat transfer), in horsepower per square foot of frontal area per 100° F. difference between the temperature of the entering air and the average of the temperatures of the entering and leaving water, at ground. (At an altitude this temperature difference may be modified.)

Head resistance, in pounds per square foot frontal area.

Horsepower absorbed, in horsepower per square foot frontal area, including both that used in overcoming head resistance and that used in sustaining and lifting the weight of the radiator and contained water, assuming for the airplane a lift-drift ratio of 5.4.

Figure of merit is defined as the ratio of the energy dissipated to the horsepower absorbed.

BASIS OF THE METHOD.

The method of estimating radiator performance under altitude conditions is based upon the following laws:

1. Mass flow of air, for a given speed of the airplane, is proportional to the air density.
2. Energy dissipated (rate of heat transfer), for a given mass flow of air, is independent of air density. This fact is shown by a series of tests conducted on a number of specimens in a wind tunnel which was entirely inclosed in a steel tank so that the air could be partially exhausted. The range of air densities used corresponds to altitudes up to about 25,000 feet. Plot No. 10 shows the results of these tests.[1]
3. Energy dissipated for a given mass flow of air may be regarded as proportional to the temperature difference indicated under "Definitions of terms." Several investigators have

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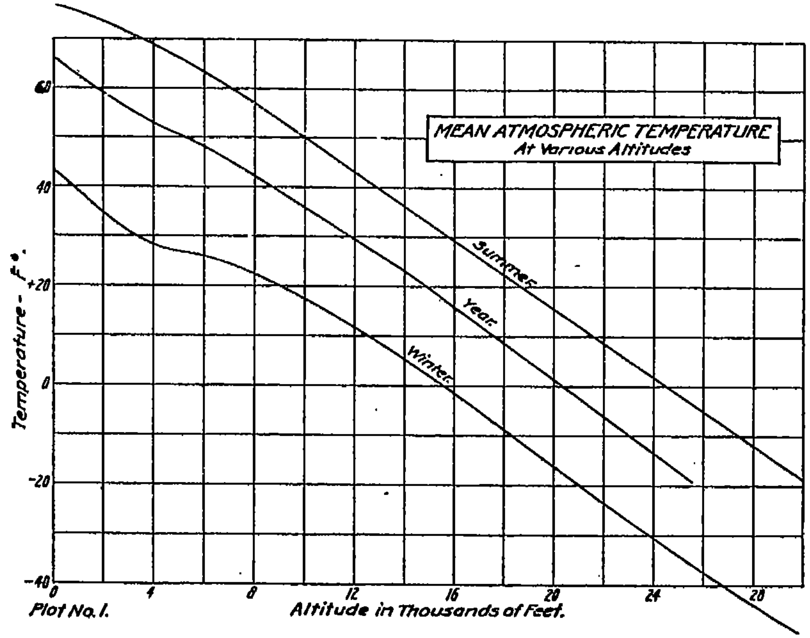
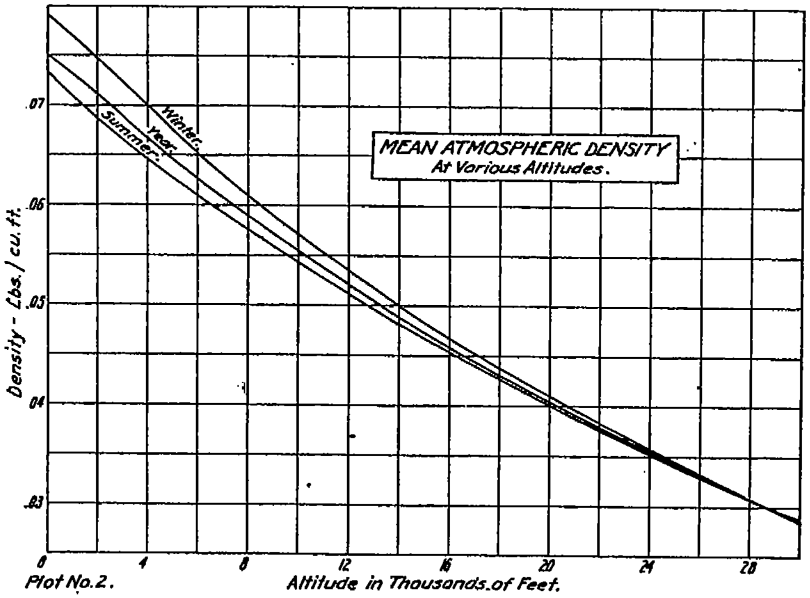
[1] The same result has previously been observed for a single copper tube with air densities equal to and greater than atmospheric. See Zeit. des Ver. deutscher Ing. 53; 43; p. 1750, Oct. 23, 1909.



Plot No. 1.



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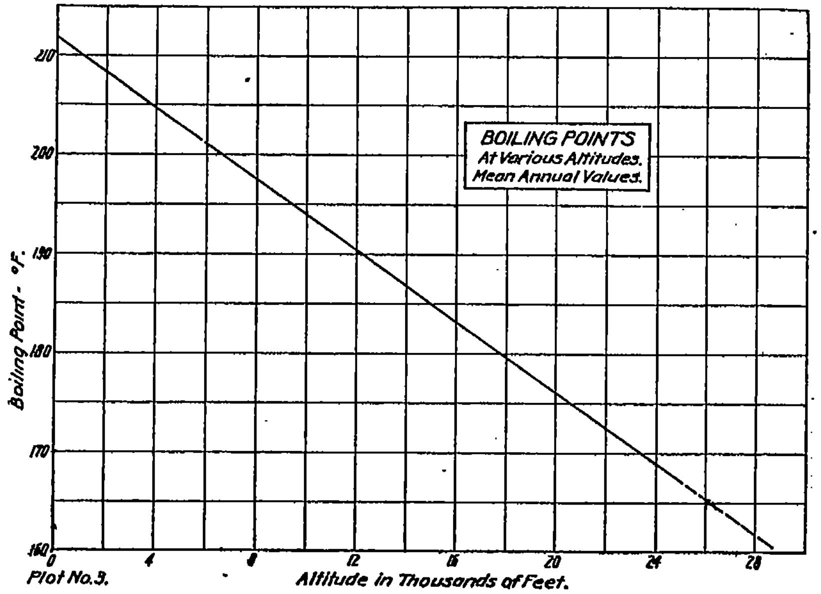

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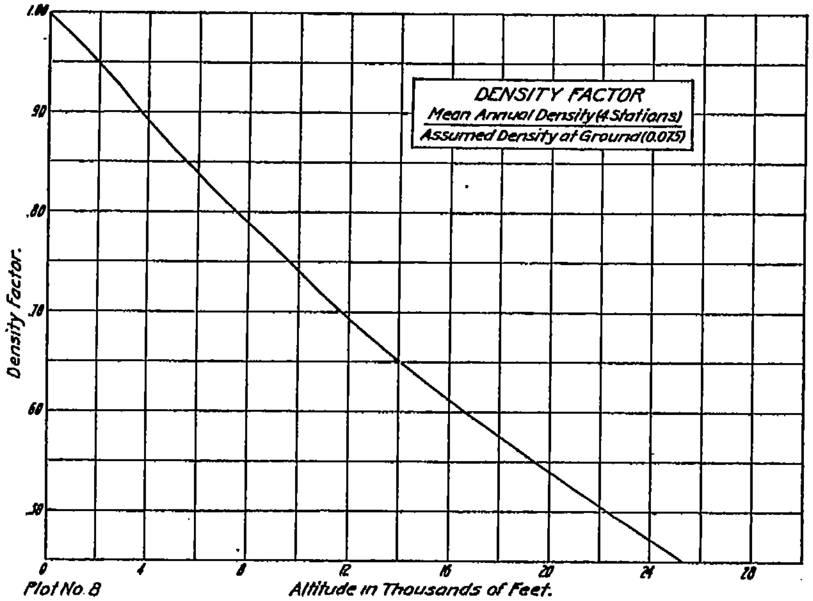
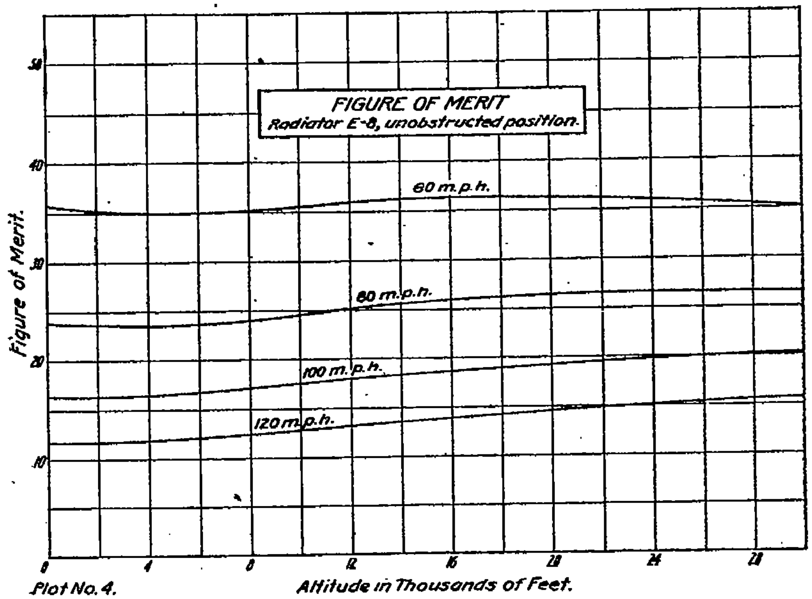


Plot No. 8



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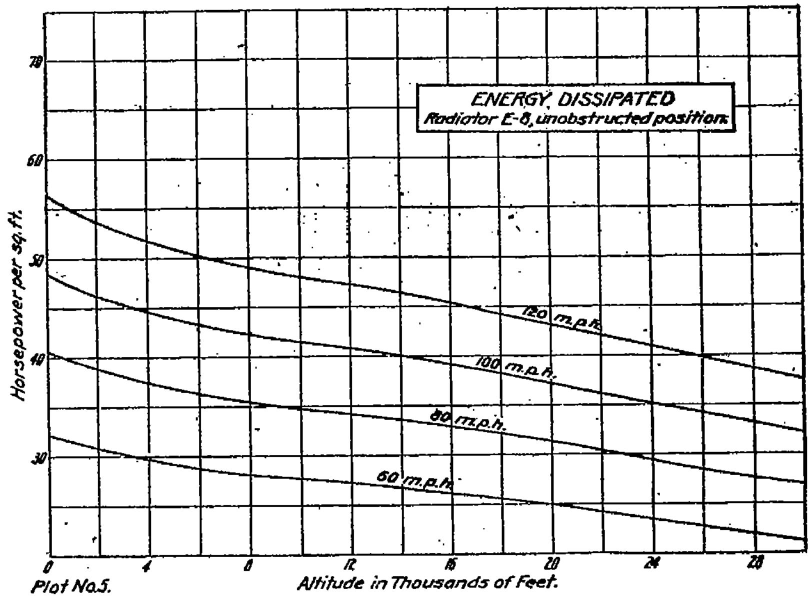

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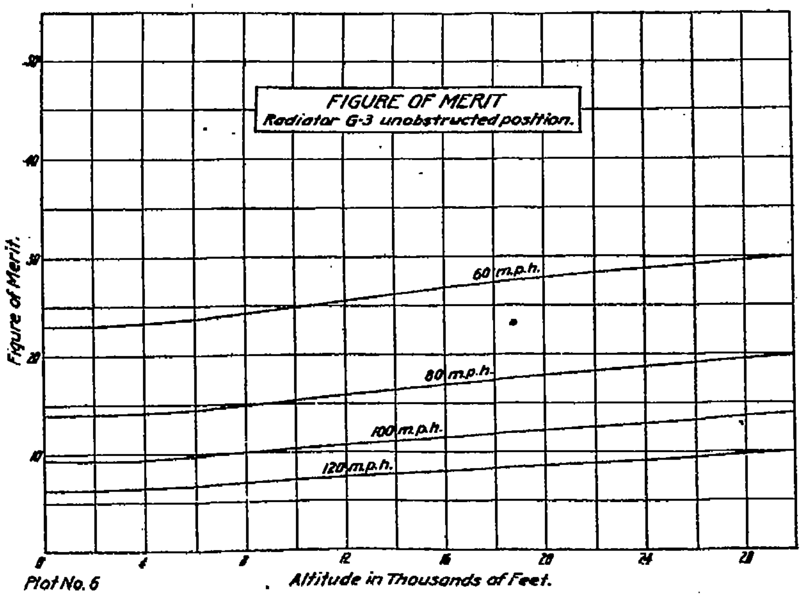
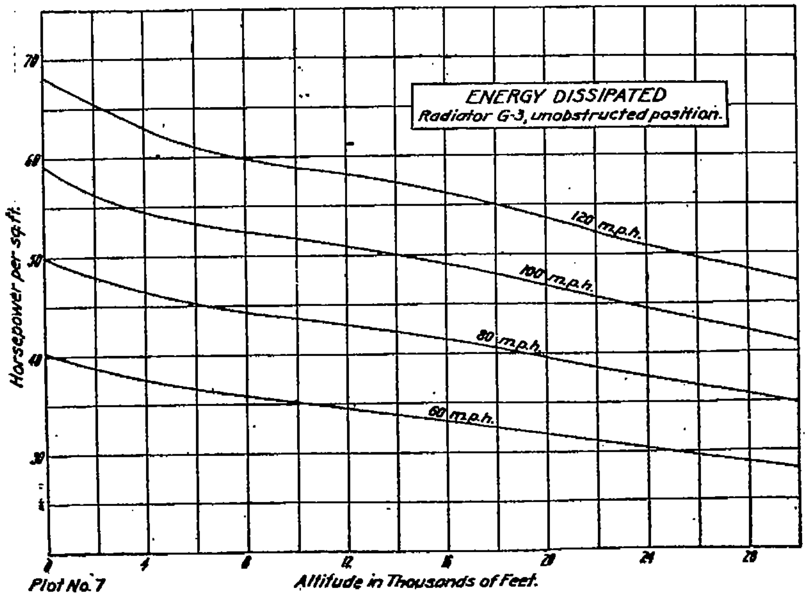


Plot No. 6



Plot No. 7

proposed empirical equations for the rate of heat transfer, in which the temperature difference occurred to a power slightly different from unity (in some cases as high as 1.2), but if the greatest value found were to be used, the difference between the result so obtained and that obtained using unity for the exponent, would be well within the range of uncertainty in atmospheric conditions at high altitudes. For the present purpose, therefore, the linear proportionality will be used.

4. Head resistance, for a given free air speed, is proportional to the density of the air. This fact is in general use by aerodynamic engineers, and while it has been verified by a part of the experimental work on which this report is based, it hardly requires to be proved here.

In order to give some idea of the atmospheric conditions that may be expected at altitudes, plots Nos. 1, 2, and 3 are included. These plots are based on data given by W. R. Gregg in the Monthly Weather Review, January, 1918. Plots 1 and 2 indicate mean summer, winter, and annual values of temperature and air density based upon observations at four stations situated in Indiana, Nebraska, South Dakota, and California. Plot No. 3 shows the boiling point of water corresponding to mean annual pressure at the same stations, only one line being plotted because the difference between annual and summer or winter means (1.5° at 25,000 feet, and less at lower altitudes) is so small that it may safely be neglected, in view of the uncertainties in all altitude conditions.

In order to make use of the data on atmospheric conditions, and in particular of the proportionalities mentioned above, it will be convenient to introduce the terms "density factor" and "temperature factor," and to define them as follows:

$$\text{Density factor} = \frac{\text{air density at altitude}}{\text{air density at ground}}$$

and

$$\text{Temperature factor} = \frac{\text{temperature difference existing at altitude}}{\text{temperature difference assumed at ground}}.$$

It will be noted that density and temperature difference "at ground" denote the assumed density and temperature difference to which the results of tests at ground have been reduced, and that the "factors" are not constants, but vary with altitude and with atmospheric conditions.

Then the actual values of density and temperature factors to be used in any particular computation will depend upon more or less arbitrary assumptions in regard to atmospheric conditions, and these assumptions will depend upon the conditions under which it is desired to study the performance of the radiator—whether for summer or winter flying, whether for mean or extreme conditions, etc. The temperature factor will also depend upon the limit set for maximum allowable water temperature.

It is now possible to express the properties of a radiator at an altitude in terms of its properties at the ground, and the density and temperature factors, as follows:

1. For a given free air speed, mass flow of air, being proportional to air density, is equal to the product of the mass flow at the ground by the density factor.
2. Energy dissipated *per 100° F.* temperature difference an altitude is the same as that dissipated per 100° F. at the ground *for the same mass flow of air.*
3. Energy actually dissipated at an altitude, being proportional to the temperature difference, is equal to the product of the energy dissipated per 100° F. by the temperature factor.
4. For a given free air speed, head resistance, being proportional to air density, is equal to the product of the head resistance at the ground by the density factor.

METHOD OF COMPUTATION.

The method of computing the performance at an altitude may be summarized as follows:

1. Choose an altitude and a free air speed.
2. Assume such conditions as will determine the values of the density and temperature factors.

3. To obtain energy dissipated, first find the mass flow of air at the ground and at the desired free air speed (from the results of ground tests), and multiply this value by the density factor to obtain the mass flow of air at the altitude.

4. Now, from the curve of energy dissipated against mass flow of air, given with the results of tests at the ground, obtain the energy dissipated per 100° F. for the mass flow computed for the altitude and multiply it by the temperature factor to obtain the energy actually dissipated at the altitude.

5. For head resistance, multiply the value at the ground and at the desired free air speed by the density factor to obtain the head resistance at the altitude.

6. Horsepower absorbed is computed as at the ground by adding to the head resistance the quotient obtained by dividing the weight per square foot frontal area of the radiator filled with water by the lift-drift ratio of the airplane, and multiplying this sum by the free air speed and the proper conversion factor.

7. Figure of merit, as at the ground, is the ratio of the energy dissipated to the horsepower absorbed.

EXAMPLE.

To estimate the performance of a radiator of the type E–8, described in Report No. 63, Part I, using results of ground tests as given in that report:

1. Assume, for illustration, an altitude of 10,000 feet and a speed of 120 miles per hour in level flight. Report No. 63, Part I, gives a curve showing energy dissipated per 100° F. temperature difference, in terms of mass flow of air, and the following quantities for ground conditions:

mass flow of air at 120 miles/hr. = 10.97 lb./sq. ft./sec.
head resistance at 120 miles/hr. = 12.5 lb./sq. ft.
weight of core and contained water = 14.15 lb./sq. ft.

2. Assume mean summer conditions of the atmosphere, and the requirement that the mean temperature of the water in the radiator shall be 30° F. below the boiling point. (These assumptions are, of course, arbitrary, and will vary with the conditions under which the plane is to be used.) Then the density factor at 10,000 feet will be the value of the "summer" curve of plot No. 2, divided by 0.0750, which is the assumed density at ground, or

$$\frac{0.0545}{0.0750}=0.727.$$

The temperature factor will be

$$\frac{(\text{boiling point}-30^\circ)-(\text{summer mean})}{100}=\frac{194.2-30-50}{100}=1.142.$$

3. Mass flow of air at 10,000 feet = (mass flow at ground) (density factor) = (10.97) (0.727) = 7.98 lb./sq. ft./sec.

4. From the curve of energy dissipated against mass flow in Report No. 63, Part I, energy dissipated at 7.98 lb./sq. ft./sec. = 42.2 H. P. per sq. ft./100° F., but with the greater temperature difference, energy dissipated at the altitude = (42.2) (temperature factor) = (42.2) (1.142) = 48.2 H. P./sq. ft.

5. Head resistance at 10,000 feet = (head resistance at ground) (density factor) = (12.5) (0.727) = 9.09 lb./sq. ft.

6. Horsepower absorbed, if a lift-drift ratio of 5.4 is assumed, =

$$\left[(\text{head resistance})+\frac{(\text{weight filled})}{(\text{lift-drift ratio})}\right]\frac{(\text{free air speed})}{(375)}=\left[9.09+\frac{(14.15)}{(5.4)}\right]\frac{(120)}{(375)}=3.75 \text{ H. P./sq. ft.}$$

7. Figure of merit $=\frac{\text{energy dissipated}}{\text{horsepower absorbed}}=\frac{48.2}{3.75}=12.8.$

DESCRIPTION OF CURVES.

Plots Nos. 4 to 7 represent the properties of two types of radiator core at altitudes; plots Nos. 4 and 6, showing figure of merit, and plots Nos. 5 and 7, energy dissipated, in terms of altitude. The conditions and requirements assumed are mean summer density and temperature of air and a mean water temperature 30° F. below the boiling point. The computations are based upon data given in plots Nos. 1, 2, and 3.

Radiator E–8 is made of flat hollow plates set edgewise to the air stream, and its performance is typical of radiators adapted to use inunobstructed positions—that is, in such positions on the plane that the flow of air toward or away from the radiator is not obstructed by other parts of the plane.

Radiator G–3 is a type of high heat transfer and high head resistance, adapted to use only in obstructed positions. Its properties are computed, however, only for the condition of being placed in an unobstructed position, since the problem of determining head resistance in an obstructed position is too complex to be introduced into this report. (See Reports No. 59, General Analysis of the Radiator Problem, and 61, Part II, Resistance Due to Nose Radiator.)

The curves indicate that while heat transfer falls off with altitude, the figure of merit may increase slightly at the higher speeds. The general form of the curves is the same for both the type of core suitable for unobstructed positions and the type suitable for obstructed positions.

Plot No. 8, based on mean summer density, shows a typical relation of "density factor" to altitude; and since head resistance is proportional to density, this plot also shows the relation of head resistance at a given free air speed to altitude. No curve of "temperature factor" is shown, because so many different assumptions may be made in regard to atmospheric conditions and operating requirements that a single curve could hardly be called typical. "Temperature factor" can easily be computed for various assumptions from data given in the plots of temperature and boiling point against altitude.

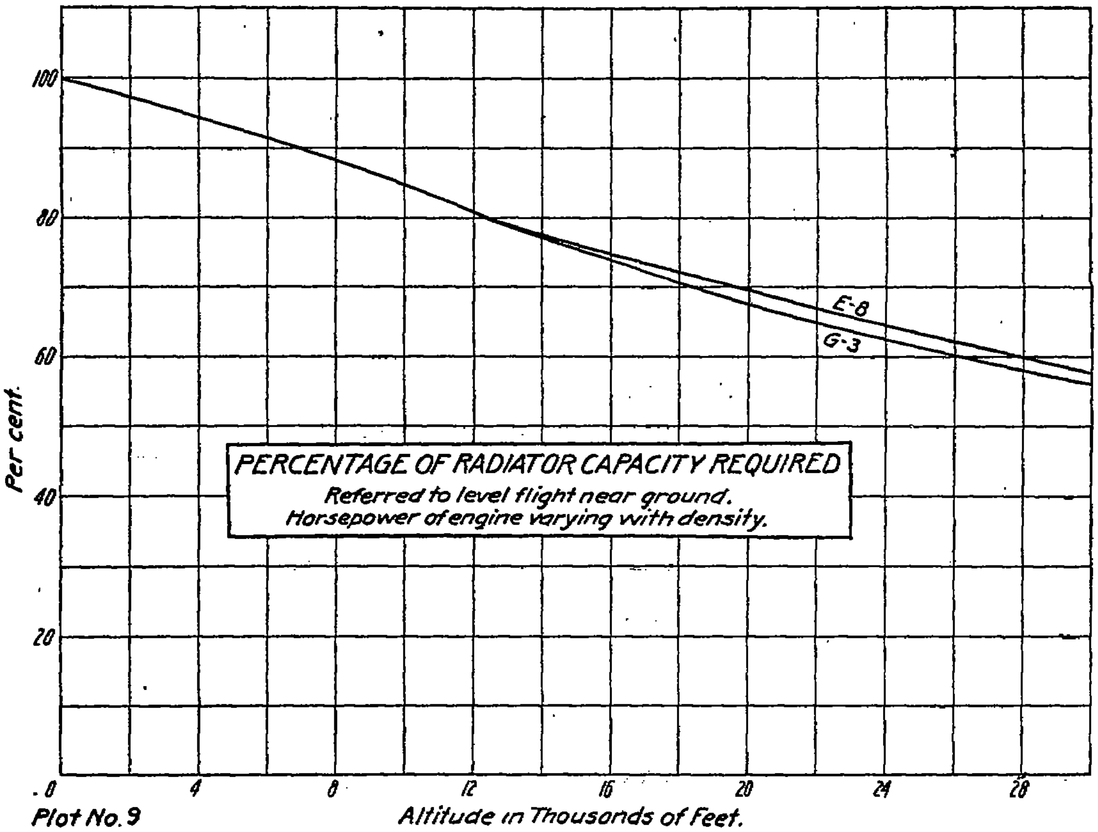
DEGREE OF MASKING REQUIRED AT ALTITUDES.

I. HORIZONTAL FLIGHT.

If the radiator is to be partly masked at the higher altitudes, plot No. 9 may be used to give an approximate idea of the degree of masking desirable, in terms of the cooling capacity required at the ground for *horizontal flight*.

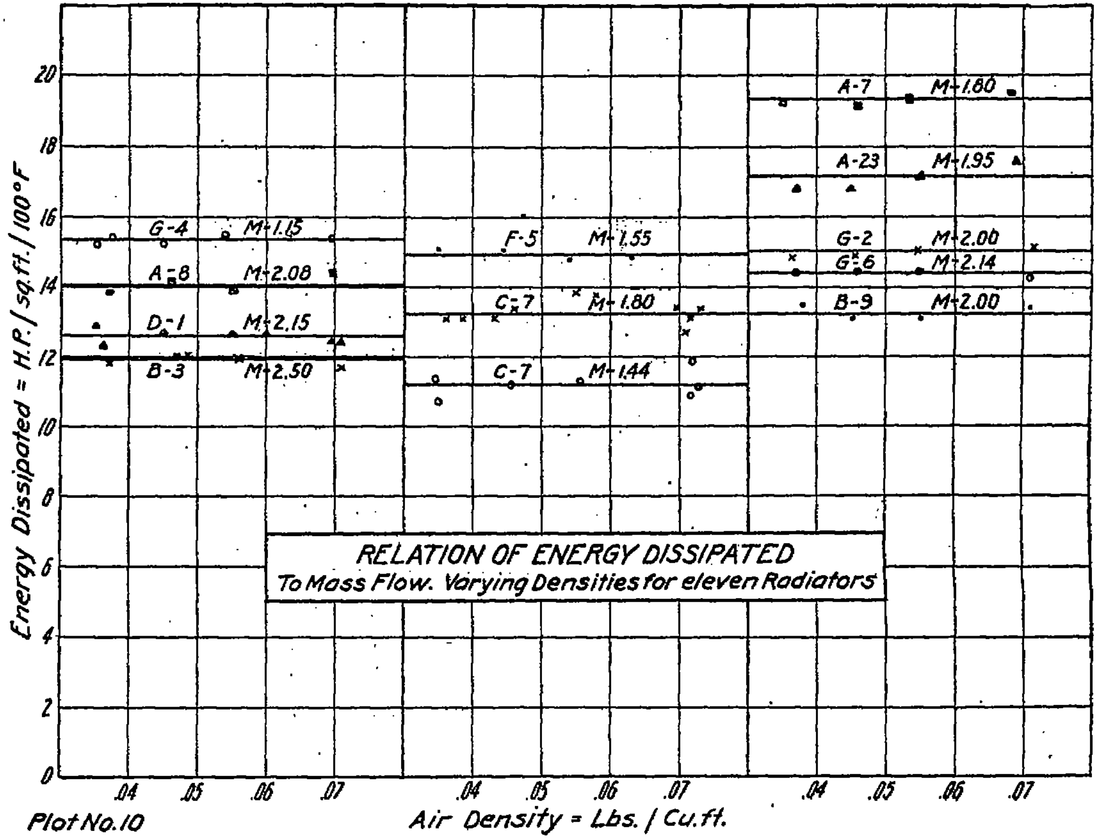
Let a radiator be chosen of such a size that it will just cool the engine when flying at a given speed (say, 120 miles per hour) horizontally, and close to the ground. Now the energy required to be dissipated, divided by the energy that the radiator is capable of dissipating, will represent what may be termed the "effective area" of radiator required at an altitude, in square feet per square foot required at the ground. The adjective "effective" is used because the decrease in heat transfer caused by a partial masking will depend not only upon the area of face covered, but upon the form of shutter used. The real indication of heat transfer will be given by the mass flow of air, rather than by area.

The power of the engine, and consequently the heat to be dissipated, may be assumed roughly proportional to the air density (see Report No. 45, Part I), and an approximate value may be found by multiplying the energy dissipated at ground by the density factor. Plot No. 9 shows the ratio of this required dissipation to the capacity for dissipation, as taken from plots Nos. 5 and 7, and represents approximately the ratio of the "effective area" desirable at an altitude to that required at the ground, if the radiator is to keep the engine at a constant temperature. These curves are plotted for a speed of 120 miles per hour, but are practically identical with the curves for other speeds. This fact, and the small difference between the two curves plotted, seems to indicate that the desirable degree of masking is a function of the altitude, and practically independent of the type of core or of the speed.



PERCENTAGE OF RADIATOR CAPACITY REQUIRED
Referred to level flight near ground.
Horsepower of engine varying with density.

Plot No. 9



RELATION OF ENERGY DISSIPATED
To Mass Flow. Varying Densities for eleven Radiators

Plot No. 10

II. CHANGE FROM CLIMBING TO HORIZONTAL FLIGHT.

When the plane changes from maximum climb to horizontal flight, its speed will be greatly increased (for some types of planes, about doubled), and this increase in speed will involve a proportional increase in mass flow of air, and a corresponding (though not proportional) increase in heat transfer. This consideration alone would require a degree of masking that would in some cases approach 50 per cent of the effectiveness of the radiator at the altitude, but it has not been included in the computations for plot No. 9 because of a wide range of its variation with different planes and their different uses. If the relation is known between the maximum climbing speed and the horizontal speed when using the same engine power, then the mass flow of air and the corresponding heat transfer can be determined from the results of tests at the ground, and the degree of masking that is desirable can be found from the two rates of heat transfer.

It may be well to note that no account has been taken of additional cooling from the surface of the engine itself or from connecting pipes, caused by the lowering of the air temperature; and again let it be emphasized that mass flow of air gives the real measure of what has been termed "effective area."

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