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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ATT No. 9041

WARTIME REPORT

ORIGINALLY ISSUED

January 1943 as
Advance Restricted Report

ALTITUDE RATING OF ELECTRIC APPARATUS

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General Electric Company

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

ALTITUDE RATING OF ELECTRIC APPARATUS

By Paul Lebenbaum, Jr.

I. INTRODUCTION

The proper functioning of electric equipment is of prime importance in the operation of the military and naval airplane of today. The wide use of such equipment and the continual increase in the operating altitude of aircraft make it essential that the factors affecting the operation of electric apparatus at high altitudes be investigated if the apparatus is to be properly designed for this new and expanding application.

This paper studies the effect of altitude on the ratings of rotating electric machines and, after determining the fundamental principles involved, discusses these in relation to the application of such machines in modern aircraft. It is shown that the rating of a self-ventilated, direct engine-driven aircraft generator decreases rapidly with altitude and, at some altitude within the operating range of the airplane, the generator may be able to dissipate only its no-load losses. It is also shown that an air-scoop-ventilated, direct engine-driven aircraft generator maintains its rating over most of the operating range of present-day aircraft. Finally, certain sea-level tests are proposed from which calculations of rating under altitude conditions can be made.

The theory and tests presented in this paper have been checked by altitude-chamber studies on an aircraft-type, direct-current generator.

II. FUNDAMENTAL ANALYSIS

A. Heat Transfer in Electric Machines

One of the principal factors determining the rating of electric apparatus is the maximum temperature to which its insulation can be subjected without failure during the required life of the machine. This operating temperature is a function

of the losses of the machine and its ability to dissipate the resultant heat.

An electric machine may dissipate its losses by four means:

1. Forced convection between winding and core surfaces and cooling air
2. Free convection between frame and ambient air
3. Radiation between frame and surrounding objects
4. Conduction between frame and mounting

The watts loss which may be dissipated by these processes is a function of the temperature difference between the machine surfaces and the ambient temperature. The machine temperature rises until the total watts loss dissipated just equals the input losses; that is, until equilibrium is reached. Thus any increase in load (and hence, loss) will increase the machine temperature unless the additional heat can be removed from the machine by an increased heat transfer. Conversely, any reduction in heat transfer will increase the machine temperature unless the loss is reduced.

The heat transfer between the machine and the ambient air also is effected by the air density. Thus at the reduced densities and temperatures encountered at altitude (fig. 1), the watts loss which can be dissipated by an electric machine may change and its rating at altitudes may be different from that at sea level.

Each of the heat-transfer processes is not considered individually, and its variation with density and temperature determined.

1. Forced Convection

The transfer of heat by the forced circulation of a gas or liquid is referred to as heat transmission by forced convection. In an electric machine, the cooling air enters the machine at an ambient temperature θ_{a1} , and in wiping the windings and core removes heat from these parts. The resultant increase in air temperature ("air rise") is denoted by θ_{ar} .

This process is shown graphically in figure 2, where θ_{s1} is the surface temperature of the windings or core of the machine and θ_d is the temperature drop between the hot surface and the cooling medium ("surface drop").

The maximum allowable winding surface temperature is determined by the insulation used in the machine. Thus, if θ_{s1}' , θ_d' , and θ_{ar}' denote values of surface temperature, surface drop, and air rise, respectively, at the point at which the ventilating air leaves the machine,

$$\theta_{s1}' = \theta_{s1} + \theta_{ar}' + \theta_d' \quad ^\circ\text{C} \quad (1)$$

θ_{ar}' is a function of the weight flow of air through the machine and the watts loss taken away by this air. Thus,

$$\theta_{ar}' = \frac{0.133 \, q_{for}}{W} \quad (2)$$

where

q_{for} watts loss dissipated by forced convection

W weight flow of cooling air through machine,
pounds per minute

$$W = \rho Q$$

ρ density of cooling air at entrance to machine,
pounds per cubic foot

Q volume flow of cooling air at entrance to machine,
cubic feet per minute

The surface drop at the exit of the machine is:

$$\theta_d' = \frac{q_{for}}{O} \quad ^\circ\text{C} \quad (3)$$

where

O over-all thermal conductance between machine surface
and cooling air, watts per $^\circ\text{C}$

The thermal conductance C is a function of the density of the cooling air ρ , its velocity v past the surface being cooled, and the area of that surface A_1 . It has been shown (reference 1) that for the turbulent flow of air in ducts

$$C \propto A (\rho v)^{\alpha} \quad (4)$$

In an electric machine the velocity v is composed of two components: the axial velocity of the cooling air through the ducts of the machine v_a , and the peripheral velocity of the rotor v_p . Tests on direct-current aircraft-type generators indicate that for ratios of axial to peripheral velocity approximately less than 2, the axial velocity can be neglected; whereas, for ratios greater than 2, the peripheral velocity can be neglected. In the practical case of self-ventilated and separately ventilated aircraft generators, the former type usually has a ratio of axial to peripheral velocity well below 2, and the latter type has a ratio well above 2. Hence the transition range need not be studied closely in the present investigation.

The axial velocity v_a is:

$$v_a = \frac{144 Q}{A_d} \text{ feet per minute} \quad (5)$$

where

A_d total area of ducts through which the cooling air flows, square inches

Thus from equations (4) and (5), and the above assumptions,

$$C_{\text{self}} \propto A_1 v_p^{\alpha} \rho^{\alpha} = \frac{1}{k_1} \rho^{\alpha} \quad (6)$$

$$C_{\text{sep}} \propto A_1 \left(\rho \frac{144 Q}{A_d} \right)^{\alpha} \propto A_1 \left(\frac{144}{A_d} \right)^{\alpha} v_a^{\alpha} = \frac{1}{k_2} v_a^{\alpha} \quad (7)$$

where k_1 and k_2 are constants for any given machine operating at constant speed, and C_{self} and C_{sep} are the over-all

thermal conductances for self-ventilated and separately ventilated machines, respectively.

In smooth ducts, $\alpha = 0.8$; in rough ducts, α may vary from 0.5 to 1.0, depending on the degree of roughness. On one aircraft-type, direct-current generator, the use of an exponent of 0.5 checked test data.

Substituting equations (2), (3), (6), and (7) into equation (1) gives:

Self-ventilated:

$$q_{for} = \frac{\theta_{a1}' - \theta_{a1}}{\frac{0.133}{W} + \frac{k_1}{\rho \alpha}} \text{ watts} \quad (8)$$

Separately ventilated:

$$q_{for} = \frac{\theta_{a1}' - \theta_{a1}}{\frac{0.133}{W} + \frac{k_2}{W}} \text{ watts} \quad (9)$$

Hence, if θ_{a1}' , θ_{a1} , ρ , and W are known at a given altitude, the watts loss which can be removed by forced convection at that altitude can be found if k_1 , k_2 , and α are known. These constants can be determined from sea-level tests on the machine.

2. Free Convection

The transfer of heat by the natural circulation of a gas, caused by a nonuniform temperature (and hence density) variation within the gas, is referred to as heat transmission by free convection.

The heat transferred from a horizontal cylinder in air is:

$$q_{free} = 1.53 \times 10^{-4} A_s P \frac{0.5(\theta_{as} - \theta_{ac})^{5/4}}{L} \text{ watts} \quad (10)$$

6

where

q_{free} watts loss by free convection

A_s area of surface subject to free convection, square inches

p atmospheric pressure, inches of mercury

θ_{ss} convecting surface temperature, °C

θ_{aa} ambient air temperature for free convection, °C

$L = \frac{L_h L_v}{L_h + L_v}$, feet

L_h horizontal length of cylinder, feet

L_v vertical height of cylinder, feet

The watts dissipated by free convection at any altitude can therefore be calculated from equation (10), since all factors are known. The surface temperature can be determined from sea-level tests. Tests taken under actual altitude conditions have indicated that the frame temperature remains essentially constant at various altitudes for the same maximum internal surface temperature, unless there are large changes in the heat dissipated from the frame of the machine.

It should be noted that the watts dissipated by free convection vary as the 0.5 power of the atmospheric pressure.

3. Radiation

Radiation is the method of heat transmission by which heat energy is transferred from one body to another through a transparent medium without any change in the temperature of the medium. When the area of the radiating body is small compared to that of its surroundings, the watts dissipated by radiation are:

$$q_R = 0.00375 \epsilon A_s \left[\left(\frac{\theta_{ss}}{100} \right)^4 - \left(\frac{\theta_{aa}}{100} \right)^4 \right] \quad (11)$$

where

- q_r watts dissipated by radiation
- ϵ emissivity of the surface of the radiating body (0.9 for a body covered with a nonmetallic paint)
- A_s area of radiating surface, square inches
- θ_{s3} radiating-surface temperature, $^{\circ}\text{C}$ absolute
- θ_{a3} ambient-air temperature or temperature of surrounding bodies (if close enough) for radiation, $^{\circ}\text{C}$ absolute

The above equation shows that the watts dissipated by radiation are independent of air density or pressure and, hence, of altitude for constant θ_{s3} and θ_{a3} . The same statements concerning these temperatures apply to this case as to the case of free convection.

4. Conduction

The heat transferred between two bodies by the conduction process is directly proportional to the conductivity of the transmitting medium; its area, and the temperature difference between the two bodies, and inversely proportional to the length of path. In an electric machine, heat is conducted through its mounting - the direction of the transfer depending on the relative temperature of the two bodies. This heat transfer is difficult to calculate since the length of path and the temperature difference are not accurately known. However, it is not affected by air density or temperature, provided the temperature of machine and mounting remain constant. Measurements of these temperatures must be made to determine the direction of heat flow, and the results obtained used to temper the calculations of total heat transferred by the other three processes. If heat is removed from the machine, it can be neglected and used as a "safety factor"; if it is added, an estimate of the quantity added may be necessary.

5. Summary of Heat-Transfer Equations

$$q_{tot} = q_{for} + q_{free} + q_r \text{ watts} \quad (12)$$

Self-ventilated:

$$q_{for} = \frac{\theta_{s1} - \theta_{a1}}{\frac{0.133}{W} + \frac{k_1}{\rho^2}} \text{ watts} \quad (8)$$

Separately ventilated:

$$q_{for} = \frac{\theta_{s1} - \theta_{a1}}{\frac{0.133}{W} + \frac{k_2}{W^2}} \text{ watts} \quad (9)$$

$$q_{free} = 1.33 \times 10^{-4} A_n v^{0.5} \frac{(\theta_{sa} - \theta_{an})^{5/4}}{L^{1/4}} \text{ watts} \quad (10)$$

$$q_R = 0.00375 c_{A_2} \left[\left(\frac{\theta_{s3}}{100} \right)^4 - \left(\frac{\theta_{a3}}{100} \right)^4 \right] \text{ watts} \quad (11)$$

B. Air Flow in Electric Machines

All the terms in the heat-transfer equations above have been discussed, except the weight flow of the air used to cool the machine W . This quantity varies with altitude in a manner which depends on the type of ventilation employed. In the case of aircraft equipment, two types of machine are used: the enclosed self-ventilated machine, where the cooling air is circulated by a fan integral with the machine; and the enclosed separately ventilated machine, where the cooling air is picked up by an air scoop on the airplane and forced through the machine by the ramming pressure obtained from the airplane's motion. Single-end, axially ventilated machines are discussed here, as this is the type in most common use on the equipment considered in this paper.

Neglecting the friction pressure drop of the air in flowing through the passages of a machine (a good assumption for small machines), the equation governing the air flow through a machine is:

$$H = \frac{\rho}{5.2} \left[\beta_m \frac{V_m^2}{2g} + \beta_n \frac{V_n^2}{2g} + \dots \right] \text{ inches of water}^* \quad (13)$$

*This equation assumes that the air density is constant throughout the machine. Because of the air temperature rise, this is not strictly true. However, the simplicity obtained by assuming a constant density warrants its use. For more accurate calculations, an average air density may be used rather than the value at the machine entrance.

where

H pressure head available for forcing cooling air through machine, measured at entrance to machine, inches of water

$\rho_m \frac{v_m^2}{2g}, \rho_n \frac{v_n^2}{2g}, \dots$ loss in pressure at contractions, expansions, bends, etc., of the airflow path, measured in velocity heads of air.

Since

$$v_m, v_n, \dots = \frac{144Q}{A_m}, \frac{144Q}{A_n}, \dots$$

$$H = \frac{Q^2 \rho}{55} \left[\frac{\rho_m}{A_m^3} + \frac{\rho_n}{A_n^3} + \dots \right] \quad (14)$$

where

$A_m, A_n, \dots$ areas at changes in path section, square inches

The bracketed expression is a constant for any machine and may be called an "air resistance," R. Hence,

$$Q = \sqrt{\frac{58H}{\rho R}} \quad \text{cubic foot per minute} \quad (15)$$

The weight flow of cooling air, therefore, is:

$$W = \rho Q$$

$$W = \sqrt{\frac{58H \rho}{R}} \quad \text{pounds per minute} \quad (16)$$

This equation defines the weight of cooling air flowing through the machine for a given pressure head H. This pressure head will vary with altitude, depending on whether the machine is self-ventilated or separately ventilated by the methods discussed above.

The pressure head developed by a fan revolving at constant speed varies directly with the air density. Therefore, in a

self-ventilated machine, the weight flow of air is directly proportional to the air density, from equation (16).

For a separately ventilated machine employing an air scoop, the head H will depend on the airplane's speed-altitude characteristic. For a constant angle of attack the lift on an airplane wing is proportional to ρV^2 , where ρ is the air density, and V is the velocity of the airplane relative to the air. Since a certain minimum lift is necessary to support the airplane, the minimum ρV^2 must remain constant, regardless of altitude. However, the pressure head in inches of water developed in the air scoop is directly proportional to ρV^2 (neglecting losses); hence the minimum air-scoop pressure head is independent of altitude for a separately ventilated generator. From equation (16), it can be seen that the minimum weight flow of air is thus proportional to the square root of the air density and therefore decreases with altitude but not as rapidly as in the self-ventilated machine, where the decrease was directly proportional to the air density.

III. APPLICATION OF FUNDAMENTAL ANALYSIS TO THE DETERMINATION OF THE ALTITUDE RATINGS OF ROTATING ELECTRIC MACHINES IN AIRCRAFT

The fundamental equations for heat transfer in rotating machines will now be used to determine the rating of electric machines under varying altitude conditions. The specific cases of self-ventilated and separately ventilated, direct engine-driven, direct-current generators will be chosen for this discussion, each generator being considered separately. These generators are overhung from the back end of the aircraft engine. The self-ventilated generator secures its cooling air from the space back of the engine, known as the engine-accessory compartment; and the separately ventilated machine, from the atmosphere external to the airplane.

The general approach to the problem of altitude ratings is:

1. The determination of the ambient and air-flow conditions for each type of generator

2. The calculation of the total watts loss which can be removed by the heat-transfer processes already discussed (heat transfer by conduction will be neglected) at the altitude at which the rating is desired.
3. The determination of the current, and hence the rating of the machine, corresponding to the total watts loss found in (2) from a curve of watts loss of the machine as a function of its line current.

A. Enclosed Self-Ventilated Generator

1. Ambient Temperatures

The ambient temperature of the cooling air θ_{a1} of a self-ventilated generator is that of the engine-accessory compartment. Tests have shown that this temperature is independent of altitude. Present information indicates that a minimum compartment temperature of 35°C , and a maximum of 65°C may be expected. This ambient temperature is also the temperature to be used in calculating the heat transfer by free convection, θ_{a2} .

The generator frame will radiate to or acquire heat from surrounding objects, depending on the relative temperature of the bodies involved. This transfer will remain substantially independent of altitude.

2. Air Flow

Previous equations have shown that the weight flow of air W through a self-ventilated generator is directly proportional to the air density, and therefore decreases with altitude.

An inspection of equations (8), (10), and (11) now shows that the watts loss which may be dissipated by a self-ventilated generator, for a constant maximum allowable surface temperature, decreases with increase in altitude. All quantities in those equations are constant except the air flow W , the air pressure p , and the air density ρ , all of which decrease with altitude. The reduction in rating depends on the relative proportions of q_{for} , q_{free} , and q_r acting to cool the generator. Table I shows the percent watts loss dissipated by each of the three heat-transfer processes at an altitude of 36,000

feet as compared with the dissipation at sea level (taken as 100 percent). For example, if the generator could dissipate all of its loss by radiation alone, its rating would be independent of altitude since q_r is independent of air density and pressure. In any actual application all processes will enter, but the watts dissipated by forced convection will be at least 30 percent of the total for the lightweight, high-output generators now used in the modern airplane and will therefore be the limiting feature.

Figure 3 shows the reduction in the watts loss that may be dissipated by forced convection in a self-ventilated generator, as a function of altitude, for constant maximum surface temperature and constant generator speed. Curves are plotted for various values of α in equation (8), and for various ratios of air rise to machine temperature rise at sea level γ . In self-ventilated machines, this latter ratio is usually greater than 0.5.

After the total watts loss which can be dissipated by the three processes of heat transfer at a given altitude has been calculated, the new current rating of the generator at that altitude is found from the curve giving the generator line current as a function of its watts loss. This curve is approximated by a constant, representing the no-load losses of the machine, plus a term which is a function of the square of the line current.

If the watts which can be dissipated at the operating altitude of the airplane are less than the no-load losses, the machine cannot even maintain its voltage at no load. Figure 3 shows that the self-ventilated generator thus has a "ceiling" of operation, at which point the machine can dissipate its no-load losses only and cannot carry any load current without exceeding its maximum allowable temperature. Since the no-load losses of a lightweight, high-output generator may be a quarter to a third of its total losses when carrying rated current, this ceiling may occur within the operating limit of the airplane.

B. Enclosed Separately Ventilated Generator

1. Ambient Temperatures

The ambient temperature of the cooling air θ_{a1} of a separately ventilated generator is that of the air outside of the airplane (neglecting a small temperature rise of the air at the entrance to the air scoop due to its compression). The Air Corps standard atmospheric air temperature decreases with altitude at a rate of -2°C for every 1000-foot increase in altitude (fig. 1). The ambient temperatures for free convection and radiation remain the same as for the self-ventilated generator.

2. Air Flow

The minimum ramming-head cooling-air pressure available at the air scoop of an airplane is independent of altitude. From equation (16), therefore, the weight flow of air in a separately ventilated generator is proportional to the square root of the air density.

Equations (10) and (11) show that the same watts loss is dissipated by free convection and radiation in the case of the separately ventilated generator as for the self-ventilated machine.

Figure 4 shows the variation in the watts loss that may be dissipated by a separately ventilated generator for constant ramming-head cooling-air pressure, constant maximum surface temperature, and constant generator speed. Curves are plotted for various values of α in equation (9) and for various ratios of air rise to machine temperature rise at sea level γ .

After determining the total watts loss which can be dissipated by the three processes of heat transfer, the altitude rating of the generator can be found from the curve of watts loss as a function of line current as was done for the self-ventilated generator.

From figure 4 and equations (10) and (11), it is apparent that a separately ventilated generator which obtains its cooling air from an air scoop on the airplane maintains, and may even increase, its sea-level rating at practically all altitudes within the operating range of present-day aircraft. In the

case of the separately ventilated generator, the reduction in cooling-air ambient temperature offsets the decrease in weight flow of cooling air. Also, due to the constancy of the ramming-head cooling-air pressure of the separately ventilated generator, the weight flow of cooling air decreases only with the square root of the air density. In the self-ventilated generator the weight flow decreases directly with the air density.

IV. CONCLUSIONS

A. Figure 3 shows that the rating of an enclosed, self-ventilated, direct engine-driven, direct-current aircraft generator decreases rapidly with altitude, and may have a "coiling" within the altitude range of the airplane on which it is mounted. This coiling is the point at which the generator will just dissipate its no-load losses without overheating.

B. Figure 4 shows that the rating of an enclosed, separately ventilated, direct engine-driven, direct-current, aircraft generator, obtaining its cooling air from an air scoop mounted on the airplane, remains essentially independent of altitude - the rating increasing slightly over its sea-level value up to 20,000 feet, and then decreasing again.

C. Sea-level tests can be taken, by means of which the rating of a given generator at a given altitude can be determined if ambient conditions at that altitude are known.

D. The analysis presented in this paper can be used to determine the air-flow requirements necessary to obtain a given rating from a given generator at any desired altitude.

E. The results of this analysis can be applied to the determination of the altitude heating and rating of types of electric apparatus other than aircraft generators, if the assumptions made here are critically reviewed and adapted to meet the new conditions.

F. This paper presents some of the fundamentals of the problem of altitude rating of electric machines and has proposed tests for its determination. It is hoped that future test data, obtained both in altitude chambers and under actual operating conditions, will be correlated and used to modify and expand the analysis where necessary.

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APPENDIX

PROPOSED SEA-LEVEL TESTS FOR GENERATORS DESIGNED

FOR AIRCRAFT APPLICATIONS

The tests proposed here are based on the assumption that the point at which the maximum allowable surface temperature θ_{s1} is measured at sea level remains the hottest point in the machine as the load on the machine is varied. Tests on aircraft-type generators have indicated that this assumption is correct. In the proposed tests the generator mounting should be insulated thermally from the test stand on which it is mounted, in order to eliminate the effects of conduction. It is also assumed that the outer surfaces of the generator remains essentially at constant temperature for a constant maximum internal surface temperature. This assumption has been checked by altitude-chamber tests.

A. Preliminary Tests

These preliminary sea-level tests determine the weight flow of cooling air forced through the generator for various running-head pressures at the entrance to the generator cooling system, the watts loss of the machine for various line currents, and the value of the exponent α in equations (8) and (9).

1. Measure the volume flow of air through the generator for various inlet running-head air pressures. Set up the generator as a separately ventilated machine and operate at minimum rated speed. Vary the volume flow from a value at which the ratio of the axial velocity of the cooling air to the peripheral velocity of the rotor is approximately 2, to a value at which this ratio is approximately 4.

2. Plot a curve of weight flow of air as a function of the running-head pressure of cooling air from the results obtained in A-1 above.

3. Calculate, or determine from dynamometer tests the watts loss of the generator as a function of its line current with the generator operating at its minimum rated speed and rated maximum allowable surface temperature. Plot a curve of total watts loss as a function of line current.

4. Take a series of heat runs on the generator at minimum rated speed at various inlet ramming-head air pressures, covering the range of pressures used in A-2. At each pressure vary the generator load current until the temperature of the hottest surface in the machine is equal to the maximum allowable surface temperature. Keep the generator ambient temperature θ_{a2} at the same value as is expected during actual operation.

5. Calculate the watts dissipated by free convection and radiation in each of the runs of A-4 from equations (10) and (11). Subtract these values from the total watts dissipated in each of the runs and plot a curve of watts dissipated by forced convection as a function of inlet ramming-head air pressure.

6. Rewrite equation (9) as:

$$\log k_p + (1-\alpha) \log W = \log \left[\frac{W(\theta_{s1}' - \theta_{a1})}{q_{for}} - 0.133 \right]$$

Plot W as a function of $\left[\frac{W(\theta_{s1}' - \theta_{a1})}{q_{for}} - 0.133 \right]$ on log-

log paper for various values of inlet ramming-head air pressure. Select a value of this pressure and find q_{for} from the curve of A-5 and W from the curve of A-2 for this pressure. Using these values of W and q_{for} , plot one point of the above curve. Repeat, using a different pressure.

7. Obtain the slope of the curve of A-6 and calculate α , knowing that this slope is equal to $(1-\alpha)$.

B. Self-Ventilated Generator

To find the altitude rating of a self-ventilated aircraft generator, proceed as follows:

1. Take a heat run at minimum rated speed at such a line current that the temperature of the hottest surface in the machine is equal to the maximum allowable surface temperature for the generator insulation. Take this heat run in an ambient temperature equal to the expected engine-accessory-compartment temperature at the altitude at which the generator is to be rated.

2. Measure the volume flow of air Q through the machine under the ambient conditions of B-1, and calculate the weight flow of cooling air through the machine.

3. From the watts loss-current curve of A-3, determine the total watts loss of the machine at the load of B-1.

4. Calculate the watts dissipated by free convection and radiation in the heat run of B-1 from equations (10) and (11).

5. Determine the watts dissipated by forced convection in the heat run of B-1 by subtracting the watts dissipated by free convection and radiation from the total watts dissipated.

6. Calculate k_1 in equation (8), using temperatures and the weight flow of air found in B-1 and B-2, the value of α found in A-7, and the value of q_{for} found in B-5.

7. Calculate the total watts dissipated at the altitude at which the generator rating is to be determined from equations (8), (10), and (11). Use values of air density and pressure, and engine-accessory-compartment temperature at the given altitude. The weight flow of air in a self-ventilated generator is directly proportional to the air density. Use values of ρ_{a1} , ρ_{a2} , ρ_{a3} , ρ_{a1} , ρ_{a2} , and ρ_{a3} from the heat run of B-1.

8. Determine the altitude-current rating of the generator by entering the watts loss-current curve of A-3 with the total watts dissipated as calculated in B-7.

C. Separately Ventilated Generator

To find the altitude rating of a separately ventilated generator, proceed as follows:

1. Determine the minimum ramming-head cooling-air pressure in inches of water available at the entrance to the generator cooling cap at the altitude at which the rating of the generator is to be found.

2. Determine the watts loss that can be dissipated by forced convection by the generator with this ramming-head pressure at sea level from the curve of A-5.

3. Calculate the value of k_g from equation (9), using the watts loss found in C-2, the weight flow of air from A-2 (correcting for any difference between the cooling-air temperatures of the runs in A-2 and C-2 in determining the weight flow), the temperatures from the heat runs of A-4, and the value of α from A-7.

4. Calculate the total watts dissipated at the altitude at which the generator rating is to be determined from equations (9), (10), and (11). Use values of air pressure and cooling-air temperature and density from figure 1. The weight flow of cooling air in a separately ventilated generator is proportional to the square root of the cooling-air density. Use values of θ_{s1} , θ_{s2} , θ_{s3} , θ_{ag} , and θ_{a3} from the heat run of A-4, corresponding to the minimum ramming-head cooling-air pressure of C-1.

5. Determine the altitude-current rating of the generator by entering the watts loss-current curve of A-3 with the total watts dissipated as calculated in C-4.

NOTATION

A_1	area of machine surface for forced convection, square inches
A_2	area of machine surface for free convection, square inches
A_3	area of machine surface for radiation, square inches
A_4	total area of machine ducts through which cooling-air flows, square inches
C_{self}	over-all thermal conductance between machine surface and cooling air for self-ventilated machines, watts per $^{\circ}C$
C_{sep}	over-all thermal conductance between machine surface and cooling air for separately ventilated machines, watts per $^{\circ}C$
ρ	density of cooling air at entrance to machine, pounds per cubic foot

- ϵ emissivity of radiating surface
- $\gamma = \frac{\text{air-temperature rise}}{\text{machine-temperature rise}}$
- H pressure head available for forcing cooling air through machine, inches of water
- $L = \frac{L_h L_v}{L_h + L_v}$, feet
- L_h horizontal length of machine for free convection, feet
- L_v vertical height of machine for free convection, feet
- p atmospheric pressure, inches of mercury
- q_{for} watts loss dissipated by forced convection
- q_{free} watts loss dissipated by free convection
- q_R watts loss dissipated by radiation
- Q volume flow of cooling air through machine measured at entrance, cubic foot per minute
- R resistance of machine to flow of cooling air
- θ_{a1} ambient-air temperature for forced convection, °C
- θ_{a2} ambient-air temperature for free convection, °C
- θ_{a3} ambient-air temperature for radiation, °C absolute
- θ_{ar} cooling-air temperature rise (air rise), °C
- θ_d temperature difference between machine surface and cooling air (surface drop), °C
- θ_{s1} machine-surface temperature for forced convection, °C
- θ_{s2} machine-surface temperature for free convection, °C
- θ_{s3} machine-surface temperature for radiation, °C absolute

- v velocity of cooling air past machine surface being cooled, foot per minute
- v_a axial velocity of cooling air through ducts of machine, foot per minute
- v_p peripheral velocity of rotor, foot per minute
- W weight flow of cooling air through machine, pounds per minute

Primed quantities are values measured at the cooling-air exit of the machine.

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1. King, W. J.: The Basic Laws and Data of Heat Transmission. Mechanical Engineering: March 1932, pp. 190-194; April 1932, pp. 275-279 and p. 296; May 1932, pp. 347-353; June 1932, pp. 410-414, and p. 426; July 1932, pp. 492-497; Aug. 1932, pp. 560-565.

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TABLE I

Comparison of the Watts Loss Dissipated from
Self-Ventilated, Direct Engine-Driven Aircraft Generators,
Employing Different Proportions of Heat-Transfer Processes
in Their Cooling

Percent of total watts dissipated at sea level*			Percent of sea-level watts dissipated at 36,000 feet*			
By forced convection $\gamma=0.67, \alpha=0.5$	By free convection	By radiation	By forced convection $\gamma=0.67, \alpha=0.5$	By free convection	By radiation	Total
100	0	0	27	0	0	27
0	100	0	0	47	0	47
0	0	100	0	0	100	100

*Maximum generator winding surface (140°C), generator frame surface, surrounding object, and engine-accessory compartment (38°C) temperatures are constant for all comparisons.

NACA

Fig. 1

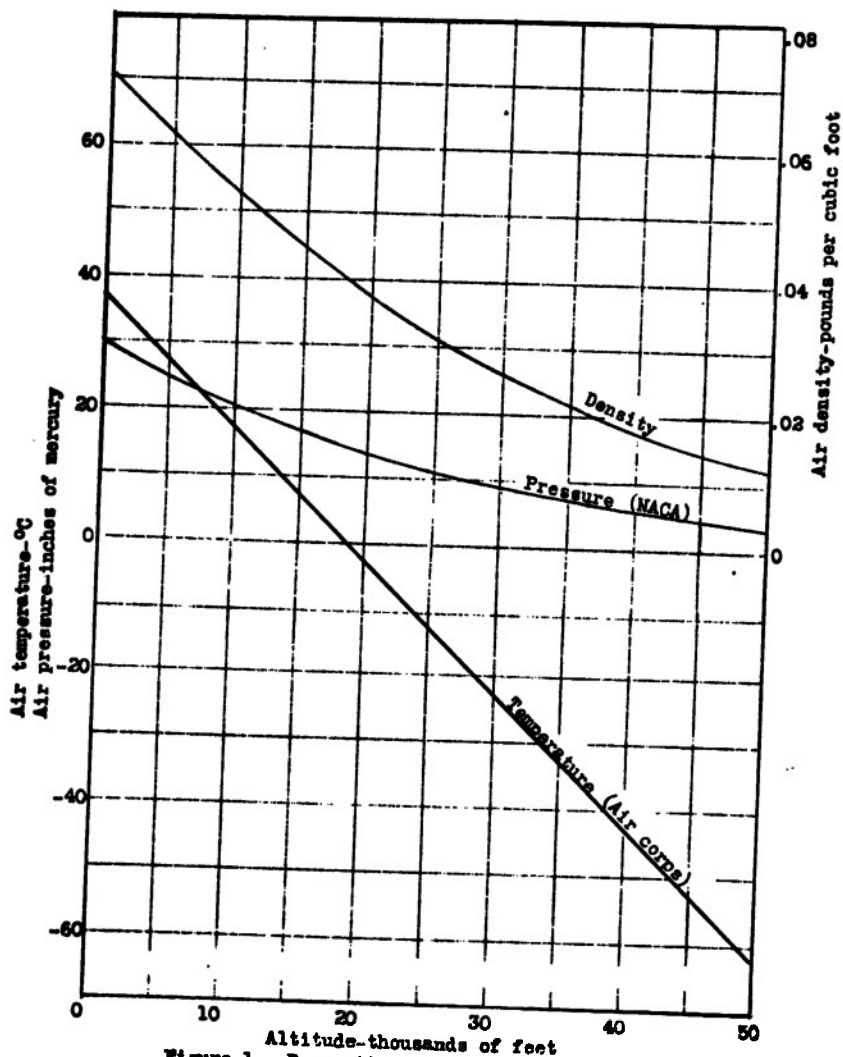


Figure 1.- Properties of atmospheric air.

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Fig. 2

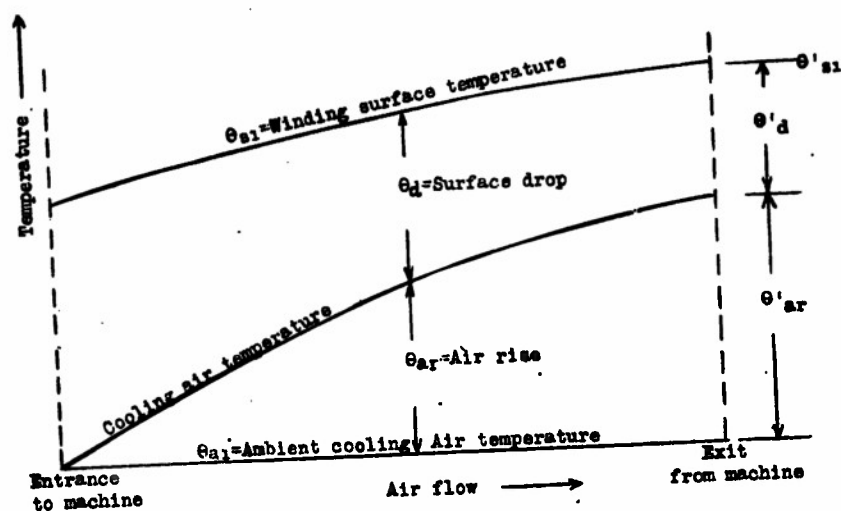


Figure 2.- Temperature-air flow diagram of a single end, axially ventilated electric machine.

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W-40

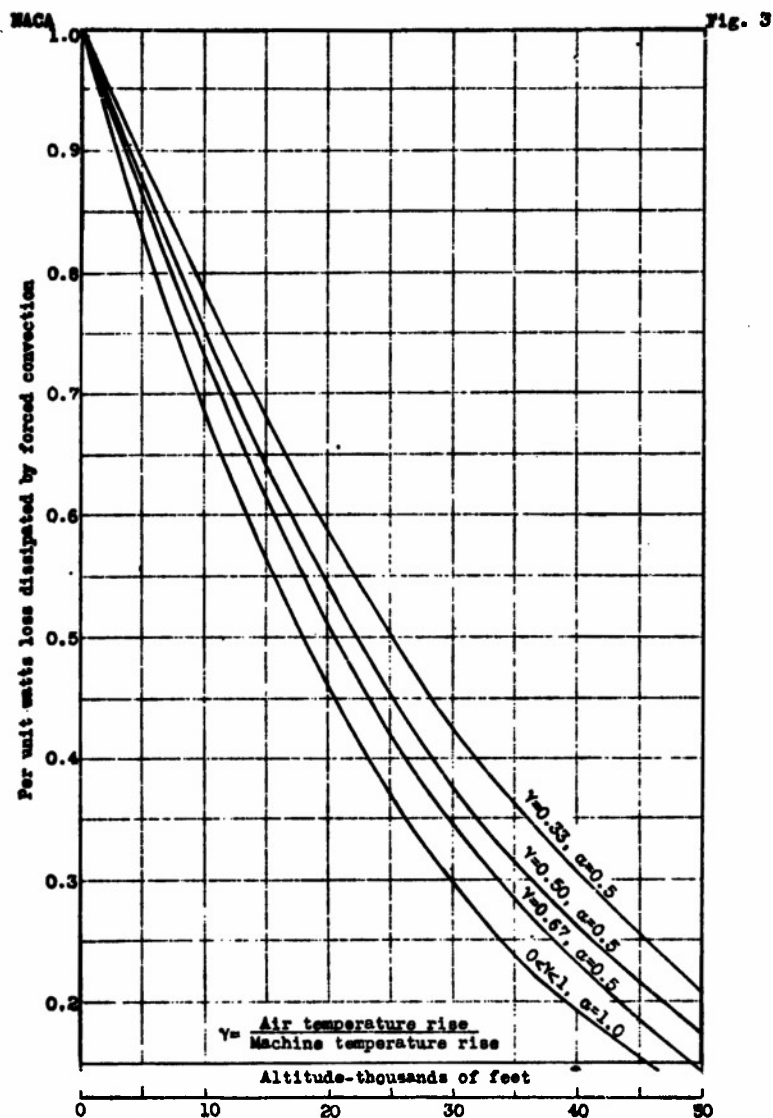


Figure 3.- Effect of altitude on the watts loss dissipated by forced convection from a self-ventilated, direct engine driven, aircraft generator. Constant maximum generator winding surface temperature (140°C.) and constant engine accessory compartment temperature (38°C.)

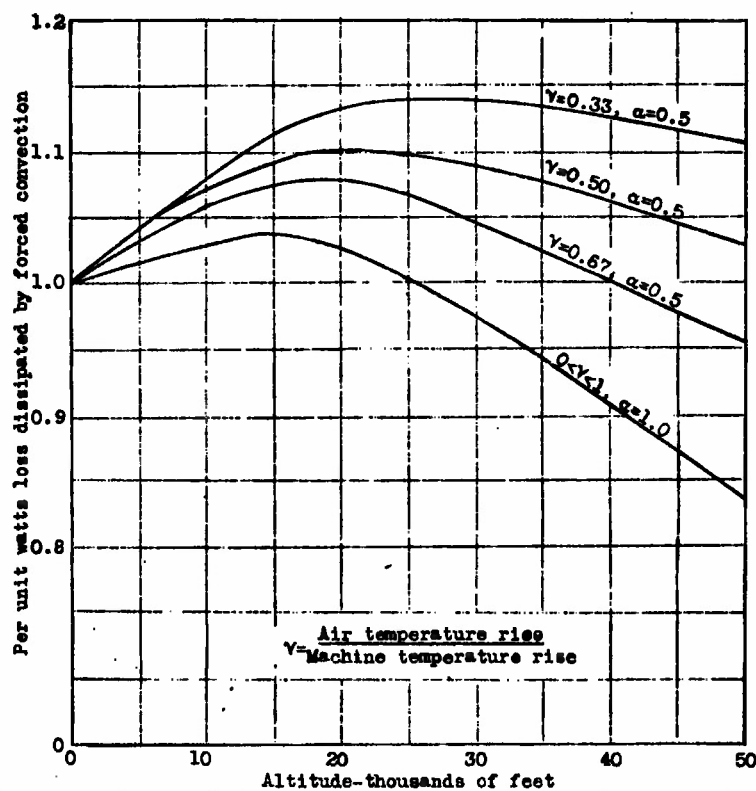


Figure 4.- Effect of altitude on the watts loss dissipated by forced convection from a separately ventilated, direct engine driven, aircraft generator. Constant maximum generator winding surface temperature (140°C.) and constant ramming head cooling air pressure.

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W-40

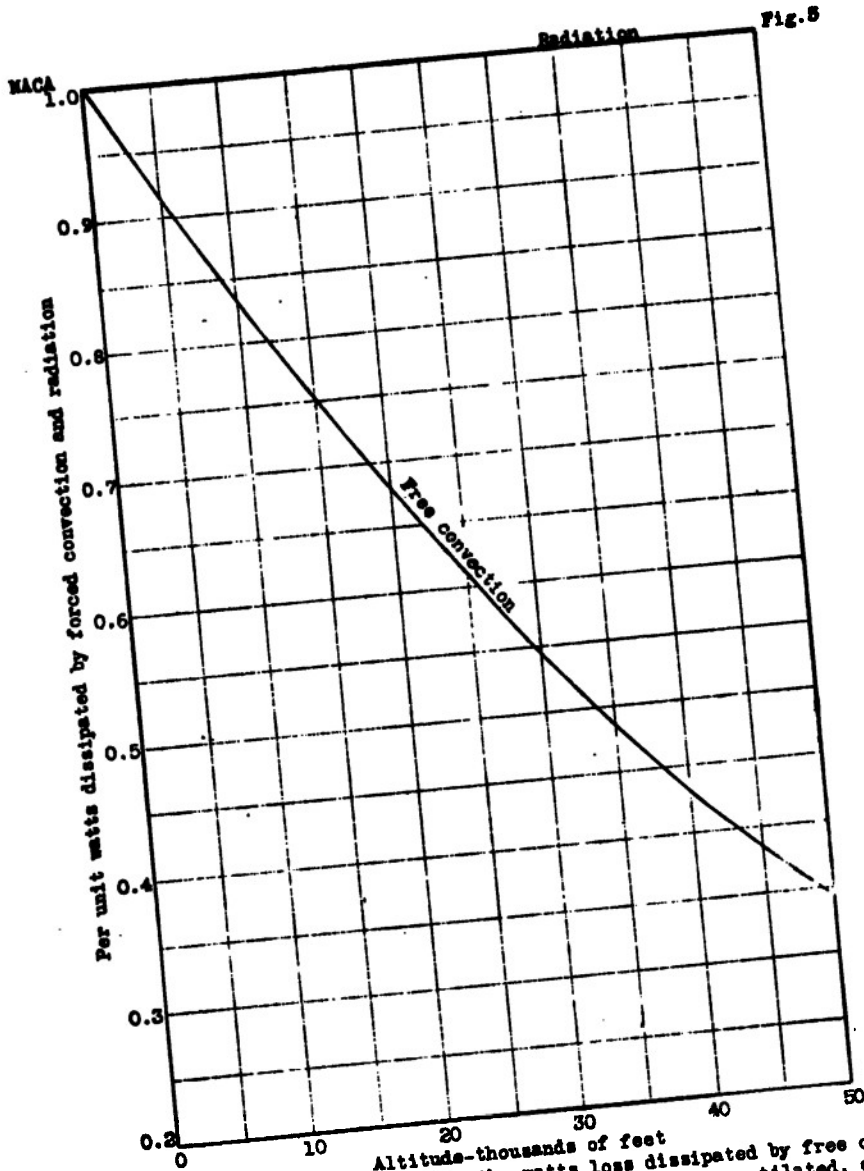


Figure 5.- Effect of altitude on the watts loss dissipated by free convection and radiation from self-and separately ventilated, direct engine driven, aircraft generators. Constant generator frame surface, engine accessory compartment, and surrounding object temperatures.

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TITLE: Altitude Rating of Electric Apparatus

AUTHOR(S) : Lebenbaum, P.

ORIG. AGENCY : National Advisory Committee for Aeronautics, Washington, D. C.

PUBLISHED BY : (Same)

ATI- 9041

REVISION
(None)

ORIG. AGENCY NO.
ARR-W-40

PUBLISHING AGENCY NO.
(Same)

DATE	DOC. CLASS	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
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P 09/01
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