AN INVESTIGATION OF A THERMAL ICE-PREVENTION SYSTEM
FOR A C-46 CARGO AIRPLANE

EFFECT OF THERMAL SYSTEM ON AIRPLANE CRUISE PERFORMANCE

By James Selna

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Moffett Field, California
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SUMMARY

As a part of a comprehensive investigation of a thermal ice-prevention system for a C-46 cargo airplane, flight tests have been conducted to evaluate the effect of the system upon the aerodynamic performance of the airplane. With the airplane operating at a cruise condition, the installation of the thermal ice-prevention system reduced the indicated air-speed by about 6 miles per hour, the equivalent of a loss of about 92 thrust horsepower. This loss in performance is attributed almost exclusively to the parasite drag of the heat-exchanger installations. The loss due to the internal drag of the thermal ice-prevention system and the loss due to the back pressure on the engines resulting from the heat exchangers is shown to be negligible.

INTRODUCTION

Previous researches relating to the prevention of ice formation upon the wings and empennage of aircraft have, in general, been directed toward the development of a practical thermal ice-prevention system which would enable the aircraft to operate safely and for prolonged periods in inclement weather. In view of the urgent need of such equipment, to permit the execution of tactical military operations regardless of weather, emphasis has been placed upon the development of a thermal system satisfactory from
the standpoint of ice prevention, and only superficial, if 
any, attention has been given to the possible detrimental 
effects of the system upon the aerodynamic performance of 
the aircraft.

The purposes of the investigation reported herein, 
which is a part of a comprehensive investigation of a ther-
mal ice-prevention system for a C-46 cargo airplane (refer-
ces 1 to 4), were (1) to determine the effect of the 
thermal ice-prevention system upon the performance of the 
C-46 airplane, (2) to establish, if possible, the factors 
contributing to any change in performance, and (3) to 
evaluate the amounts of such contributions. The investi-
gation was conducted on the C-46 airplane as successful 
flights in natural-icing conditions (reference 4) have 
established the suitability of the thermal ice-prevention 
system installed in that airplane as a practical means of 

case prevention.

The investigation included flight tests, with the air-
plane operating at a cruise condition, to determine experi-
mentally the change in airplane performance resulting from 
the installation of the thermal ice-prevention system. 
Consideration was also given, experimentally and analytically, 
to the determination of the contribution of the following 
factors to the change in airplane performance: (1) the 
increase in exhaust-gas back pressure resulting from the 
heat exchangers, (2) the external drag of the heat-exchanger 
installations, (3) the internal drag of the thermal ice-
prevention system, and (4) the weight of the thermal ice-
prevention system.

This research was conducted at the Ames Aeronautical 
Laboratory as a part of a comprehensive investigation of the 
thermal ice-prevention system of the C-46 airplane which was 
initiated at the request of the Air Technical Service Command 
of the U.S. Army Air Forces.

DESCRIPTION OF EQUIPMENT

Airplane

The C-46 cargo airplane utilized in this investigation 
is a low-wing monoplane of the heavy military cargo type 
(fig. 1). The following specifications of the C-46 airplane, 
pertinent to this investigation, have been taken from ref-
reference 5:
### Airplane

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<thead>
<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>Manufacturer</td>
<td>Curtiss-Wright</td>
</tr>
<tr>
<td>Type</td>
<td>C-46, military-cargo</td>
</tr>
<tr>
<td>Army number</td>
<td>41-12233</td>
</tr>
<tr>
<td>Number of engines</td>
<td>2</td>
</tr>
<tr>
<td>Length</td>
<td>77 ft 1 in.</td>
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<tr>
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<tr>
<td>Over-all height (three-point position)</td>
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<tr>
<td>Gross weight (max. for landing)</td>
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<td>Engine-supercharger gear ratio (low blower)</td>
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<td>to 5700 ft (Ratings based on 100-octane, amendment 5, performance grade No. 125 fuel)</td>
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<td>Diameter</td>
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### Thermal Ice-Prevention Equipment

The thermal ice-prevention equipment, as originally installed in the C-46 airplane and as revised for tests in natural-icing conditions, is completely described in references 3 and 4, respectively. For the investigation reported herein the thermal ice-prevention system was in the revised condition described in reference 4. The original heat-exchanger installation for the C-46 airplane is shown in figure 3. Figure 3 shows the special fairings which were constructed and installed over the heat exchangers for a phase
of this investigation. Figure 4 shows a heat-exchanger installation replaced with a standard production exhaust stack.

**Instrumentation**

Calibrated standard instruments were installed in the airplane to indicate engine manifold pressure, engine speed, pressure, altitude, and indicated airspeed. A shielded mercury-in-glass thermometer, mounted outside the fuselage at station 286, was used to indicate the ambient-air temperature.

**TESTS**

The effect of the thermal ice-prevention system on the performance of the airplane was measured in flight in terms of indicated airspeed while maintaining constant manifold pressure on the engines, and in terms of manifold pressure while maintaining a constant indicated airspeed. All tests were conducted at 10,000 feet density altitude, with the engines operating at 1900 rpm and low blower, and at an airplane gross weight of approximately 38,000 pounds.

The tests were conducted under the following four operating conditions:

1. Heat exchangers in place, heated air discharged overboard, engine manifold pressure maintained constant at 30 inches of mercury

2. Heat exchangers in place, heated air delivered to the surface-heating system engine manifold pressure maintained constant at 30 inches of mercury

3. Heat exchangers removed, standard production exhaust stacks installed, engine manifold pressure maintained constant at 30 inches of mercury

4. Heat exchangers removed, standard production exhaust stacks installed, indicated airspeed maintained constant at values previously established by tests of condition 1

These conditions provide the change in performance caused by the thermal system in terms of airspeed (condi-
tions 1, 2, and 3) and in terms of manifold pressure (conditions 1, 3, and 4). The effect of the heat-exchanger fairings (fig. 3) upon the performance of the airplane was established by flights with the fairings in place and removed, with the airplane operating under conditions 1 and 2.

Data during each test were recorded manually at intervals of approximately 1 minute for a sufficient length of time after equilibrium conditions had been established to assure attainment of representative results.

RESULTS

The results of the flight tests are presented in table I. The values of ambient-air temperature, pressure altitude, and indicated airspeed listed in the table are the averages of the recorded data for each test condition. The variation of individual readings of these variables from the average values presented did not exceed ±10°F, ±50 feet, and ±5 miles per hour, respectively. The values of the ambient-air temperature have not been corrected for the effect of kinetic heating.

The indicated airspeeds obtained during the tests at conditions 1, 2, and 3 are presented in figure 5 as functions of pressure altitude. Since the relationship of indicated airspeed to pressure altitude for conditions 1 and 2 was substantially identical, only one curve has been drawn through the experimental points for those two conditions.

DISCUSSION

Over-All-Performance Change Resulting from the Installation of the Thermal System

The results (table I and fig. 5) indicate that the performance change resulting from the installation of the thermal system amounted to approximately 6 miles per hour indicated airspeed or 1.4 inches of mercury manifold pressure at the test conditions.

Sufficient performance data are available for the C-46 cargo airplane to interpret these performance changes
in terms of brake horsepower. Figure 6 presents curves of indicated airspeed and manifold pressure as functions of brake horsepower which have been plotted from the data of reference 5. Although none of the curves of figure 6 are for the 10,000-foot density altitude test condition, the fact that the curves are parallel allows the assumption to be made that the curve for the test conditions would also have the same slope. Thus, calculations involving the change in brake horsepower for a given change in airspeed or manifold pressure can be made, using the slopes of the curves presented in figure 6.

The following derivation illustrates how the data of figure 6 were employed to evaluate the performance difference caused by the exchanger installations in terms of brake horsepower and, by assuming a propulsive efficiency, in terms of thrust horsepower:

$$\eta \quad \text{propulsive efficiency (assumed to be constant for all test conditions)}$$

$$\text{(thp)}_1 \quad \text{thrust horsepower developed by the airplane in condition 1} \quad [(\text{bhp})_1 \eta]$$

$$\text{(thp)}_3 \quad \text{thrust horsepower developed by the airplane in condition 3} \quad [(\text{bhp})_3 \eta]$$

$$\text{(thp)}_4 \quad \text{thrust horsepower developed by the airplane in condition 4} \quad [(\text{bhp})_4 \eta]$$

$$\text{(thp)}_{b.p.} \quad \text{thrust—horsepower reduction attributed to heat—exchanger exhaust—gas back pressure} \quad [(\text{bhp})_{b.p.} \eta]$$

$$\text{(thp)}_{int} \quad \text{thrust—horsepower reduction attributed to internal drag of the thermal system} \quad [(\text{bhp})_{int} \eta]$$

$$\text{(thp)}_{ext} \quad \text{thrust—horsepower reduction attributed to external drag of the thermal system} \quad [(\text{bhp})_{ext} \eta]$$

Since the manifold pressure, engine speed, and density altitude are the same at conditions 1 and 3, the thrust horsepower developed by the airplane would be the same were it not for the effects of the heat-exchanger exhaust-gas back pressure when operating at condition 1. Thus,

$$\text{(thp)}_1 = \text{(thp)}_3 - \text{(thp)}_{b.p.}$$

or
It is also evident that the difference between the thrust horsepower developed by the airplane in conditions 1 and 4 is equivalent to the combined effects of the internal drag \((\text{thp})_{\text{int}}\) and the external drag \((\text{thp})_{\text{ext}}\). Thus,

\[
(\text{thp})_{\text{int}} + (\text{thp})_{\text{ext}} = (\text{thp})_1 - (\text{thp})_4
\]

or

\[
(\text{thp})_{\text{int}} + (\text{thp})_{\text{ext}} = (\text{thp})_3 - (\text{thp})_4
\]

Equations (1) and (2) may be combined to yield the following relationship:

\[
(\text{thp})_{\text{b.p.}} + (\text{thp})_{\text{int}} + (\text{thp})_{\text{ext}} = (\text{thp})_3 - (\text{thp})_4
\]

or

\[
(\text{thp})_{\text{b.p.}} + (\text{thp})_{\text{int}} + (\text{thp})_{\text{ext}} = (\text{thp})_3 - (\text{thp})_4
\]

Thus the sum of the power losses caused by the exchanger installations is equivalent to the difference in power required to operate at conditions 3 and 4. The brake-horsepower loss \([ (\text{thp})_3 - (\text{thp})_4 ]\) may be evaluated from figure 6 for either the manifold-pressure difference or the airspeed difference between conditions 3 and 4. In the following calculations, the brake-horsepower is determined by both methods.

1. **Horsepower loss computed from airspeed data.** — From table I the average airspeeds for conditions 3 and 4 may be taken as 169 and 163 miles per hour, respectively. The brake horsepower for these airspeeds (curve 1, fig. 6(a)) corresponds to 810 and 750 brake horsepower. Therefore,

\[
(\text{thp})_3 - (\text{thp})_4 = 810 - 750 = 60 \text{ brakehorsepower per engine, or}
\]

120 brake horsepower for the airplane
and, assuming a propulsive efficiency of 0.8

\[(\text{thp})_b.p. + (\text{thp})_{\text{int}} + (\text{thp})_{\text{ext}} = 0.8 \times 120\]

\[= 96 \text{ thrust horsepower total}\]

2. **Horsepower loss computed from manifold-pressure data.**

From table I the manifold pressures at conditions 3 and 4 were 30 and 28.6 inches of mercury, respectively. Therefore, from figure 6(b), curve 3, \((\text{php})_3 = 900\) and \((\text{bhp})_4 = 845\). Therefore,

\[(\text{bhp})_b.p. + (\text{bhp})_{\text{int}} + (\text{bhp})_{\text{ext}}\]

\[= 900 - 845\]

\[= 55 \text{ brake horsepower per engine, or}\]

110 brake horsepower for the airplane

and

\[(\text{thp})_b.p. + (\text{thp})_{\text{int}} + (\text{thp})_{\text{ext}} = (110)(0.8)\]

\[= 88 \text{ thrust horsepower total}\]

The experimental data for methods 1 and 2 were taken independently of each other, and the methods provide reasonable agreement. Therefore, the performance change in terms of thrust horsepower caused by the installation of the thermal system will be taken as 92 thrust horsepower, which is an average of the values obtained by the above two methods.

**Reduction of Power Attributed to Heat-Exchanger Exhaust-Gas Back Pressure**

An estimate of the reduction of power caused by the heat-exchanger exhaust-gas back pressure may be made on the basis of general data available. The effects of back pressure on a Fiat two-row, 18-cylinder, air-cooled, 1000-horsepower engine, type A80-RC-41, when operated at constant manifold pressure and carburetor-air temperature are given in reference 6 in terms of atmospheric pressure as follows:
\[(\text{bhp})_a = (\text{bhp})_s \left(1 + \frac{\Delta P}{K}\right)\]

where

- \((\text{bhp})_a\) = brake horsepower at 59°F carburetor-air temperature
- \((\text{bhp})_s\) = brake horsepower at standard sea-level atmospheric conditions
- \(\Delta P\) = atmospheric-pressure difference between sea level and the atmospheric pressure at which \((\text{bhp})_a\) is desired, millimeters of mercury
- \(K\) = constant dependent on manifold pressure

If it is assumed that the Pratt and Whitney R-2800 engines employed in the C-46 airplane are similar to the Fiat engine with regard to back-pressure effects, the effects of the back pressure caused by the heat-exchanger installations on the C-46 cargo airplane may be calculated. The exhaust-gas pressure drop through the left outboard heat exchanger has been measured to be approximately 0.5 to 0.7 inch of mercury at the test conditions. If the value of 0.7 and the value of \(K\) (3500) taken from reference 6 for 30 inches of mercury manifold pressure is used, the effect of the heat exchangers at the 8000-foot pressure-altitude test conditions is about 5 brake horsepower per engine or 8 thrust horsepower for the airplane.

Reference 7 provides the following general relationship for constant-boost operation of an aircraft engine for small changes in atmospheric pressure and temperature:

\[(\text{bhp}) \propto p^{-0.1} T^{-0.8}\]

where

- \(p\) = atmospheric pressure, absolute
- \(T\) = atmospheric temperature, absolute

The exponential values of -0.1 and -0.8 are the mean values given by reference 7. Thus, for the 8000-foot pressure-altitude test conditions, since brake horsepower varies as \(p^{-0.1}\), the effect of the heat-exchanger back pressure is about 4 brake horsepower per engine or 6.4 thrust horsepower for the airplane.
Either of the values of thrust-horsepower reduction attributed to exhaust-gas back pressure, as derived from the relationships given in reference 6 or 7, is not more than 0.6 percent of the total power developed by the engines, and would cause a decrease in indicated airspeed of about one-half mile per hour (fig. 6).

Reduction of Power Attributed to the Internal Drag of the Thermal System

As indicated in table I and figure 5, there was no measurable difference between the performance of the airplane when the heated air was discharged (condition 1) and when the heated air was delivered into the surface-heating system (condition 2).

If it is assumed, in either case of operation, that the same amount of air enters the heat exchangers and all the kinetic energy of the air is expended, a maximum value of \((\text{thp})_{\text{int}}\) may be calculated. From the data of reference 4, the heated-air flow rate through all the heat exchangers at the 8000-foot pressure-altitude conditions may be approximated as 14,000 pounds of air per hour. The indicated airspeed, given in figure 5, for this condition is 163 miles per hour and the total kinetic energy of the 14,000 pounds of air per hour would amount to about 8½ thrust horsepower. In any actual case, the horsepower loss caused by internal drag would be less.

Reduction of Power Attributed to the External Drag of the Thermal System

It has been established that the exhaust-gas back pressure and the internal-drag effects of the thermal system contribute only slightly to the total performance difference measured. These effects are estimated to total less than 15 thrust horsepower. The remainder, approximately 77 thrust horsepower, is attributed to the external drag of the heat-exchanger installations. It is evident from figure 2 that the external drag would be large, and it is evident from the test results (table I) that the fairings (fig. 3) had no measurable beneficial effect.
Considerable external drag, however, is not necessarily inherent to heat-exchanger installations. If the heat exchangers were located within the nacelles and the air-inlet scoops located in the stagnation region of the cowling, the external drag could be reduced considerably. The installation on the C-46 airplane was installed for the purpose of investigating the surface-heating system, and the available time was not sufficient to permit complicated nacelle alterations to be made for submerging the exchangers within the nacelles.

Additional Airplane Gross Weight Attributed to the Thermal System

The performance tests were all conducted with the airplane at approximately the same weight and, therefore, the test measurements did not include data on the effects of the additional weight contributed to the airplane by the thermal system.

Based on weight studies made of previous thermal systems similar to that installed in the C-46 cargo airplane, the weight added to the bare airplane (i.e., without any form of ice-prevention equipment) by the installation of the thermal system has been approximated to be 500 pounds. The 1900-rpm cruise charts of reference 5 indicate that at 8000 feet pressure altitude, and a constant manifold pressure of 30.2 inches of mercury, a change in airplane gross weight from 35,000 to 40,000 pounds (an increase in weight equal to 10 times the estimated weight of the thermal system) produces a corresponding change in indicated airspeed of 2 miles per hour. Thus, the installation weight evidently has a negligible effect on the performance of the airplane at the test conditions.

The additional fuel weight which must be carried by the airplane at the test conditions to overcome the effects of the heat-exchanger installations may be calculated as follows:

At the 8000-foot pressure-altitude 163-miles-per-hour test conditions (conditions 1 and 2), the additional power required to overcome the effects of the heat-exchanger installations is \((bhp)_1 - (bhp)_4\). The difference in power required at conditions 3 and 4 \( [(bhp)_3 - (bhp)_4] \) has been evaluated as about 115 brake horsepower, or about 57
brake horsepower per engine. Also, by equation (1),
(bhp)_3 - (bhp)_{b.p.} = (bhp)_1. Thus, neglecting the back-
pressure effects, the horsepower difference [(bhp)_1 - (bhp)_4]
may be taken as 57 brake horsepower per engine. Figure 7
presents airplane fuel consumption as a function of brake
horsepower and has been plotted from data given in reference
5. From Figure 7, for the power range employed in the tests,
it is evident that a brake-horsepower difference of 57 brake
horsepower causes an increased fuel consumption of about
7 gallons per hour or about 45 pounds of fuel per hour. This
value would be slightly less if the effects of (bhp)_{b.p.}
were considered.

CONCLUSIONS

1. The performance change resulting from the installa-
tion of the thermal system in the C-46 cargo airplane amounted
to approximately 6 miles per hour indicated airspeed or 92
thrust horsepower at the 10,000-foot density-altitude test
conditions.

2. The performance change resulting from the installa-
tion of the thermal system in the C-46 airplane is almost
entirely due to the parasite drag of the heat-exchanger in-
stallations.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Hoffett Field, Calif.
REFERENCES


4. Selma, James, Neel, Carr B., Jr., and Zeiller, E. Lewis: An Investigation of a Thermal Ice-Prevention System for a C-46 Cargo Airplane. IV - Results of Flight Tests in Dry-Air and Natural-Icing Conditions. NACA ARR No. 5A03c, 1945.


<table>
<thead>
<tr>
<th>Flight number</th>
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<th>Average ambient- air temperature (°F)</th>
<th>Engine manifold pressure (in.Hg)</th>
<th>Engine speed (rpm)</th>
<th>Average pressure altitude (ft)</th>
<th>Average air density (slugs per cu ft)</th>
<th>Average corrected indicated airspeed (mph)</th>
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Figure 1.—The Curtiss-Wright C-46 cargo airplane for which the NACA designed and installed thermal ice-prevention equipment.
Figure 2.— Two views of typical heat-exchanger installation, without fairing, on the Curtiss-Wright C-46 cargo airplane.
Figure 3.— Typical heat-exchanger installation, with fairing, on the Curtiss-Wright C-46 cargo airplane.

Figure 4.— View showing standard production exhaust stack on the Curtiss-Wright C-46 cargo airplane.
Figure 5.— Variation of indicated airspeed with pressure altitude for the Curtiss-Wright C-46 cargo airplane with and without the heat-exchanger installations in place. Flight conditions: 10,000 feet density altitude; 30 inches of mercury manifold pressure and 1900 rpm.
(a) Brake horsepower as a function of indicated airspeed.

(b) Brake horsepower as a function of manifold pressure.

Figure 6.—1900 rpm performance curves for Curtiss-Wright C-46 cargo airplane.
Figure 7.—Variation of fuel consumption with brake horsepower for 1900 rpm operation of a Curtiss-Wright C-46 cargo airplane.

Data given by reference 5 as including a 5% safety factor.

Data corrected to yield 0% safety factor.