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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2517

AN INVESTIGATION OF AIRCRAFT HEATERS

XXXVII - EXPERIMENTAL DETERMINATION OF THERMAL AND HYDRODYNAMICAL BEHAVIOR OF AIR FLOWING ALONG A FLAT PLATE CONTAINING TURBULENCE PROMOTERS

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University of California

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SUMMARY

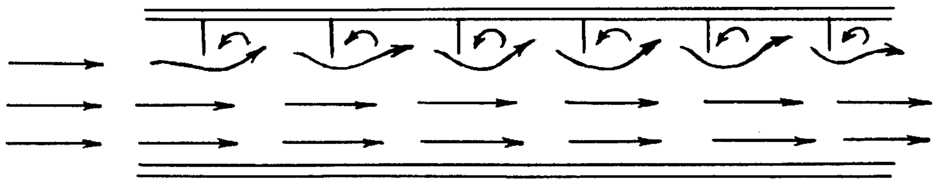
This report contains heat-transfer and pressure-drop data for a system in which air flows over a heated flat plate containing strips of metal placed normal to the direction of air flow. These strips are referred to as "boundary-layer interrupters" or "turbulence promoters."

The heat-transfer rates and static-pressure drops are increased for this system over that for a flat plate alone because of the eddies, turbulence, and fin effect caused by the interrupters. The increase of the heat-transfer rates is large when compared at equal weight rates of air. However, when compared at equal values of power consumed in pumping the air along the test section, the values of the unit thermal conductance are the same for flow over a flat plate alone, over a flat plate with either 1/8- or 3/8-inch interrupter strips, or with wooden "pin fins."

INTRODUCTION

This report contains additional data which may be used to extend the knowledge of basic heat-transfer systems. In references 1 and 2 heat-transfer and pressure-drop data are presented for air flowing over flat plates containing "pin fins" and for air flowing through a passage containing a wave-shaped surface.

Data are presented herein for the system in which air is passed over a heated flat plate on which are mounted strips of metal placed normal to the direction of air flow (fig. 1). These strips are referred to as "boundary-layer interrupters" or "turbulence promoters." The principal function of these interrupters is to cause eddies and turbulence in the fluid as it flows over an otherwise smooth plate, as shown in the following sketch.



The flat plate containing the interrupters was one side of a rectangular duct unit. The other side was movable in order to vary the duct width. Two heights of interrupters were used (1/8 and 3/8 in.), mounted at 1-inch intervals.

Local values of the unit thermal conductance as a function of the distance along the interrupter plate are evaluated and compared with the values obtained in the absence of the interrupters. A similar comparison is made for the measured static-pressure drops and pumping power required.

It is believed that the data presented in this report and in references 1 to 4 may be used to evaluate the role of eddies and turbulence in increasing heat-transfer rates and static-pressure drops. A designer of heater units for aircraft use may therefore estimate more accurately the thermal and hydrodynamical behavior of a given system.

This work was conducted at the University of California under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

A	heat-transfer area of plate, square feet
$f_{c_{ave}}$	average unit thermal conductance, Btu/(hr)(sq ft)(°F)
f_{c_x}	local unit thermal conductance, Btu/(hr)(sq ft)(°F)
G	weight rate per unit average cross-sectional area (area evaluated in absence of interrupter strips),(lb)/(hr)(sq ft)

Δh_{vap}	heat of vaporization for water at atmospheric pressure (14.7 lb/sq in. abs.) and 212° F, Btu/(lb)
Δp	static-pressure drop across plate, (in. of water)
q	heat-transfer rate, Btu/(hr)
R_{av}	average time rate of steam condensation per section under load conditions, (lb)/(hr)
R'_{av}	average time rate of steam condensation under no-load conditions, (lb)/(hr)
t_p	surface temperature of test plate, °F
W	weight rate of air, (lb)/(hr)
x	distance along test section of heated plate from leading edge, inches
y_o	duct width, inches
τ_o	temperature of air at entrance of test section, °F
τ_x	computed local mixed-mean air temperature, °F

DESCRIPTION OF APPARATUS

The test equipment is very nearly the same steam-condensing calorimetric apparatus as that used in the pin-fin tests described in reference 1.

Ten steam-condensate collectors were fastened to the back of the heated plate in order to obtain local heat-transfer rates. To the face of the plate were affixed 17 interrupter strips, at 1-inch intervals, extending across the entire height of the plate. Tests were made using 1/8-inch interrupters and 3/8-inch interrupters (fig. 1).

Static-pressure taps were located approximately 12 inches upstream and 12 inches downstream from the heated plate.

The panel of the duct opposite the heated plate was made movable in order to vary the duct width. The heated plate was 12 by $16\frac{3}{4}$ inches.

METHOD OF ANALYSIS

Heat Transfer

The local unit thermal conductance f_{c_x} was determined as a function of the distance from the leading edge of the heated test plate x, the duct width y_o, and G the weight rate per unit area of air flowing through the duct.

The heat transferred from the condensing steam in the steam chest to the air flowing through the passage was calculated from

$$q = \Delta h_{vap}\left(R_{av} - R'_{av}\right) \tag{1}$$

where Δh_{vap} is the heat of vaporization for water at atmospheric pressure and 212° F, R_{av} is the average rate of condensation per section under "load" conditions, and R'_{av} is the average rate of condensation per section under "no-load" conditions. The terms "load" and "no load" apply to the test conditions in which air was passed and not passed, respectively, over the test plate while condensation data were obtained.

The temperatures of the air at the entrance and the exit of the test section were measured. The latter, together with the temperatures at intermediate points along the test section, was also calculated from the measurements of condensation rates, air weight rate, and air temperature at the entrance.

The local unit thermal conductance is then calculated from

$$q = f_{c_x} A\left(t_p - \tau_x\right) \tag{2}$$

or

$$f_{c_x} = \frac{q}{A\left(t_p - \tau_x\right)} \tag{3}$$

where A is the heat-transfer area corresponding to the measured heat-transfer rate q, t_p is the temperature of the metal surface (assumed to be at 212° F), and τ_x is the computed local mixed-mean air temperature.

Static-Pressure Drop

The measured nonisothermal static-pressure drops were corrected to apply to a $16\frac{3}{4}$-inch finned plate.

RESULTS AND DISCUSSION

Heat Transfer

The values of the local unit thermal conductance f_{c_x} are presented in figures 2 and 3 as a function of the distance along the heated plate x, the weight rate per unit cross-sectional area G, the duct width y_o, and also the height of the interrupters. The variation of the local unit thermal conductance with distance along the heated plate for the two interrupter plates and the flat plate alone is shown in figure 4. The average unit thermal conductance is plotted in figure 5 as a function of the weight rate per unit cross-sectional area for the two interrupter plates, in figure 6 as a function of the duct width, and in figure 7 as a function of the height of the interrupters.

The local unit thermal conductance is approximately constant with distance along the heated plate except along the first 3 inches of the plate. The pronounced increase at a point about 2 inches from the leading edge appears in every test. This increase also appears for tests in which the flat plate was used alone. Such an increase was also evident in two other similar pieces of test equipment (references 1 and 5) which were constructed in a different manner. No satisfactory explanation has been found for these increases of f_{c_x}.

As shown in figures 4, 5, and 7, the heat-transfer rate over a flat plate is increased from 50 to 200 percent, depending on duct width and height of interrupters, by using interrupters as turbulence promoters. Calculations show that any added heat transfer through the 1/8-inch interrupter strips acting as fins is small. Thus the increase of heat-transfer rate by the 1/8-inch interrupters is due mainly to the added turbulence. However, rough calculations reveal that for the 3/8-inch interrupters up to 25 percent of the total heat rate is due to the heat transferred into the air by the fin effect of the interrupters. The measured heat-transfer rate of the plate with the 3/8-inch interrupters over that for the plate with the 1/8-inch interrupters, due to the added or reduced turbulence and fin effect, is only from 5 to 30 percent, depending on the duct width.

Pressure Drop

The nonisothermal static-pressure drop across the heated plate is plotted in figure 8 against the weight rate per unit area and in figure 9 against the duct width.

The pressure drop across the test section in the absence of the interrupters is shown for comparison in figure 9.

Heat Transfer as a Function of Power Consumption

Figure 10 shows the average unit thermal conductance plotted against $W\Delta p$ which is proportional to the power consumed as the fluid flows across the test section. Figure 10 also shows that the data for the flat plate, 1/8- and 3/8-inch interrupter plates fall within 15 percent of a line drawn through the mean of the data. This line has a slope of 0.24. The analytical value of the slope for the flat plate is 0.28. This information indicates that any of these three systems will yield approximately the same unit thermal conductance, and thus approximately the same heat rate, for any fixed power consumption through the heater.

Most of the data for the wooden-pin-finned plate (based on the plate area, reference 1) agree with those presented in figure 10. However, the data for the steel-pin-finned plate would appear higher than those other data when plotted in figure 10 because of the useful extended surface of the fins. Thus if turbulence promoters are to be used in a heater unit, the type which offers additional heat-transfer surface should be employed.

CONCLUSIONS

From the results of an investigation of the thermal and hydrodynamical behavior of air flowing along a flat plate containing turbulence promoters, the following conclusions were drawn:

1. With the use of the so-called "boundary-layer interrupters" as turbulence promoters, the heat-transfer rates are increased from 50 to 200 percent over that for a flat plate alone.

2. The increase of heat transfer resulting from the use of the 3/8-inch interrupters over that from the use of the 1/8-inch interrupters due to the additional or reduced turbulence and fin effect was from 5 to 30 percent.

3. For the same value of power consumed in pumping the air along the test section, the values of the unit thermal conductance are approximately equal for each of the following systems:

(a) Flat plate alone
(b) Flat plate with 1/8-inch interrupters
(c) Flat plate with 3/8-inch interrupters
(d) Flat plate with wooden pin fins

4. Further analysis and data are required to determine generalized variables which may be used to fix the performance of variously spaced and sized turbulence promoters.

Department of Engineering
University of California
Berkeley, Calif., March 26, 1946

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2. Boelter, L. M. K., Sanders, V. D., Young, G., Morgan, M., and Morrin, E. H.: An Investigation of Aircraft Heaters. XXXIV - Experimental Determination of Thermal and Hydrodynamical Behavior of Air Flowing between a Flat and a Wave-Shaped Plate. NACA TN 2426, 1951.

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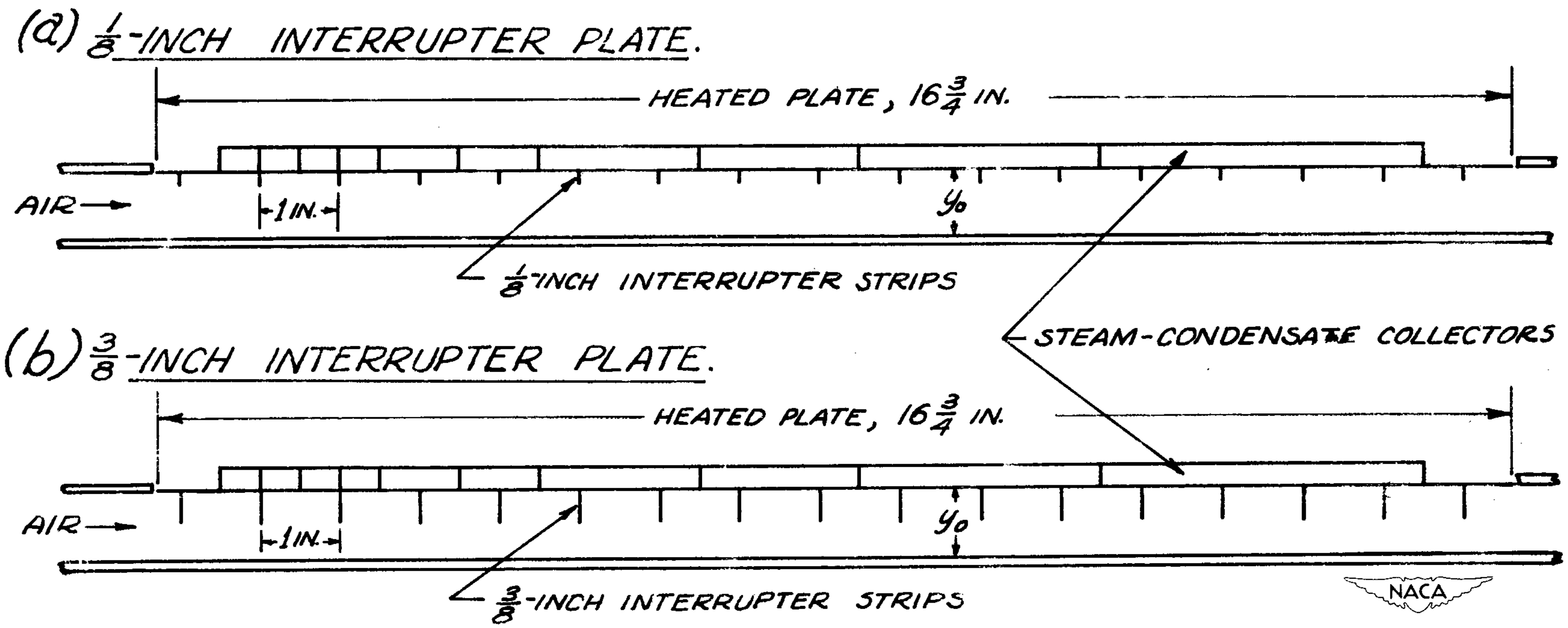


Figure 1.- Schematic diagram of interrupter plates.

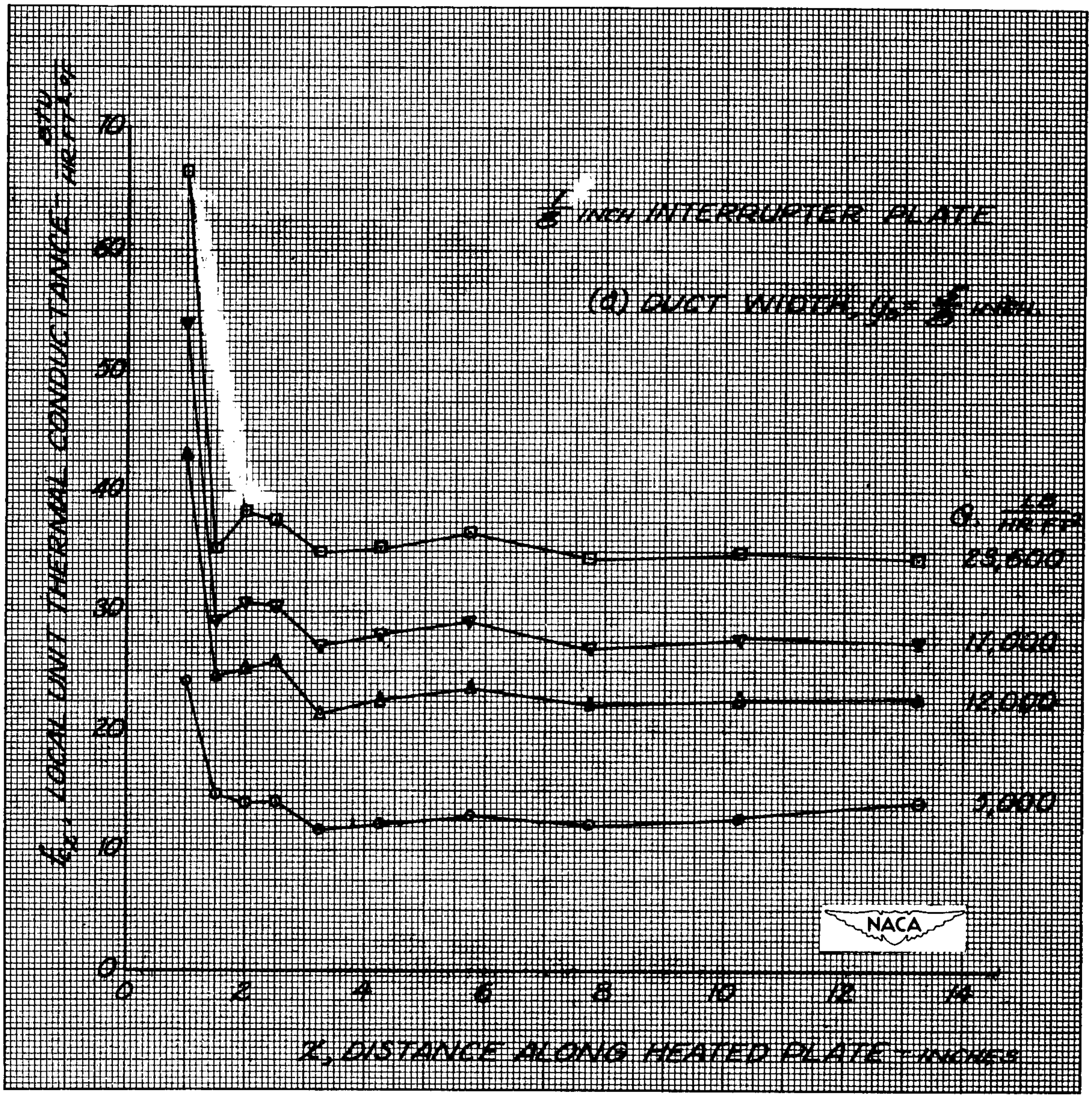
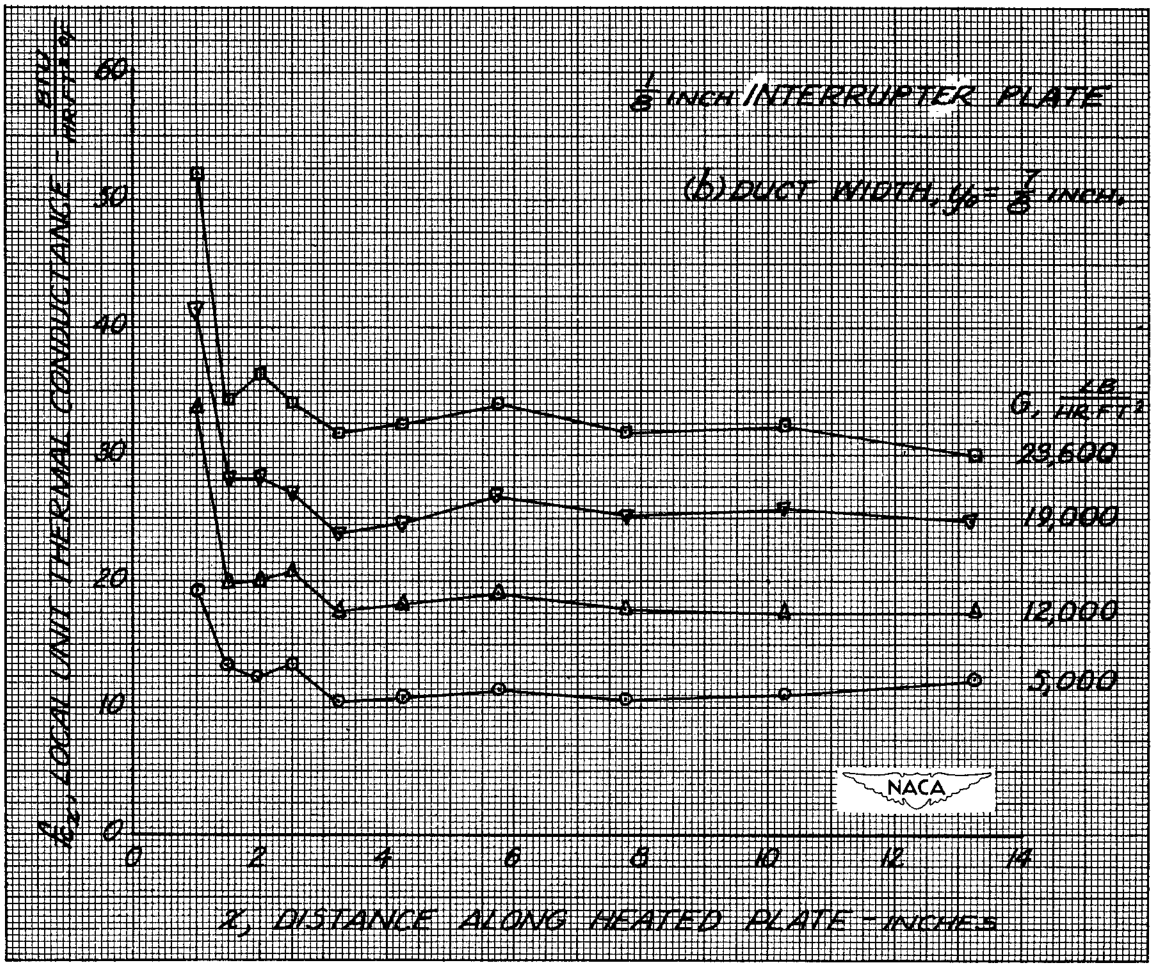


Figure 2.- Variation of local unit thermal conductance with distance along heated plate for 1/8-inch interrupter plate.



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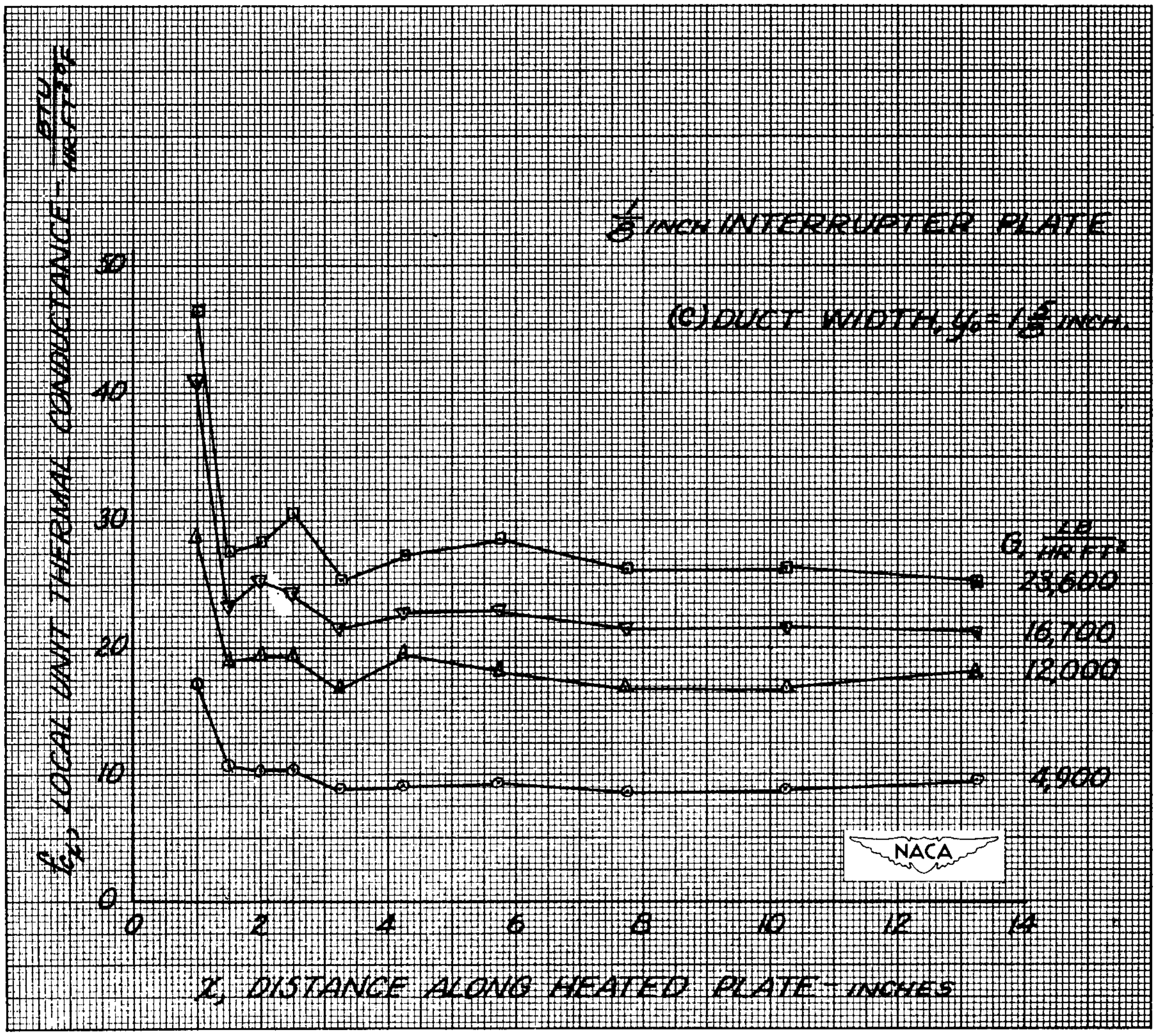

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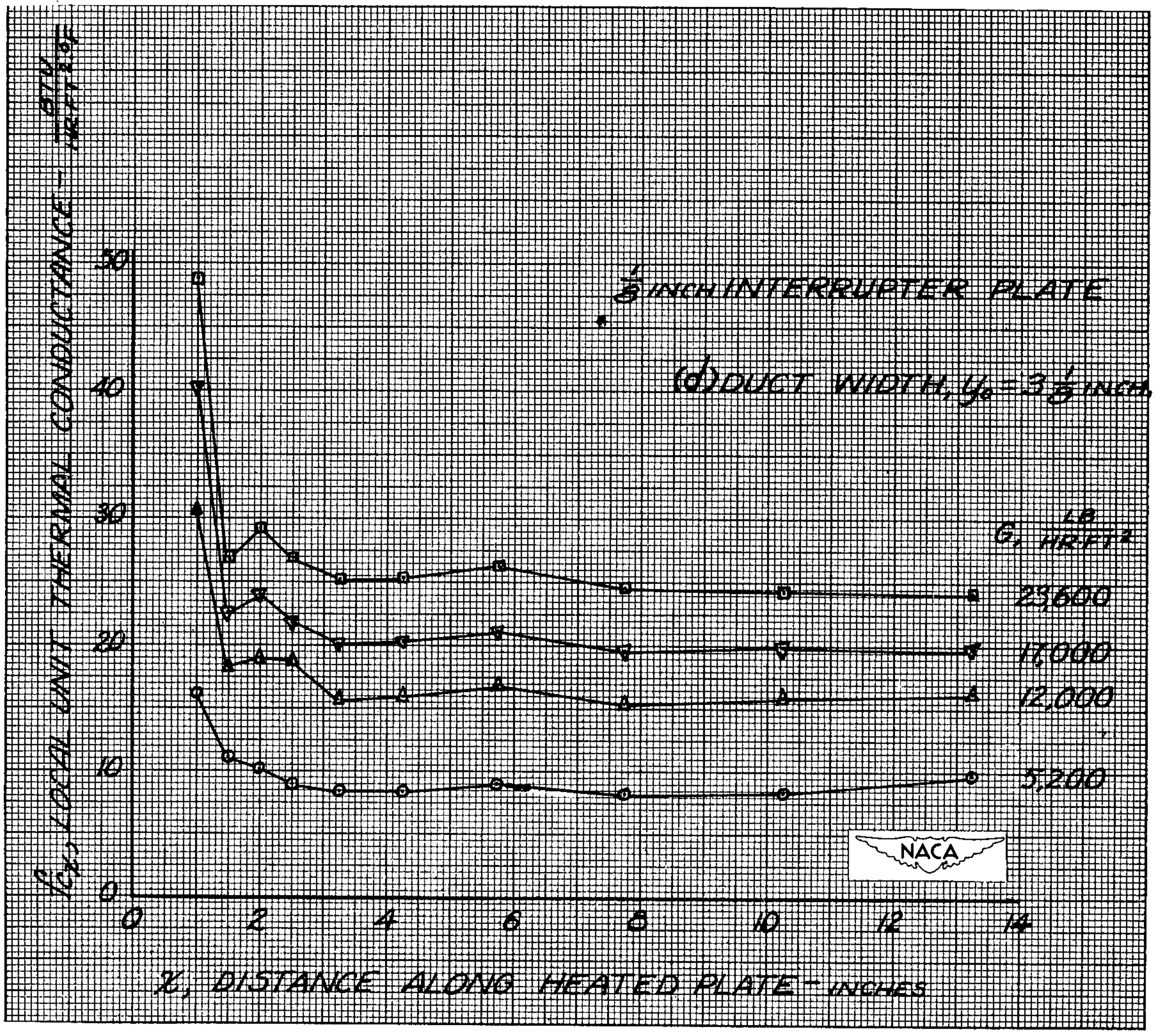

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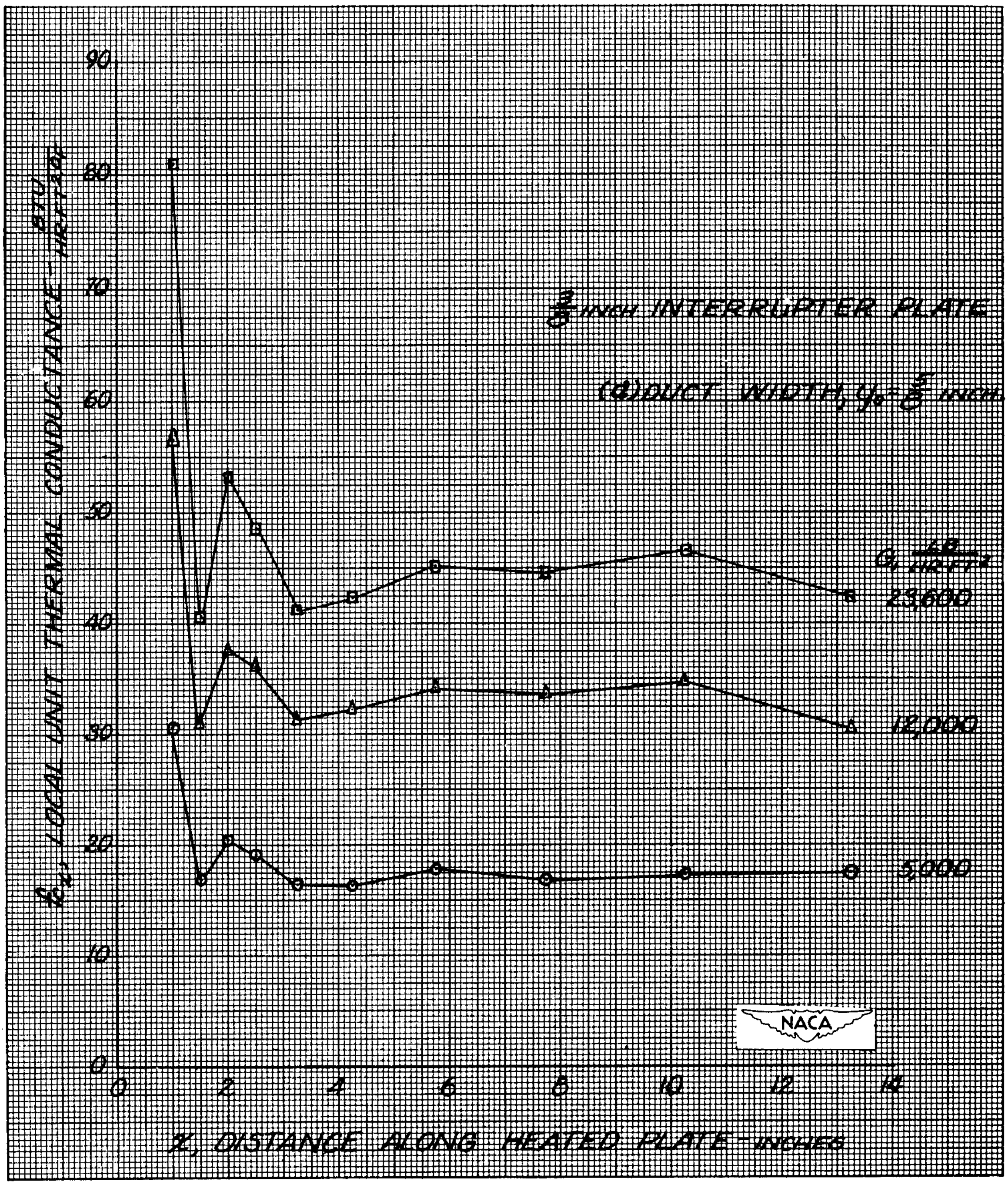
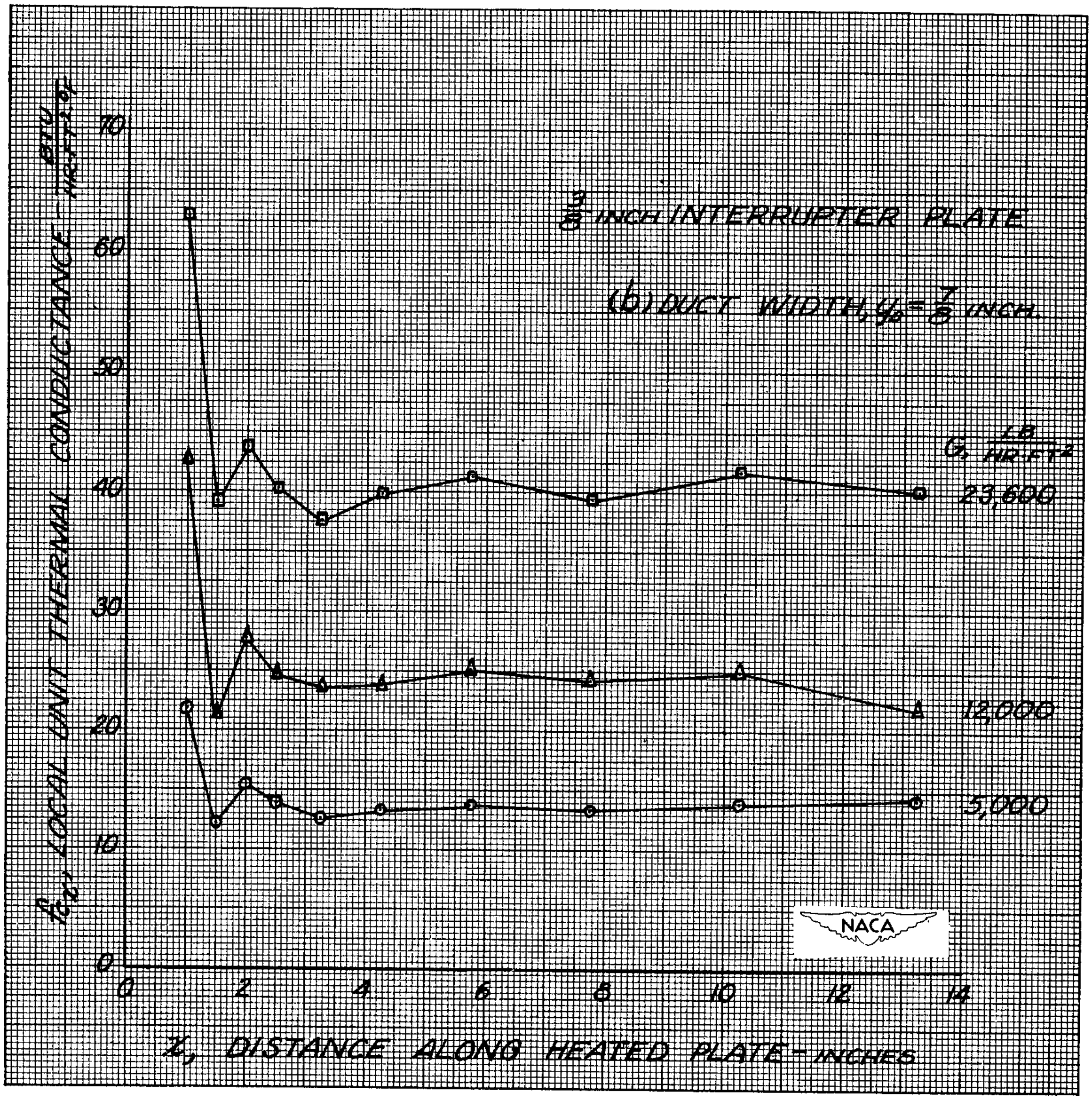


Figure 3.- Variation of local unit thermal conductance with distance along heated plate for 3/8-inch interrupter plate.



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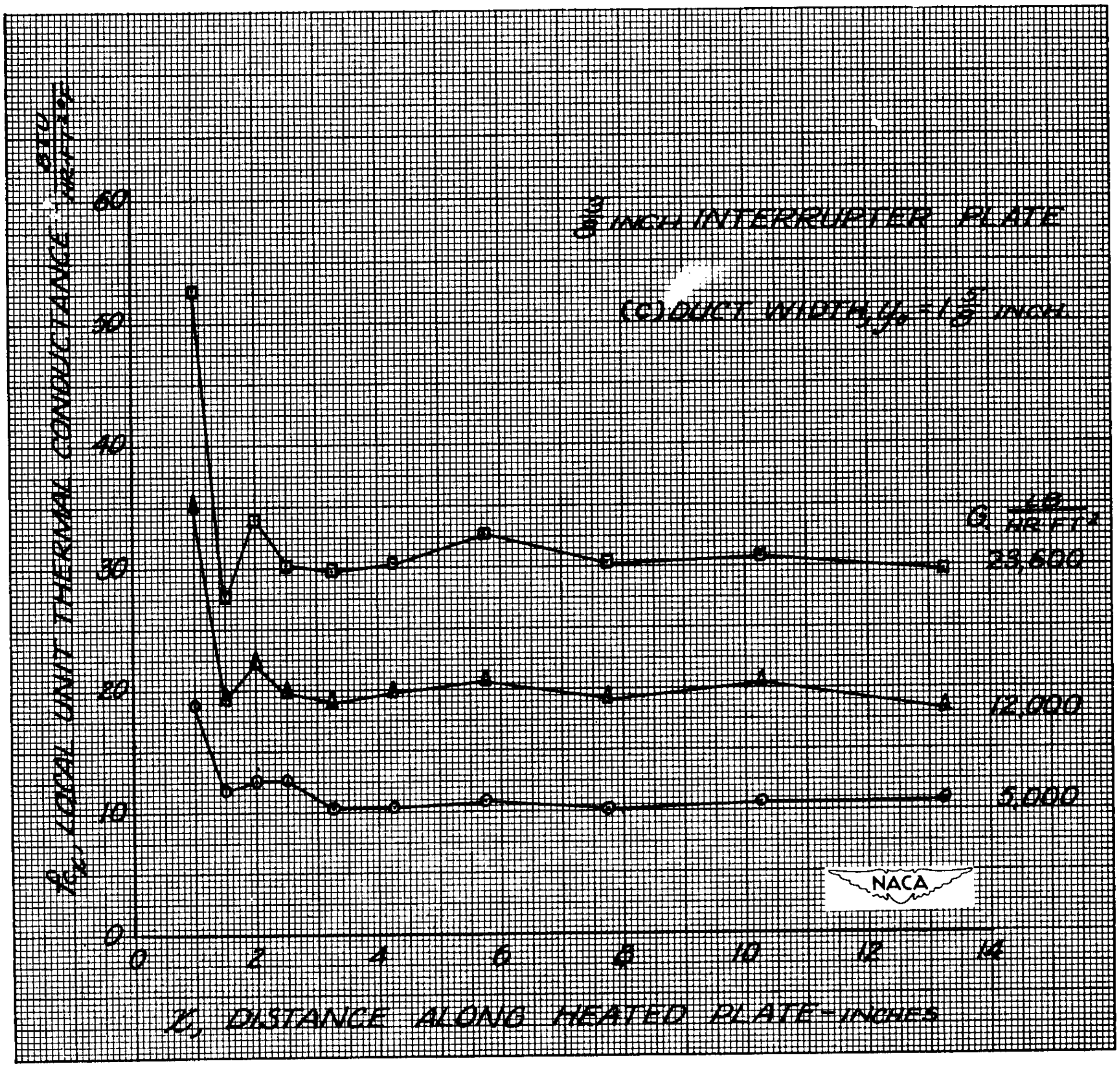

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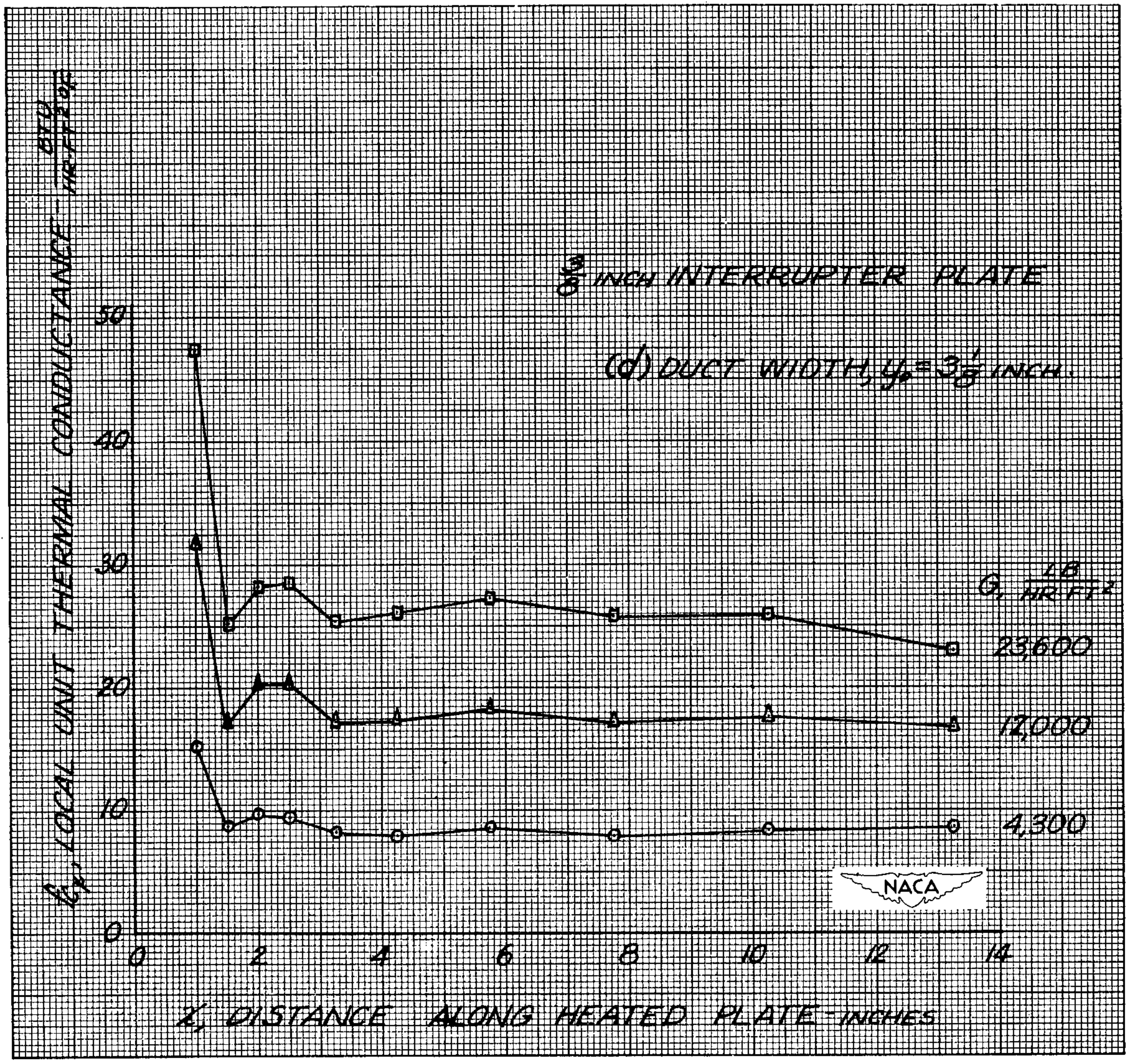

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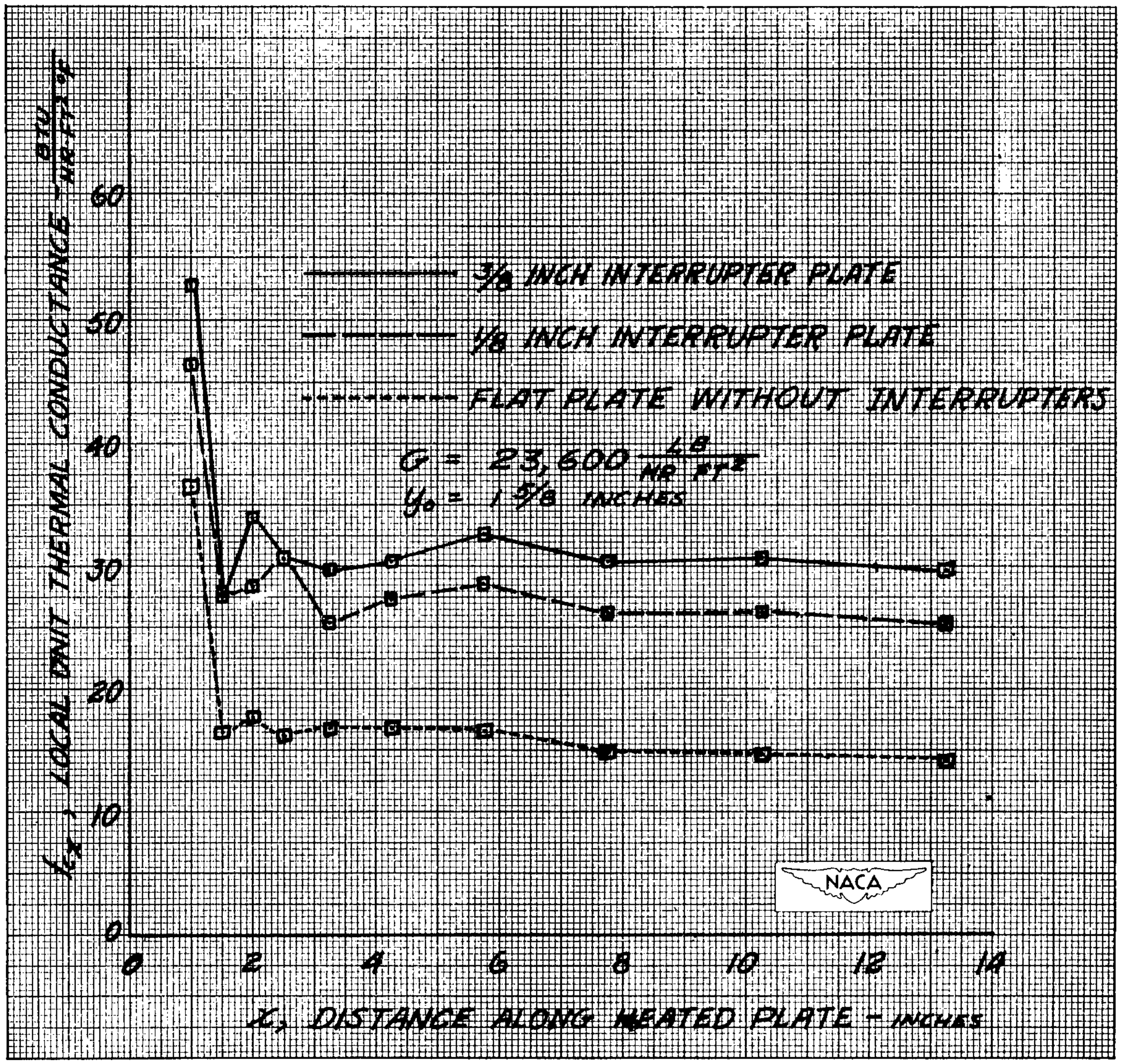


Figure 4.- Comparison of heat-transfer rates over interrupter plates and flat plate.

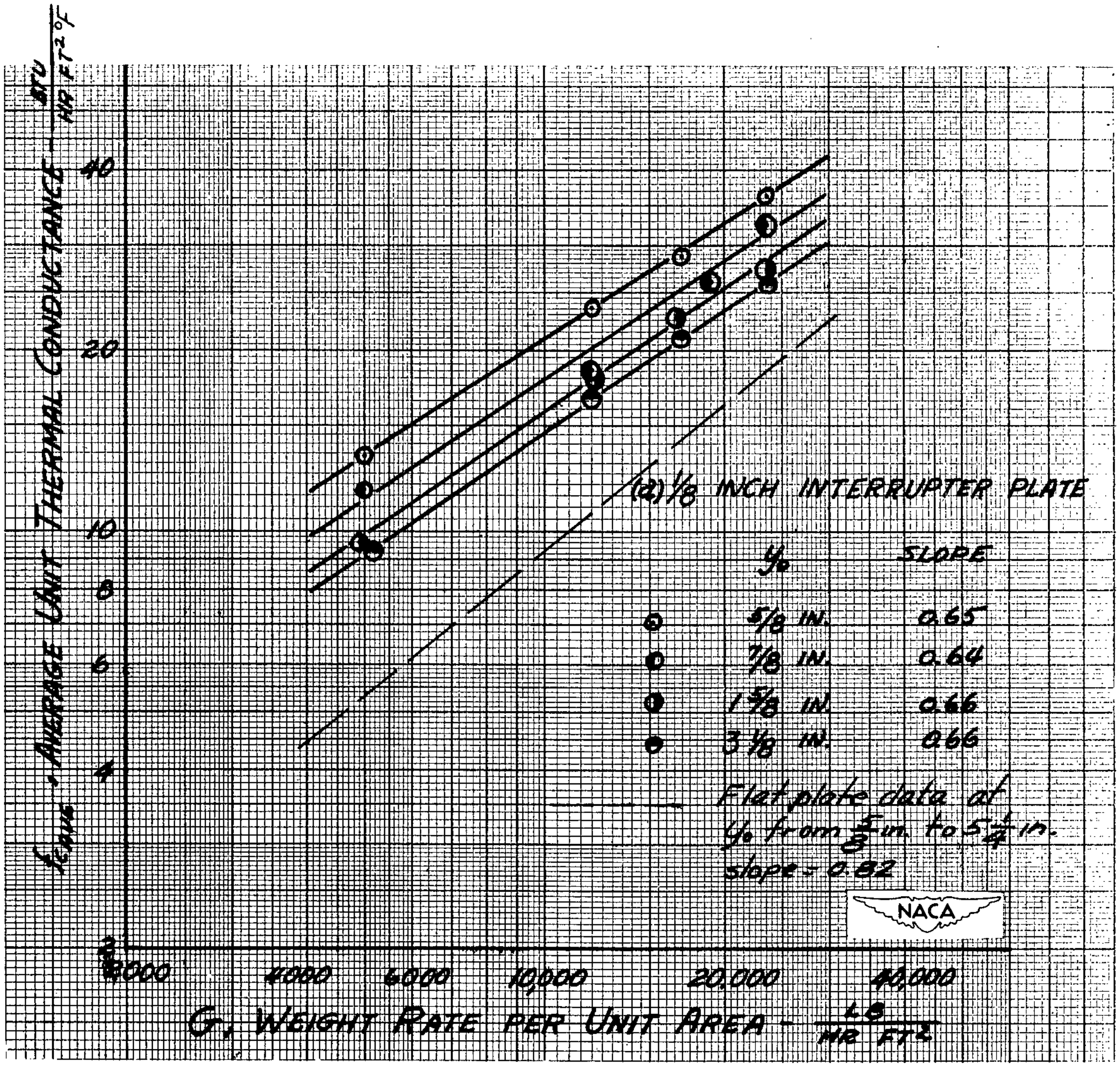
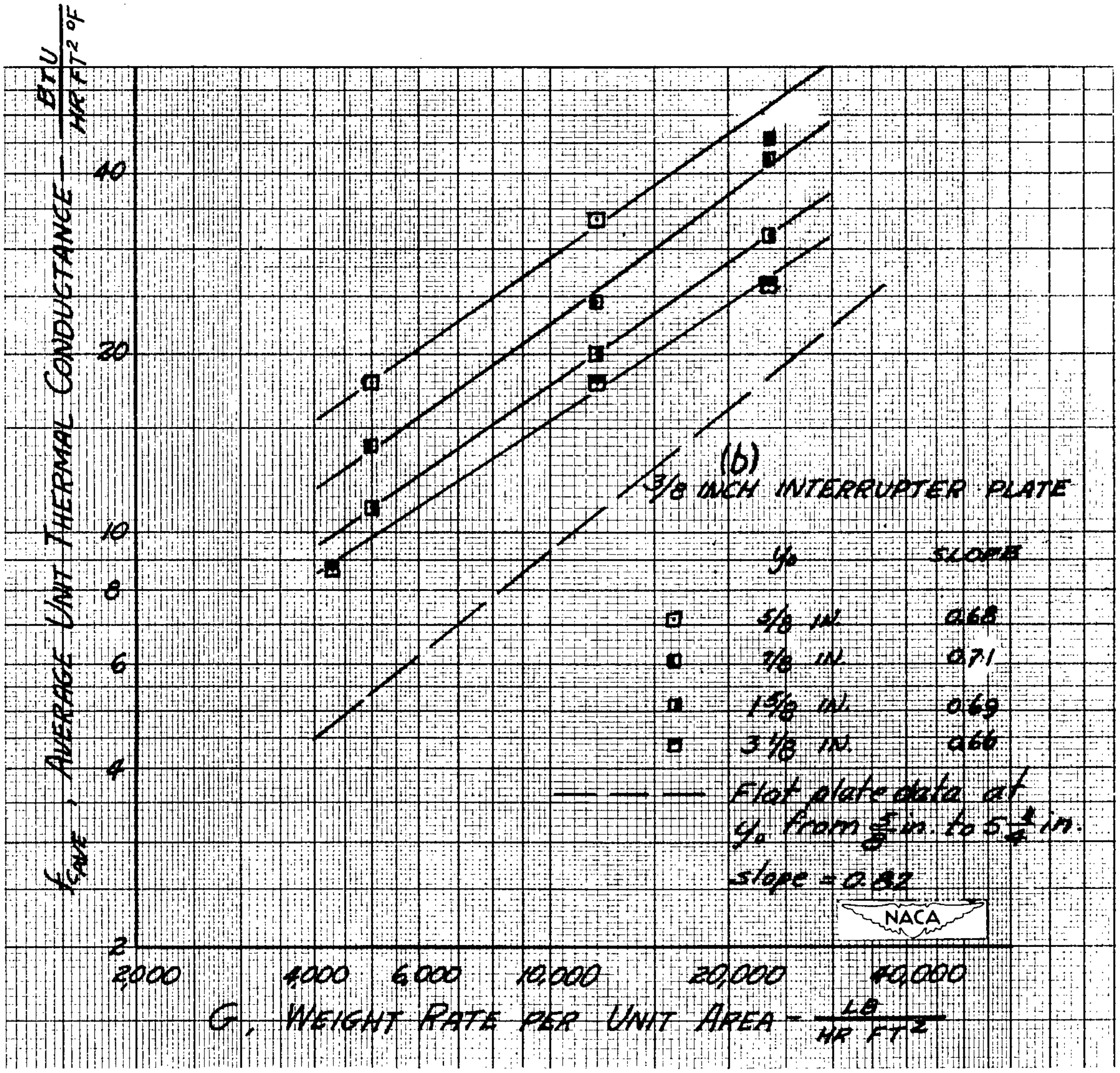


Figure 5.- Variation of average unit thermal conductance with weight rate per unit area.



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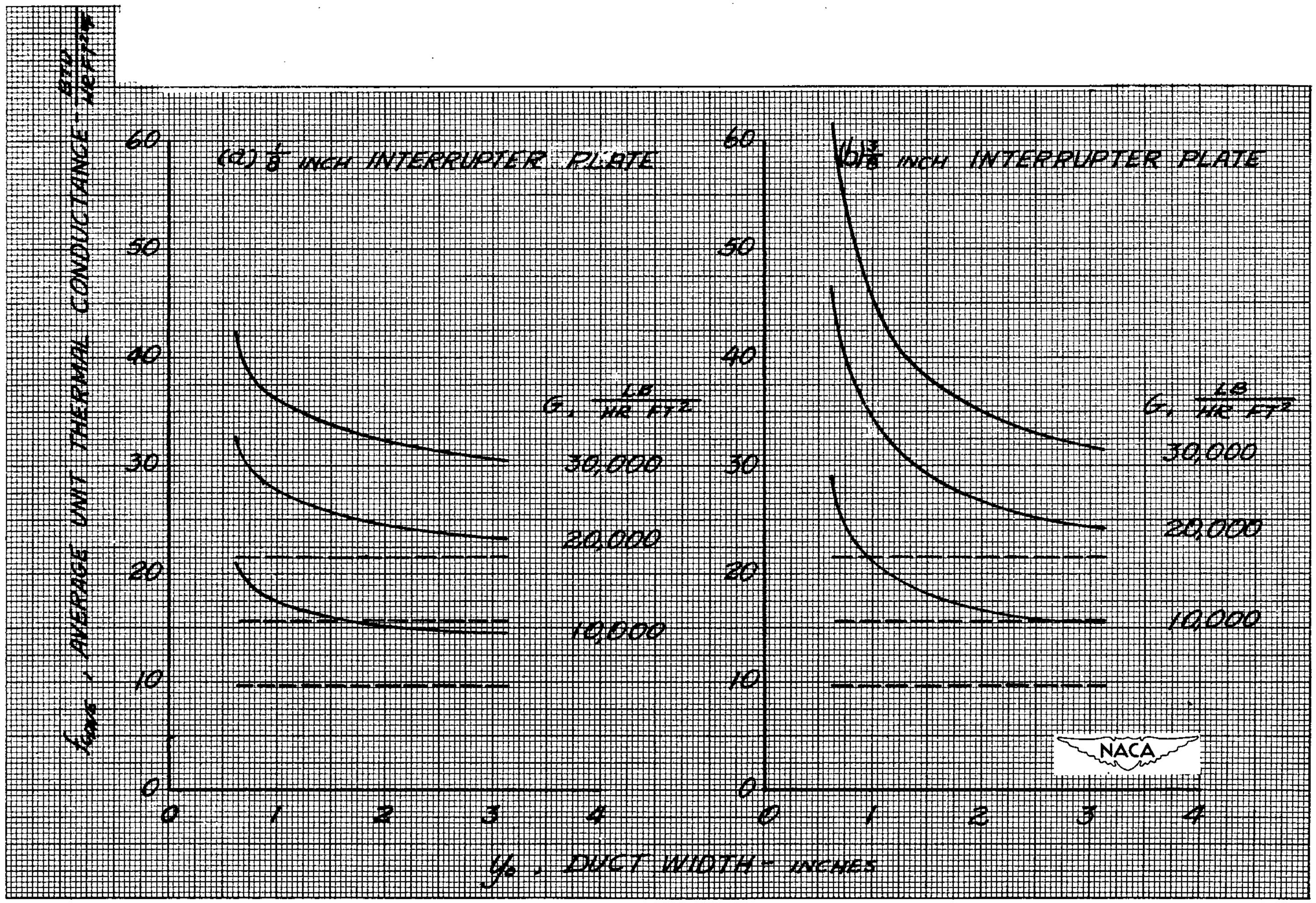


Figure 6.- Variation of average unit thermal conductance with duct width. (Dotted lines represent flat-plate data, reference 1.)

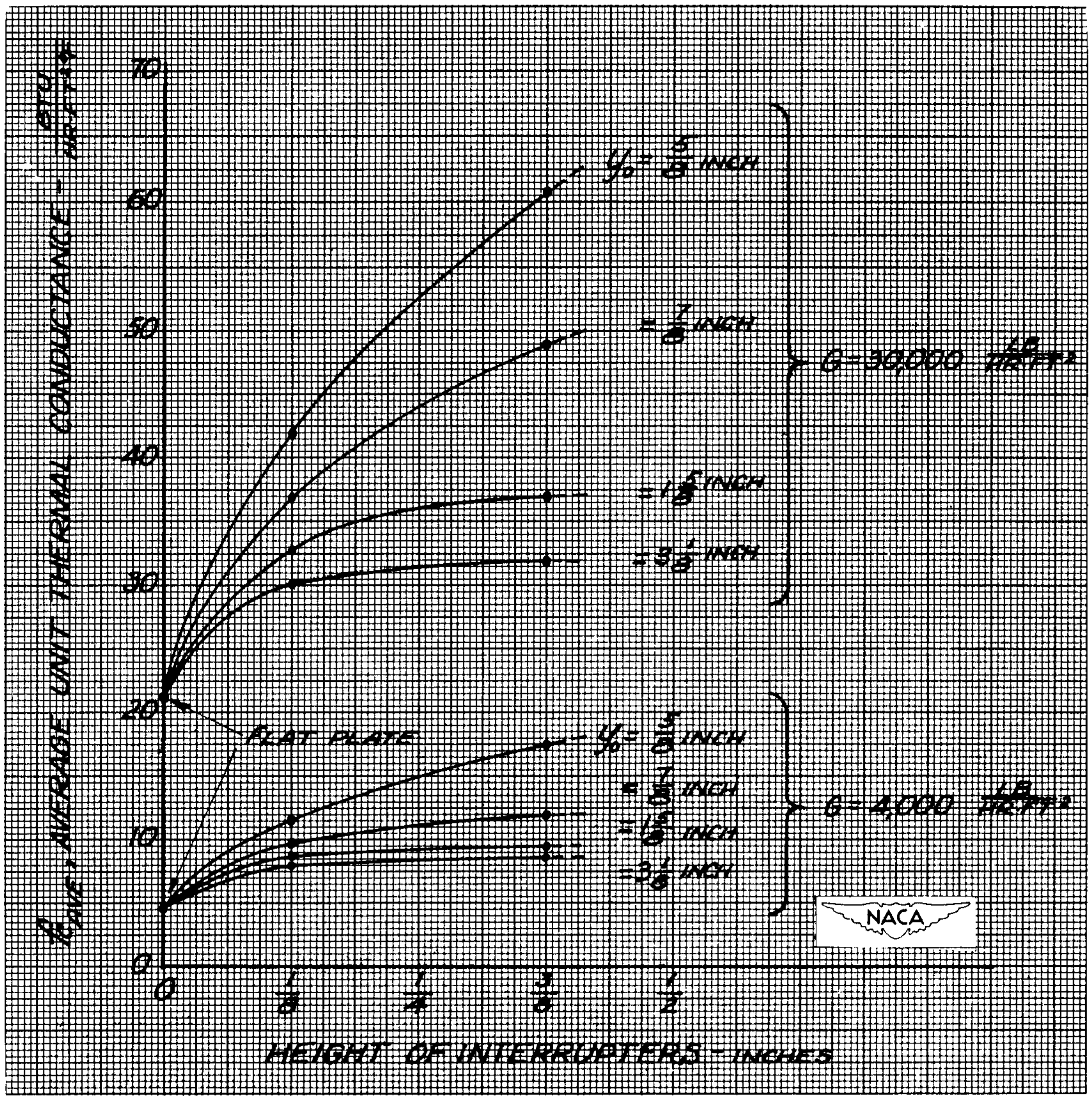


Figure 7.- Variation of average unit thermal conductance with height of interrupters.

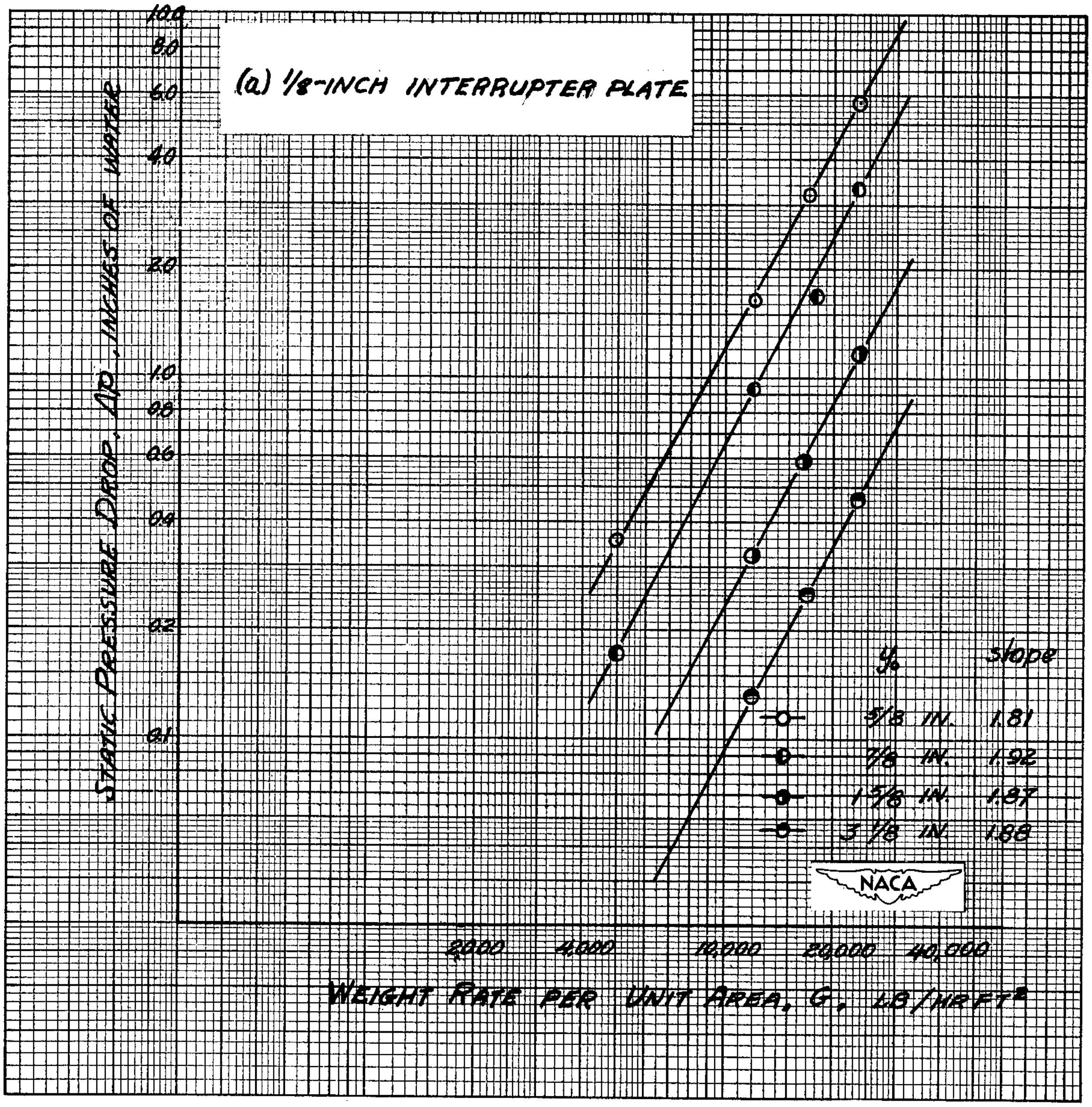
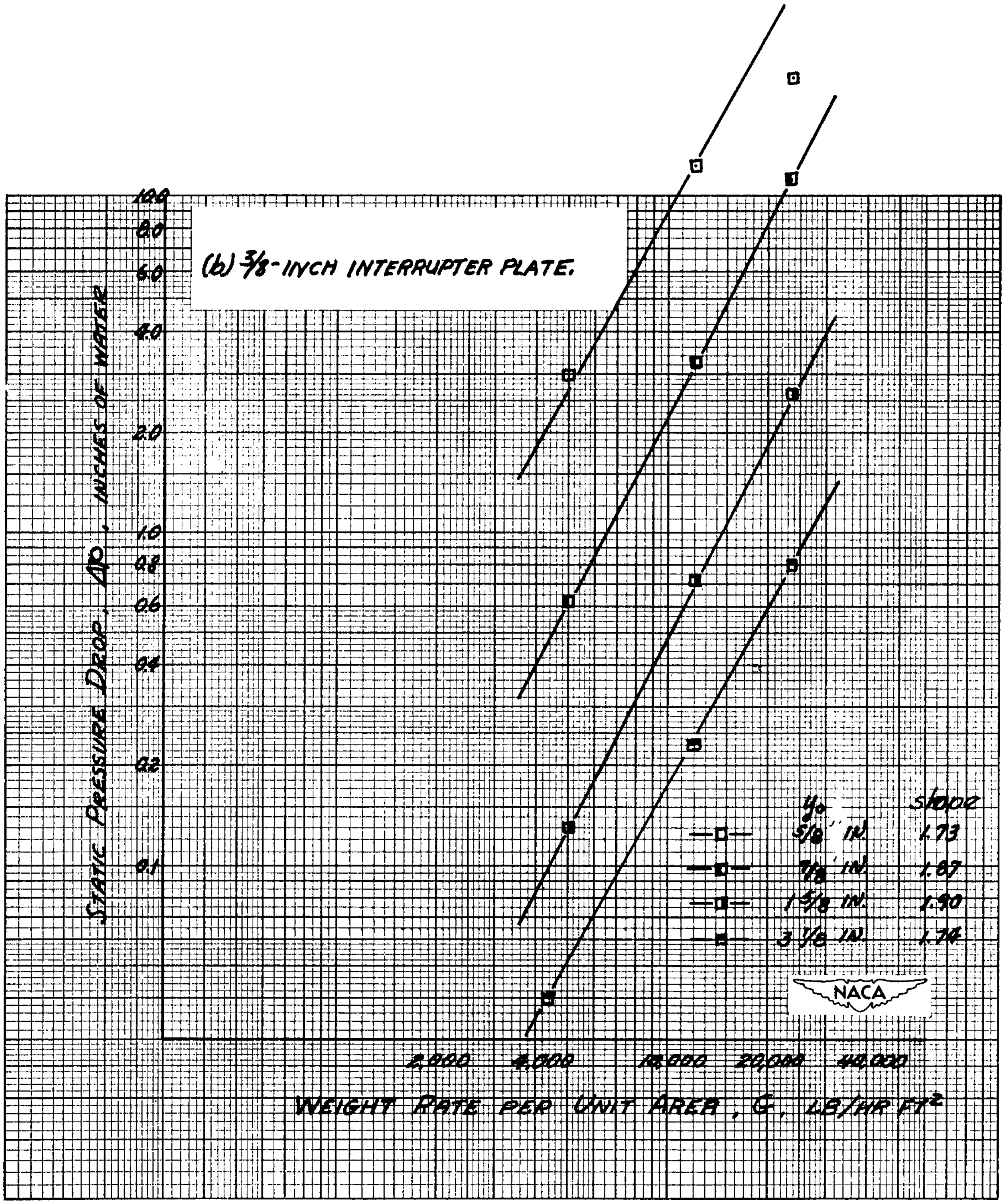


Figure 8.- Variation of pressure drop across interrupter plate with weight rate per unit area.



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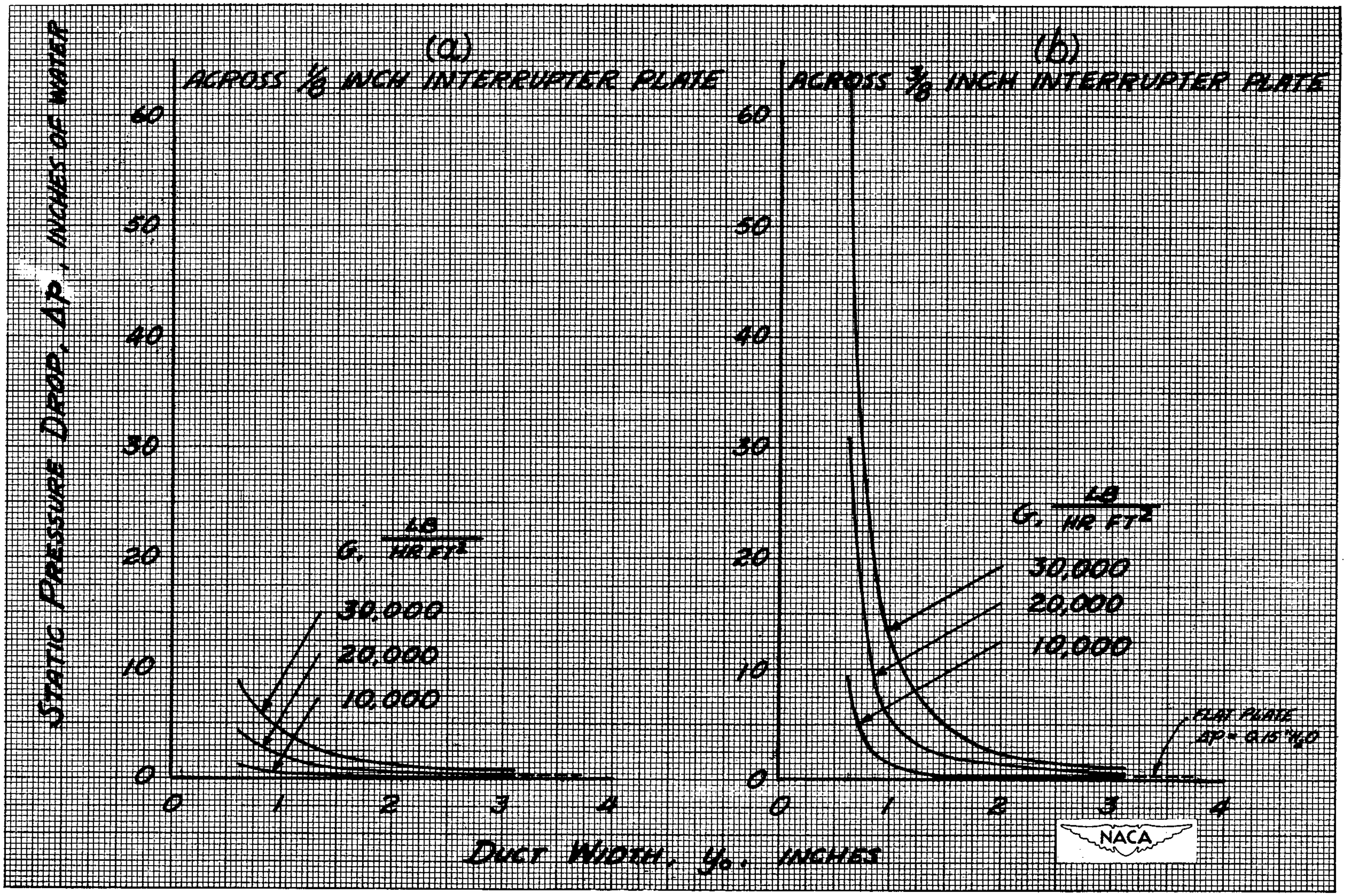

Figure 9.- Variation of pressure drop with duct width.

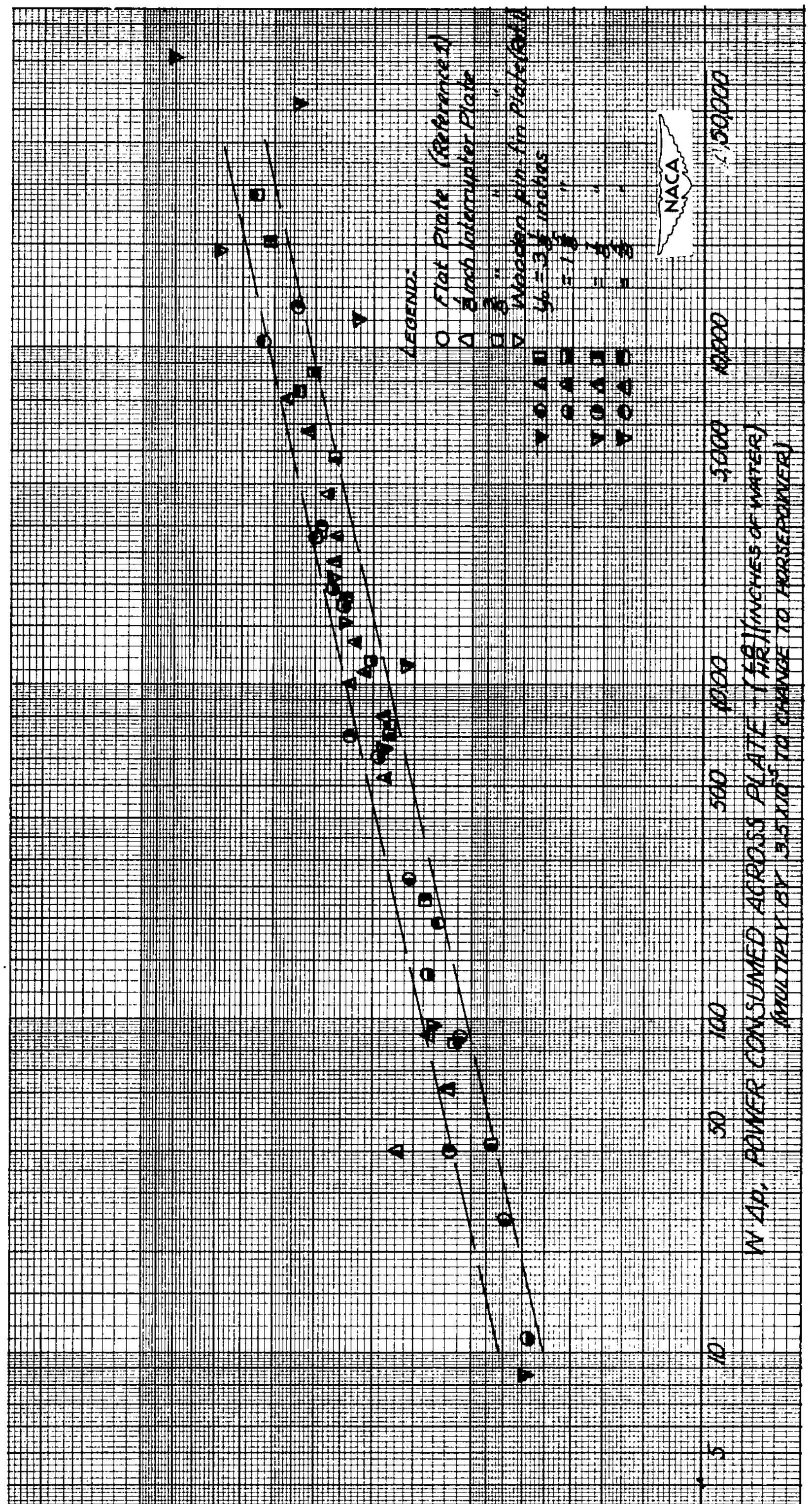

Figure 10.- Variation of heat-transfer rate with power consumed for flat plate, 1/8-inch interrupter plate, 3/8-inch interrupter plate, and wooden pin-fin plate at several duct widths.

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This report contains heat-transfer and pressure-drop data for air flowing over a heated flat plate containing strips of metal placed normal to the direction of air flow. The heat-transfer rates and static pressure drops are increased for this system over that for a flat plate alone because of the eddies, turbulence, and fin effect caused by the interrupters.

Copies obtainable from NACA, Washington

1. Heat Transfer Theory and Experiment (3.9.1)
2. Heat Exchangers (3.9.2)
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II. Young, George
III. Greenfield, M. L.
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