9188
NACA TN 2852

TECH LIBRARY KAFB, NM
0065803

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2852

AN INVESTIGATION UTILIZING AN ELECTRICAL ANALOGUE OF CYCLIC DE-ICING OF A HOLLOW STEEL PROPELLER WITH AN EXTERNAL BLADE SHOE

By Carr B. Neel, Jr.

Ames Aeronautical Laboratory
Moffett Field, Calif.

Washington
December 1952

AFMDC
TECHNICAL LIBRARY
AFL

TECH LIBRARY KAFB, NM
0065803

.J

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2852

AN INVESTIGATION UTILIZING AN ELECTRICAL ANALOGUE OF CYCLIC DE-ICING OF A HOLLOW STEEL PROPELLER WITH AN EXTERNAL BLADE SHOE

By Carr B. Neel, Jr.

SUMMARY

A study has been made of the heat requirement for the cyclic de-icing of hollow steel propellers fitted with external blade heating shoes. Solutions to the equations for the heat flow in cyclic heating of propellers were obtained, using an electrical analogy. The study showed how the energy requirement for propeller de-icing with existing blade shoes could be decreased, and illustrated the effect of blade-shoe design on the energy requirement. It was demonstrated, for example, that by increasing the heating intensity and decreasing the heating period from those currently used the energy requirement could be decreased in the order of 60 percent. In addition, it was shown that heating requirements could be decreased further, by as much as 60 percent, through proper design of the shoes. The investigation also showed the energy requirement to increase with decreasing liquid-water content and air temperature. Uncertainties as to the exact values of convective heat-transfer coefficient prevailing over the surface of the blade and ice layer resulted in uncertainties of approximately proportional magnitude in the values of required heating intensity.

INTRODUCTION

Propeller ice protection for aircraft is generally provided by electrical heating. In the development of external heating shoes, emphasis was placed primarily on the determination of the heating intensity required. Preliminary tests indicated power requirements for continuous heating to be so large that cyclic operation, with attendant power savings, was almost mandatory. Subsequent tests (reference 1) included some variation in cyclic time and other pertinent factors, but were mainly concerned with heating pattern and heating intensity for one blade and shoe configuration.

Tests of cyclically operated propeller blade shoes have been too limited in scope to provide a comprehensive picture of the effects of various parameters on blade-shoe performance. Electrical simulation of the flow of heat from the heating element of a blade shoe during cyclic operation offered a means for obtaining more complete data on cyclic de-icing. By use of an electrical analogy, a large range of configurations and operating conditions could be covered readily. Such a study of a similar problem was first made by Tribus (reference 2). This work was limited in its scope, reproducing portions of the data obtained in reference 1 and covering only the general aspects of the problem.

The present study is the first phase of a general investigation of the cyclic de-icing of propellers protected with heater elements installed on either the external or the internal surface of the blade. This report concerns heating shoes mounted externally on a hollow steel blade. The purpose of this investigation is twofold: (1) to present data which will show the operator of existing propeller blade shoes how to obtain efficient operation under various meteorological conditions, and (2) to indicate to the designer of blade shoes the factors influencing proper design and selection of insulating materials. Quantitative values are given in both cases. An electrical analogue was used in the study to provide a solution to the heat-flow equations representing transient heat flows in a cyclically heated propeller and blade-shoe combination.

FACTORS INFLUENCING HEATING REQUIREMENTS FOR CYCLIC DE-ICING

In order to aid in the understanding of the problem of cyclic propeller de-icing, the factors governing heating requirements for cyclic de-icing will be mentioned. Among the important variables influencing the heating requirements are the duration of the heating period and the heating intensity supplied to the blade shoes. It would be expected that as the heating period is decreased, the heating intensity must be increased to maintain de-icing protection. Also, the meteorological conditions (liquid-water content and air temperature) and flight conditions (airspeed and altitude) affect the energy requirements. The thickness and thermal conductivity of the insulation material used in the construction of the blade shoes are additional factors. The influence on propeller heating requirements of variations in each of these parameters, with the exception of airspeed and altitude, was studied.

DESCRIPTION OF EQUIPMENT

Electrical Analogue

The electrical analogue used in the study of cyclic de-icing is shown in figure 1. The analogue consists essentially of a network of electrical resistances and capacitances connected in such a manner as to simulate a thermal circuit. In the electrical circuit, electrical resistance and capacitance represent thermal resistance and capacitance, current flow represents heat flow, and voltage difference represents temperature difference. The resistances of the analogue network consist of potentiometers connected as rheostats, while the capacitances consist of condensers which were connected to obtain the desired values. The method of utilizing an electrical analogy for the solution of transient heat-flow problems is thoroughly treated in references 3, 4, and 5.

Special Circuits

Intermittent application of current, representative of cyclic heating, was accomplished by means of a switching system actuated by a synchronous electric motor. Since the power input to the blade shoe is constant during the heating part of the cycle, a source of constant current was provided for the electrical simulation of power input to the heater element. Additional constant-current circuits were arranged to represent the application of heat at the blade surface resulting from aerodynamic heating and release of the heat of fusion of the supercooled drops impinging on the blade surface as they solidified to ice.

To represent the periodic accumulation of ice on the blade shoe, relay circuits were employed which switched in resistors and condensers representing the equivalent values of thermal resistance and capacitance of the ice layers. The continuous growth of the ice formation was represented in the analogy, using the assumption that the ice built up in three layers of equal volume throughout each cycle. Periodic precharging of these condensers, just prior to their connection into the circuit, to represent the increase in temperature of the ice layers due to the addition of aerodynamic heating and release of the heat of fusion of the ice upon formation was achieved by means of a circuit utilizing the constant-current power supply and the ice-accumulation relays. These relays were synchronized with the cyclic heating through the same switching system.

Because during application of heat certain portions of the blade-shoe surface underneath the ice formation reached the melting point of ice before release of the formation, special circuits, termed "heat-of-fusion circuits," were provided which held the surface temperature of these regions at a constant voltage representing 32° F until release of

the ice accumulation. This represented the absorption of heat by the ice layer during the melting process.

Measuring Equipment

A recording oscillograph, shown in figure 2, was used to record the voltage changes representative of the temperature changes occurring during cyclic heating. The same instrument was utilized to measure the current flow representative of heat flow.

CHARACTERISTICS OF PROPELLER, BLADE SHOE, AND ICE FORMATIONS

Configuration and Characteristics of Propeller Blade

The propeller selected for this study is typical of those currently in use on transport airplanes. The aerodynamic and physical characteristics of the bare propeller blade (without blade shoes) are given in figure 3. The symbols presented in this figure and those used elsewhere in the report are defined in appendix A. Cross sections of the blade with shoes installed showing the section contours at the radial stations analyzed are presented in figure 4. The values for the properties of blade-metal density, specific heat, and thermal conductivity used in the study are given in table I.

Configuration and Characteristics of Blade Heating Shoe

Study of conventional blade shoe.- A blade shoe typical of those currently in use was simulated for this phase of the investigation. The shoe was assumed to extend from the blade shank to the tip. As illustrated in figure 4, the shoe extended chordwise a distance of about 1-3/4 inches on both sides of the blade from the leading edge for the entire length of the shoe. The insulating material was considered to consist of layers of rubber 0.03 inch thick above and below the heater element. Values taken for the physical properties of the insulating material are shown in table I. A uniform chordwise heating distribution was assumed.

Study of effects of variations in characteristics of blade shoe.- The effects on heating requirements of variations in the physical properties and thickness of the blade-shoe insulation material were studied for one radial station at one meteorological and operating condition. The program for the systematic study of these effects is presented in the following table. Multiplying factors for the properties of the insulation

material are based on layers of rubber 0.03 inch thick above and below the heater element.

Effect studied	Location of insulation relative to heater	Multiplying factor for thermal resistance, R	Multiplying factor for thermal capacity, C	Physical significance
Variations in properties for insulation above heater element (insulation below heater 0.03-inch rubber)	Above	0.5	1	
		.2	1	
		0	1	
		0	0	No insulation
		1	0	
		.5	.5	1/2 thickness
Variations in properties for insulation below heater element (insulation above heater 0.03-inch rubber)	Below	2	1	
		5	1	
		10	1	
		∞	0	Perfect insulation
		1	0	
		2	2	2 × thickness
Variations in properties for insulation above and below heater element	Above	0	0	No insulation above, perfect insulation below
	Below	∞	0	
	Above	0	0	No insulation (heater on blade-metal surface)
	Below	0	0	
	Above	.5	.5	1/2 thickness above, 2 × thickness below
	Below	2	2	

Configuration and Characteristics of Ice Formations

The configurations of the ice formations assumed are illustrated in figure 4. The chordwise extent of the formations was based on calculations of the farthest point aft of water-drop impingement, using the data of reference 6, while the shape of the accretions was based on photographs of actual ice formations and experience with the accretion of ice on

propeller blades. Table I presents the values of the physical properties of the ice layers used in the investigation.

Division of Blade, Shoe, and Ice Formations for Analogue Study

In the analogue study, the blade, shoe, and ice formations were divided into regions throughout which conditions were assumed constant. The blade was divided radially at 4 stations and chordwise into 11 segments, with the smallest divisions in the leading-edge region at the location of the blade shoe. (See fig. 4.) Each segment was subdivided into one layer representing the blade metal, six layers (three on each side of the heating element) representing the shoe material, and three layers corresponding to three ice increments.

OPERATING AND METEOROLOGICAL CONDITIONS SELECTED FOR ANALOGUE CALCULATIONS

Airplane Operating Conditions

The airplane operating conditions selected for all the tests were chosen as being typical of those for transport airplanes currently in operation and are given as follows:

Forward true airspeed	300 mph
Propeller rotational speed	1100 rpm
Pressure altitude	20,000 feet

Blade-Shoe-Heater Operating Conditions

A total-cycle-time duration of 80 seconds was maintained for all tests of cyclic heating. Three ratios of duration of heating period to total-cycle time were investigated, as follows:

Cycle ratio	Time on (sec)	Time off (sec)
1 to 4	20	60
1 to 8	10	70
1 to 16	5	75

Meteorological Conditions

The basic meteorological conditions selected were:

Liquid-water content	0.1 gm/m^3
Water-drop diameter	15 microns
Free-air temperature	-12° F

Limited studies also were made at values of liquid-water content of 0.2, 0.4, and 0.6 gram per cubic meter, and at air temperatures of 0° and -20° F. The liquid-water content of 0.1 gram per cubic meter was selected as a reasonable low value since low values of water content, combined with low air temperature, represent the most severe conditions for a propeller cyclic de-icing system. The air temperature of -12° F was computed from the data of reference 7, and was based on the probability of encountering a lower value of air temperature once in 1000 icing encounters for the conditions of 0.1 gram per cubic meter and 15 microns diameter.

TEST PROCEDURE

Arrangement of Analogue Circuits to Simulate Cyclic De-Icing of a Propeller

Appropriate values of electrical resistance and capacitance were placed on the analogue to simulate the thermal circuit of the propeller blade. Preliminary calculations and tests indicated that radial heat conduction was negligible. Therefore, independent circuits were set up for each propeller station. The heat-transfer equation used in the evaluation of the effective thermal resistance from the ice surface to the surrounding air and the equilibrium temperature of the ice surface is developed in appendix B. The method of reference 8 was used to compute the values of heat-transfer coefficient which determine the values of the air thermal resistance. In the computation of electrical values, a ratio of analogue time to actual time of 1 to 50 was taken to allow the use of condensers of a size sufficiently small for insertion on the analogue panels, and to allow the data to be obtained rapidly. Thus, a 1-second increment of time on the analogue represented a 50-second interval of time on the propeller blade.

Prior to gathering the transient-temperature data, the values of equilibrium surface temperature were set for each of the blade segments. In the region of the ice cap, the heat-of-fusion circuits were set for all segments but the one exhibiting the smallest temperature rise. With the blade shoe operating cyclically, the heater input intensity was adjusted so that the surface temperature of this segment just

reached 35° F at the instant of termination of the heating cycle. It was assumed that this would assure a complete release of all portions of the ice formation.

Recording of Data

With the analogue values properly adjusted, separate records were taken of the temperature variations of the blade-shoe surface, heater element, and blade metal, and variations of the heat flow from the heater element during simulated cyclic de-icing of the propeller. Curves also were obtained of the variation of the heater-element temperature with time during the initial period of a continuous application of heat.

RESULTS

Cyclic-Heating Data

Typical data from analogue.- Curves representative of the data obtained from the analogue are shown in figures 5 and 6. Figure 5 presents, for one segment of the propeller, the temperature variations for the blade-shoe surface, heater, and blade metal, and the variations in magnitude and direction of the heat flow from the heater element. Typical temperature variations for all segments of the exposed surfaces of the blade and shoe are shown in figure 6 for one propeller station. These data can be considered to be typical for the other stations as well.

Effects of variations in operating conditions for one blade-shoe configuration.- The blade-shoe configuration simulated for these tests consisted of the conventional shoe previously described in figure 4 and table I, which was intended to be typical of those currently in use. The results of tests to determine the effect of variations in the cyclic-heating ratio and air temperature on the required heating intensity for the four radial stations analyzed are shown in figure 7. For these tests the liquid-water content was maintained at 0.1 gram per cubic meter. Table II presents the maximum heater temperatures reached during operation under the above conditions.

Figure 8 gives the results of tests to illustrate the effect of a variation in liquid-water content on the minimum value of air temperature for which cyclic de-icing can be accomplished with a heating intensity of 10 watts per square inch of blade-shoe-surface area and a duration of heating time of 20 seconds. These data were obtained for radial station 48 only.

The results of an investigation at typical values of heating intensity and cyclic ratio currently in use are shown in figure 9. This figure indicates the minimum free-air temperature for which cyclic de-icing can be achieved with a heating intensity of 8 watts per square inch and a cyclic ratio of 20 seconds on and 60 seconds off, for one value of liquid-water content.

Effects of variations in blade-shoe material and construction for fixed operating conditions.- These tests were performed for the basic meteorological conditions of 0.1 gram per cubic meter water content and -12° F free-air temperature, and for radial station 48 only. Figure 10 illustrates the effect of variations in the thermal properties of the insulation material above the heater element on the heating requirements as a function of heat-on time. Similar data for the insulation layer below the heater element are presented in figure 11. Figure 12 shows the combined effect of variations in the properties for the insulation layers both above and below the heater element. Further tests to illustrate this combined effect are given in figure 13, which compares the heating requirements for the conventional shoe and a shoe having different thicknesses of rubber insulation above and below the heater.

Effects of variations in heat-transfer coefficients.- As in the previous experiments, these tests were limited to station 48 and were conducted for the conditions of 0.1 gram per cubic meter and -12° F. The effect of a variation of ±20 percent from the calculated heat-transfer coefficient on the heating requirements is shown in figure 14 for the conventional shoe and a modified shoe.

Continuous-Heating Data

A typical curve of the initial heater-element-temperature change resulting from a continuous application of heat is presented in figure 15. Data showing the time required for the heater temperature to reach values of 150°, 175°, and 200° F for continuous heating under the same operating conditions as for cyclic heating (table II) are given in table III. These data were obtained for the conventional blade shoe from curves similar to that shown in figure 15. The values presented in this table would provide information applicable to the case of malfunctioning of the cycling switch wherein excessive temperatures might cause failure of the blade-shoe insulation.

DISCUSSION

As mentioned previously, the heating efficiency and resulting energy requirement for a given blade shoe are dependent on the procedure followed

in the operation of the shoe. In addition, the design of the shoe and the selection of materials used in its construction can also influence its performance. Consequently, the results of this investigation have been examined from the viewpoints of both the operator and the designer.

Blade-Shoe Performance as Influenced by Variations in Operating Conditions

Effect of variation in duration of heating period.- From figure 7 it is evident that as the duration of the heating period is decreased, the required heating intensity for de-icing is increased. The required increase in heating intensity, however, is not proportionately as large as the decrease in heating period, resulting in a decrease in the overall energy requirement for a decreased heat-on time. This effect is illustrated in figure 16, in which is shown the possible decrease in required energy as a function of heat-on time. The values of energy requirement are based on the product of heating intensity and heating time as obtained from figure 7. Figure 16 shows that by decreasing the duration of heating time from 20 seconds to 5 seconds, the energy requirement can be decreased by about 60 percent.

There are three factors which must be considered, however, before this saving can be effected. These are (1) the more rapid temperature rises in and under the heating shoe resulting from the increased heating intensity required for short heating periods, (2) the increased size of the ice accretions thrown from the blade because of longer heat-off time, and (3) the adaptability of a short cyclic heating time to the source of electrical power. The data in table II indicate that the maximum heater temperatures would not be excessive at heating intensities as high as 27 watts per square inch. In addition, the maximum temperature reached at the surface common to the blade and shoe was shown from the analogue data to be well below 100° F. Considering the second factor, the tolerable size of ice accretion is dependent upon conditions which are established by the particular installation, and may require some compromise on the part of the designer. Finally, the inclusion of a short heating time, such as a 1-to-16 cyclic ratio, for propeller heating with the other electrical demands for the airplane may or may not present the designer with a problem. For example, on a four-engine airplane with four-bladed propellers the successive heating of one blade at a time would provide a required cyclic ratio of 1 to 16. This procedure has the possible disadvantage of unbalancing the propeller if the removed ice accretions are large. If it is impractical to heat one blade at a time, the power supply would have to be used intermittently to maintain the 1-to-16 cyclic ratio, which defeats the purpose of the short heating time. Two solutions to this situation are: (1) to use the power supply for intermittent electrical de-icing of other components of the airplane, and (2) to develop an intermittent-duty generator, which should be considerably lighter than a continuous-duty generator of comparable output.

Effect of variation in free-air temperature.- Figure 7 shows that as the free-air temperature is decreased, the required heating intensity is increased. The effect of air temperature on required heating intensity is shown to have a dominant influence on the de-icing performance of blade shoes. The deviation of the curves for station 72 from the general pattern for the other three stations is due primarily to the increased equilibrium temperature at this station resulting from the higher velocity.

Effect of variation in liquid-water content.- The data of figure 8 show that as the liquid-water content is increased, the air temperature at which cyclic-de-icing protection is obtained with a given heating intensity can be decreased. From these results, it may also be stated that at any given air temperature the energy requirement for de-cing decreases as the water content increases. This characteristic of propeller cyclic de-icing is due (1) to the effect of the higher rate of release of the latent heat of fusion resulting from the more rapid rate of formation of ice at the higher values of water content, and (2) to the increased insulating effect of the thicker ice layer which forms at the higher water-content values. The feature of a decreasing energy requirement for cyclic de-icing with increasing water content was initially reported in reference 2, and is in contrast to the case of energy requirements for an ice-prevention system in which the surface temperature must be maintained continuously above the freezing point.

It is of interest that icing tunnel tests of cyclically heated stationary airfoils (references 9 and 10) showed practically no influence of variations in liquid-water content on the energy required for de-icing. It is believed that these data are not incompatible with the conclusions of the analogue study. The results from cyclically heated stationary airfoils cannot be compared with the case of cyclically heated rotating propellers, where the criteria for ice removal are considerably different. In the case of propellers, it is necessary only to raise the surface temperature to 32° F to obtain de-icing, since at this temperature the adhesion of ice decreases to zero (reference 11), and the aerodynamic and centrifugal forces remove the accretions. For wings, on the other hand, the aerodynamic forces provide the only means for shedding the ice accretions. This is an uncertain action and, as a result, the ice formations are not removed when the surface temperature reaches 32° F, but instead continue to absorb heat until removal finally occurs. In view of this additional energy input, it is reasonable that the energy-requirement variation with changes in liquid-water content for intermittently heated wings should lie somewhere between the variations for cyclically heated propellers (decreasing energy requirement with increasing water content) and continuously heated wings (increasing energy requirement with increasing water content).

It has been demonstrated that the power requirements for de-icing increase both with decreasing liquid-water content and with decreasing air temperature. Unfortunately, it is a characteristic of icing conditions

that as the air temperature decreases, the value of water content likely to be encountered decreases also (reference 7). Thus, for the propeller cyclic-de-icing system, the power requirements are doubly increased at low air temperatures. There is some degree of compensation, however, in that as the water content decreases, the necessity for de-icing also decreases, inasmuch as the formations do not tend to become as large or deleterious as at higher values of water content. The prevalent meteorological conditions must be considered in the design and efficient operation of blade-heating shoes with adequate de-icing protection. It is believed that the water-content values together with the air-temperature values studied in this investigation provide a reasonable coverage of such conditions.

Radial distribution of required heating intensity.- Curves of the variation of heating intensity required for de-icing as a function of radial station for the conventional blade-shoe configuration are presented in figure 17 for the case of a free-air temperature of -12° F. These data show that the heat requirements decrease with increasing radial station. This is a result of the increased aerodynamic heating and rate of formation of ice caused by the higher velocities at the outer radial stations. The higher rates of ice formation provide a more rapid addition of heat from the latent heat of fusion of the ice, which, when combined with the increased aerodynamic heating, more than compensates for the increased heat loss resulting from the higher convective heat-transfer coefficients prevailing over the outer radial stations.

The distribution of required heating intensity exhibited in figure 17 indicates that for the case of existing blade shoes, which generally have a uniform heating distribution radially, the outermost regions of the blade shoe would tend to be de-iced first. Thus, at incipient de-icing failure of the innermost regions of the blade shoe, the outer stations still would tend to shed ice, a condition which is aided by the higher centrifugal forces in these areas. This point is substantiated by the photographs of reference 1, which show the outer regions of the blade to be cleared while the inner portions are covered with ice for a uniform radial distribution of heat. This is a desirable characteristic, inasmuch as it is the outer portions of the blade which develop most of the thrust and consequently are affected most adversely by the formation of ice (reference 12).

Examination of maximum-heater-temperature data.- The data presented in table II, which shows the maximum heater temperatures reached during cyclic de-icing, provide an indication of the feasibility of utilizing the higher heating intensities for the shorter durations of heating time. If the heater temperature should become excessive, the insulation material surrounding the heater element could fail, resulting in electrical failure of the blade shoe, with possibly more serious consequences. The data of table II show the maximum heater temperatures to be fairly constant at any given condition, regardless of the heating intensity. The maximum temperature reached was 145° F at a heating intensity of 27 watts per

square inch with a 5-second heating period. This temperature is well below the failure temperature of the blade-shoe insulating materials currently in use. The highest heater temperatures occurred under the conditions of lowest air temperature, which required the highest heating intensities. It is obvious, of course, that if the heating intensity is adjusted for de-icing at a low air temperature, the maximum heater temperature will exceed the values presented in table II during operation at a higher air temperature. A similar situation would exist at values of liquid-water content greater than 0.1 gram per cubic meter.

The possible failure of the system used to cycle the power to the blade shoes presents a hazard, particularly at the higher values of heating intensity. If the cycling switch should become jammed, for example, allowing power to the blade shoe to be supplied for an indefinite period, the heater temperature may quickly exceed the allowable limit. Table III gives an indication of the amount of time the power could be applied continuously before certain operating temperatures would be exceeded. These data are intended to provide information which could be utilized in the design of a safeguard to protect the blade shoes in the event of occurrence of a cycling-system failure.

The maximum temperature of the blade-metal surface reached during cyclic heating is of importance if the temperature exceeds the allowable limit of the bonding agent used in the installation of the blade shoe. An examination of the data revealed that the maximum blade-metal temperature reached was 85° F, well below the maximum allowable temperature of bonding agents currently in use.

Blade-Shoe Performance as Influenced by Variations in Blade-Shoe Material and Construction

Effect of variations in insulation layer above heater element.- Figure 10 shows that as the thermal resistance and thermal capacity of the insulation layer above the heater element are decreased, the required heating intensity is decreased. For a conventional blade shoe, the effect of a decrease in resistance is much greater than a proportional decrease in capacity. For example, reducing the thermal resistance to zero results in a decrease in the required heating intensity of about 50 percent of that required with a 0.03-inch-thick layer of rubber, at a heat-on time of 5 seconds, whereas decreasing the capacity to zero results in a reduction in required heating intensity of only 15 percent for the same heating conditions. A saving in heating intensity and, hence, in required power of about 55 percent is possible for a 5-second heat-on time by eliminating the insulation layer completely.

Figure 18 presents an indication of the power saving possible by reducing the thermal resistance from the value for a rubber insulation layer 0.03 inch thick. This figure shows that substantial savings in

power are to be gained through reasonable reductions in the thermal resistance.

Effect of variations in insulation layer below heater element.- Figure 11 shows that as the thermal resistance of the insulation layer below the heater element is increased, the required heating intensity is decreased. Likewise, the required heating intensity is decreased as the thermal capacity is decreased. As in the case of the insulation layer above the heater element of a conventional blade shoe, the effect of a change in resistance is considerably greater than a proportional change in capacity. A saving in required power of about 50 percent could be obtained with perfect insulation below the heater.

Figure 19 presents an indication of the power saving possible through increases in the thermal resistance from the value for a layer of rubber 0.03 inch thick. Again, considerable power savings can be effected by reasonable increases in the thermal resistance.

Effect of variations in the insulation layers both above and below the heater element.- Figure 12 illustrates the effect of combining the variations in the insulation layers both above and below the heater element. A curve is shown for the case of no insulation above the heater and perfect insulation below. This indicates the ultimate in design of an external blade shoe. In this case, all the heat delivered to the heater is being utilized to raise the temperature of the ice; none of the heat is being wastefully absorbed by the blade. This curve is nearly flat, displaying very little rise in required heating intensity with decrease in heat-on time. Obviously, the most efficient region of operation is at the shorter durations of heating time. By operating at a heating-time duration of 5 seconds, for example, the power requirement can be reduced to 38 percent of that necessary for a conventional shoe operating at the same heating time. This is representative of a reduction in total energy to only 14 percent of that required for the conventional shoe operating at 20-seconds heat-on time. The contrasting inefficiency of the conventional blade shoe is further illustrated in the transient heat-flow data of figure 5, in which it is shown that roughly half the total heat delivered flows into the blade during the heating phase of the cycle, leaving only about half the heat input to perform the function of removing the ice.

Figure 12 also shows the effect of reducing to zero the insulation resistance and capacitance beneath the heater element, with no insulation above the heater. This configuration is the equivalent of mounting the bare heater directly on the propeller blade, and would be approached in practice by the application of an electrically conductive film to the blade surface, a process which has been recently developed. With this configuration, considerable power may be saved over that required for a conventional shoe at heat-on times greater than 5 seconds.

Because of the problem of abrasion, it may not be feasible to allow the heater element to be exposed in the manner suggested. The abrasion problem, in fact, has led to the use of fairly thick layers of rubber above the heater for its protection (0.03 inch thick in the case of the conventional shoe simulated in this investigation). This is undesirable from the thermal standpoint, however. One possible solution to this problem lies in the development of a material with decreased thermal resistance and suitable abrasion-resistance characteristics.

A more immediate solution to the thermal problem alone would be to reduce the thickness of the layer of rubber insulation above the heater, as suggested by the data of figure 13. If the thickness of this layer is reduced by a factor of 2, the power requirement may be decreased about 25 percent. Additional power economy may be achieved by increasing the thickness of the layer of rubber under the heater element. The combined effect of utilizing a layer of rubber half the original thickness above the heater and twice the original thickness below is shown in figure 13 to reduce the power requirement about 30 percent. Protection of such a blade shoe from abrasion might be accomplished through installation of a thin strip of metal along the leading edge of the blade over the shoe. Tests to determine the thermal effect of such an abrasion strip 0.002 inch thick showed no increase in the heat requirements.

A further means of reducing the over-all energy requirements for propeller de-icing would be to reduce the chordwise extent of the blade shoe. It should be noted that such a procedure would be feasible only if the resulting coverage is sufficient to provide adequate protection, a factor which is determined by the chordwise extent of the ice accretion. In all of the blade-shoe configurations investigated embodying insulation under the heater, the required heating intensities were influenced negligibly by variations in the chordwise extent of the heater. In the case of the heater element mounted directly on the blade, however, chordwise heat conduction is sufficiently high that any reduction in heater width is reflected in an increase in the required heating intensity. The extent of this effect is illustrated in figure 12, in which is shown the heating-intensity curve for the case where the heater is reduced about 30 percent in width. Although the required heating intensity is increased, the total energy requirement is decreased by over 15 percent due to the reduction in area of the heater.

Blade-Shoe Performance as Influenced by Variations in Heat-Transfer Coefficients

The data of figure 14 show that changes in the values of the convective heat-transfer coefficients result in approximately proportional changes in the required heating intensity for de-icing. This serves to illustrate the importance of knowledge of the exact values of the heat-transfer coefficients prevailing over the propeller blade, especially in

the region of ice formation, where the heat-transfer coefficients exert the major influence on heat requirements.

Analysis of Values of Heating Intensity Required for De-Icing

A review of the values of heating intensity required for de-icing as indicated by the data of this report show the values to be generally higher than the heating-intensity value of 8 watts per square inch, commonly in use. General agreement exists, however, between the heating-intensity values presented herein for the conventional blade shoe operated at a 20-second heating time and 0° F air temperature, and the value of 10 watts per square inch recommended in reference 1 for similar operating conditions.

An examination of the data taken at 8 watts per square inch (fig. 9) and a heating-time duration of 20 seconds (typical of operational values of heating intensity and heating time commonly in use) shows that complete protection can be expected with a conventional blade shoe operating under these conditions down to an air temperature of about 10° F, with only partial protection provided below this temperature down to about -5° at which point no further de-icing can be expected.

In order to obtain a rough check of the values of heating intensity presented in this report, a comparison was made of values of heating intensity shown to be required in the investigation of reference 1 and values extrapolated from the data of the present report for the same operating conditions. Three cases from reference 1 were chosen in which the conditions were closest to those simulated herein. The data were obtained from reference 1, utilizing photographs showing the radial extent of residual ice formations to establish the position of marginal de-icing protection. These photographs, combined with the information on blade-shoe construction and meteorological and operating conditions, provided means for extrapolation of the heating-intensity values of this report. The results of this comparison are given as follows:

Figure No. (reference 1)	Duration of heat-on time (sec)	Heating intensity (w/in.^{2})	
		Reference 1	Extrapolated from data of this report
19(a)	24	6.5	7.9
20(a)	12	8.0	9.1
20(b)	24	8.0	8.0

This general agreement is considered to be good, especially in view of the rather extensive extrapolations involved, and serves to substantiate the data presented in this report.

CONCLUSIONS

The following conclusions have been reached as the result of an analytical study of cyclic de-icing with blade heating shoes mounted on a hollow steel propeller. The percentage values of energy saving presented apply directly only to the case of hollow steel blades of approximately the same configuration as that tested. However, the general conclusions are applicable to all propeller blades fitted with external heating shoes. All cyclic heating durations are based on a total cycle time of 80 seconds.

1. Considerable saving of energy can be effected with blade shoes currently in operation by applying higher heating intensities for shorter durations of time than are generally in use. For the case of conventional shoes of the type commonly used, by operating at a 5-second duration of heating time, the total energy can be decreased to about 40 percent of that required for operation at a 20-second heating duration.

2. Considerable saving of energy can be effected through proper design of blade shoes. For example, if the thickness of the insulation layer above the heater of a conventional blade shoe is decreased by a factor of 2 and the thickness of the insulation below the heater is doubled, the energy can be decreased to about 70 percent of that required for a conventional shoe operated at the same cyclic ratios. Through appropriate design and selection of insulating materials, the energy requirement can be decreased to a value approaching 38 percent of that needed for a conventional shoe operated at 5-seconds heating time.

3. The maximum heater temperatures reached under conditions of efficient de-icing for the above cases are relatively independent of heating intensity, and are well within safe limits of operation for existing insulation materials.

4. As the liquid-water content of the air stream increases, the energy required to remove ice from the propeller decreases. Meteorological conditions which impose the most stringent heating requirements on a cyclically heated propeller are low values of liquid-water content together with low air temperatures.

5. Uncertainties as to the exact values of convective heat-transfer coefficient prevailing over the surface of the blade and ice layer result

in uncertainties of approximately proportional magnitude in the values of required heating intensity.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Sept. 26, 1952

APPENDIX A

SYMBOLS

b	chord of blade section, feet
c_p	specific heat of air at constant pressure, Btu per pound, $^{\circ}F$
c_{p_i}	specific heat of ice at constant pressure, Btu per pound, $^{\circ}F$
c_{p_w}	specific heat of water at constant pressure, equal to 1 Btu per pound, $^{\circ}F$
C	thermal capacity of blade-shoe insulation material, Btu per $^{\circ}F$
c_l	blade-section lift coefficient, dimensionless
D	propeller diameter, feet
e_o	saturation vapor pressure with respect to water at temperature t_o, millimeters of mercury
e_s	saturation vapor pressure with respect to ice at temperature t_s, millimeters of mercury
g	acceleration due to gravity, equal to 32.2 feet per second, second
h	convective surface heat-transfer coefficient, Btu per hour, square foot, $^{\circ}F$
h_b	blade-section maximum thickness, feet
J	mechanical equivalent of heat, equal to 778 foot-pounds per Btu
L_f	latent heat of fusion of ice, equal to 144 Btu per pound
L_s	latent heat of sublimation of ice at temperature t_s, Btu per pound
M_a	weight rate of water-drop impingement per unit of surface area, pounds per hour, square foot
p	local barometric pressure, millimeters of mercury
q	rate of heat flow per unit of surface area of the ice formation, Btu per hour, square foot
r	temperature-recovery factor, dimensionless

R thermal resistance of blade-shoe insulation material, $^{\circ}F$ per Btu, second

t_o ambient-air temperature, $^{\circ}F$

t_s temperature of outer surface of ice layer, $^{\circ}F$

U speed of free stream with respect to propeller-blade section, feet per second

APPENDIX B

DEVELOPMENT OF EQUATION FOR CALCULATION OF HEAT TRANSFER FROM THE SURFACE OF AN ICE LAYER DURING ITS FORMATION

During the formation of ice on an object traveling through a cloud composed of supercooled water drops, heat is transferred from the surface of the ice to the surrounding air at a rate determined by the individual rates of heat loss or gain resulting from convection, evaporation, impingement of the water drops, and release of the heat of fusion of the ice. This transfer of heat may be expressed by the following equation, which differs slightly from that derived in reference 2, where the positive terms represent the flow of heat from the ice to the surrounding atmosphere:

$$q = h\left(t_s - t_o - r\frac{U^2}{2Jgc_p}\right) + h\frac{0.622L_s}{pc_p}(e_s - e_o) - M_a c_{p_w}\frac{U^2}{2Jgc_{p_w}} - \left[M_a L_f - M_a c_{p_w}(32 - t_o) + M_a c_{p_i}(32 - t_s)\right] \tag{1}$$

Substituting appropriate values for the constants in equation (1) and collecting terms, the heat flow from the ice surface is given by

$$q = h\left(t_s - t_o - 8.33r\,U^2 \times 10^{-5}\right) + 2.6h\frac{L_s}{p}(e_s - e_o) + M_a\left(0.47t_s - t_o - 127 - 2U^2 \times 10^{-5}\right) \tag{2}$$

Values of the effective coefficients of heat transfer from the surface of the ice were obtained from the slope of the curve of q plotted as a function of t_s as established by equation (2) for each segment of the ice formation. Since these curves showed very nearly a linear variation of heat transfer from the ice surface with ice-surface temperature, fixed values of electrical resistance were used in the analogue simulation of the thermal resistance to this heat flow. Values of equilibrium surface temperature for each segment were taken from these curves at the point where q equalled zero.

REFERENCES

1. Lewis, James P.: De-Icing Effectiveness of External Electric Heaters for Propeller Blades. NACA TN 1520, 1948.

2. Tribus, Myron: Intermittent Heating for Protection in Aircraft Icing. (Thesis submitted in partial satisfaction of requirements for Ph.D. degree in engineering.) Univ. of Calif., Dept. of Engr., 1949.

3. Paschkis, Victor, and Baker, H. D.: A Method for Unsteady-State Heat Transfer by Means of an Electrical Analogy. Transactions of A.S.M.E., Feb. 1942.

4. Avrami, M., and Paschkis, V.: Application of an Electric Model to the Study of Two-Dimensional Heat Flow. Transactions of American Institute of Chemical Engineers, June 25, 1942.

5. Bromberg, R., and Martin W.: Theory and Development of a Thermal Analyzer. (Final Report) Univ. of Calif., L. A., Dept. of Engr., Aug. 1947.

6. Bergrun, Norman R.: An Empirical Method Permitting Rapid Determination of the Area, Rate, and Distribution of Water-Drop Impingement on an Airfoil of Arbitrary Section at Subsonic Speeds. NACA TN 2476, 1951.

7. Lewis, William, and Bergrun, Norman R.: A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States. NACA TN 2738, 1952.

8. Martinelli, R. C., Guibert, A. G., Morrin, E. H., and Boelter, L. M. K.: An Investigation of Aircraft Heaters. VIII - A Simplified Method for the Calculation of the Unit Thermal Conductance Over Wings. NACA ARR, March 1943.

9. Lewis, James P., and Bowden, Dean T.: Preliminary Investigation of Cyclic De-Icing of an Airfoil Using an External Electric Heater. NACA RM E51J30, 1952.

10. Gray, Vernon H., Bowden, D. T., and von Glahn, U.: Preliminary Results of Cyclical De-Icing of a Gas-Heated Airfoil. NACA RM E51J29, 1952.

11. Loughborough, Dwight L., and Haas, E. G.: Reduction of the Adhesion of Ice to De-Icer Surfaces. Jour. Aero. Sci., vol. 13, no. 3, Mar. 1946.

12. Neel, Carr B., Jr., and Bright, Loren G.: The Effect of Ice Formations on Propeller Performance. NACA TN 2212, 1950.

TABLE I.- VALUES OF PHYSICAL PROPERTIES SELECTED FOR BLADE METAL, BLADE-SHOE INSULATION MATERIAL, AND ICE ACCRETION

Component	Density (lb/ft^3)	Specific heat ($Btu/lb,^{\circ}F$)	Thermal conductivity ($Btu/hr,ft^2,^{\circ}F/in.$)
Blade metal	490	0.107	300
Blade-shoe insulation material (conventional shoe)	81.6	0.31	1.42
Ice accretion	50	0.47	14

TABLE II.- MAXIMUM-HEATER TEMPERATURES REACHED DURING CYCLIC HEATING OF CONVENTIONAL BLADE SHOE

Propeller station (in.)	Free-air temperature (°F)	Heating intensity[1] (watts/in.²)	Duration of heat-on time (sec)	Maximum-heater temperature (°F)
24	0	11	20	103
		13	10	100
		17	5	104
	-12	14	20	113
		16.5	10	111
		22	5	122
	-20	17	20	135
		20	10	128
		27	5	145
36	0	11	20	109
		13	10	106
		17	5	104
	-12	14	20	127
		16.5	10	121
		21	5	123
	-20	17	20	142
		20	10	136
		26	5	144
48	0	9.5	20	108
		12	10	105
		15	5	105
	-12	13	20	130
		15.5	10	123
		20	5	117
	-20	15.5	20	140
		18.5	10	138
		23.5	5	140
72	0	6	20	95
		7.3	10	97
		9	5	93
	-12	12	20	130
		14	10	125
		18	5	123
	-20	13.5	20	135
		16	10	131
		21	5	128

[1]Heating intensities presented are minimum values required for de-icing at each condition.

NOTE: Liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds; forward true airspeed, 300 mph; propeller speed, 1100 rpm; pressure altitude, 20,000 feet.

TABLE III.- TIME REQUIRED FOR HEATER TO REACH VARIOUS TEMPERATURES UNDER CONDITIONS OF CONTINUOUS HEATING FOR CONVENTIONAL BLADE SHOE

Propeller station (in.)	Free-air temperature (°F)	Heating intensity[1] (watts/in.^{2})	Time in seconds required for heater to reach a temperature		
			150° F	175° F	200° F
24	0	11	---	---	---
		13	210	---	---
		17	44	126	426
	-12	14	184	---	---
		16.5	79	216	---
		22	15	43	93
	-20	17	91	251	---
		20	42	100	---
		27	8	14	36
36	0	11	186	---	---
		13	75	190	---
		17	23	57	117
	-12	14	70	164	---
		16.5	34	72	150
		21	10	24	45
	-20	17	40	87	190
		20	18	38	70
		26	6	12	21
48	0	9.5	163	---	---
		12	60	151	---
		15	24	53	103
	-12	13	56	122	---
		15.5	32	49	91
		20	12	25	40
	-20	15.5	40	77	155
		18.5	20	35	59
		23.5	8	14	24
72	0	6	---	---	---
		7.3	---	---	---
		9	98	---	---
	-12	12	52	108	---
		14	26	58	118
		18	10	22	45
	-20	13.5	39	78	278
		16	20	42	84
		21	7	18	34

[1]Values of heating intensity correspond to those presented in table II.

NACA

NOTE: Liquid-water content, 0.1 gm/m^3; forward true airspeed, 300 mph; propeller speed, 1100 rpm; pressure altitude, 20,000 feet.

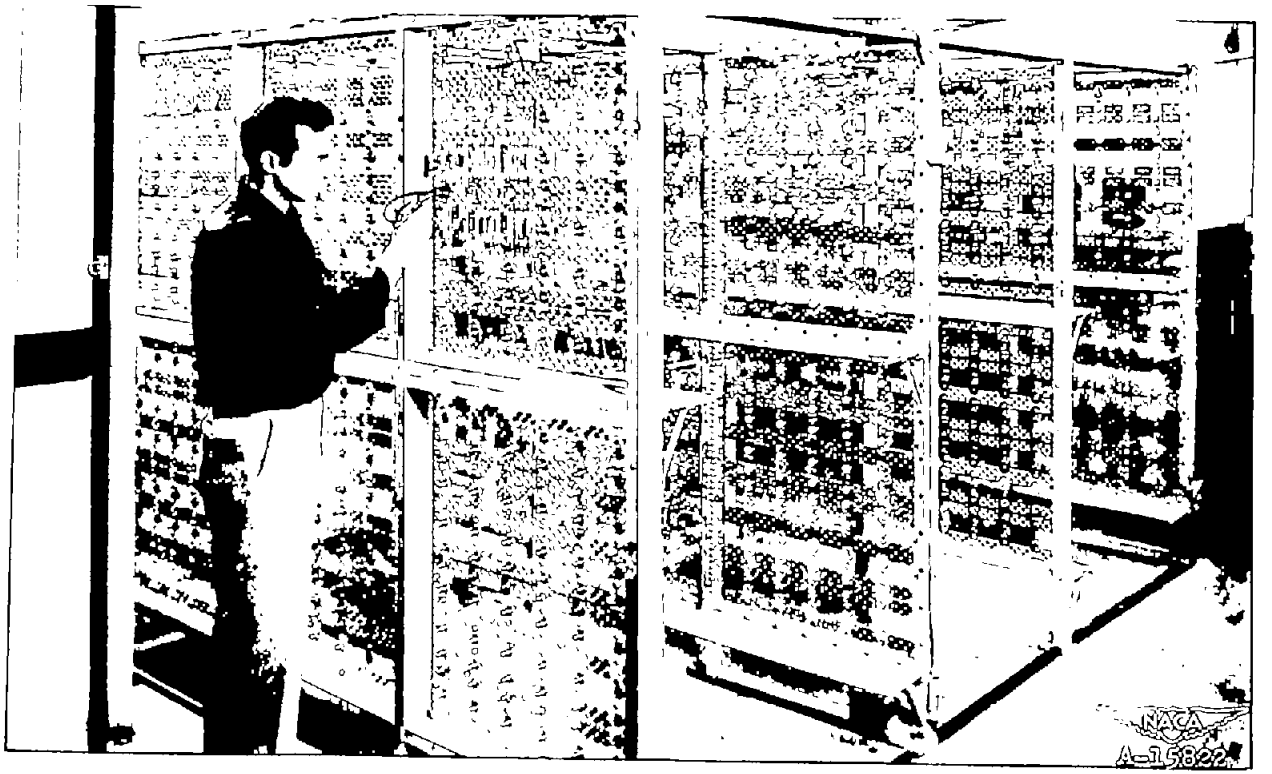


Figure 1.– Electrical analogue used in the investigation of propeller cyclic de-icing.

Figure 2.– Recording apparatus used with electrical analogue.

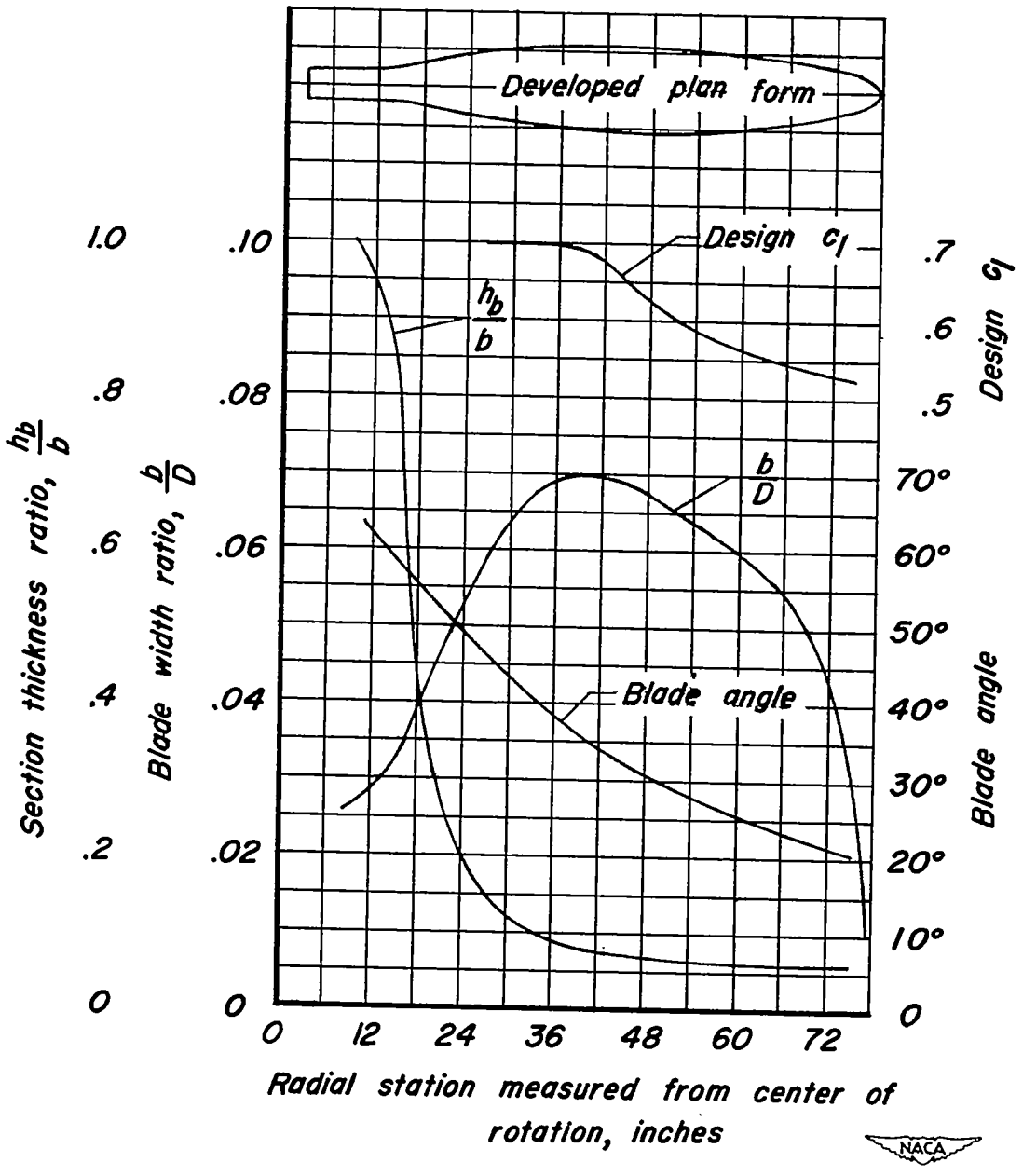


Figure 3.- Characteristics of bare propeller blade investigated. Diameter, 13 feet.

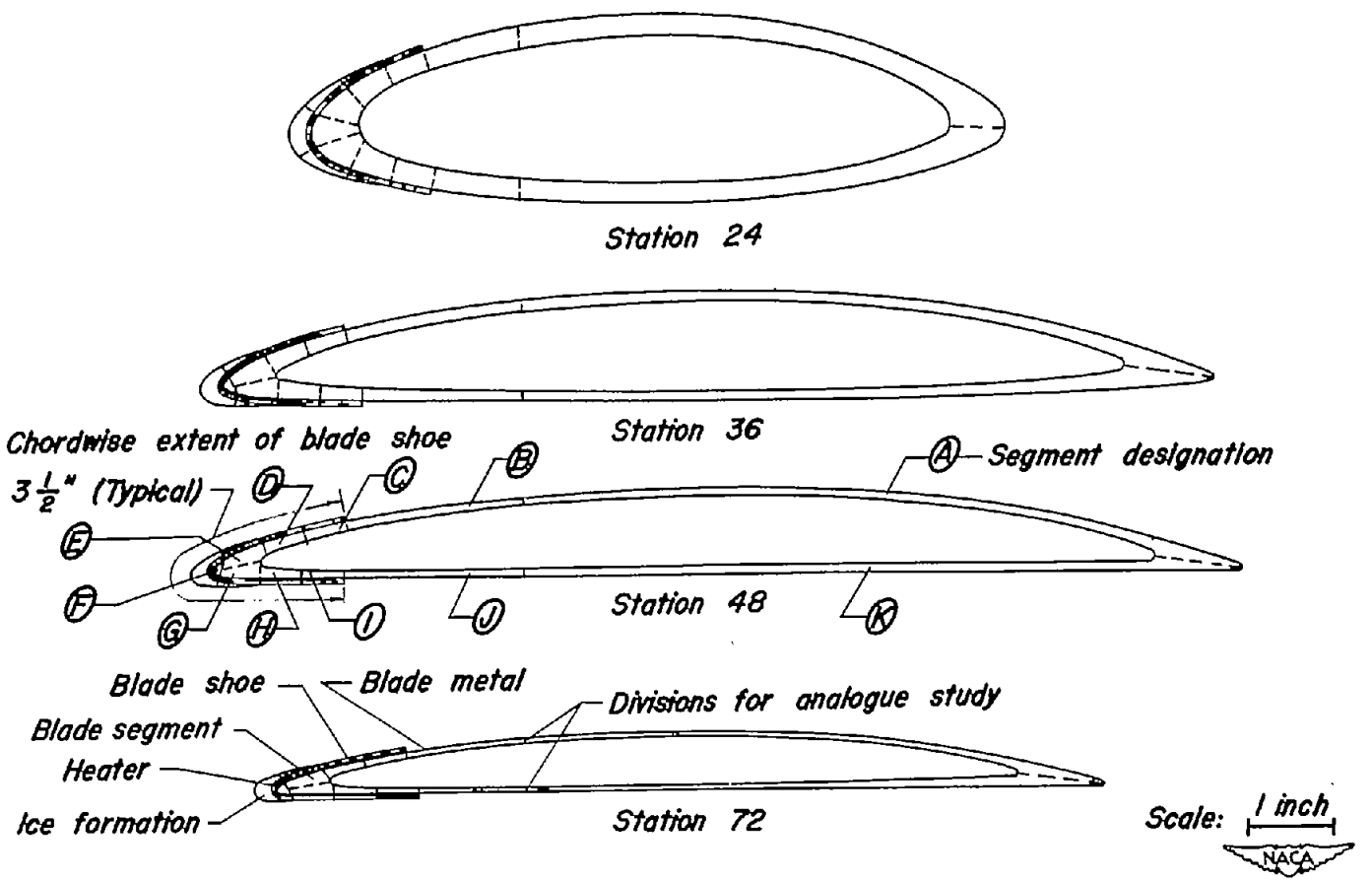


Figure 4.- Cross-section contours of propeller blade at radial stations investigated showing blade shoe, ice formations, and division of blade for analogue study.

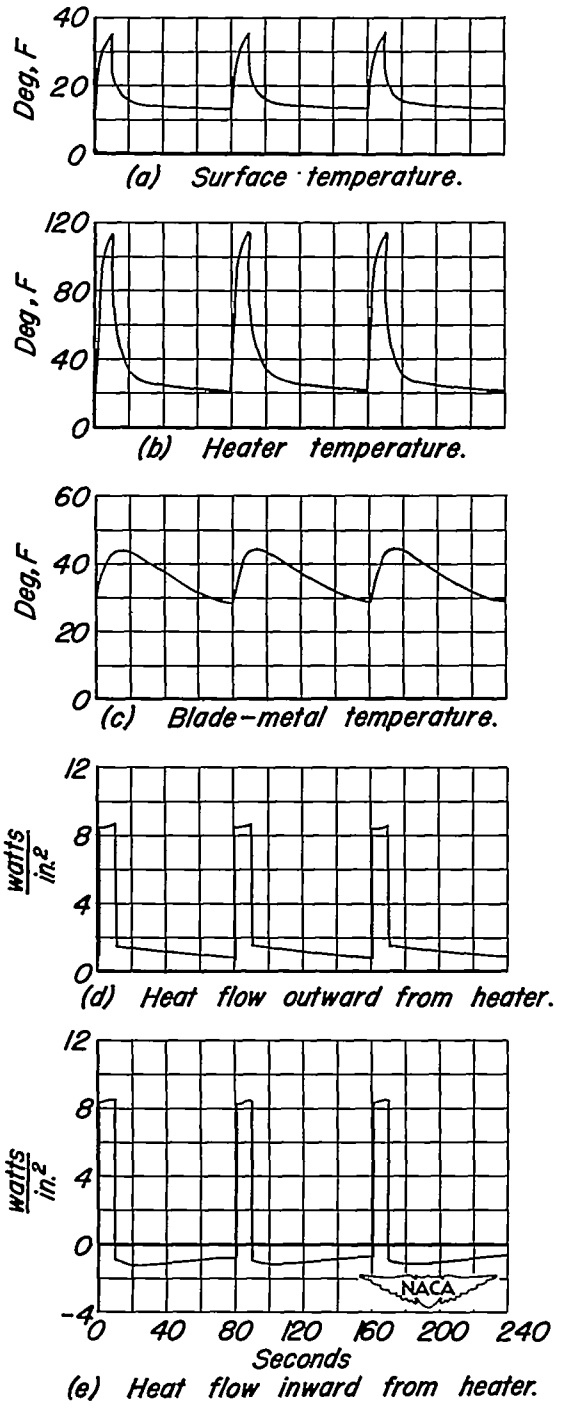


Figure 5.- Typical data obtained with electrical analogue for one blade segment during simulated cyclic de-icing.

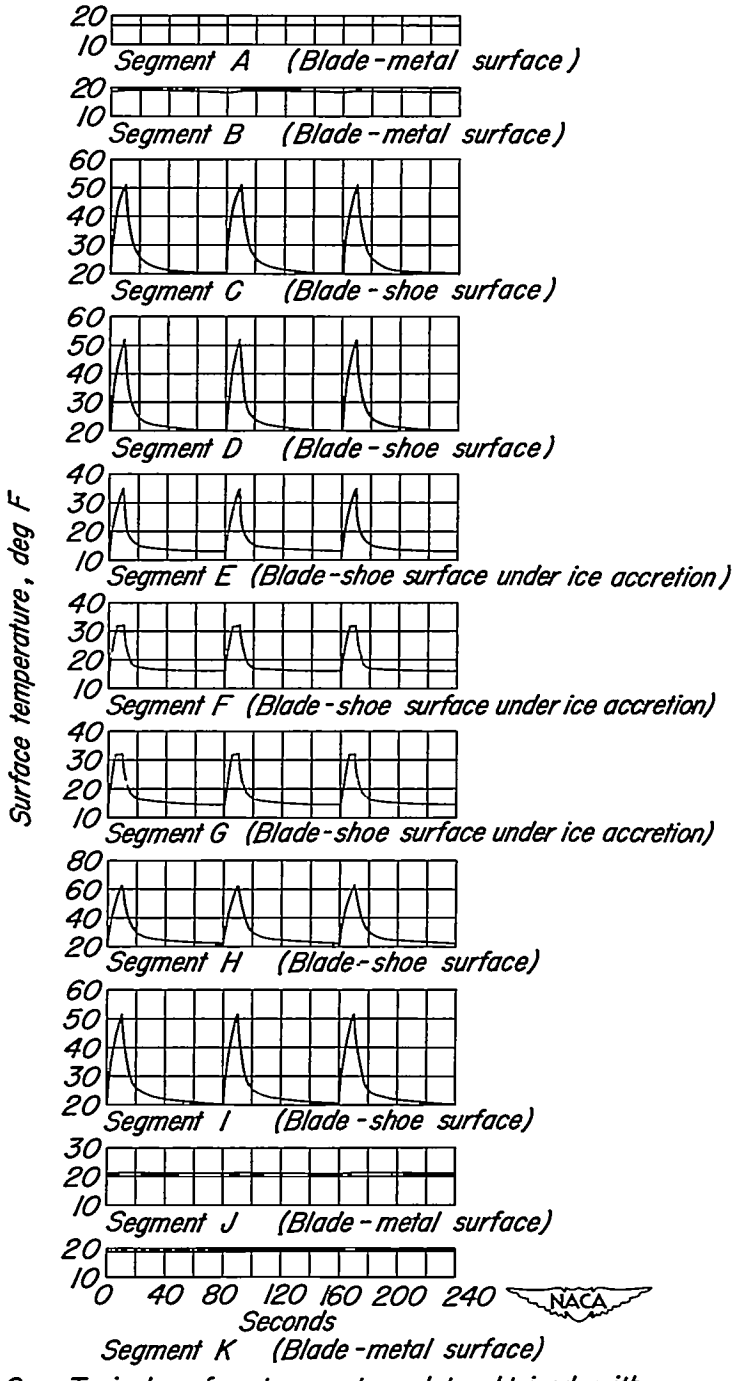
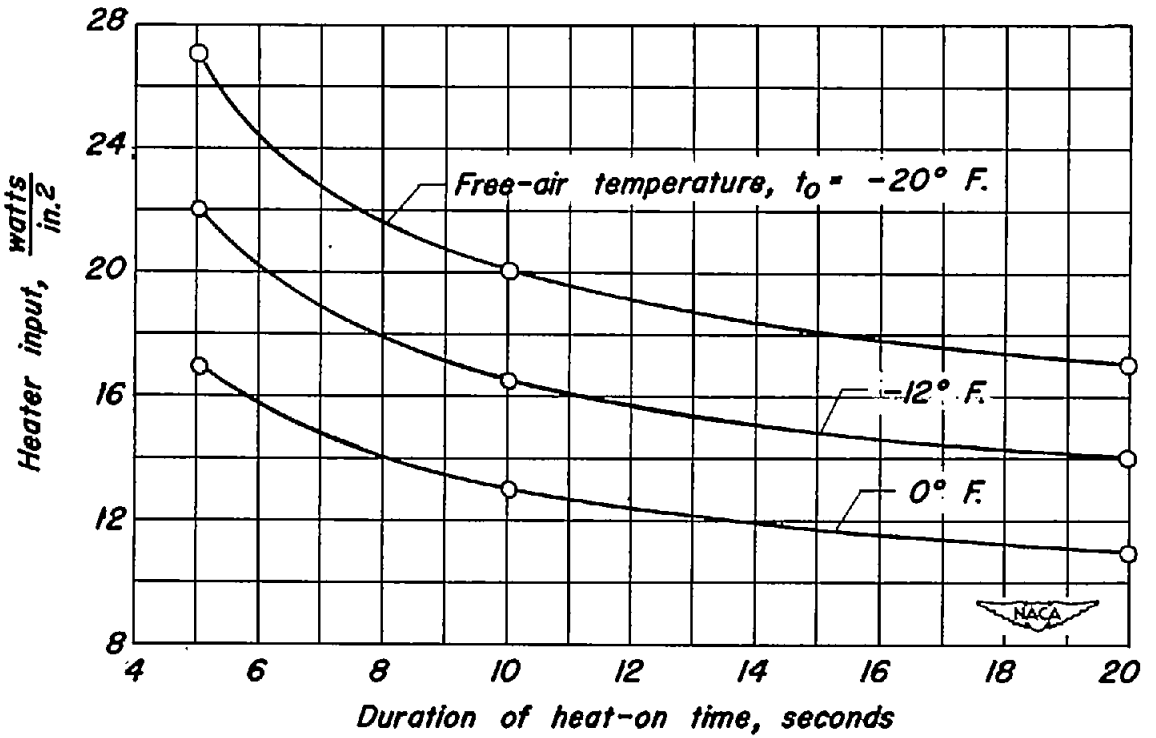
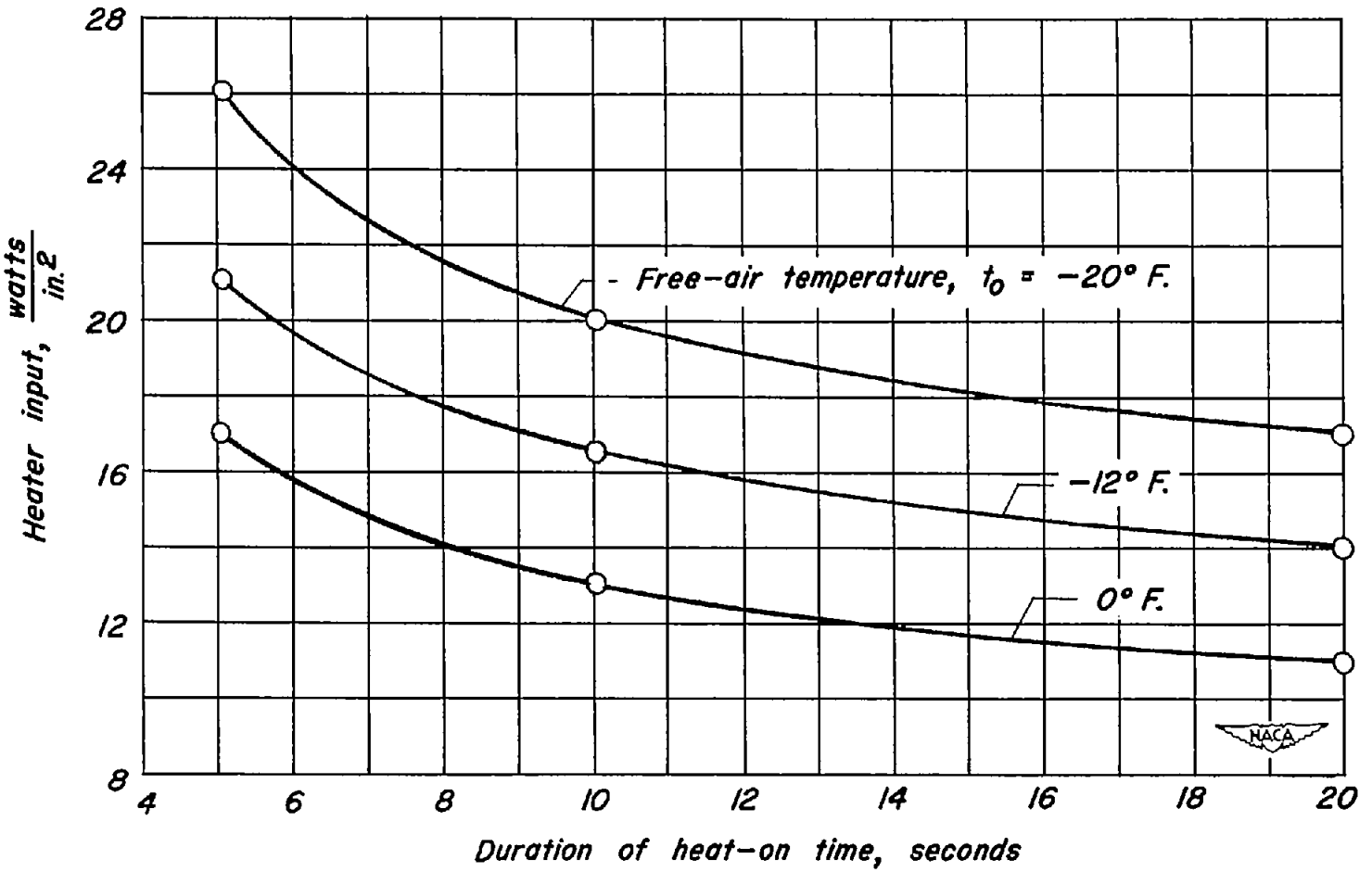


Figure 6.- Typical surface-temperature data obtained with electrical analogue for propeller station 48 during simulated cyclic de-icing.



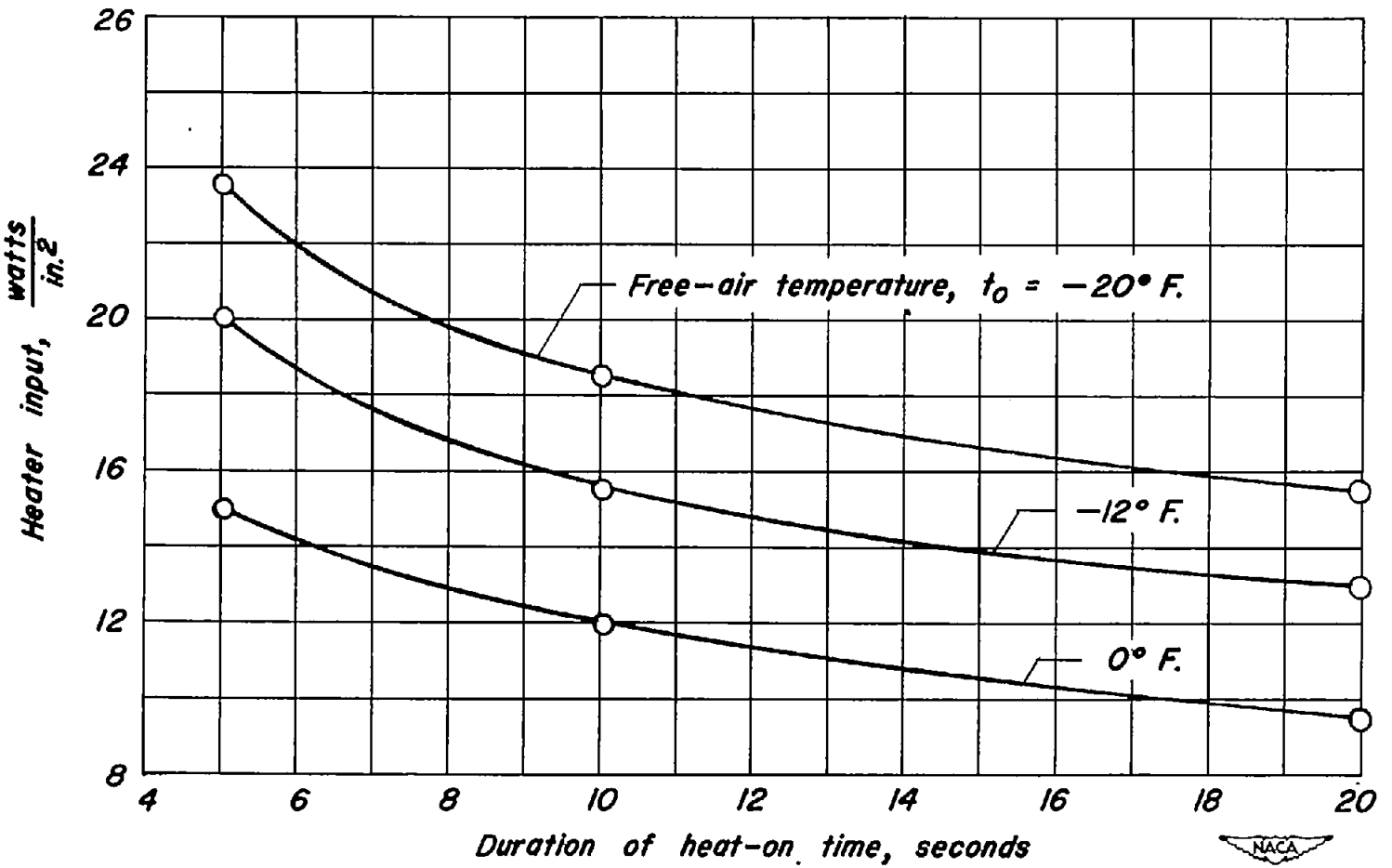
(a) Station 24

Figure 7.- Propeller blade-shoe heating intensity required for de-icing as a function of cyclic heating time on for various free-air temperatures. Conventional blade-shoe configuration. Liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds.



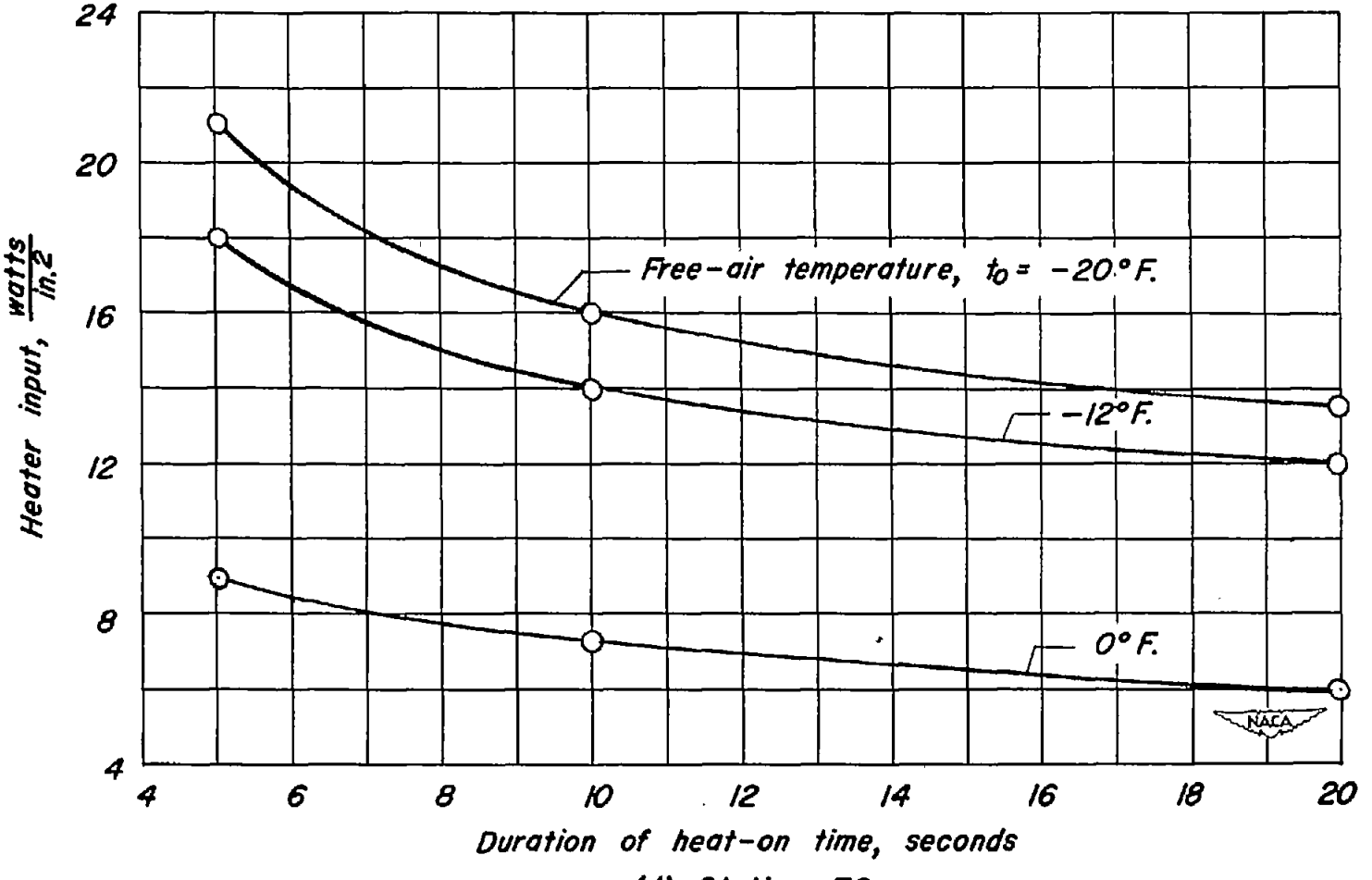
(b) Station 36.

Figure 7 . — Continued.



(c) Station 48.

Figure 7.— Continued.



(d) Station 72.

Figure 7.— Concluded.

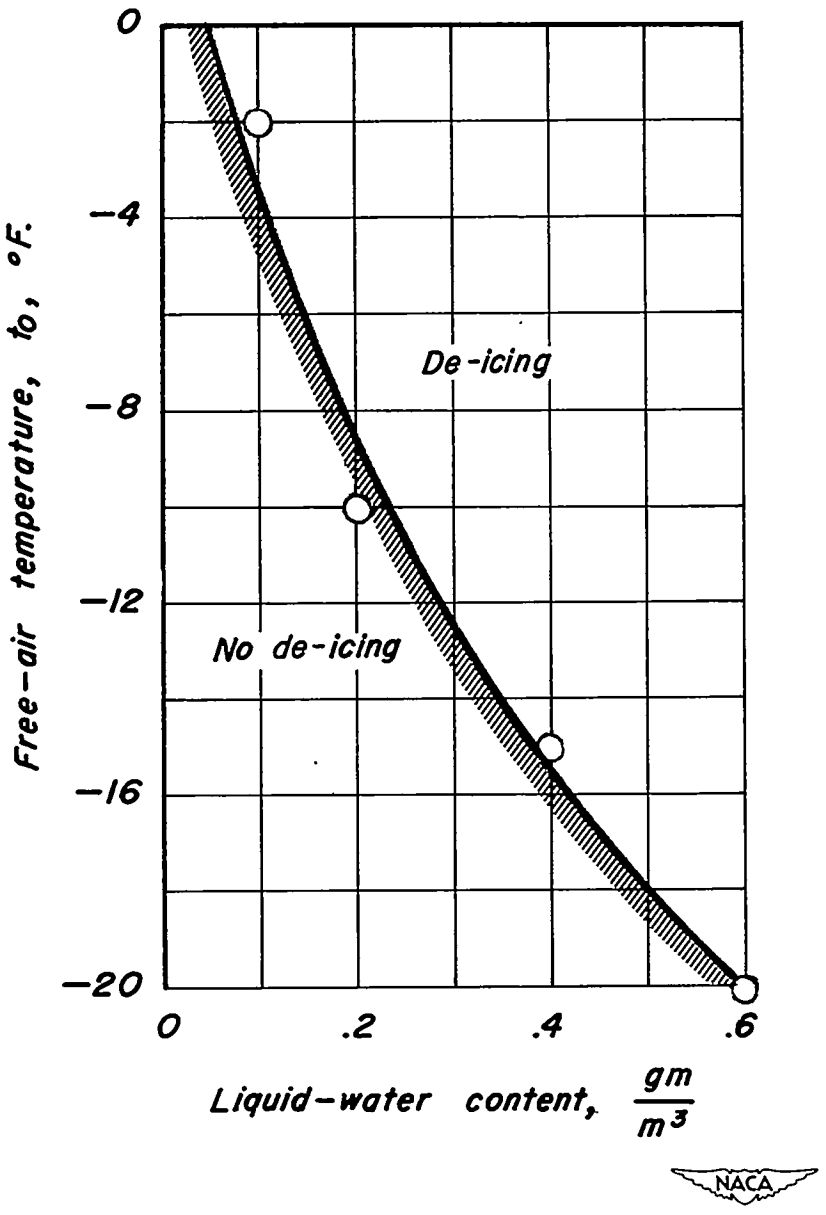


Figure 8. - Variation with liquid-water content of free-air temperature down to which cyclic de-icing can be accomplished with a heating intensity of 10 watts per square inch and a heat-on time of 20 seconds. Conventional blade-shoe configuration; total cycle time, 80 seconds; radial station 48.

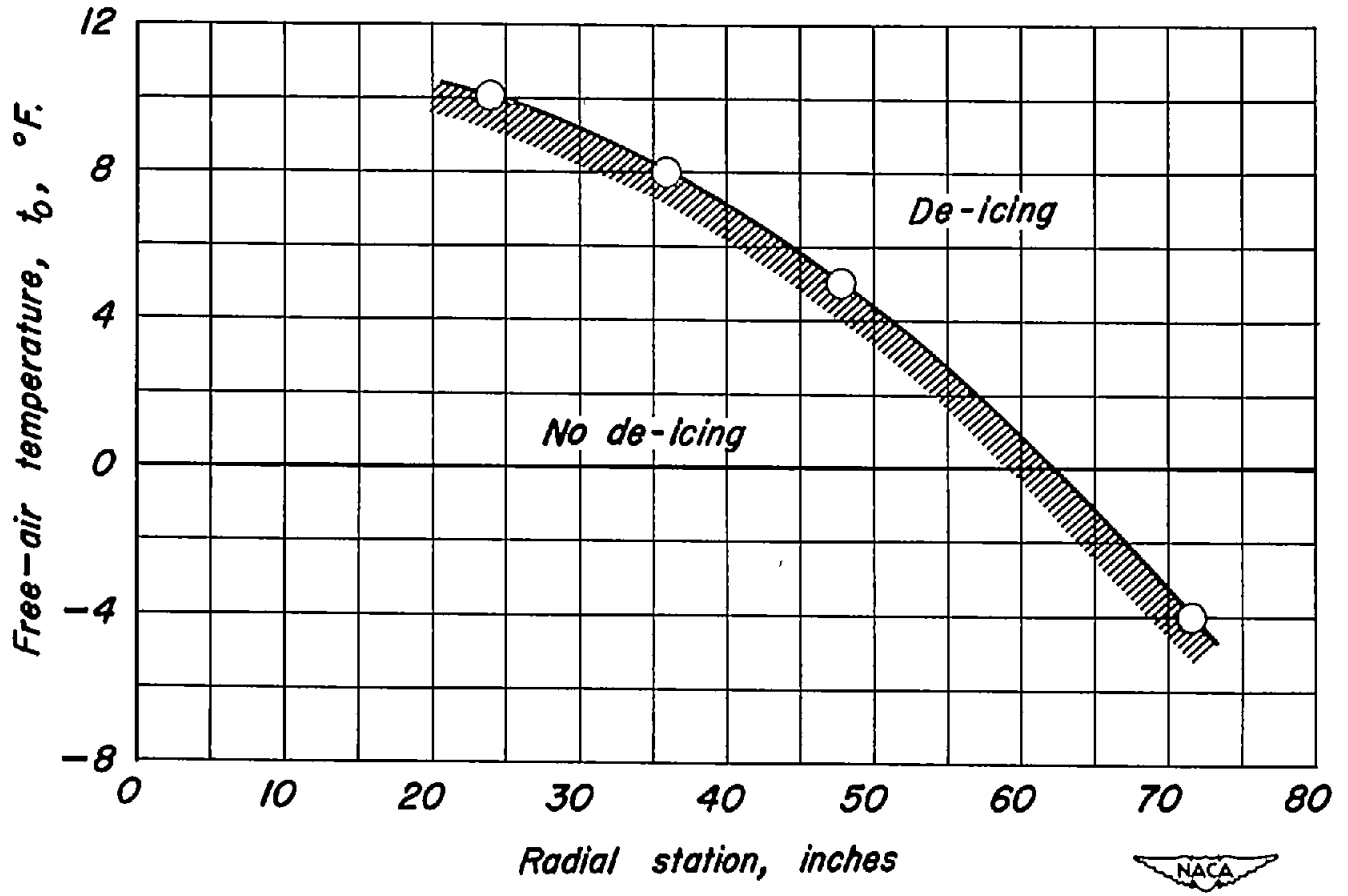
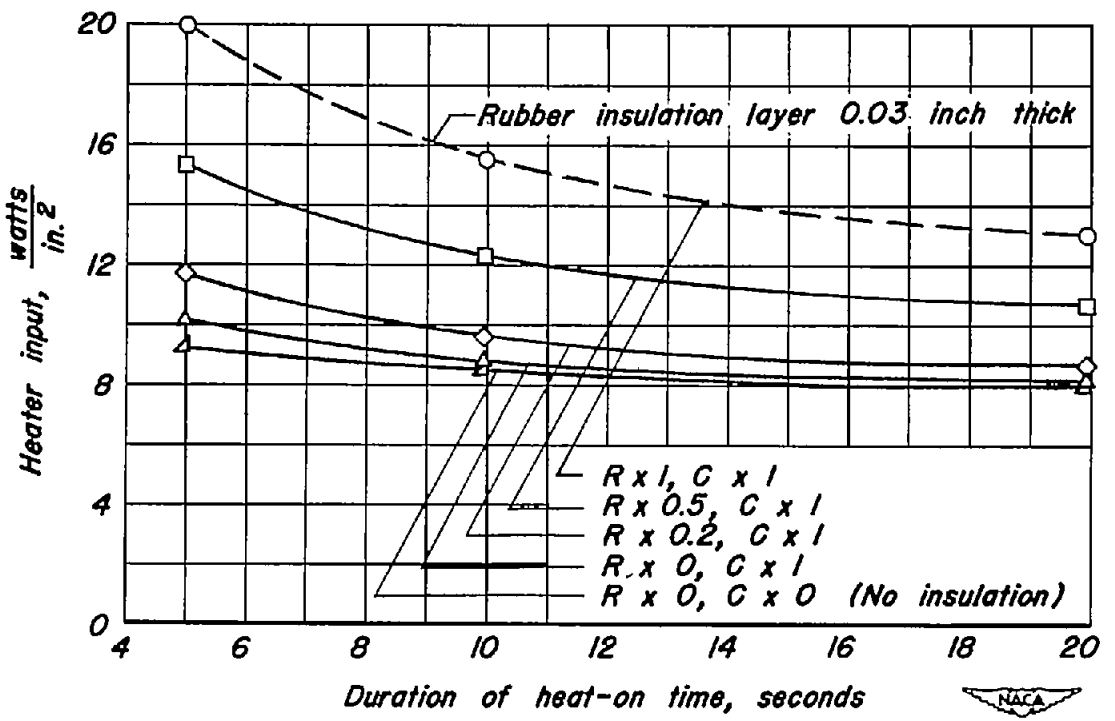
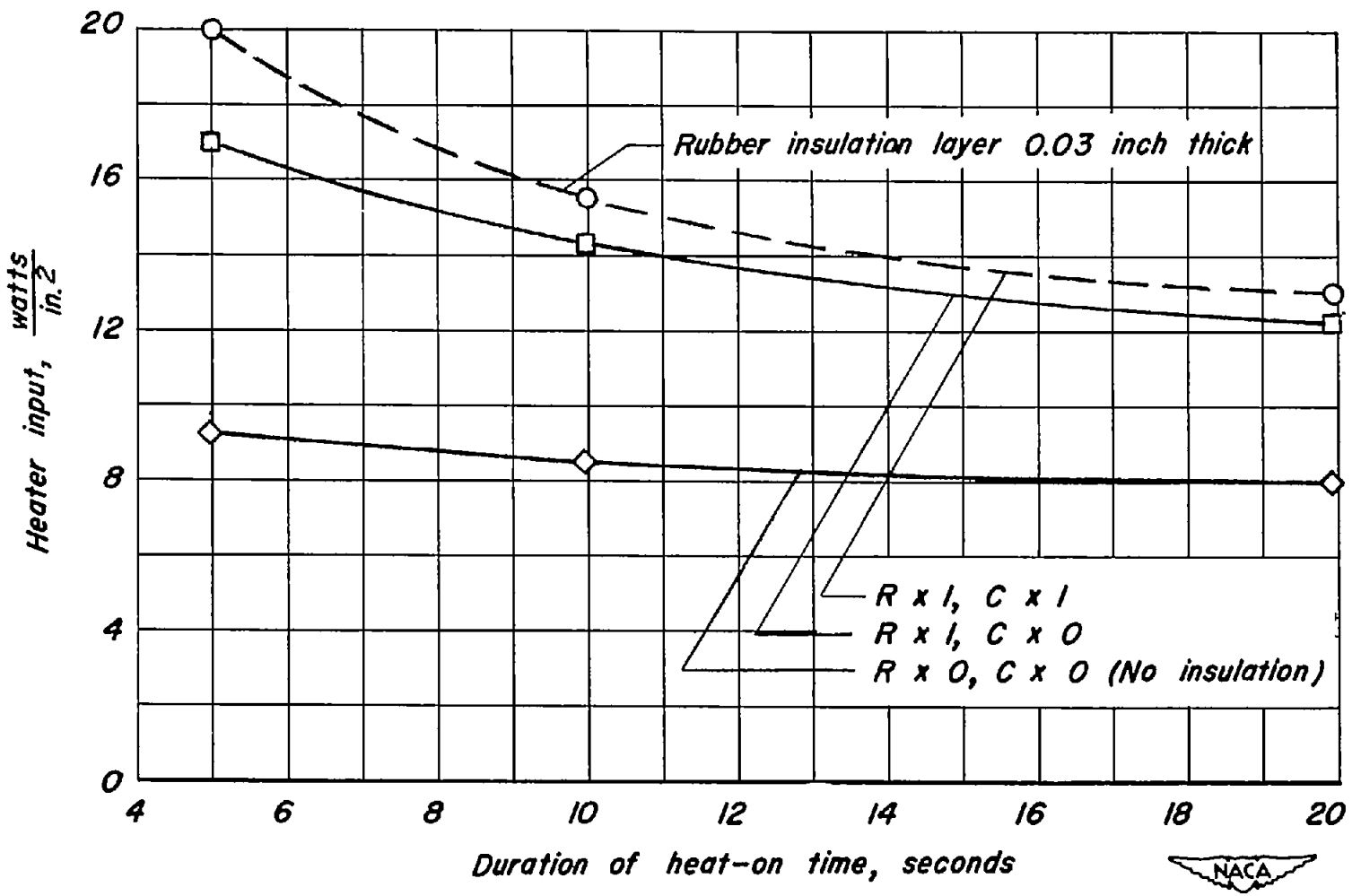


Figure 9.- Variation with radial station of free-air temperature down to which de-icing can be accomplished with a uniform heating intensity of 8 watts per square inch at a cyclic ratio of 20-seconds heat-on time and 60-seconds heat-off time. Conventional blade-shoe configuration; liquid-water content, 0.1 gm/m³.



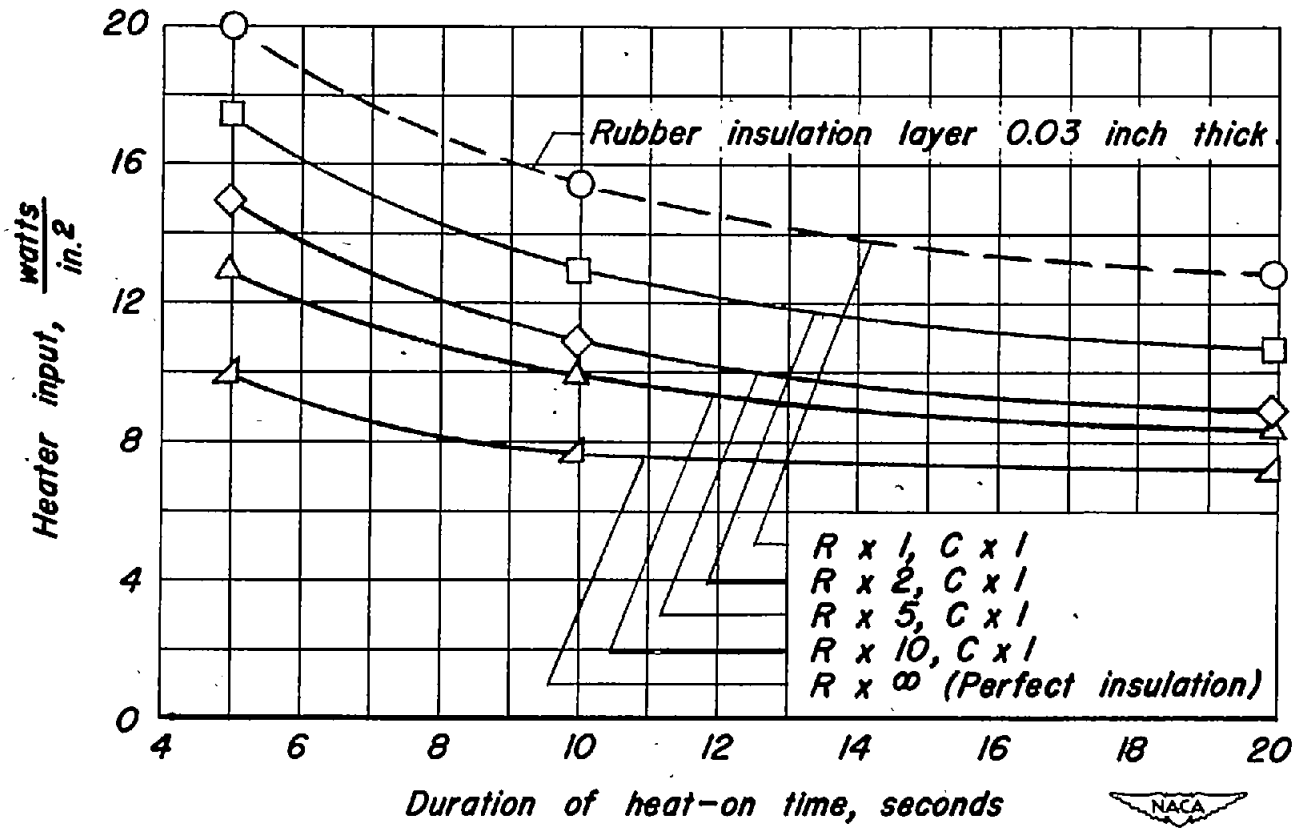
(a) Variation of thermal resistance.

Figure 10.- Effect of variation in properties of the insulation layer above the heater element on the heat required for cyclic de-icing. Values based on a rubber insulation layer 0.03 inch thick. Station 48; free-air temperature, -12°F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds. Insulation layer below heater element 0.03-inch-thick rubber for all cases.



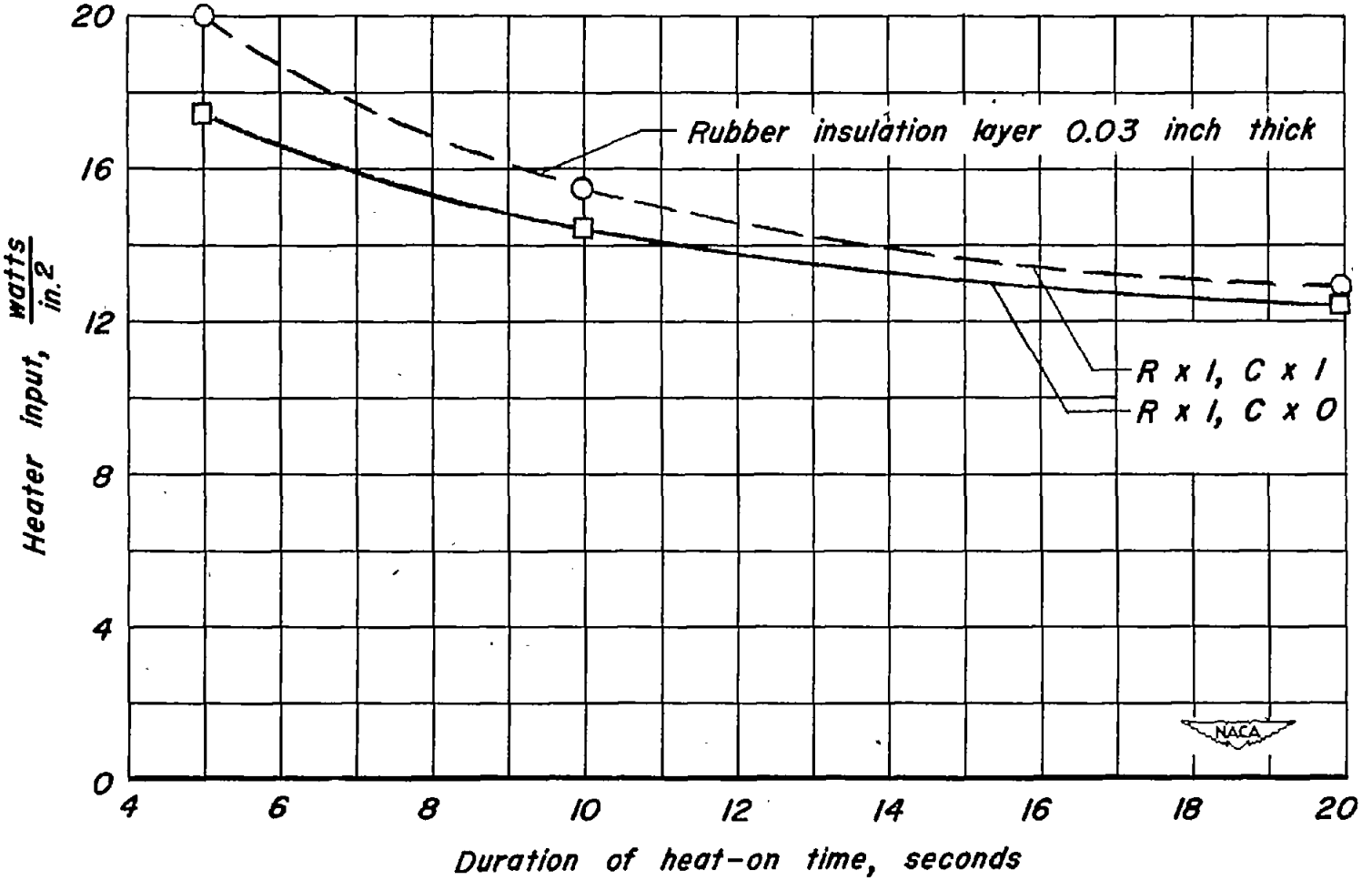
(b) Variation of thermal capacity.

Figure 10.— Concluded.



(a) Variation of thermal resistance.

Figure 11.- Effect of variation in properties of the insulation layer below the heater element on the heat required for cyclic de-icing. Values based on a rubber insulation layer 0.03 inch thick. Station 48; free-air temperature, -12° F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds. Insulation layer above heater element 0.03-inch-thick rubber for all cases.



(b) Variation of thermal capacity.

Figure 11.— Concluded.

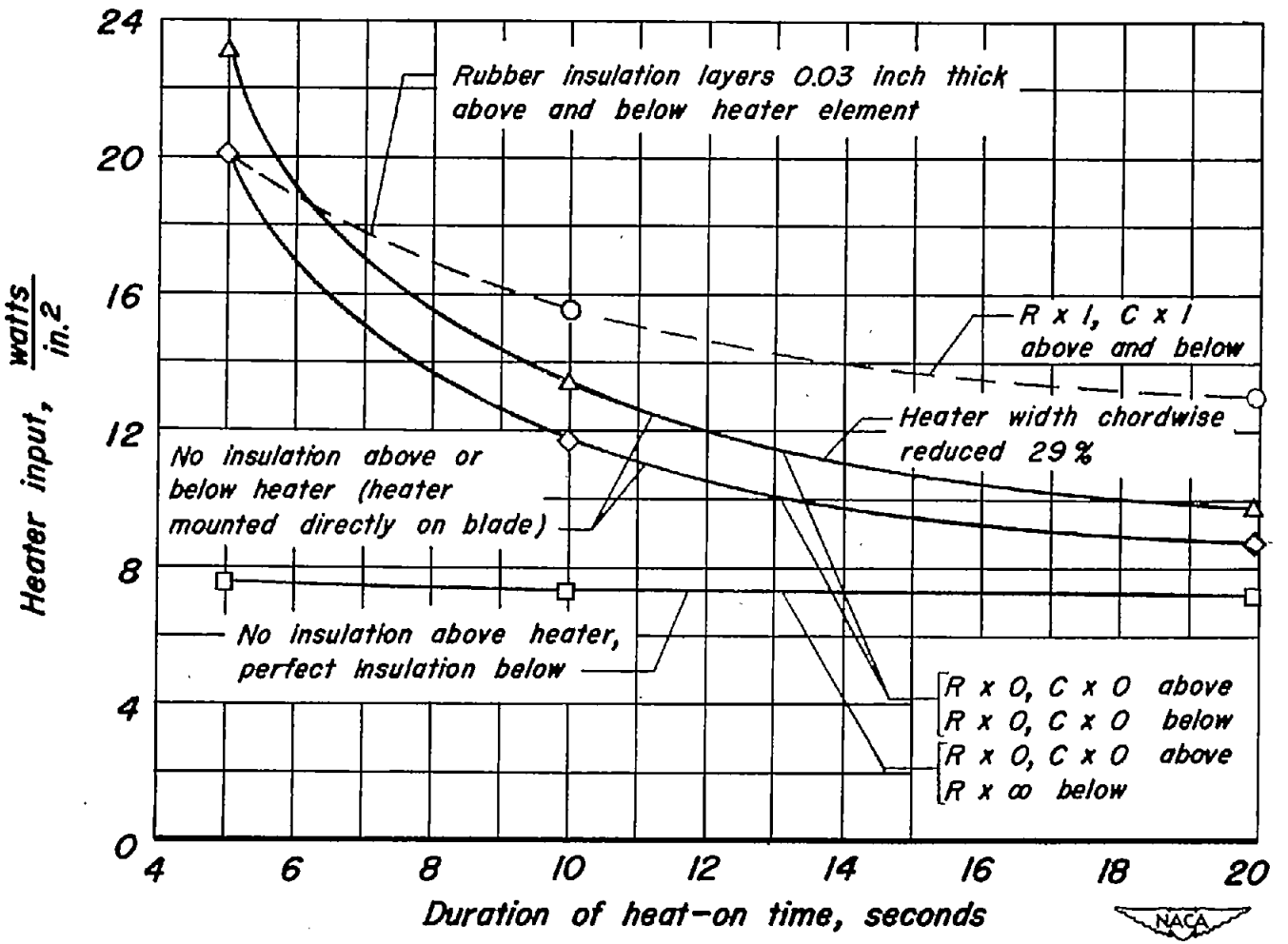


Figure 12.- Effect of variation in properties of the insulation layers both above and below the heater element on the heat required for cyclic de-icing. Values based on rubber insulation layers 0.03 inch thick. Station 48; free-air temperature, -12°F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds.

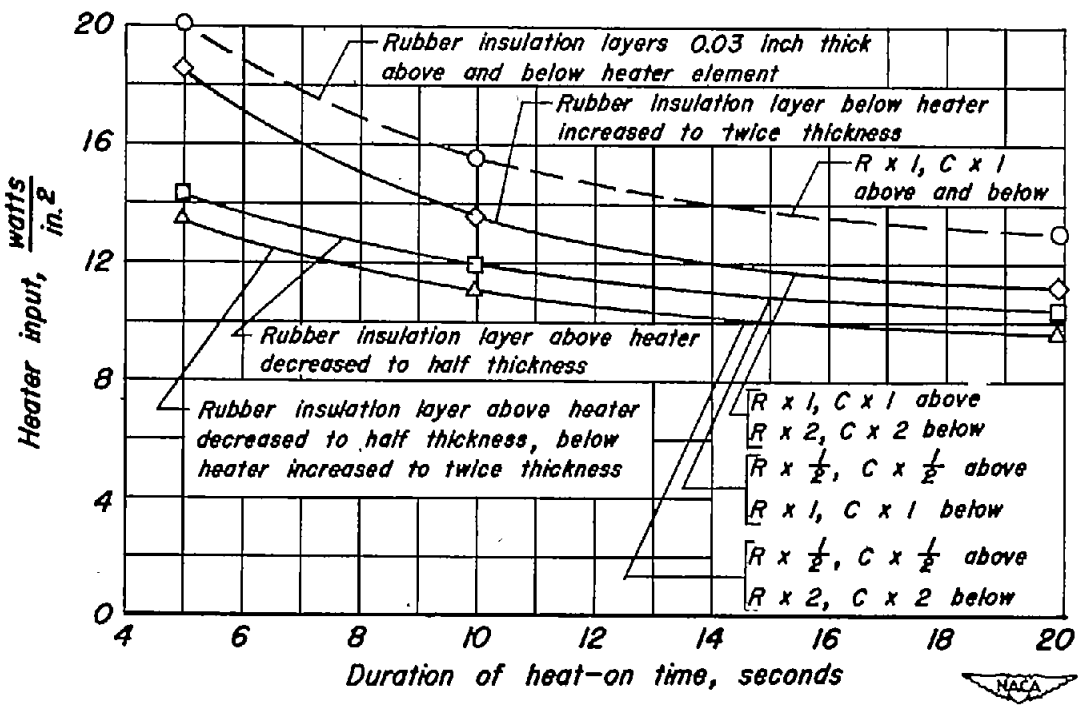
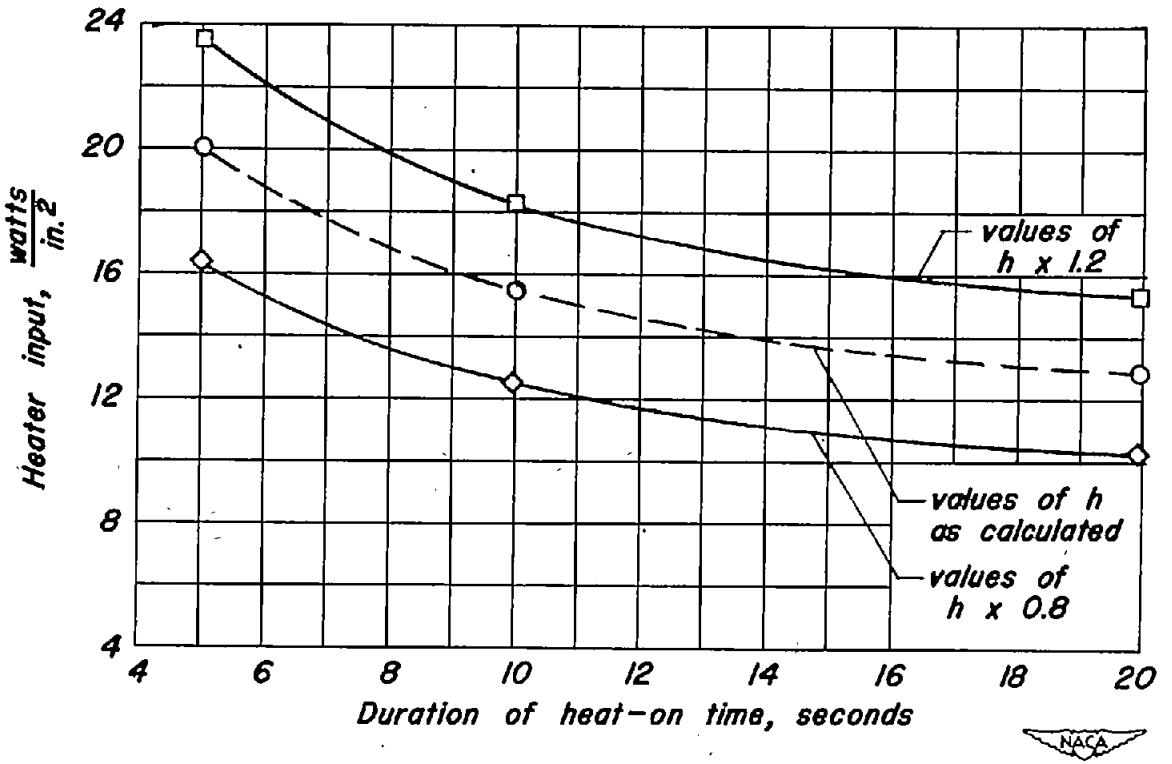
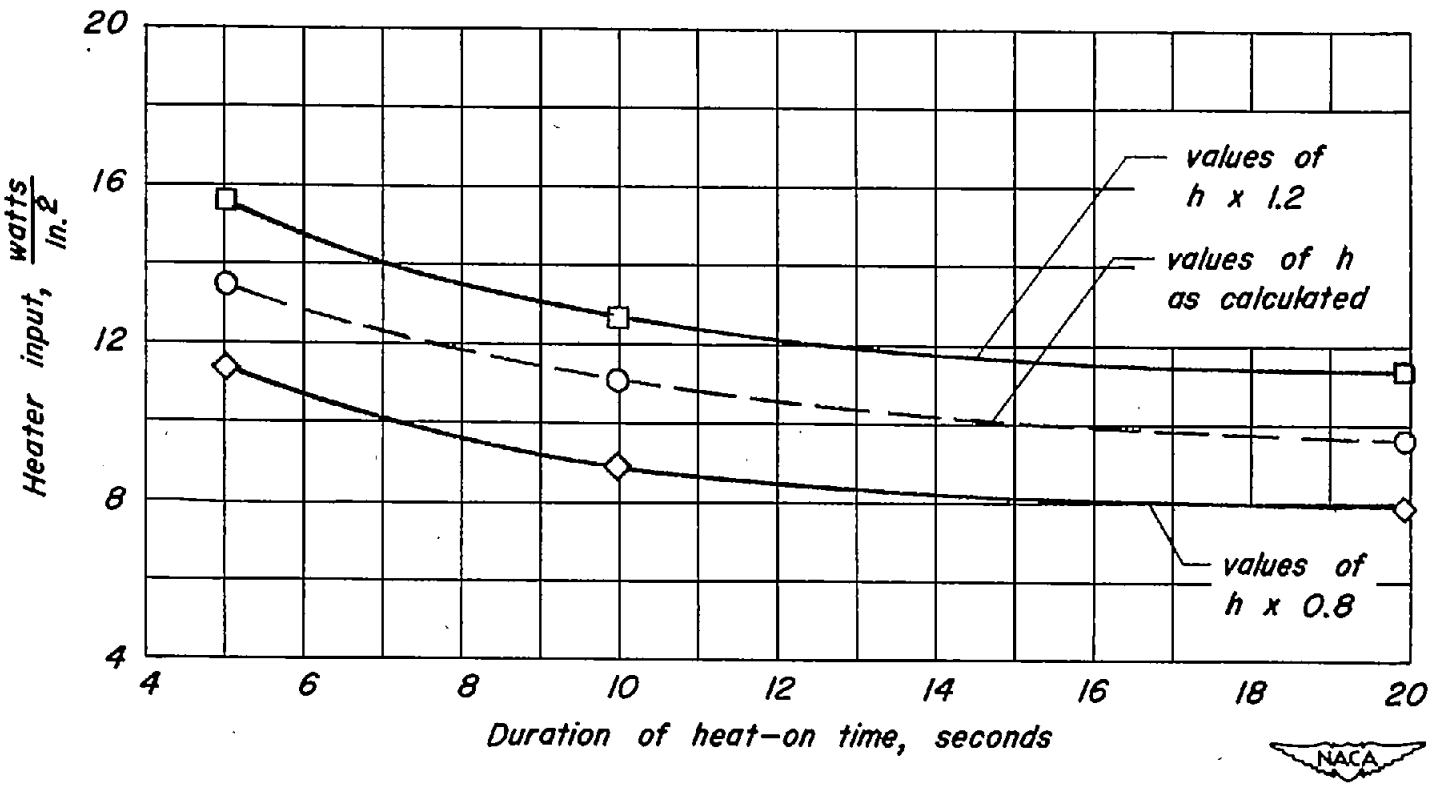


Figure 13.- Effect of variation in thickness of rubber insulation layers above and below heater element on the heat required for cyclic de-icing. Station 48; free-air temperature, -12° F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds.



(a) Rubber insulation layers above and below heater 0.03 inch thick.

Figure 14.- Effect of variation in heat-transfer coefficients for entire blade on the heat required for cyclic de-icing. Station 48; free-air temperature, -12° F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds.



(b) Rubber insulation layer half thickness above heater, twice thickness below heater.

Figure 14.— Concluded.

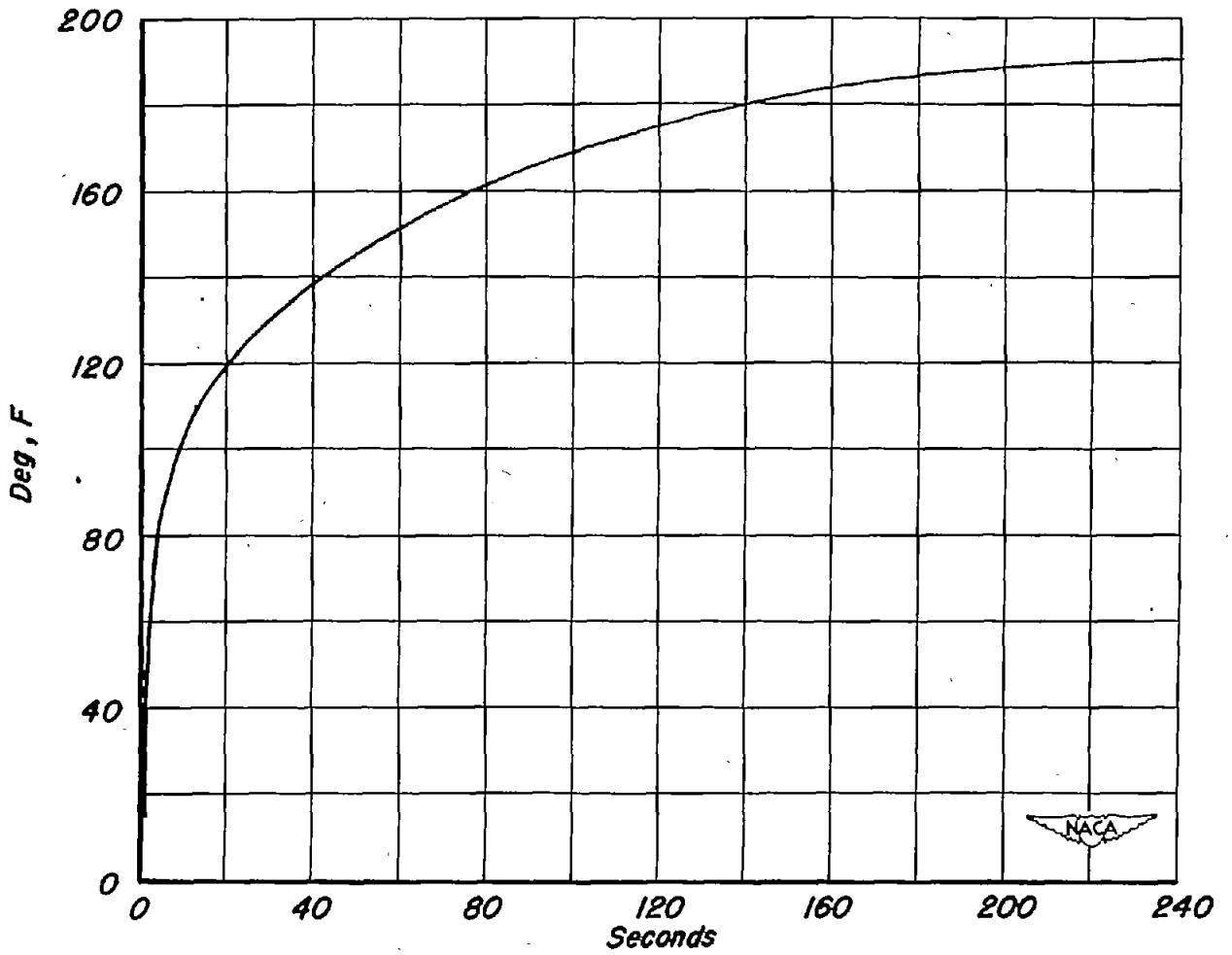
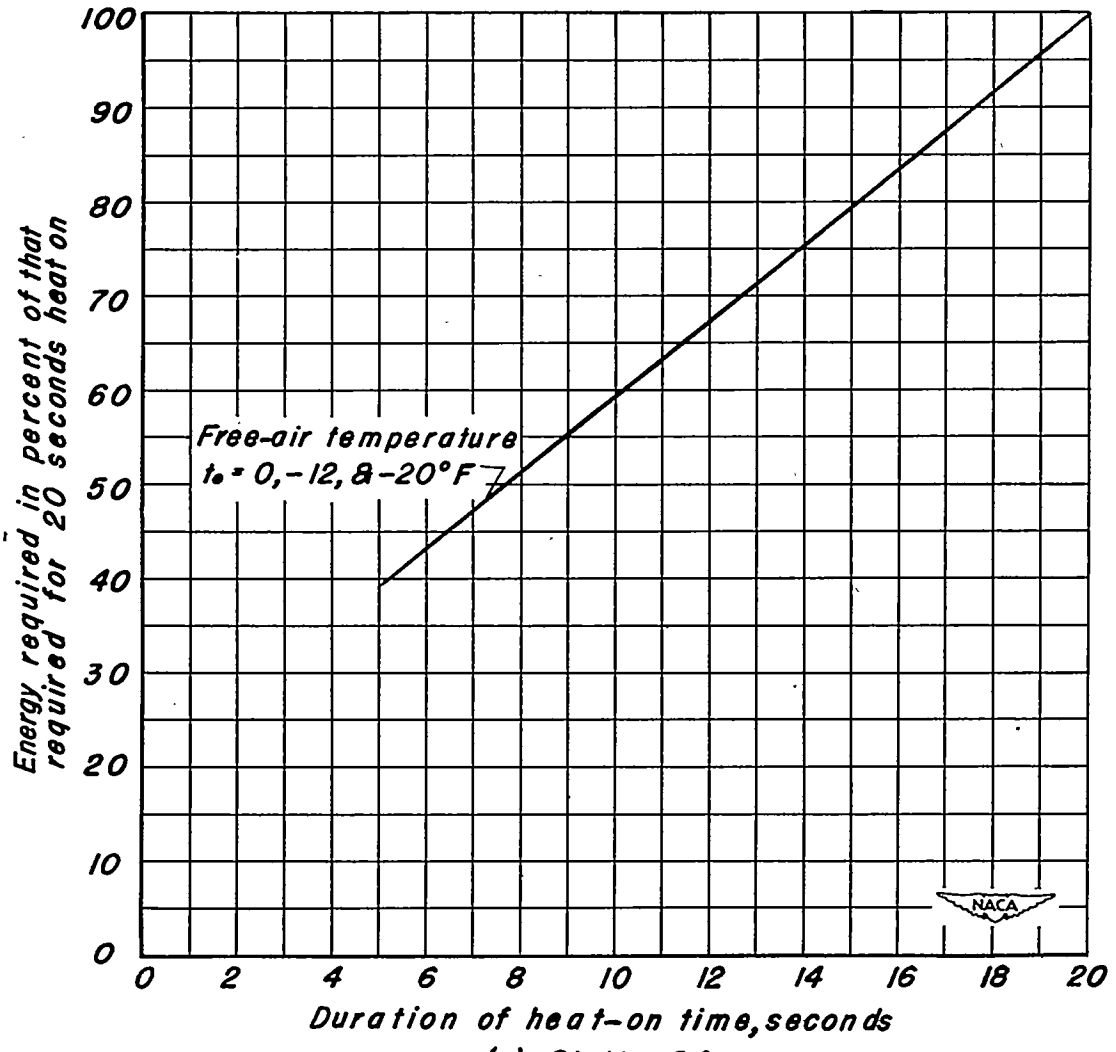
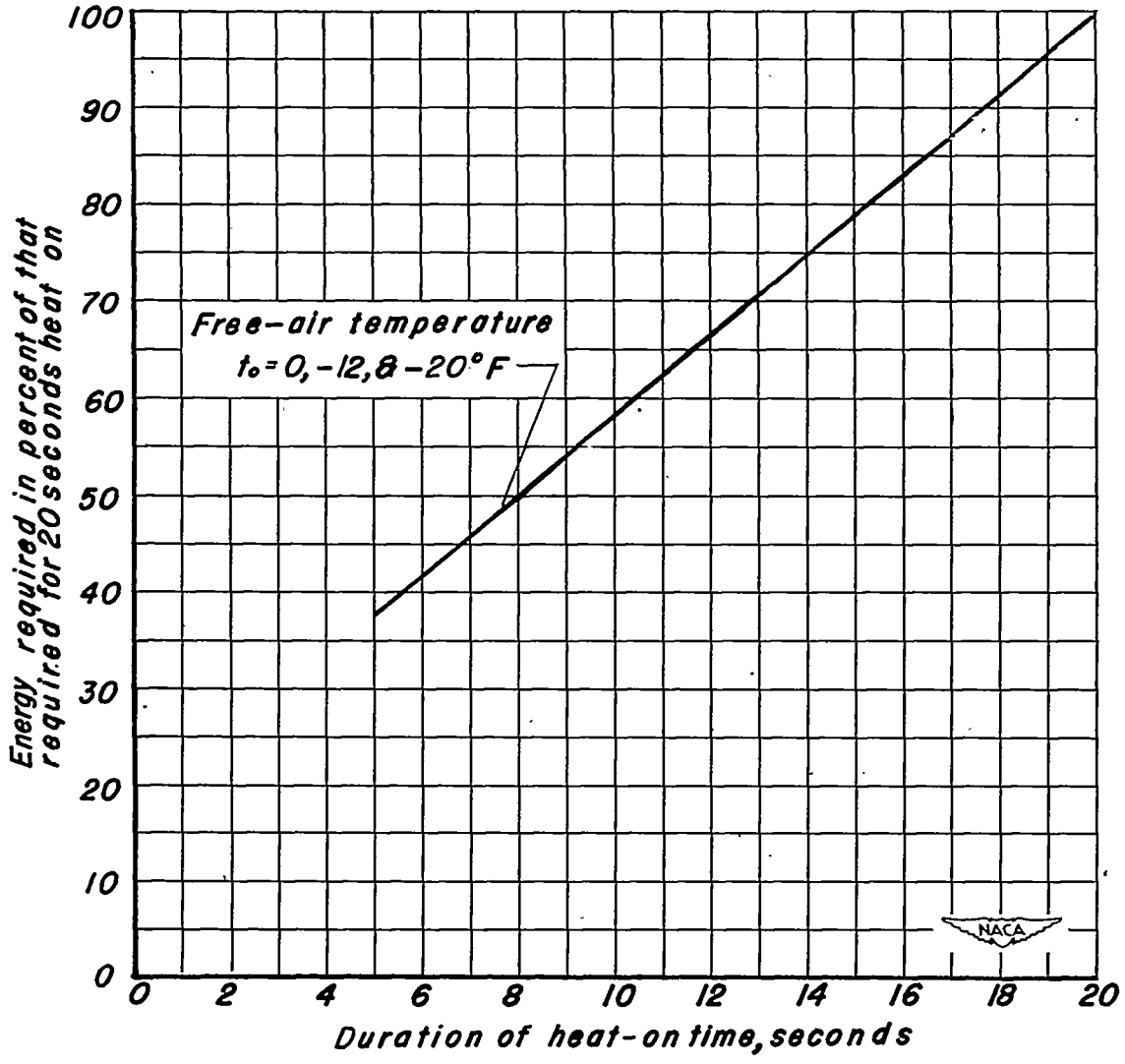


Figure 15.- Typical curve of transient heater temperature with heat applied continuously to a propeller-blade de-icing shoe.



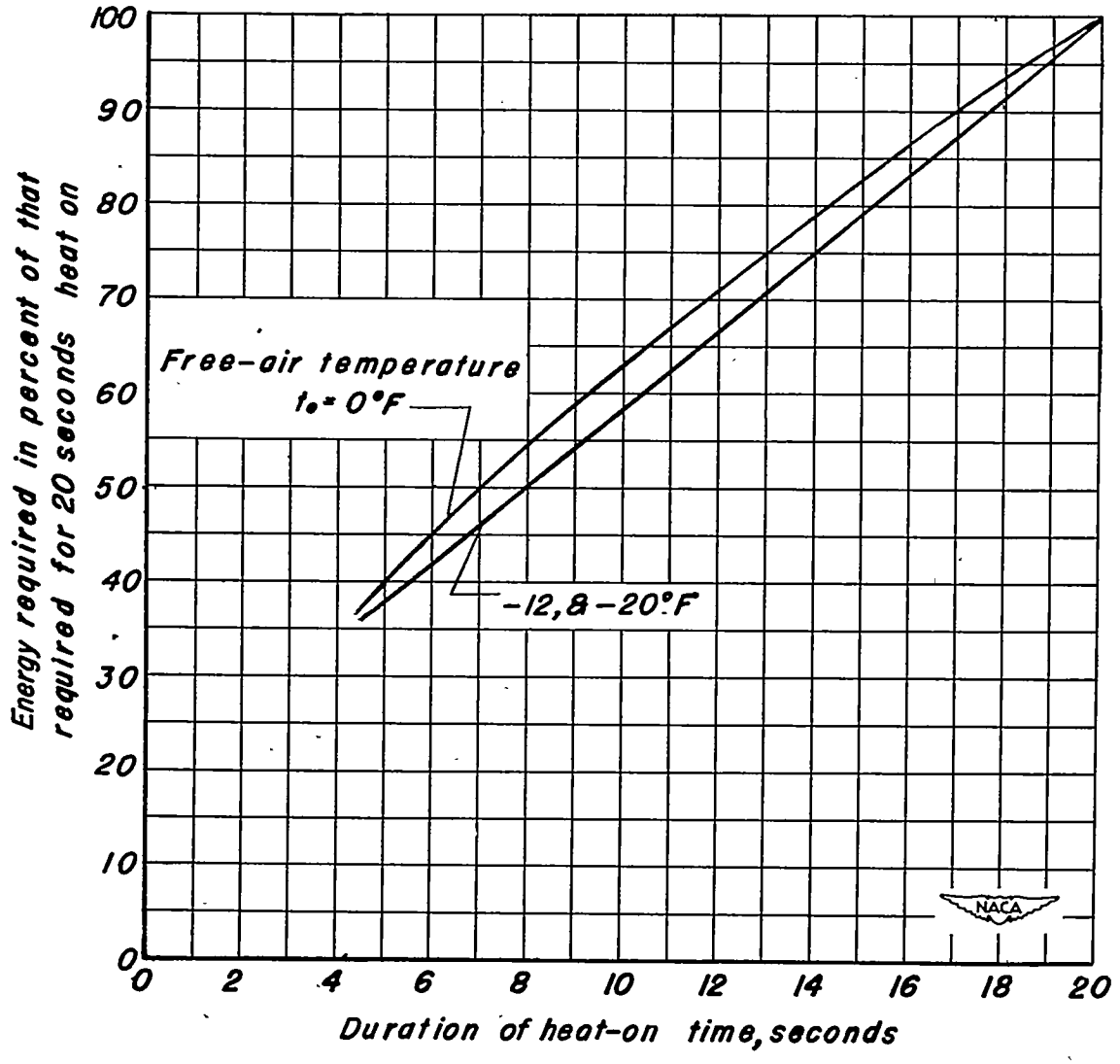
(a) Station 24.

Figure 16.- Effect of varying the heat-on time on the energy required to cyclically de-ice a propeller blade using an 80-second cycle. Conventional blade-shoe configuration; liquid-water content, 0.1 gm/m³.



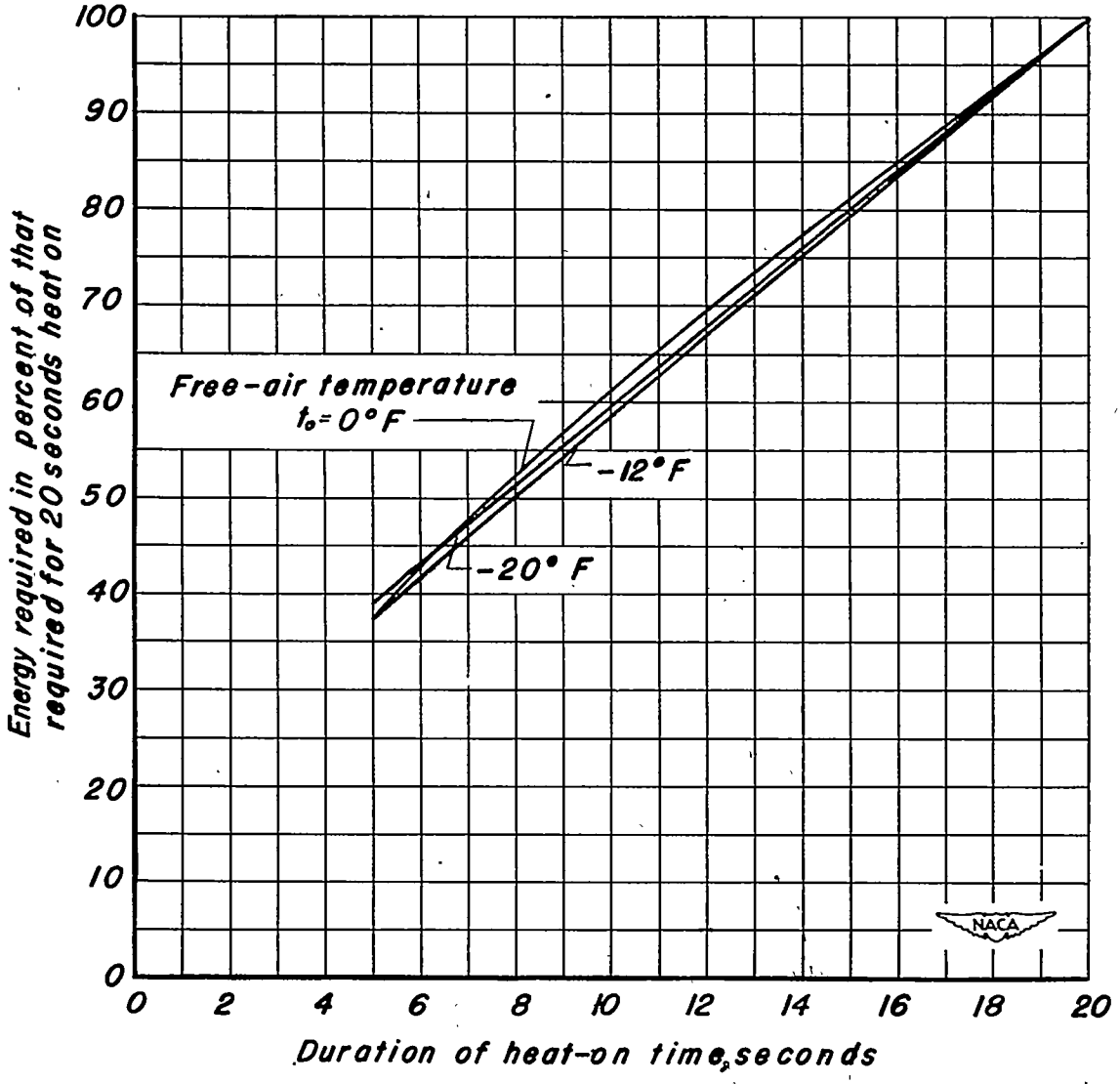
(b) Station 36.

Figure 16.- Continued.



(c) Station 48.

Figure 16.– Continued.



(d) Station 72

Figure 16.— Concluded.

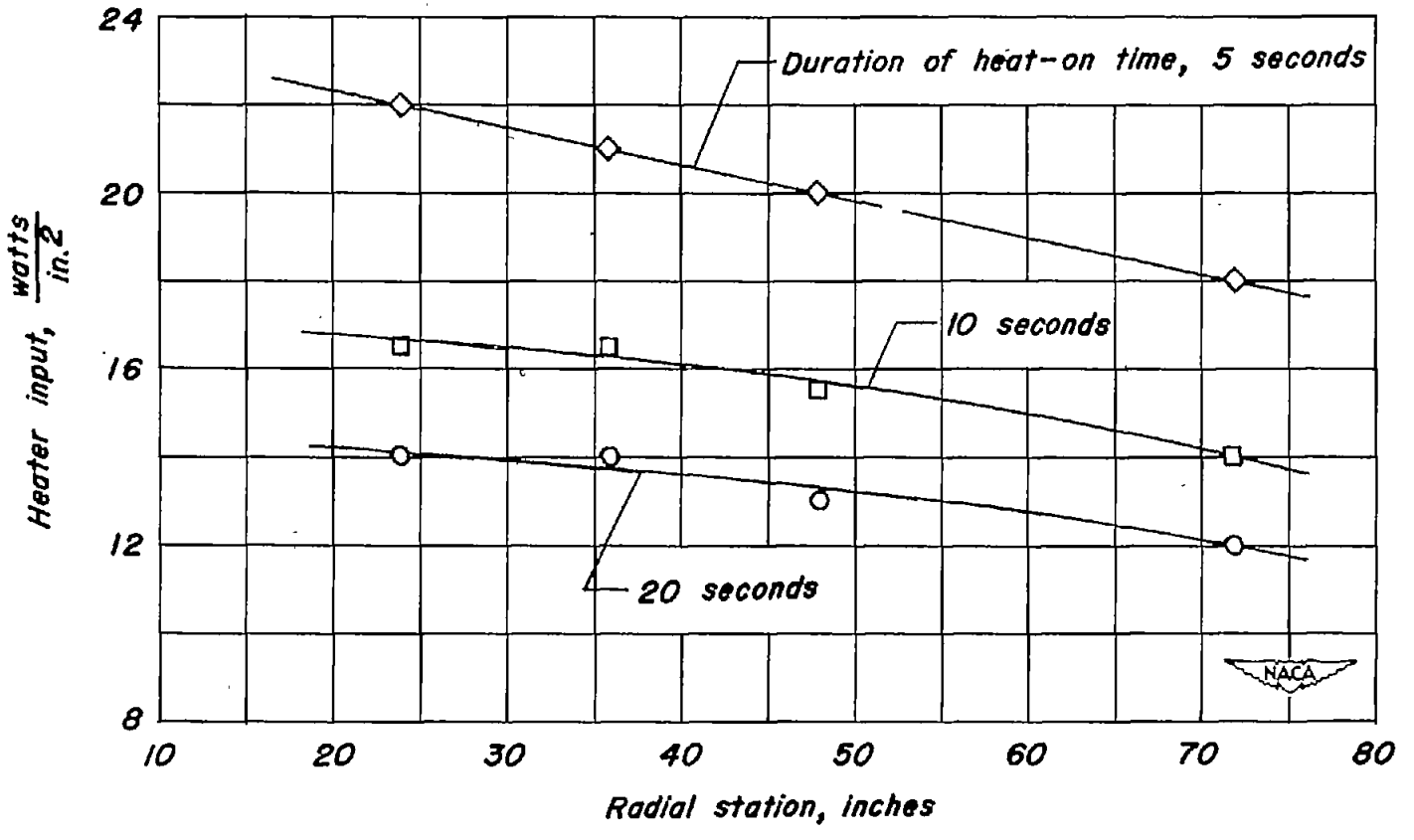


Figure 17.- Variation of heating intensity required for de-icing as a function of radial station for various values of heat-on time. Conventional blade-shoe configuration; total cycle time, 80 seconds; free-air temperature, -12°F; liquid-water content, 0.1 gm/m³.

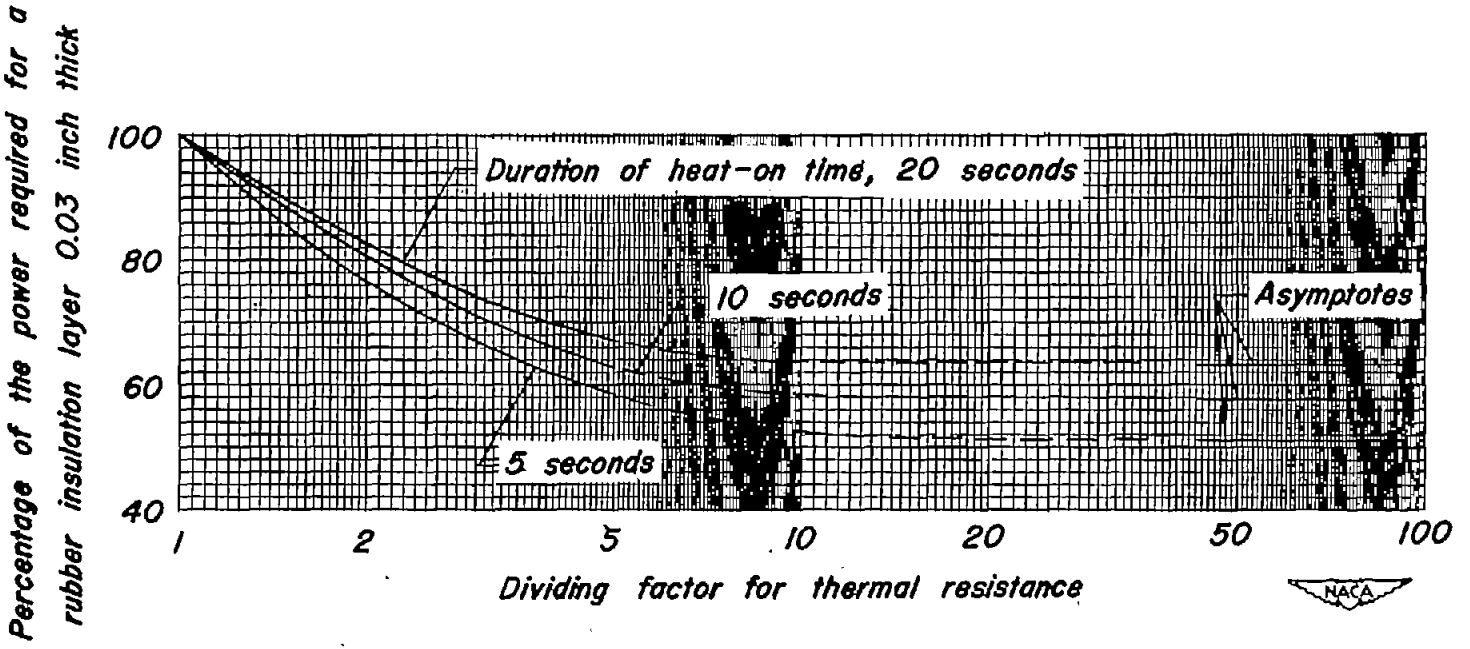


Figure 18.- Effect of reducing the thermal resistance of the insulating layer above the heater element on the power required for cyclic de-icing, based on the power requirement for a heating shoe consisting of rubber insulation layers 0.03 inch thick above and below the heater element. Station 48; free-air temperature, -12°F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds.

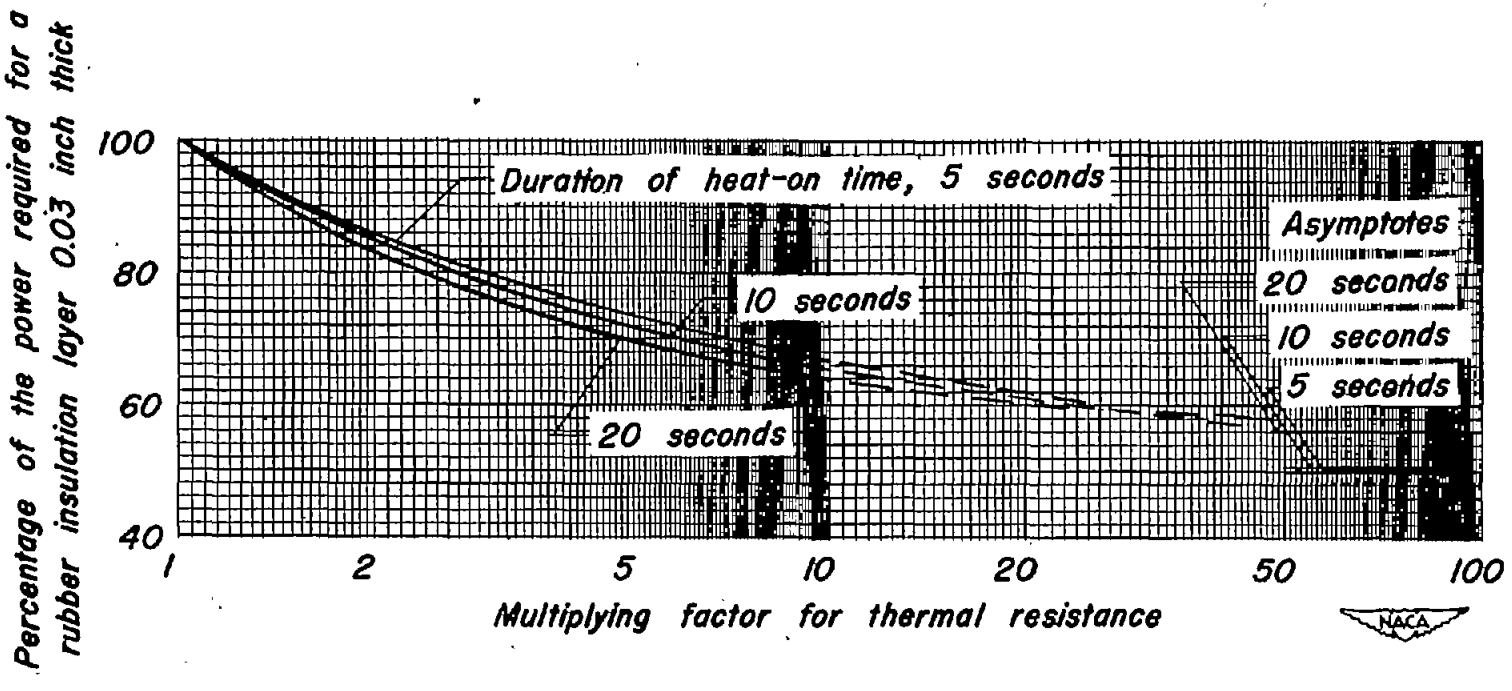


Figure 19.- Effect of increasing the thermal resistance of the insulating layer below the heater element on the power required for cyclic de-icing, based on the power requirement for a heating shoe consisting of rubber insulation layers 0.03 inch thick above and below the heater element. Station 48; free-air temperature, -12° F; liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds.

NACA-Langley - 12-22-53 - 1000