NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4141

THE USEFUL HEAT CAPACITY OF SEVERAL MATERIALS FOR BALLISTIC NOSE-CONE CONSTRUCTION

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SUMMARY

An analysis has been made of the heat-absorption characteristics of several materials which might be considered for construction of ballistic missile heat sinks. The numerical analysis, which took into account the variation of material properties with temperature, was made for conditions corresponding to a typical ballistic-missile trajectory.

Four materials, each characteristic of a group of materials, were considered - copper, Inconel-X, graphite, and beryllium.

It was found that significant weight saving could be achieved by the use of graphite or beryllium in place of copper. Inconel-X was found to be unsatisfactory because of its low thermal conductivity.

It is indicated that large errors in computed temperature distributions in materials can arise if the Fourier heat-conduction equation is approximated in the conventional fashion.

INTRODUCTION

When a ballistic missile enters the earth's atmosphere at high speed, its total kinetic and potential energy is ultimately dissipated in the form of heat. A portion of this energy is delivered to the atmosphere by viscous dissipation and by radiation and the remainder must be absorbed by the missile. The portion absorbed by the missile can either be stored in a heat sink or absorbed and rejected by an internal cooling system.

The simplicity of the heat-sink system is attractive. However, the problem of choosing a suitable material to act as the heat absorber is difficult. The principal requirements which must be met are:

(a) The material must maintain the structural integrity of the missile.

(b) It must be as light as possible.

(c) It must lend itself to fabrication into the required shapes.

If these seemingly obvious requirements are examined in more detail, it is found that many ramifications exist. For example, the heat-sink material can fail structurally in several ways.

(a) It can lose its strength because of high temperature and fail conventionally under the action of air and deceleration loads.

(b) It can fail mechanically due to thermal stresses.

(c) Failure can occur due to loss of material by spalling of the surface, melting, or sublimation.

(d) It can fail by ignition of the material resulting from an unstable exothermic reaction of the material with the air stream.

The obvious requirement of lightness for any material used in aircraft or missile construction is most stringent for the final stage of ballistic missiles. The weight of the material required to absorb the heat generated during entry into the atmosphere can be a large fraction of the total weight of the entry stage. Since the initial gross weight can be from 10 to 50 times the weight of the entry stage, depending primarily on the range of the missile, each pound saved in final stage weight represents a saving of from 10 to 50 pounds in initial gross weight.

It is necessary that the material selected be amenable to fabrication into the required shape. However, it is probably not necessary that the material lend itself to mass-production techniques or that it be inexpensive since the cost of heat-sink material will be an insignificant fraction of the total missile cost.

With the above requirements in mind, several groups of materials were considered. Each of the several groups have one or more desirable attributes. These attributes are:

(a) High strength-to-weight ratio at elevated temperature.

(b) High melting or sublimation temperature.

(c) High thermal conductivity.

(d) High specific heat.

(e) High ductility.

(f) Low coefficient of thermal expansion.

(g) High resistance to oxidation.

The first group comprises heavy ductile materials with high thermal conductivity such as copper, gold, and silver. This group is also characterized by relatively low melting temperature and low specific heat.

The second group is composed of more or less refractory metals of medium density which retain their strength at elevated temperatures. Typical members of this group are the nickel-chromium-iron stainless steels, the cobalt turbine blade alloys, Inconel-X, etc. This group is characterized by relatively high resistance to oxidation and by low values of specific heat and thermal conductivity.

The third group is composed of the lightweight metals. Beryllium is outstanding in this group. It is characterized by high strength-weight ratio, high specific heat and thermal conductivity, high resistance to short-time oxidation, and a reasonably high melting point. It has the disadvantage of having poor ductility.

The fourth group is composed of semimetals of which carbon (graphite) is the outstanding member. Graphite is characterized by a very high sublimation temperature, high thermal conductivity and specific heat, and low density. It has, however, poor high-temperature oxidation resistance and low strength.

The problem, then, is to examine typical members of each of these groups and determine their suitability as heat-sink materials. The questions which should be answered are:

(a) What thickness of material is required to prevent melting or sublimation of the surface?

(b) What are the comparative weights per unit area of materials thick enough to prevent melting of the surface?

(c) What are the temperature gradients in the material, which, with the physical properties, determine the thermal stress in the material?

NOMENCLATURE

A	frontal area of nose cone
c	specific heat
C_D	drag coefficient
h	heat-transfer coefficient
k	thermal conductivity

L	slab thickness
Q	total heat absorbed per unit surface area
T	temperature
V	speed
W	weight of nose cone
x	linear coordinate
α	thermal diffusivity
ϵ	emissivity
ρ	density of slab
σ	Stefan-Boltzmann constant
θ	time from entry into atmosphere

Subscripts

e	entry conditions
s	surface
r	recovery

COMPUTATIONS

The computations were carried out numerically for four materials - copper, Inconel-X, beryllium, and graphite. The specific problem that was solved was to compute temperature time histories in slabs of various thickness using external heat-transfer relations corresponding to entry into the atmosphere from a typical ballistic trajectory. The equation solved was the Fourier one-dimensional heat-conduction equation with thermal properties varying with temperature,

$$\rho c(T)dx \frac{\partial T}{\partial \theta} = \frac{\partial}{\partial x} k(T) \frac{\partial T}{\partial x} dx \tag{1}$$

with boundary conditions,

$$x = L \qquad \frac{\partial T}{\partial x} = 0$$

$$x = 0 \qquad T = T_s$$

and

$$k(T_s)\,\frac{\partial T_s}{\partial x} = h(\theta)\Big[T_r(\theta) - T_s\Big] - \epsilon\sigma T_s{}^4$$

where θ is taken as the time from the entry of the missile into the atmosphere. The total heat absorbed during the entry was calculated from

$$Q = \int_0^{\theta}\left[k(T_s)\,\frac{\partial T_s}{\partial x}\right]_{x = 0} d\theta \qquad (2)$$

Numerous simplyfying assumptions are inherent in this procedure. They are:

(a) One-dimensional heat flow normal to the face of the slab is assumed.

(b) The rear face of the slab is assumed to be insulated.

(c) Variation of material density with temperature is neglected.

(d) The front face of the slab radiates as a gray surface with a constant emmissivity, ϵ, of 0.7.

(e) The hot gas in the boundary layer adjacent to the slab is assumed not to radiate to the slab.

The functions, $T_r(\theta)$ and $h(\theta)$ are shown in figure 1. They were computed for the stagnation point of a 5-foot-diameter hemisphere in a ballistic trajectory with an entry speed of 23,000 feet per second and with a drag parameter (cf. ref. 1) W/C_DA of 345. Dissociation and ionization of the air were neglected. Although neglect of dissociation and ionization certainly cannot be justified from a physical standpoint, there is some evidence that large changes in convective heat transfer should not be expected between the cases of air considered as a perfect and real gas, references 2 and 3. In addition, the primary purpose here is to compare several materials rather than to obtain an exact solution of the convective heat-transfer problem; hence it is felt that the approximation is justified.

DISCUSSION OF RESULTS

Thermal Properties

The thermal properties, conductivity and specific heat, of the four materials examined are shown in figures 2 through 5. They are averaged values taken from a number of sources in references 4 to 7. It is notable that, in general, the properties vary widely over the useful (i.e., up to the melting point) temperature range of the materials. Hence, one should expect sizable differences between a numerical solution of the one-dimensional transient heat-flow equations (cf. eqs. (1) and (2)) and the usual approximate solutions in which specific heat, thermal conductivity, and density are lumped into a constant term, $\alpha = \frac{k}{\rho c}$, thermal diffusivity.

The necessity of considering the variation of thermal properties with temperature is shown in figure 6. In this figure, the surface temperature for a 2-inch graphite slab is shown for two cases. In the first case, average values of thermal conductivity and specific heat were used and in the second case, the variation of these properties with temperature was considered. It can be seen that the more exact solution resulted in computed surface temperatures about 1250° R less than those computed by averaging the thermal properties. Graphite is an extreme example because of the wide variation of both specific heat and thermal conductivity with temperature. A similar computation for the case of a copper slab showed only a small difference between the approximate and exact solutions since the thermal properties of copper do not vary widely with temperature.

Temperature Histories

Temperature time histories of the front and rear faces of 1-inch-thick slabs of the four materials considered are shown in figures 7 through 10. Also included are curves showing the total heat absorbed as a function of time. The effect of the thermal properties on the temperatures attained by the slabs is apparent in these figures. The copper slab, for example, has at most a 650° R temperature difference between the front and rear surfaces. On the other hand, the Inconel-X slab, which has a very low thermal conductivity, has a temperature difference of more than 2050° R between the front and rear surfaces. The inner portions of this material, as can be seen, are completely ineffective in absorbing heat, hence do nothing but add weight to the heat sink. Beryllium and graphite have intermediate maximum temperature differences of 1300° and 1700° R, respectively.

The effect of slab thickness on the maximum surface temperature attained during the entry phase of the trajectory is shown for copper, graphite, and beryllium in figure 11. Inconel-X is not included since the surface reached the melting temperature regardless of the thickness. The amount of heat absorbed per unit weight of material is noted on each curve at the surface temperature corresponding to 75 percent of the melting (or sublimation) temperature. From this figure, it can be seen that both graphite and beryllium are greatly superior to copper as heat-sink materials from a weight standpoint. Graphite is especially attractive, weighing only about 1/24 as much as copper. Beryllium weighs less than 1/6 as much as copper.

Material Limitations

Graphite is subject to rapid oxidation and vaporization at the high surface temperature involved. Its use as a heat-sink material would be predicated on the ability to protect the surface from the air stream by means of coatings.

Beryllium is reported (cf. ref. 4) to be oxidation-resistant up to the surface temperatures involved in the example trajectory. It is, however, a brittle material, and its low ductility poses severe fabrication difficulties.

A comparison of the maximum surface temperature gradients attained in the trajectory for the four materials analyzed is interesting. These gradients were computed for the case of 1-inch-thick slabs. They are as follows:

Copper	1344° R per inch
Beryllium	6420° R per inch
Inconel-X	7690° R per inch
Graphite	8250° R per inch

The temperature gradient for Inconel-X was limited because the surface melted before the maximum gradient was reached. The surface temperature gradient is important from the standpoint of possible loss of material by spalling of the surface and the results shown above clearly indicate the superiority of copper in this respect.

CONCLUSIONS

An analysis of the heat-absorption capabilities of several widely different types of materials which might be considered for ballistic nose cones has revealed certain features associated with each type of material.

1. A typical refractory metal, Inconel-X, was found to be completely unsatisfactory. The very low diffusivity of the material caused the surface to reach the melting point early in the entry. The greater portion of the material experienced practically no temperature rise; hence it was completely ineffective as a heat sink.

2. Copper is attractive mainly because of its high thermal conductivity and ductility. It results in very heavy construction, which, however, has excellent resistance to thermal shock. The surface of a copper nose cone would have to be protected from oxidation.

3. Graphite is greatly superior to copper from a weight standpoint. The required weight of graphite is only about 1/24 as much as copper if each material is allowed to reach a surface temperature equal to 75 percent of the melting or sublimation temperature. It is, however, subject to high surface temperature gradients which could conceivably lead to spalling of the surface. It would probably have to be coated to prevent oxidation of the surface and the problem of developing a high-temperature coating which would allow exploitation of the high sublimation temperature of graphite would be difficult.

4. Of the metals analyzed, beryllium appears attractive from several standpoints. Primarily, it is a very lightweight material with a high specific heat and thermal conductivity. Its use as a heat-sink material would result in a sixfold weight saving compared to the use of copper. Its oxidation resistance is good, hence protection of the surface probably would not be required. It has several drawbacks at the present state of development of beryllium metallurgy. It is brittle, which could lead to difficulty from spalling, and, at the present time, is difficult to form in large sections.

5. Use of the usual approximate form of the Fourier heat-conduction equation can lead to large errors in computed temperature time histories for materials whose properties vary significantly with temperature.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
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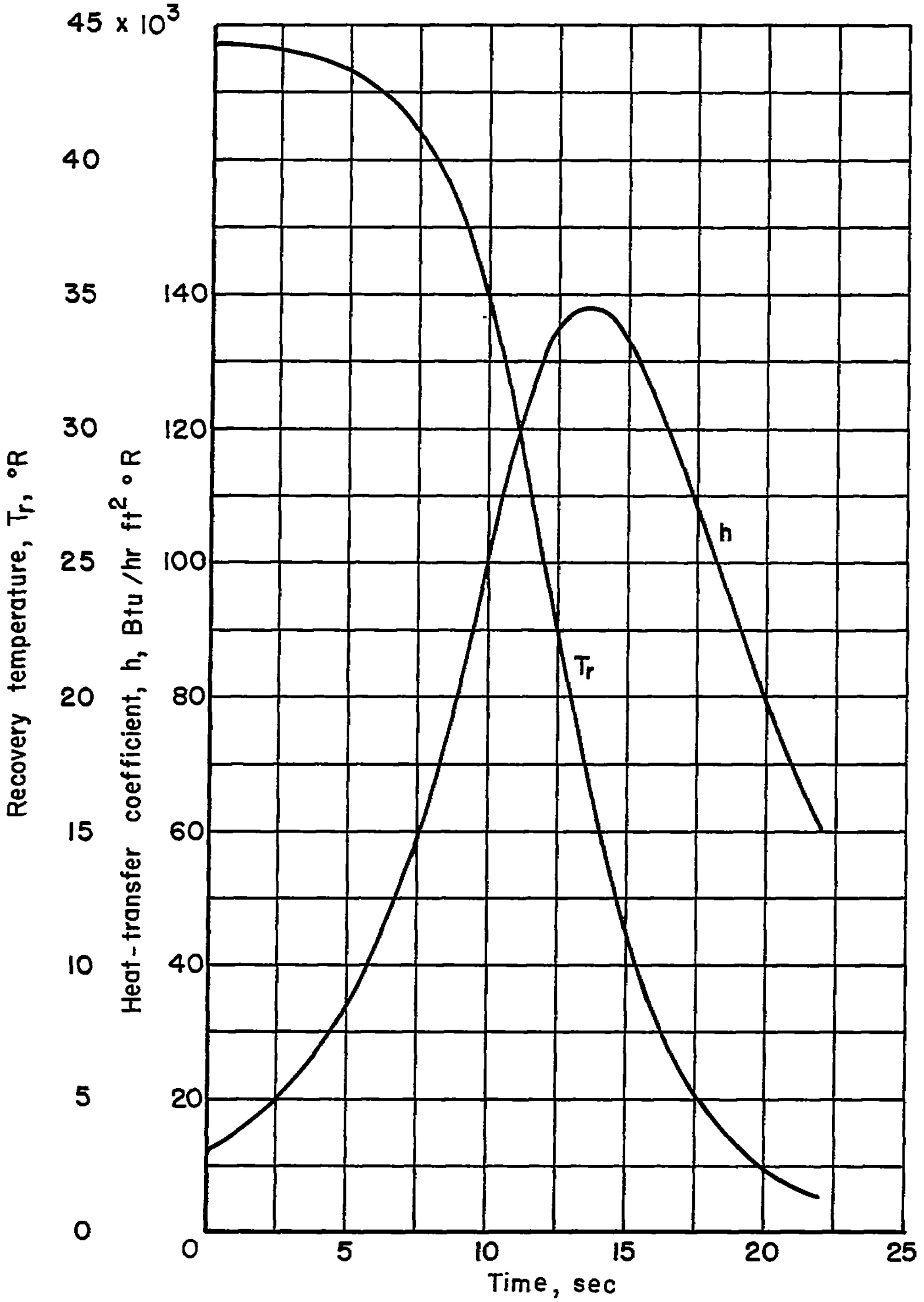

Figure 1.- External heat-transfer characteristics for stagnation point of hemisphere; V_e = 23,000 ft/sec, W/C_DA = 345.

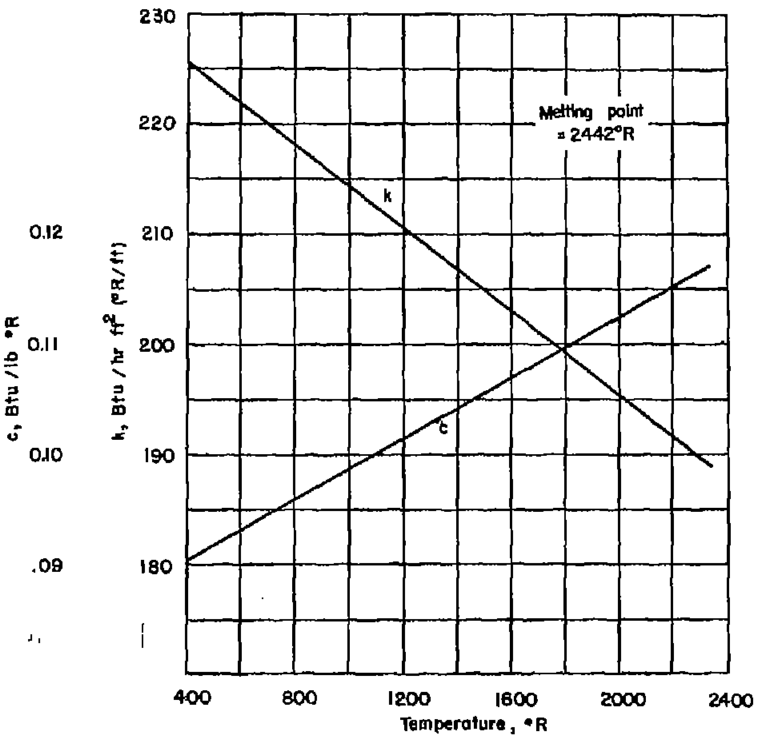

Figure 2.- Thermal properties of copper.

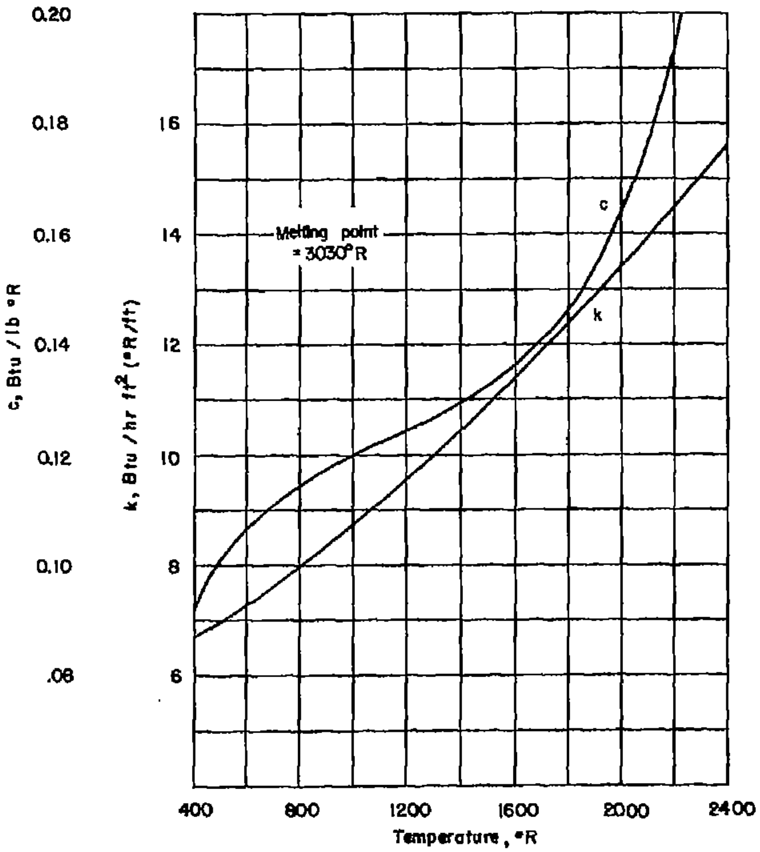

Figure 3.- Thermal properties of Inconel-X.

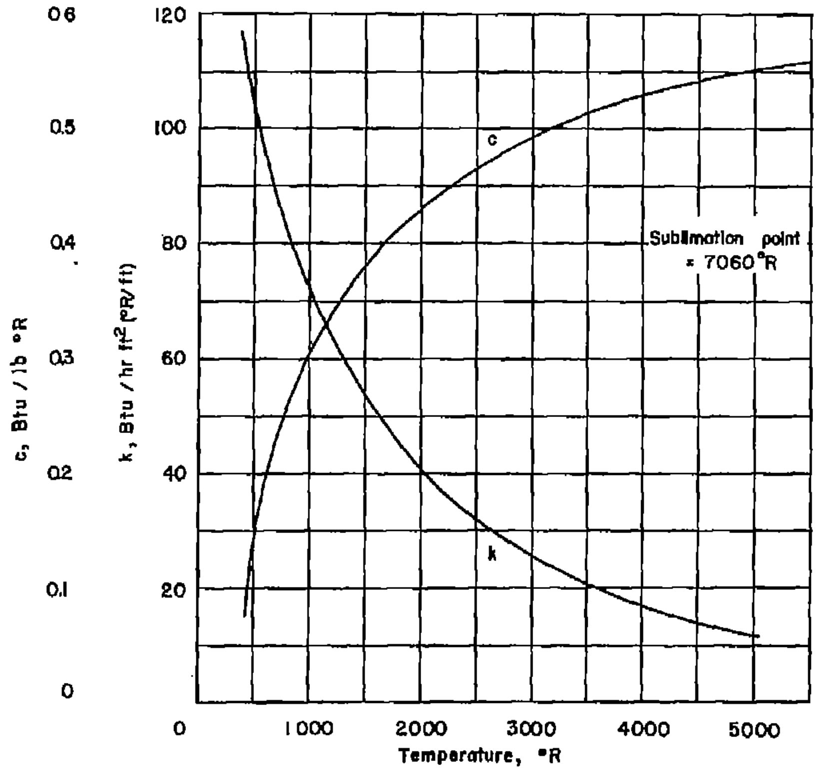

Figure 4.- Thermal properties of graphite.

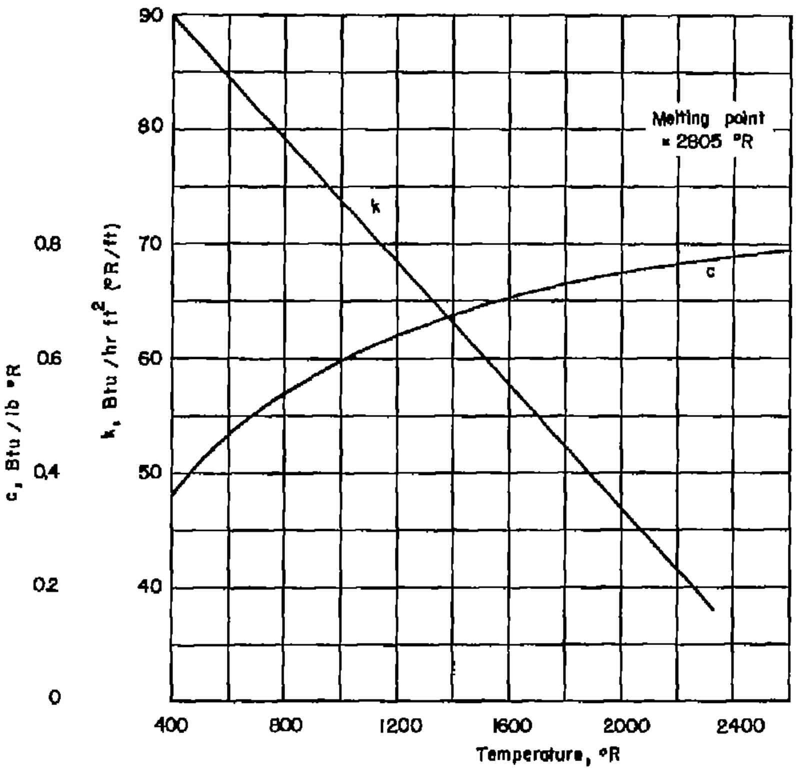

Figure 5.- Thermal properties of beryllium.

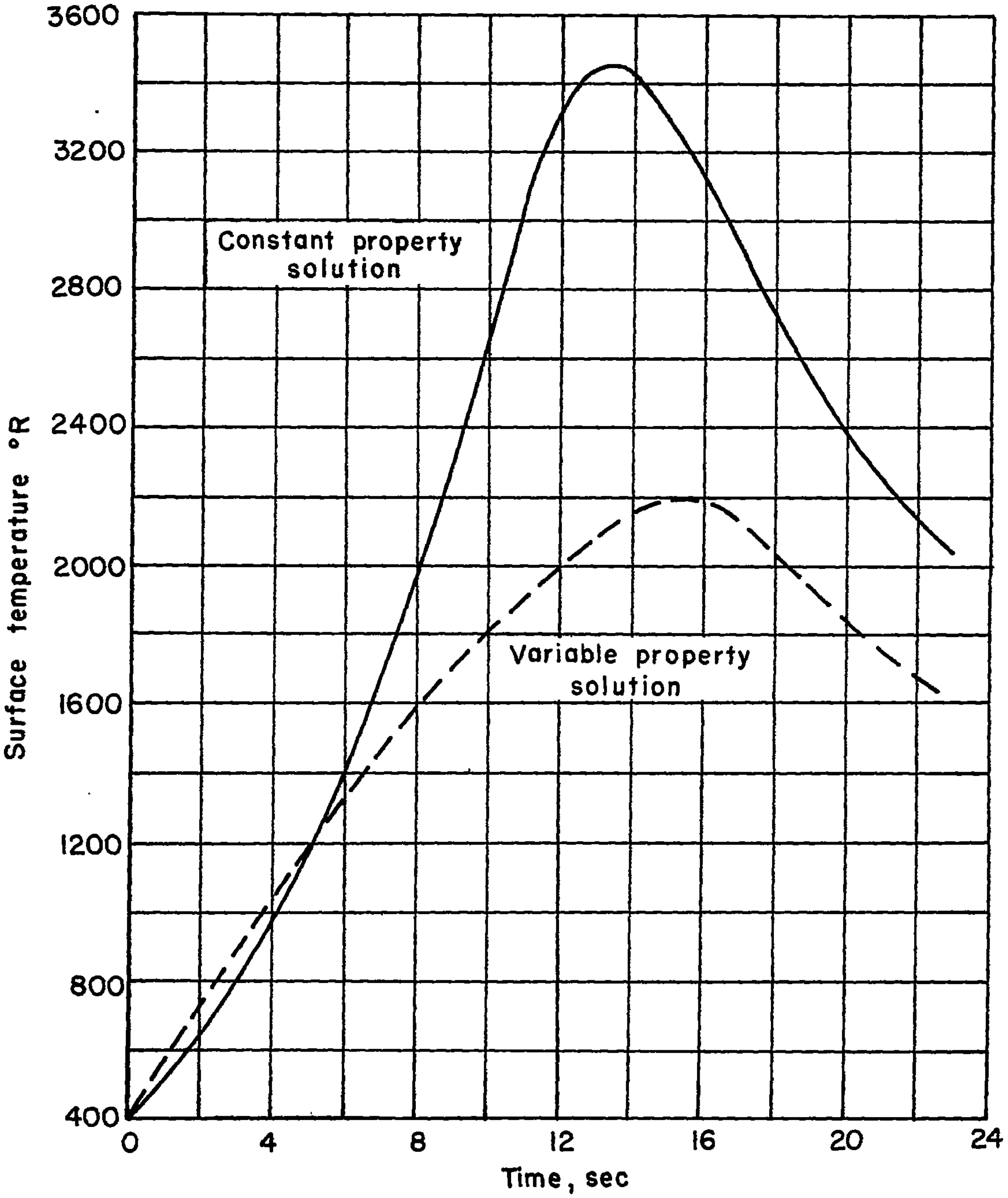

Figure 6.- Comparison of constant and variable property solution of heat-conduction equation on surface temperature of 2-inch graphite slab.

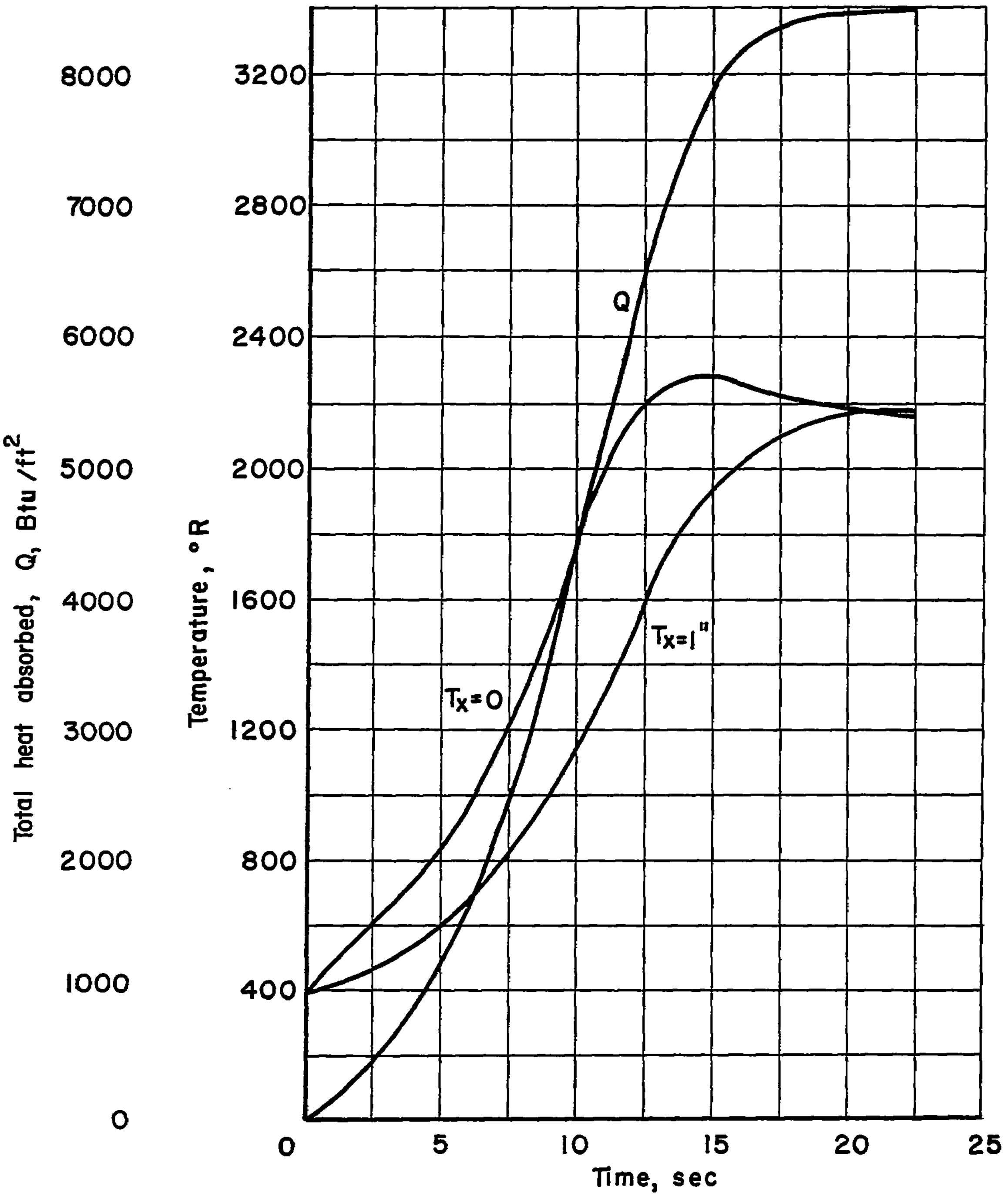

Figure 7.- Temperature distribution characteristics and heat absorbtion capacity of copper; 1-inch slab.

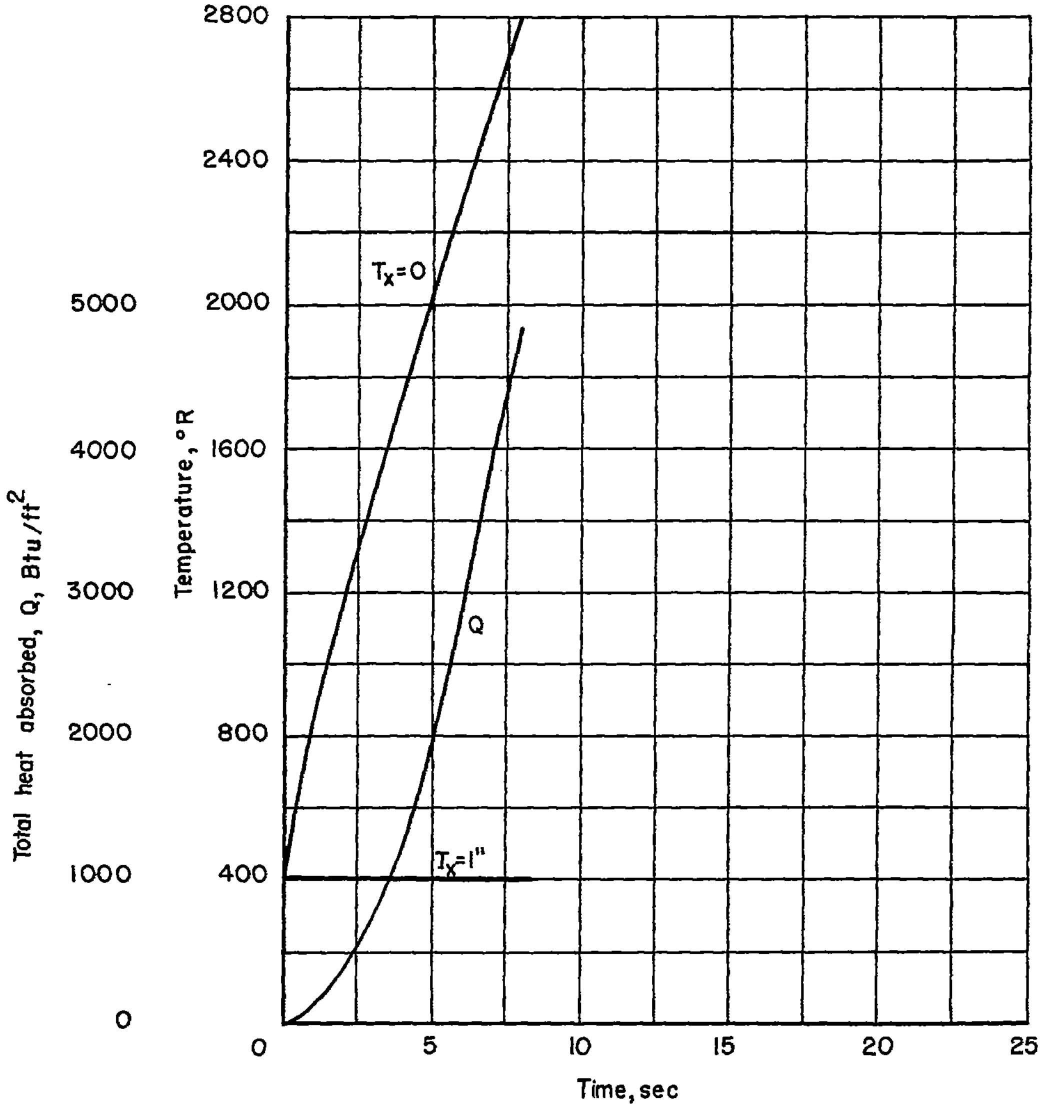

Figure 8.- Temperature distribution characteristics and heat absorbtion capacity of Inconel-X; 1-inch slab.

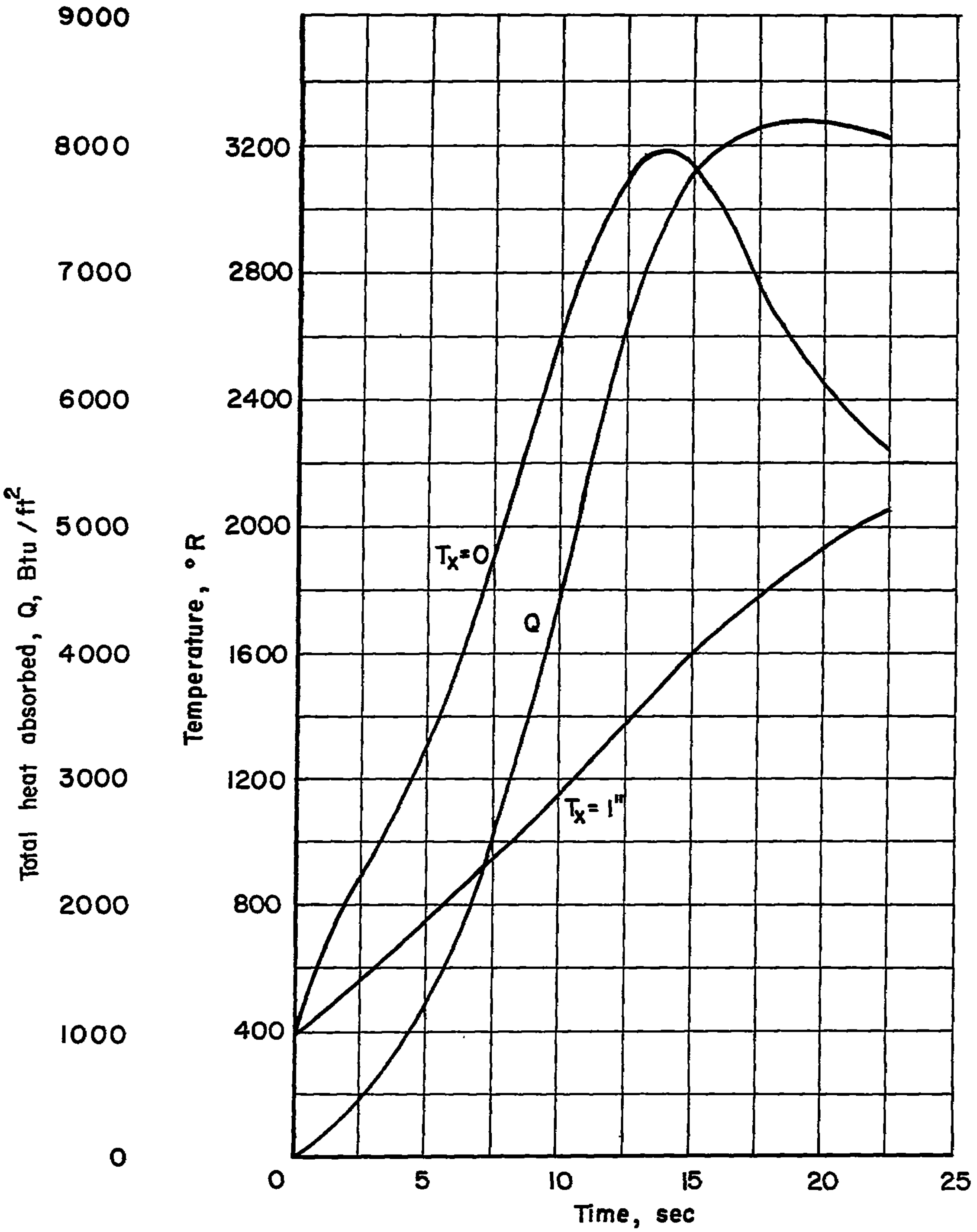

Figure 9.- Temperature distribution characteristics and heat absorbtion capacity of graphite; 1-inch slab.

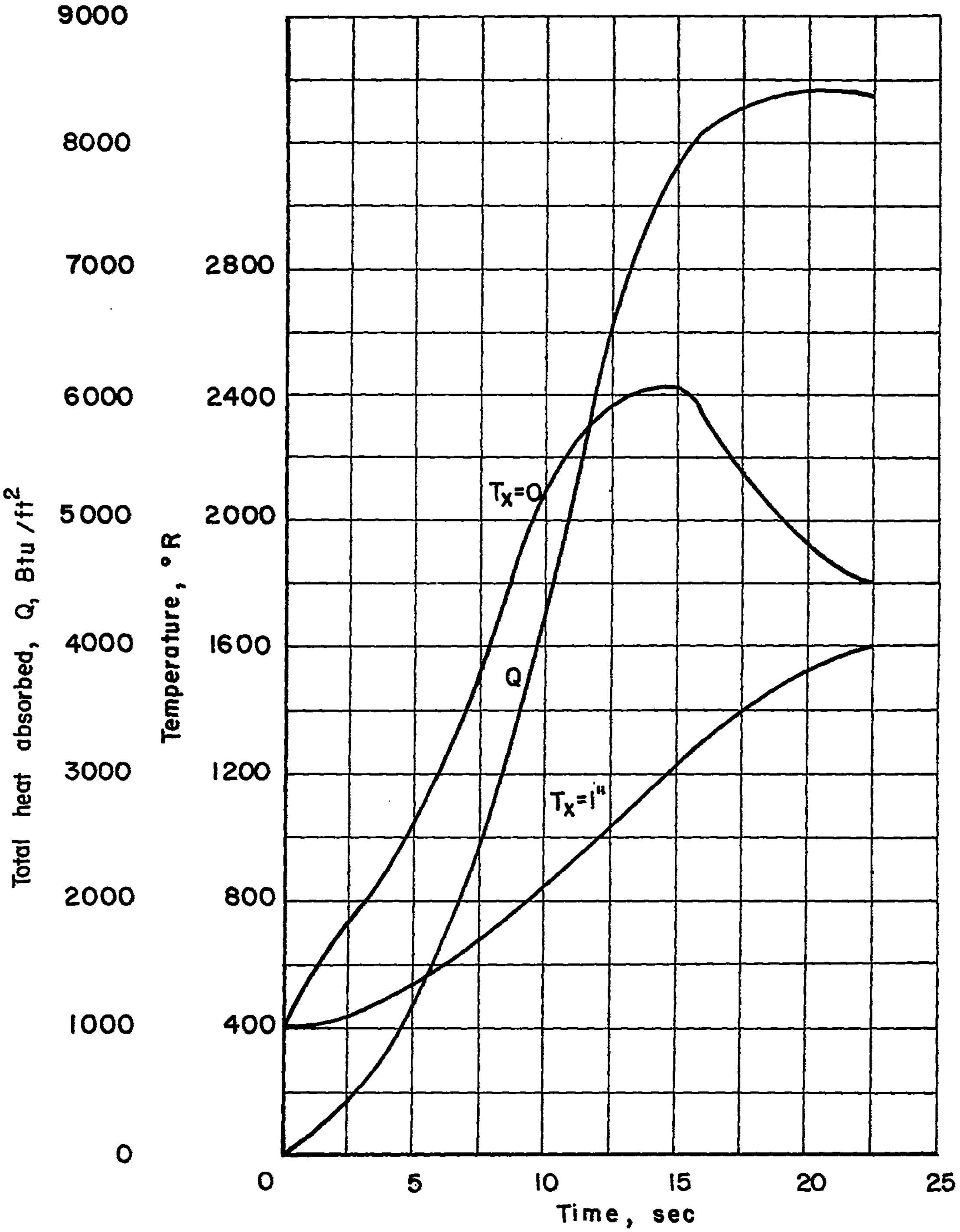

Figure 10.- Temperature distribution characteristics and heat absorbtion capacity of beryllium; 1-inch slab.

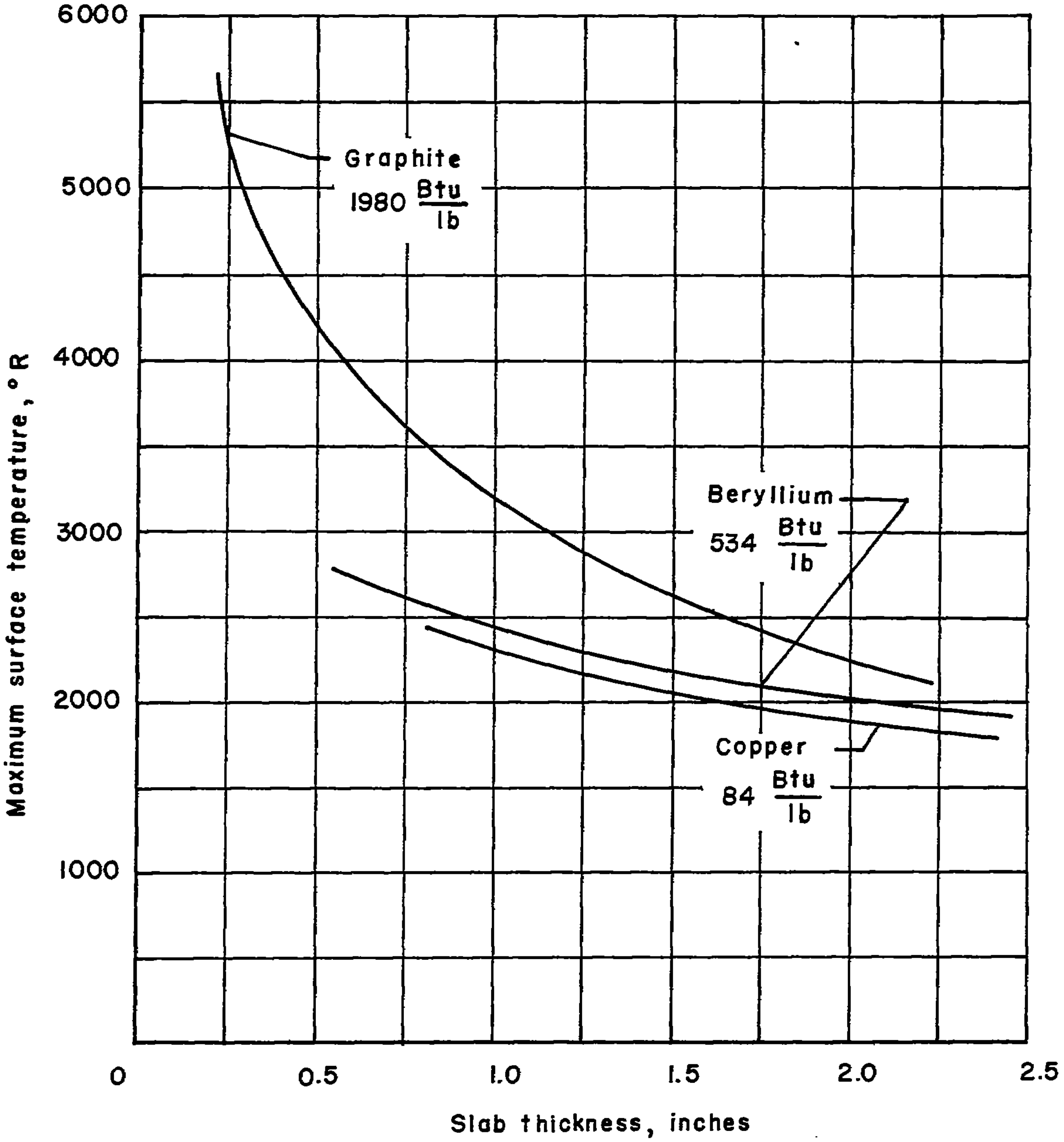

Figure 11.- Effect of slab thickness on maximum surface temperature.

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