#2720

10.0

NATIONAL BUREAU OF STANDARDS REPORT

2720

SURFACE TEMPERATURES WITH THERMAL INDICATORS

by

S. M. Genensky
A. F. Robertson

Report to
Quartermaster Corps
Philadelphia Research & Development Laboratories
U. S. Army

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section is engaged in specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant reports and publications, appears on the inside of the back cover of this report.

Electricity. Resistance Measurements. Inductance and Capacitance. Electrical Instruments. Magnetic Measurements. Applied Electricity. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Gage.

Heat and Power. Temperature Measurements. Thermodynamics. Cryogenics. Engines and Lubrication. Engine Fuels. Cryogenic Engineering.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Measurements. Infrared Spectroscopy. Nuclear Physics. Radioactivity. X-Rays. Betatron. Nucleonic Instrumentation. Radiological Equipment. Atomic Energy Commission Instruments Branch.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Gas Chemistry. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Aerodynamics. Engineering Mechanics. Hydraulics. Mass. Capacity, Density, and Fluid Meters.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Organic Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion.

Mineral Products. Porcelain and Pottery. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure. Chemistry of Mineral Products.

Building Technology. Structural Engineering. Fire Protection. Heating and Air Conditioning. Floor, Roof, and Wall Coverings. Codes and Specifications.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Machine Development.

Electronics. Engineering Electronics. Electron Tubes. Electronic Computers. Electronic Instrumentation.

Radio Propagation. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Frequency Utilization Research. Tropospheric Propagation Research. High Frequency Standards. Microwave Standards.

Ordnance Development.
Electromechanical Ordnance.
Ordnance Electronics.
These three divisions are engaged in a broad program of research and development in advanced ordnance. Activities include basic and applied research, engineering, pilot production, field testing, and evaluation of a wide variety of ordnance matériel. Special skills and facilities of other NBS divisions also contribute to this program. The activity is sponsored by the Department of Defense.

Missile Development. Missile research and development: engineering, dynamics, intelligence, instrumentation, evaluation. Combustion in jet engines. These activities are sponsored by the Department of Defense.

- Office of Basic Instrumentation
- Office of Weights and Measures.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT **NBS REPORT**

1000-10-4803 August 3, 1953 2720

SURFACE TEMPERATURES
WITH
THERMAL INDICATORS

by

S. M. Genensky
and
A. F. Robertson
Fire Protection Section
Building Technology Division

To

Quartermaster Corps
Philadelphia Research & Development Laboratories
U. S. Army

Requisition No. 49-106-567-53
Project No. 7-12-01-001

SURFACE TEMPERATURES WITH THERMAL INDICATORS

by

S. M. Genensky and A. F. Robertson

Abstract

At the request of the Quartermaster Corps, analytical and numerical solutions have been obtained for the surface temperature rise of homogeneous, semi-infinite solids and similar solids with one or two finite lamina of other materials on the exposed surface when heated by a time invariant radiant energy source. By the use of these two methods of calculation it has been possible to estimate the surface temperature rise for skin and inert assemblies intended to simulate skin when these are heated by radiant energy which is totally absorbed at the surface. It is shown that, as a result of their thermal properties, the temperature rise of the Quartermaster temperature indicators is very different from that to be expected of skin under similar conditions.

---

1. INTRODUCTION

The Quartermaster Research and Development Laboratories have developed thermal indicators and requested that an analysis be made of the extent to which these indicators with various types of backing materials may be considered as simulating temperature changes on the surface of opaque skin when exposed to thermal radiation.

This report presents some results of analytical and numerical calculations which may be of assistance in evaluating the usefulness of these indicators. The calculations have been made with the objective of estimating the maximum surface temperature rise of homogeneous or laminated materials which have been exposed to a time invariant pulse of radiant energy of one-half second duration. Calculations have been performed with the use of thermal data furnished by the Quartermaster Corps on various assemblies proposed as representing:

a. Human skin

b. Homogeneous skin simulants

c. Quartermaster temperature indicator assemblies

Most of the calculations have been made by means of an analytical solution of the problem for the case of a finite lamina in good thermal contact with a semi-infinite backing. A few additional numerical solutions have been obtained by means of SEAC, the National Bureau of Standards digital computer, for the more complex assembly of two finite lamina in contact with a semi-infinite backing.

Because of limited funds available for the work, no attempt has been made to obtain solutions for all the assemblies proposed. The solutions for the one, two, and three body composite systems considered have been obtained for a wider range of thicknesses and thermal properties than was requested, in an effort to make the work more general.

2. THE PROBLEM AND WORK DONE

The work requested(1) was very broad. It included the following "jobs":

1. Investigate the effect of fabric covering on the temperature rise of skin or indicator and backing exposed beneath the fabric.

2. Calculation of surface temperature rise of skin, using the assemblies and thermal properties furnished.

(1) Philadelphia Quartermaster Research and Development Laboratories letter QMDP 423.112 RP, 30 March 1953, signed by John M. Davies.

3. Calculation of the surface temperature rise of semi-infinite materials which have been proposed as skin simulants.

4. Calculation of the surface temperature rise of a variety of temperature indicator assemblies with several different backing materials.

It was suggested that items 2 to 4 be calculated for an energy pulse of one-half second duration. An investigation of item 1 was considered too complex in view of the funds available. Work was, therefore, confined to items 2, 3, and 4.

The thermal properties used in performing the calculations are shown in Table 1. Most of these were obtained from the Quartermaster Corps.(1)

Table 2 presents the eight different skin assemblies for which calculations were requested (Job 2). The manner in which the suggested assemblies were modified in solving for temperature rise by both analytical and SEAC calculations is indicated.

Table 3 presents the thermal properties of four finite simple slab materials and one semi-infinite composite assembly which have been proposed as simulating behavior of skin (Job 3). For the finite specimens a number of thicknesses were proposed for solution. However, for the half-second pulse used, all of these can be considered as semi-infinite at the time when surface temperatures are a maximum and thus one solution serves for all thicknesses requested.

Table 4 presents the fifteen different indicator mounting and assembly arrangements for which calculations were requested (Job 4). As a result of discussions with Quartermaster officials, it was decided to concentrate work on solution of indicators having type C assembly. This table shows the manner in which the six-layer system was simplified. The fact that the thermal properties of the thin surface indicator layer were different from those of the backing was neglected and a constant value of k was assumed for the next four layers; the semi-infinite backing representing the sixth layer completes the system.

3. ANALYSIS AND RESULTS

As mentioned earlier, both an analytical solution of a two material composite semi-infinite body, and a numerical solution for a three material semi-infinite slab were obtained. The latter made use of SEAC. All solutions were developed with the following assumptions:

1. The input energy pulse is zero at time zero and equal to ϕ between time zero and one-half second, after which it is again zero.

2. The materials are opaque.

3. The thermal properties of the bodies being heated are constants.

4. There are no losses from the heated body to the surroundings and all of the incident energy is absorbed.

5. At all solid interfaces both temperature and heat flux are continuous functions of distance.

6. The bodies being heated are inert.

It was agreed that computations should be made for the maximum temperature rise at the surface of the specimen. This would occur at the end of the radiant exposure or one-half second. It was hoped that an analytical solution might be found or developed for the multi-layer specimens. Such a solution was not found and appeared impractical to develop for assemblies more complex than those of two materials.

The analytical solution for a finite surface layer on a semi-infinite solid was developed as follows. Consider a semi-infinite solid having a surface layer of finite thickness B in intimate contact with the remainder of the solid. The temperature within the solid is considered a function of depth x and time t and may be written $\theta(x,t)$. Initially the solid and surrounding medium are assumed to be at temperature $\theta(x,0) = 0$ $(-\infty < x < \infty)$. Further, the exposed face of the solid is subjected to a constant flux ϕ from time $t > 0$ to $t = T$, the termination of the experiment, and the temperature $\theta(x,t)$ as x tends toward infinity is zero for all time t. The exposed solid has thermal conductivity k_1 and thermal diffusivity α_1 and the backing or

underlying layer has thermal conductivity k_2 and thermal diffusivity α_2. At the solid interface both the temperature and conductive flux are assumed continuous. Mathematically the problem may be expressed as follows:

$$\frac{\partial \theta(x,t)}{\partial t} = \alpha_1 \frac{\partial^2 \theta(x,t)}{\partial x^2} \qquad (0 < x < B) \quad (0 < t \leq T)$$

$$-k_1 \frac{\partial \theta(0,t)}{\partial x} = \phi \qquad (0 \leq t \leq T)$$

$$\lim_{x \to 0} \theta(B - x,t) = \lim_{x \to 0} \theta(B + x,t) \qquad (x > 0,\ 0 \leq t \leq T)$$

$$\lim_{x \to 0} k_1 \frac{\partial \theta(B-x,t)}{\partial x} = \lim_{x \to 0} k_2 \frac{\partial \theta(B+x,t)}{\partial x} \qquad (x > 0,\ 0 \leq t \leq T)$$

$$\frac{\partial \theta(x,t)}{\partial t} = \alpha_2 \frac{\partial^2 \theta(x,t)}{\partial x^2} \qquad (B < x < \infty) \quad (0 < t \leq T)$$

$$\lim_{x \to \infty} \theta(x,t) \to 0 \qquad \text{for all } t$$

$$\theta(x,0) = 0 \qquad (-\infty < x < \infty)$$

and the solution of this problem, which of course assumes linear heat flow, may be expressed as follows:

$$\frac{\theta(x,t)}{\phi} = \lambda \sum_{0}^{\infty} (-1)^n \xi^n \left\{ \left[2\sqrt{\frac{t}{\pi}}\, e^{-\left[\frac{2B(n+1)-x}{2\sqrt{\alpha_1 t}}\right]^2} \right. \right.$$

$$- \frac{2B(n+1)-x}{\sqrt{\alpha_1}} \operatorname{erfc}\left(\frac{2B(n+1)-x}{2\sqrt{\alpha_1 t}}\right)$$

$$+ 2\sqrt{\frac{t}{\pi}}\, e^{-\left[\frac{2B(n+1)+x}{2\sqrt{\alpha_1 t}}\right]^2}$$

$$\left. - \frac{2B(n+1)+x}{\sqrt{\alpha_1}} \operatorname{erfc}\left(\frac{2B(n+1)+x}{2\sqrt{\alpha_1 t}}\right) \right]$$

$$+ \frac{2}{k_1}\sqrt{\frac{\alpha_1 t}{\pi}}\, e^{-\left[\frac{x^2}{4\alpha_1 t}\right]} - \frac{x}{k_1} \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha_1 t}}\right) \qquad (1)$$

for $(0 \leqslant x \leqslant B)$

and

$$\frac{\theta(x,t)}{\phi} = \lambda \sum_{0}^{\infty} (-1)^n \xi^n \left\{ 2\sqrt{\frac{t}{\pi}}\, e^{-\left[\frac{\frac{(2n+1)B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}}{2\sqrt{t}}\right]^2} \right.$$

$$- \left[\frac{(2n+1)B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}\right] \operatorname{erfc}\left(\frac{\frac{(2n+1)B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}}{2\sqrt{t}}\right)$$

$$+ 2\sqrt{\frac{t}{\pi}}\, e^{-\left[\frac{\frac{(2n+3)B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}}{2\sqrt{t}}\right]^2}$$

$$\left. - \left[\frac{(2n+3)B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}\right] \operatorname{erfc}\left(\frac{\frac{(2n+3)B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}}{2\sqrt{t}}\right)\right\}$$

$$+ \frac{2}{k_1}\sqrt{\frac{\alpha_1 t}{\pi}}\, e^{-\left[\frac{\frac{B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}}{2\sqrt{t}}\right]^2}$$

$$- \frac{\sqrt{\alpha_1}}{k_1}\left[\frac{B}{\sqrt{\alpha_1}} + \frac{x-B}{\sqrt{\alpha_2}}\right] \operatorname{erfc}\left(\frac{\frac{B}{\sqrt{\alpha_1}} \quad \frac{x-B}{\sqrt{\alpha_2}}}{2\sqrt{t}}\right) \qquad (2)$$

for $(B \leq x < \infty)$

where $\theta(x,t)$ is the temperature, a function of position x and time t.

Further

$$\xi = P/Q \qquad \text{and} \qquad \lambda = M/Q$$

where

$$P = \frac{k_2}{\sqrt{\alpha_2}} - \frac{k_1}{\sqrt{\alpha_1}} , \qquad Q = \frac{k_2}{\sqrt{\alpha_2}} + \frac{k_1}{\sqrt{\alpha_1}}$$

and

$$M = 1 - \frac{k_2\sqrt{\alpha_1}}{k_1\sqrt{\alpha_2}}$$

This equation served as the basis upon which all analyses involving hand and desk calculator computations were carried out. Since this temperature rise is directly proportional to ϕ, a more general solution is obtained by expressing the results of calculations in terms of θ/ϕ which for brevity we call "temperature rise". These computations were restricted to ascertaining this surface temperature rise of various homogeneous and composite solids exposed to the time invariant energy pulse for one-half second. It is to be emphasized that since the analytic approach was confined to semi-infinite solids composed of at most one finite layer in intimate contact with the rest of the solid, the computations can at best be regarded as approximations to the structures offered for analysis.

For an energy pulse of one-half second, the maximum temperature rise occurs when x=0 and t=0.5. Substituting these values in equation (1) gives:

$$\frac{\theta(0,0.5)}{\phi} = \frac{2}{k_1}\sqrt{\frac{\alpha_1}{2\pi}} +$$

$$+\lambda\sum_{0}^{\infty}(-1)^n \xi^n \left\{ 2\sqrt{\frac{2}{\pi}}\, e^{-\left[\frac{(n+1)B\sqrt{2}}{\sqrt{\alpha_1}}\right]^2} - \right.$$

$$\left. - \frac{4B(n+1)}{\sqrt{\alpha_1}}\, \mathrm{erfc}\left(\frac{B(n+1)\sqrt{2}}{\sqrt{\alpha_1}}\right)\right\}$$

Figures 1 to 7 and Table 5 present the results of the calculations. An attempt has been made to furnish generalized data by study of a wider range of variables than was requested for the specific problems involved. All these figures present the maximum surface temperature rise one-half second after exposure to a constant intensity radiant energy input pulse of ϕ cal/sec cm^2. In these figures the symbol Ⓑ is used to designate the thickness in inches of each of the individual layers.

Figures 1 through 4 and table 5 are for two material composite bodies or for homogeneous materials and represent the results of the analytical solution of the problem.

Figures 5 through 7 present results of the SEAC numerical solution of the problem for three material composite bodies. Data are presented for both surface and two subsurface interfaces as a function of time for the duration of the one-half second exposure.

It should be remembered that most solutions presented involve some simplifying assumptions and in all cases where the indicator assembly has been studied the presence of the thin, translucent indicator surface film has been completely neglected. This is justified because of its very small thickness and the fact that it cannot be considered as opaque.

Table 5 gives surface temperature rise of various homogeneous solids. These calculations were based upon values from Table 3.

Figure 4 is a plot of surface temperature rise of various composite solids with the same surface layer and various high conducting backings. The surface layer is 10×10^{-3} inches thick and has a conductivity $k_1 = 3 \times 10^{-4}$ cal/cm °C sec. The figure also indicates the surface temperature rise of a homogeneous solid made of the surface material, and contains a band which indicates the probable range in which the surface temperature of human skin might fall.

4. DISCUSSION OF RESULTS

Figure 1 presents the results of the analytical solution for simplified skin and indicator assemblies. It shows that the indicator assemblies cannot be expected to demonstrate the same thermal behavior as skin even when the conductivity of the backing is varied over wide limits.

Figure 2 curve B shows the surprisingly constant temperature rise of the surface of a composite body when the conductivity of the 3×10^{-3} in. thick surface layer is varied over wide limits. The $k\rho c$ of the backing is maintained constant at 17.5×10^{-4} cal^2/cm^4°C^{2}sec. Data presented in table 5 indicate that the probable temperature rise of skin $\frac{\theta}{\phi}$ is likely to be between the values of 20 and 35 $\frac{°C \text{ sec cm}^2}{\text{cal}}$. These temperature limits correspond to $k\rho c$ products of about $5\frac{1}{4}$ and 16 cal^2/cm^4°C^2 sec for homogeneous materials.

The importance of the $k\rho c$ product may be appreciated when it is considered that:

$$\frac{\theta(0,t)}{\phi} = \frac{2}{k}\sqrt{\frac{\alpha t}{\pi}} \qquad (t \geqslant T)$$

is the solution of the analytic problem presented earlier when $x = 0$, $k_1 = k_2$, and $\alpha_1 = \alpha_2$.

This may be written as:

$$\frac{\theta(0,t)}{\phi} = 2\sqrt{\frac{t}{\pi}}\sqrt{\frac{1}{k\rho c}}$$

When t = 0.5 sec, we have

$$\frac{\theta(0,0.5)}{\phi} = \sqrt{\frac{2}{\pi}}\sqrt{\frac{1}{k\rho c}}$$

An examination of figure 3 leads to the conclusion that a composite semi-infinite solid with surface layer twenty or more thousandths of an inch thick might well be considered a thermally homogeneous semi-infinite solid having the conductivity and diffusivity of the surface material. This statement holds with reasonable accuracy for the range of conductivities and diffusivities found in table 1 listed under indicator materials. It might be argued that figure 3 was based upon a composite semi-infinite solid with $k_1 > k_2$ and thus the conclusion drawn here is not necessarily applicable to the semi-infinite solids of figure 1 where, for the most part, $k_1 < k_2$. However, observe that the $k\rho c$ of the surface layer of composite solids used in constructing figure 1 are less than those used in the construction of figure 3 and thus the equation derived in the previous paragraph indicates that, if the semi-infinite solid were composed solely of the outer material, the surface temperature of the solids of figure 1 would be higher than those of figure 3. This means that heat finds more resistance in the surface layers of solids of figure 1 than those of figure 3. Consequently, it is not unreasonable to expect that a twenty-thousandths inch layer of the surface materials in figure 1 may be considered semi-infinite for the purpose of calculating surface temperature rise.

The data presented in figure 4 were obtained in an attempt to "drag down" the indicator surface temperature rise by the use of highly conductive backings. It is evident that this objective was not obtained because of the rather thick indicator assembly and its low $k\rho c$ product. It therefore appeared desirable to provide an indicator backing having different thermal properties.

The suggested change does not appear too feasible, as the absorbent properties of the paper appear essential for proper operation of the indicator.

Figures 5, 6, and 7 show temperature rise for three material composite bodies as obtained on SEAC by numerical methods. This method of solution provides time-temperature rise data for the surface and two material interfaces. The solution for skin, figure 5, indicates that only the first two layers are involved in the initial transient heating process and therefore the surface temperature rise at 0.5 sec is comparable with data of figure 1, curve c, for a conductivity of $9 x 10^{-4}$cal/cm°Csec for the backing. It will be observed that the SEAC solution provides a surface temperature rise about 20% greater than was found by analytical methods.

No method is readily available for checking the accuracy of the other two SEAC solutions presented in figures 6 and 7. It is likely that the error will be considerably less than the figure mentioned above because a finer grid was used in these computations. It does, though, seem hardly likely that the almost perfect check observed for surface temperature rise for plastic in figure 7, with the similar data for polyethylene in figure 1, represents the true condition. It is likely than an error of 4 or more percent is present in both figures 6 and 7.

5. CONCLUSIONS

The following conclusions appear to be justified from the work which has been accomplished:

1. An analytic solution has been obtained for the surface temperature rise of a two material composite semi-infinite body during heating by a time invariant radiant energy pulse.

2. A code has been devised to permit use of SEAC for solution of surface temperature rise when two finite lamina of different materials are placed on the surface of a semi-infinite solid.

3. The two methods of solution have been used to calculate the surface temperature rise of a wide variety of homogeneous, two layer and three layer bodies after

one-half second exposure to a time invariant radiant energy which is totally absorbed at the exposed surface.

4. It is shown that the Quartermaster temperature indicator assemblies have thermal properties which prevent their thermal behavior from simulating that of skin when subjected to the same thermal radiation exposure.

Table 1.

Thermal Properties of Skin and Indicator from Reference 1

Pig Skin

Material	ρ g/cm^3	c cal/g°C	k cal/cm°Csec	ρc cal/cm^3°C	$k/\rho c$ cm^2/sec	$k\rho c$ cal^2/cm^4°C^{2}sec
Epidermis	.8	.86	.0005	.69	.0007	.00035
Dermis	.8	.77	.0009	.62	.0015	.00056
Fat	.7	.55	.0004	.39	.0010	.00015
Muscle	.8	.91	.0011	.73	.0015	.00080

Indicator Materials

Material	ρ g/cm^3	c cal/g°C	k cal/cm°Csec	ρc cal/cm^3°C	$k/\rho c$ cm^2/sec	$k\rho c$ cal^2/cm^4°C^{2}sec
Indicator	.8	.4	.0002	.32	.000625	.000064
Carbon Black	1.8	.17	.0002	.31	.00065	.000062
Adhesive	.93	.50	.0005	.47	.0011	.000235
Tape	1.45	.45	.0005	.65	.00077	.000325
Paper	.7	.37	.0003	.26	.0012	.000078
Polyethylene	.92	.55	.0008	.51	.0016	.000408
Wood						
Pine	.51	.4	.00027	.20	.0013	.000054
Oak	.61	.4	.00035	.24	.0014	.000084

Table 2.

Some of the Suggested Calculations of Skin Temperatures and Manner in which Assemblies were Changed for Actual Calculations

Item Number	Proposed		As Calculated	
	Thickness	k	Thickness	k
	in.	cgs	in.	cgs
1	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}
	80	9	∞	9
	80	4		
	160	11		
1(a) Seac Solution	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}
	80	9	80	9
	80	4	∞	4
	160	11		
2	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}
	80	9	∞	9
	80	4		
	∞	11		
3	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}
	80	25	∞	25
	80	4		
	∞	11		
4	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}
	80	25	∞	25
	80	10		
	∞	11		
5	3×10^{-3}	5×10^{-4}	3×10^{-3}	5×10^{-4}
	80	25	∞	25
	80	10		
	∞	25		
6	3×10^{-3}	10×10^{-4}	3×10^{-3}	10×10^{-4}
	80	25	∞	25
	80	10		
	∞	25		
7	3×10^{-3}	5×10^{-4}	40×10^{-3}	9×10^{-4}
	40	9	∞	4
	80	4		
	∞	11		
8	3×10^{-3}	5×10^{-4}	80×10^{-3}	9×10^{-4}
	80	9	∞	4
	40	4		
	∞	11		

Table 3.

Suggested Calculations for Homogeneous Skin Simulants

Thickness B in inches for various k and ρc

1 Average of * M&H figures for skin	2 QM guess at Hardy's best figures for skin	3 Polyethylene	4 Pine wood	5 Polyethylene layer over pine
$k = .0008$ $\rho c = .7$	$k = .0025$ $\rho c = .7$	$k = .0008$ $\rho c = .51$	$k = .0003$ $\rho c = .20$	$k_1 = .0008$ $\rho c_1 = .51$ $k_1/\rho_1 c_1 = .0016$ Thick. = .06 in.
.06	.06	.06	.06	
.25		.25		$k_2 = .0003$ $\rho c_2 = .20$ $k_2/\rho_2 c_2 = .0013$ Thick. = .94 in.
.5	.5	.5	.5	
1.				

* Moritz & Henriques

Table 4.

Suggested Calculations for Indicator Mountings

A. Active Material on Carbon Black

Thickness of Layers, in.

	1	2	3	4	5
Indicator	.0005	.0005	.0005	.0005	.0005
Carbon Black	.002	.002	.002	.002	.002
Polyethylene	.5		.06	∞	
Wood		.5	.44		∞

B. Active Material on Paper with Adhesive

	1	2	3
Indicator	.0005	.0005	.002
Paper	.004	.004	.004
Adhesive	.002	.002	.002
Polyethylene	.5		
Wood		.5	.5

C. Active Material on Paper with Adhesive Tape

	1	k	2	k	3	4	5
Indicator	.0005		.0005		.0005	.0005	.002
Paper	.004		.004		.004	.004	.004
Adhesive	.002	.0003 (Paper through Adhesive)	.002	.0003 (Paper through Adhesive)	.002	.002	.002
Tape	.001		.001		.001	.001	.001
Adhesive	.002		.002		.002	.002	.002
Polyethylene	.5	.0008				.06	.5
Wood			.5	.00027		.44	

D. Indicator on Paper, Air Backing

	1	2
Indicator	.0005	.002
Paper	.004	.004
Space	.063	.063
Wood	.5	.5

Table 5.

Surface Temperature Rise
of
Various Homogeneous Semi-Infinite Solids
Reference Table 2

Solid	k	ρc	Temperature Rise $\frac{\theta}{\phi}$
	cal/sec cm°C	cal/cm^3°C	°C sec cm^2/cal
*	25×10^{-4}	0.7	19.1
**	8	0.7	33.7
Polyethylene	8	0.5	39.5
Wood	3	0.2	103.0

* QM guess at Hardy's best figures for skin
** Average of Moritz & Henriques' figures for skin

FIG 1

SURFACE "TEMPERATURE RISE"
VS.
CONDUCTIVITY OF BACKING

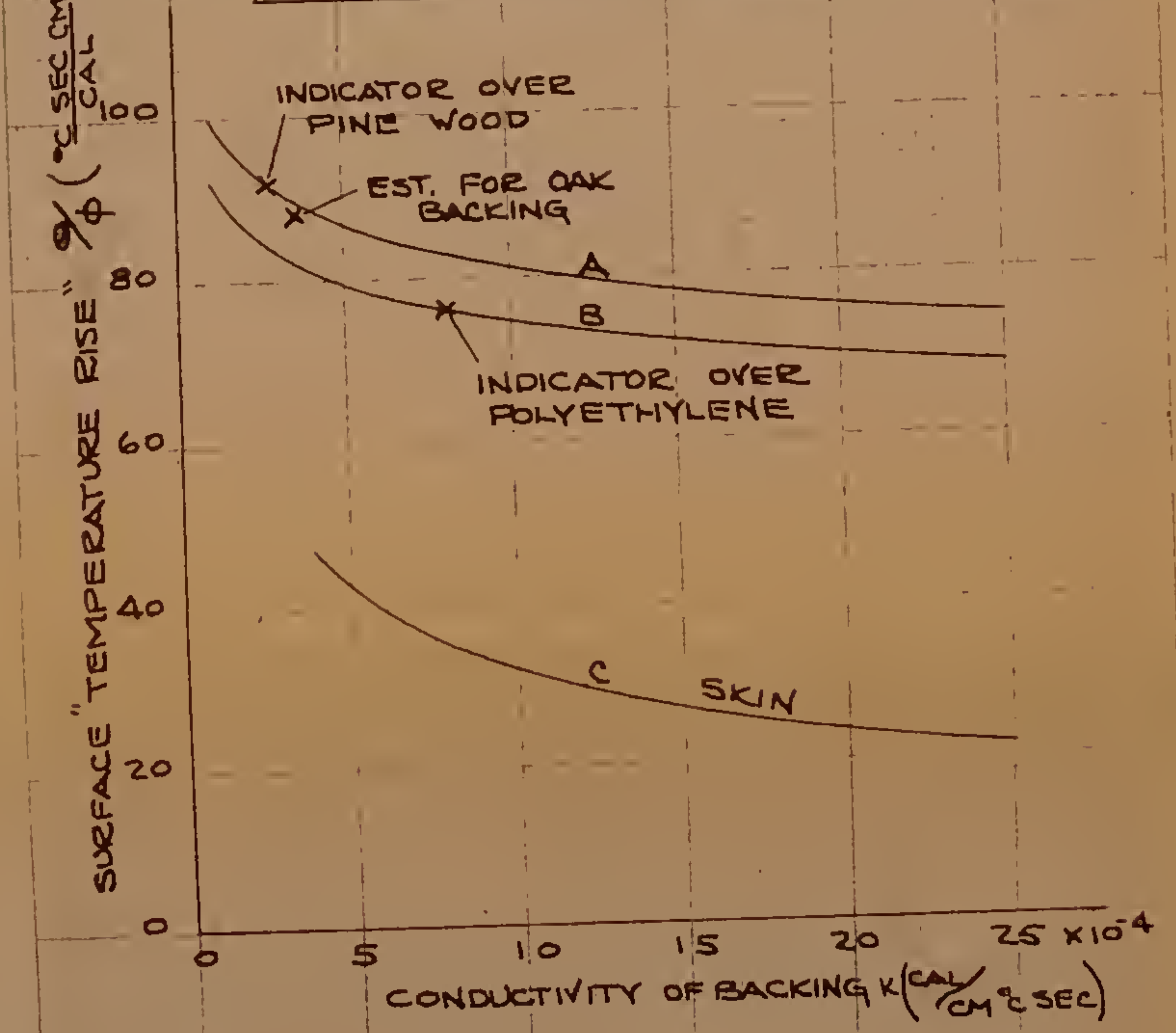
CURVE		PROPERTIES		REFERENCE
		SURFACE	BACKING	
A	K ρc Ⓑ	3×10^{-4} 0.273 10×10^{-3}	VARIABLE 0.2 ∞	TABLE 4 ITEM C-1
B	K ρc Ⓑ	3×10^{-4} 0.273 10×10^{-3}	VARIABLE 0.5 ∞	TABLE 4 ITEM C-2
C	K ρc Ⓑ	5×10^{-4} 0.7 3×10^{-3}	VARIABLE 0.7 ∞	TABLE 2 ITEM 1-5

(2)

FIG 1

SURFACE "TEMPERATURE RISE" VS. CONDUCTIVITY OF BACKING

CURVE	PROPERTIES	SURFACE	BACKING	REFERENCE
A	K	3×10^{-4}	VARIABLE	TABLE 4
	ρC	0.273	0.2	ITEM
	Ⓑ	10×10^{-3}	∞	C-1
B	K	3×10^{-4}	VARIABLE	TABLE 4
	ρC	0.273	0.5	ITEM
	Ⓑ	10×10^{-3}	∞	C-2
C	K	5×10^{-4}	VARIABLE	TABLE 2
	ρC	0.7	0.7	ITEM
	Ⓑ	3×10^{-3}	∞	1-5



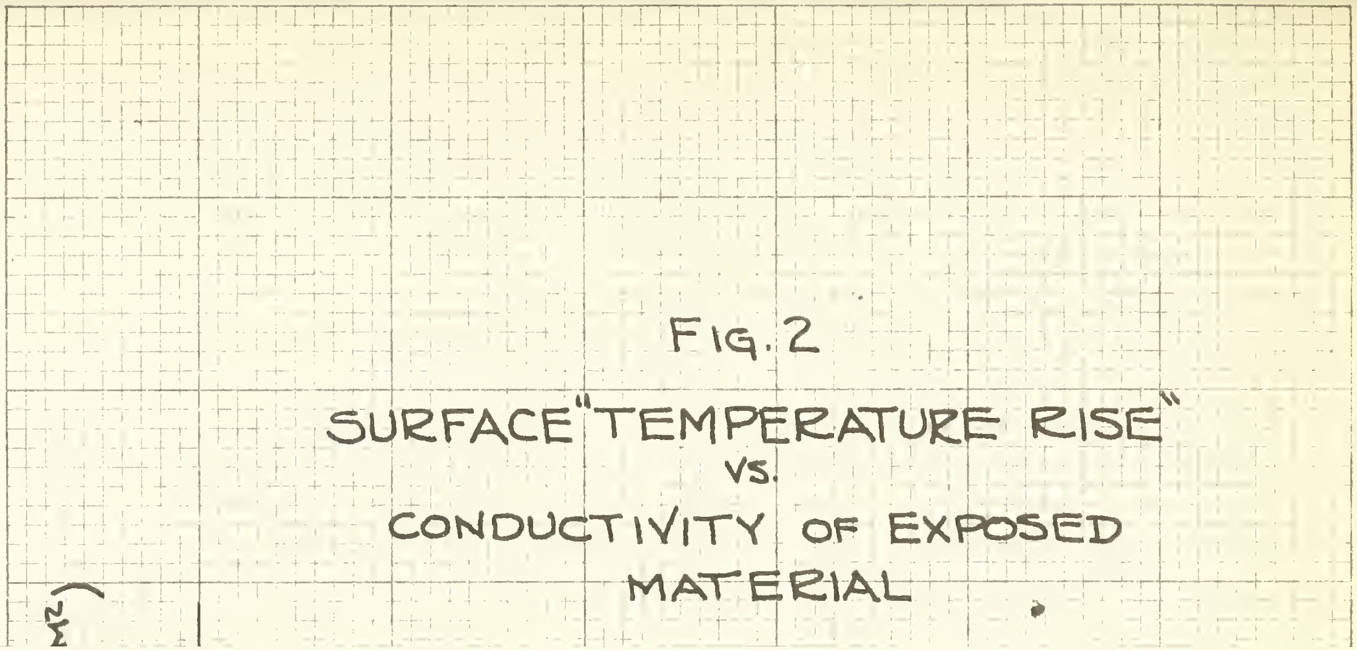
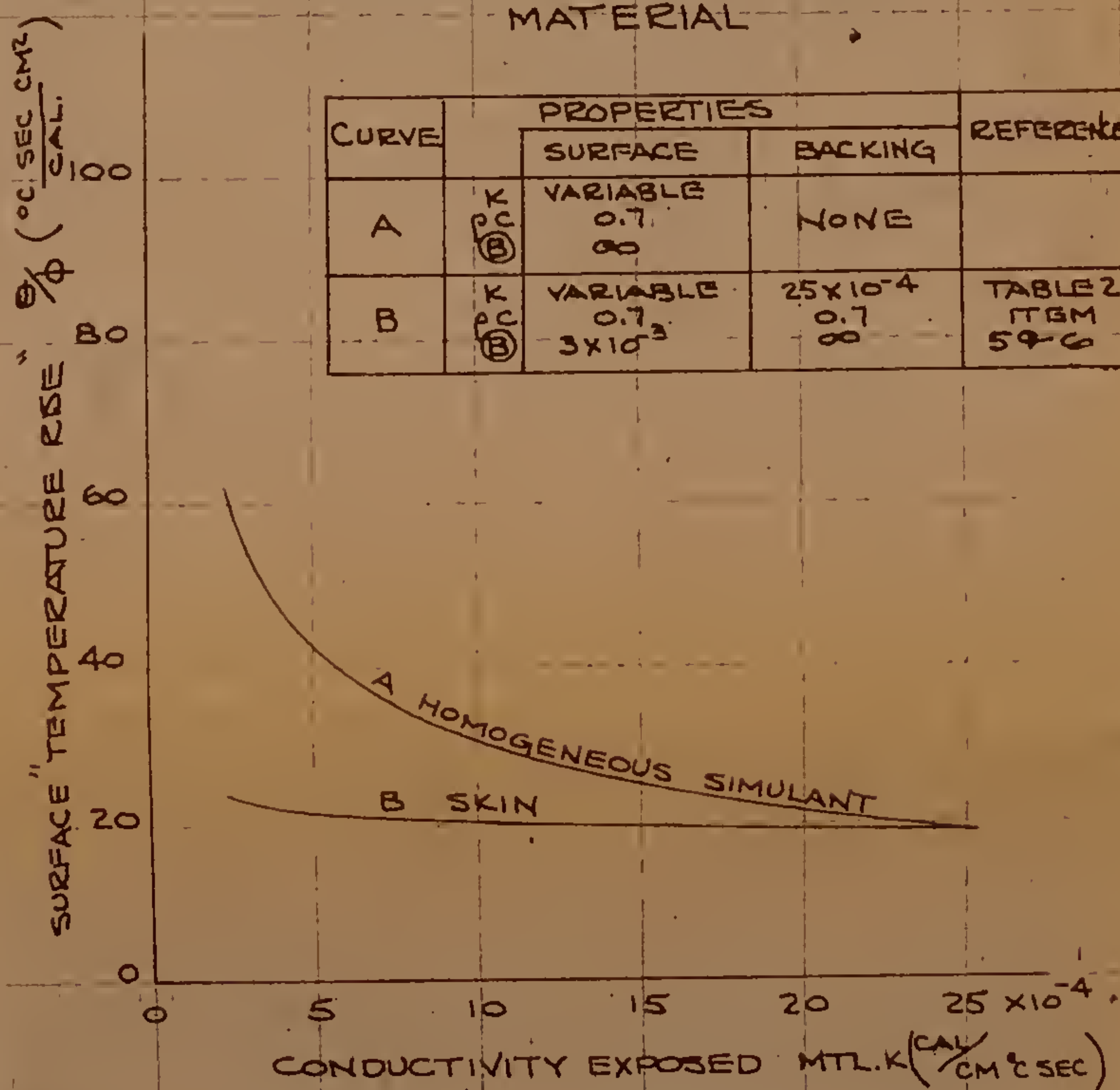


Fig. 2

SURFACE "TEMPERATURE RISE"
VS.
CONDUCTIVITY OF EXPOSED
MATERIAL

FIG. 2

SURFACE "TEMPERATURE RISE"
VS.
CONDUCTIVITY OF EXPOSED
MATERIAL



CURVE		PROPERTIES SURFACE	PROPERTIES BACKING	REFERENCE
A	K ρC Ⓑ	VARIABLE 0.7 ∞	NONE	
B	K ρC Ⓑ	VARIABLE 0.7 3×10^{3}	25×10^{-4} 0.7 ∞	TABLE 2 ITEM 59-6

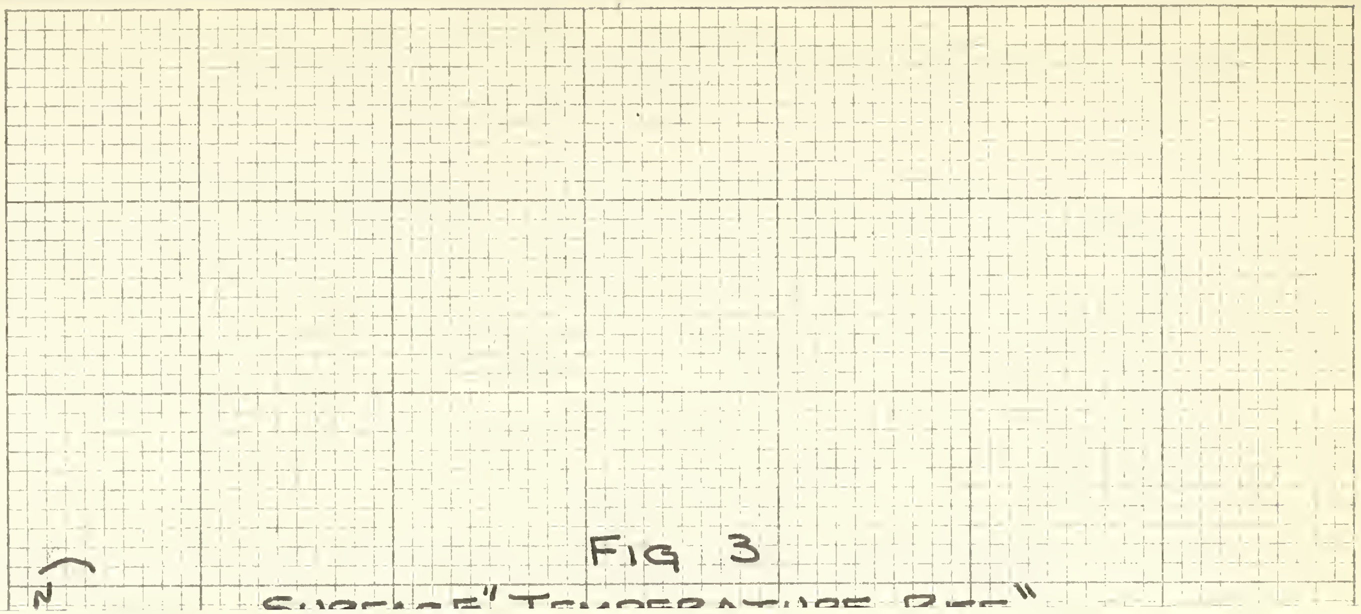


Fig 3

Fig 3

SURFACE "TEMPERATURE RISE" VS. EXPOSED LAYER THICKNESS

	PROPERTIES		REFERENCE
	SURFACE	BACKING	
K	9×10^{-4}	4×10^{-4}	TABLE 2
ρc	0.7	0.7	ITEM
β	VARIABLE	∞	798

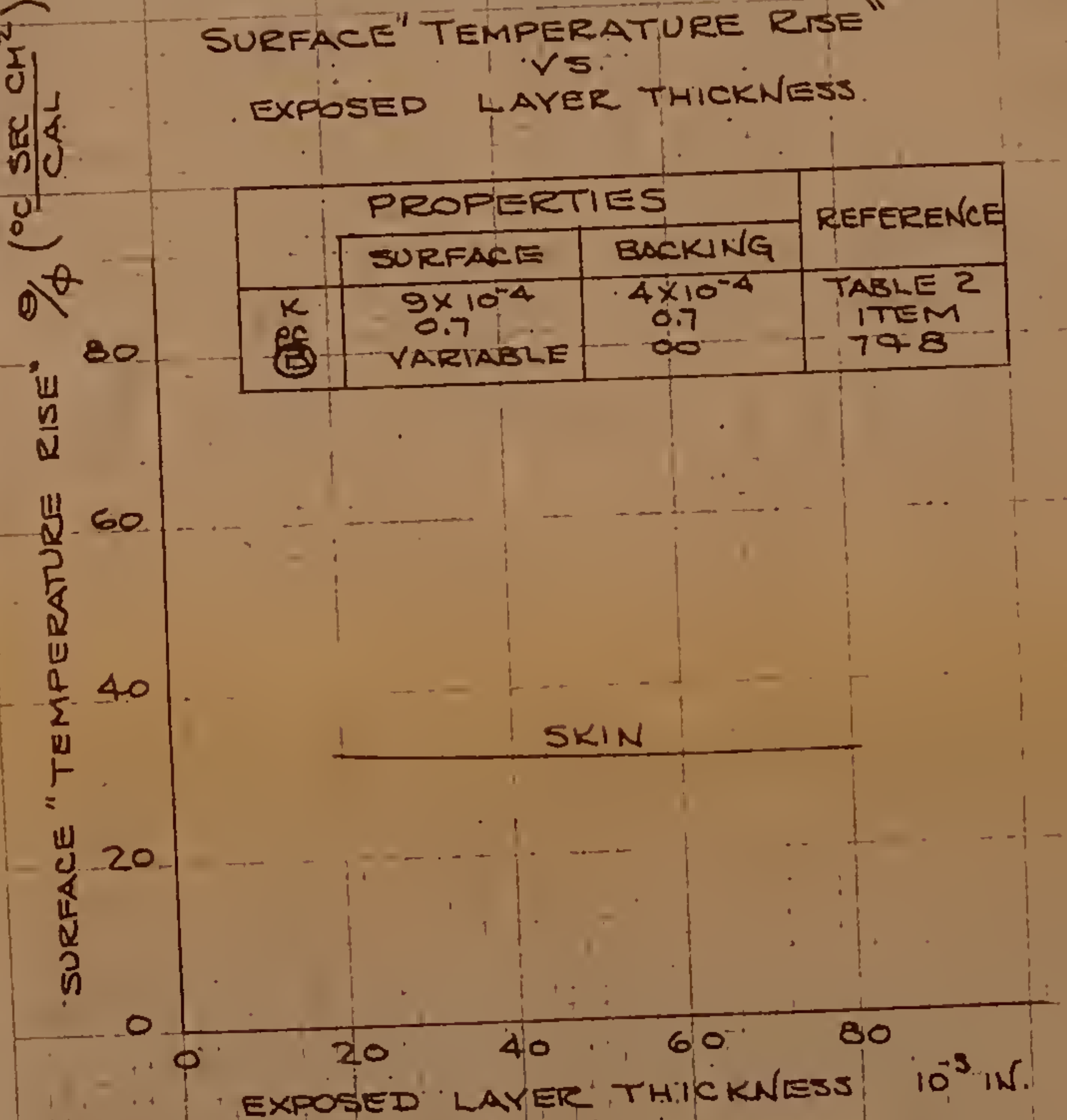


Fig. 4

EFFECT OF

METALLIC BACKINGS

ON

FIG. 4
EFFECT OF METALLIC BACKINGS ON INDICATOR "SURFACE TEMPERATURE"

FIG. 5

SEAC SOLUTION

SKIN "TEMPERATURE RISE"

VS.

TIME

FIG. 5

SEAC SOLUTION

SKIN "TEMPERATURE RISE"

VS.

TIME

	EPIDERMIS	DERMIS	FAT	REFERENCE
K	5×10^{-4}	9×10^{-4}	4×10^{-4}	TABLE 2
ρc	0.69	0.62	0.39	ITEM 1a
Ⓑ	3×10^{-3}	80×10^{-3}	80×10^{-3}	

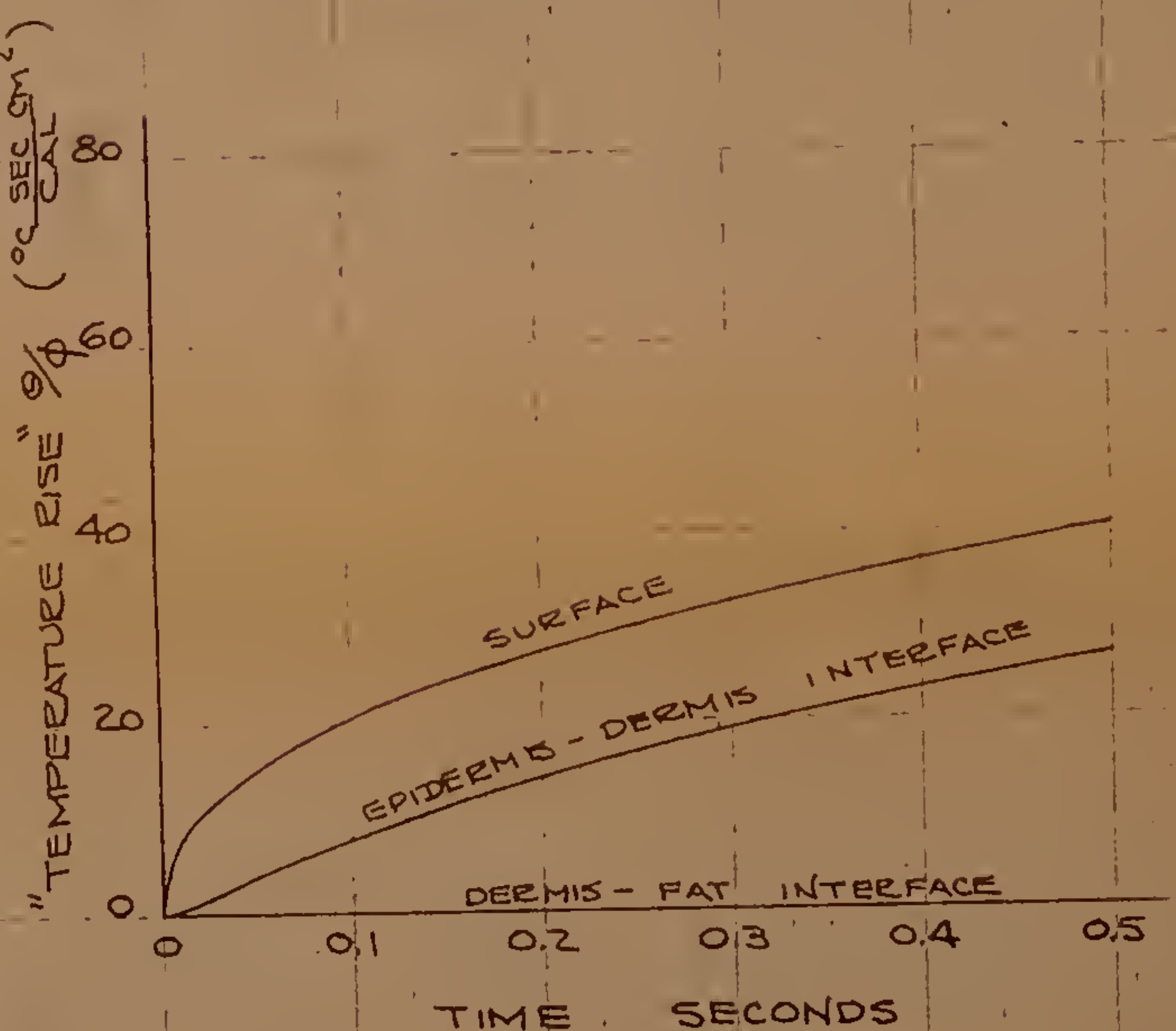


FIG 6

SEAC SOLUTION

"TEMPERATURE RISE"

VS.

TIME

FIG 6

SEAC SOLUTION
"TEMPERATURE RISE"
VS.
TIME

	INDICATOR PAPER	ADHESIVE TAPE	OAK BACKING	REFERENCE
K	3×10^{-4}	5×10^{-4}	3.5×10^{-4}	TABLE 4
ρc	0.26	0.47	0.24	C-1
Ⓑ	4×10^{-3}	5×10^{-3}	∞	

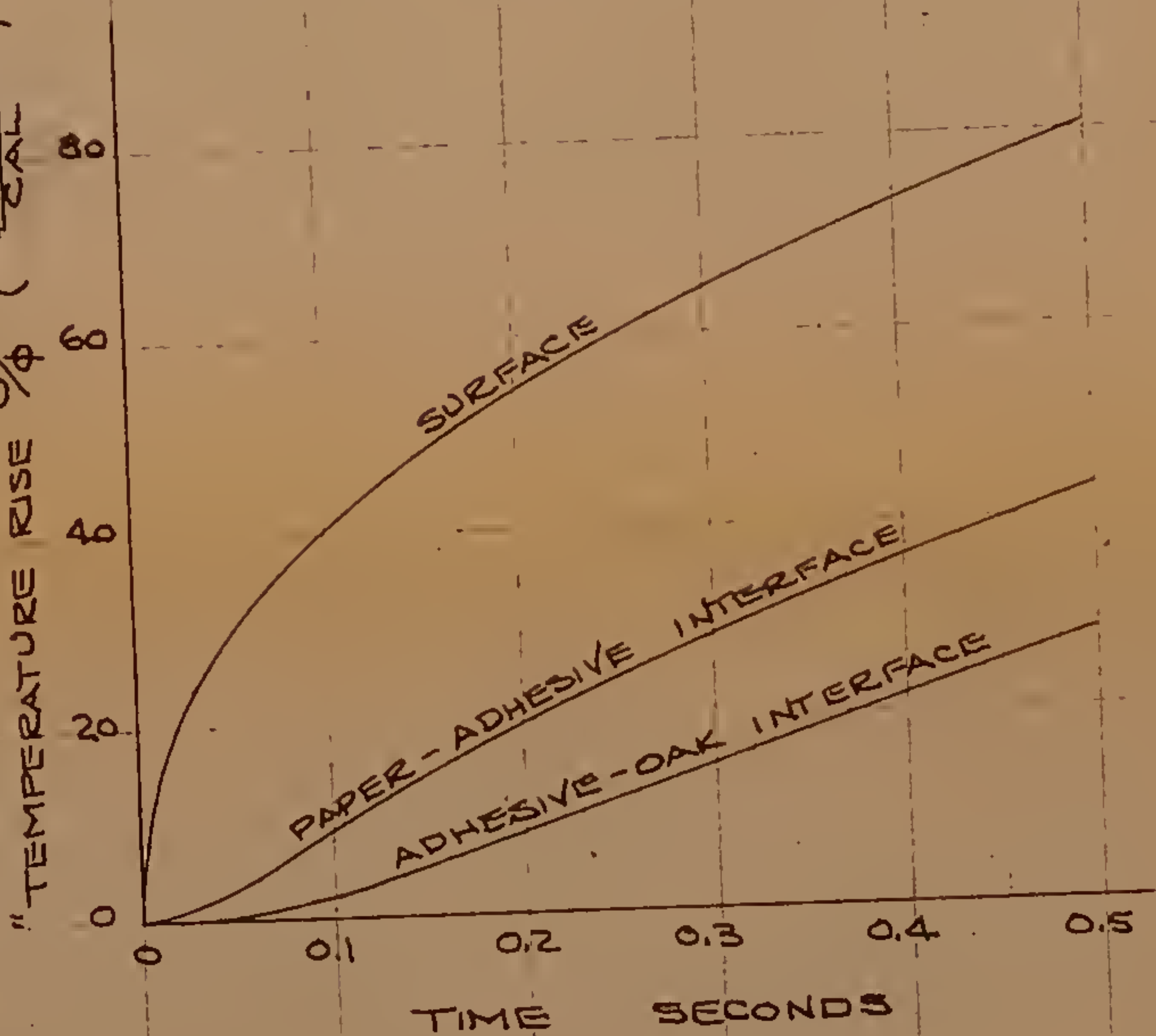


FIG. 7

SEAC SOLUTION

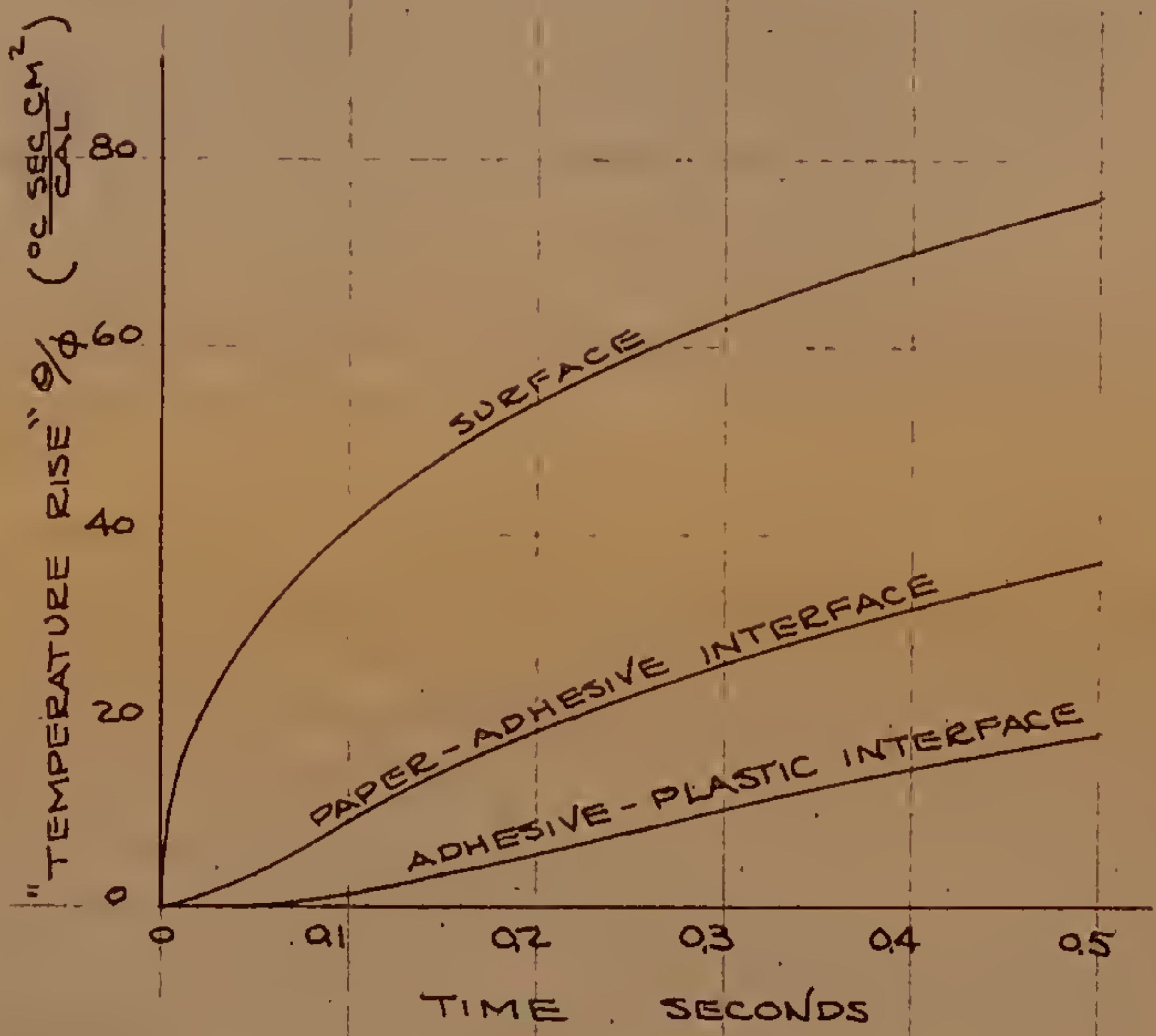
"TEMPERATURE RISE"

VS.

TIME

FIG. 7
SEAC SOLUTION
"TEMPERATURE RISE"
VS.
TIME

	INDICATOR PAPER	ADHESIVE TAPE	PLASTIC BACKING	REFERENCE
K	3×10^{-4}	5×10^{-4}	8×10^{-4}	TABLE 4
ρc	0.26	0.47	0.5	C-2
ⓑ	4×10^{-3}	5×10^{-3}	∞	



THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.00). Information on calibration services and fees can be found in NBS Circular 483, Testing by the National Bureau of Standards (25 cents). Both are available from the Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.

NBS