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U. S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

Aviation Medical Acceleration Laboratory

NADC-MA-6217 26 December 1962

Flame Contact Studies
III. Determination of Thermal Properties of Materials in Thin Layers

Bureau of Medicine and Surgery
Subtask MR005.13-1005.1 Report No. 30

Bureau of Naval Weapons
WepTask RAE 20J 010/2021/F012 10 002
Problem Assignment No. J44AE22-2

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SUMMARY

A method is described whereby thermal diffusivity and conductivity may be determined in thin layers of material. It is demonstrated by application in a study of fabrics ranging in thickness from 0.12 to 0.29 mm. The system is adaptable to use in similar measurements in living skin.

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INTRODUCTION

The preceding papers have presented an apparatus and procedures for the study of heat transfer on contact with flame (1), and the validation of a mathematical system of analysis of the data so obtained (2). The present report describes the procedure for the determination of diffusivity and thermal conductivity and its application to fabrics made of the heat-resistant synthetic fiber (Du Pont HT-1) discussed in the first of this series of papers.

MATERIALS AND METHOD

The flame contact apparatus used, the fabrics, and the experimental procedure for the determination of temperature-time histories and heat flux were those described in detail in the preceding papers. For the present purposes it was necessary only to measure the temperature rise at the fixed depth within the simulated skin, and in the simulant covered with single layers of fabric of thicknesses less than the critical thickness (1). For convenience, the exposure time chosen was 3.0 seconds. The fabric thicknesses measured by micrometer and by the circular disk gauge* were 0.12, 0.15, 0.20, 0.25, and 0.29 mm, corresponding to

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* Gauge using 3/8" pressor foot set at 4.8 lb/in^2 pressure. The cooperation of Margaret B. Hays of the Naval Material Laboratory, Philadelphia, Pa. in providing these measurements and the exact weights of the fabrics is gratefully acknowledged.

weights of approximately 2, 3, 4, 5, and 6 oz/yd^2 respectively. With the exception of the lightest-weight fabric, which was a plain weave, all the fabrics were either 2/2 or 3/3 twills, closely woven so that direct pathways for heat transfer from the source to the backing were obviated (Fig. 1, 3/3 twill, 6 oz/yd^2).

The procedure for determining the thermal conductivity of the fabric consisted of matching the observed temperature rise of the simulated skin under the fabric layers with the theoretical temperature rise calculated from Equation 1 (1) for the various thermal conductivities associated with the density and specific heat of the fabric.

The density of the fabric was 0.677 gm/cm^3 as determined from the measured weights and thicknesses and verified by fluid displacement measurements.

The specific heat value used was 0.29 cal/gm^{o}C given by the manufacturers* as the theoretical specific heat of the HT-1 polymer. Since the air contained in the yarn is negligible in terms of its contribution to the specific heat of the fabric it is expected that no appreciable error is introduced by this procedure when heating is effected by flame contact.

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* E. I. Du Pont de Nemours Inc., Textile Fibers Dept., Wilmington, Delaware.

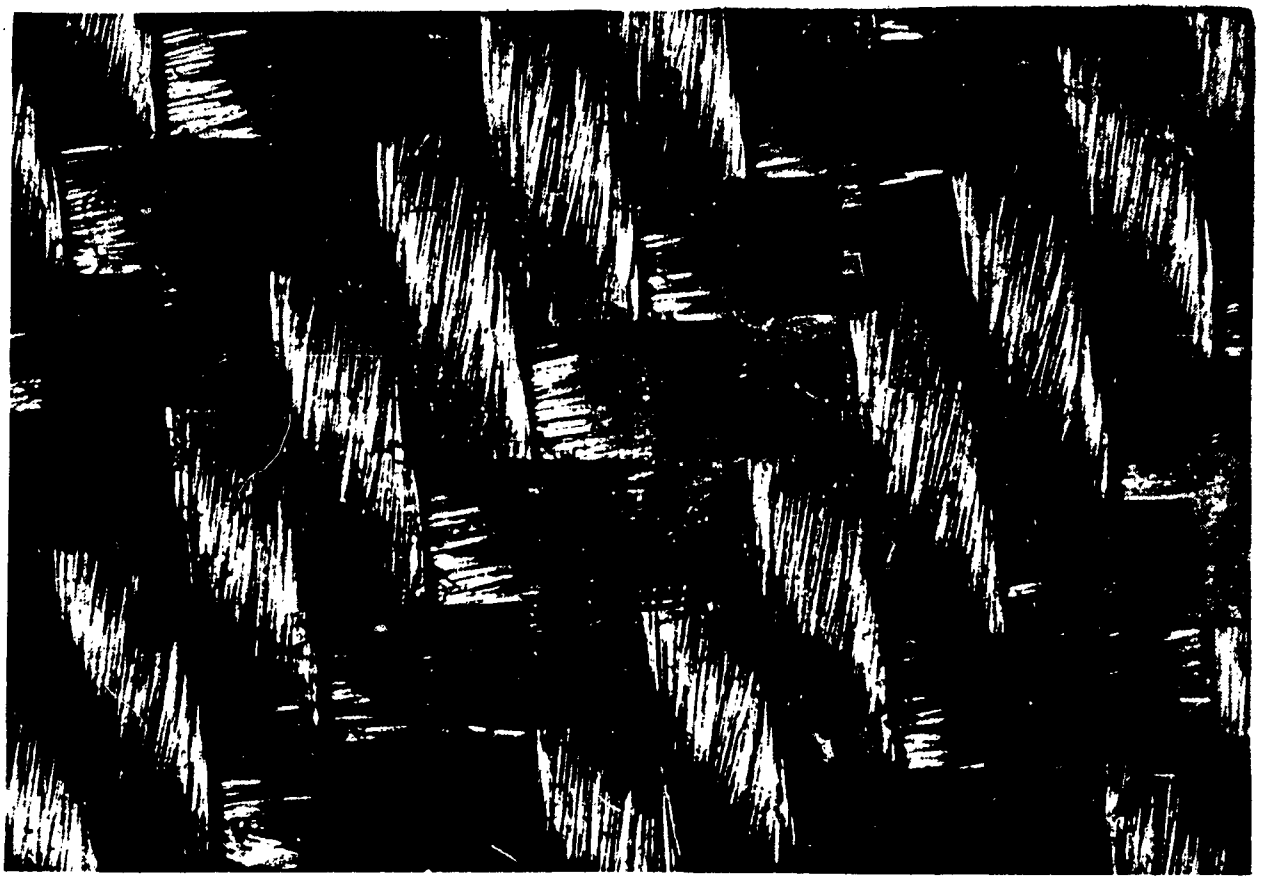

Figure 1. 3/3 twill, 6 oz/yd^2.

EXPERIMENTAL RESULTS AND DISCUSSION

The temperature rises measured at the exposure time of 3 seconds with the fabric-simulated skin assembly were 29.30 ± 0.20, 27.07 ± 0.90, 24.38 ± 0.87, 21.84 ± 1.30, and 19.59 ± 0.82° C/H under fabric thicknesses of 0.012, 0.015, 0.020, 0.025, and 0.029 cm respectively, with heat fluxes of from 1.1 to 1.3 cal/cm^2 sec. Matching these experimental values with the theoretical values derived from calculations of U_2/H using a series of assumed quantities for k_1 yielded a thermal conductivity of 6.1×10^{-5} cal/cm°C sec.

Figure 2 shows the plot of the experimentally determined points compared with the theoretical curve for U^2/H vs. thickness. The amount of variation introduced by a change of ± 0.02 cal/gm°C in the specific heat, or by $\pm 1 \times 10^{-5}$ cal/cm°C sec in the thermal conductivity is indicated by the lines drawn through the extremes. It is obvious that any greater change would destroy the fit of the curve to the experimental data. Therefore, the correct value is confined within quite narrow limits.

Having established that this system is not only feasible but also very sensitive, it was desirable to simplify the procedure for general applicability. This was done by plotting the diffusivity of the fabric (layer 1) against the temperature rise within the simulated-skin backing. An exposure time of 3 seconds, and a fabric thickness of 0.05 cm was used in

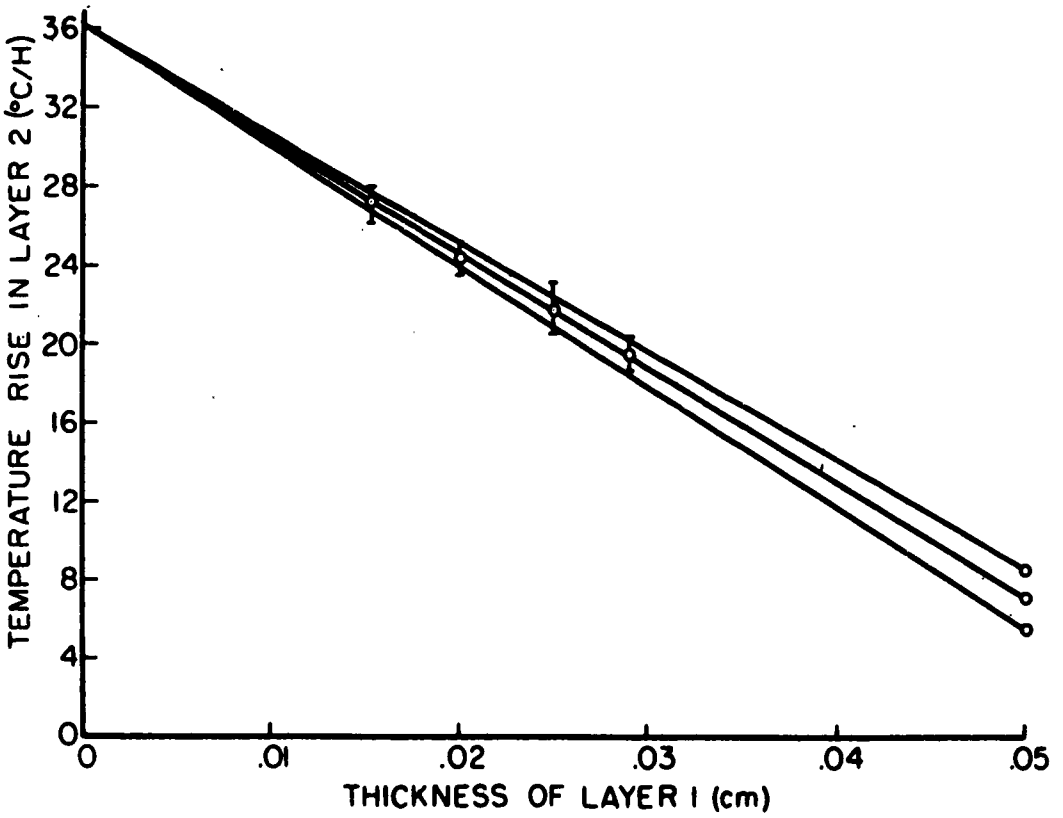

Figure 2. Comparison of theoretical and experimental data, temperature rise within simulated skin under HT-1 fabric.

computing these data (Fig. 3). This thickness was selected for two reasons: 1) convenience in computing temperature rise (necessitates carrying n to only one or two terms as opposed to four or five for lesser thicknesses), and 2) latitude in range of thicknesses referable to these data (as seen in Fig. 1 of the preceding paper the portion of the curve for U_2/H at thicknesses less than 0.05 cm is essentially a linear function of the thickness of layer 1). Therefore, the temperature rise at a thickness of 0.05 cm can be found by either graphical or numerical extrapolation of a straight line drawn between the experimental data on temperature rise and thickness and the Y intercept, 36.2°C/H, the temperature rise of the bare simulated skin. Then to find the diffusivity of the material, the temperature rise at 0.05 cm so found is referred to the "standard" chart, Fig. 3, and the corresponding diffusivity of layer 1 is read on the ordinate. If the volume specific heat is known, then the thermal conductivity is quickly obtained as the product of the diffusivity and the volume specific heat. For example, the temperature rise, U_2/H, measured under the HT-1, 0.25 mm thick, was 21.84°C/H; extrapolation to a thickness of 0.05 cm yields a value of 7.1°C/H; referring this value to the "standard" chart (Fig. 3), the diffusivity indicated is 31×10^{-5} cm/sec; the density and specific heat given are 0.677 gm/cm^3 and 0.29 cal/gm°C, respectively, therefore, the volume specific heat is 0.196 cal/cm^3°C, and the thermal conductivity is calculated as the product of diffusivity and

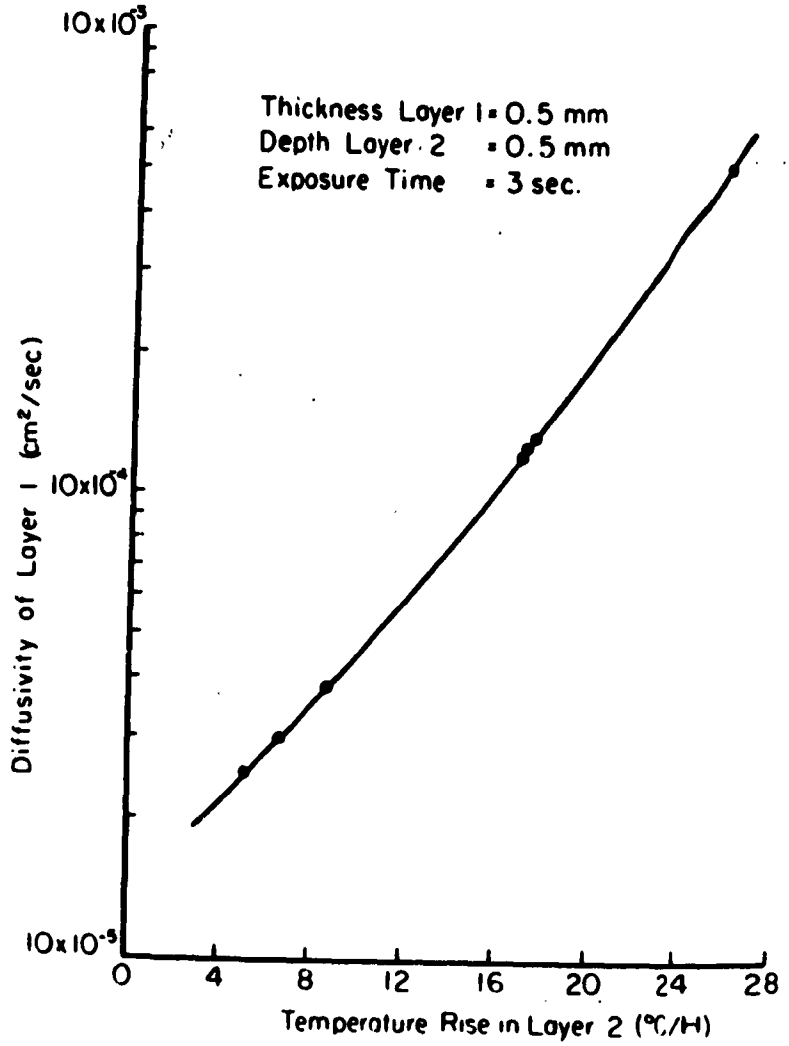

Figure 3. Diffusivity of layer 1 material vs. temperature rise at depth in layer 2.

volume specific heat, 6.1×10^{-5} cal/cm sec ^{o}C. Similarly, for the silicone rubber material studied earlier (2), extrapolation to a thickness of 0.05 cm yields 17.8^{o}C/H as U_2/H; the corresponding diffusivity from Fig. 3 is 13.6×10^{-4} cgs; the volume specific heat given is 0.47 and the thermal conductivity found is 6.4×10^{-4} cgs, the value given by the manufacturer.

As illustrated earlier (2), surface temperatures, interface temperatures and temperatures at any depth within the two layers may be determined by computation once the thermal properties have been established. Applying this system, the surface and interface temperature rises appropriate to the HT-1 fabric-covered simulated skin were computed for the exposure time of 3 seconds and are shown in Fig. 4. It is seen that the critical thickness occurs at about 0.06 cm and that the surface temperature rise is much greater than that of the silicone rubber (112.4^{o}C/H, (2)), as would be expected since the thermal conductivity of the latter is tenfold that of the HT-1 fabric. Thus, the fabric is seen to be a good insulator providing a large temperature gradient over a thin layer of material and thereby retarding the temperature rise of the underlying surface, an observation borne out in field tests of fire-resistant clothing of this material (7). In the same manner it is possible to generate families of curves delineating temperature-time histories of fabric-covered skin as desired within the range of heat flux, time and destruction temperature of

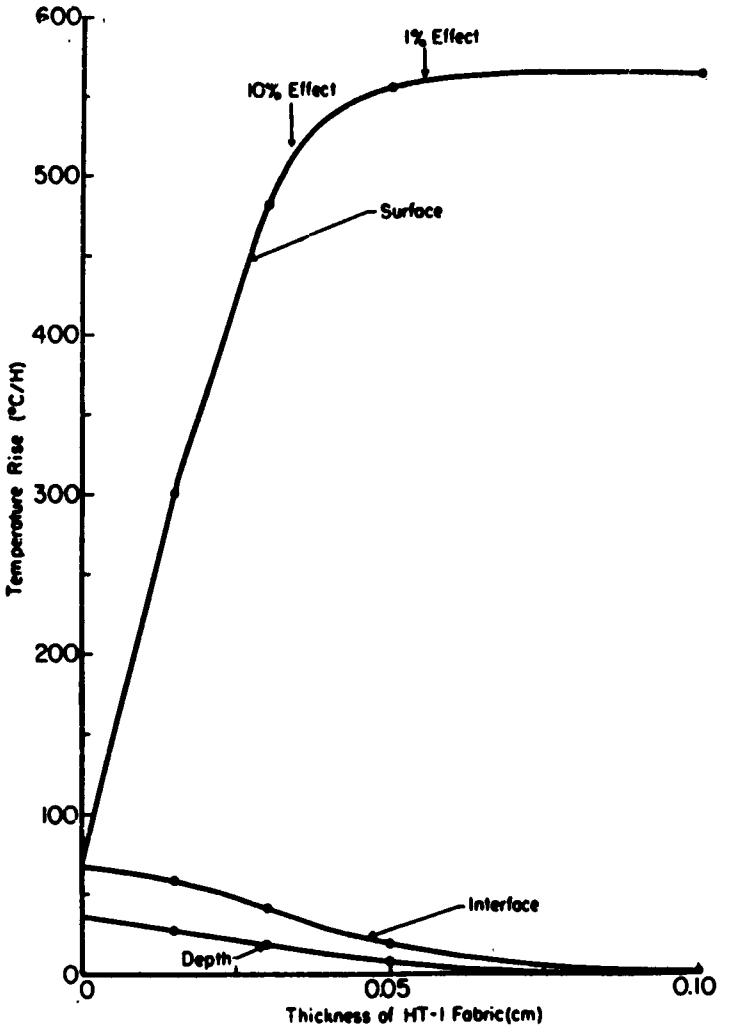

Figure 4. Surface, interface, and depth temperatures rises in HT-1 fabric skin simulant assembly.

the fabric. Thus, it would seem that the problem of assessing actual tissue damage could be solved by these simple measurements in conjunction with currently available knowledge (3, 4, 5). However, it has been pointed out by the authors themselves that the diffusivity of the simulated skin is in fact different from that of living skin (6) and therefore these measurements cannot be applied directly to this problem. On the other hand, the establishment of this set of mathematical expressions which have been proven experimentally to describe the heating process precisely, provides a powerful tool for attacking the problem indirectly. Thus, by utilizing the converse of the present procedure the system may be applied to physiological measurements: 1) the diffusivity of the living skin as layer 2 may be determined from surface temperature measurements made during heating of the skin covered by a thin layer of material of appropriate known thermal properties; 2) if the density and the specific heat are determined or known, thermal conductivity may be computed, and 3) temperature rises at depth may be determined without disturbing the subsurface tissue. In this way information such as the temperature at the skin receptor sites may be determined if the depth of the sites is known or is determinable after the heat exposure.

CONCLUSIONS

It is concluded that the technique described herein provides a sensitive and accurate means of determining the thermal properties in thin layers of

fabric and similar materials. In addition, the mathematical expressions applied are such that the system may be used for analyses of the underlying layer from a knowledge of the properties and the temperature-time history of the overlying layer, thus constituting a relatively simple means of studying the thermal properties of intact living tissue without alteration of the tissue itself.

REFERENCES

1. Stoll, A.M. and L.R. Munroe. Flame Contact Studies: I. Apparatus and method for determination of heat transfer through fabric during flame contact. U.S. Naval Air Development Center, Johnsville, Pa., Report No. NADC-MA-6215.

2. Stoll, A.M. and M.A. Chianta. Flame Contact Studies: II. Experimental validation of mathematical analysis of heat flow. U.S. Naval Air Development Center, Johnsville, Pa., Report No. NADC-MA-6216.

3. Moritz, A.C. and F. C. Henriques, Jr. Studies of Thermal Injury II: The relative importance of time and surface temperature in the causation of cutaneous burns. Am. J. Path. 23: 695, 1947.

4. Henriques, F.C. Jr. Studies of Thermal Injury V: The predictability and significance of thermally induced rate processes leading to irreversible epidermal injury. Arch. Path. 43: 489, 1947.

5. Stoll, A.M. and L.C. Greene. Relationship between pain and tissue damage due to thermal radiation. J. Appl. Physiol. 14: 373, 1959.

6. Derksen, W.L., G.P. DeLhery and T.I. Monahan. Thermal and optical properties of the NML skin simulant. Lab. Proj. 5046-3, 18 Jan. 1960.

7. Stoll, A.M. Thermal protection capacity of aviator's textiles. Aerospace Med. 33: 846, 1962.

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