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Apparatus for Determining Thermal Conductivity of Insulation Materials

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Synopsis

The initial object of this investigation was to design and build an apparatus capable of screening insulation materials for use in arctic shelters. A further object was to determine its suitability for determining thermal conductivity. The apparatus comprised a steel heat sink embedded in a 6-in. core of polyurethane foam coated with glass-reinforced plastic. The specimen rested upon the heat sink, and a constant temperature bath rested, in turn, on the specimen. A potentiometer was used to measure the temperature of the sink by means of a connecting thermocouple. After calibration, the apparatus was found to be highly accurate in determining thermal conductivity.

INTRODUCTION

The initial object of this investigation was to design and build an apparatus capable of screening insulation materials for use in arctic shelters. A further object was to determine its suitability for determining thermal conductivity.

During the development of the plastic shelter program it became necessary to compare various plastic foams and paper honeycomb constructions from the standpoint of thermal insulation. Equipment for determining thermal conductivity by the guarded hot plate method, an ASTM and Federal Test Method Standard, was not available and could not be obtained because of its high cost and the lack of space for it. An apparatus was required which was small, inexpensive, and simple to operate, which would provide the necessary information, and which would be capable of being fabricated in-house in order that it might be made swiftly and inexpensively.

INVESTIGATION

Design Considerations

After a study of various types of equipment used for determining thermal conductivity was completed, it was decided to design an apparatus of the Cenco-Fitch type. In this method, a source of heat at constant tempera-

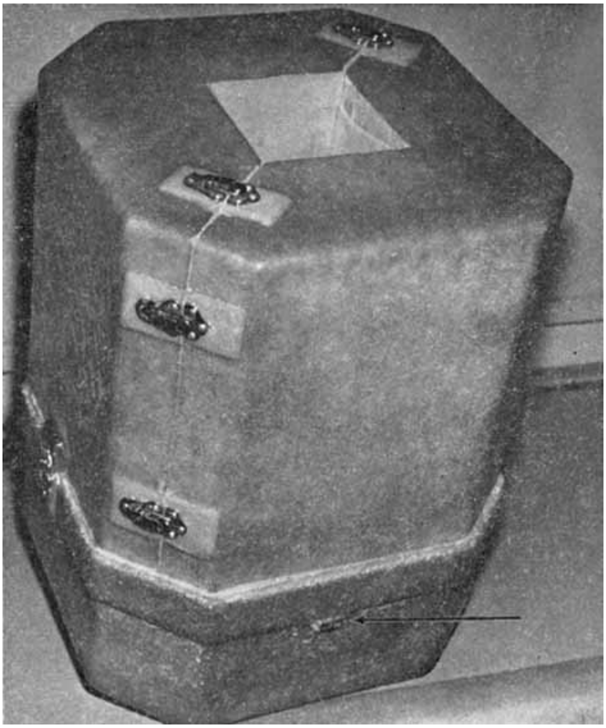

Fig. 1. Side and top view of assembled apparatus. Arrow indicates thermocouple receptacle for attachment to temperature recorder.

ture is placed on top of the specimen which, in turn, rests on a heat sink. The heat sink temperature gradually changes as heat is conducted through the specimen, and a plot of temperature versus time is made. The slope of the resulting curve represents the thermal insulation value of the specimen in degrees per unit time. Unfortunately, portions of the curves previously obtained by this method were always nonlinear so that the slope changed drastically, depending on which portion of the curve was being studied. This was attributed to a variety of factors, chief of which was poor design and construction.

Design of Apparatus

After several prototypes of an apparatus were designed, one was obtained which worked satisfactorily and which produced a linear curve over an 8-hr. test period. Figure 1 shows the final apparatus completely assembled. Figure 2 shows the base and the two sides of the apparatus. When assembled, the two sides rested on the base. A $6 \times 6 \times 2$-in. iron plate heat sink was imbedded in a polyurethane core 6 in. from the bottom and sides of the base. A thermocouple was attached to the plate by means of a threaded bolt screwed to the center of the bottom of the plate. The thermocouple extended to the outside of the base and ended in a plug to

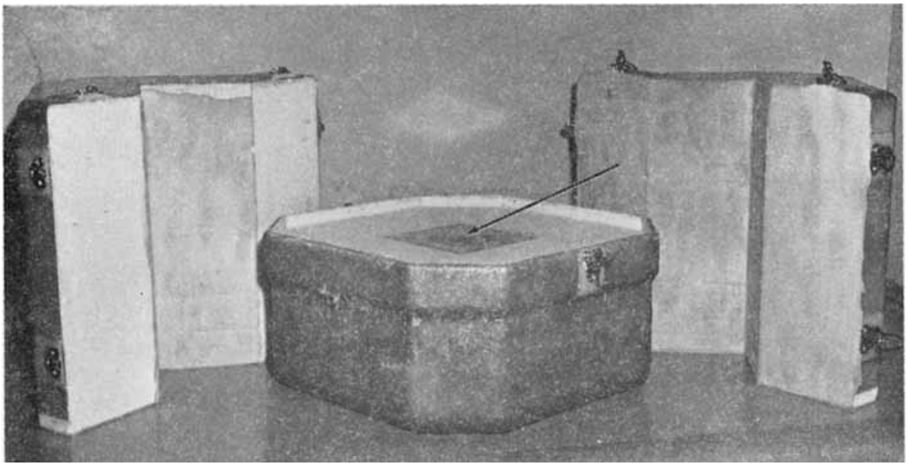

Fig. 2. Base and two sides of apparatus. When assembled, the two sides rest on the base. Arrow indicates heat sink.

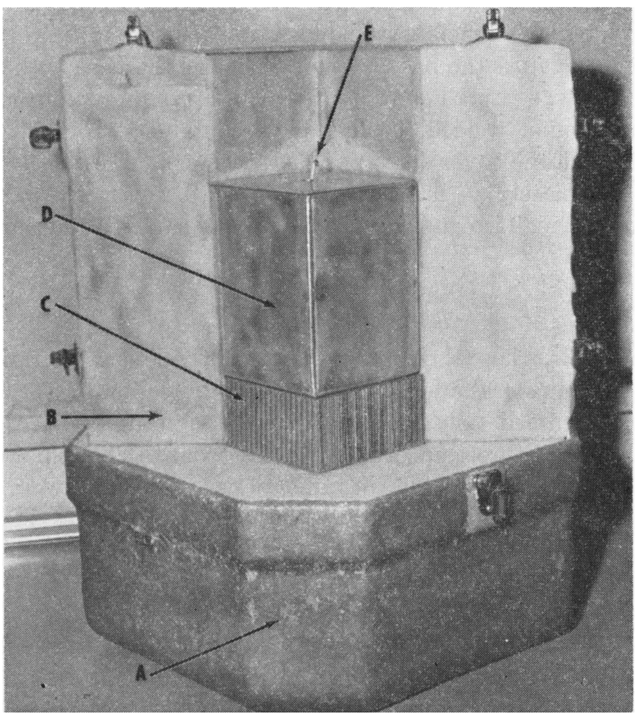

Fig. 3. Base (A), one side (B), and paper sandwich specimen (C) in place; container with fluid (D) and thermometer (E) atop specimen.

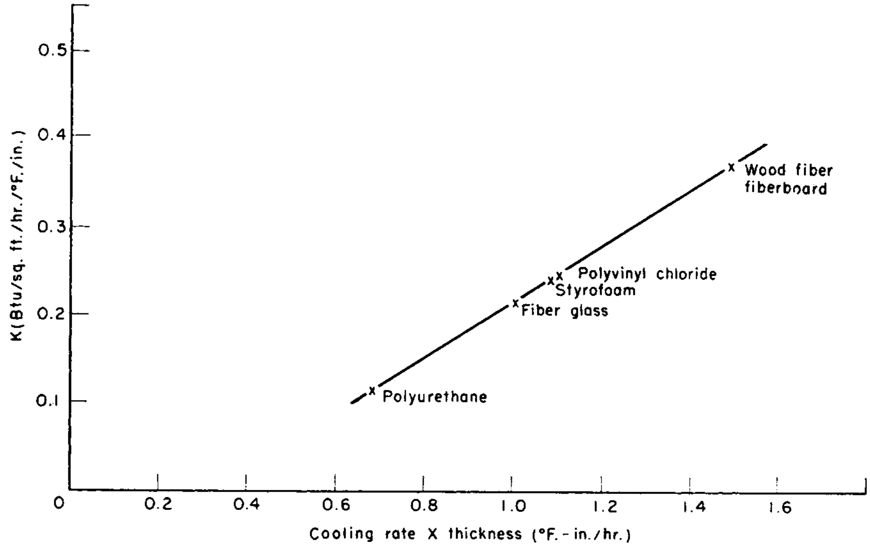

Fig. 4. Calibration curve of apparatus.

which could be attached an automatic temperature recorder or potentiometer. The exterior was finished with a spray-up of glass-reinforced plastic. Metallic fasteners were bonded on each side to keep the top side sections tight against the base. Figure 3 shows the base with one side in place in the rear, a paper honeycomb test specimen on top of the heat sink, and an aluminum, welded, cooling bath container with a thermometer protruding from the cover on top of the specimen. Flexible polyurethane sheets approximately $^1/_8$ in. thick were placed between the sides in order to take up any small irregularities in the mating surfaces and thus eliminate thermal currents.

Calibration

Five materials, whose thermal conductivities had been determined by the National Bureau of Standards, were used to calibrate the apparatus. They were: foamed polyurethane, fiber glass insulation, foamed poly(vinyl chloride), Styrofoam, and wood fiberboard. The specimens were approximately 6 × 6 × 1 in. in dimensions. The tests were performed three times. The cooling liquid was a bath of ice cubes in water. A potentiometer was used to measure the drop in temperature of the heat sink. The temperatures were recorded 2 hr. and 6 hr. after the beginning of the test and were accurate to 0.01°F. During the test, the thicknesses of the specimens were measured to the closest 0.001 in. with a depth gage. The specimens were measured at six locations around the perimeters. The apparatus was kept in a room at a constant temperature of 73.5°F. during the entire test, and care was taken to insure that the room temperature and the heat sink temperature were the same at the beginning of the test.

RESULTS AND DISCUSSION

Inspection of data obtained from previous experiments in which paper honeycomb core sandwich constructions of various thicknesses were tested indicated that the cooling rate varied inversely as the thickness and that the product of the cooling rate and the thickness was a constant for a given material. The specimens were, therefore, corrected for thickness variations by multiplying their cooling rates by their thicknesses.

The results of the calibration tests are shown in Table I. Although only three tests were run for each material, the averages of the deviations from the average were all less than 2%. The overall average was a little over 1%. The standard deviations were very low, averaging 0.0178. Figure 4 shows the calibration curve. All five materials are on a straight line in the K range of 0.118–0.375 which covers the thermal conductivity range of most important insulation materials.

During exploratory cooling rate tests, slightly curved lines were obtained when polyurethane foam test specimens were $^1/_2$ in. thick or less. When specimens used were 2 in. or more and they had very low thermal conductivities, incorrect results were obtained. These results were obtained because a very large flow of heat was conducted through the walls of the

TABLE I
Calibration Data

Material	Thermal conductivity, B.t.u./ft.^{2}/hr./°F./in.	Thickness, in.	Cooling rate, °F./hr.	Cooling rate times thickness, °F.-in./hr.	Deviation from average, %	Standard deviation
Polyurethane	0.118	1.012	0.680	0.688		
		1.004	0.670	0.672		
		1.020	0.675	0.688		
			Avg.	0.683	1.03	0.009
Glass fiber	0.217	0.936	1.093	1.023		
		0.928	1.103	1.024		
		0.981	1.040	1.020		
			Avg.	1.022	0.13	0.002
Styrofoam	0.246	1.046	1.044	1.092		
		1.046	1.051	1.099		
		1.046	1.086	1.136		
			Avg.	1.090	1.90	0.024
Poly(vinyl chloride)	0.247	1.068	1.029	1.099		
		1.070	1.055	1.128		
		1.052	1.054	1.109		
			Avg.	1.112	0.95	0.015
Wood fiberboard	0.375	1.065	1.440	1.533		
		1.050	1.425	1.496		
		1.037	1.404	1.456		
			Avg.	1.495	1.74	0.039

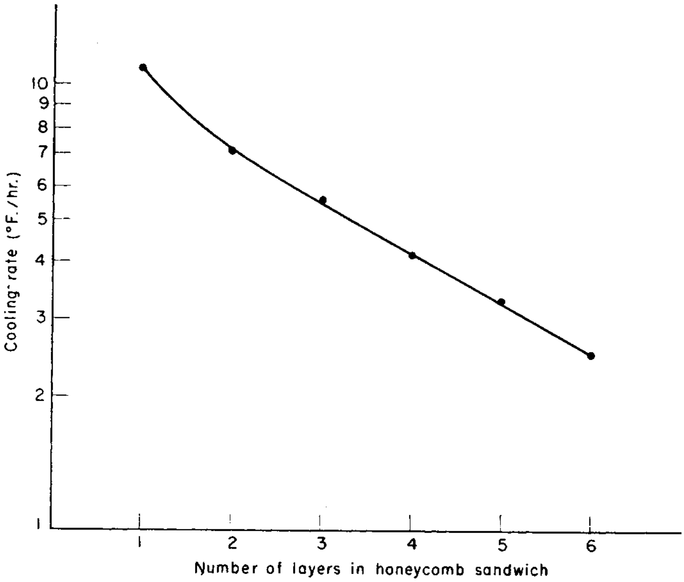

Fig. 5. Curve of cooling rate vs. layers in sandwich.

apparatus and around the specimen rather than through the specimen Test specimens should, therefore, be limited to approximately 1 in.

Since the calibration curve was a straight line, the formula for it was calculated and found to be

$$y = 0.3165x - 0.098$$

where x = cooling rate (°F.-in./hr.) and y = thermal conductivity (B.t.u./ft.^{2}/hr./°F./in.). The use of the equation probably would give more accurate results than the use of the calibration curve since it would eliminate errors in reading data from the curve.

The mean temperature t_m of the test specimen during the test was

$$t_m = (73.5 + 32)/2 = 52.8°\text{F.}$$

If it were desired to learn what the K value would be at some other mean temperature, the equation

$$K_2 = K_1[1 + \alpha(t_2 - t_1)]$$

should be used, where K_2 is the thermal conductivity at temperature t_2, K_1 is the known thermal conductivity at t_1, and α is a constant for the material. The value of α ranges from 0.0012 to 0.0016. The value of the expression $(t_m - t)$ is therefore small, and if α is considered to be an average value of 0.0014 in the absence of knowledge of its true value, only a small error will be obtained In general, K increases with an increase in temperature.

The apparatus was used to screen various materials which were being considered as insulation cores in sandwich constructions for shelters. Initially, only plastic foams were evaluated. Later, paper honeycomb constructions were considered as core materials, and it became desirable to learn the insulation capabilities of cores made with multiple layers of honeycomb paper. Cores were fabricated with sheets of kraft paper bonded between the layers of honeycomb. The results of this work were reported elsewhere.[1] One of the curves in the report is reproduced as Figure 5. The remarkable accuracy of the apparatus is demonstrated by the low scatter of the data making up the curve.

CONCLUSION

It is concluded that the apparatus described herein is both economical and highly accurate in determining the thermal conductivity of insulation materials.

Reference

1. Materials Research Laboratory Report No. 9039-5, Ft. Belvoir, Va.

Résumé

L'objet initial de cette étude était de concevoir et de construire un appareil capable de protéger les matériaux d'isolants employés dans les abris de l'Arctique. Un objet ultérieur était de déterminer s'il pouvait servir pour la détermination de la conductivité thermique. L'appareil comprend un récipient en acier chauffé et enrobé dans une masse de 6 pouces de mousse de polyuréthanne recouverte de plastique renforcé avec du verre. L'échantillon repose sur le récipient chauffé et, à son tour, un bain à température constante repose sur l'échantillon. On utilise un potentiomètre pour mesurer la température du récipient au moyen d'un thermocouple. Après calibrage, on a trouvé que l'appareil possédait une précision élevée pour la détermination de la conductivité thermique.

Zusammenfassung

Das ursprüngliche Ziel dieser Untersuchungen war es einen Apparat zur Testung von Isolierstoffen zum Gebrauch in arktischen Unterkünften zu konstruieren. Weiters wurde seine Brauchbarkeit zur Bestimmung der Wärmeleitfähigkeit untersucht. Der Apparat besass eine in einen mit Glas verstärkten kunststoffüberzogenen 6-Zoll Polyurethanschaumkern eingebettete Stahlwärmeableitung. Die Probe lag auf der Wärmeableitung und auf der Probe ihrerseits befand sich ein Bad mit konstanter Temperatur. Ein Potentiometer wurde zur Messung der Temperatur der Wärmeableitung mittels eines Thermoelements verwendet. Nach Kalibrierung gestattet der Apparat eine äusserst genaue Bestimmung der Wärmeleitfähigkeit.

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