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HEAT TRANSFER OF FIBROUS INSULATION BATTINGS

BY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Heat losses by convection, conduction, and radiation through battings made of solid and hollow regular fibers (fiber diameter D_f = 25-μm), fine fibers (12-μm < D_f < 15-μm), and microfibers (D_f < 10-μm) have been investigated by using laboratory-scale heat flow apparatus and heat transfer analysis. It is found that these heat losses are interrelated functions of batting thickness, batting bulk-density, and fiber diameter. Natural convective heat loss is found to be negligible for all the battings. Conductive heat loss is

20. ABSTRACT (Cont'd)

essentially inversely proportional to batting thickness and relatively independent of fiber properties. Radiative heat loss is found to decrease with increasing bulk density and decreasing fiber diameter. Hence, microfiber battings can be thinner than battings made from other fibers to provide similar thermal insulation. On the basis of the same bulk density and batting thickness, microfibers can provide a maximum of about 25% and 10% higher clo values than regular and fine fibers, respectively. In view of the low radiative heat loss of microfibers and the high resilience of regular fibers, they should be combined to form economical composite battings. In addition, reflective battings made from reflective layers and low bulk-density fibers should also be pursued for applications where laundering is not required.

Preface

The present investigation on the heat transfer of fibrous insulation battings was conducted by the author in the Material Research and Engineering Division of the Individual Protection Laboratory (IPL) under Project No. 1L162723AH98AE041. Numerous discussions with Ms. Deirdre Rapacz of IPL and her experimental assistance are acknowledged.

Some of the results from this investigation are being extended and applied to tentage thermal insulation liners currently being developed at the Aero-Mechanical Engineering Laboratory. The continued support from IPL in this development is appreciated.

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HEAT TRANSFER OF FIBROUS INSULATION BATTINGS

INTRODUCTION

For the United States soldiers, sufficient thermal protection at low temperatures is one of the major requirements for their efficient performance in cold climates. Synthetic fibers are presently being used in the Army as thermal insulation batting materials for cold weather except that in extreme cold climates down, an expensive natural fiber, is still being used. Polyester regular fibers of 25-μm diameter, either solid or hollow, are the current standard batting materials for Army personnel thermal insulation items, such as clothing, handwear, and sleeping bags.[1] As synthetic fiber technology advances, new fibers with better thermal insulation properties are produced in the hope of eventually replacing down. Presently, there are several new fibers being considered for Army use. Two important ones are fine fibers with diameters of 12 to 15 μm, and microfibers with diameters less than 10 μm. In addition, multihole hollow regular fibers are also being developed for consideration. Manufacturers of the new fibers have made various claims for their superior performance. Recent reviews on current thermal insulation materials[2,3] indicated that relative performance of the various types of fibers is not well known, and there is a need to examine the thermal insulation mechanisms of battings made from these fibers.

An evaluation of microfiber battings in their pre- and post-laundered conditions using the military field laundry was performed by Mikelson.[4a] While microfiber battings were found to be more effective in thermal insulation than other battings, a significant loss of clo* was found for these battings after military laundering.

In the present work, laboratory-scale heat transfer measurements were made on regular and fine fiber battings. Measurements are compared with those of microfiber battings.[4a,4b] Relative performance of the three kinds of fibers is investigated in terms of convective, conductive, and radiative heat losses as functions of batting thickness, bulk density, and fiber diameter. In addition, composite and reflective battings made from layers of regular fibers, fine fibers, and reflective materials are also examined. Guidelines for future fiber and batting development are presented.

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*For definition of symbols, see List of Symbols

BATTING MATERIALS

Battings made of three general groups of fibers as shown in Table 1 are investigated. The three groups of fibers based on fiber diameter D_f are: (1) regular fiber with D_f equal to 25 μm, (2) fine fiber with D_f between 12 and 15 μm, and (3) microfiber with D_f less than 10 μm. Regular fiber consists of two types. One is solid fiber and the other one is hollow fiber (hollow tube-shaped fiber). Both types are claimed to be lofty because of their relatively low-bulk densities, and hollow fibers are supposed to trap more air than other fibers. Currently, both types of regular fibers are being used by the Army. Diameters of the fine fibers are between those of regular and microfibers. Fine fiber battings are supposed to provide effective thermal insulation for relatively thin batting thicknesses. Microfibers have the smallest diameter. They are made into both low bulk-density and high bulk-density battings. Microfibers are claimed to have more fiber-to-air contact surfaces than other fibers and to provide equivalent thermal insulation for thinner batting thicknesses. Each of the selected fibers has its own distinctive characteristics. Together they represent a set of current important fibers for clothing and equipage thermal insulation applications.

TABLE 1. Properties of Insulation Batting Materials

	Fiber Group	Fiber Diameter, D_f	Material	Material Density, ρ_m	Nominal Areal Density, ρ_a	Bulk Density, ρ_b
				lb/ft^3	lb/yd^2	lb/ft^3
(1)	Solid Regular Fiber	25	Polyester	86.2	4	0.38
	Hollow Regular Fiber	25	Poyester	86.2	4	0.40
(2)	Fine Fiber	12-15	Polyester	86.2	4	0.84
(3)	Low Density Microfiber	36-38 Majority 1-3	43% Polyester 57% Polyolefin (Polypropylene)	86.2 58.5	4	0.76-00.82
	High Density Microfiber	Majority 7-8 Majority 1-3	100% Polyester 100% Polyolefin (Polypropylene)	86.2 58.5	4 4	2.7 2.6-3.1

Polyester is the major material used for all regular and fine fibers. Both polyester and polypropylene are used in high bulk-density microfiber materials; low bulk-density microfiber materials are a blend of polypropylene microfibers with conventional polyester fibers. All the battings investigated are commercial products rated at 4-oz/yd^2 areal density. Bulk-densities of uncompressed battings can be separated into three levels: regular fiber batting, the lowest; fine fiber and low-density microfiber battings, the medium; and high-density microfiber batting, the highest. In view of this distribution of bulk densities, regular and fine fiber battings can be compressed to increase their bulk-densities so that they become the same as those of microfiber battings. If various batting layers are used in the compression process, identical bulk-density and batting thickness (equivalent to the condition of the same weight of fibers in the same batting thickness) can be obtained between regular and microfiber battings, and between fine fiber and microfiber battings. Values of clo_b measured under this condition can then be used to investigate the net effect of fiber diameter on the heat flow or thermal insulation of the battings. This experimental technique was used in the present investigation.

EXPERIMENTS

In a cold environment, body heat can be lost through clothing to the environment by convection, conduction, and radiation. The relative amounts of heat loss by these three heat transfer mechanisms depend on the properties of the clothing assembly, especially its insulation batting, and the environmental conditions. As initial screening or comparison tests on the thermal insulation effectiveness of end-item clothing assemblies, it is suitable to use the Standard Test Method ASTM D1518-77 for Thermal Transmittance of Textile Materials between Guarded Hot-Plate and Cool Atmosphere.[5] In this test method, the lower surface of a horizontal uncompressed clothing assembly or an insulation batting is heated by a guarded hot plate. The upper surface of the test sample is exposed to a controlled lower temperature environment in a climatic chamber. Such a test arrangement gives the total clo measurement consisting of the clo_b of the test sample and the clo of the air layer above it. Usually the latter is subtracted from the total clo to obtain clo_b .

For the present investigation, since compression of battings is required, it is more suitable to use the Standard Test Method ASTM C518-76 for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter.[6] In this test method, a batting is positioned between two horizontal, temperature-controlled black surfaces. The batting thickness is controlled by varying the position of the upper black surface. Either a hot or a cold temperature can be set at either surface. If the hot temperature is set at the upper surface, natural convective heat flow through the batting is eliminated. Batting clo_b is determined as a function of batting thickness and bulk-density. Compared to Test Method ASTM D1518-77, this test method is more versatile and convenient to use and is well suited for the present batting heat transfer study.

The main difference between the test conditions of the two test methods is the boundary condition of the upper surface of the batting as described above. If conduction is the dominant mode of heat transfer in the batting, similar clo_b values should be measured from both test methods. If radiation is also important, different clo_b values may be obtained from the two test methods. Both test methods were used by Mikelson in his study.[4a,4b] His results showed that for the same thickness of uncompressed microfiber battings, identical clo_b values were obtained from the two test methods. For the same thickness of uncompressed regular fiber battings, clo_b values from Test Method ASTM C518-76 using a Dynatech R/D Company Rapid K Thermal Conductivity Instrument were slightly higher than those from Test Method ASTM D1518-77.

In view of the above discussion, the Rapid K Thermal Conductivity Instrument was chosen for clo_b measurements of the regular and the fine fiber polyester battings. A maximum of four layers of the battings were compressed in steps to obtain clo_b as functions of wide ranges of batting thicknesses and bulk-densities. These measurements are then compared with those of the microfiber battings from Mikelson.[4a,4b]

In addition to the thermal insulation measurements, air permeability of the battings was also measured to supplement the Rapid K Thermal Conductivity Instrument using the orifice method in accordance with Federal Test Method Standard No. 191A, Test Method 5450.[7] Other instruments used included a standard Certain-Teed Corporation Measure-Matic Unit for uncompressed batting thickness measurements, and a Hewlett Packard Model 3052A Data Acquisition System for data collection and processing.

HEAT TRANSFER IN BATTINGS

Overview

Fig. 1 shows the important parameters of the Rapid K Instrument for a batting thermal insulation test. An insulation batting of thickness d is

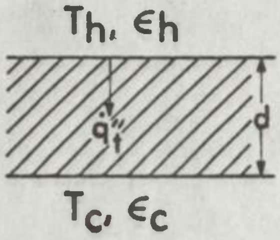

Figure 1. Parameters of rapid K thermal conductivity instrument.

positioned between the hot plate at surface temperature T_h and the cold plate at surface temperature T_c. From the measured total heat flux $\dot{q}''_t$ through the batting, the apparent thermal conductivity k_{ap} of the batting is calculated using the following equation:

$$\dot{q}''_t = k_{ap} \left(\frac{T_h - T_c}{d}\right) \qquad (1)$$

From the definition of clo_b, k_{ap} is related to clo_b in the British engineering units as follows:

$$clo_b = \frac{1.136 \times d}{k_{ap}} \qquad (2)$$

Equation (1) is analogous to the steady-state heat conduction equation for a solid. In a porous fibrous batting, in addition to conductive heat transfer, convective and radiative heat transfer can also occur due to the trapped air and the high porosity in the batting. Therefore, in fibrous thermal insulation study, the apparent thermal conductivity k_{ap} is introduced and it consists of the following three components:

$$k_{ap} = k_{cd} + k_{cv} + k_r \qquad (3)$$

In equation (3), k_{cd}, k_{cv} and k_r are the batting conductivity for conduction, for convection, and for radiation, respectively. From equation (1), $\dot{q}''_t$ can then be expressed in terms of its three heat transfer components, conduction $\dot{q}''_{cd}$, convection $\dot{q}''_{cv}$, and radiation $\dot{q}''_r$, as follows:

$$\dot{q}_t'' = (k_{cd} + k_{cv} + k_r) \frac{(T_h - T_c)}{d} \quad (4)$$

$$= k_{cd} \frac{(T_h - T_c)}{d} + k_{cv} \frac{(T_h - T_c)}{d} + k_r \frac{(T_h - T_c)}{d}$$

$$= \dot{q}_{cd}'' + \dot{q}_{cv}'' + \dot{q}_r''$$

In general, the three conductivities in equation (3) are complicated functions of the properties of the air-fiber structure, the imposed thermal boundary condition, and the external air flow condition. In the present investigation, the three conductivities of the selected fibrous battings are examined as functions of their air-fiber properties at constant T_h and T_c. (T_h = 95°F and T_c = 55°F as required by Test Method ASTM D1518-77). The effect of external forced air flow is beyond the capability of the Rapid K Instrument; only natural convective heat flow can be studied in the Rapid K Instrument. It is constructive to note that if T_h and T_c are set at the upper plate and at the lower plate of the Rapid K, respectively, $\dot{q}_{cv}''$ will become identically zero. The conductive heat flux $\dot{q}_{cd}''$ can be calculated separately by knowing k_{cd} (equation (4)); along with the measured $\dot{q}_t''$, $\dot{q}_r''$ can be calculated using equation (4). Relative magnitudes of $\dot{q}_{cd}''$ and $\dot{q}_r''$ can then be studied using this technique.

As mentioned earlier, heat transfer measurements of uncompressed and compressed battings were made in the Rapid K Instrument. To illustrate the physical meaning of equations (1) to (4), total heat flux $\dot{q}_t''$ of the uncompressed battings and of the air space (without batting) with T_h set at the upper plate surface are shown in Fig. 2. It is seen that in the pure air space ($k_{cd} = k_a$ in this case), the conductive heat flux $\dot{q}_{cd}''$ is only a small fraction of the total heat flux $\dot{q}_t''$; since convective heat flux $\dot{q}_{cv}''$ is identically zero, majority of $\dot{q}_t''$ is radiative heat flux $\dot{q}_r''$ (equation (4)). This $\dot{q}_r''$ is decreased by all the battings in various degrees; for the same uncompressed batting thickness, high-density microfiber is most effective (lowest k_{ap}), fine fiber and low-density microfibers are the second, and regular fibers are the third. These results suggest that different fibers provide different values of k_{ap} and $\dot{q}_t''$. They are further examined by investigating their individual components.

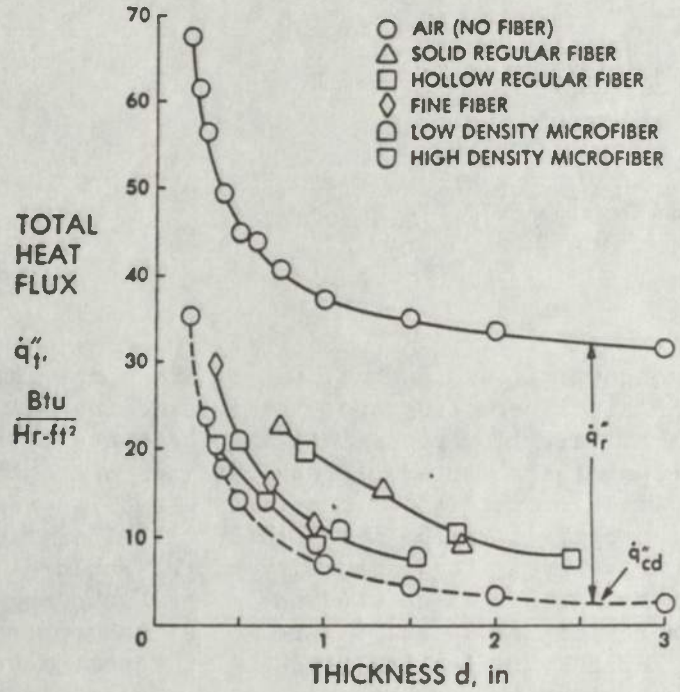

Figure 2. Total heat flux through air and uncompressed battings.

Natural Convection

The amount of heat loss through a batting by natural convection depends on the relative magnitudes between two forces. One is the buoyancy force generated by the temperature gradient across the batting, and the other one is the resistance force to air motion presented by the fibers. The ratio of these two forces is expressed by the Rayleigh number Ra defined as[8]

$$Ra = \frac{g B \rho^2 c_p G (T_h - T_c) d}{\mu k_a} \tag{5}$$

The air permeability G in equation (5) is defined as

$$G = \frac{Q \eta}{\Delta P / d} \tag{6}$$

where Q is the air permeability commonly used in textiles. In the expression of Ra, G and d are functions of the batting; the other parameters are functions of the air inside the batting.

Table 2 shows the measured Q values from the Federal Test Method 5450 for the single layer uncompressed battings.[7] As expected, Q decreases as the bulk-density increases from regular fiber battings to microfiber battings.

This is simply because there are more fibers per unit batting volume in the high bulk-density battings to restrict air flow. The hollow fiber batting shows slightly higher air resistance as compared to the solid fiber batting. This is most likely because for the similar bulk-density and fiber diameter, there are more fibers per unit batting volume in the hollow fiber batting than in the solid fiber batting. Comparison between the fine fiber and the low bulk-density microfiber battings shows that the latter provides higher air resistance to air flow than the former although both battings have similar bulk-densities. Again, this is because there are more smaller diameter fibers per unit batting volume in the microfiber batting than in the fine fiber batting.

TABLE 2. Natural Convection of Single-Layer Uncompressed Battings

	Regular Fibers		Fine Fibers	Microfibers	
	Solid	Hollow		Low Density	High Density
Q, $ft^3/min\text{-}ft^2$	742	673	493	47.1	11.2
$G \times 10^5, ft^2$	0.012	0.0109	0.0035	0.00054	0.000067
Ra	6.79	6.06	0.73	0.18	0.012
$\dot{q}_t''$ Btu/hr-ft^2 (T_h at bottom with convection)	23.2	---	---	---	34.2
$\dot{q}_t''$, Btu/hr-ft^2 (T_h at top without convection)	22.5	---	---	---	33.3

The calculated values of G and Ra based on the Q measurements, and T_h = 95°F and T_c = 55°F in the Rapid K Instrument are shown in Table 2. The behavior of G among the various battings is similar to that of Q as expected from equation (6). The distribution of Ra is also similar, showing that microfiber battings present more resistance to natural convective heat flow than fine fiber battings, which in turn are more resistant to natural convection than regular fiber battings.

It has been shown theoretically and confirmed experimentally[8,9] that natural convection within a fibrous insulation material is unimportant as compared to conduction and radiation if Ra is less than 40 for the material. Based on this criterion, natural convection is negligible for all the battings examined since their Ra values are less than 40 as shown in Table 2. This is confirmed experimentally by comparing the total heat flux $\dot{q}_t''$ values measured when T_h was set at the lower surface, and when T_h was set at the upper surface of the Rapid K Instrument. The resultant $\dot{q}_t''$ values for the solid regular fiber batting and the high-density microfiber batting are shown in Table 2. It is seen that $\dot{q}_t''$ increased by only 3% for both battings when T_h

was set at the lower surface to induce natural convection. In view of the negligible natural convection, all tests in the Rapid K Instrument were conducted with T_h set at the upper surface to eliminate natural convection entirely so that conduction and radiation can be studied accurately. Therefore, k_{cv} and $\dot{q}''_{cv}$ in equation(4) are identically zero for the present investigation. It is of interest to note that even at T_c = -40°F, the value of Ra is only 24 (below 40) from equation (5), indicating natural convective heat loss is still negligible under such an extreme cold condition.

Conduction

Heat conduction through a batting can take place via the air trapped among the fibers and via the fibers themselves. Various mathematical models have been proposed for the combined conduction conductivity k_{cd} for the air-fiber structure. It was found that k_{cd} for battings lies between $k_{cd,1}$ determined from a parallel model, and $k_{cd,2}$ determined from a perpendicular model.[10,11,12] The former model assumes all fibers to be parallel to the heat flow direction, and the latter model assumes all fibers to be perpendicular to the heat flow direction. In a typical batting, most fibers are oriented perpendicular to the heat flow direction as a result of the manufacturing process. Therefore, k_{cd} would have a value somewhere between $k_{cd,1}$ and $k_{cd,2}$. Expressions for $k_{cd,1}$ and $k_{cd,2}$ are as follows:

$$k_{cd,1} = \frac{v_f}{v_b} k_f + \frac{v_a}{v_b} k_a = k_a \left(1 + (c-1)\frac{v_f}{v_b}\right) \tag{7}$$

$$k_{cd,2} = k_f k_a \Big/ \left(\frac{v_a}{v_b} k_f + \frac{v_f}{v_b} k_a\right) = k_a c \Big/ \left(1 + (c-1)\frac{v_a}{v_b}\right) \tag{8}$$

where $k_f = ck_a$.

From the values for the material density, areal density, and bulk-density in Table 1, values of fiber/batting volume ratio v_f/v_b for the battings are calculated and shown in Fig. 3. It is seen that for all the battings, volume of the fibers occupies less than 3.6% of the total batting volume. Values of $k_{cd,1}$ and $k_{cd,2}$ for the polyester battings (c=2) calculated from equations (7) and (8) are shown in Table 3. Results show that the difference between $k_{cd,1}$ and $k_{cd,2}$ are extremely small because of the low v_f/v_b ratios. For v_f/v_b = 3.6%, the average of $k_{cd,1}$ and $k_{cd,2}$ is only 2% maximum higher than the thermal conductivity of air k_a for the regular fiber battings as shown in Fig. 3. Therefore, for all practical purposes, the trapped air among the fibers is responsible for the conductive heat loss in all the battings; contribution from the fibers are negligible. This means that for a fixed temperature difference, as far as conduction heat loss is concerned, batting thickness is the deciding factor (thicker for a lower temperature gradient and $\dot{q}''_{cd}$); the geometry and properties of the fibers are unimportant. However, for radiation heat loss, fibers play an important role as shown in the next section.

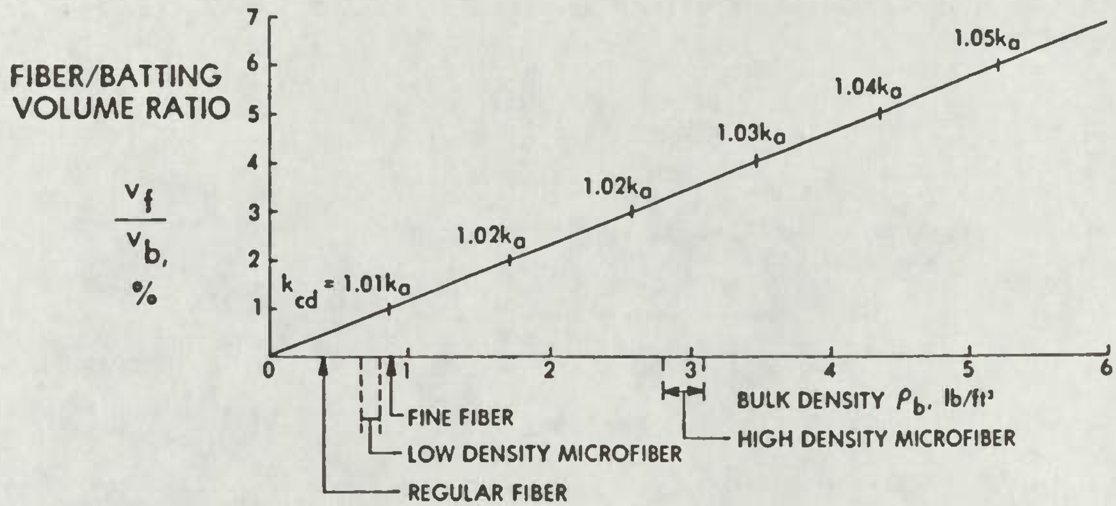

Figure 3. Fiber/batting volume ration and conduction conductivity as functions of batting bulk density.

TABLE 3. Batting Thermal Conductivity as a Function of Fiber/Batting Volume Ratio

	0	1	2	3	4	5	6
$k_{cd,1}$	k_a	$1.01k_a$	$1.02k_a$	$1.03k_a$	$1.04k_a$	$1.05k_a$	$1.06k_a$
$k_{cd,2}$	k_a	$1.005k_a$	$1.01k_a$	$1.015k_a$	$1.02k_a$	$1.026k_a$	$1.031k_a$

Radiation

The emissivity of human skin is similar to that of a black emitting surface. Therefore, even at a skin temperature of about 95°F, the radiation emitted from human skin is significant. One of the functions of the fibers in a batting is to intercept the radiation from the heat source (human skin) and transfer it back to minimize radiation heat loss. For two emitting surfaces such as those in the Rapid K Instrument, if there is no batting between the hot and the cold surfaces, the radiative heat flux $\dot{q}_r''$ is

$$\dot{q}_r'' = \frac{\sigma\,(T_h^4 - T_c^4)}{\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1} \qquad (9)$$

The relative magnitudes between $\dot{q}_r''$ and $\dot{q}_{cd}''$ in this case can be seen from Fig. 2. For a relatively small difference between T_h and T_c, $T_h^4 - T_c^4$ can be approximated as

$$T_h^4 - T_c^4 \cong 4\, T_h^3\, (T_h - T_c) \qquad (10)$$

Equation (9) can then be written as

$$\dot{q}_r'' = \frac{(4\, \sigma\, T_h^3\, d)}{\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1} \left(\frac{T_h - T_c}{d}\right) \qquad (11)$$

If the radiation conductivity k_r is defined as

$$k_r = \frac{4\, \sigma\, T_h{}^3 d}{\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1} \qquad (12)$$

then equation (11) becomes equation (13)

$$\dot{q}_r'' = k_r \left(\frac{T_h - T_c}{d}\right) \qquad (13)$$

for the radiation heat loss is similar to the expression for pure conduction heat loss. However, unlike k_{cd}, k_r depends also on the batting thickness and the emissivities of the emitting surfaces as shown in equation (12).

If a batting is positioned between the hot and the cold surfaces and the batting mainly scatters and does not absorb radiation from T_h and T_c, $\dot{q}_r''$ can be expressed as

$$\dot{q}_r'' = \frac{\sigma(T_h^4 - T_c^4)}{\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1 + Nd} = \frac{(4\, T_h^3\, d)}{\frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 1 + Nd} \frac{(T_h - T_c)}{} = k_r\, \frac{(T_h - T_c)}{d} \qquad (14)$$

The radiation conductivity k_r as defined in equation (14) in this case has an additional term, Nd, due to radiation scattering by the fibers. Equation (14) has been successfully used for fiberglass insulation material which has low absorptivity.

For the present fibrous battings, which both absorb and scatter radiation, k_r cannot be expressed in simple relationships as equations (12) and (14), but is a complicated function of the following parameters:

$$k_r = f\,(T_h, T_c, \varepsilon_h, \varepsilon_c, \rho_b, d, D_f, P, N) \qquad (15)$$

Larkin[14], Aronson et al[15], and Viskanta[16] have used numerical integration and experimental techniques to investigate $\dot{q}_r''$ and k_r for fiberglass insulation material and the emissivity of polypropylene battings. They found that fiber diameter, D_f, has significant effect on the radiation transfer through fibrous battings. Their results showed that small diameter fibers with $D_f<10$ μm are more effective in scattering the radiation back to the hot emitting surface; as D_f increases from 10 μm, the scatter effectiveness decreases. This behavior expressed in terms of k_r is qualitatively shown in Fig. 4. Of particular interest is the reversal behavior of k_r in the $D_f<10$-μm microfiber range. This suggests that 5-μm$<D_f<$10-μm microfibers should have similar k_r values as $0<D_f<$5-μm microfibers.

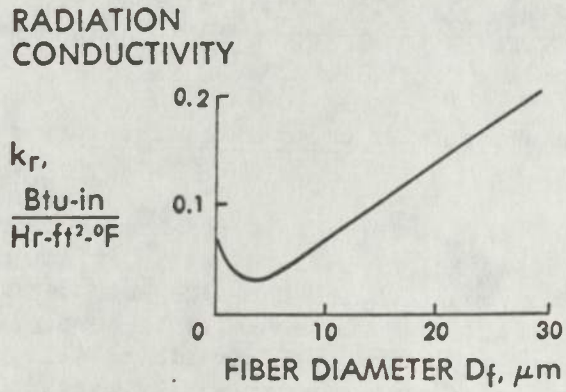

Figure 4. Radiation conductivity as a function of fiber diameter.

For the present battings, since $k_{cv}=0$ and k_{cd} is essentially equivalent to k_a, k_r then is equal to $k_{ap} - k_a$ from equations (3) and (4). Results of k_r for the uncompressed battings along with that for air are shown in Fig. 5. It is seen that k_r for air is linearly proportional to d as expected from equation (13). Different degrees of k_r reduction from air are obtained from the battings. High-density microfibers are most effective in minimizing radiation loss; low-density microfibers and fine fibers are second, and regular fibers the third. Results in Fig. 5 also show that there is no significant difference in k_r between solid and hollow regular fibers, and between polyester and polypropylene microfibers. For all the battings, k_r increases slightly as d increases, a phenomenon commonly referred to as "thickness effect" in the insulation literature.

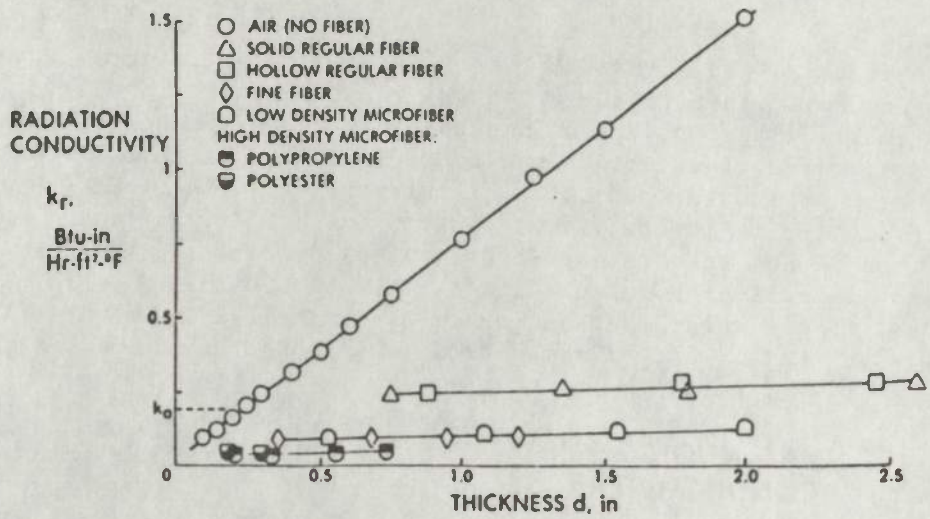

Figure 5. Radiation conductivity as a function of uncompressed batting.

Note that the comparison made in Fig. 5 is for the uncompressed battings which have different bulk-densities. To determine the effect of fiber diameter D_f on k_r, one has to compare k_r at the same bulk-density ρ_b and the same thickness d, equation (15). This was achieved by compressing layers of the lower bulk-density regular fiber and the fine fiber battings to match the bulk-densities of the uncompressed higher bulk-density microfiber battings. Sets of ρ_b and d curves for the regular and the fine fiber battings thus obtained are compared with those of the microfiber battings in Fig. 6 to 11. It is seen that in these figures there are discrete points where the two types of battings have the same ρ_b and d values.

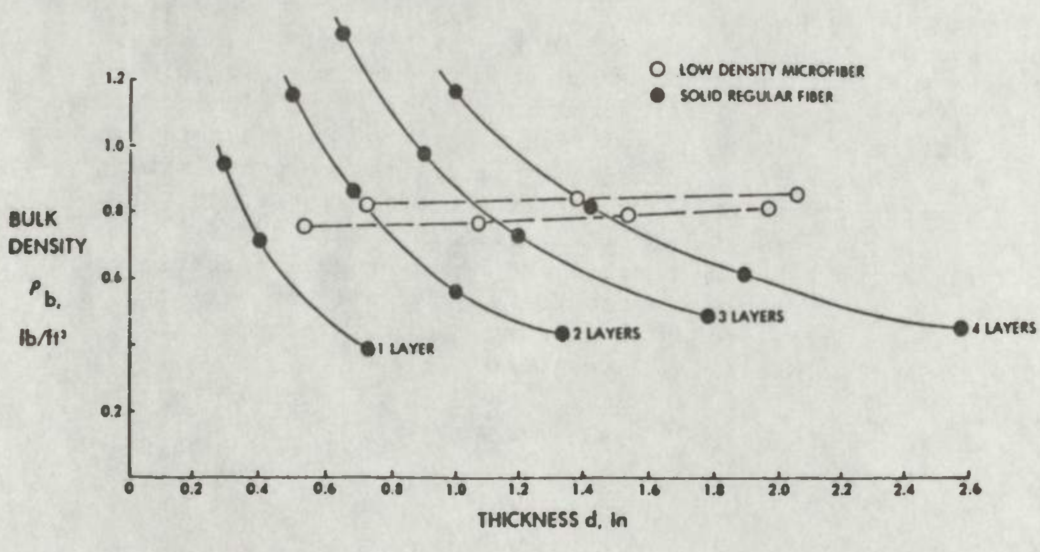

Figure 6. Comparison of bulk density and thickness between uncompressed low-density microfiber battings and compressed solid regular fiber battings.

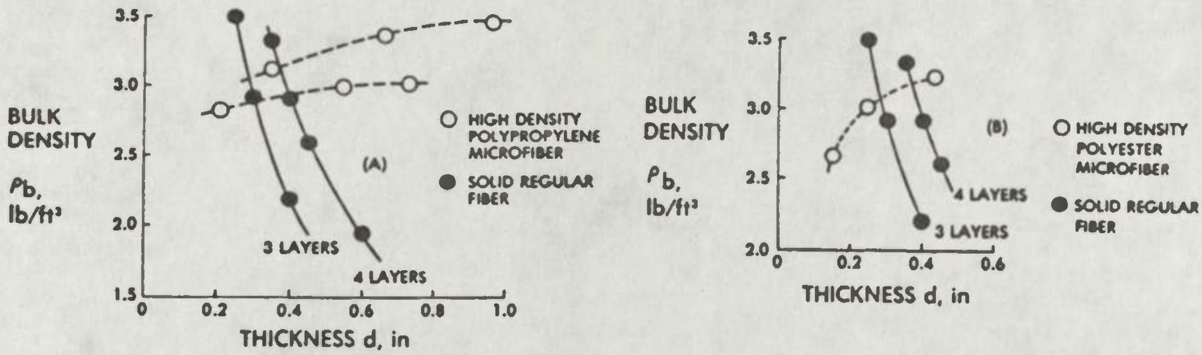

Figure 7. Comparison of bulk density and thickness between uncompressed high-density microfiber battings and compressed solid regular fiber battings.

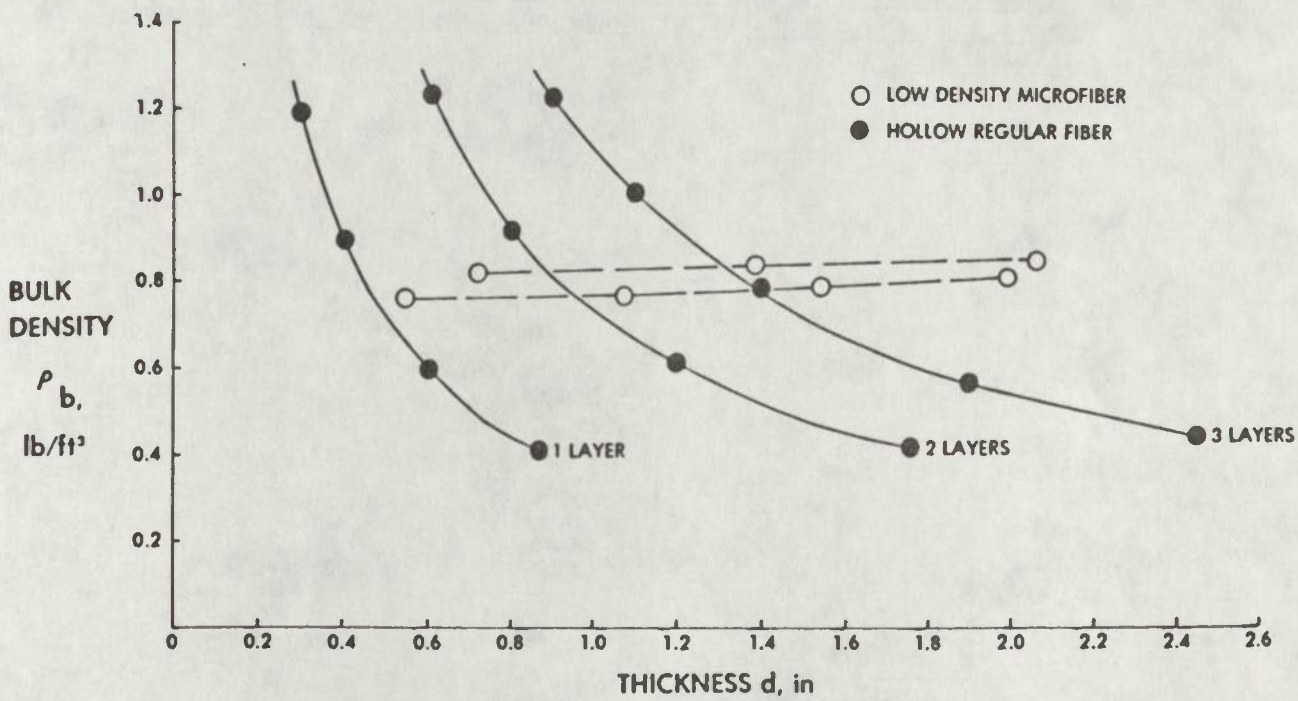

Figure 8. Comparison of bulk density and thickness between uncompressed low-density microfiber battings and compressed hollow regular fiber battings.

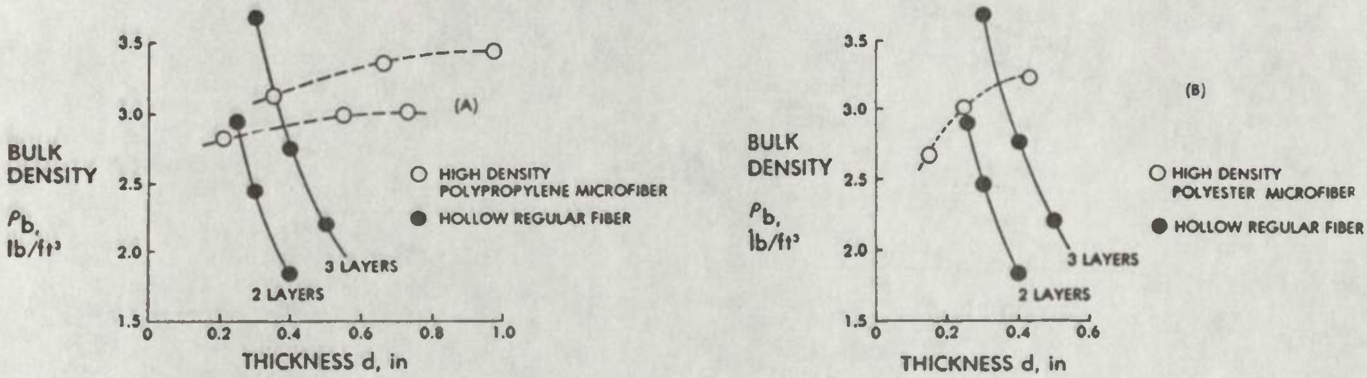

Figure 9. Comparison of bulk density and thickness between uncompressed high-density microfiber battings and compressed hollow regular fiber batings.

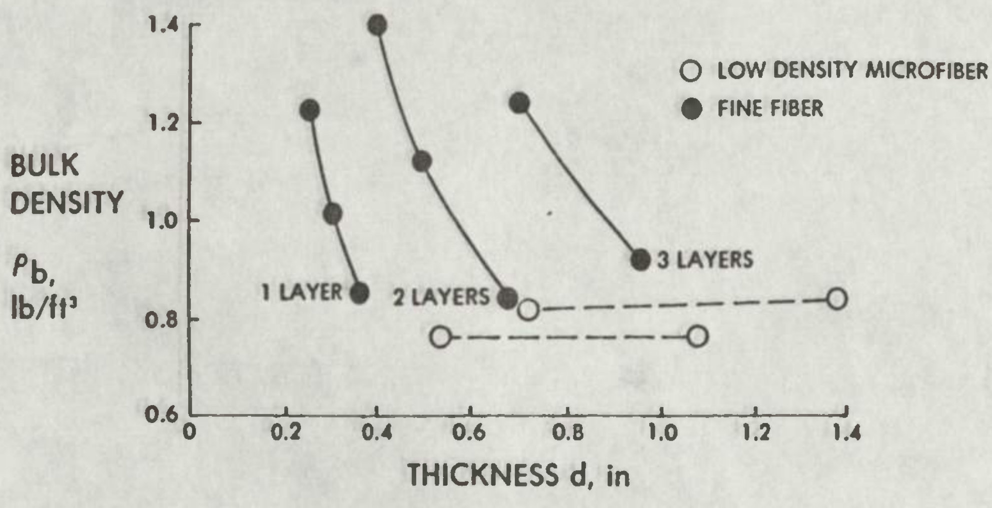

Figure 10. Comparison of bulk density and thickness between uncompressed low-density microfiber battings and compressed fine fiber battings.

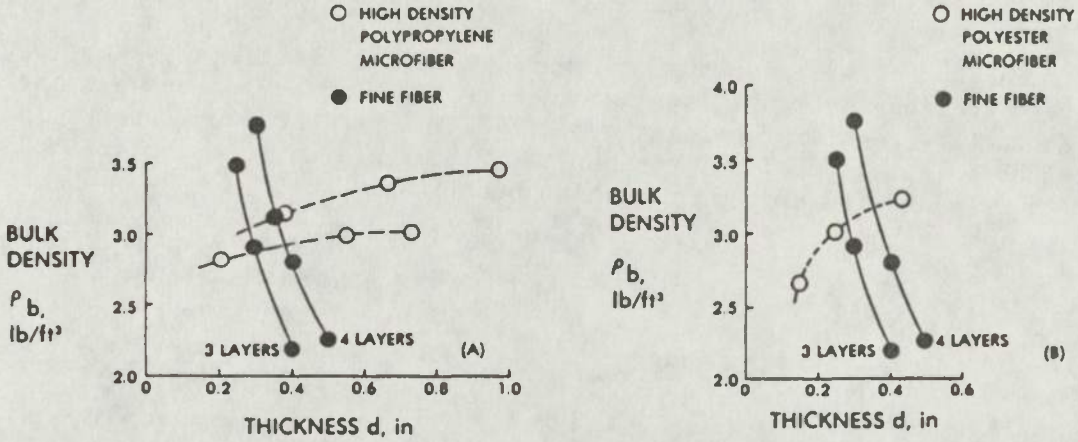

Figure 11. Comparison of bulk density and thickness between uncompressed high-density microfiber battings and compressed fine fiber battings.

Before comparing k_r values at identical sets of ρ_b and d, it is constructive first to examine k_r as a function of ρ_b and d for each type of batting. Fig. 12 shows the results for the solid regular fiber battings. It is seen that at uncompressed state, k_r is about 40% higher than k_a, showing the significant radiation heat loss component in the total heat loss. Upon compression, k_r decreases fairly rapidly (by intercepting the radiation from the hot surface) and becomes equal to k_a at some values of the bulk-density. Further increase in bulk-density decreases the radiation heat loss component. The radiation blockage effect by increasing bulk-density is seen from the constant d = 0.74" line in Fig. 12.

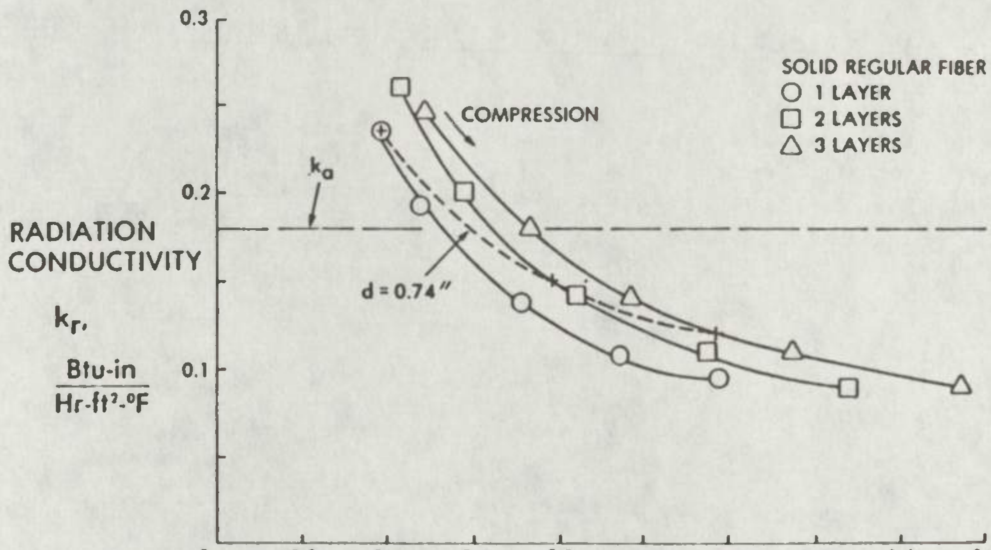

Figure 12. Radiation conductivity of solid regular fiber battings.

Similar k_r behavior for the hollow regular fiber battings as that for the solid regular fiber battings is shown in Fig. 13. Comparison between the solid and hollow regular fibers at d = 0.74" from Fig. 12 and 13 shows small differences in k_r. Therefore, whether the fibers are solid or hollow does not appear to make a difference in radiation heat loss.

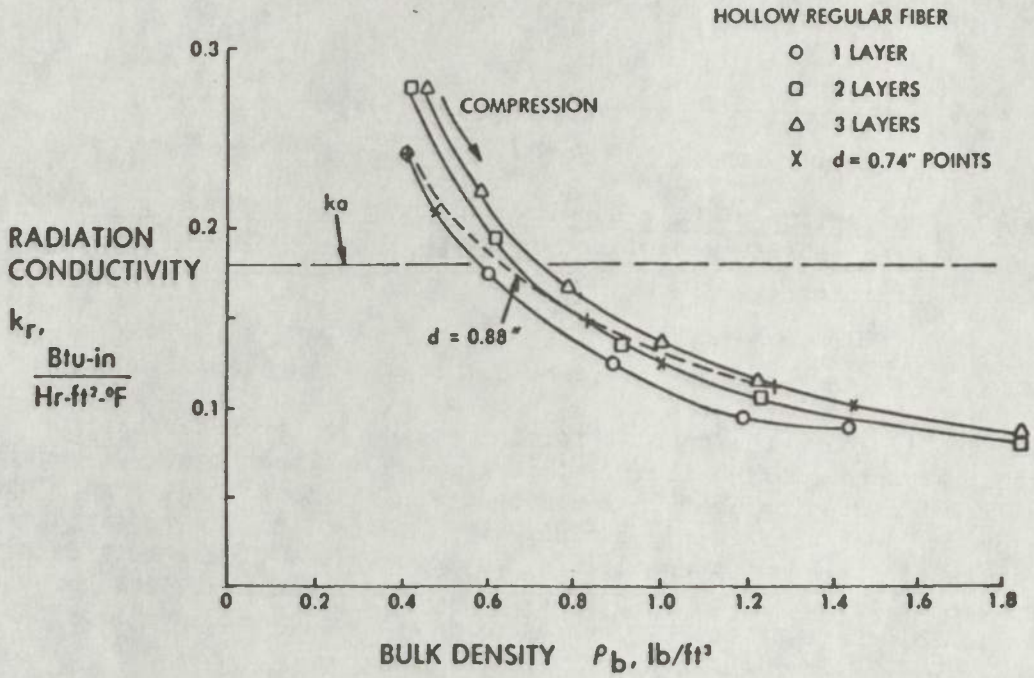

Figure 13. Radiation conductivity of hollow regular fiber battings.

For the higher bulk-density fine fiber battings, k_r values and behavior are significantly different from those of the regular fiber battings. As seen in Fig. 14, for the fine fiber battings at uncompressed state, k_r is only about 50% of k_a (as compared to 140% of k_a for the regular fiber battings).

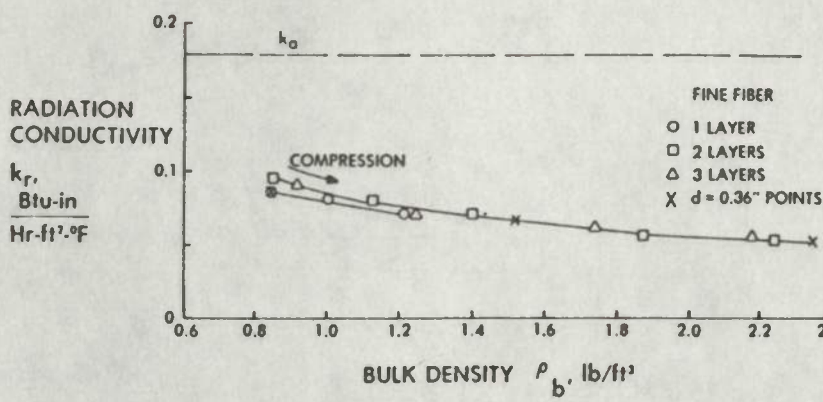

Figure 14. Radiation conductivity of fine fiber battings.

The rate of decrease in k_a upon compression is smaller than that of the regular fiber battings. Apparently at higher bulk-densities, large amount of the radiation from the hot surface has been blocked already. Further increase in bulk density only results in a small decrease in k_r.

Comparison of the k_r values between microfiber battings and the other battings at the same $_b$ and d values is summarized in Tables 4, 5, and 6.

TABLE 4. Comparison of k_r and Clo_b between Solid Regular Fiber (SRF) and Microfiber Battings

(A) SRF vs Low Density Microfibers (LMF)

d, in	0.77		1.16		1.04		0.71	
ρ_b, lb/ft^3	0.76		0.76		0.82		0.82	
	SRF	LMF	SRF	LMF	SRF	LMF	SRF	LMF
k_r	0.156	0.103	0.174	0.109	0.158	0.109	0.145	0.101
Clo_b	2.59	3.1	3.73	4.58	3.49	4.1	2.49	2.88

(B) SRF vs High Density Polypropylene Microfibers (HMF)

d, in	0.3		0.4		0.37	
ρ_b, lb/ft^3	2.9		2.9		3.13	
	SRF	HMF	SRF	HMF	SRF	HMF
k_r	0.062	0.034	0.059	0.050	0.053	0.048
Clo_b	1.42	1.6	1.9	1.95	1.81	1.85

(C) SRF vs High Density Polyester Microfibers (HMF)

d, in	0.28		0.36	
ρ_b, lb/ft^3	3.07		3.22	
	SRF	HMF	SRF	HMF
k_r	0.056	0.033	0.051	0.033
Clo_b	1.35	1.5	1.77	1.94

Typically, the k_r values of the microfibers are about 35% less than those of the solid and the hollow regular fibers, and about 20% less than those of the fine fibers. This decrease in k_r in the microfiber battings is attributed to their smaller fiber diameters. These results are consistent with those from Larkin[14] (Fig. 4) and Aronson et al.[14,15]

TABLE 5. Comparison of k_r and Clo_b between Hollow Regular Fiber (HRF) and Microfiber Battings

(A) HRF vs Low Density Microfibers (LMF)

d, in	0.89		0.97		1.4		1.31	
ρ_b, lb/ft^3	0.82		0.76		0.79		0.84	
	HRF	LMF	HRF	LMF	HRF	LMF	HRF	LMF
k_r	0.152	0.098	0.168	0.108	0.166	0.116	0.157	0.113
Clo_b	3.14	3.65	3.34	3.84	4.61	5.4	4.42	5.1

(B) HRF vs High Density Polypropylene Microfibers (HMF)

d, in	0.38		0.26		0.35	
ρ_b, lb/ft^3	2.9		2.85		3.13	
	HRF	HMF	HRF	HMF	HRF	HMF
k_r	0.061	0.042	0.054	0.032	0.055	0.048
Clo_b	1.8	1.95	1.27	1.4	1.69	1.75

(C) HRF vs High Density Polyester Microfibers (HMF)

d, in	0.35		0.25	
ρ_b, lb/ft^3	3.16		3.0	
	HRF	HMF	HRF	HMF
k_r	0.055	0.032	0.051	0.034
Clo_b	1.69	1.88	1.24	1.3

Due to the decrease in k_r for the microfibers, their batting clo_b values are generally higher than those of the other fiber battings as shown in Tables 4, 5, and 6. Based on these clo_b values, the percentage increase in clo_b of the microfibers differs for each type of fiber, depending on the relative importance of conduction and radiation. Generally microfibers provide higher

TABLE 6. Comparison of k_r and Clo_b Between Fine Fiber (FF) and Microfiber Battings

(A) FF vs Low Density Microfibers (LMF)

d, in	0.7	
ρ_b, lb/ft^3	0.82	
	FF	LMF
k_r	0.095	0.1
Clo_b	2.82	2.85

(B) FF vs High Density Polypropylene Miocrofibers (HMF)

d, in	0.3		0.39		0.36	
ρ_b, lb/ft^3	2.9		2.9		3.1	
	FF	HMF	FF	HMF	FF	HMF
k_r	0.047	0.035	0.046	0.036	0.045	0.045
Clo_b	1.51	1.59	1.97	2.06	1.83	1.82

(C) FF vs High Density Polyester Microfibers (HMF)

d, in	0.029		0.036	
ρ_b, lb/ft^3	3.06		3.16	
	FF	HMF	FF	HMF
k_r	0.044	0.032	0.044	0.032
Clo_b	1.47	1.55	1.83	1.94

clo values than regular fibers. The percentage increase is higher for the low-density than the high-density microfibers, as shown in Table 7. This does not mean that the low-density microfibers are more effective than the high-density microfibers. The different increases are due to the fact that comparisons are made at low (0.8 lb/ft^3) and at high (3 lb/ft^3) bulk-densities where the ratios of k_a/k_r are different. For the comparison between fine and microfibers, the decrease in k_r provided by the microfibers contributes insignificant difference in clo_b (Table 7) because conduction dominates radiation in these battings.

TABLE 7. Percentage Increase in Clo_b of Microfiber Battings as Compared to Other Fiber Battings at Identical Bulk-Density and Thickness

LMF			HMF (Polypropylene)			HMF (Polyester)		
SRF	HRF	FF	SRF	HRF	FF	SRF	HRF	FF
17-23	15-17	0	2-13	4-8	0	9-10	5-11	5-6

The comparison in clo_b among regular, fine, and microfiber battings can best be illustrated in Fig. 15. It is seen that hollow and solid regular fibers have similar insulation performance. Fine fibers have similar insulation effectiveness as low-density microfibers; both are about 0.5 clo_b higher than regular fibers at the same bulk-density and thickness. To be equivalent in clo_b to fine and microfibers for the same thickness, the bulk (areal)-density of regular fibers has to be increased (to decrease radiation loss from the emitting surface).

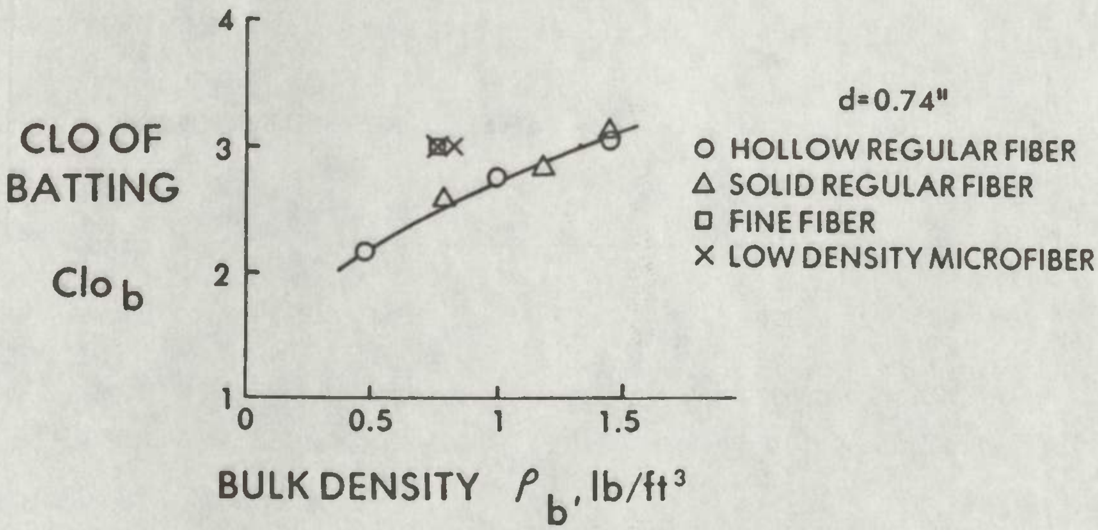

Figure 15. Comparison of clo_b among regular, fine, and microfiber battings.

DISCUSSION

Overall Comparison

The present heat transfer investigation of battings shows that heat losses by natural convection, conduction, and radiation are complicated functions of fiber and batting properties. Of these properties, batting thickness d, fiber diameter D_f, and batting bulk-density $_b$ are the three important ones. It is found that natural convective heat loss is not important in all the present battings. Higher bulk-density fine fiber and microfiber battings provide higher resistance to induced convective air flow than lower bulk-density regular fiber battings. Microfibers in turn show higher air flow suppression than fine fibers. These different degrees of air flow resistance may result in less forced convective heat loss in microfibers than in fine and regular fibers in an actual insulation clothing item.

Conduction and radiation are the two main heat losses in all the present battings. For uncompressed state, both conductive and radiative heat losses are significant for solid and hollow regular fibers; conductive heat loss is more significant than radiative heat loss for fine and microfibers. When the battings are compressed, radiative heat loss decreases much more rapidly in regular fibers than in fine and microfibers. Within the present batting-bulk density range, the air layer in the batting is responsible for the conductive heat loss; geometry and properties of the fibers have insignificant effects on this heat loss. The main function of the fibers is to support and maintain a batting thickness (air layer). Hence, conductive heat loss is inversely proportional to batting thickness, or the bulkier the batting is, the more warmth it provides.

Radiation heat loss is primarily a function of batting bulk-density and fiber diameter. Higher bulk-densities are more effective in decreasing radiation loss from the emitting hot surface (human skin) and smaller diameter fibers are more effective in scattering radiation back to the emitting surface. Thus, microfiber battings are more effective in reducing radiation heat loss than fine fiber and regular fiber battings. Consequently, a microfiber batting at half the thickness of a regular fiber batting provides the same clo_b.[4] However, since conduction dominates radiation in microfiber battings, loss of thickness (such as after military laundering[4]) reduces clo_b significantly. On the other hand, radiation loss is higher than conduction loss in regular fiber battings; loss of thickness does not reduce clo_b significantly. Furthermore, the stronger regular fibers tend to maintain their batting thickness better than microfibers. Fine fiber appears to be a good compromise between regular and microfibers.

In view of the above relative merits of regular, fine, and microfibers, it is evident that a batting should have microfibers to decrease radiation heat loss and larger diameter fibers to provide stable batting thickness to minimize conduction heat loss. This is exactly what natural down provides.

Examination of electron microscopic photographs of down[17] reveals that it consists of a cluster of 20-μm to 24-μm width filaments (regular fibers) emanating from a quill point; from the filaments extend numerous 3.8-μm to 4.6-μm width fibrillae (microfibers). Clusters of down thus form a light weight, resilient, and effective insulation structure. The approach of combining microfibers and larger diameter fibers in the low-density microfiber batting appears to be in the right direction. However, in view of the reversal behavior of k_r in the $0<D_f<10$-μm microfiber diameter range (Fig. 4), it is not necessary for the fibers to be as small as $D_f<5$ μm and result in a batting that becomes much thinner after military laundering. It appears that 5-μm$<D_f<$10-μm fibers should provide a stronger batting with similar k_r values.

Composite Battings

If small and large diameter fibers are not blended as in the low-density microfiber battings, another alternative is to form composite battings from layers of small and large diameter fibers. Some examples of composite battings for potential application in the Army's current 20-oz/yd^2 extreme-cold sleeping bags[18] were tested in the Rapid K Instrument. Results are shown in Fig. 16 and 17. One can see that composite battings C and D in both

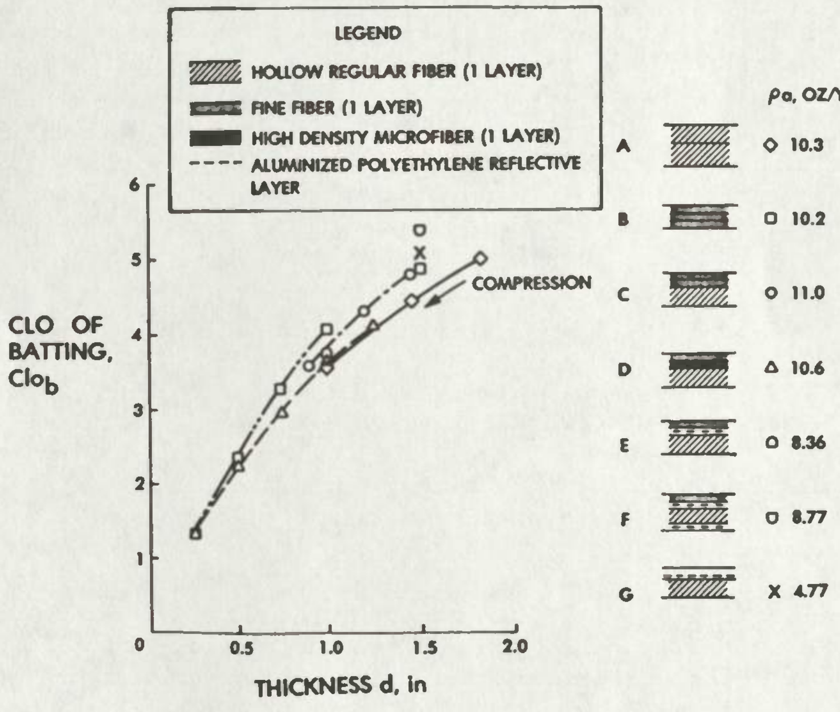

Figure 16. Performance of 10 oz/yd^2 composite and reflective battings.

figures provide similar clo_b values as the 100% hollow regular fiber batting A for smaller thicknesses. As expected, this advantage increases when 100% fine fiber is used in batting B. It should be realized that the amount of decrease in the bulk of a rolled-up sleeping bag is considerably larger than the amount of decrease in a single layer d in the present study.

In terms of decreasing radiation heat loss, reflective layers are most effective. This is shown by batting E, F, and G which offer similar clo_b values as the other battings but at smaller thicknesses and lower weights. In batting G, the reflective layer reflects radiation directly back to the hot emitting surface. Beyond the reflective layer in the batting, heat loss is mainly conduction. Therefore, the low bulk-density fibers together with the reflective layer form the effective batting G in terms of insulation per unit weight or thickness. To keep the reflective layer in place, a fine fiber layer is used in batting E as a spacer between the hot emitting surface and the reflective layer.[20] It is noted that the fine fiber spacer does not significantly affect the clo_b of batting G, but does add some weight to it. Introducing a second reflective layer in batting F to reflect the radiation from the regular fibers further slightly increases clo_b. Comparison of battings E, F, and G suggests that to minimize radiation loss effectively, the

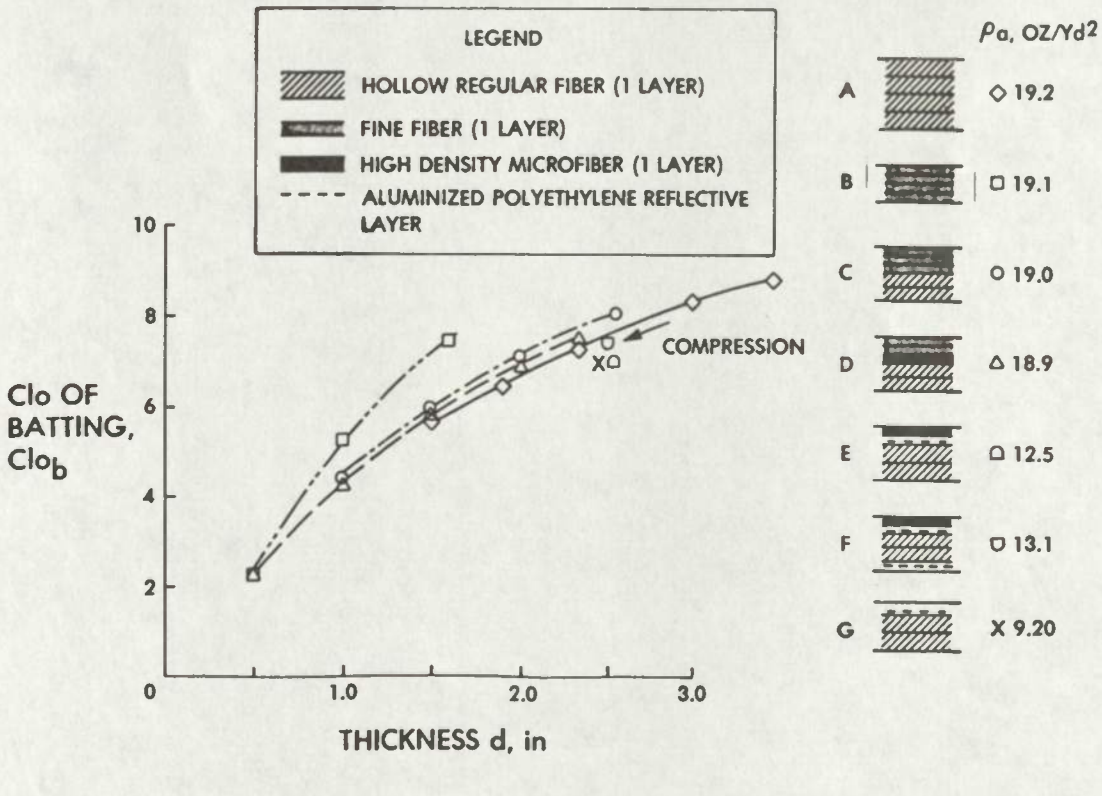

Figure 17. Performance of 20 oz/yd^2 composite and reflective battings.

most important position for a reflective layer is immediately adjacent to the emitting hot surface (human skin). Beyond this first layer, additional reflective layers only moderately increase clo_b. It should be realized that no cover fabrics were used for the battings in Fig. 16 and 17. Cover fabrics and quilting could affect the insulation performance of batting materials.

It appears that composite batting design either with or without reflective layers should be particularly applicable to the portion of a sleeping bag in contact with the ground. This portion is usually compressed when in use by the weight of the soldier. A precompressed or high-density batting, such as the high bulk-density microfiber, should be ideal for this portion. A more rigid high bulk-density batting near the ground should also provide more comfort for the soldier. This concept of local or end-use design for sleeping bags was also emphasized by Osczevski and Farnworth.[21] Such an end-use design approach should be pursued for all thermal insulation protection systems for soldiers.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made based on the present heat transfer investigation of fibrous insulation battings:

1. Microfibers present higher resistance to induced natural convective air flow than fine fibers, which in turn show higher resistance than regular fibers. However, natural convective heat loss is generally negligible for regular, fine, and microfiber battings.

2. Conductive heat loss is essentially a function of batting thickness. The function of fibers is to support and maintain a batting thickness. Therefore, light weight, high resilience, and good durability would be the important desired features for fibers to be effective in minimizing conductive heat loss.

3. Radiative heat loss decreases as batting bulk-density increases and fiber diameter decreases. For this reason, microfiber battings are more effective in thermal insulation than other battings for a given batting thickness; or to provide the same insulation, microfiber battings can be thinner than others. It is recommended that investigation on this advantage offered by microfibers be pursued in actual insulation clothing items.

4. No significant difference in radiation heat loss is found between battings made from solid and hollow fibers.

5. It is recommended that future batting development be directed toward composite battings made from 5-μm D_f<10-μm microfibers and regular fibers; they can be blended together in the batting, or more ambitiously, they can be formed together to make a synthetic down fiber structure. Concurrently, reflective battings made from low bulk-density fibers and reflective layers should also be pursued.

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LIST OF SYMBOLS

c Ratio of k_f/k_a

c_p Specific heat of air

clo_b Clo value of batting itself

d Batting thickness

D_f Fiber diameter

g Gravitational acceleration

G Air permeability (equation (6))

k_a Thermal conductivity of air

k_{ap} Apparent thermal conductivity of batting; $k_{ap} = k_{cv} + k_{cd} \; k_r$

k_{cd} Conduction conductivity of batting

$k_{cd,1}$ Conduction conductivity of batting based on parallel model (equation (7))

$k_{cd,2}$ Conduction conductivity of batting based on perpendicular model (equation (8))

k_{cv} Convection conductivity of batting

k_f Thermal conductivity of fiber

k_r Radiation conductivity of batting

N Radiation scattering parameter of fibrous batting

ΔP Pressure difference across batting

P Radiation absorption parameter of fibrous batting

$\dot{q}''_{cd}$ Conductive heat flux through batting

$\dot{q}''_{cv}$ Convective heat flux through batting

$\dot{q}''_{r}$ Radiative heat flux through batting

$\dot{q}''_{t}$ Total heat flux through batting

Q Air flow rate per unit batting area

Ra Rayleigh number (equation (5))

T_c Cold plate surface temperature

T_h Hot plate surface temperature

v_a Volume of air in batting

v_b Volume of batting, including fibers and air

v_f Volume of fibers in batting

B Coefficient of volumetric expansion of air

ε_h Emissivity of hot plate surface

ε_c Emissivity of cold plate surface

η Dynamic viscosity of air

ρ Air density

ρ_a Areal density of batting

ρ_b Bulk density of batting

ρ_m Fiber material density

σ Stefan-Boltzmann constant

μ Absolute viscosity of air