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Effect of Floor Surface Temperature on Comfort Part IV: Cold Floors

The effect of floor surface temperature on comfort has been the subject of a continuing study at Kansas State University since 1958. Previously published results have dealt with the effect of warm floors on the comfort sensations reported by college-age and elderly male and female subjects, including both sedentary individuals and those performing light work.[1,2,3,4] Floor surface temperatures used in these studies were 75 to 100 F with ambient air temperatures from 75 to 80 F. The project, originally established through a cooperative research project between Kansas State University's Mechanical Engineering Department and the American Society of Heating and Ventilating Engineers (ASHVE, now ASHRAE), later continued with funds supplied by the Kansas State University Engineering Experiment Station. During the period from 1959 through May, 1966 support was provided by the Division of Occupational Health, U.S. Public Health Service. The results to be presented in this paper deal with a study of college age male and female subjects exposed to floor surface temperature below the air temperature for periods of three hr while engaged in sedentary activities.

LITERATURE REVIEW

Since 1948, there have been several studies of foot comfort, skin temperatures of the feet and the effect of floor surface materials on comfort. Munro and Chrenko[5] studied the effect of air temperature, velocity and floor surface material on thermal sensation and skin temperature of the feet. Tests were conducted with air temperatures of 55 and 65 F and an exposure period of 60 min using two subjects, both with shoes and without. The results with shoes showed no significant difference in thermal sensation for different flooring materials. Measured skin temperatures were significantly different for the different flooring materials at 55 F. It was concluded that the air temperature was the dominant factor in thermal comfort for the feet. It should be noted that the floor was neither heated nor cooled and had, therefore, essentially the same surface temperature as the air.

Muncey and Hutson,[6] using 15 normally clothed subjects exposed for 1-1/2 hr periods, found only a very small effect of flooring material on foot temperature. They did find that the effect of the surface material appeared to be greater for younger than for older people. Again, the floor surface temperature was approximately equal to air temperature. Schule[7,8] conducted similar studies and used an artificial foot as did Billington.[9]

Muncey[10] using 15 subjects found that foot comfort was dependent only on the temperature of the foot and the surrounding air temperature and was not affected by the flooring material. A "comfortable" foot temperature was found to lie in the range of 68.0 to 80.6 F.

Chrenko[11] studied the effect of heated floors on foot temperature and thermal sensation. A skin temperature of 93.6 F on the sole of the foot was associated with a 50% incidence of discomfort.

Muncey and Holden[12] conducted experiments in which a thermal gradient existed in the test room, approximating winter conditions. The floor temperature was varied to produce a thermal gra-

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dient in the air from one to 30 in. above the floor. Foot temperatures for comfort ranged from 69.9 to 88.0 F. They concluded that the air temperature surrounding the feet was a major consideration in determining the occupant's thermal sensation.

It should be restated that previous studies have not attempted to evaluate the effect of the radiation exchange between the floor surface and the lower extremities of the body. In all but the latter two studies, the mean radiant temperature could be assumed equal to air temperature.

It is obvious that the floor surface temperature affects (a) the temperature of the foot (conduction), (b) temperature of the air layers near the floor and (c) heat loss or gain by radiation. This paper attempts to estimate the contribution of the radiation effect on a hypothetical basis as well as presenting skin temperature and thermal sensation data for cooled floors.

TEST FACILITIES

The experimental program was carried out in the KSU-ASHRAE Environmental Test Chamber which was placed in operation at Kansas State University in 1963. The test chamber is 12 by 24 ft with a ceiling height of 8 ft. Except for the floor surface, the remaining surfaces in the test chamber were maintained at the same temperature as the air.

The surfaces of the test room including the floor consist of aluminum panels. For these tests, no floor covering was used. As indicated above, in the thermal conductance of the floor is an important factor for subjects with bare feet. With shoes, however, the thermal resistance of the shoe sole and stocking is the controlling resistance. Therefore, the surface temperature and the resulting radiation exchange are the major factors which affect the heat transfer.

Air motion in the test room was less than 45 fpm throughout the occupied space. A complete description of the present facility, located in the Institute for Environmental Research Building at Kansas State University, is found in Ref 13.

TEST SUBJECTS

The test subjects, 24 males and 24 females with a mean age of 19 years, ranged in age from 18 to 25. All subjects were volunteers and received payment for their participation. No subject was allowed to participate in more than one test. All subjects were clothed in cotton twill shirts and trousers. The shirts were worn outside the trousers. Male subjects wore cotton undershorts or briefs, but no undershirts or T-shirts. The women wore brassieres and underpants. Female subjects wore flats with footlets, i.e., stockings to cover only the lower portion of the foot but not showing above the shoe. The boys wore loafer type slip-on shoes and thin socks that extended to just above the ankle. Subject data are presented in Table I.

Table I - Subject Data

Subject No.	Age	Sex	Height (in.)	Weight (lb)
101	19	M	72	149
102	19	F	65	115
103	19	M	69	152
104	20	F	68	139
105	19	M	72	170
106	20	F	66	144
107	18	M	74	171
108	21	F	68	138
109	19	M	73	186
110	20	F	66	166
111	19	M	66	154
112	19	F	66	124
201	21	M	67	123
202	19	F	62	124
203	19	M	75	170
204	19	F	67	125
205	19	M	71	173
206	25	F	64	133
207	19	M	70	154
208	21	F	64	119
209	19	M	72	164
210	18	F	68	147
211	22	M	68	173
212	18	F	65	113
301	22	M	69	200
302	21	M	70	160
303	18	M	68	159
304	23	M	69	198
305	18	M	70	163
306	23	M	67	126
307	21	F	64	109
308	18	F	64	111
309	19	F	65	119
310	19	F	69	155
311	19	F	69	150
312	19	F	69	166
401	19	M	68	173
402	20	F	70	144
403	18	M	68	153
404	19	F	67	153
405	18	M	70	174
406	18	F	66	106
407	19	M	73	195
408	22	F	63	119
409	20	M	70	189
410	19	F	61	97
411	19	M	68	210
412	18	F	68	133

EXPERIMENTAL PROCEDURE

The tests were conducted in the afternoon between 1:00 and 5:00 p.m. The subjects, 12 for each test,

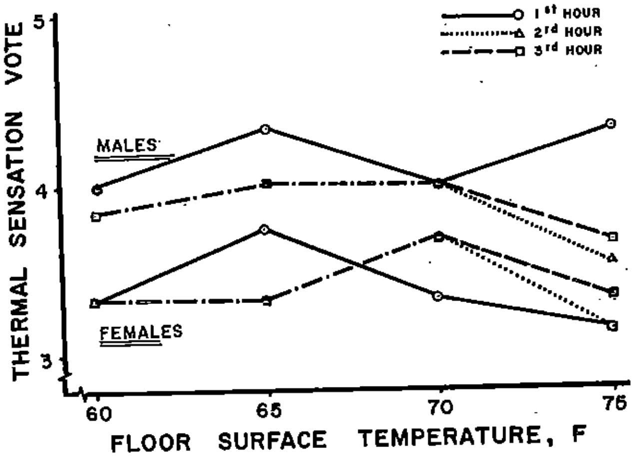


Fig. 1 Mean thermal sensation votes vs floor surface temperature for college-age males and females seated at rest, air temperature 75 F

six males and six females, were brought into the laboratory at 1:00 p.m., dressed in the standard Kansas State University uniform described above. The attending nurse performed the pre-test examinations, including oral temperature, weight and height of each subject. At approximately 1:30 p.m., the subjects were taken into the test room and two thermistor skin temperature probes were taped to the right foot of each individual. The male and female subjects were alternated along the east and west wall of the test room, seated in a classroom chair with attached writing arm. One probe was placed on top of the instep, the other on the bottom. The subjects were oriented as to the test procedures and were instructed to keep both feet on the floor during the entire 3-hr test period. Subjects were allowed to study or read but were not allowed to play cards. Drinking water was provided ad libidem and subjects were permitted to smoke. After the application of the thermistors, the test period was started. Foot temperatures were recorded every 15 min. Thermal Sensation Votes and Foot Comfort Votes were obtained at the end of the first hour and every 30 min thereafter. Four test conditions were selected using 75 F air temperature for all tests and four floor surface temperatures of 60, 65, 70 and 75 F. Relative humidity was maintained 45%. The seven-point thermal sensation scale and the five-point foot comfort scale are shown in Table II.

Table II - Thermal Sensation Voting Scales

Thermal Sensation Vote (for the entire body)	Foot Comfort Vote
1. Cold	A. (1)* Cold
2. Cool	B. (2) Cool
3. Slightly Cool	C. (3) Neutral
4. Neutral	D. (4) Warm
5. Slightly Warm	E. (5) Hot
6. Warm	
7. Hot	

* Number assigned for data processing.

RESULTS

Mean thermal sensation votes as a function of floor surface temperature are shown in Fig. 1 for male and female subjects. Each mean was based on responses from six subjects. The changes in mean thermal sensation votes shown for the range of floor surface temperatures investigated are not considered significant. The consistently lower response of female versus male subjects is illustrated in Fig. 1 and in Table III. This difference is partly the result of differences in foot wear and thickness of the shoe sole.

It will be noted in Fig. 1 and Table III that the Thermal Sensation Vote was between 4, neutral, and 3, slightly cool. This was the result of the air temperature being held at 75 F for all tests. Since it was the objective of this experiment to study the effect of floor surface temperature on foot comfort, the magnitude of the Thermal Sensation Vote was not as significant as the foot comfort data, provided, of course, that the Thermal Sensation Vote was near 4, neutral.

Table III - Mean Thermal Sensation Votes
3 hour exposure

Floor Temp F	Male	Female
60	3.83	3.33
65	4.00	3.33
70	4.00	3.66
75	3.50	3.33

The decrease in foot comfort vote with decreasing floor surface temperature is shown in Figs. 2 and 3 for male and female subjects, respectively. A statistically significant effect of floor temperature on foot comfort vote was detected at the 5% level of significance.* Table IV shows the contrast between mean foot comfort votes at the end of the 3-hr exposure period for male and female subjects.

* Less than five chances in 100 that the differences in means could be attributed to chance variation alone.

Fig. 2 Mean foot comfort vote vs floor surface temperature for college-age males seated at rest, air temperature 75 F

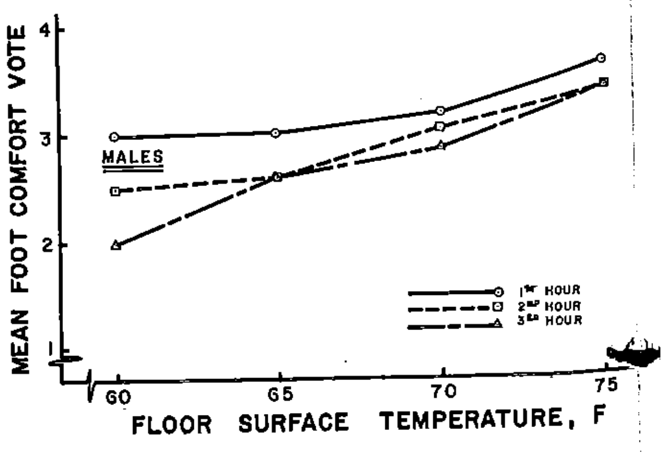


Table IV - Mean Foot Comfort Votes
3 hour exposure

Floor Temp F	Male	Female
60	2.00	1.16
65	2.66	1.66
70	2.83	2.00
75	3.33	2.33

Foot temperature data were analyzed to determine the correlation of foot comfort vote with foot temperature. The results are given in Table V. For male subjects, a "cool" comfort vote was associated with a mean foot temperature of 83.9 F and a "neutral" vote with 88.2 F at the bottom of the instep. Temperatures on the top of the instep were essentially the same. For female subjects, a "cold" foot comfort vote was associated with a bottom instep temperature of 79.6 F and a "neutral" vote with a temperature of 83.5 F. Again, temperatures on the top of the foot were essentially the same.

Table V - Foot Comfort Vote and Foot Temperature

	Mean Foot Temperature, F Bottom of foot	
Foot Comfort Vote	Males	Females
A. Cold (1)*	-	79.6
B. Cool (2)	83.9	80.5
C. Neutral (3)	88.2	83.5
D. Warm (4)	86.3	-
E. Hot (5)	-	-

Table VI gives the percent incidence of "cold" votes for male and female subjects, all votes used (n = 30). These results indicate that the female subjects were significantly affected by the 60 F floor temperature.

Table VI - Percent Incidence
of "Cold" Foot Comfort Votes (n = 30)

Floor Surface Temperature F	Males %	Females %
60	10	70
65	0	13
70	0	17
75	0	7

To illustrate the relative influence of the floor surface temperature on the body heat exchange, the net heat exchange by radiation was calculated between an upright cylinder, approximating a man, and an enclosure, using Gebhart's method.[14] This method accounts for multiple reflections between gray surfaces separated by a non-absorbing medium. The walls and ceiling of the enclosure were assumed to be at one uniform surface temperature and the floor surface at another temperature. Assuming the following data, the net radiant exchange

* Number assigned for data processing.

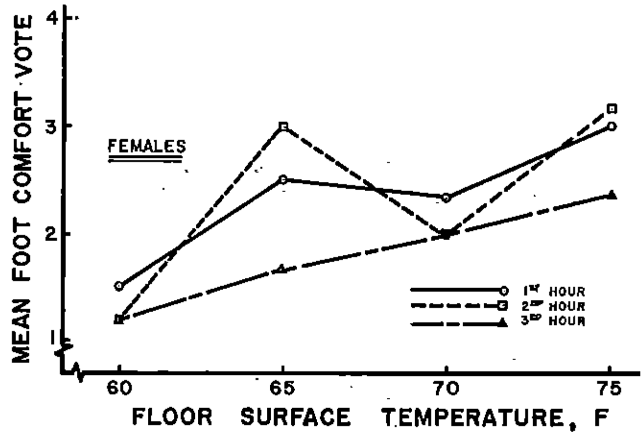


Fig. 3 Mean foot comfort vote vs floor surface temperature for college-age females seated at rest, air temperature 75 F

as a function of the shape factor from the body to the floor, F_{12}, was determined and is given in Fig. 4.

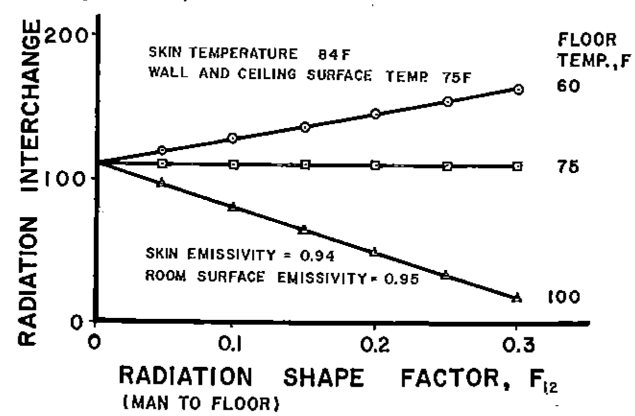
Body Radiating Area	= 12.2 sq ft
Emissivity of Clothing and Skin	= 0.94
Emissivity of Room Surfaces	= 0.95
Temperature of Wall and Ceiling Surfaces	= 75 F
Floor Surface Temperature	= 60, 75, 100 F

The heat exchange determined by Gebhart's method was compared with the heat exchange determined with the approximate equations given below:

$$Q_{net} = \sigma A_R \epsilon_1 \left[T_1^4 - T_{MRT}^4 \right] \qquad (1)$$

$$T_{MRT} = F_{12} T_2 + F_{13} T_3 \qquad (2)$$

Fig. 4 Radiant interchange between a cylinder (approximating a man) and an enclosure as a function of shape factor, man to floor



where

Q_{net}	=	net radiant heat exchange, Btuh
σ	=	Stephan-Boltzman Constant
A_R	=	Body radiation area, sq ft
ϵ_1	=	emissivity of skin and clothing
T_1	=	surface temperature of skin and clothing, R
T_{MRT}	=	Mean Radiant Temperature, R
T_2	=	Floor Surface Temperature, R
T_3	=	Wall and Ceiling Surface Temperature, R
F_{12}	=	Shape Factor, body to floor area
F_{13}	=	Shape Factor, body to walls and ceiling.

Eqs 1 and 2 neglect the multiple reflections between the various surfaces in the enclosure, thereby simplifying the calculations. For two cases (12- x 24- x 8-ft room and 10- x 10- x 10-ft room), the values of radiant heat transfer obtained using Gebhart's method were approximated by Eqs 1 and 2 with an error of less than 2%.

From Fig. 4 it is seen that, for the model chosen, the radiant exchange with a uniform environment (walls, floor and ceiling all at 75 F) is 110 Btuh. For a shape factor, F_{12}, of 0.3, the influence of the warm or cold floor ranges from 20% of the uniform value for a 100 F floor to 150% for a 60 F temperature. For the tests reported here with 12 seated subjects in the 12-x 24-ft test room, the estimated shape factor, subject to floor, is 0.33. Fig. 5 shows the variation of F_{12} with floor area for the same model assumed previously with the model at the center of a square floor. (Calculation of shape factors was accomplished with the assistance of Ref 15 by Tripp et, al.).

It should be noted that the model chosen was representative of one subject used in these and other tests in the seated position. The radiation area for a clothed standing man is often taken as 17 to 20 sq ft. The results are to be considered as indicative of the relative magnitudes of the effect and not in absolute terms.

CONCLUSIONS

Limited tests involving cold floors, indicate that thermal sensations of both male and female college-age subjects are not seriously affected by floor surface temperatures as low as 60 F, air temperature 75 F. Subjects were clothed, seated at rest and exposed to the test conditions for 3 hr. Foot comfort votes indicated that both male and female subjects objected to a floor temperature of 60 F. In addition, a floor temperature of 65 F may be too cool for female subjects. Foot

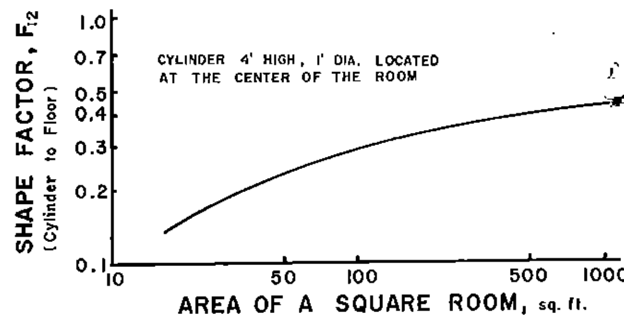


Fig. 5 Radiation-shape factor from an upright cylinder to a square floor cylinder located at the center of the floor

skin temperatures, measured on the bottom and top of the foot inside the shoe, roughly correlated with foot comfort vote.

The apparent discrepancy between the thermal sensation votes of near neutral and foot comfort votes of cool or cold results from the subjective measures employed. The ASHRAE Comfort Standard 55-66 defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." To assess a subject's thermal sensation in these experiments, the question is asked in terms of the scale shown in Table II. The results show that the mean overall or whole body reaction is neutral to slightly cool even though the subject may report cool or cold feet. Whether a person with these responses is comfortable (minimum discomfort) and is therefore satisfied with his environment is not certain. The total feeling of comfort must be an integrated response to many inputs.

In the case of heated or cooled floors, the effect of the surface temperature is evaluated in terms of the relative magnitudes of the heat exchange by radiation, convection and evaporation. The effect of floor surface temperatures on the thermal comfort can also be assessed through the use of the operative temperature, T_o,[16] which relates the convective and radiative heat transfer from a subject.

For the conditions of this experiment, T_o ranges from 71.6 to 75 F for floor surface temperatures of 60 to 75 F, air temperature of 75 F and a shape factor F_{12} of 0.3. If T_o = 75 F is assumed to be the value for thermal comfort of seated persons, the variation of T_o due to the floor temperature is relatively small showing fair agreement with the results in Fig. 1.

Based on theoretical calculations, floor surface temperatures of 100 F may reduce the radiant heat transfer to 20% of that occurring in a uniform environment. For a 60 F floor temperature, the heat transfer may increase to 150%. The radiant heat transfer in a uniform environment (air temperature equal MRT) is approximately 25 to 30% of the total. The influence of the floor temperature varies with the size and surface temperature of the floor and the location of the man.

ACKNOWLEDGEMENTS

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DISCUSSION

GEORGE M. RAPP (New Haven, Conn.): The authors have made a most useful contribution to the cold floor problem. However, radiation exchange alone, as shown in their Figs. 4 and 5, has little significance unless it is interpreted in terms of its net effect on comfort. Appropriately, the authors do report, as an index of comfort, the operative temperature range $t_o = 71.5$ F for floor temperatures between 60 and 75 F and for a single shape factor of $F_{12} = 0.3$, and they compare their results with a comfort value assumed at 75 F. They do not disclose the method by which their calculated values of net radiation exchange ($Q_{r,net}$) were translated into operative temperature except by reference to a previous ASHRAE paper (see their Ref 16).

Using the method described in our paper just presented [Trans. No. 2048], it may be of interest to calculate the operative temperature which includes the effect of radiant exchange with the floor.

In Fig. A, the Effective Radiant Field (ERF) is defined as the net radiation exchange between the floor and a clothed body hypothetically at air temperature; h_r and h are, respectively, the coefficients of heat transfer by radiation alone and by combined radiation and convection. A_r and A_D represent respectively the effective radiating area of the seated body in a 4π environment and the total (DuBois) body surface area. The Comfort Equation, $t_o = t_a + ERF/h$, gives the desired relation between operative temperature, ambient air temperature and ERF.

Using the data from Fig. A, Table A shows operative temperature vs floor temperature for the three shape factors and ambient air temperature used in the authors' experiments. The comfort (reference) operative temperature for a seated subject is 75 F.

If we assume that a ± 2.5 F range in operative temperature may be acceptable before the onset of discomfort, the data in Table A indicates that, in medium and large size rooms, floor surface temperatures higher than 90 F should produce a whole body discomfort or excessive warmth; and, conversely, that floor temperatures of 60 F or less

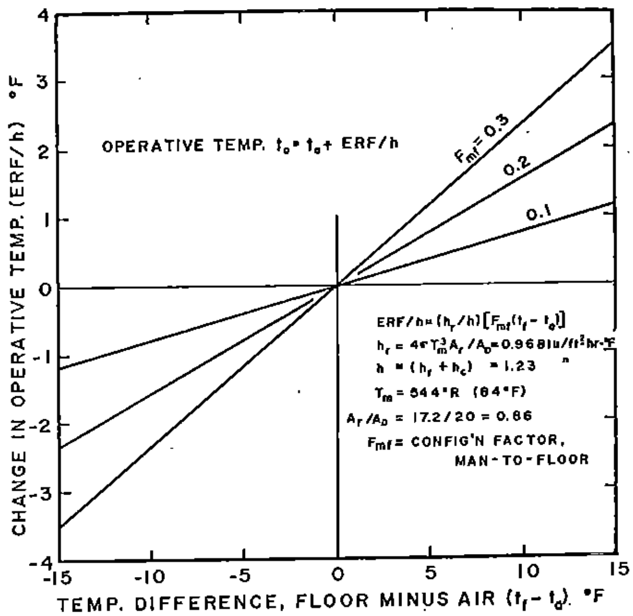

Figure A Change in operative temperature of clothed man in an environment where the wall and ceiling surfaces are at ambient (air) temperature but the floor is at a different temperature.

NOTE: The change is caused by the Effective Radiant Field created by this difference between floor and ambient temperature. The reference Operative Temperature (namely, air temperature) corresponds with that of a hypothetical uniform environment wherein temperatures of the air and all room surfaces are the same.

-- in large rooms particularly -- are too cool for comfort.

I note that the area 12.2 ft^2 is chosen for the effective radiating area (A_r) of the man-equivalent model representative of their test subjects in seated position. Dunkle (ASME Trans., Series C, Feb. 1963, p. 71) deduced, from his experimental measurements of human shape factors, the value 17.2 ft^2. The average nude (DuBois) area of the actual subjects used is 19.4 ft^2. If this is multiplied by the 1.16 ratio of clothed-to-nude

Table A. Summary of Operative Temp. vs Floor Temp. at Air Temp. of 75 F.

Floor temp., t_f F	Operative temperature, t_o F *		
	F_{mf} = 0.3 (e.g., large rooms)	F_{mf} = 0.2 (e.g., medium rooms)	F_{mf} = 0.1 (e.g., small rooms)
60	72.2	73.3	74.1
75	75.0	75.0	75.0
90	78.1	77.1	76.0
105	81.4	79.3	77.1

* Man in seated posture.

area as determined by Guibert and Taylor (Journal of Applied Psychology, Vol. 5, July 1952, p. 24), and the result multiplied again by 0.75, which commonly is accepted by many physiologists as the effective fraction of the whole body area for 4π irradiation, the value of A_r would more logically be 16.9 ft^2. Would the authors please explain how they obtained the area they used?

L. L. BOYER (Lancaster, Pa.): Except for the floor surface temperature, the parameters which influence thermal comfort are maintained at constant values in this study. The efforts to effect such controls are appreciated. However, the constant values at which some of these parameters are maintained could be misleading. Actual building situations may not be depicted. For example, all room surfaces except for the floor surface are maintained at the same temperature as the air. Interior wall temperatures in modern buildings with suspended ceilings are usually several degrees above air temperature, due to radiation from lights, floor and ceiling, even where cool air is introduced through ventilating ceilings. (Spaces with cold floors in slab-on-grade construction are perhaps an exception.) These warmer-than-air surfaces become more and more important with the higher lighting levels being utilized in modern buildings.

In addition, the concept of a cold floor and neutral temperature ceiling is not valid in a typical multistory building space. In an air-conditioned multistory building, floor and ceiling temperatures are nearly identical, whether the ceiling plenum is of the static type, return-air type, or supply-air type. These additional considerations could alter the mean whole body thermal sensation vote pattern in these and other comfort studies where room surface temperatures are made equal to air temperature.

As a separate comment, some data should be given on vertical air temperature gradients, and in those cases where the 75 F average air temperature was measured.

JOHN W. DUNHAM (La Crosse, Wis.): I failed to find a chart for calculation of F_{13} for Eq (2). I assume that a ratio is being used and F_{13} is equal to (1 - F_{12}), but would like clarification on this point.

AUTHORS' REPLY: The authors wish to thank Mr. Rapp, Mr. Boyer and Mr. Dunham for their remarks. The calculation of the operative temperature and the concept of Effective Radiant Field as applied by Mr. Rapp, enhance the value of this paper. The data presented in Table A support the experimental results and agree with the authors' conclusions. The sample calculations were included for illustration only, and should be used for qualitative analysis of the effect of the floor surface temperature on whole body comfort. The body area chosen for the calculations was that of one of the subjects used in these and other experiments. As indicated by Mr. Rapp, an area of 19 to 20 sq ft is more typical of male, college-age subjects.

Mr. Boyer points out the need for further research dealing with other configurations of surface temperature distributions in an attempt to duplicate field situations. For completeness of the paper, the test room air temperature is measured at the center of the space, 4.0 ft from the floor. The temperature gradients within the occupied space are less than 1.0 F.

In response to Mr. Dunham's question, F_{13} is taken as $(1 - F_{12})$ which assumes that F_{11} is equal to zero. This would be the case for the cylindrical model used in the example.