Design of Outdoor Urban Spaces for Thermal Comfort

by HARRIET J. PLUMLEY, *research assistant, School of Landscape Architecture, State University of New York College of Environmental Science and Forestry, Syracuse, N. Y.* *This research was supported in part by funds provided by the Northeastern Forest Experiment Station through the Pinchot Institute for Environmental Forestry Research, Consortium for Environmental Studies.*

ABSTRACT.—Microclimates in outdoor urban spaces may be modified by controlling the wind and radiant environments in these spaces. Design guidelines were developed to specify how radiant environments may be selected or modified to provide conditions for thermal comfort. Fanger's human-thermal-comfort model was used to determine comfortable levels of radiant-heat exchange for various activities, clothing types, and climatic conditions. A comparison of these radiant quantities with measured and calculated quantities of radiant exchange expected for a person in urban spaces revealed several design guidelines.

EFFORTS BY PUBLIC AGENCIES and private interest groups to revitalize the central business districts in American cities have often included large expenditures for outdoor pedestrian spaces. Many such amenity spaces have failed to receive more than light use. This failure has been attributed partly to a general disregard for the physical-comfort needs of the users *(Whyte 1972)*. The need for thermal comfort is ubiquitous, but it seems often to be forgotten in the designs of outdoor spaces.

The general aim of this study was to determine how designers could modify climatic conditions in urban spaces for thermal comfort. Human thermal comfort is "that condition in which a person expresses satisfaction with the thermal environment" *(Fanger 1970)*. It is a subjective response based on both physiological and psychological states of a person in a given environment.

Climatic factors that affect heat exchange with the body are air temperature, humidity, radiation, and air movement. Other factors include the person's activity level, clothing type, and emotional and physical conditions. Previous studies *(Lewis et al. 1971, Vittum 1974)* have shown that air temperatures and relative humidities do not vary significantly throughout the downtown outdoor space system despite differences in physical structures and arrangements. Wind speeds and radiation were much more variable. The designer could therefore modify microclimates in outdoor spaces through control of the wind and radiant environments. This paper focuses on the radiant heat environment.

A person exchanges radiant heat with his surroundings as does any other physical object. Solar radiation always adds heat to a person. The atmosphere and terrestrial objects add or remove heat from a person depending on the temperature difference between the person's outer surface and the surrounding surfaces. If the surroundings are warmer, the person gains heat. If they are cooler, he loses heat.

Several questions were addressed in order to understand the design possibilities for altering radiant-heat exchanges in outdoor spaces. How much radiant heating or cooling is needed for thermal comfort? When is the radiant heating or cooling needed? How much radiant-heat exchange is available to a person in an urban space? A comparison of the desirable and available radiant-heat exchange quantities revealed design guidelines that could be used for selecting and designing outdoor spaces with comfortable radiant environments.

RADIANT EXCHANGE FOR THERMAL COMFORT

A person must maintain a constant deep body temperature by balancing heat gains and losses with the environment. Thermal conditions that enable a person to maintain heat balance through minor physiological adjustments (a state of thermal neutrality) are the conditions people subjectively select as comfortable *(Bruce 1960, Fanger 1970)*.

Studies with human subjects have shown that radiant heating and cooling can comfortably compensate for cool and warm air temperatures respectively, as long as air movement is low. The radiant environment may be asymmetric about the person as long as nearby ground and vertical surfaces are within comfortable temperature ranges — ground surfaces should be between 17 and 40°C; vertical surfaces should be between 15 and 50°C *(Gagge et al. 1965, Gagge et al. 1967, McNall and Biddison 1970)*.

Determination of Comfortable Ranges of Radiant-Heat Exchange

Fanger's *(1970)* human thermal-comfort model was used in this study to determine radiant-exchange quantities that will yield thermal neutrality depending on other climatic conditions and a person's activity level and clothing type. Fanger's model has been tested extensively with human subjects (in indoor controlled climatic environments) to find the relationship between a person's heat balance and his subjective thermal response.

Although there is no single thermal environment that can satisfy all persons, there are ranges of conditions that are comfortable to a majority of people. Fanger tested his thermal-comfort equation to determine the percentage of people who express dissatisfaction at different thermal sensation conditions, as defined by his model. For the purpose of this study, I selected the range of thermal responses that were found to satisfy more than 50 percent of the people. This includes thermal sensations from slightly cool to slightly warm. The ranges of comfortable radiant-exchange quantities calculated from Fanger's model should be applicable to all healthy persons regardless of age, sex, geographic location, or body size, as long as differences in clothing habits are recognized *(Fanger 1970, Rohles and Johnson 1972)*.

QUANTITIES OF RADIANT EXCHANGE IN OUTDOOR URBAN SPACES

Three sources of radiant heat exchange, exclusive of artificial radiant heat, are available to persons in outdoor environments:

1. Solar radiation: the direct beam, the diffuse radiation from the atmosphere, and reflected radiation from the ground and the vertical surfaces.
2. Longwave radiant exchange with the sky.
3. Longwave radiant exchange with terrestrial surfaces (ground, vertical, and overhead surfaces).

Determination of Radiant-Exchange Quantities

Many environmental factors and a person's physical factors affect the amounts of radiant heat exchanged with a person from these three sources. For this reason, radiant quantities were determined for some specific conditions for persons located in a city in the northeastern United States. Syracuse, N.Y., was chosen for convenience. Conditions were chosen for times when people are most apt to be using outdoor spaces and for typical urban street configurations and surface materials.

A sample of quantitative estimates of a person's net radiant exchange with each of the three sources was calculated. Solar radiant quantities were calculated by using the equations in Terjung and Louie *(1971)*. Fanger's *(1970)* information on the radiant geometry of a person was used to determine solar radiant quantities absorbed by a person. Solar radiation on cloudy days was computed from Ångstrom's equation as given in Gates *(1962)*. Calculations of net radiant exchanges with the sky and terrestrial surfaces were made with a modified radiation law as described in Plumley *(1975)*. Sky temperatures were derived from Brunt's table of atmospheric radiation in Brown *(1973)*. Terrestrial surface temperatures of typical urban materials were measured in Syracuse during different climatic conditions. The information on a person's radiant area in view of surrounding flat surfaces was taken from Fanger *(1970)*.

Tables of radiant exchanges for the following conditions are presented in Plumley *(1975)*:

1. Solar radiation absorbed by a person on clear days for four different body postures.
2. Total solar radiation absorbed by a person on clear days in the shade of a building, a thin-canopy tree, and a dense-canopy tree.
3. Solar radiation reflected by a glass wall and absorbed by a person.
4. Total solar radiation absorbed by a person on totally overcast days (altostratus and stratus clouds).
5. Net longwave radiant exchange under clear and cloudy skies during different air temperatures (for a person in three typical urban street configurations).
6. Net longwave radiant exchange with typical urban ground and vertical surface materials, shaded and unshaded, at four different times of the day for four air temperature conditions (cool, moderately warm, warm, and hot) typical of the spring, summer, and fall seasons in the northeastern United States.

Summary of Analysis of Radiant Exchange Quantities

Net radiant exchanges of less than 20 to 30 kcal/hr/person were considered to be insignificant because this small amount does not produce a change in a person's thermal-sensation level, as based on an analysis of Fanger's model *(Plumley 1975)*. Therefore, physical factors in the environment that showed insignificant differences in the radiant-exchange quantities for a person were considered to be unimportant for the design of urban spaces.

Some of the results of an analysis of the radiant quantities are presented here, as taken from Plumley *(1975)*:

Solar radiation

1. Direct solar radiation provides much more radiant heat to a person than any of the terrestrial surfaces. Even on cloudy days at noon, diffuse solar radiation can provide 5 to 10 times more radiant heat than terrestrial surfaces.
2. Differences in ground-surface reflectivities (in the range of 20 to 40 percent) are not important during morning or late afternoon. During the midday, higher-albedo materials significantly increase the amount of solar radiation incident on a person. The albedo of shaded ground surfaces is unimportant.
3. Solar radiation reflected from a typical large tinted-glass office window does not provide significant amounts of heat to people.
4. To maximize the solar radiation available to a sitting person (for cool days) seats should be positioned to face the sun, and the ground material should be moderately reflective (like light brick or concrete).
5. To minimize the solar radiation a person receives (on warm days) shade from trees with dense canopies should be provided. Trees with thin canopies, like honeylocusts *(Gleditsia*

Figure 1.—Solar radiation absorbed by a person in the open and in the shade of trees with dense and thin canopies.

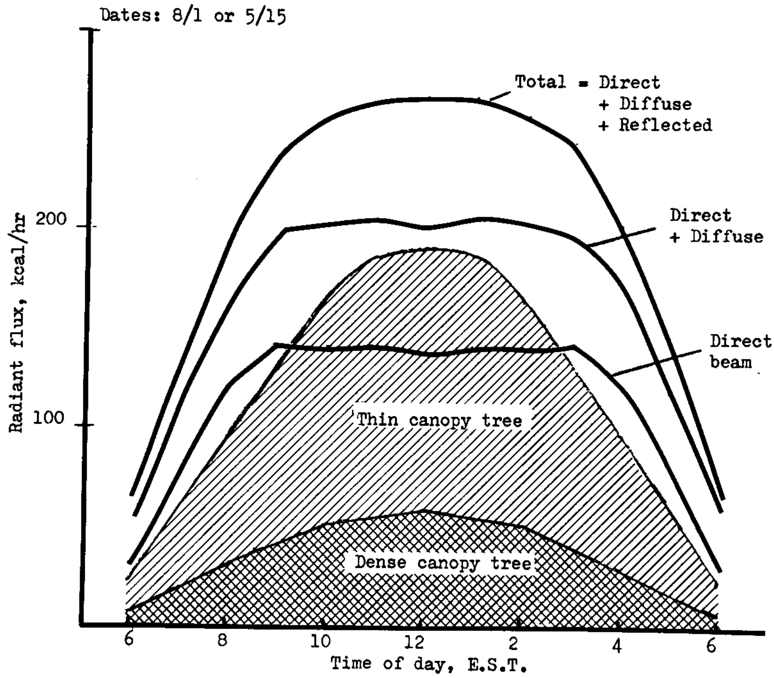


Table 1.—Effect of radiant exchange for a person on an urban street under clear and cloudy skies

Condition	Activity			Effect
	Sitting	Walking slowly	Walking quickly	
Clear skies............	< 85°F.	< 75°F.	< 60°F.	Cooling
	upper 80s to 99°F.	upper 70s to 99°F.	upper 60s to 90°F.	Neutral
	—	—	> 95°F.	Heating
Cloudy skies............	< 65°F.	< 55°F.	—	Cooling
	upper 60s to 95°F.	upper 50s to 85°F.	40° to 75°F.	Neutral
	> 95°F.	> 85°F.	> 75°F.	Heating

Note: The air temperatures considered here are for the range from 30 to 99°F. The clothing types used for this table were those typically worn during the different air temperatures.

triacanthos), are not as effective for shading as dense-canopy trees (fig 1).

Radiant Heat Exchange with the Sky

1. The sky can be a source of radiant cooling or heating depending on the air temperature and cloudiness. During warm weather the clear sky can have a cooling effect only for seated persons or slow walkers (table 1).
2. In cool weather radiant cooling is undesirable, and spaces should provide overhead obstructions to those portions of the sky not in the direction of the sun.
3. In warm weather radiant cooling is

desirable. Spaces for sitting should not be located directly under overhead canopies and should preferably be located away from building walls in order to maximize the sky view.

Radiant Heat Exchange with Terrestrial Surfaces

1. Ground and vertical surfaces can be sources of radiant heating or cooling depending on their surface temperatures, surface dimensions, proximity to the person, and the person's activity level. Graphs were constructed to show a person's radiant exchanges with ground and vertical surfaces, each of dimensions large enough to provide the near maximum exchange (figs. 2 and 3). Surface dimensions larger than these do not significantly increase the radiant exchange for a person. This was determined from an analysis of Fanger's *(1970)* view factors between a person and ground and vertical surfaces.
2. Ground surfaces generally provide more radiant exchange than either vertical surfaces (walls) or overhead surfaces (trees or awnings). The latter usually provide negligible quantities of net radiant exchange.
3. The surface areas of ground or vertical surfaces need not be very large to provide significant amounts of radiant exchange. On warm days unshaded ground surfaces as small as 4 square meters or vertical surfaces 14 meters long and 4 meters high can provide undesirable amounts of radiant heat to a person.
4. Radiant exchange with vertical surfaces becomes insignificant for persons located more than 3 meters from the surface. (This applies to walls, 10 meters high and 14 meters long, with surface temperatures between 10 and 40°C—typical of the extremes found in the summer and fall seasons in Syracuse.
5. During warm weather, shaded ground surfaces offer significantly less radiant heat to persons than unshaded surfaces, with the exception of vegetative ground materials (fig. 4).
6. Walls shaded by dense-foliage trees offer significantly less radiant heat to persons than unshaded walls. Walls shaded by vines or shrubs did not show significantly lower surface temperatures than the unshaded portions, and differences in net radiant exchange with persons were negligible.

DESIGN GUIDELINES

Comparisons of available radiant exchanges were made for: (1) conditions providing the maximum amount of radiant heat gain, and (2) conditions providing the least amount of radiant heat gain (or most radiant heat loss) from each of the three radiant-exchange sources. An example of these comparisons is presented for a seated person at noontime on a warm day (fig. 5).

Comparisons of radiant heat exchange for thermal comfort and radiant exchange available to persons revealed some simple design guidelines (figs. 6 and 7). Four elements, as indicated on the charts, should be considered in the design of a space depending on the air temperature conditions, time of day, and the person's activities:

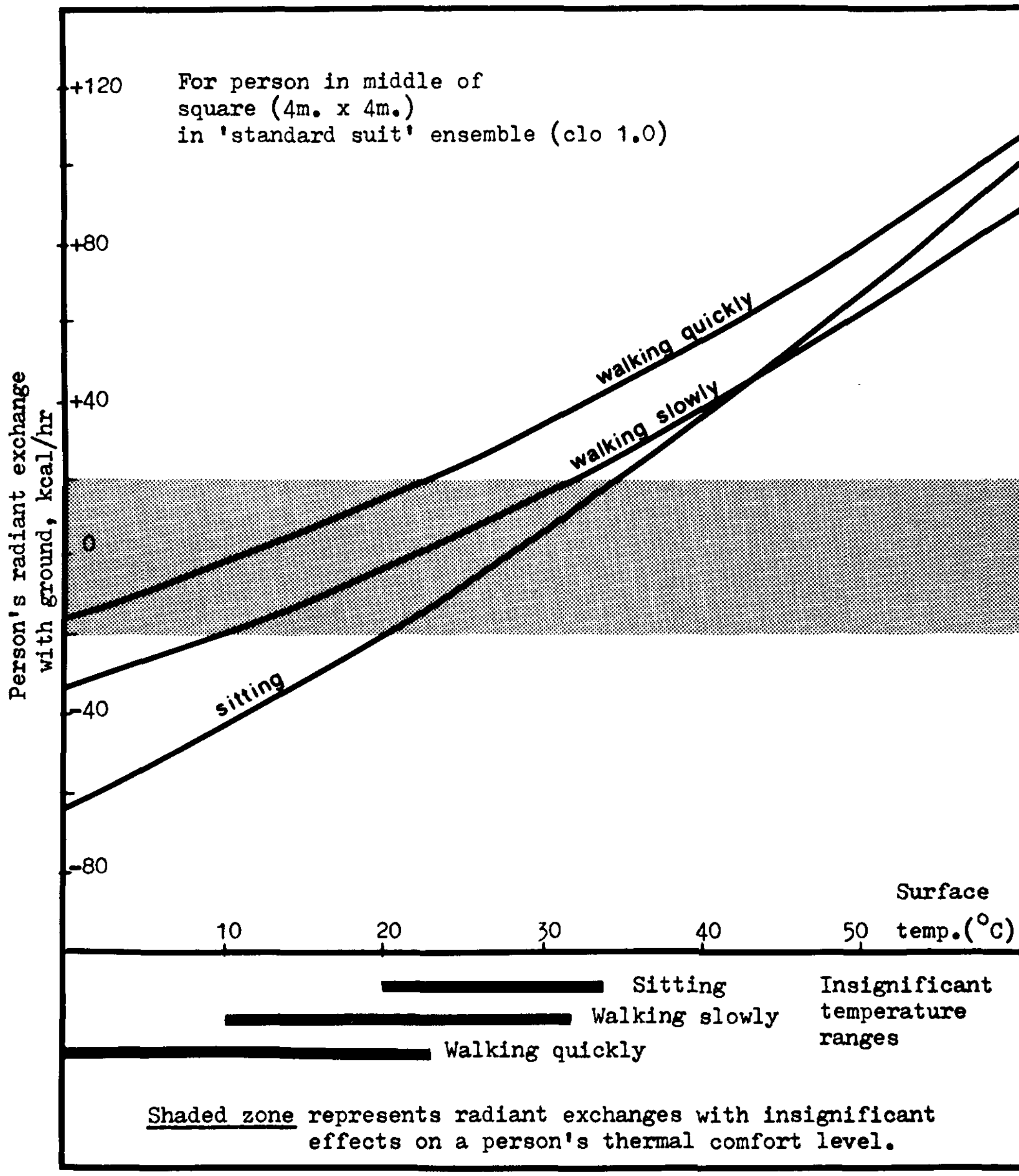
1. Direct solar radiation should either be available or should be shaded by thin or dense-canopy trees.
2. Ground and vertical terrestrial surfaces should be shaded or unshaded.
3. Sky views overhead and to the sides of persons should be either blocked or made as large as possible.
4. Wind speeds should be either calm, low (1 to 3 mph), or moderate (4 to 5 mph).

Footnotes accompanying the charts provide additional specifications for some of the categories.

Artificial Radiant Sources

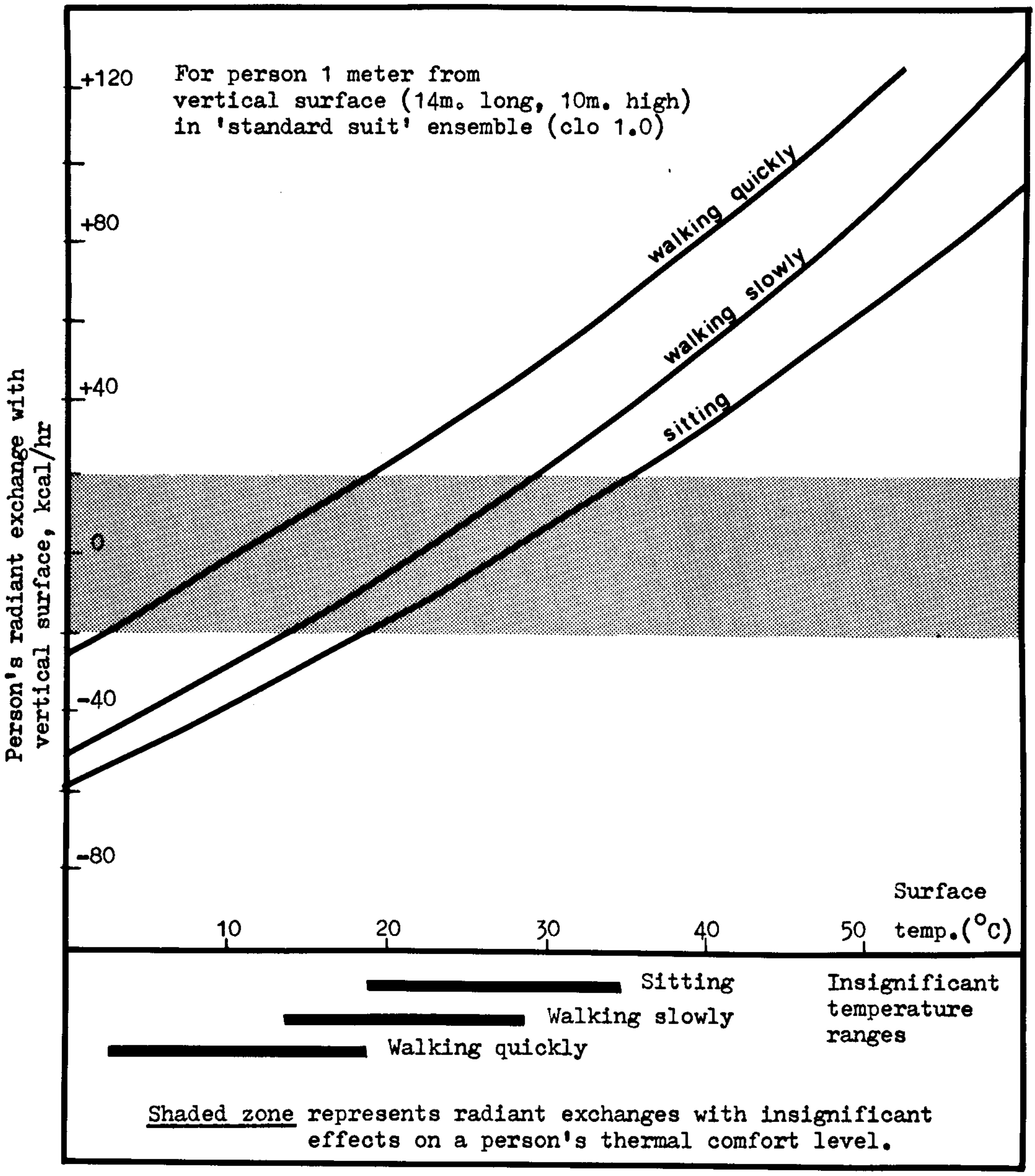
Spaces can be designed to include artificially-warmed ground and vertical

Figure 2.—Effect of ground-surface temperature on radiant exchange between a person and the ground.



Note: If clo 0.5, subtract 15 kcal/hr from radiant flux.
If clo 1.5, add 15 kcal/hr to radiant flux.

Figure 3.—Effect of surface temperature of a vertical surface on radiant exchange between a person and the vertical surface.



Note: If clo 0.5, subtract 20 kcal/hr from radiant flux.
If clo 1.5, add 20 kcal/hr to radiant flux.

Figure 4.—Person's radiant exchange with shaded and unshaded ground surfaces on a clear warm day.

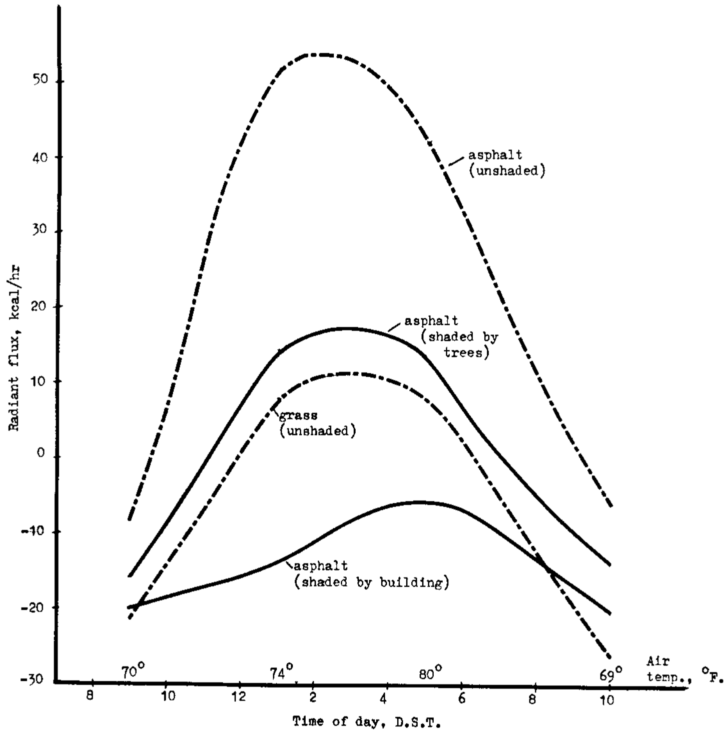
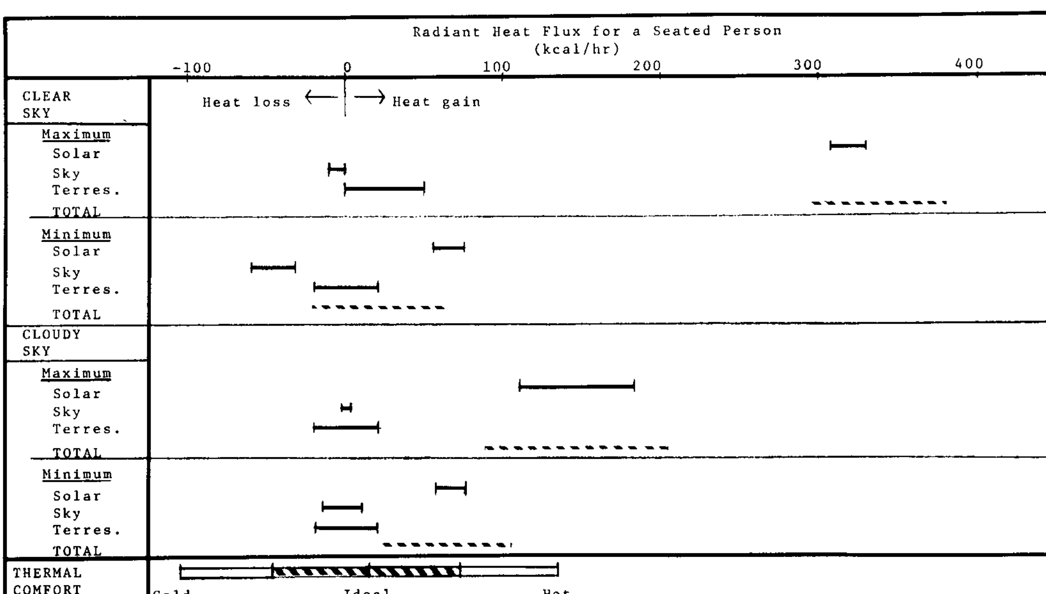


Figure 5.—Comparison of desirable and available radiant exchanges.

WARM DAY - NOONTIME



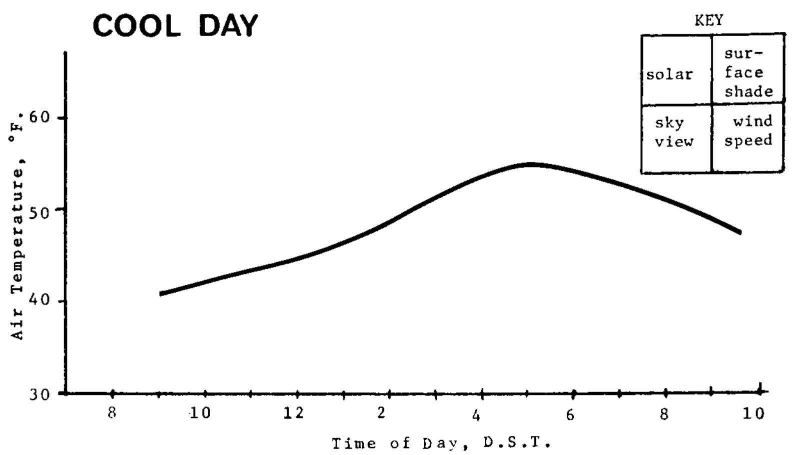
Climatic conditions: Air temp. 25°C. (77°F.), relative humidity 60%, low wind speed(1mph)
Clothing: Lightweight ensemble (clo 0.5)

Design Notes: Spaces should be designed to minimize radiant heat gain to persons for either clear or cloudy days.

Figure 6.—Design guideline chart for clear cool days.

Where the design elements are not sufficient to provide thermal comfort, the relative degree of discomfort is indicated below the activity/time of day category.

1. If ground and vertical surfaces can be artificially warmed to 40 and 50°C, respectively, a person seated near a wall in a space with a small sky view can receive enough radiant heat to feel only slightly cool.
2. If a person has a large sky view, solar radiation should be maximized (seats facing the sun and ground materials that are moderately reflective to the sun).
3. Solar radiation available to the person should be maximized. Vertical surfaces should not be near the person unless they are heated.
4. The best place on a street for a person to walk would be away from vertical walls, but on the side of the street. A row of trees between the person and the buildings can reduce the sky view.
5. If the sky view is small, a person should be over a low reflective ground material.
6. Hard, dense materials (not vegetation or wood) should be used for the ground surface. Heated ground and vertical surfaces could provide enough radiant heat for thermal comfort.
7. Ground surfaces may be shaded or unshaded. Walls facing the sun should be shaded. A person will not be cooled by wind unless he has been perspiring.



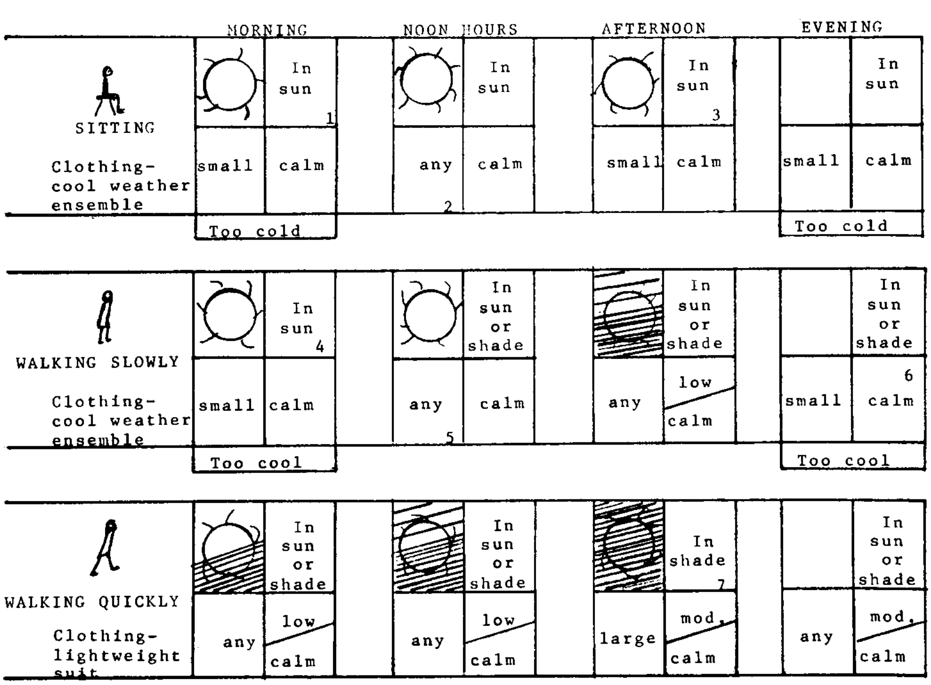
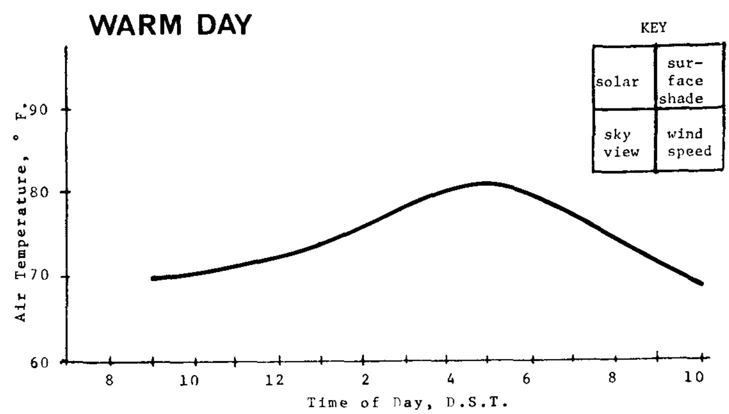
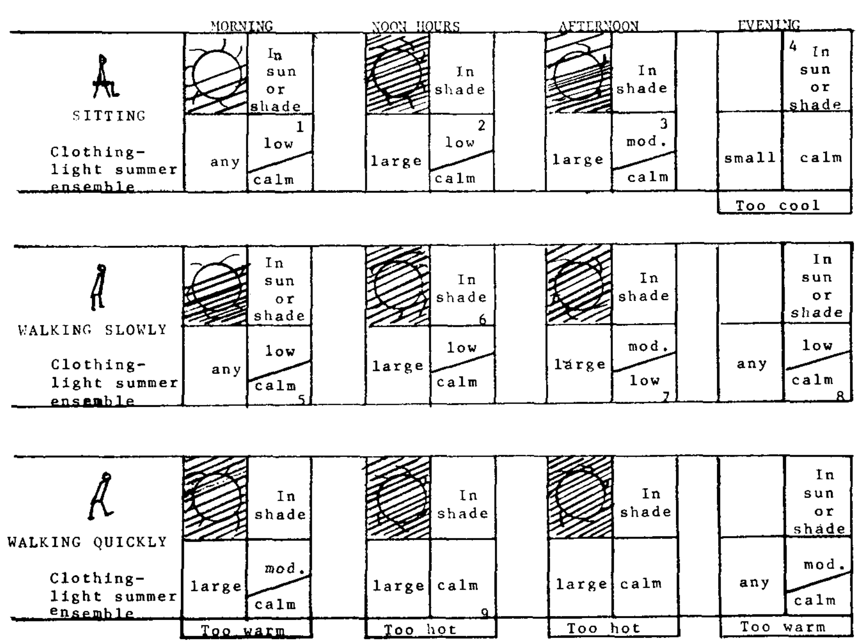


Figure 7.—Design guideline chart for clear warm days.

Where the design elements are not sufficient to provide thermal comfort, the relative degree of discomfort is indicated below the activity/time of day category.

1. If direct sun is desired, a breeze is necessary and a reduced sky view is desirable.
2. Unshaded vegetative ground surfaces and unshaded vertical surfaces are acceptable. *If direct sun is desired, artificially cooled* ground and vertical surfaces (for example, a water wall) with surface temperatures of at most 17 and 15°C, respectively, can provide enough radiant cooling for a person to feel only slightly warm.
3. Unshaded vegetative ground surfaces are acceptable. Light shade from solar radiation can be comfortable if the space is breezy and the person is in light summer clothing.
4. Artificially warmed ground and vertical surfaces can provide enough radiant heat to compensate for the cool air temperatures even under slightly breezy conditions.
5. If direct sun is desired, a breeze and a larger sky view are necessary. Dense tree shade is comfortable unless the space is windy and a person is dressed *in light* summer clothing.
6. Unshaded vegetative surfaces can be used. Persons in medium weight suit ensembles may be too warm despite these microclimatic considerations.
7. A person in medium-weight suit ensemble will be too warm.
8. If the space is breezy, it is important to minimize the sky view for a person in light summer clothing.
9. Air movement across a person will add heat to him unless he is wet with perspiration.





surfaces (for example, cooled water walls) for warm weather. Seated persons can be comfortable during noon hours at 0°C in spaces that provide the cool weather needs (fig. 6) plus ground and vertical surfaces of 40 and 50°C respectively. Spaces designed for warm-weather needs (fig. 7) can be fairly comfortable for seated persons at 31°C if cooled ground and vertical surfaces of 17 and 15°C respectively can be included.

Limitations of the Design Guidelines

These design guidelines should be applicable to cities with latitudes and climatic conditions similar to Syracuse. They are based on the thermal-comfort needs of the average healthy person who has equilibrated to the outside thermal environment. They do not take into account the special thermal desires of particular groups of people; for example, office workers coming from cool air-conditioned buildings seeking sunshine for warmth, or a tan or perspiring construction workers in need of a cool breezy space.

Outdoor spaces offering a variety of radiant environments may best satisfy a majority of the people. However, the radiant environments indicated in the design guidelines should be among the available options.

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