Effect of Synthetic Surfaces and Vegetation in Urban Areas on Human Energy Balance and Comfort

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ABSTRACT.—The thermal balance of a standard man was quantified for a variety of urban and rural summer daytime microclimates. The resulting net heat-load data were correlated with the relative amounts of vegetation and synthetic materials at each site. By extrapolating these results, it is possible to estimate the expected heat load of a proposed development before it is built.

THERE IS LITTLE DOUBT that the day-to-day weather as well as the overall climatic pattern in an area affect which activities people pursue, how well they perform, and generally whether they feel comfortable *(Huntington and Cushing 1924)*. Recently Belding and Hatch *(1955)* and Tromp *(1966)* definitely linked climatic variables with human comfort when they observed that climatic parameters such as air temperature, humidity, and wind speed cause distinct and repeatable human physiological stress responses.

The objective of our study was to examine and quantify the thermal exchanges between a theoretical subject and several urban- and suburban-type sites to determine which were the most and least comfortable and why. From the results, specific factors of site design that significantly affect human comfort can be identified and utilized by city planners for future development.

DETERMINING HUMAN THERMAL COMFORT

Inequalities in the temperatures of terrestrial objects results in an exchange of energy between the objects as they approach thermal equilibrium with each other. The major means by which energy is exchanged are radiation (R), convection (C), conduction (G), and the evaporation or condensation of water (LE). Over a sufficiently long period of time, the summation of all the energy gains and losses by an object or human subject will equal zero:

$$R+C+G+LE=0 \quad [1]$$

The instantaneous rate of heat gain or loss, which must be compensated for to maintain the body core-temperature constant, has been established as an important factor in human comfort. But quantification of the instantaneous net heat load for human subjects is complicated by the facts that each of the processes of equation 1 act in not one but several ways and that clothing alters the exchanges in a variety of ways. Fanger *(1970)* presented a similar model for a human subject that demonstrates how a single process such as evaporation is complicated in the human energy balance problem:

$$M+R+G+G+Ed+E_{sw}+E_{re}+L+C=0 \quad [2]$$

where:

M = Metabolic heat production.
Ed = Heat loss by skin diffusion.
E_{sw} = Heat loss by evaporation of sensible sweat.
E_{re} = Latent respiratory heat loss.
L = Dry respiratory heat loss.

In equation 2 the single evaporation term of equation 1 (LE) has been broken into three separate terms (Ed, E_{sw}, and E_{re}), each representing a form of energy exchange by evaporation that must be determined independently.

Before this relationship was derived, the rates of energy gain and loss, which determined the limits of the comfort zone, were established by asking a sample of people how they felt in a series of test environments. Those environments in which subjects most frequently said they were comfortable were then designated as comfortable; and upper and lower limits were established. Belding and Hatch *(1955)* then evaluated these limits, using a relationship similar to equation 2; and they concluded that the limits of the human comfort zone are ±500 calories per minute for an average subject.

MATERIALS AND METHODS

Data Collected and Site Description

Data were taken in June and July 1974 on The University of Connecticut campus at Storrs (latitude 41°47′30″, longitude 72°14′33″W, average elevation 215 meters). The University campus represents an urban-like environment built to be esthetically pleasing and surrounded by undeveloped woodlands. Eight sites that were felt to be microclimatically dissimilar were selected. Figures 1 through 7 are photographs and scale drawings that cover full 360° views of these sites.

Site 1 is not pictured, but is a typical area beneath the canopy of a 20-m-tall black oak *(Quercus velutina)* forest with moderate undergrowth.

At each site wet and dry bulb temperatures were measured with a Bendix aspirated psychrometer, wind speed with a Hasting's omnidirectional air meter, and surface temperatures of facing solids with a Barnes PR-10 infrared thermometer. Solar radiation was monitored with a Kipp pyranometer located in the northwest corner of site 2.

Data were taken at each site once every 2 hours of each data day beginning at site 1 and progressing sequentially through site 8. At the end of each run, measurements were repeated at site 2 to give some indication of how conditions had changed during the course of the data collection. Data runs were begun at 0730, 0930, 1130, 1330, 1530, and 1730 solar time. Transit time from site to site was approximately 3 minutes, and the total time elapsed from the start to the finish of a data run averaged 1 hour. A total of 8 data days were obtained for use in later analysis.

Data Reduction

Equation 2 was modified by splitting the radiation term into a solar radiation component (S) and an infrared radiation component (IR). The solar component was then evaluated, using the techniques of Underwood and Ward *(1966)*, giving the working model:

$$S-(r+t)\,S+M+IR+G+Ed+E_{sw}+E_{re}+L+C=0 \qquad [3]$$

where:

r = the reflectivity of the subject to solar radiation.

t = the transmissivity of the subject to solar radiation.

To quantify equation 3 and utilize it to compare the sites it was necessary to make a number of assumptions to rule out the variability between human subjects. For this study, the subject was assumed to be a young male, aged 20 to 35 years, with a surface area of 1.8 m^2, who was walking at 1.5 m sec^{-1} and whose orientation with respect to the sun was constantly changing. His skin temperature was assumed, from the basis of a literature review, as 32°C. A corresponding clothing temperature of 35°C was established from supplementary experimentation in which the actual temperature differences between the skin and outer clothing surfaces were monitored and found to average 3°C. Con-

Figure 1.—Site number two. (+) denotes measurement site.

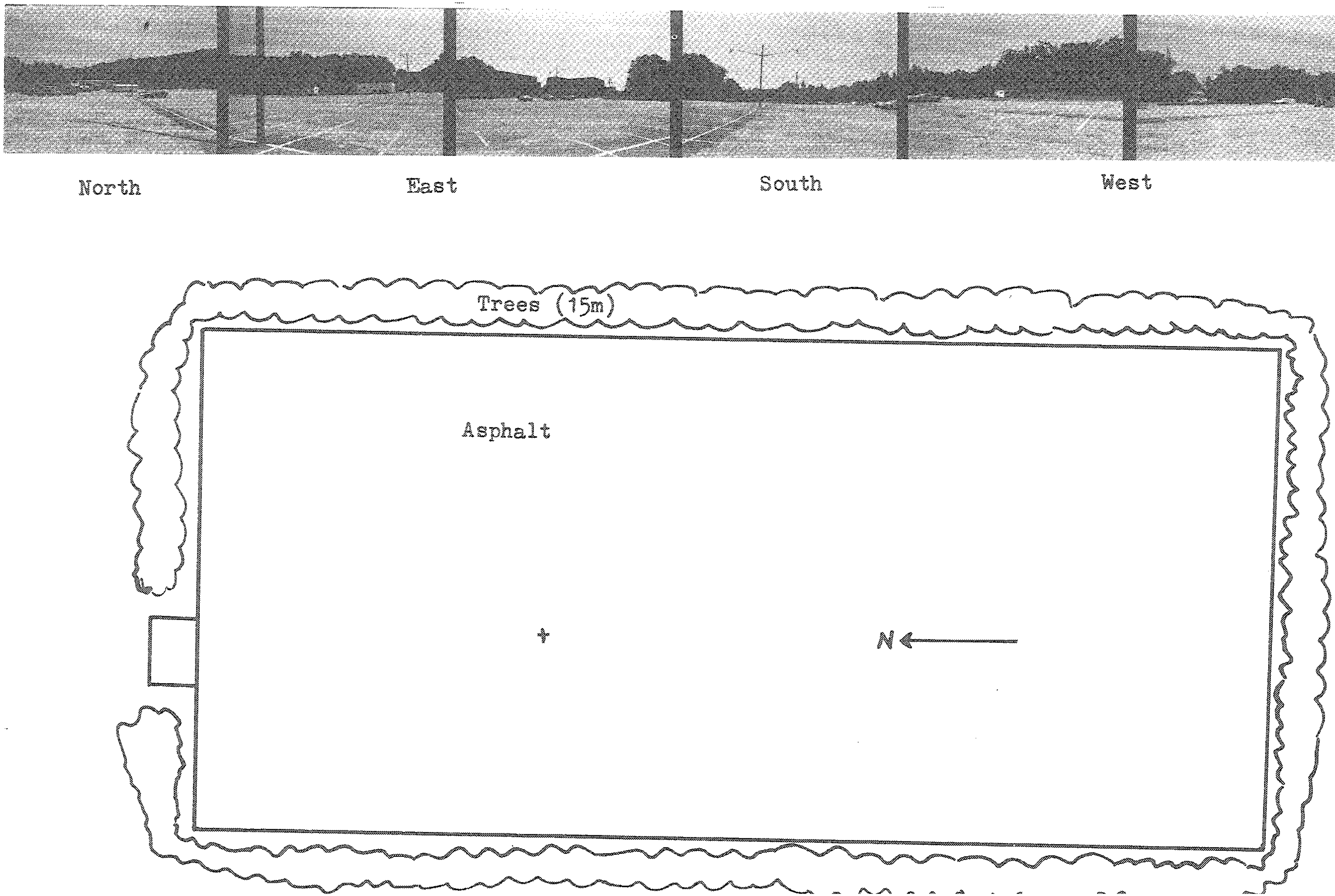


Figure 2.—Site number three. (+) denotes measurement site.

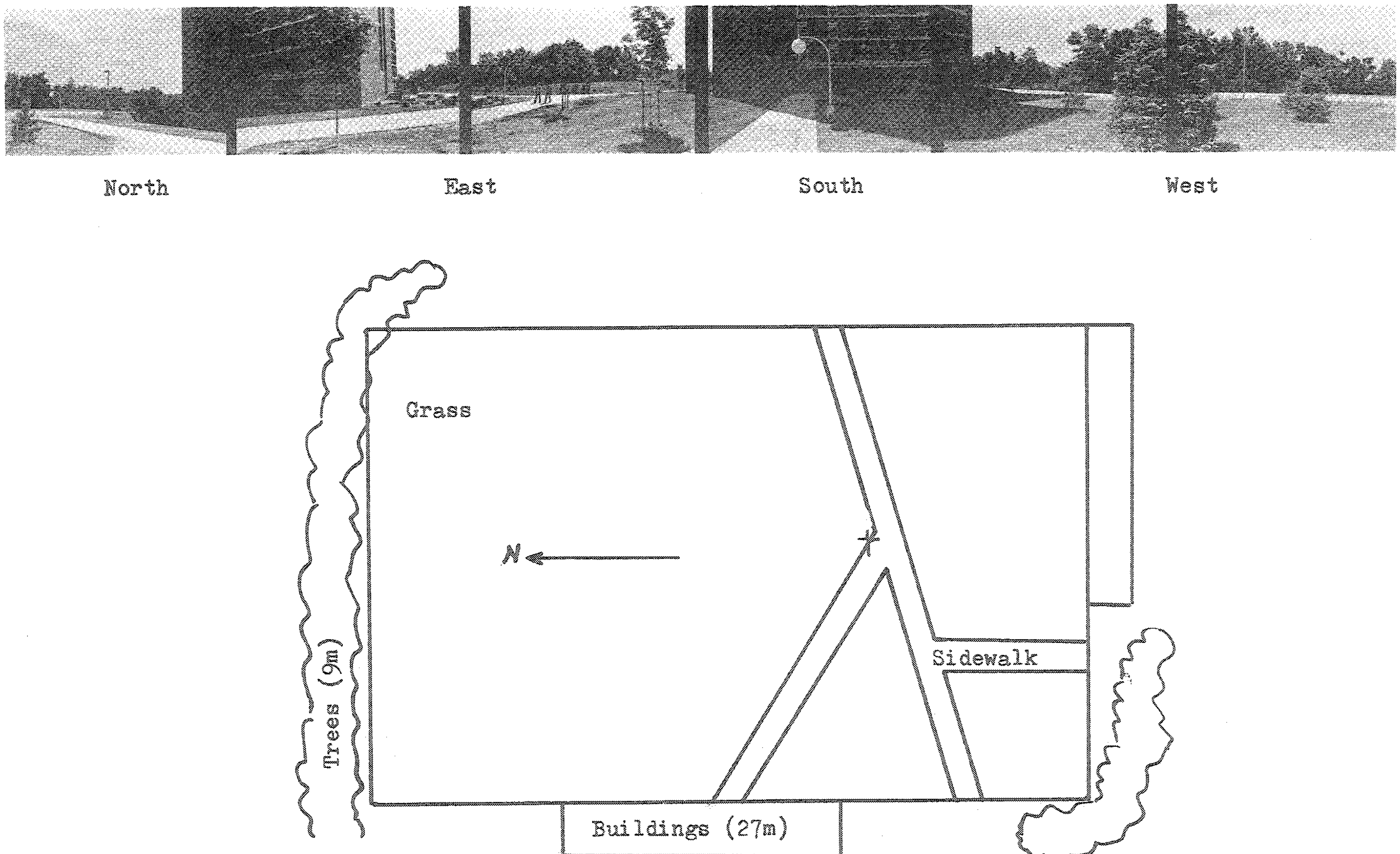
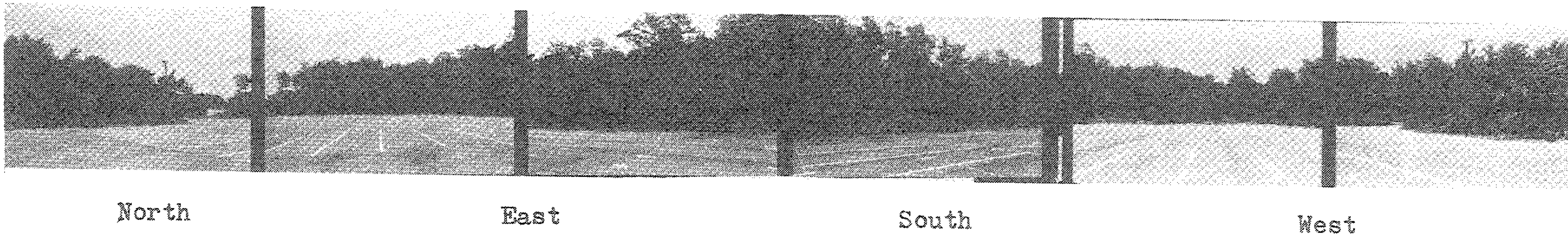


Figure 3.—Site number four. (+) denotes measurement site.



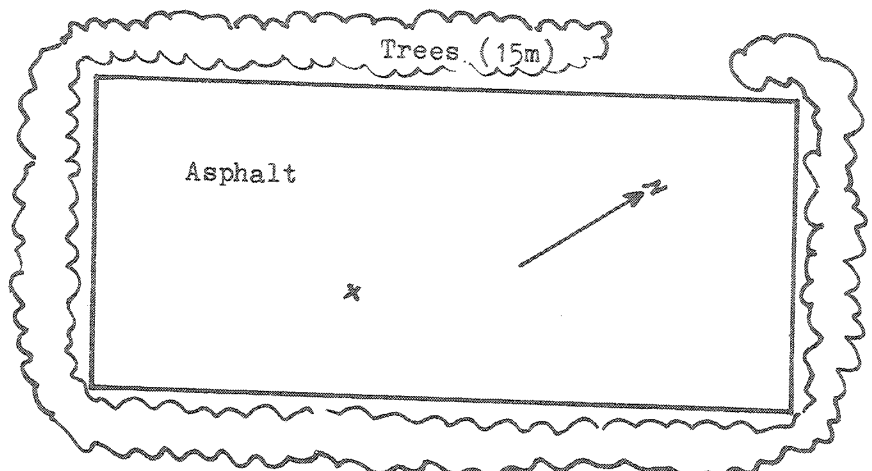


Figure 4.—Site number five. (+) denotes measurement site.

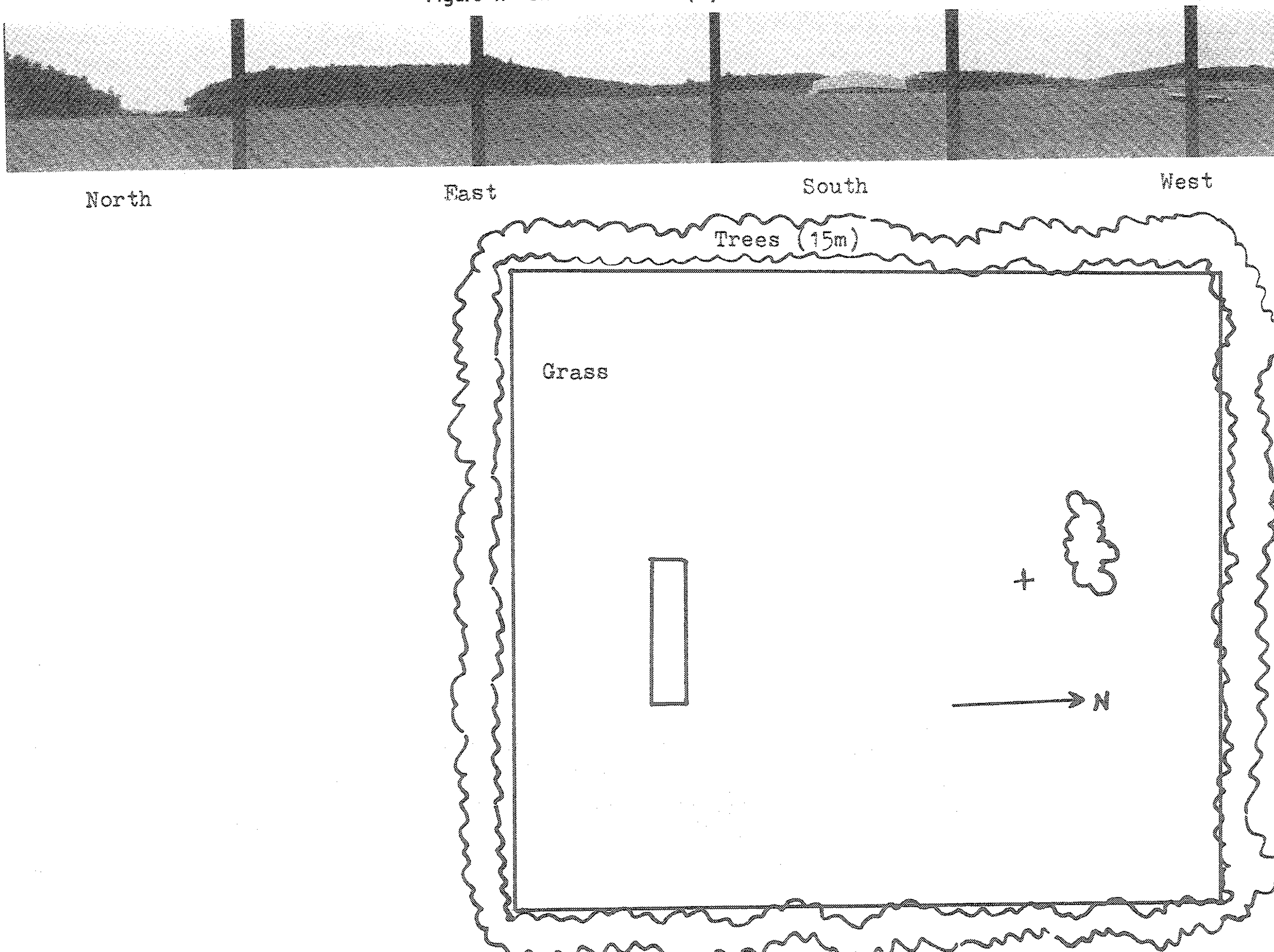
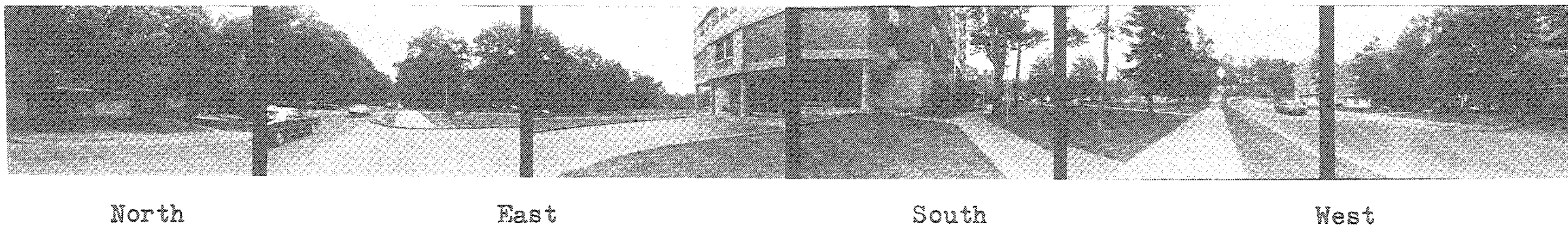


Figure 5.—Site number six. (+) denotes measurement site.



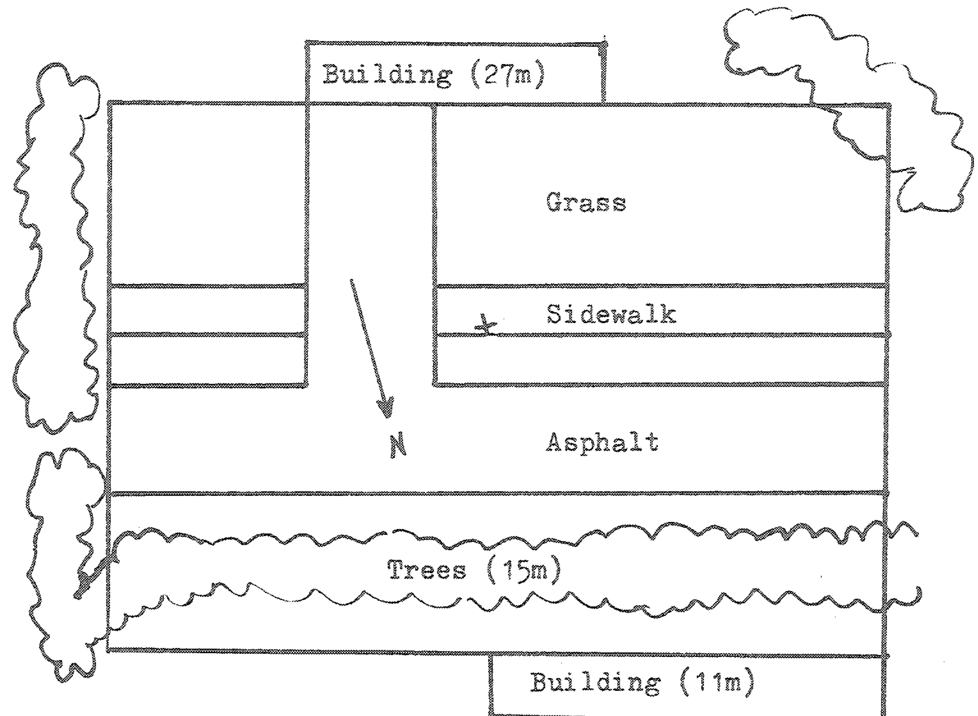
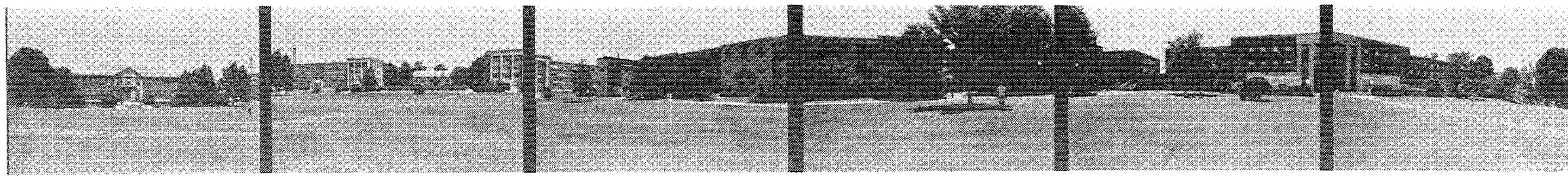


Figure 6.—Site number seven. (+) denotes measurement site.



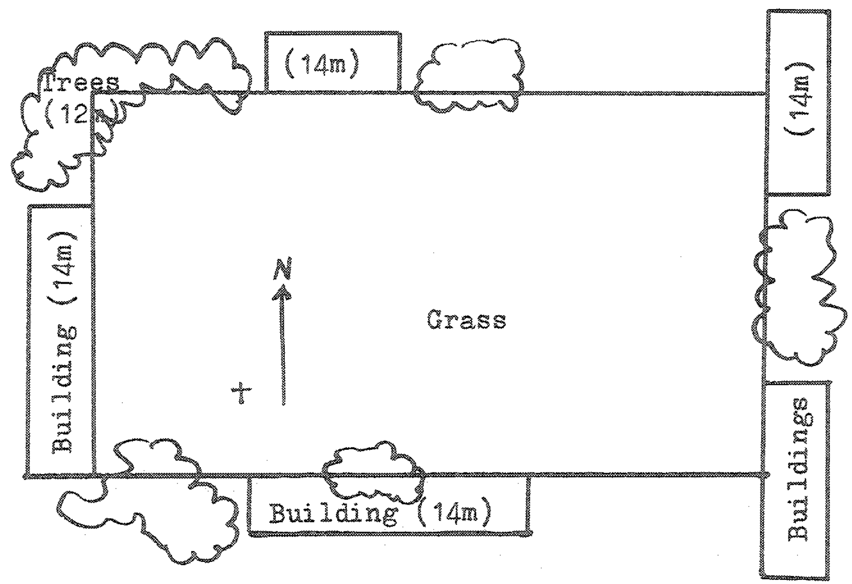
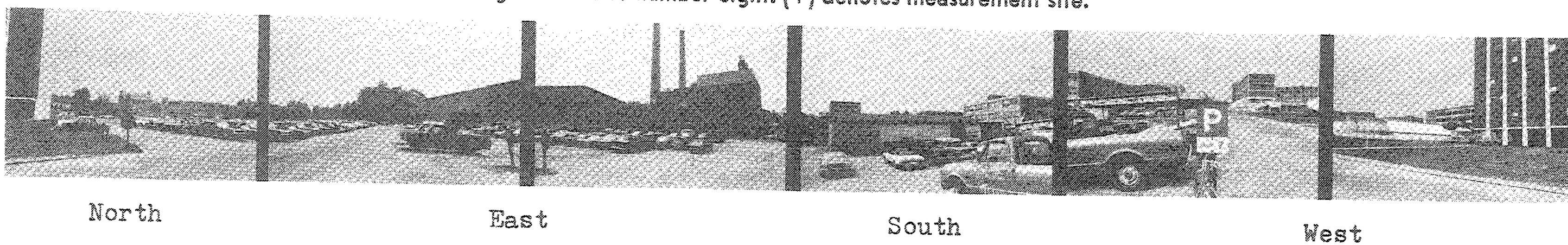
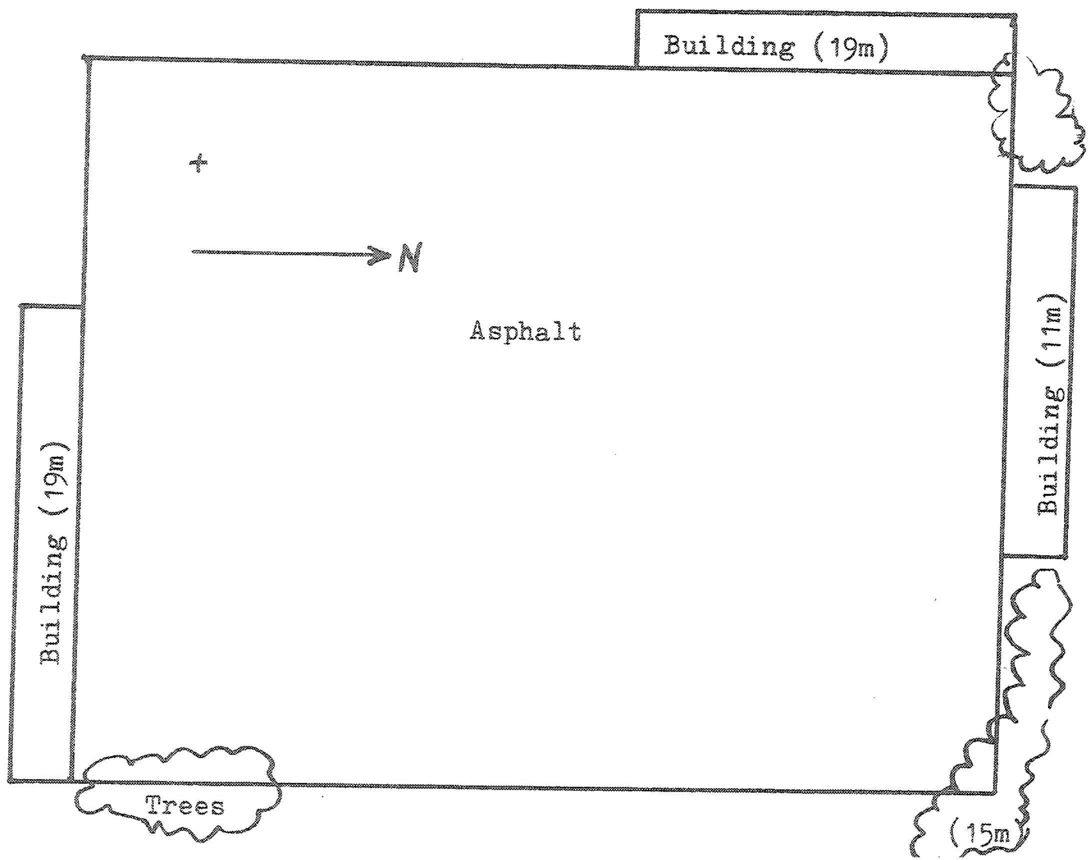


Figure 7.—Site number eight. (+) denotes measurement site.





duction (G) for a standing subject was assumed negligible. Finally, it was assumed that the subject would be in complete equilibrium with his clothing so that any heat gained or lost at the outer surface of the clothing would represent an equal heat gain or loss to the subject.

After making these assumptions and reducing all units to cal min^{-1} for the subject, we devised a working model from equation 3:

$$(DRA)\ (s)\ .8 + M + Vf_{s\text{-}o_n}\ (Ro_n - R_s) + 10.56\ (36 - pa) + 3.8\ (44 - Pa) + 2.3\ (34 - ta) + 33.18hc\ (35 - ta)$$

= net heat load before evaporation of sweat (cal. min^{-1}) [4]

where:

DRA = The direct radiational area determined, using the work of Underwood and Ward *(1966)*.

$Vf_{s\text{-}o_n}$ = The view factor between the subject and the indicated object (n) in the environment, determined by using the graphic methods of Fanger *(1970)*.

R_s and Ro_n = The radiosites of the subject and objects respectively calculated by the Stefan-Boltzmann Law: $R = \epsilon\sigma T^4$, where the emissivity (ϵ) was assumed unity, σ is the Stefan-Boltzmann constant, and T is surface temperature (°K).

Pa = Air vapor pressure (cm Hg).

ta = Air temperature (°C).

hc = Convective coefficient, using Fanger's *(1970)* equation: $hc = 10.4\sqrt{v}$, where v is the wind velocity (m sec^{-1}).

M = Metabolic heat production, assumed constant at 3016 cal min^{-1}.

RESULTS AND DISCUSSION

The sites were evaluated with equation 4 and were compared in terms of relative humidity, vapor pressure, wind speed, and air temperature as well as net heat load. Figure 8 shows a graph of the net heat loads for each site averaged for all 8 test days. On this graph, points above the x-axis represent positive heat loads or conditions in which a subject must get rid of excess heat by evaporation of liquid sweat in order to be comfortable. Thus, those sites that reach the greatest positive values and are above the x-axis the longest time during the day are the most uncomfortable. Sites 2, 4, 6, and 8 were singled out in this manner.

Table 1 gives the percentage of the total view of each site represented by various groupings of materials and averaged midday air temperatures, humidities, and wind speeds. Despite the obvious physical differences among sites 1 to 8, the average air temperature, vapor pressure, and wind speed varied little. A comparison of the view factor information in table 1 with the net heat-load data revealed a correlation between midday net heat loads (0930 through 1530) and the percentage view factors of synthetic and vegetative materials.

Regression analyses were made of the importance of the view-factor groupings of vegetation, synthetic materials, sky, and not sky in determining net heat loads. Separate analyses were made for day-long averages, for transition periods (0730 and 1730), and for midday periods. Table 2 shows some results of these regressions.

Table 2 shows that there was very little correlation between net heat load and either vegetative or synthetic view-factor groupings during the transition periods when surface temperatures were relatively low. Further, the correlations for individual days and times became higher as the overall synoptic conditions became hotter. This indicates that the

Figure 8.—Average net heat loads for June and July data days.

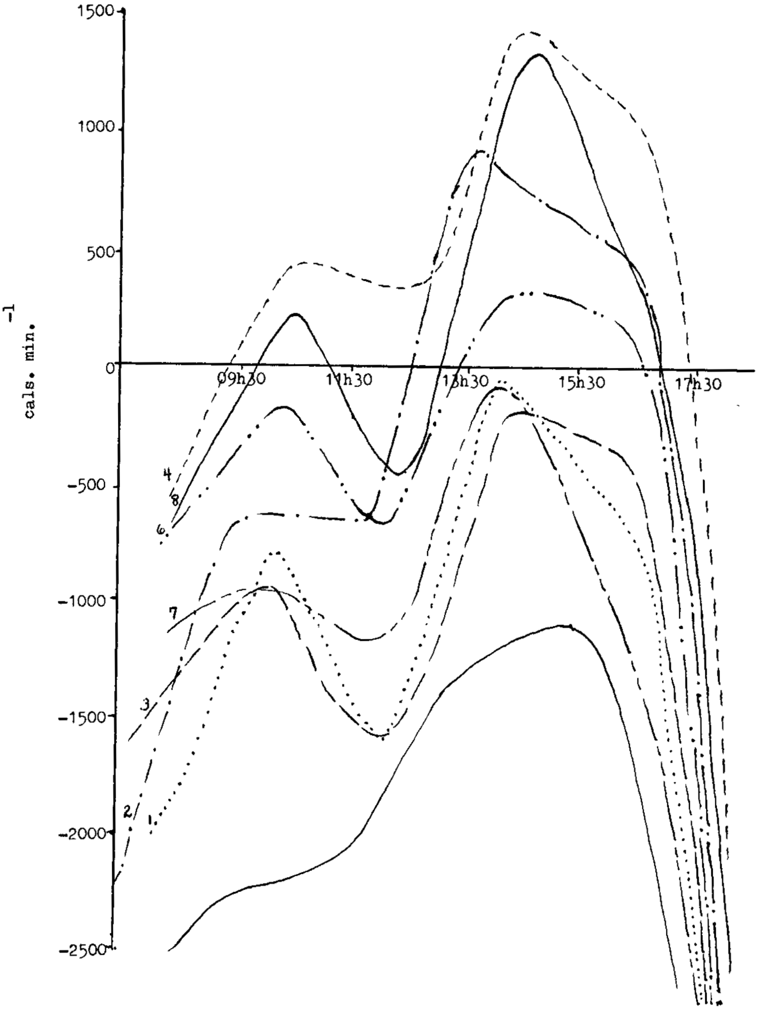


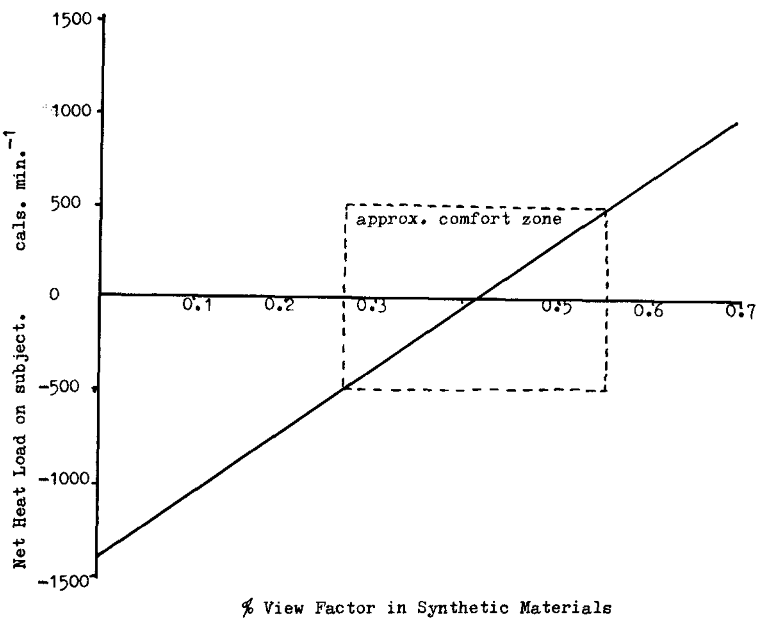
Table I.—View-factor descriptions of sites and their average midday air temperature, vapor pressure, and wind speed

Site	Sky	Vegetation	Synthetic material	Average midday		
				Air temperature	Vapor pressure	Wind speed
	Pct.	*Pct.*	*Pct.*	°*C*	*cmHg*	*m sec*$^{-1}$
1	0	100	0	24°	12.0	0.46
2	49	3	48	26°	10.4	.91
3	24	57	19	26°	10.2	1.06
4	28	24	48	27°	10.2	.73
5	50	50	0	26°	10.5	.94
6	27	37	37	27°	10.1	.96
7	40	46	14	26°	10.3	.92
8	43	0	57	27°	10.3	.98

Table 2.—Partial results of the statistical correlations between the indicated view-factor category and averaged net heat loads

Period	View-factor category	Sites	r	$S_{y \cdot x}$ (cal. min^{-1})
Midday, June and July . . .	Synthetic materials	1-8	0.88	334
	Synthetic materials	1-4, 6-8	.93	270
	Vegetation	1-8	— .88	338
	Vegetation	1-4, 6-8	— .87	359
Transition, June and July . . .	Synthetic materials	1-8	.69	361
	Vegetation	1-8	— .46	420

Figure 9.—Average midday heat load versus the fraction of view in synthetic materials.



effect of these view-factor groupings in the urban microclimate increases as the overall climatic stress becomes more and more positive.

During the midday periods, correlations between net heat load and vegetative and synthetic categories were high. The regression analysis of the midday heat loads versus the percentage view factor in synthetic materials suggests that 87 percent of the variation in heat load from site to site can be explained by changes in the percentage view of synthetic materials.

Figure 9 shows this empirically defined relationship between the view-factor grouping of synthetic materials and midday net heat loads:

$$\text{Net heat load} = -1463 + 3574 \, Vf_{syn}. \quad [5]$$

By reading the percentage of the view factor present, at a proposed site, of synthetic materials from the x-axis, an estimate of the expected heat load can be read from the point of intercept with this line. Given relationships of this nature, one should be able to design a site to fall within the comfort zone by manipulating vegetative shields and building spacing.

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