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THE POTENTIAL OF VEGETATION IN REDUCING SUMMER COOLING LOADS IN RESIDENTIAL BUILDINGS

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The Potential of Vegetation in Reducing Summer Cooling Loads in Residential Buildings*

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ABSTRACT (March 1987)

The potential of trees and other vegetation to greatly reduce building cooling loads has been recorded in a number of studies, but the meso- and microclimate changes producing such savings are not well understood. This paper describes a preliminary attempt to model the effects of landscaping on temperature, humidity, windspeed and solar gain in urban climates using information from existing agricultural and meteorological studies, with particular attention placed on quantifying the effects of plant evapotranspiration. The climate model is then used in conjunction with the DOE-2.1C building simulation program to calculate the net reductions in air-conditioning requirements due to trees and other vegetation.

Preliminary results show that an additional 25% increase in the urban tree cover can save 40% of the annual cooling energy use of an average house in Sacramento, and 25% in Phoenix and Lake Charles. If this additional tree cover is located to optimize summer shading, the savings are further increased to more than 50% in Sacramento and 33% in the other two cities. The calculated savings are minimal for Los Angeles because the base case cooling energy use is small (65 hours) on the assumption that window venting is used whenever possible in lieu of mechanical cooling. There are additional benefits in lowering peak power consumption, where the savings are as much as 34% in Sacramento, 18% in Phoenix, 22% in Lake Charles, and 44% in Los Angeles. Parametric analysis reveals that most of the savings can be attributed to the effects of increased plant evapotranspiration, and only 10% to 30% to shading. The energy penalties of reduced windspeeds are found to be small in all four locations.

These preliminary results suggest that while the conservation benefits of planting trees are appreciable at the individual house level, equally dramatic savings can be realized at the urban level through modifications of the urban climate by increasing the total amount of vegetative cover. Such a conservation strategy may be effective in counteracting the summer heat island evident in cities and improve ambient conditions, as well as reduce summertime air-conditioning requirements.

KEYWORDS: Air Conditioning, Cooling, Energy Conservation, Environment, Heat Islands, Modeling, Peak Power Demand, Residential, Shading, Vegetation, Evapotranspiration

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INTRODUCTION

Many horticulturalists and landscape architects have noted that, in addition to their aesthetic value, trees, shrubs, and lawns also have an added value for saving energy, particularly in cooling climates. Case studies in recent years have documented dramatic differences in cooling energy use between houses on unlandscaped and landscaped sites (Laechelt 1976, Buffington 1979, Parker 1983). A good discussion of the microclimate effects of urban vegetation is given in Hutchison et.al. (1983). This paper will forego a general literature survey and describe only the development of a simple quantitative model for the microclimatic effects of urban vegetation, and the predicted savings in cooling energy shown by this model for various vegetation conditions in different cooling climates.

The microclimate model described in this paper is based on a growing literature of recent meteorological and agricultural studies documenting and analyzing the effects of vegetation on the temperature, windspeed, and humidity of their microclimates (Geiger 1957, Rosenberg 1974, Oke 1978). To predict the effect of these changes on building energy use, the microclimate model is then linked with the DOE-2.1C building energy simulation program to calculate cooling energy savings for a typical one-story house.

DOE-2.1C is a documented public-domain building energy program that simulates the energy performance of a building hour-by-hour depending on its climate, building envelope, equipment use, and occupant schedules (U.S. Dept. of Commerce 1980). For its climate input, DOE-2.1C uses hourly weather tapes which are generally available from sources such as the U.S. National Oceanic and Atmospheric Administration (NOAA). The vegetation model developed in this work is implemented partly by modifying the input weather file, and partly by altering the building description input file, since DOE-2.1C can accept information to some degree on the surrounding conditions. Since most hourly weather files are based on airport data, the modified weather produced by the model should be interpreted as due to *relative* differences in vegetation from airport conditions.

For this preliminary work, our intention is to quantify the relative importance of different vegetation effects such as shading, wind reduction, or evapotranspiration, and to show that in addition to the savings for individual houses due to direct shading from a tree, there are additional potential savings at a neighborhood or city-wide level through the moderation of summertime urban temperatures. To avoid misleading impressions of accuracy, we have kept the modeling of microclimatic effects simple on purpose. We will discuss the limitations of the simplifying assumptions, how they affect the results, and potential methods for improving the model.

MODELING THE MICROCLIMATE EFFECTS OF VEGETATION

During the daytime cooling season, trees and vegetation reduce air-conditioning loads through several processes: (1) reduce solar gain on windows, walls, and roofs by shading, (2) reduce long-wave heat gain by maintaining lower surface temperatures than impermeable surfaces such as asphalt and concrete, and (3) reduce conductive and

convective heat gain by lowering drybulb temperatures through plant evapotranspiration. These cooling benefits must be weighed, however, against the possible detrimental effects of (1) reduced net outgoing long-wave radiation, (2) increased latent cooling loads from the added moisture (i.e., higher humidity ratios) from evapotranspiration, and (3) reduced natural ventilation potential and convective heat loss due to lowered windspeed. The last factor is of minor significance for houses cooled strictly by air conditioning, but can be significant in houses that capture outdoor air movement to maintain comfort conditions.

1. Reduced solar gain

The shading effects of trees can be simulated on the DOE-2.1C program as exterior building shades, once the geometry and transmissivity of the trees have been determined. Tree transmissivities vary by species, ranging from 6% to 30% during summer months (Thayer 1983, McPherson 1984). For this study we consider two conditions of tree shading : (1) uniform increases in the tree canopy area reflecting tree plantings in residential neighborhoods without particular attention to placement for summertime shading, and (2) trees placed for shading on the west or south side of the house.

For the first condition, we have modeled the shading effect of a typical canopy with an average tree height of 10 m. as a "building shade" uniformly distributed around a house at a height of 6.5 m. (Figure 1). We assume that the trees extend to the edge of the house, but do not provide direct shade over the roof. Percent increases in the canopy density are approximated as equivalent reductions in the transmissivity of the "building shade". A one-to-one correspondence is assumed between increases in canopy area density and reductions in solar transmission since trees have an average transmissivity of 20%, but are generally planted more densely around houses (for discussion of tree shading patterns in typical residential areas in California, see Myrup and Morgan 1972, pp. 13-21). We have considered transmissivities of 90% and 75% in the "building shade", corresponding to increases of 10% and 25% in the urban tree canopy density. We judge that increases over 25% are unlikely due to physical constraints in the city and the fact that typical American cities already have existing tree covers approaching 30% of their surface areas (Myrup and Morgan 1972).

To explore the conservation potential of trees planted for summer shading, we have modeled the effects of one tree planted on the west, and two more on the south side of the house (Figure 2). We have assumed that each mature tree has a top view projection area of 50 m^2 and a suburban housing density of one house per 500 m^2 of land. Therefore, the equivalent increases in the urban tree canopy for these two configurations are 10% and 30%, which correponds to one or three trees per typical housing lot.

Tree shading reduces not only the direct solar gain striking the building envelope, but also the diffuse light reflected from sky and surrounding surfaces. This change is approximated in the DOE-2.1C model by modifying the inputs for sky- and ground-form-factors (the amount of each visible from a building surface), and the ground reflectance of the surroundings.

In addition, tree shading alters the exchange of long-wave radiation between the building and its surroundings. During the day, vegetative surfaces reduce long-wave heat gain to the house because their surface temperatures are low compared to hard surfaces

such as sidewalks, asphalt, or bare ground. At night, however, trees reduce radiative cooling by blocking the amount of night sky visible from the walls and roof. The impact of these changes on building cooling loads cannot be modeled by the DOE-2.1C program, but a simple calculation shows that the effects are small compared to those due to reductions in direct solar gain (Myrup and Morgan 1972).

2. Reduced Wind Speed

Whereas shading and evapotranspiration are beneficial in reducing summer cooling loads, reductions in wind speed are detrimental during those hours in the cooling season when natural ventilation can be used to extend the comfort zone, and thus reduce reliance on mechanical cooling. During peak cooling hours when ambient temperatures are very high, wind speed reductions may reduce cooling loads slightly by lowering the amount of wind-driven infiltration.

For houses in open terrain, reductions in wind speed due to shelterbelts can be estimated from the density and height of the trees, their orientation relative to the wind, and their distance from the house (Nageli 1946, DeWalle 1983). For houses in typical suburban areas, however, wind speed reductions at the building height (0-5 m above ground) are due partly to the general roughness, density, and height of the urban canopy as well to the location of nearby trees. Since we are interested in typical suburban conditions, we chose an empirical function relating wind speed reductions to increased tree canopy densities.

In his study of urban microclimates in Davis CA, McGinn (1982) found that wind speeds at 5 m above ground for various tree canopies compared to that for a control open field site varied as a function of the density, and not height of the canopy (Figure 3). Polynomial regression of the concurrent wind speed data for five canopy densities varying from 3% to 35% resulted in the following equation:

$$u = u_o(0.946 - .091C + .0043C^2 - .00007C^3) \quad (1)$$

where u = wind speed at site
u_o = wind speed on open urban field
C = percent canopy cover

Although there have been more detailed efforts to correlate wind speed changes in urban areas to physical parameters such as surface roughness or average building height (Myrup and Morgan 1972), we chose at this point to use Equation 1 because it was developed from suburban data using a control site quite similar to the conditions at most weather stations (an open urban field) and shows the relationship of wind speed reductions to increased tree canopy density.

3. Evapotranspiration

A major microclimatic impact of trees and other vegetation that is frequently overlooked is their capability to affect daily temperature swings through the evaporation and transpiration of moisture through leaves, a phenomenon agriculturalists call *evapotranspiration.**

From the point of view of energy conservation, a tree can be regarded as a natural "evaporative cooler" using up to 100 gallons of water a day (Kramer 1960). This rate of evapotranspiration translates into a cooling potential of 230,000 kcal/day. This cooling effect is the primary cause for the 5 C differences in peak noontime temperatures observed between forests and open terrain, and the 3 C difference found in noontime air temperatures over irrigated millet fields as compared to bare ground (Geiger 1957, p. 294). Temperature measurements in suburban areas recorded similar but smaller variations in daytime peaks of 2 to 3 C between neighborhoods under mature tree canopies and newer areas with no trees (McGinn 1982 p. 59). More pronounced cooling effects have been measured in large urban parks where evapotranspiration has been further driven by wind, resulting in an "oasis" 4 C cooler than surrounding neighborhoods (Figure 4).

To develop a quantitative model for microclimate modifications due to evapotranspiration, it is necessary first to determine the amount of evapotranspiration as a function of time and ambient conditions, and then to relate that amount of added moisture to changes in the microclimate. To estimate the amount of plant evapotranspiration, we rely on an empirical model originally developed for estimating water loss in crops. Because of its importance to agriculture, botanists and micro-meteorologists have proposed numerous methods for measuring and predicting evapotranspiration rates in crops (Rosenberg 1974 p. 186-193). These studies distinguish between *actual* and *potential* evapotranspiration. The former is a measure of the actual amount of moisture released by plants under given conditions, and is highly sensitive to both air conditions as well as the availability of ground water. The latter is a measure of the theoretical amount of evapotranspiration possible assuming an ample supply of water.

Since the goal of our work is to assess the potential cooling effects of vegetation, we assume that the vegetation will be well watered and, hence, releasing water at the potential evapotranspiration rate. After reviewing several models, we decided to use one developed by Jensen and Haise (1963) from the study of 1,000 reported measurements in which potential evapotranspiration is given as a function of dry-bulb temperature and solar radiation. †

$$ETP = (.0252T - .078)R_s \tag{2}$$

where ETP = potential evapotranspiration in centimeters of water/day
T = ambient air temperature in C
R_s = solar and sky radiation in centimeters of evaporated water/day

* The replacement of vegetation by hard impermeable surfaces such as asphalt and concrete is frequently mentioned as one of the causes for the summer "heat island" in the cities. Although some studies indicate that humidities are generally lower in downtown areas, others have found evapotranspiration rates in *suburban* areas are similar to those in the countryside due to the prevalence of artificial watering (Oke 1979). Thus, the net change in urban evapotranspiration is still debatable and needs to be investigated further .

† This formula is modified from the original where evapotranspiration and radiation are expressed in terms of inches of water per day, and the temperature in degrees Fahrenheit.

Jensen and Haise (1963) state that studies over the previous 15 years have demonstrated repeatedly that evapotranspiration rates were more closely related to net solar radiation than to air temperature or humidity. Their equation for potential evapotranspiration was based on measurements of the ratio of evapotranspiration to solar radiation (ETP/R_s) for crop conditions and locations where the vaporization of water was judged to be unlimited (Figure 5). The data set included four types of crops (alfalfa, cotton, oats, and winter wheat) in five states (Arizona, California, Nebraska, Washington, Kansas, and Texas).

We selected this model for our preliminary work because it was based on empirical data for arid and semi-arid locations where evaporative cooling would be effective, and required as input only solar and dry-bulb temperature data easily available from weather tapes. A validation effort by Jensen and Haise (1963) for a clipped grass field in Davis, California, indicated that the model was accurate over periods of five days or more, while an independent test by Rosenberg (1974, p. 190) indicated good results for cases with minor advection due to wind, but serious underprediction for cases with large advection. The use of this model in our study should be regarded as an interim step, since it remains to be seen whether it is applicable for all climates and plant types, or for predicting hourly evapotranspiration rates in suburban settings. Although some data exist on evapotranspiration rates for different types of trees, we think it inappropriate at this stage to include this detail into our simple microclimate model.

In order to translate the evapotranspiration rate into changes in the ambient air conditions, we need to determine the amount of air within which this cooling occurs. Although existing data indicate that this cooling can be localized at the neighborhood level (Figure 4), correct solution of these local effects requires a three-dimensional urban climate model. For this preliminary work, we have made the simplifying assumptions that (1) the air over the city is well mixed with no differences in potential temperatures and humidity ratios (i.e., the only temperature differences are due to the adiabatic lapse rate), and (2) the cooling effect of evapotranspiration from an increased number of trees is uniform throughout the urban microclimate.

We assume that the evaporatively cooled air is uniformly mixed into an air volume defined by the area of the city times the average *mixing height* over the city, with an additional "air change" term to take into account wind speed. At large wind speeds, the mixing volume is simply proportional to the wind speed itself. At very low wind speeds, the mixing volume is the summation of the newly displaced air plus the remaining unsaturated air from previous hours. Therefore, the mixing volume will be larger than that of the wind-driven volume. To approximate this condition, we assume that the volume rate decreases linearly as a function of wind speed to $wlh/2$ and then stays constant (solid line in Figure 6):

$$\begin{aligned} \textit{Volume rate} &= uwh & u &\geq u_c \\ &= u_c wh & u &< u_c \end{aligned} \tag{3}$$

where u = wind speed
w,l = characteristic length and width of city
h = height of mixed air layer
u_c = characteristic wind speed defined as $l/2\Delta t$

Δt = calculation time internal, 1 hour in this case

We also have used an alternative approximation that the volume rate is zero at wind speeds below u_c (dotted line in Figure 6). The resultant microclimatic effects using the two approximations did not differ significantly.

The *mixing height* defines a volume below which the air is assumed well-mixed. As an essential element in many meteorological models, this height has been the subject of numerous measurement and theoretical modeling efforts. General meteorological principles suggest that the *mixing height* is low at night (less than 300 meters), rises quickly after sunrise, and reaches anywhere from 0.5 to 3 km by early afternoon (Oke 1978, p. 53-54). The height at a specific time and location, however, is quite variable and depends on a wide range of climate parameters.

For our study, we used an empirical model developed by Leahey and Friend (1971) from New York data for predicting the *mixing height* over an urban heat island.

$$h^2 = \frac{2}{c_p \rho u \alpha} \int_{x1}^{x} [H + Q_s - \sigma(T_0^4 - T_{0c}^4)] dx \tag{4}$$

where
h = mixing height (m)
H = artificial heat release rate (kW/m^2)
$x1$ = starting transition point of heat island (m)
x = distance from transition point (m)
c_p = specific heat of air ($kJ/kg\ K$)
ρ = air density (assumed to be constant)(kg/m^3)
σ = Stefan-Boltzmann constant ($5.7\ 10^{-8}\ kW/m^2\ K^4$)
u = wind speed (m/sec)
T_0 = ground surface urban temperature (K)
T_{0c} = ground surface temperature at transition point (K)
α = difference between rural and urban lapse rates (K/m)
Q_s = sensible heat flux (kW/m^2)

It should be noted that this formula has been used over the first five kilometers downwind from the transition point, and that the mixing heights used in our energy performance simulations are the averages of the mixing heights obtained over the five-kilometer zone for each time interval.

We chose this model over others because it incorporates the effects of man-made urban heat and of the cooling downwind in an urban area. To illustrate our use of the Leahey-Friend model, the following assumptions are used as inputs with a hourly weather tape for Sacramento CA : (1) a constant heat island magnitude of 3.5 C, (2) an artificial heat addition rate based on Torrance and Shum (1975, Figure 7), (3) a rural lapse rate of .004 C/m based on sounding data from Vandenberg Air Force Base, and (4) no change in albedo. The calculated *mixing heights* for a typical clear summer day are shown in Figure 8. These heights average around 600 m at night and remain under 1 km until 12 p.m., when they start to rise, reaching a maximum of 3 km by 5 p.m. As shown by the spikes on Figure 8, the model is very sensitive to the hourly wind speed. For comparison between different locations, Figure 9 shows summer *mixing heights* averaged over

entire urban areas for several hot climates using the Leahey-Friend model. As with the evapotranspiration calculation, many questions still remain about the appropriateness of using this *mixing height* model for all climates and urban conditions.

Once the *mixing height* is known, we can compute the *volume rate* for a city based on Equation 3. Using Equation 2 to calculate the evapotranspiration rate as a function of temperature and insolation, we then estimate the resultant changes in the urban microclimate. We assume that the increased tree canopy does not alter the overall heat balance of the urban microclimate, i.e., the effect of the additional evapotranspiration is adiabatic and results in lowered drybulb temperatures, increased humidity ratios, but no change in wetbulb temperatures. We have implemented the above steps into a weather preprocessor program that modifies the drybulb temperatures and humidity ratios on a standard hourly weather tape depending on the input urban canopy density and the original temperatures, solar radiation, and wind speeds each hour. This modified weather tape is then used as input to the DOE-2.1C program. Figures 10 to 12 show the modified dry-bulb temperatures on a typical summer day for Sacramento, Phoenix, and Lake Charles. Since the original weather tape reflects existing conditions, the percent coverages noted should be interpreted as *increases* in, rather than total, tree canopy densities.

After we have developed a better understanding of the microclimate effects using the simple city-wide model, we intend to refine it by improving the calculation of evapotranspiration rates and accounting for uneven air mixing and localized effects with different techniques such as two- or three-dimensional atmospheric diffusion models.

PROTOTYPE HOUSE DESCRIPTION

The prototype building simulated using the DOE-2.1C program is a one-story detached house of wood-frame construction with 143.1 m^2 of floor area, 14.3 m^2 of windows (10% of floor), and 123.4 m^2 of wall area (Figure 13). Construction details are based on standard U.S. building practices (NAHB 1979), while operating conditions and infiltration rates are taken from statistical surveys of current house conditions. The house has a thermal integrity typical of current construction in the warm U.S. locations, with R=3.35 m^2K/W ceiling, R=1.94 walls, no slab perimeter insulation, single-pane windows, and an air change rate of 0.7 ach averaged over the winter months. The hourly air change rate varies with outdoor temperature and windspeed, and is calculated using the empirical Achenbach-Coblenz equation. The house has been simulated with an air-conditioner with a rated cooling capacity of 34,600 kJ/hr and an SEER of 9.2. The cooling thermostat is set at 25.5 C, and natural venting is assumed when the temperature and enthalpy of outside air is lower than that indoors, and the cooling loads for that hour can be totally met by ambient air at 10 air changes per hour. The windows are assumed to have shades half drawn during the summer, resulting in a shading coefficient of 0.63. (a detailed description of the assumptions and methodology used in DOE-2.1C residential simulations is given in Huang 1986.)

To investigate the sensitivity of the predicted cooling energy savings to building insulation levels, simulations were also done for the same prototype house with neither ceiling nor wall insulation. This alternate condition is more typical of houses in warm

locations that predate the 1973 oil crisis. However, since we expect future houses will be built at least with current insulation levels, we used only the results for the insulated house in our analysis.

PREDICTED COOLING ENERGY SAVINGS FOR PROTOTYPE HOUSE

The microclimate model including shading, evapotranspiration, and wind reduction effects is used in conjunction with the DOE-2.1C program to simulate the cooling energy use for the typical one-story house described above in four locations: Sacramento, Phoenix, Lake Charles, and Los Angeles. The base case condition is represented by the unmodified weather tape. Two increased canopy conditions of 10% and 25% or 30% are then considered. To assess the impact of individual effects, incremental sensitivity analyses are done, considering first shading, then shading and wind reduction, and finally, shading, wind reduction, and evapotranspiration. In reality, of course, the three effects occur simultaneously.

Results for cases with the generalized canopy are shown in Table 1, and those with trees planted for shading are shown in Table 2. For comparison, energy savings for an uninsulated house under the generalized canopy is shown in Table 1A. For all cases, the results show insignificant cooling energy increases due to decreased wind speed. It should be noted, however, that the DOE-2.1C simulations account for natural ventilation in terms only of lowering the building cooling load, and not of raising the comfort threshold by inducing indoor air movement. In addition, the ventilation algorithm used in the program assumes a fixed air change rate at 10/hour when windows are open. In reality, the cooling energy penalties due to reduced winds are probably larger than shown, although the amount will vary greatly depending on the design and orientation of the house relative to the wind direction.

The results, however, do show sizable reductions in annual cooling energy requirements due to shading and evapotranspiration for three of the four cities. For Los Angeles, the reductions are minimal because the base case cooling energy use is very low (65 cooling hours) calculated using the assumption that window venting is used whenever possible. For the other cities, a 10% increase in the generalized canopy produces savings of 261 kWh (18%) in Sacramento, 725 kWh (11%) in Phoenix, and 412 kWh (11%) in Lake Charles, while a 25% canopy increase produces savings of 603 kWh (42%), 1766 kWh (25%), and 1071 kWh (27%) in the same three cities. If the increased tree canopies are ideally planted for summer shading, the savings are further increased by 2 to 8% for the 10% increased canopy, and 7% to 10% for the 25% increased canopy. Test simulations show even more dramatic savings for a 50% increase in the tree canopy density, but we judge such an increase to be physically impossible.

Compared to that for a current construction house, the percent energy savings for an uninsulated house under the generalized canopy are very similar (Table 1A), but the total savings are substantially larger because of the greater cooling requirements. Increased tree cover will produce some energy savings for an uninsulated house even in Los Angeles, whereas for a typical house there is almost no cooling load.

In analyzing the causes of the cooling energies reductions, shading accounts for only 6%-17% of the total savings in the generalized canopy cases, and for 10%-35% even in the shading cases. The remaining savings result from the lowered temperatures due to evapotranspiration. The ratio of the two savings is affected by the thermal integrity of the house, which we have assumed to be moderate. Older houses of lower thermal integrity will show greater savings due to shading, while the opposite will be true for tight new houses.

In all four locations, the results show savings in peak cooling loads of 8% to 11% for a generalized canopy increase of 10%, and 12% to 30% for a canopy increase of 25%. For the summer shade canopy, the peak energy savings are 9% to 20% and 17% to 44%, respectively.

ECONOMICS

A simplified economic model along with the estimates of possible power and energy savings for the four tree canopy conditions are used to calculate the Cost of Conserved Energy (CCE) and the Cost of Avoided Peak Power (CAPP). CCE is obtained by dividing the annualized investment ($/yr) by the annual saved energy, i.e.

$$\textit{Cost of Conserved Energy } (CCE) = \frac{\textit{Annualized Investment } (\$/yr)}{\textit{Saved Annual Energy } (kWh/yr)}, \tag{5}$$

$$\text{Annualized Investment} = \textit{Total Investment} \times \frac{d}{1-(1+d)^{-n}},$$

where d = discount rate,
n = time horizon.

CAPP is obtained by dividing the total investment normalized for life of a nominal power plant (normally 20 years) by the avoided peak power, i.e.

$$\textit{Cost of Avoided Peak Power } (CAPP) = \frac{\textit{Total Investment } (\$)}{\textit{Avoided Peak Power } (kW)}. \tag{6}$$

The Present Value (PV) of the power and energy saved by planting trees for the four canopy configurations simulated are shown in Tables 3 and 4. Two economic scenarios based on the age of trees and their prices are selected to provide upper and lower limits for the costs of conserved energy and power. In the first scenario we assume planting seedlings at a price of $5 per tree (McPherson 1984, p. 173) which take 10 years to reach full height at maturity (McPherson 1984, p. 159). For the second scenario, we assume planting 5-ft (1.5m) trees at a price of $60 per tree including labor costs (Heisler 1984, page 173) which take 7 years to grow to full size. We add these costs to that for water in order to obtain the total cost of each tree.

The water consumption of a tree is estimated to be $\sim$ 1 kg/h (Bernatzky 1982), which translates to an annual consumption of $\sim$ 2000 gal/year. Current prices of water varies between 7-10 cent per hundred gallons*. Therefore, total water consumption of a tree is about $2/yr. The additional water needed by a tree to maintain high summertime evapotranspiration rates is generally made up from available ground water. In addition to the above, we have made the following assumptions:

- The energy and power conservation potential of trees during the initial growing period is neglected.
- As trees mature, their roots grow deep in the ground and for most parts of the country they will become self-sufficient in absorbing water from ground; they do not need further watering.
- Even though the average life span of a tree is high (100 years) we have assumed here a time horizon of 20 years, same as an average power plant.
- Interest rate is assumed to be 7% real.

The results from Tables 3 and 4 are encouraging. The cost of conserved energy (CCE) and avoided peak power (CAPP) is between 0.3 to 4.3 ¢/kWh and 19 to 217 $/kW for all four locations studied. The present value of conserved energy is much higher in Phoenix and Sacramento than Los Angeles. The high but indeterminate values of conserved cooling energy in Los Angeles are due to the small base case air conditioning energy use calculated assuming night ventilation whenever possible. It is interesting to note that the average price of electricity is about 8 ¢/kWh, and major utilities in California offer a rebate of $100-$300 for each kW of peak power avoided. Therefore, even with the upper limit cost of trees the CCE and CAPP seem extremely appealing.

DISCUSSION

Because of the exploratory nature of this study, many technical issues have been raised which we hope can be addressed in the future. Some of these require measured data to validate or improve theoretical models, others need better understanding of physical processes and more detailed modeling of those processes. The most critical issues are :

1. Evapotranspiration rates

   The Jensen-Haise model had been developed for daily periods in arid and semi-arid climates. There is a need to gather hourly evapotranspiration data for verifying the accuracy of the model on an hourly basis. If such an investigation yields negative results, we would then have to look for a more suitable model, or to find a procedure for distributing the calculated evapotranspiration rate by the hour of day. We also need to compare the calculated evapotranspiration rates to measured data for different climate conditions, notably the hot-humid locations. Lastly, we need to

* The current price of water from the San Francisco East Bay Municipal Utility District is 63.5 cents per one hundred cubic feet.

investigate whether this model is appropriate to use in estimating evapotranspiration in trees rather than crops.

The Jensen-Haise model calculates *potential* rather than *actual* evapotranspiration. Therefore, the simulated savings in cooling energies represent maximum theoretical limits. Although we realize that it would be more realistic to investigate *actual* evapotranspiration rates, such an effort requires much more data on soil and plant conditions.

2. Mixing heights

We need to investigate the appropriateness of using the Leahey-Friend model for different cities in different climates. The model has also proven to be highly sensitive to certain input parameters such as the magnitude of the urban heat island and the amount of artificial heat flux. Therefore, we also need more data for characterizing the urban climate.

3. Adiabatic mixing

There are two basic assumptions in the existing microclimate model that need to be studied and refined. These are that (1) the increased urban canopy does not change the basic heat balance of the urban climate, and (2) that the cooling effect of the plant evapotranspiration is well-mixed into the entire urban air volume. Both of these assumptions need further study and refinement.

4. Localized effects

In the present microclimate model, we have overlooked the fact that the cooling effects of trees may be concentrated in the vicinity of the vegetation rather than uniformly distributed throughout an urban area. This localization is suggested by measurements showing variations in daytime temperatures within a city, with noticeably cooler values near large urban parks (Duckworth 1954, Oke 1978). This uneven temperature distribution implies that our simple model may be underpredicting cooling effects in the immediate vicinity of trees, and overpredicting them for more distant areas.

Two possible methods to estimate localized microclimate effects due to trees include use of a three-dimensional urban climate model (Bornstein 1984), or an atmospheric dispersion model such as the SHORTZ program developed by the Environmental Protection Agency (Bjorklund 1982).

In this paper, we also have not covered in detail shading and wind reduction effects due to specific types, geometries, and location of trees relative to the house. These, however, can be handled in a straightforward manner with the existing model if the tree transmissivity, geometry and location are known (Thayer 1983).

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Table 1.

Savings in annual cooling energy use and peak cooling power for 1-story prototype house with increased urban tree canopy with generalized shading.

(All entries except Column 1 are savings compared to the base case in that column)

	Increased urban canopy density with generalized shading								
	None	10% increase				25% increase			
		Δ = savings				Δ = savings			
Location	Base case (not savings)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)
Sacramento									
Annual kWh	**1420**	34	26	**261**	**18.4**	101	90	**603**	**42.5**
Peak kW	**7.10**	0.09	0.14	**0.66**	**9.3**	0.26	0.31	**1.62**	**22.8**
Cooling hrs	**904**	14	9	**144**	**15.9**	46	40	**395**	**43.7**
Phoenix									
Annual kWh	**6911**	63	60	**725**	**10.5**	187	185	**1766**	**25.6**
Peak kW	**8.87**	0.06	0.13	**0.66**	**7.4**	0.19	0.22	**1.03**	**11.6**
Cooling hrs	**3647**	10	4	**151**	**4.1**	41	35	**438**	**12.0**
Lake Charles									
Annual kWh	**3908**	28	26	**412**	**10.5**	84	78	**1071**	**27.4**
Peak kW	**7.17**	0.07	0.12	**0.57**	**7.9**	0.20	0.23	**1.18**	**15.3**
Cooling hrs	**2489**	7	0	**156**	**6.3**	18	10	**449**	**18.0**
Los Angeles									
Annual kWh	**359**	~ 0	~ 0	**~ 0**	**~ 0**	~ 0	~ 0	**~ 0**	**~ 0**
Peak kW	**4.46**	~ 0	~ 0	**0.50**	**11.3**	0.25	0.25	**1.34**	**30.0**
Cooling hrs	**65**	8	5	**41**	**63.0**	13	10	**55**	**84.6**

Table 1A.

Savings in annual cooling energy use and peak cooling power for an uninsulated 1-story prototype house with increased urban tree canopy with generalized shading.

(All entries except Column 1 are savings compared to the base case in that column)

	Increased urban canopy density with generalized shading								
	None	10% increase				25% increase			
		Δ = savings				Δ = savings			
Location	Base case (not savings)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)
Sacramento									
Annual kWh	**3386**	217	294	**777**	**23.0**	661	701	**1987**	**58.7**
Peak kW	**9.56**	0.29	0.28	**0.41**	**4.3**	0.45	0.47	**1.03**	**10.8**
Cooling hrs	**1333**	26	40	**193**	**14.5**	125	126	**625**	**46.8**
Phoenix									
Annual kWh	**9619**	217	191	**926**	**9.6**	806	773	**2998**	**31.1**
Peak kW	**10.10**	0.10	0.12	**0.21**	**2.1**	0.10	0.12	**0.45**	**4.4**
Cooling hrs	**3766**	18	15	**160**	**4.2**	140	132	**626**	**16.6**
Lake Charles									
Annual kWh	**5502**	95	55	**569**	**10.3**	303	260	**1808**	**32.8**
Peak kW	**10.60**	0.01	0.08	**0.52**	**5.0**	0.15	0.22	**1.98**	**18.8**
Cooling hrs	**2531**	13	2	**129**	**5.0**	62	52	**473**	**18.7**
Los Angeles									
Annual kWh	**696**	42	11	**222**	**31.9**	137	117	**318**	**45.7**
Peak kW	**8.49**	.15	.02	**0.46**	**5.5**	0.44	0.44	**2.84**	**33.5**
Cooling hrs	**281**	23	7	**165**	**58.7**	76	66	**269**	**95.7**

Table 2.

Savings in annual cooling energy use and peak cooling power for a 1-story prototype house with increased urban tree canopy located for summer shading.

(All entries except Column 1 are savings compared to the base case in that column)

	Increased urban canopy density located for summer shading								
	None	10% increase (=1 tree/house)				30% increase (=3 trees/house)			
		Δ = savings				Δ = savings			
Location	Base case (not savings)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)	shade only (Δ)	shade +wind (Δ)	shade+wind +evapotrans. (Δ)	(% Δ)
Sacramento									
Annual kWh	**1420**	122	114	**343**	**24.2**	225	218	**757**	**53.3**
Peak kW	**7.10**	0.66	0.72	**1.24**	**17.5**	0.76	0.81	**2.44**	**34.4**
Cooling hrs	**904**	36	29	**165**	**18.3**	64	95	**514**	**56.9**
Phoenix									
Annual kWh	**6911**	208	208	**873**	**12.6**	417	418	**2289**	**33.1**
Peak kW	**8.87**	0.47	0.53	**0.80**	**9.0**	0.53	0.57	**1.57**	**17.7**
Cooling hrs	**3647**	18	16	**157**	**4.3**	86	79	**619**	**17.0**
Lake Charles									
Annual kWh	**3908**	81	80	**466**	**11.9**	145	144	**1354**	**34.7**
Peak kW	**7.17**	0.36	0.44	**0.89**	**12.4**	0.41	0.46	**1.55**	**21.7**
Cooling hrs	**2489**	17	13	**170**	**6.8**	44	40	**584**	**23.5**
Los Angeles									
Annual kWh	**359**	~ 0	~ 0	**~ 0**	**~ 0**	~ 0	~ 0	**~ 0**	**~ 0**
Peak kW	**4.46**	0.43	0.45	**0.90**	**20.2**	0.53	0.55	**1.96**	**43.9**
Cooling hrs	**65**	12	8	**43**	**66.2**	18	17	**55**	**84.6**

Table 3.

Present value of saved cooling energy kWh and peak cooling energy in 1986 dollars for a 1-story prototype house with increased urban tree canopy with generalized shading. *

	Increased urban tree canopy density with generalized shading						
	None	10% increase(= 1 tree/house)			25% increase(= 2 ½ trees/house)		
		Present Value			Present Value		
Location	Base case power use (kW)	shade only	shade +wind	shade+wind +evapotrans	shade only	shade +wind	shade+wind +evapotrans
Sacramento	**7.10**						
CCE‡ (¢/kWh)		6.8-31.6	8.8-33.7	**0.9-4.0**	5.7-26.5	6.5-29.9	**0.9-4.5**
CAPP† ($/kW)		264-1261	170-812	**22-105**	226-1094	192-917	**31-152**
Phoenix	**8.87**						
CCE (¢/kWh)		3.6-17.2	3.8-18.0	**0.4-1.4**	3.2-14.3	3.2-14.5	**0.3-1.5**
CAPP ($/kW)		333-1896	183-872	**36-172**	311-1495	268-1291	**57-276**
Lake Charles	**7.17**						
CCE (¢/kWh)		8.1-38.8	8.9-41.5	**0.6-2.6**	7.0-31.8	7.5-34.5	**0.5-2.5**
CAPP ($/kW)		339-1620	198-950	**41-198**	296-1420	257-1235	**50-241**
Los Angeles	**4.46**						
CCE (¢/kWh)		n.a.	n.a.	**n.a.**	n.a.	n.a.	**n.a.**
CAPP ($/kW)		n.a.	n.a.	**47-227**	237-1136	236-1137	**44-212**

* The two values for each entry correspond to planting seedlings or 5-ft trees at $5 and $60, respectively. Water consumption for a growing tree is estimated to average ~ $2/yr for 10 years for the seedling and 7 years for the 5-ft tree. A time horizon (n) of 20 years for trees and a discount rate (d) of 7% real is assumed.)

†Cost of Avoided Peak Power (CAPP) = $\frac{\textit{Total Investment } (\$)}{\textit{Saved Power } (kW)}$ normalized for life of a nominal power plant (normally 20 years).

‡Cost of Conserved Energy (CCE) = $\frac{\textit{Annualized Investment } (\$/yr)}{\textit{Saved Annual Energy } (\textit{Annual } kWh)}$.

Annualized Investment = $\textit{Total Investment} \times \frac{d}{1-(1+d)^{-n}}$.

Table 4.

Present value of saved cooling energy kWh and peak cooling energy in 1986 dollars for a 1-story prototype house with increased urban tree canopy located for summer shading. *

	Increased urban tree canopy density located for summer shading						
	None	10% increase(= 1 tree/house)			30% increase(= 3 trees/house)		
		Present Value			Present Value		
Location	Base case power use (kW)	shade only	shade +wind	shade+wind +evapotrans	shade only	shade +wind	shade+wind +evapotrans
Sacramento	**7.10**						
CCE‡ (¢/kWh)		1.9-8.8	2.0-9.4	**0.7-3.1**	3.1-14.3	3.2-14.8	**0.9-4.3**
CAPP† ($/kW)		36-172	33-158	**19-92**	93-449	88-421	**29-140**
Phoenix	**8.87**						
CCE (¢/kWh)		1.1-5.2	1.1-5.2	**0.3-1.2**	1.7-7.7	1.7-7.7	**0.3-1.4**
CAPP ($/kW)		50-242	45-214	**30-142**	134-643	124-598	**45-217**
Lake Charles	**7.17**						
CCE (¢/kWh)		2.8-13.4	2.9-13.5	**0.5-2.3**	4.9-22.1	4.9-22.4	**0.5-2.4**
CAPP ($/kW)		66-315	54-259	**26-127**	173-831	154-741	**46-220**
Los Angeles	**4.46**						
CCE (¢/kWh)		n.a.	n.a.	**n.a.**	n.a.	n.a.	**n.a.**
CAPP ($/kW)		55-264	53-253	**26-126**	134-643	129-620	**36-174**

* The two values for each entry correspond to planting seedlings or 5-ft trees at $5 and $60, respectively. Water consumption for a growing tree is estimated to average ~ $2/yr for 10 years for the seedling and 7 years for the 5-ft tree. A time horizon (n) of 20 years for trees and a discount rate (d) of 7% real is assumed.

†Cost of Avoided Peak Power (CAPP) = $\frac{\textit{Total Investment } (\$)}{\textit{Saved Power } (kW)}$ normalized for life of a nominal power plant (normally 20 years).

‡Cost of Conserved Energy (CCE) = $\frac{\textit{Annualized Investment } (\$/yr)}{\textit{Saved Annual Energy } (\textit{Annual } kWh)}$.

Annualized Investment = $\textit{Total Investment} \times \frac{d}{1-(1+d)^{-n}}$.

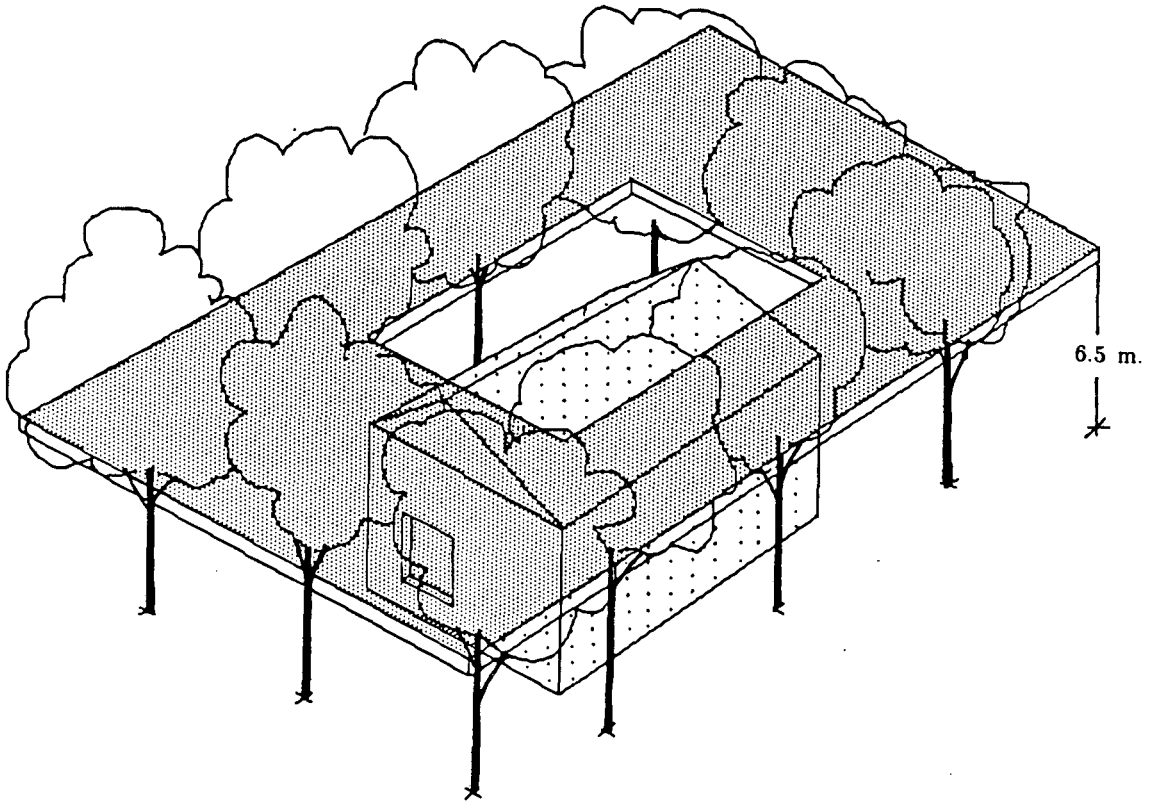
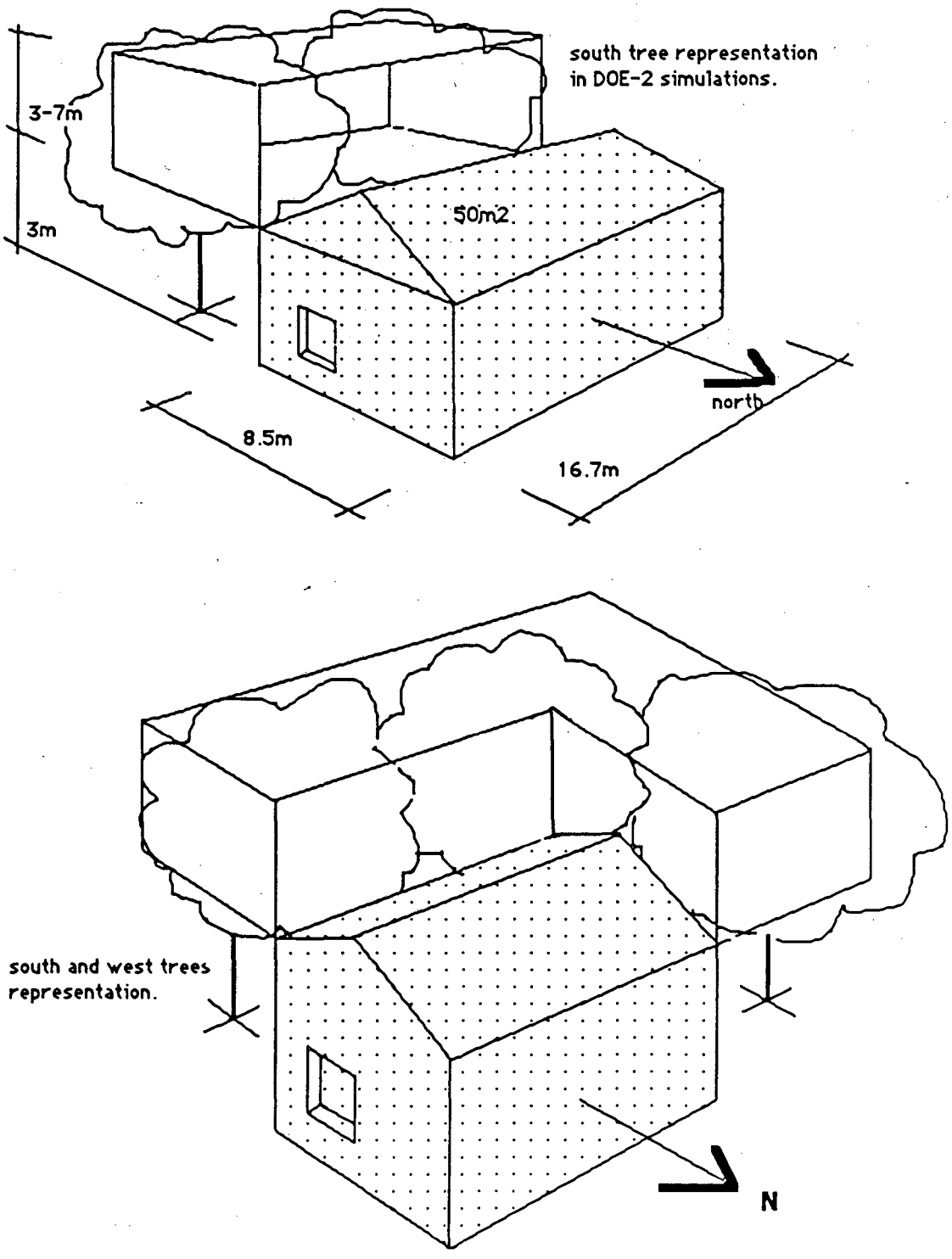


Figure 1. Generalized tree canopy shading as modeled in DOE-2.1C simulation



XBL 8612-4958

Figure 2. Tree canopy planted for shading as modeled in DOE-2.1C simulation

(a) is the model for one tree on the south side of the house,
(b) is the model for three trees on the south and west side of the house.

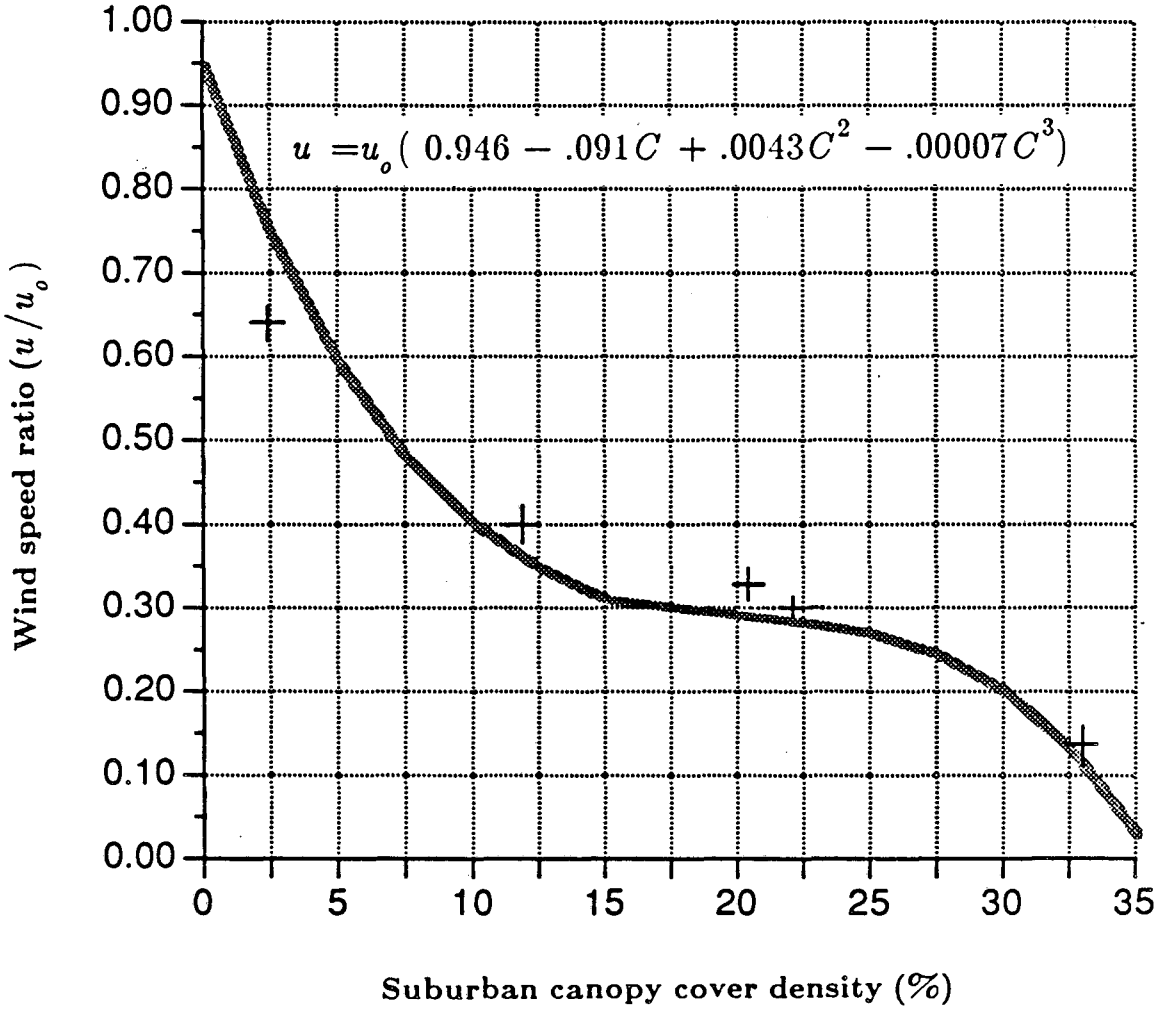


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Figure 3. Wind speed reductions for different tree canopy densities as a ratio of wind speed at control site with no trees.

(source: McGinn 1982, p. 65)

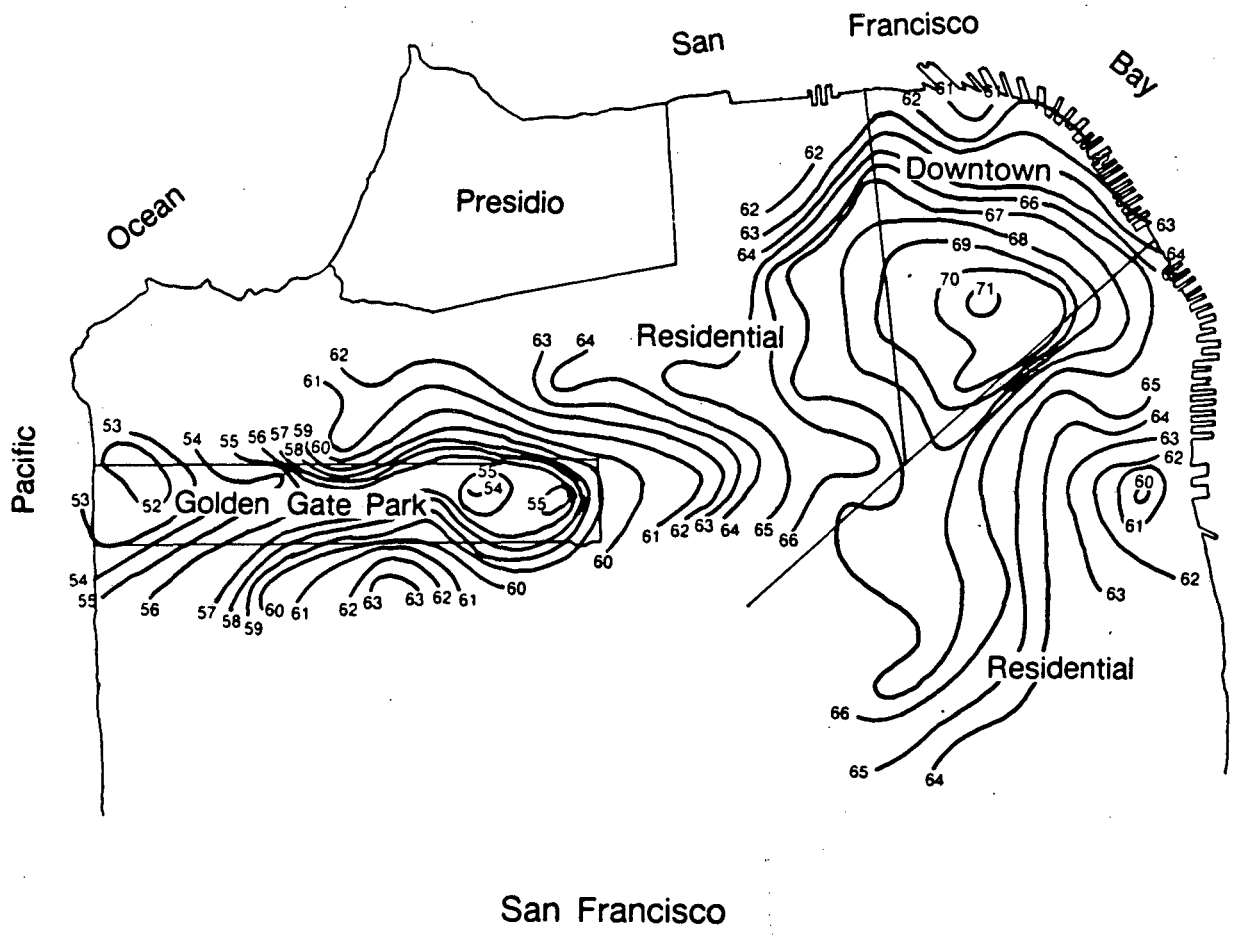


Figure 4. City temperatures (F) in San Francisco at 11 p.m. on 2 March 1952.

The rectangle at left-center represents Golden Gate Park with a temperature of 54 F, while the surrounding neighborhood is at 62 F, a difference of 8 F or 4 C.

(reproduced with permission from the *Bulletin of the American Meteorological Society*, **35**, No. 5, p. 202, F. S. Duckworth and J. S. Sandberg, "The effect of cities upon horizontal and vertical temperature gradients", copyright 1954.)

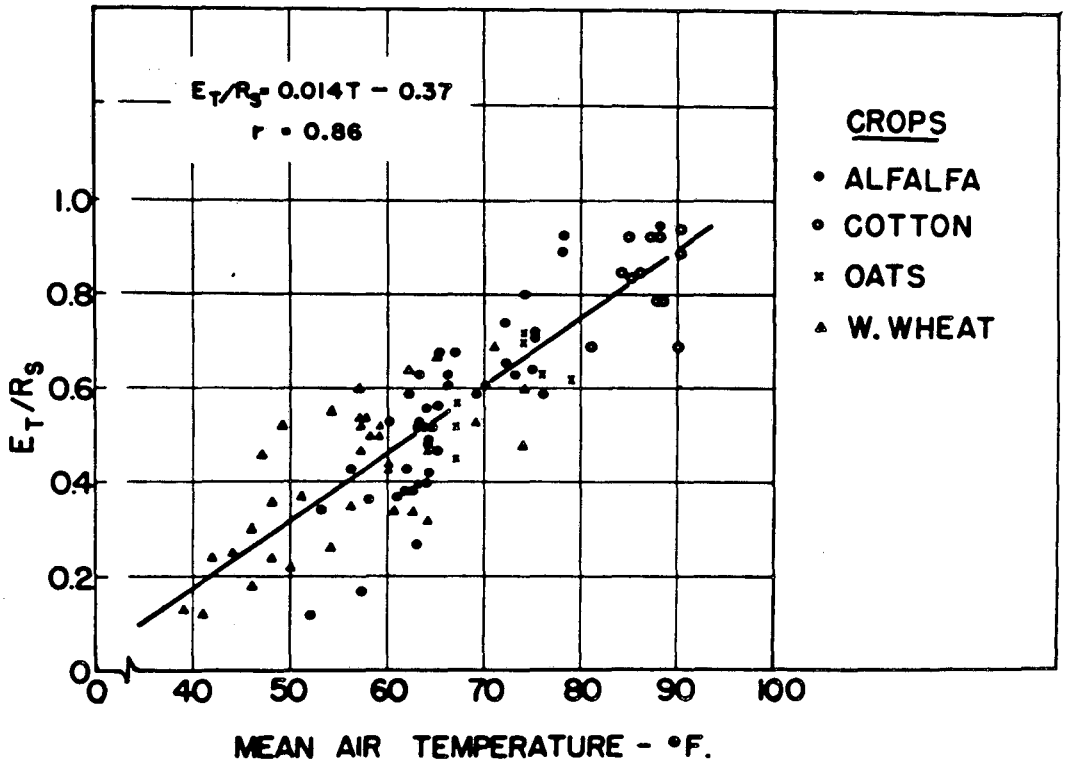


Figure 5. Variations in the E_T/R_s ratio for selected field crops in relationship to mean air temperature.

(reprinted with permission from *Proceedings of the American Society of Civil Engineers*, **89**: IR4, p. 33, M E.Jensen and H. R. Haise, "Estimating evapotranspiration from solar radiation", copyright 1963.)

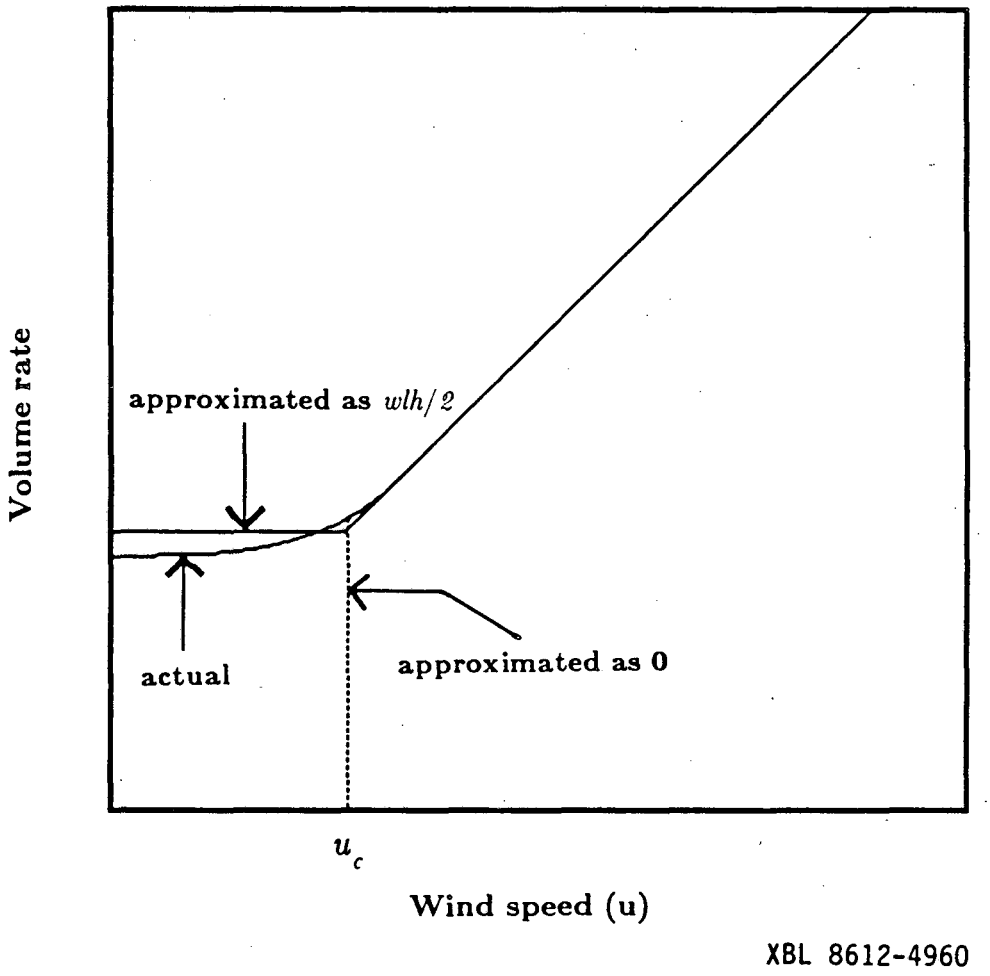


Figure 6. Approximation of air volume rate at low wind speeds used in microclimate vegetation model.

u_o = characteristic wind speed defined as $l/2\Delta t$, where l is the characteristic length and Δt is the time step.

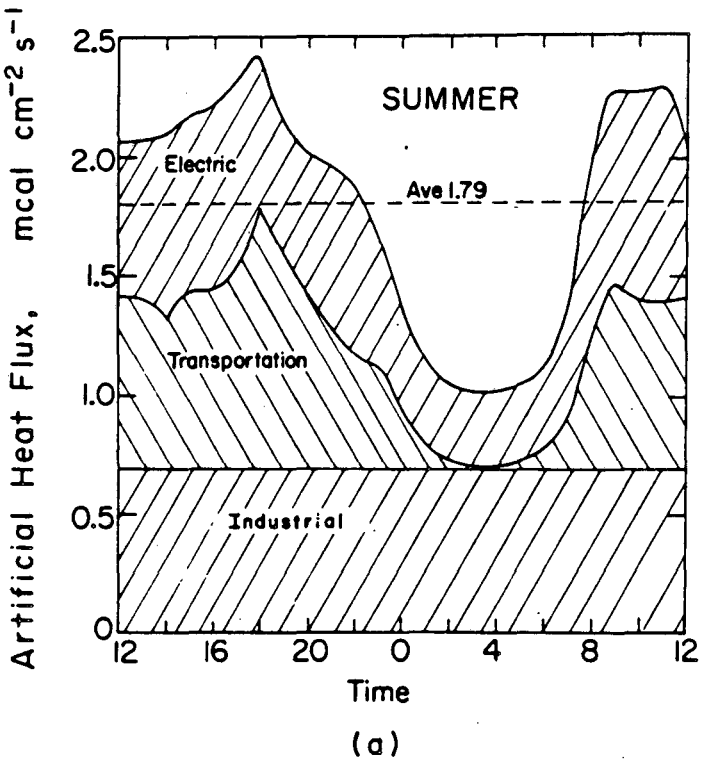


Figure 7. Artificial urban heat gain intensity during the summer due to human activity.

Conversion: 1 mcal $cm^{-2}s^{-1}$=48 W/m^2

(reprinted with permission from *Atmospheric Environment*, **10**, p. 332, K.E. Torrance and J.S. Shum 1975, "Time-varying energy consumption as a factor in urban climate", copyright 1975, Pergamon Press, Ltd.)

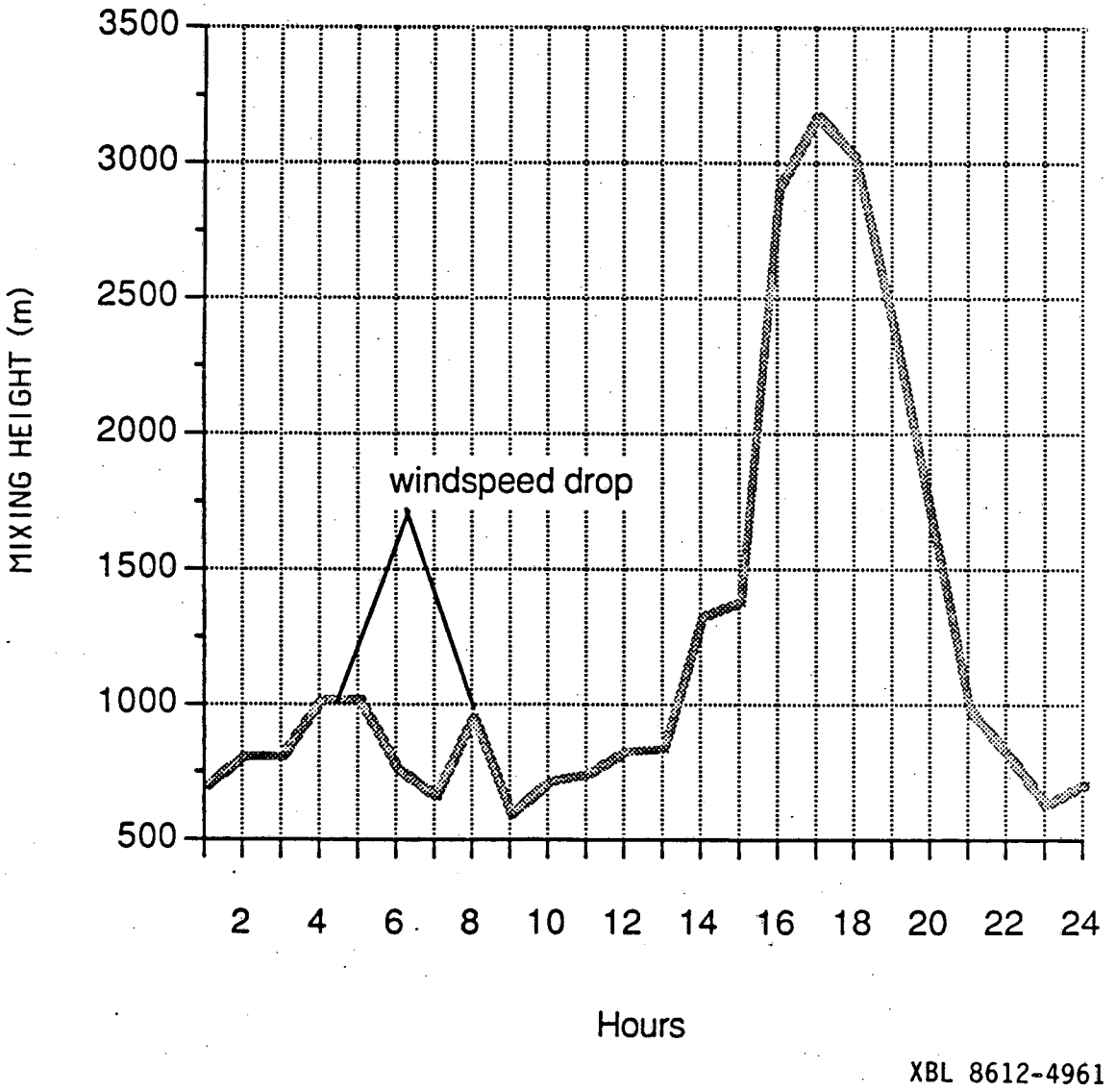


Figure 8. Mixing heights calculated for a typical summer day (July 10) in Sacramento CA using the Leahey-Friend model.

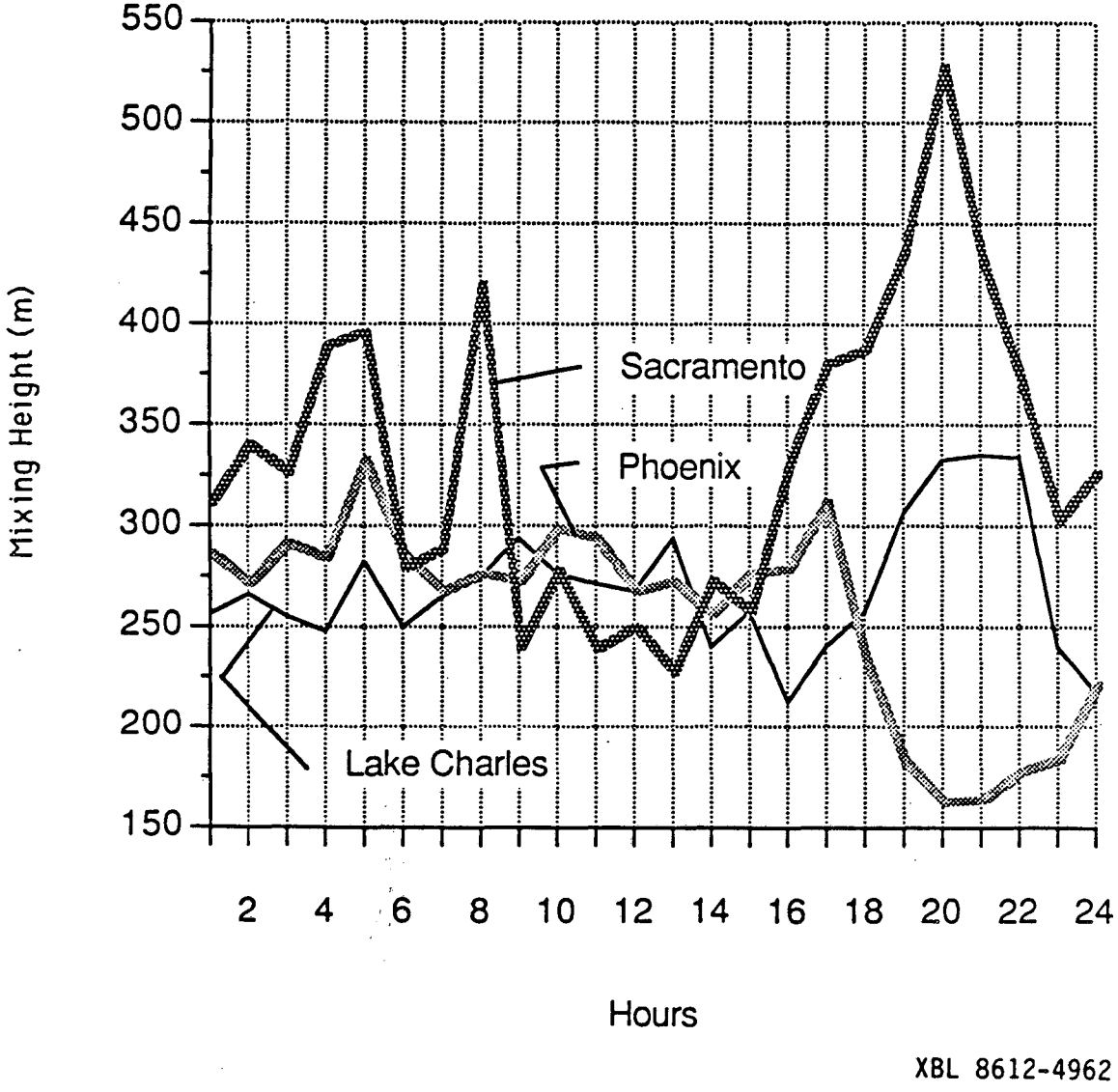


Figure 9. Average summer mixing heights calculated for Sacramento, Phoenix, and Lake Charles using the Leahey-Friend model.

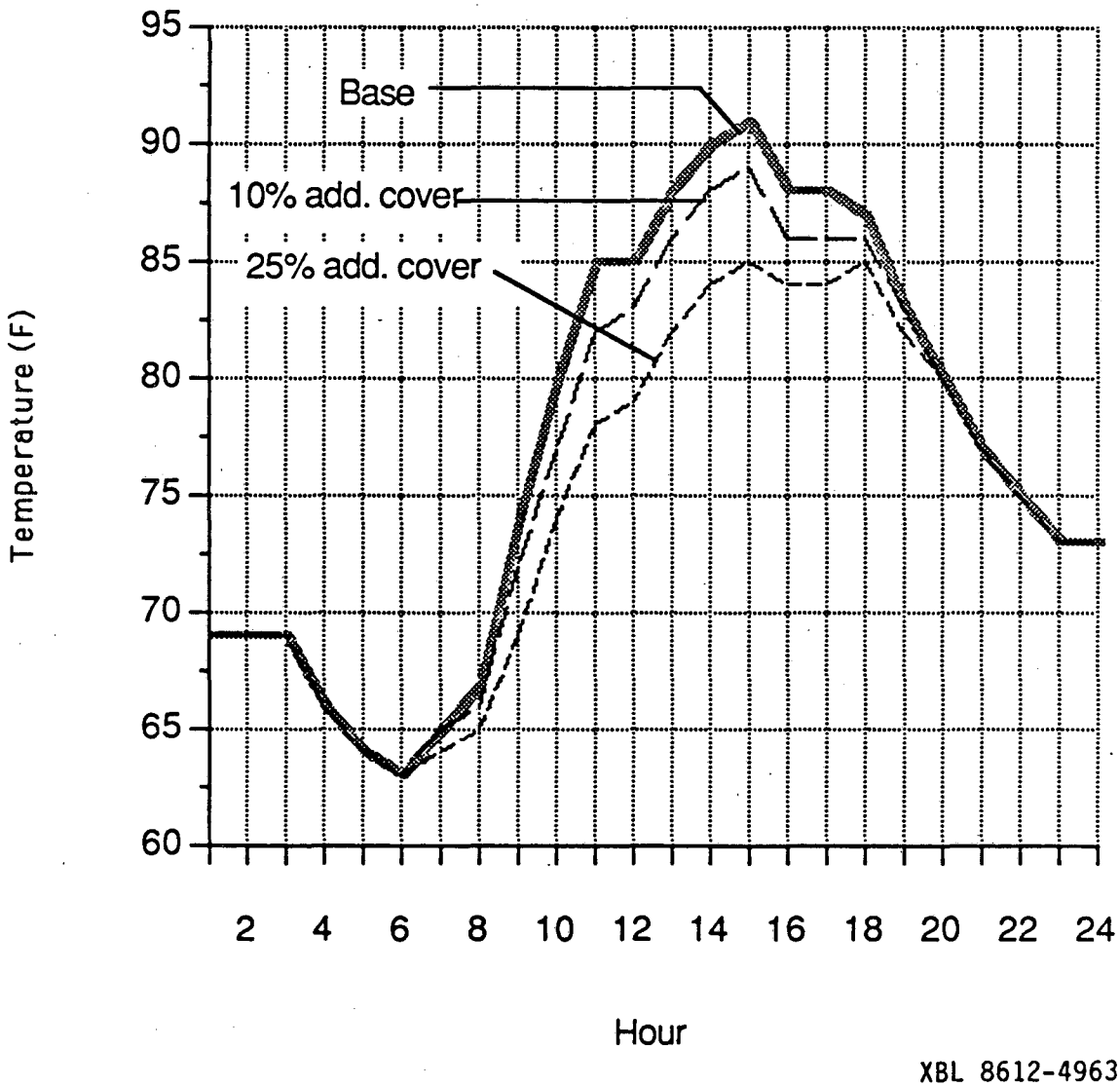


Figure 10. Drybulb temperature modifications calculated by microclimate vegetation model for a typical summer day (July 27) in Sacramento CA with increases of 10% and 25% in the urban tree canopy density.

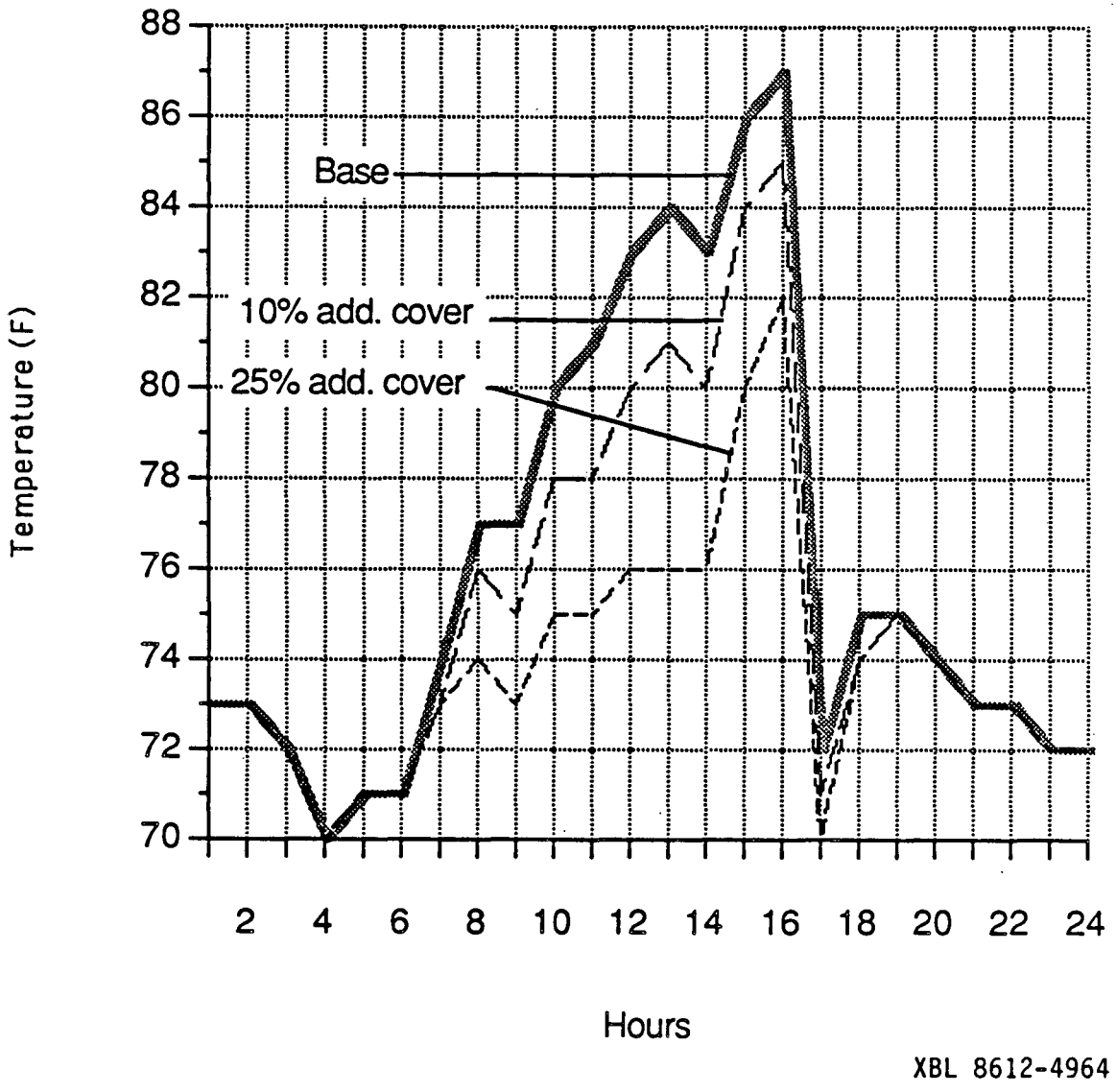


Figure 11. Drybulb temperature modifications calculated by microclimate vegetation model for a typical summer day (June 2) in Lake Charles LA with increases of 10% and 25% in the urban tree canopy density.

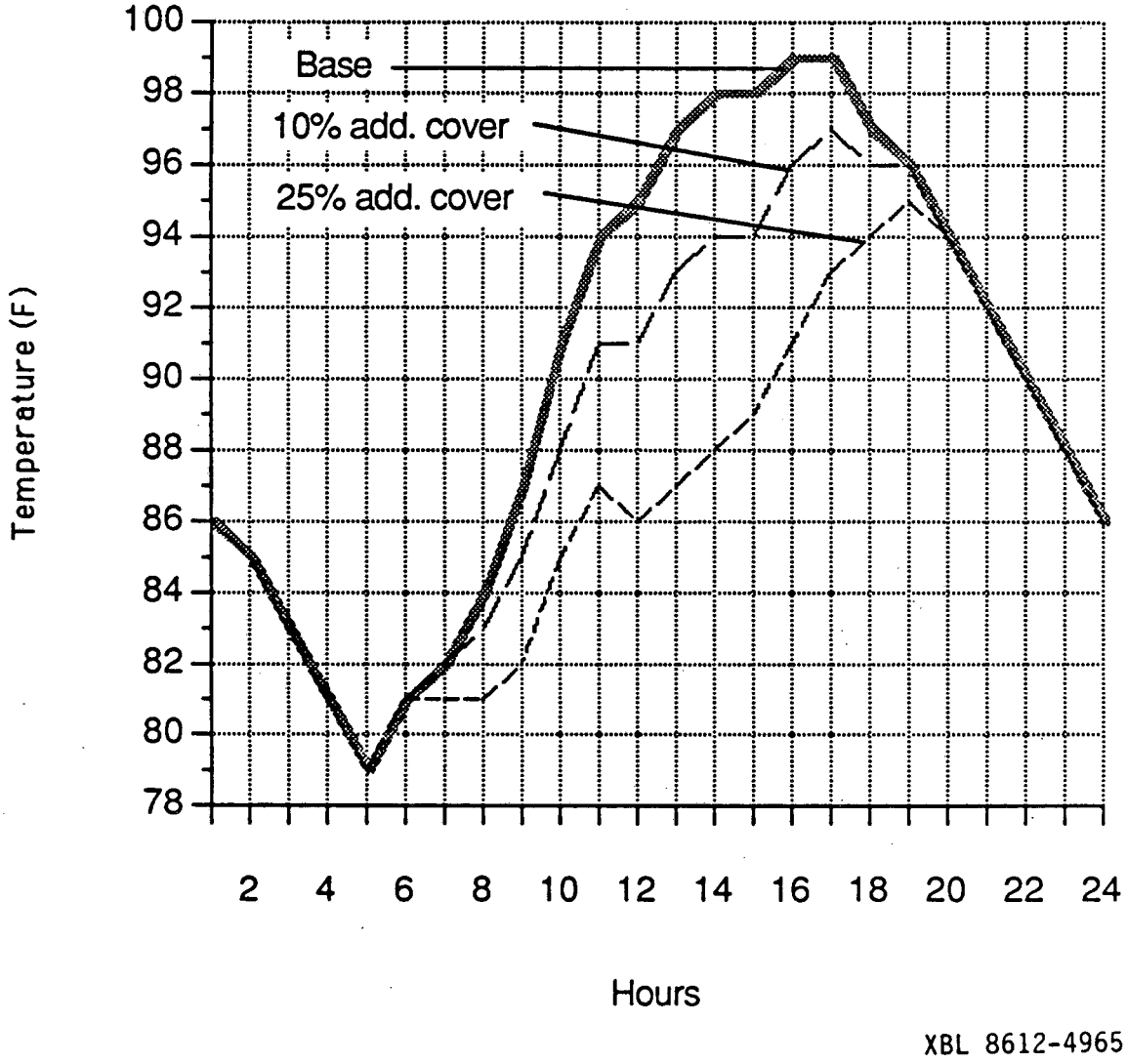
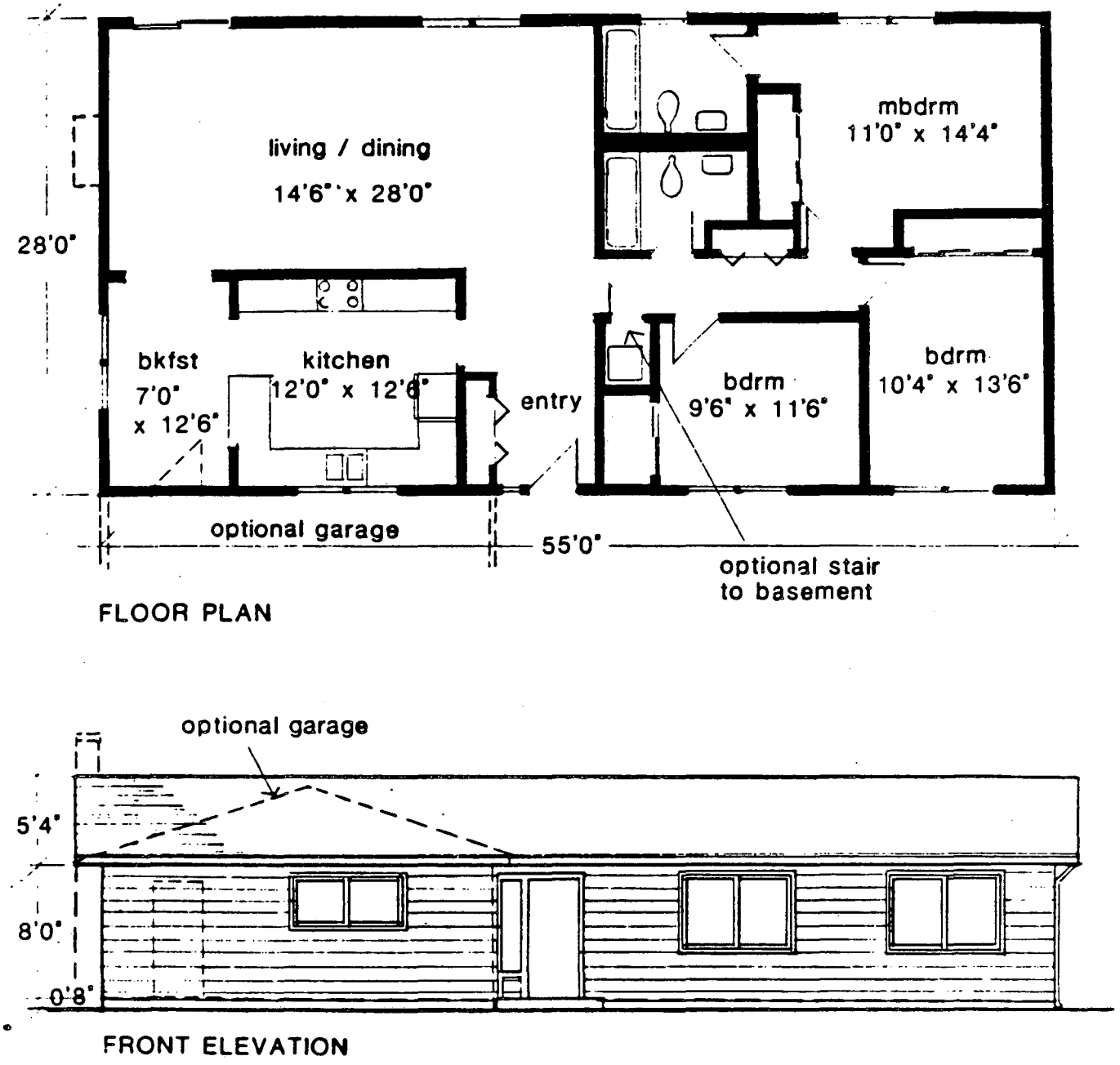


Figure 12. Drybulb temperature modifications calculated by microclimate vegetation model for a typical summer day (August 15) in Phoenix AZ with increases of 10% and 25% in the urban tree canopy density.



Scale 1/8"= 1'0"
JH 14 8 81

Total floor area 1540 sq ft
Total glazing 154 sq ft

XBL 8110-11932

Figure 13. Floor plan and elevation of prototype one-story ranch house

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