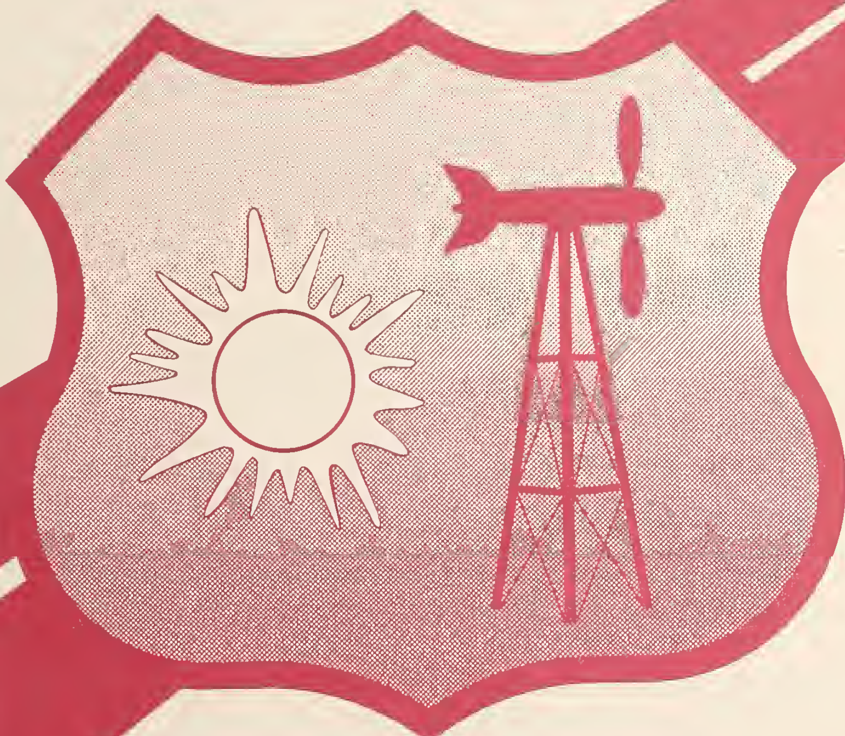
lo. FHWA-RD-79-81

# MENTATION OF EARTH HEATING FOR PURPOSES OADWAY DEICING

December 1978
Final Report



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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
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Washington, D.C. 20590

## FOREWORD

This report describes a study which examined methods for thermally augmenting earth heat so that pavement heating systems like the one in successful operation in West Virginia can be used in more severe winter climates. Extensive discussions of the various methods considered and detailed information for designing a system are presented.

Research in pavement heating is included in the Federally Coordinated Program of Highway Research and Development as Task 7 of Project 1L, "Improving Traffic Operations During Adverse Environmental Conditions."

Mr. Richard N. Schwab is the Project Manager and Mr. Philip Brinkman is the Task Manager.

Copies of this report are being distributed to each FHWA regional office and individual researchers.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

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**16. Abstract** This report describes the results of a team effort to set forth the technology of thermal augmentation of earth heating systems and to identify the most cost effective renewable energy source to be used for this purpose. The unaugmented West Virginia earth heat pipe system, which has been in operation for 4 years, was selected as the reference design. A representative section of this design was analytically modeled. The exchange of thermal energy between the pavement surface and the enviornment was described by a series of experimentally verified expressions. The enviornment was characterized by actual hourly weather data for the average and most severe years in three climate zones. A computer was employed to follow the hour by hour performance of the West Virginia design with and without augmentation throughout the year. The results of this computer analysis permitted the formulation of an engineering approach to the design of augmented and unaugmented earth heating systems.

The study shows that, for purposes of augmenting earth heating systems, the most cost effective renewable source of energy is the heat content of summertime air. The recommended system collects ambient air energy during the summertime and stores it in the earth below the pavement from where it is passively extracted for use during the wintertime. Although this augmented system's performance is inadequate in severe wintertime climates, the additional demand energy to make it adequate is minimal. The system design is such that various demand energy sources may be incorporated at a minimum cost.

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## 1. DESIGN AND PERFORMANCE OF THE WEST VIRGINIA UNAUGMENTED EARTH HEAT PIPE INSTALLATION

Pavement heating systems are expensive and can only be justified in hazardous locations or locations where snow and ice cause unacceptable congestion. This study explores the use of the renewable energy sources of earth, air, wind, and sun to perform this function and, therefore, does not ask the public to make an energy tradeoff. In this respect, it meets one of the criteria of technology; the improvement of the quality of life. However, even this improvement can be at a cost unacceptable to the public.

For most of this decade, the Federal Highway Administration has had under investigation the use of the natural heat of the earth to thermally remove ice and snow from critical highway surfaces. The advent of the heat pipe and the development of its technology made it possible to design practical systems wherein large volumes of earth are thermally coupled to highway pavements. Initial research of the earth heating system was conducted at Fairbank Highway Research Station, McLean, Virginia (Reference 1). Subsequently, an earth-heated ramp was installed in the Oyler Avenue Interchange on the Oak Hill Express Highway, Oak Hill, West Virginia (Reference 5). The use of the heat pipe for snow and ice control on bridge and airport runway surfaces using alternate energy sources has also been recently investigated (References 2, 3, and 4).

In most locations of the United States, the temperature of the earth at depths below 7.6 metres (25 feet) remains fairly constant throughout the year and is approximately equal to the average annual air temperature. The earth temperature exceeds $10^{o}C$ ($50^{o}F$) in many locations which experience substantial winter snowfalls. On the average, each cubic metre of earth yields 0.652 Kw-hr of thermal energy for every $1^{o}C$ ($1.8^{o}F$) drop in its temperature. This thermal energy yield is sufficient, if dissipated at the proper temperature in one square metre of pavement surface, to melt about 7.0 cm (about 2.76 inches) of ordinary snow. The temperature of the earth cannot be permitted to drop too far; otherwise, the rate of snow melting will decrease until the performance of the system becomes unacceptable. The volume of earth that must be thermally coupled to each unit area of pavement surface is determined not only by the amount of snow that must be melted annually but by the desired rate of melting (cm/hr), the air temperature and wind velocity conditions under which melting must be accomplished, the energy lost from the pavement system during winter nonmelting periods, the equilibrium earth temperature in the region where the pavement heating system is located, and the degree of temperature recovery of the system during the summer months. There are locations in the United States where the climate is so severe and the average ground temperatures are too low to permit the design of unaugmented earth heating systems regardless of how much earth volume is coupled to the pavement surface. The need to augment the earth energy source in these locations is a technical necessity.

Obviously, the task of precisely characterizing a particular system is formidable. Not only is it necessary to obtain good weather data for the installation site, but the properties of the disturbed and undisturbed earth beneath and contiguous to the pavement must be determined. Furthermore, the nature of the hydraulic gradient in the water table (if any) penetrated by the heat pipe field should be known.

As presently constituted, the heat pipe system will withdraw heat from the earth whenever the pavement temperature falls below the temperature of the earth. In the process, it continuously maintains the pavement temperature throughout the winter above the temperature of an unheated pavement. Properly designed, the system is always thermally positioned to accommodate unpredictable snow and ice occurrences. This desirable feature obviates the need for controls; however, it imposes an energy drain on the system beyond that required for just snow and ice removal. In regions where the climate is severe and, consequently, where the average earth temperature is low, it may be economically impractical to couple sufficient earth volume to the pavement surface to achieve acceptable system performance.

The present study was directed at determining the pavement system energy (Kw-hr/$m^2$-year) and specific power (W/$m^2$) requirements for snow and ice removal in selected severe, moderate, and mild winter climate zones. Additionally, methods of thermally augmenting the basic earth heat pipe system were investigated for use in those regions where acceptable performance cannot otherwise be economically obtained without augmentation.

The basic unaugmented heat pipe pavement heating system is well exemplified by the Oak Hill, West Virginia, installation. The system was installed during the 1975-1976 winter season, and its performance continues to be monitored both photographically and thermally. A plan view of the interchange and the position of the heat pipe ramp is shown in Figure 1. The heat pipes (1213) are installed in the south facing down Ramp B. The total ramp pavement surface is 1502.97 $m^2$ (16,178 $ft^2$).

The disposition of the heat pipes in the pavement sections is shown in Figure 2. A typical pavement section is 18.59 m (61 feet) long and 4.88 m (16 feet) wide and contains 72 heat pipes. The linear length of heat pipes in a typical 90.67 $m^2$ (976 $ft^2$) section is 295.35 m (969 feet) or, on the average, one foot of length for each square foot of pavement area.

The heat pipes extend down into the earth below the pavement as illustrated in Figure 3. The majority of the heat pipes extend into the earth a distance of 18.29 m (60 feet) and are disposed in a fan-shaped arrangement so as to couple the maximum volume of earth. The angle with respect to the horizontal of the outermost pipe is 45 degrees. The heat pipes are installed in a staggered pattern in the pavement such that the center-to-center spacing in the pavement is 20.32 cm (8 inches), whereas the holes are drilled on 60.96 cm (2 feet) centers at each location (Figure 3). Except for the installation of the heat pipes, the pavement construction and materials conform to the Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-69.

The drilling of the holes for the placement of the heat pipes was done after laying of the concrete treated base. The drilling of the holes at the angles indicated in Figure 3 did not prove to be a problem even though rock and fractured rock was encountered at the site. After installation, a slurry of Aqua-Gel (bentonite) was poured into the annulus around each heat pipe so as to form a thermal bond between the heat pipe and the earth. Each heat pipe was grouted into place before pouring of the concrete pavement.

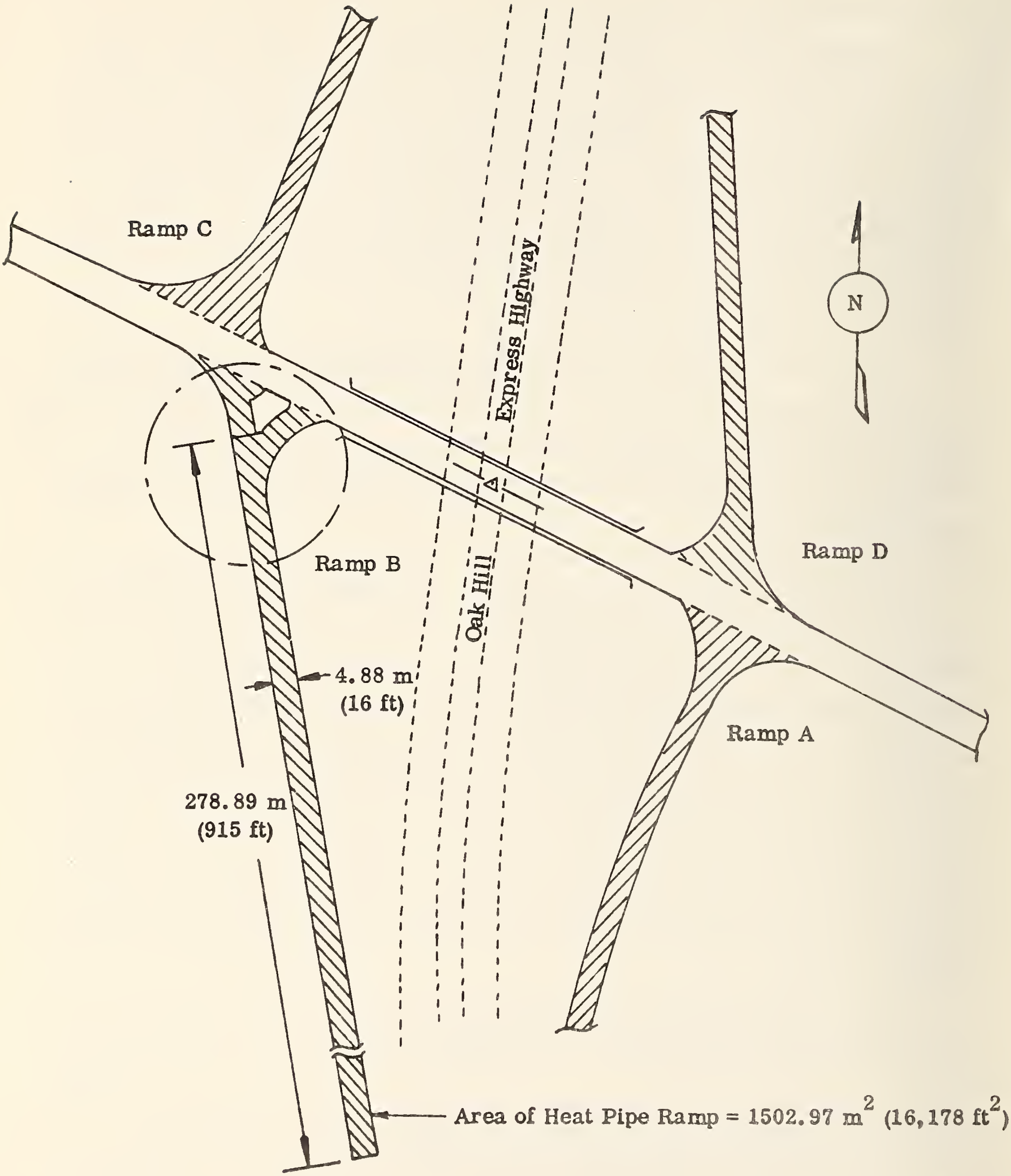



FIGURE 1

PLAN VIEW OF OYLER AVENUE INTERCHANGE
EARTH HEAT PIPE INSTALLATION

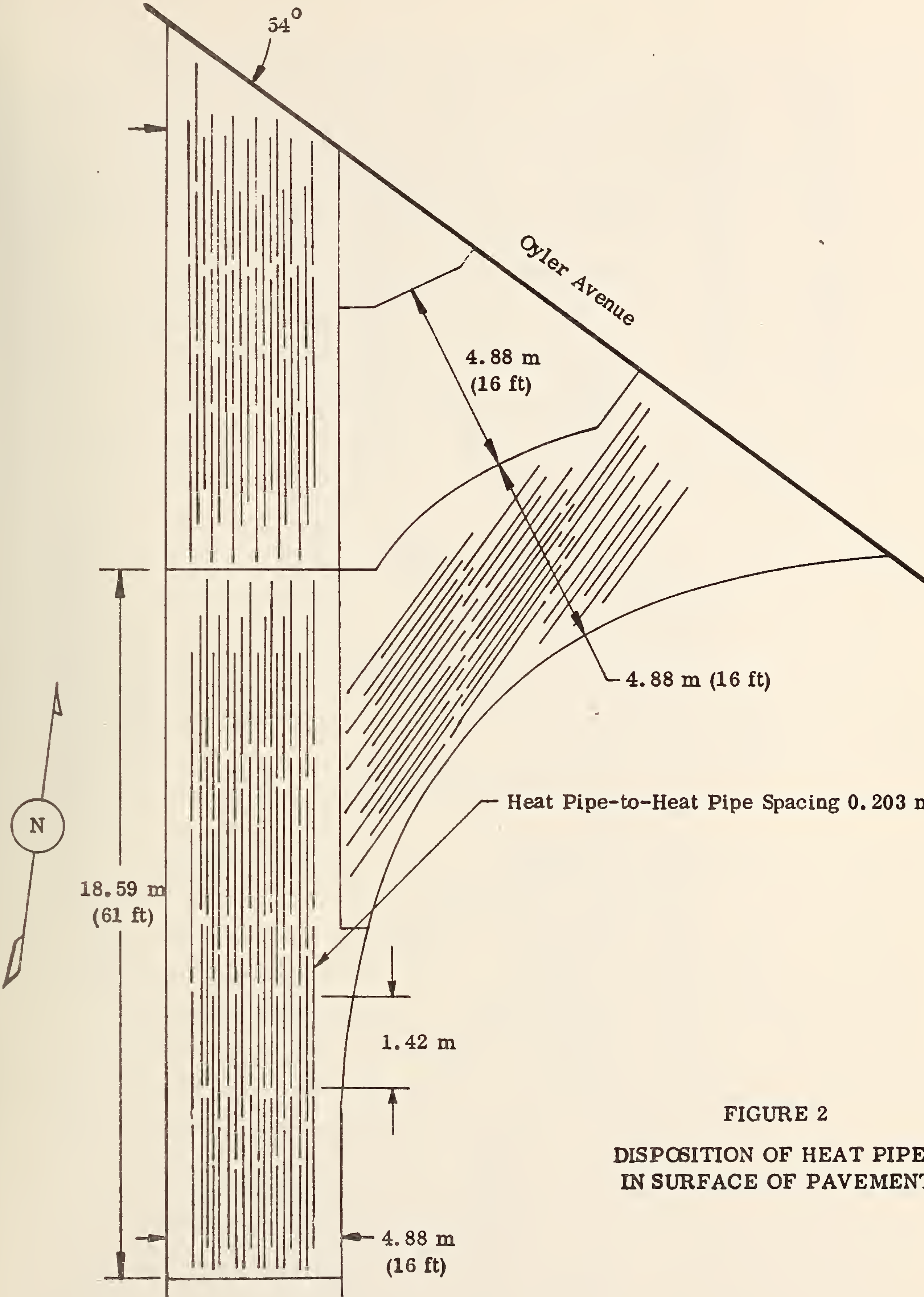



FIGURE 2

DISPOSITION OF HEAT PIPES IN SURFACE OF PAVEMENT

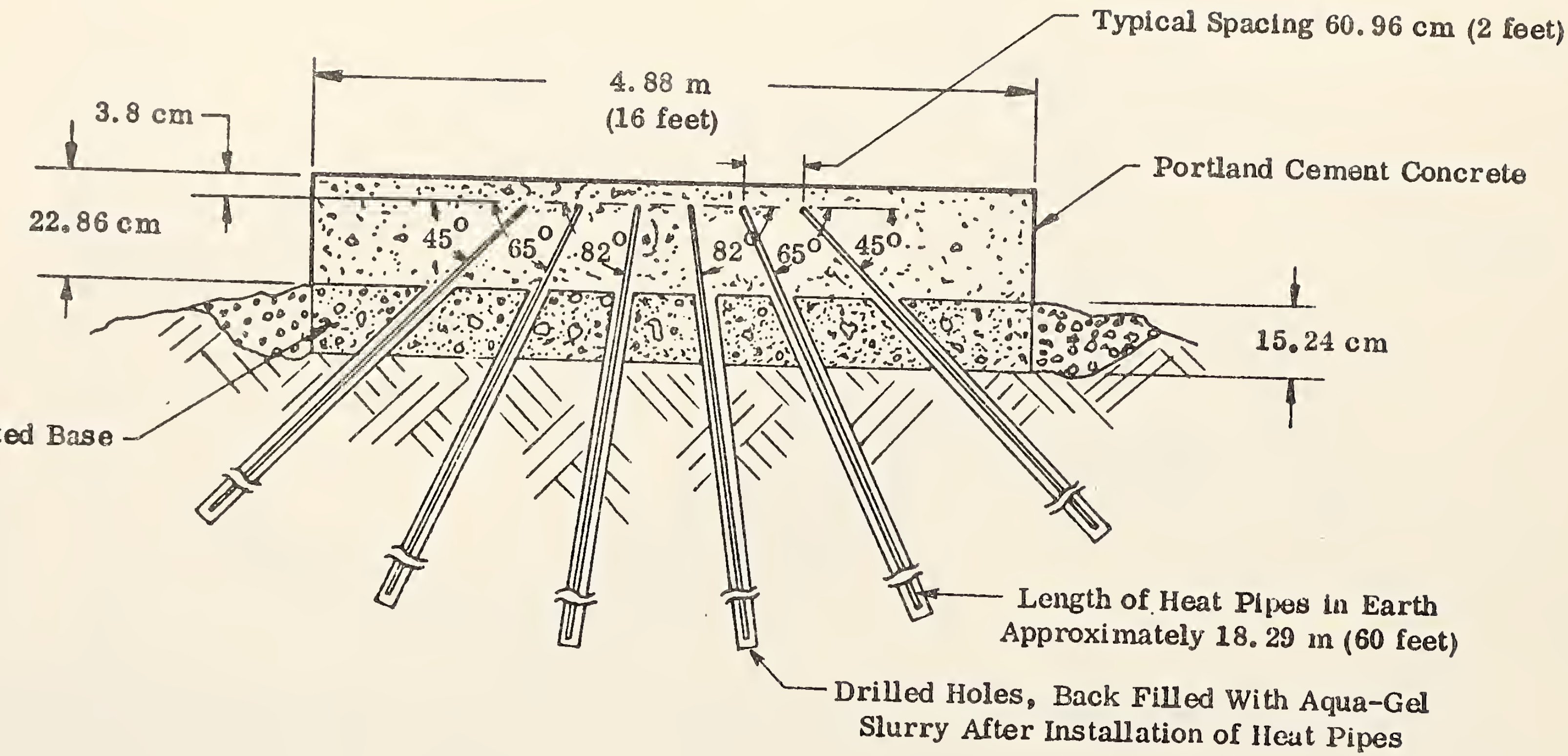



FIGURE 3

ELEVATION VIEW OF HEAT PIPE ARRANGEMENT
IN STANDARD PAVEMENT SECTION

The disposition of the heat pipe sections in the pavement was carefully controlled. The free end of each heat pipe was oriented toward Oyler Avenue so that, when the heat pipe was in place, the lowest elevation occurred at the location where the pipe was bent to penetrate into the earth. This permitted gravity flow of the condensed internal working fluid back down into the earth section of the heat pipe.

A heat pipe was specially designed and processed for this field installation. A sketch of the heat pipe is shown in Figure 4. It is constructed from a mill run of schedule 40 iron pipe. The pipe was procured without the normal mill corrosion protection coatings. It was cleaned internally both mechanically and with solvents. A carbon steel spring was inserted into the lower half of the heat pipe as shown in Figure 4. The helical pitch of the spring was such that the condensed liquid flowing down into the earth portion of the heat pipe was forced to come in contact with the entire internal circumference of the heat pipe. After welding on end caps, each pipe was heated to $200^{\circ}$F and outgassed using a high capacity vacuum pump. Following this, a measured amount of high purity anhydrous ammonia was metered into the pipe. The lower half of the heat pipe was then heated and a check for noncondensible gas was made. Residual gas was bled from the pipe and the fill tube was sealed by welding. A final leak check was made on the completed pipe. Epoxy coating was applied to exposed portions of the pipe to prevent corrosion.

The heat pipe pavement heating system as installed at Oak Hill represents the performance and cost baseline design used in this study. The performance of the system was monitored photographically during the severe winter of 1976-1977. The construction and first year wintertime performance is recorded in an excellent U. S. Department of Transportation documentary film. The cost of the system was reported as $\$236.8/m^2$ ($\$22/ft^2$) by Mr. P. Brinkman (Reference 5). This compares with a reported cost of $\$108/m^2$ ($\$10.2/ft^2$) for an electrically heated elevated ramp of about ten times the size located in Louisville, Kentucky (Reference 40).

In addition to photographic coverage, thermocouples were installed at a number of locations in the pavement and in the earth. A minimal amount of weather instrumentation was also installed at the site. In addition, weather information is available from the Beckley airport located 24 Km (15 miles) from the site. The site

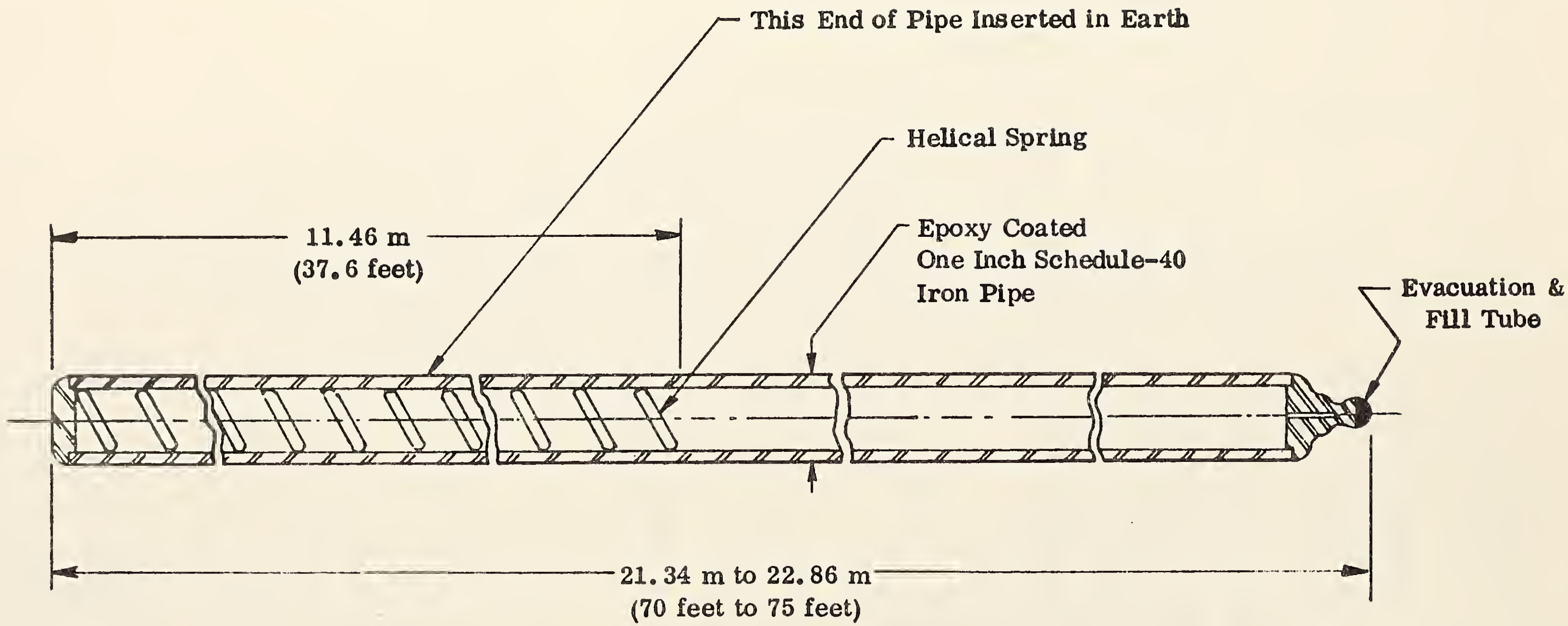



FIGURE 4

HEAT PIPE CROSS SECTION

is in a mountainous location but regionally it falls within the classification of a moderate climate zone.

The winter of 1976-1977 was the first full winter of operation. The average January air temperature was $-7.9^{O}C$ ($17.8^{O}F$) and the lowest January air temperature recorded was $-29^{O}C$ ($-20^{O}F$). At the start of winter, the average earth temperature at depths greater than 9 m (30 feet) was $13.1^{O}C$ ($55.5^{O}F$) which is what would be expected based on annual average air temperatures for this region. The lowest pavement temperature as measured by thermocouples embedded vertically in the pavement was $1^{O}C$ ($34^{O}F$) and this occurred when the air temperature was $-29^{O}C$. Pavement temperatures nearer the heat pipes were higher as would be expected.

The Oak Hill earth heat pipe heated ramp was kept substantially free of ice and snow throughout the severe winter of 1976-1977 with one exception. During the early part of January 1977, a storm sequence occurred which resulted in ice forming on the ramp. The storm began as a driving rain which lasted most of the day. The air temperature gradually declined until the rain changed to snow. The total snowfall was estimated to be approximately 15 cm (6 inches). Wind velocity gradually increased to estimated gusts of 48 Km/hr (30 mph) and its direction was approximately transverse to the ramp. The wind chill index after snowfall ceased was estimated at $-37^{O}C$ ($-35^{O}F$).

Ice thickness on parts of the ramp was estimated to be 2.5 cm (1 inch) by Mr. J. Baldwin of the West Virginia Department of Highways. This would indicate that drifting accumulated, at a minimum, 20 cm (7.8 inches) of normal density snow on the ramp. This drifting occurred during the period of high winds and very low temperature. Snow fences were not installed which accounted for the drifting.

This particular icing event may be atypical; however, it illustrates the behavior and performance limitations of unaugmented earth heat pipe systems. Neglecting power requirements for snow melting, the high winds and very low temperatures (Chill Index III, Reference 6) created an estimated system power demand of 380 $W/m^2$ (120 $Btu/hr\text{-}ft^2$). Based on experimental data (Reference 1), this system is normally capable of delivering 146 $W/m^2$ (46.3 $Btu/hr\text{-}ft^2$) assuming that the average field earth temperature in January is $10^{O}C$ ($50^{O}F$) and the pavement surface is $0^{\circ}C$ ($32^{\circ}F$).

For short periods and under certain conditions, the system can deliver power in excess of its normal capability. For this icing event, the average pavement temperature at the start of snowing was estimated from measurements to be $7.2^{\circ}C$ ($45^{\circ}F$). This represents a significant heat content with respect to the freezing temperature and, taken alone, it can generate, for a few hours, as much power for snow melting as the entire heat pipe system. This transient capability is illustrated in Figure 5 where, during the first hour, the integrated capability is calculated to be 250 $W/m^2$.

A method of combining the pavement heat content and the heat pipe field power capability is presented in Reference 1. Based on procedures outlined in this reference, the 6-hour capability of this system is 172 $W/m^2$ (54.6 $Btu/hr\text{-}ft^2$). The required power demand to thermally clear the ramp under the wind, temperature, and drifting conditions experienced is obviously in excess of the system capabilities. These conditions occasionally follow snow storms as weather fronts move across the country.

During the winter of 1977-1978, the lowest recorded temperature (2 occasions) was $-23.3^{\circ}C$ ($-10^{\circ}F$) and the average January temperature was $-5.9^{\circ}C$ ($21.4^{\circ}F$). At the start of winter, the average earth temperature in the middle of the heat pipe field was $12.6^{\circ}C$ ($54.7^{\circ}F$). The minimum pavement temperature occurred in early February 1978 when the air temperature again fell to $-23.3^{\circ}C$ and after a week during which the air temperature averaged $-9.6^{\circ}C$ ($14.7^{\circ}F$). The minimum pavement temperature was measured to be $-1^{\circ}C$ ($30^{\circ}F$). An icing event very similar to that previously described was also experienced during the winter of 1977-1978.

Photographic coverage and data accumulation continues at the West Virginia earth heat pipe test installation. At the beginning of the 1978-1979 winter, average earth temperature in the middle of the heat pipe field was $12^{\circ}C$ ($53.6^{\circ}F$). A major snowfall of 20.3 cm (8 inches) occurred during the latter part of January 1979. The pavement cleared this snowfall satisfactorily.

The current winter actually represents the fourth year of energy drain on the heat pipe system. During the 1975-1976 winter, much of the heat pipe field had been installed, although much of the concrete was poured during the latter part of the win-

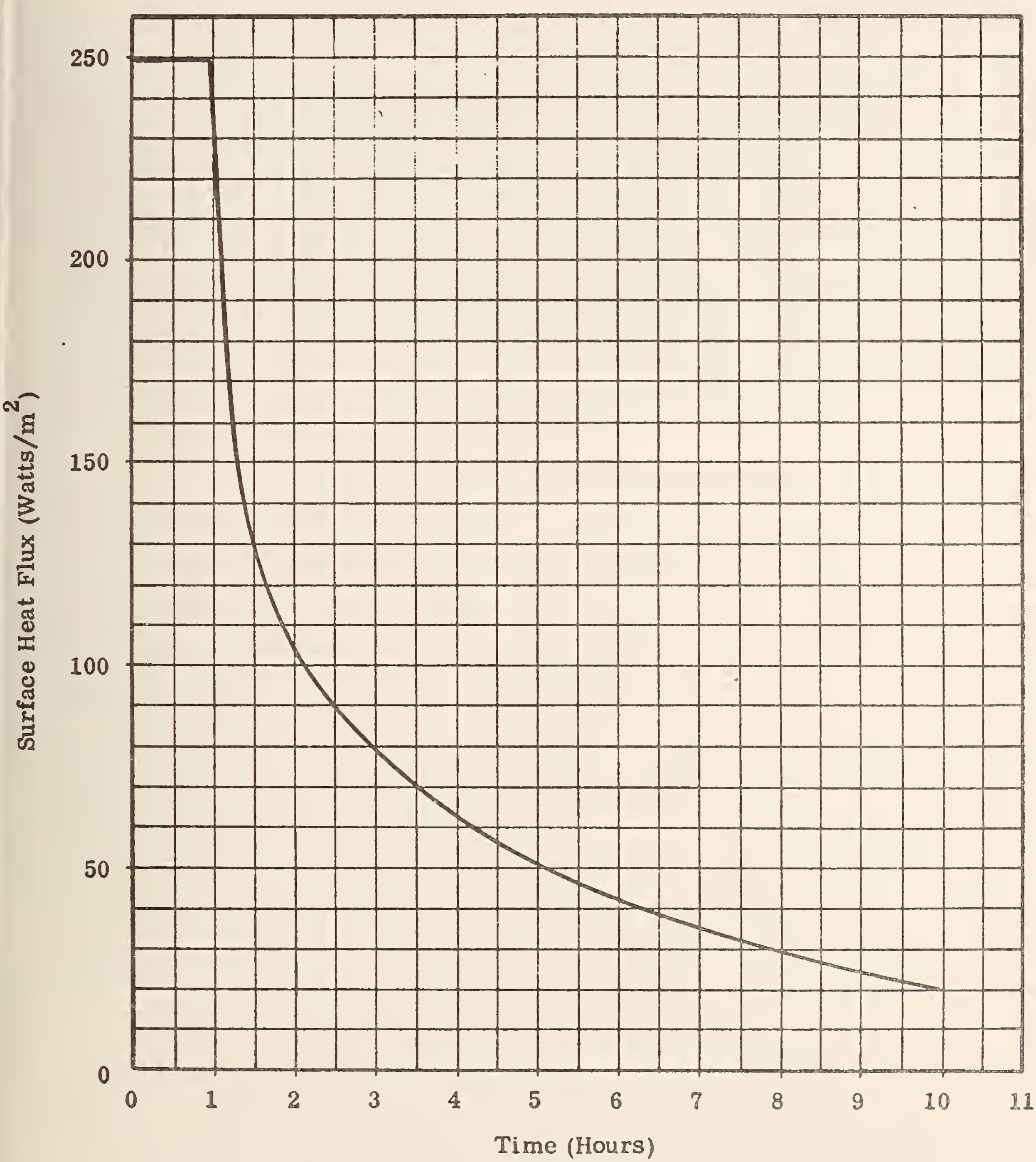



FIGURE 5

SURFACE POWER AS A FUNCTION OF TIME
WHEN A CONCRETE SLAB INITIALLY AT 7.2°C
IS SUDDENLY SUBJECTED TO SNOW MELTING

ter season. Will the system recover during the summer the energy dissipated during the winter is a question that has been asked of the authors many times over the past several years. The average temperature of the undisturbed earth in the late fall of 1978 as measured 13.7 m (45 feet) away from the ramp is 13.2°C (55.8°F). Thus, it appears that after three winters of operation (two of which were unusually severe) the average earth temperature at the middle (and therefore the place least likely to recover) of the field has decreased 1.2°C (2.2°F). Computer studies indicate that 80% of the total expected average earth temperature decrease has already occurred and that, after six years, further decreases in average earth temperature in the field become insignificant.

# 2. TECHNICAL DISCUSSION

## 2.1 Summary

During this study, effort was concentrated in two areas. The University of Wyoming focused on developing a climatic data base for New York City, Dodge City, Kansas, and Madison, Wisconsin, which were the three cities selected to represent climate zones of varying severity. This climatic data base was used to determine the power and annual energy requirements necessary to maintain an idealized surface ice free. This information was used to select a representative average and worst winter for each of the three cities, and these six winters formed the basic data base for the more detailed model studies of pavement-earth systems.

Dynatherm focused its effort on characterizing energy sources for use in augmentation, methods of integrating these sources with the earth heat pipe system, an experimental investigation of the thermal behavior of a heat pipe and the earth source under environmental conditions, and system design. The direct or indirect use of coal, oil, and natural gas for purposes of augmentation were excluded from this study. Solar, wind, air, and waste product energy sources were investigated. Of these, it was concluded that, for practical reasons, the generation of energy from waste products is better handled in large central facilities associated with population centers. With respect to solar, wind, and air energy sources, a choice between these rests fundamentally on economics. In certain locations, considerations other than economics may prevail. The collection of the thermal energy in summertime air is the least expensive of the collection systems investigated.

The attractiveness of the unaugmented earth heat pipe system is that it is passive and, although the first cost is high at the present time, the installed system does not incur operating costs. It remains a possibility that the snow melting performance of unaugmented heat pipe systems may be extended by utilizing and/or controlling the movement of water below the water table in locations where the water table is close to the surface of the earth.

## 2.2 Climatological Investigation

### 2.2.1 Weather Data Base

Two types of hourly weather data were obtained from NOAA through the Los Alamos Scientific Laboratory. The primary data source used in this study was the hourly Airway Surface Observations which was the more comprehensive source but unfortunately did not include the solar irradiation. The hourly 280 Solar Radiation data source was therefore used to complement the Airway Surface Observations by providing both the missing solar radiation data and a secondary source to fill in the gaps that occurred in some of the other weather parameters. The merging of the hourly weather records from these two sources resulted in the hourly record that is summarized in Table 1.

Approximately twelve years of hourly weather data for each of three cities was procured originally, but much of this data could not be used for this study due to large gaps in the 280 Solar Radiation record. The overall periods for which data are available for the three cities studied are given in Table 2.

In addition to these periods where the 280 Solar Radiation record was nonexistent, there still existed gaps in the merged data base for some of the weather parameters. Sizeable gaps exist mainly in the solar radiation data. A tabulation of the winters where the weather records are complete enough to perform an accurate heat transfer analysis are presented in Table 3.

The gaps in the merged records were filled in by taking corresponding measured periods just ahead and behind the gaps and inserting their hourly average for the corresponding missing hourly parameter. In future studies, solar radiation estimates will be made based on the date and existing cloud cover.

### 2.2.2 Thermal Model Used to Characterize Winter Weather

The primary parameter which was used in characterizing the severity of winter weather was the amount of energy required to maintain an idealized surface ice free. The preliminary estimates of the energy which is required to prevent roadway icing were based on the energy that must be supplied to an idealized surface that is exposed to the natural elements to prevent its temperature from (a) ever falling below

| Data Element | Item or Element | Airway Surface Observations | 280 Solar Radiation |
|---|---|---|---|
| 01 | Tape Deck | X* | X |
| 02 | Station Number | X | X |
| 03 | Year | X | X |
| 04 | Month | X | X |
| 05 | Day | X | X |
| 06 | Hour | X | X |
| 07 | Ceiling | X | |
| 08 | Visibility | X | X |
| 09 | Wind Direction | X | |
| 10 | Wind Speed | X | |
| 11 | Dry Bulb Temperature | X | X |
| 12 | Wet Bulb Temperature | X | X |
| 13 | Dew Point Temperature | X | X |
| 14 | Relative Humidity | X | |
| 15 | Sea Level Pressure | X | |
| 16 | Station Pressure | X | |
| 17 | Sky Condition | X | |
| 18 | Total Amount of Cloud Cover | X | X |
| 19 | Total Opaque Amount of Cloud Cover | X | X |
| 20 | Amount of Level One Cloud Cover | X | X |
| 21 | Type of Clouds in Level One | X | X |
| 22 | Height of Clouds in Level One | X | X |
| 23 | Amount of Level Two Cloud Cover | X | X |
| 24 | Type of Clouds in Level Two | X | X |
| 25 | Height of Clouds in Level Two | X | X |
| 26 | Summation of Amounts at the Second Cloud Layer | X | X |
| 27 | Amount of Level Three Cloud Cover | X | X |
| 28 | Type of Clouds in Level Three | X | X |
| 29 | Height of Clouds in Level Three | X | X |
| 30 | Summation of Amounts at the Third Cloud Layer | X | X |

*Denotes data element is present in hourly record.

TABLE 1

MERGED HOURLY WEATHER RECORDS

| Data Element | Item or Element | Airway Surface Observations | 280 Solar Radiation |
|---|---|---|---|
| 31 | Amount of Level Four Cloud Cover | X | X |
| 32 | Type of Clouds in Level Four | X | X |
| 33 | Height of Clouds in Level Four | X | X |
| 34 | Wind Phenomena | X | |
| 35 | Liquid Precipitation | X | X |
| 36 | Frozen Precipitation | X | X |
| 37 | Obstructions to Vision | X | X |
| 38 | Radiation (Langleys Per Hour) | | X |
| 39 | Solar Elevation (Degrees) | | X |
| 40 | Extra-Terrestrial Radiation | | X |
| 41 | Sunshine (Minutes) | | X |
| 42 | Snow Cover | | X |
| 43 | Solar Week | | X |
| 44 | Solar Hour | | X |
| 45 | Percent of Possible Radiation | | X |

TABLE 1 (Continued)

MERGED HOURLY WEATHER RECORDS

| Location | Airway Surface Observations | 280 Solar Radiation |
|---|---|---|
| New York, New York (JFK Airport) | 7/52 - 12/61 | - - - |
| New York, New York (Central Park) | - - - | 7/52 - 8/61 |
| Dodge City, Kansas | 7/52 - 12/64 | 7/52 - 12/58 |
| Dodge City, Kansas | - - - | 7/59 - 12/64 |
| Madison, Wisconsin | 7/52 - 12/64 | 7/52 - 12/57 |
| Madison, Wisconsin | - - - | 9/59 - 12/59 |
| Madison, Wisconsin | - - - | 2/60 - 9/62 |
| Madison, Wisconsin | - - - | 3/64 - 12/64 |

TABLE 2

PERIODS OF AVAILABLE WEATHER RECORDS

| Location | Winters | Number of Winters |
|---|---|---|
| New York, New York | 1952-1953 through 1956-1957<br>1958-1959 through 1960-1961 | 8 |
| Dodge City, Kansas | 1952-1963 through 1957-1958<br>1959-1960 and 1960-1961<br>1962-1963 | 9 |
| Madison, Wisconsin | 1952-1953 through 1956-1957<br>1960-1961 and 1961-1962 | 7 |

TABLE 3

WINTERS WITH FAIRLY COMPLETE WEATHER RECORDS

$1^{\circ}C$ and (b) from ever falling below $1^{\circ}C$ during a precipitation event. The surface is assumed to be horizontal, infinite in extent (no characteristic length), and perfectly insulated on its bottom side. Since this model neglects any heat transfer downward from the surface, the power that must be supplied to the surface to keep it from falling below $1^{\circ}C$ can be determined directly from a surface energy balance. Even though this model greatly oversimplifies the actual problem, it should produce reasonable initial energy estimates for purposes of selecting the worst and average winters at the selected sites.

Figure 6 depicts this initial model with the various modes of heat transfer that were included. These are defined as:

$\dot{q}_{solar}$ = solar irradiation

$\dot{q}_{atm}$ = atmospheric irradiation

$\dot{q}_{l,w}$ = long wave radiation emitted by the surface

$\dot{q}_{conv}$ = convective heat transfer rate

$\dot{q}_{f}$ = power required to melt the frozen precipitation as it falls and bring the surface to $1^{\circ}C$ ($33.8^{\circ}F$)

$\dot{q}_{evap}$ = power required to supply water evaporation losses

$\dot{q}_{req}$ = power that must be supplied by an external source to keep the surface from falling below $1^{\circ}C$ ($33.8^{\circ}F$)

A surface energy balance indicates that:

$$\dot{q}_{req} = \dot{q}_{conv} + \dot{q}_{l,w} + \dot{q}_{f} + \dot{q}_{evap} - \alpha_{s}\,\dot{q}_{solar} - \alpha_{atm}\,\dot{q}_{atm}$$

if $\dot{q}_{req} > 0$

otherwise $\dot{q}_{req} = 0$

where $\alpha_{s}$ and $\alpha_{atm}$ are the surface absorptivities for solar and atmospheric radiation respectively. Both of these parameters were assumed to be 0.8 which is fairly characteristic of highway materials.

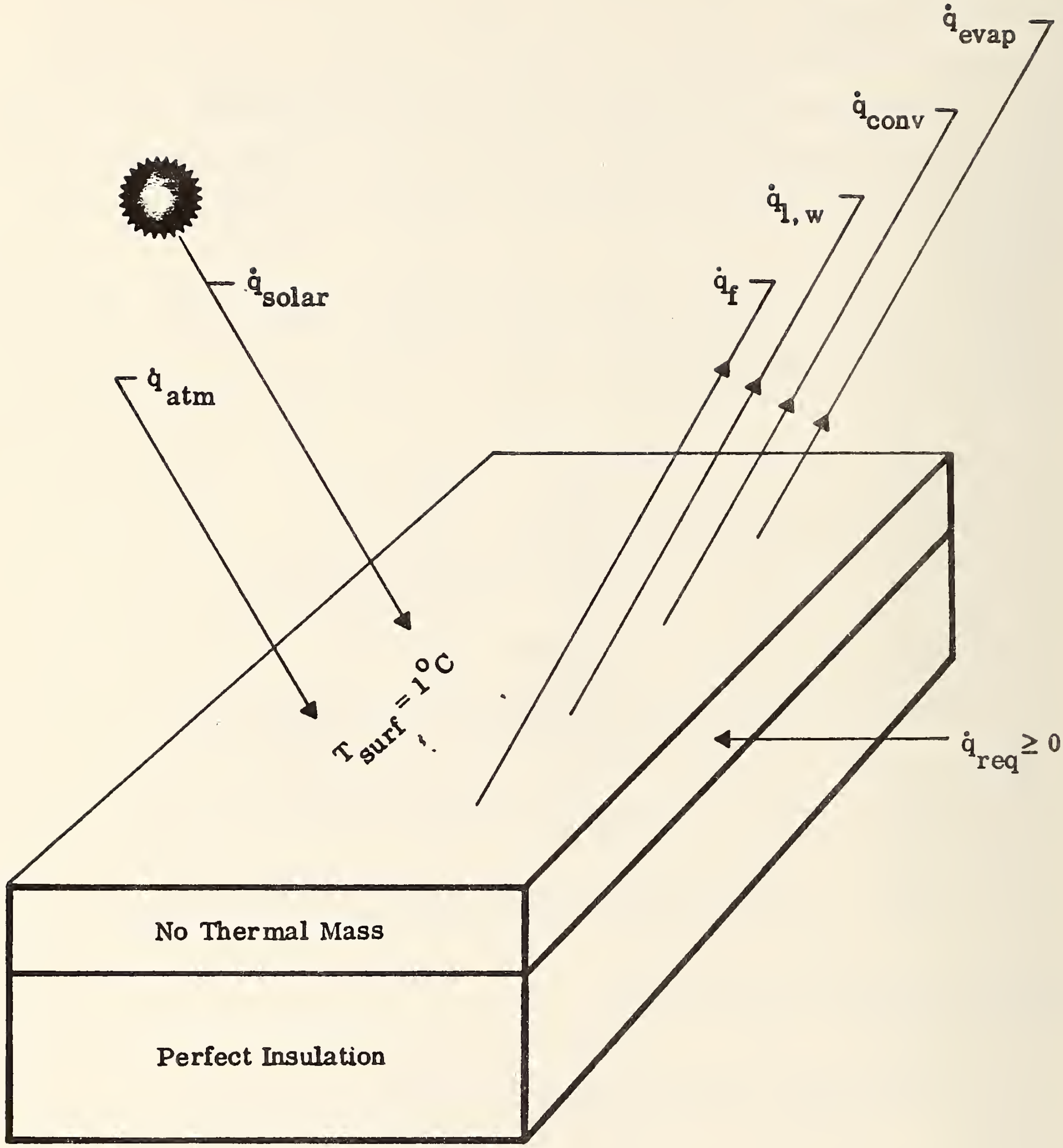



FIGURE 6

IDEALIZED SURFACE HEAT TRANSFER MODEL

The solar irradiation is the only parameter in the above equation that can be obtained directly from the weather data. The other modes of heat transfer were calculated from the following empirical correlations:

$$\dot{q}_{atm} = \sigma T_{air}^{4} \left[ 1 - 0.261 \exp \left[ - 7.77 \times 10^{-4} (273 - T_{air})^{2} \right] \right]$$

where $\sigma$ is the Stefan-Boltzman constant ($5.672 \times 10^{-8}$ $W/m^2-K^4$) and $T_{air}$ is the air temperature at screen height (1 to 2 m) in $^{o}K$. The above empirical correlation (Reference 7) is for clear-sky atmospheric radiation and is based upon the strong correlation between the screen temperature and water vapor in the lower atmosphere. The correlation coefficient for this relation is given to be 0.992 for a large amount of data taken at five very different sites. This is remarkable when compared to the correlation coefficients given for the commonly used Brunt relation which has different recommended equation coefficients for each site. The clear-sky assumption was used as a conservative simplification since an overcast or fog will increase the atmospheric radiation but generally not by more than 25 percent over the corresponding clear-sky value. The influence of cloud cover will be included in some of the subsequent more detailed analysis but its inclusion here was not felt to be warranted. It would significantly complicate the model since both the amount of lower cloud cover and its height are included in any reasonable empirical correlation and, even then, the accuracy of these correlations do not appear to be very well established. It should also be pointed out here that good simulations of the passive response of bridges in both Colorado and Wyoming were generally obtained during cloudy conditions with the use of this clear-sky assumption.

$$\dot{q}_{l,w} = \epsilon \sigma T_{surf}^{4}$$

where $\epsilon$ is emittance of the surface which was set at 0.8 and $T_{surf}$ is the surface temperature ($274.15^{o}K$).

$$\dot{q}_{conv} = \left[ 1.004\, T_{m}^{0.3}\, V^{0.7} + 0.6764\, (T_{surf} - T_{air})^{0.3} \right] \left[ T_{sur} - T_{air} \right]$$

where $\dot{q}_{conv}$ is in $W/m^2$, $T_m$ is $(T_{surf} + T_{air})/2$ in $^{o}K$, and V is the air velocity in m/sec at a two metre reference height. This air-earth interface heat transfer correlation was determined from experiments conducted over a smooth dry-lake (Reference 8).

$$\dot{q}_f = \dot{m}_f \left[ c_i \, (273.15 - T_{air}) + h_{fs} + c_w \, (1^\circ C) \right]$$

if $\qquad T_{air} < 273.15 \text{ K } (0^\circ C)$

otherwise $\qquad \dot{q}_f = \dot{m}_f \left[ h_{fs} + c_w \, (1^\circ C) \right]$

where $h_{fs}$ is the heat of fusion ($3.3373 \times 10^5$ Joules/kg), $c_i$ and $c_w$ are the specific heats of ice (2092 Joules/kg-$^\circ$C) and water (4184 Joules/kg-$^\circ$C) respectively, and $\dot{m}_f$ is the frozen precipitation rate. The above expression assumed that the temperature of the frozen precipitation can be characterized by the air temperature when $T_{air}$ is below freezing.

$$\dot{q}_{evap} = \dot{m}_{evap} \, h_{fg}$$

where $\dot{m}_{evap}$ is the rate of water evaporation from the surface and $h_{fg}$ is the latent heat of vaporization for water at 1$^\circ$C ($2.499 \times 10^6$ Joules/kg). $\dot{m}_{evap}$ is calculated from Schulyakovskiy's empirical correlation (Reference 9).

$$\dot{m}_{evap} \left( \frac{\text{kg}}{\text{m}^2\text{-sec}} \right) = (1.74 + 1.30 \, V) \, (e_s - e_a) \, (10^{-6})$$

where $e_s$ is the saturated water vapor pressure at the 1$^\circ$C surface temperature (6.5662 mb) and $e_a$ is the partial pressure of water in the air. $e_a$ is calculated from the relative humidity RH and the saturated water vapor pressure at air temperature $e_w$.

$$e_a = (RH) \, e_w$$

where $e_w$ is obtained from the Goff-Gratch formula (Reference 10).

$$\log_{10} e\ (\text{mb}) = -7.90298\,(373.16/T_{air} - 1) + 5.02808\left[\log_{10}(373.16/T_{air})\right]$$
$$- 1.3816 \times 10^{-7}\left[10^{11.244\,(1 - T_{air}/373.16)} - 1\right]$$
$$+ 8.1328 \times 10^{-3}\left[10^{-3.49149\,(373.16/T_{air} - 1)} - 1\right] + 3.0057$$

If the above calculated rate of evaporation ($\dot{m}_{evap}$) is larger than the total rate of frozen and/or liquid precipitation $\dot{m}$, $\dot{m}_{evap}$ was replaced by $\dot{m}$.

2.2.3 Calculation of Precipitation Rates

The precipitation data from the Airways Surface Observation and the Solar Radiation set turn out to be more qualitative than quantitative as illustrated by Table 4 that summarizes this information.

When the precipitation rates for the latter three categories (I, II, and III) were arbitrarily set to 0.1, 0.2, and 0.3 inches of water equivalent per hour respectively, the calculated monthly snowfall depths were found to be around an order of magnitude too large when compared to the measured monthly values given in the Climatological Data, National Summary. Daily frozen precipitation (snow, sleet, and hail) depths and total precipitation (water equivalent) are the finest measures of precipitation rates that are generally available from the Climatic Center. This information has been used to normalize the predicted daily precipitation rates for the six years of interest.

In the cases where there are no obscurations to vision other than falling precipitation, the reported visual range can be used to help quantify the precipitation rate. The scale used by the National Weather Service to report visibility is given by Table 5. The attenuation of visible light by snow is an order of magnitude larger than by rain having the same mass flux, and the correlation between the attenuation coefficient and mass flux for all types of snow is given by H. W. O'Brien (Reference 11) to be:

$$\log \sigma = 0.0693 \log \dot{m}_f - 2.12$$

| Category | Approximate Precipitation Rate Range | Liquid Precipitation | Frozen Precipitation |
|---|---|---|---|
| 0 | 0 Inches of Water Equivalent Per Hour | No Precipitation<br>a. rain, rain showers or freezing rain<br>and/or<br>b. drizzle, freezing drizzle, or rain squalls | No Precipitation<br>a. snow, snow pellets, or ice crystals<br>and/or<br>b. showers, snow grains, or squalls<br>and/or<br>c. sleet, hail, or small hail |
| I | 0 to 0.1 Inches of Water Equivalent Per Hour | Light Precipitation<br>a. rain, rain showers, or freezing rain<br>and/or<br>b. drizzle, freezing drizzle, or rain squalls | Light Precipitation<br>a. snow, snow pellets, or ice crystals<br>and/or<br>b. showers, snow grains, or squalls<br>and/or<br>c. sleet, hail, or small hail |
| II | 0.1 to 0.3 Inches of Water Equivalent Per Hour | Moderate Precipitation<br>a. rain, rain showers, or freezing rain<br>and/or<br>b. drizzle, freezing drizzle, or rain squalls | Moderate Precipitation<br>a. snow, snow pellets, or ice crystals<br>and/or<br>b. showers, snow grains, or squalls<br>and/or<br>c. sleet, hail, or small hail |
| III | Greater Than 0.3 Inches of Water Per Hour | Heavy Precipitation<br>a. rain, rain showers, or freezing rain<br>and/or<br>b. drizzle, freezing drizzle, or rain squalls | Heavy Precipitation<br>a. snow, snow pellets, or ice crystals<br>and/or<br>b. showers, snow grains, or squalls<br>and/or<br>c. sleet, hail, or small hail |

1 inch = 25.4 mm

TABLE 4

PRECIPITATION DATA SET

| Statute Mile | Increments in Miles |
|---|---|
| 0 - 3/8 | 1/16 |
| 3/8 - 2 | 1/8 |
| 2 - 2-1/2 | 1/4 |
| 2-1/2 - 3 | 1/2 |
| 3 - 15 | 1 |
| 15 - 95 | 5 |
| 100 Miles or More | - - |

1 mile = 1.609 km

TABLE 5

VISIBILITY RECORD

where $\sigma$ is the attenuation coefficient in $m^{-1}$ and $\dot{m}_f$ is the mass flux in $g/m^2$-sec. The correlation for this equation was given to be 0.80.

The meteorological range is defined to be that distance for which the contrast transmission of the atmosphere is two percent. If we assume that the visual range VR corresponds to this definition, it can be shown that (Reference 12):

$$VR = 3.912/\sigma$$

We therefore find that:

$$\sigma = 10^{-2.12} \dot{m}_f^{0.693}$$

or,

$$\dot{m}_f = 8.203 \, VR^{-1.443}$$

The frozen precipitation rates were calculated using this empirical formula and checked to see if they fell within the range given in the data. If the calculated rate fell out of the data range, it was set to the upper range limit if it was too large and the lower limit if it was too small. In the case of "heavy" precipitation, the upper limit was arbitrarily set to 0.6 inches (1.5 cm) of equivalent water per hour.

There are several factors that complicate the direct use of visual range to help quantify the precipitation rate. For instance, it appears that around 10 percent of the snow events are accompanied by rain; but the major complication arises from the fact that some obscuration to vision other than snow or sleet are listed for approximately 40 percent of the snow events. These obscurations are classified as one or both of the following:

- fog, ice fog, ground fog, blowing dust, or blowing sand
- smoke, haze, smoke and haze, dust, blowing snow or blowing spray

These obscurations also caused numerous cases of zero visibility during snowing events for Dodge City, usually in the form of blowing snow; but this problem did not occur in the other two cities.

Since the influence that these obscurations have on the visual range cannot be ascertained from this type of qualitative information, the visual range was arbitrarily doubled (Figure 7) to help correct for obscuration. If the calculated precipitation rate was then smaller than the range indicated by the precipitation data, the rate was set to the lower limit of the precipitation range. If the calculated rate was larger than the indicated range, the precipitation rate was arbitrarily set to the values in Table 6

TABLE 6

SELECTED PRECIPITATION RATES BY CATEGORY

| Precipitation Category | Precipitation Rate Equivalent Water |
|---|---|
| I | 0.126 cm/hr (0.05 in/hr) |
| II | 0.51 cm/hr (0.20 in/hr) |
| III | 1.25 cm/hr (0.49 in/hr) |

which are smaller than the upper limits given for each category.

A comparison between the yearly frozen precipitation predicted by this rather unrefined method and the depth of snow, sleet, and hail quoted in the Climatological Data, National Summary is given in Tables 7, 8, and 9. The density of snow can vary over an order of magnitude from around 0.015 to 0.30 $g/cm^3$ with 0.1 $g/cm^3$ used as the general rule of thumb.* When a snow density of around 0.1 $g/cm^3$ is assumed, these tables indicate that the correlation between the measured and the calculated frozen precipitation was accurate enough to obtain reasonable power predictions in order to determine the average and worst years. As was previously mentioned, the 24-hour frozen precipitation rates have been incorporated into the data base for the six years

*The average density for fresh snow is given to be 0.077 $g/cm^3$ for Burlington, Vermont (Reference 13) and 0.085 $g/cm^3$ for Montreal (Reference 14). A general correlation between the density of freshly-fallen snow and surface temperature does not appear possible (References 15, 16, 17). It should also be noted that the predicted water equivalent values cannot be compared to the total monthly precipitation values given in the National Summaries since almost no month has only frozen precipitation for the three cities studied.

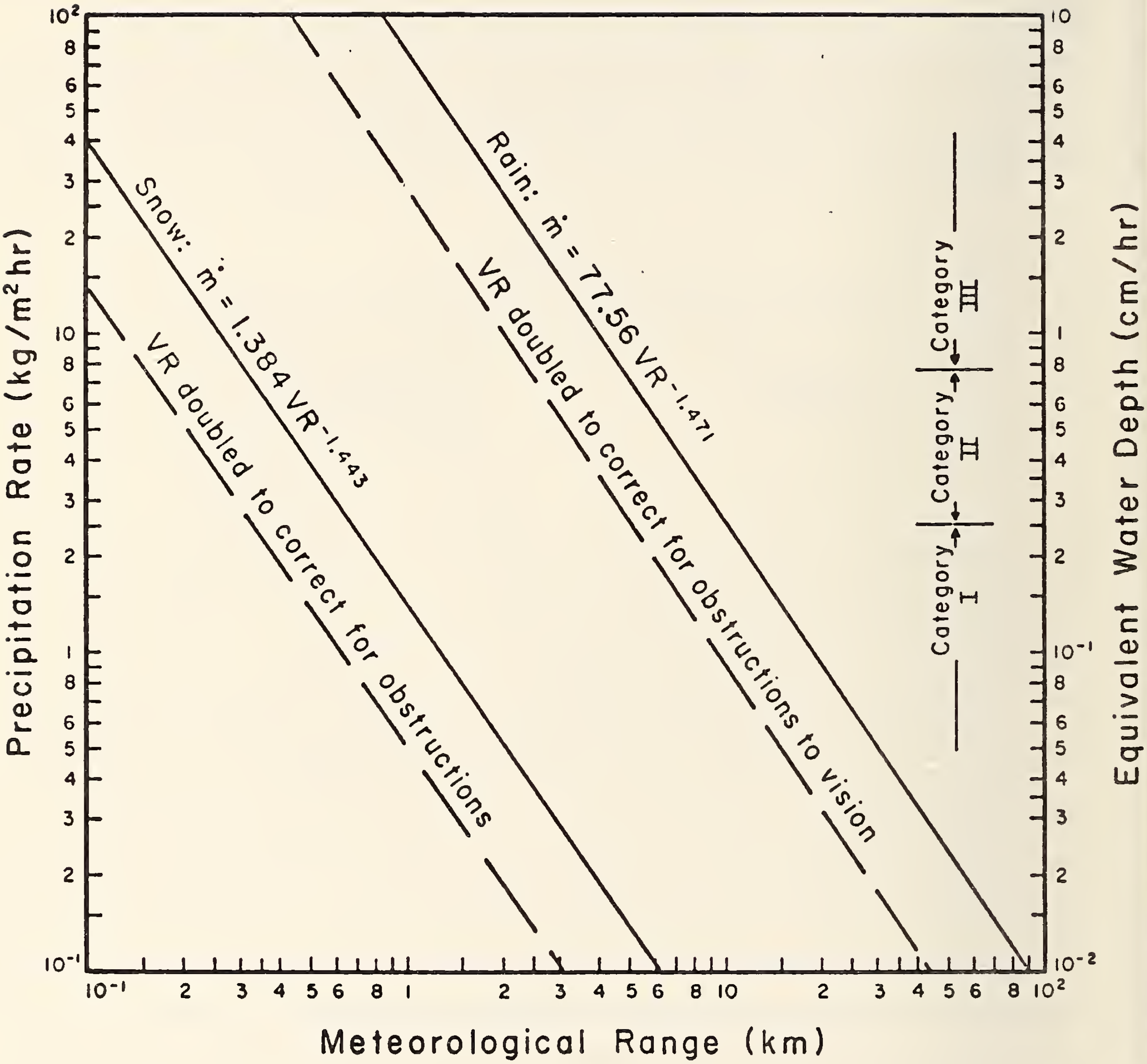



FIGURE 7

PRECIPITATION RATES FOR SNOW AND RAIN VERSUS METEOROLOGICAL RANGE of interest in order to normalize the calculated rates with little impact on the original estimates.

The method described above to predict frozen precipitation rates was also used to calculate rainfall rates with the exception that correlation suggestion by O'Brien is now:

$$\dot{m}_{lp} = 1.384\ VR^{-1.443}$$

## 2.2.4 Results of Calculations and Selection of Average and Worst Years

Summaries of the annual weather characteristics and energy requirements are presented in Tables 7, 8, and 9 for the three cities. Based on the annual energy required to keep the idealized surface from ever falling below $1^{\circ}C$ or only during precipitation events, the selection of the worst year for each city from this data set was clear. These years also had the largest measured snowfall and degree-days below $1^{\circ}C$. The selection of a year to represent the average year for a city was not as obvious. In this case, the energy requirements were still the major consideration but the weather parameters and record gaps were also considered in the selection of these average years. The six years selected as the data base for the future model studies are:

| Location | Worst Winter | Average Winter |
|---|---|---|
| New York City | 1960-1961 | 1956-1957 |
| Dodge City | 1959-1960 | 1957-1958 |
| Madison | 1961-1962 | 1954-1955 |

Comprehensive monthly and yearly summaries of the weather characteristics and energy requirements have been tabulated for each year in Reference 39. The spectra for temperature, wind speed, frozen precipitation rate, solar irradiation, wind power, power required, and power required only during precipitation events have also been graphed for the four major winter months of the six selected years.

| Weather Characteristic | Unit | 7/52–6/53 | 7/53–6/54 | 7/54–6/55 | 7/55–6/56 | 7/56–7/57 | 7/58–6/59 | 7/59–6/60 | 7/60–6/61 | Average |
|---|---|---|---|---|---|---|---|---|---|---|
| Number Days Having a Freeze | -- | 50 | 59 | 68 | 86 | 68 | 82 | 73 | 73 | 70 |
| Degree-Days Below $1^{o}C$ | -- | 82 | 160 | 185 | 213 | 163 | 274 | 161 | 298 | 192 |
| Frozen Precipitation | cm $H_2O$ | 2.9 | 3.3 | 3.1 | 8.5 | 3.9 | 3.6 | 11.4 | 13.3 | 6.2 |
| Measured Snowfall | cm | 34.3 | 43.9 | 28.7 | 77.7 | 55.6 | 46.0 | 85.6 | 143.5 | 64.4 |
| Hours of Snow or Freezing Rain | Hours | 146 | 122 | 120 | 200 | 188 | 144 | 204 | 218 | 168 |
| Average Wind Speed | m/s | 5.0 | 4.9 | 5.5 | 5.7 | 5.4 | 5.5 | 5.6 | 5.0 | 5.3 |
| Average Wind Power | $W/m^2$ | 167 | 139 | 190 | 197 | 156 | 199 | 192 | 161 | 175 |
| Average Solar Radiation | $W/m^2$ | 152 | 172 | 169 | 163 | 158 | 163 | 160 | 148 | 161 |
| Required Energy* | $kwh/m^2$ | 109 | 151 | 173 | 211 | 160 | 228 | 180 | 242 | 182 |
| Required Energy* During Precip. | $kwh/m^2$ | 16.3 | 22.8 | 19.5 | 34.4 | 24.7 | 21.3 | 44.6 | 50.9 | 29.3 |
| Maximum Power* | $W/m^2$ | 483 | 659 | 624 | 1153 | 576 | 1379 | 1145 | 935 | 869 |
| | | | | | | Average Year | | | Worst Year | |

*To keep an idealized surface from falling below $1^{o}C$.

TABLE 7

SUMMARY OF WEATHER CHARACTERISTICS FOR NEW YORK CITY

| Weather Characteristic | Units | 7/52-6/53 | 7/53-6/54 | 7/54-6/55 | 7/55-6/56 | 7/56-6/57 | 7/57-6/58 | 7/59-6/60 | 7/60-6/61 | 7/62-6/63 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number Days Having a Freeze | -- | 109 | 105 | 112 | 131 | 118 | 115 | 128 | 112 | 101 | 115 |
| Degree-Days Below 1°C | -- | 289 | 307 | 340 | 452 | 367 | 333 | 542 | 304 | 406 | 371 |
| Frozen Precipitation | cm $H_2O$ | 8.3 | 11.2 | 5.8 | 10.0 | 20.1 | 8.6 | 14.2 | 3.5 | 2.8 | 9.4 |
| Measured Snowfall | cm | 39.4 | 23.6 | 16.3 | 55.1 | 71.6 | 51.6 | 84.1 | 23.1 | 14.5 | 42.1 |
| Hours of Snow or Freezing Rain | Hours | 219 | 192 | 182 | 256 | 286 | 420 | 362 | 218 | 200 | 259 |
| Average Wind Speed | m/s | 7.0 | 7.0 | 7.1 | 6.6 | 6.8 | 6.5 | 6.9 | 6.6 | 5.3 | 6.6 |
| Average Wind Power | $W/m^2$ | 308 | 298 | 306 | 258 | 287 | 239 | 294 | 264 | 137 | 266 |
| Average Solar Radiation | $W/m^2$ | 233 | 218 | 223 | 237 | 217 | 197 | 217 | 213 | 208 | 218 |
| Required Energy* | $kwh/m^2$ | 241 | 256 | 275 | 336 | 296 | 273 | 390 | 250 | 266 | 287 |
| Required Energy* During Precip. | $kwh/m^2$ | 44.7 | 52.8 | 60.5 | 71.0 | 77.9 | 79.7 | 109 | 42.4 | 56.2 | 66.0 |
| Maximum Power* | $W/m^2$ | 885 | 917 | 928 | 1052 | 748 | 855 | 804 | 580 | 852 | 847 |
| | | | | | | | Average Year | Worst Year | | | |

*To keep an idealized surface from falling below 1°C.

TABLE 8

SUMMARY OF WEATHER CHARACTERISTICS FOR DODGE CITY

| Weather Characteristics | Units | 7/52-6/53 | 7/53-6/54 | 7/54-6/55 | 7/55-6/56 | 7/56-6/57 | 7/60-6/61 | 7/61-6/62 | Average |
|---|---|---|---|---|---|---|---|---|---|
| Number Days Having a Freeze | -- | 151 | 140 | 142 | 158 | 146 | 148 | 156 | 149 |
| Degree-Days Below 1°C | -- | 575 | 555 | 714 | 844 | 750 | 730 | 942 | 730 |
| Frozen Precipitation | cm $H_2O$ | 9.9 | 5.2 | 9.2 | 8.0 | 10.0 | 8.6 | 11.5 | 8.9 |
| Measured Snowfall | cm | 71.1 | 52.3 | 84.1 | 76.0 | 78.0 | 56.1 | 125.2 | 77.5 |
| Hours of Snow or Freezing Rain | Hours | 626 | 355 | 539 | 494 | 409 | 359 | 649 | 490 |
| Average Wind Speed | m/s | 4.7 | 4.6 | 4.2 | 4.4 | 4.7 | 4.3 | 4.2 | 4.4 |
| Average Wind Power | $W/m^2$ | 136 | 121 | 99 | 115 | 130 | 87.8 | 84.6 | 111 |
| Average Solar Radiation | $W/m^2$ | 164 | 168 | 161 | 169 | 189 | 184 | 176 | 173 |
| Required Energy* | $kwh/m^2$ | 389 | 369 | 420 | 461 | 447 | 426 | 522 | 433 |
| Required Energy* During Precip. | $kwh/m^2$ | 97.6 | 58.4 | 102 | 86.8 | 82.3 | 76.9 | 136 | 91.4 |
| Maximum Power* | $W/m^2$ | 1536 | 1677 | 1229 | 925 | 848 | 939 | 1172 | 1046 |
| | | | | Average Year | | | | Worst Year | |

*To keep an idealized surface from falling below 1°C.

TABLE 9

SUMMARY OF WEATHER CHARACTERISTICS FOR MADISON, WISCONSIN

## 2.3 Modeling of West Virginia System and Results of Computer Runs

### 2.3.1 Modifications to the Thermal Model Used to Characterize Winter Weather

The atmospheric irradiation term $\dot{q}_{atm}$ (as defined in Section 2.2.2) was modified to account for cloud cover, and daily measured values of precipitation were obtained from NOAA for the average and worst years for the three selected cities. The energy requirements for an idealized surface were recalculated.

These modifications substantially lowered the values of energy required during precipitation and modestly decreased the values for total energy for all sites in both the average and the worst years.

The decrease in energy required during precipitation for Dodge City was approximately 50% which was due to a corresponding decrease in the precipitation. On the other hand, the decrease in energy required in New York City was mainly due to cloud effects. The data for Madison exhibited both influences; that is, some cloud cover and less snow. The peak power requirements for the worst year increased for New York City and decreased for Dodge City and Madison.

The long wave radiation from clouds is not insignificant and neglecting it can increase the calculated required energy by as much as 19% for an idealized surface maintained at $1^{o}C$ throughout the winter and by over 25% for an idealized surface maintained at $1^{o}C$ only during precipitation events.

### 2.3.2 Computer Model Used to Characterize West Virginia System

The design of the West Virginia unaugmented earth heating system is shown in Figures 1, 2, 3, and 4. The computer model was composed of a single innermost heat pipe and idealized as shown in Figure 8. An inner heat pipe in this location is surrounded by planes of symmetry which may be considered adiabatic walls when the heat pipe is working. The angle between these adiabatic walls is conservatively assumed to be 15.5 degrees. When the pipe is not working, the model is conservative since energy actually flows into the system both horizontally and vertically. When the heat pipe is functioning, energy available to the heat pipe is transferred via conduction from the ground adjacent to and beneath the pipe. The heat pipe supplies

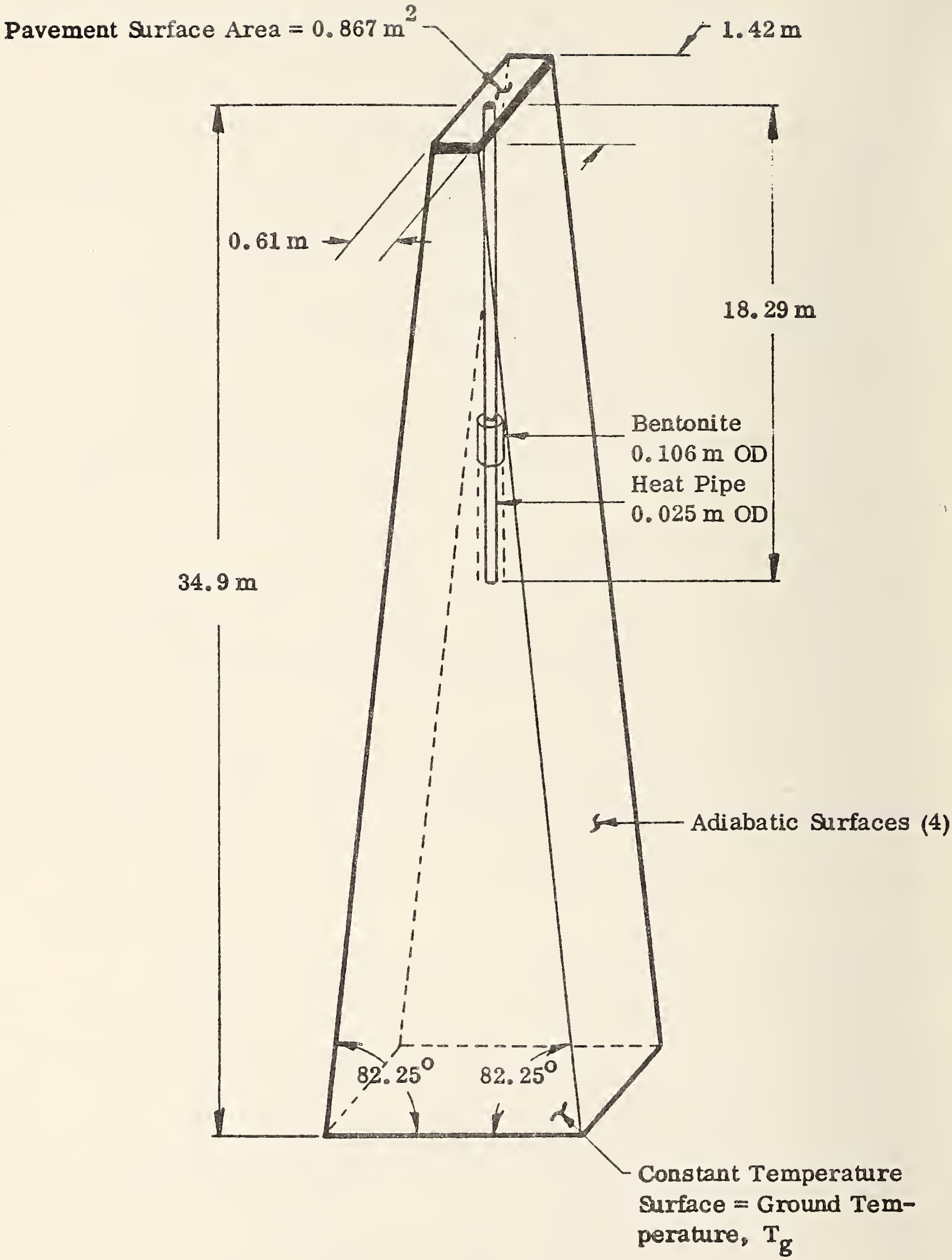



FIGURE 8

IDEALIZATION OF SINGLE WEST VIRGINIA EARTH SYSTEM HEAT PIPE COUPLED TO VOLUME OF EARTH energy to 0.867 $m^2$ (9.33 $ft^2$) of pavement surface as in the actual installation. The earth portion of the heat pipe is 18.29 m (60 feet) long.

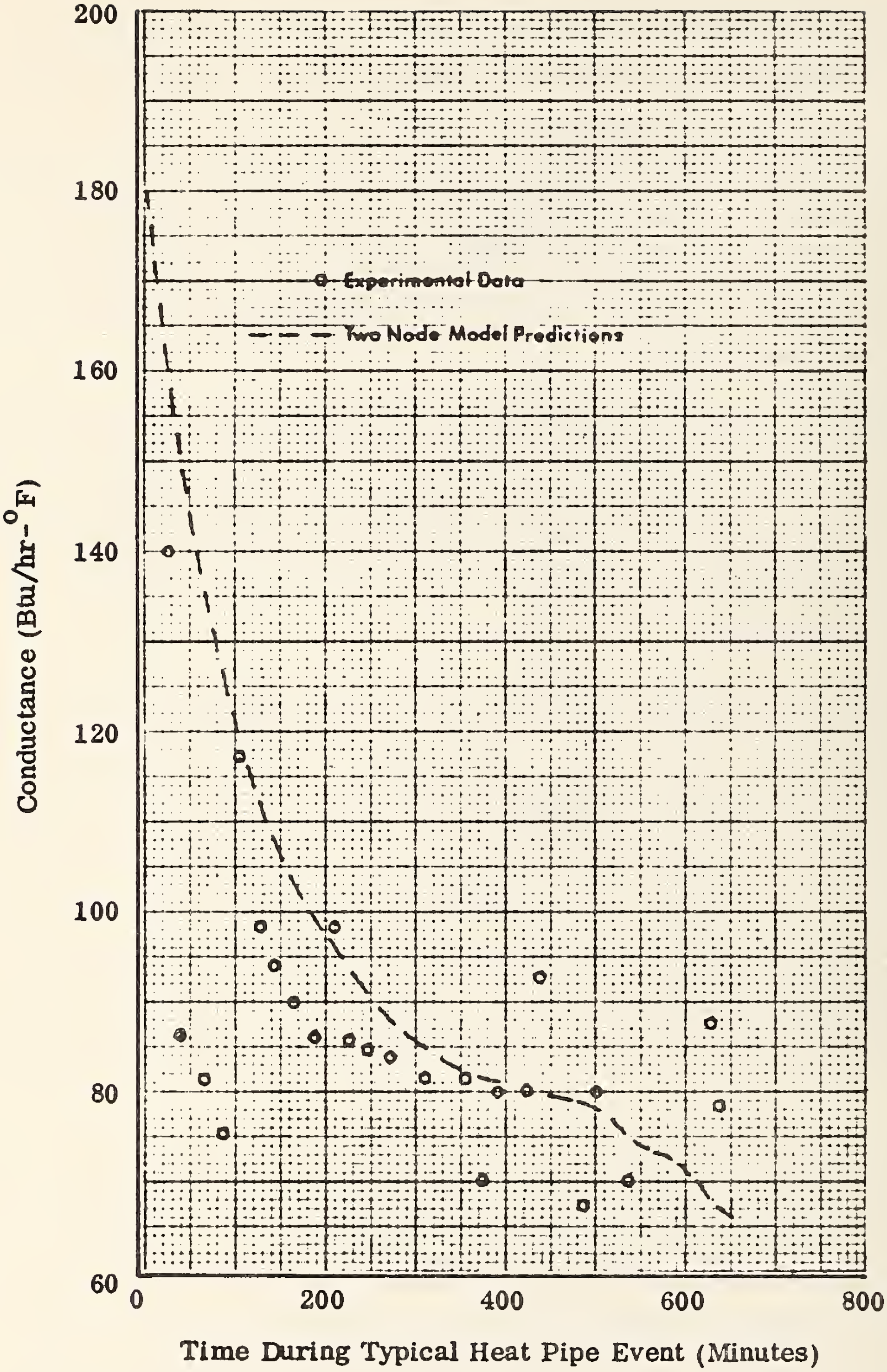
To further simplify the noding scheme used in the model, the rectangular prism shown in Figure 8 was treated as a series of solid cylinders, whose area at any given depth matched the rectangular area of the prism. At each node, the vertical area was considered to be constant and was determined by the distance of the node from the pavement surface.

The heat pipe model assumed a 0.025 m (0.98 inch) diameter pipe with infinite conductance through the pipe wall. This pipe size is smaller than the standard 1 inch IPS (0.0339 m) used in West Virginia. The major effect of this discrepancy in pipe size is that the thermal resistance between the pipe and the pavement surface is higher in the model.

The conductance between the heat pipe and surrounding ground nodes was measured experimentally at the Sybille Canyon project located in Southeastern Wyoming. The power delivered to the bridge deck by a single heat pipe was measured experimentally by a set of electrical heat pipes. The heat pipe field was observed to rapidly recover to some local depressed temperature when the heat pipes were off. Using the measured values of the heat pipe wall temperature, the power, and this locally depressed field temperature, a non-steady state conductance was obtained between the heat pipe and surrounding ground nodes when the heat pipe was on.

By adjusting the size of the two nodes, a non-steady state conductance was obtained which matched the experimental conductance very closely as shown in Figure 9. Figure 9 represents a typical result of this conductance model for several cases observed throughout the 1977-1978 Winter. This two node conductance model is simple, yet accurate, in predicting the observed dynamic characteristics of the system when the pipe is operating.

All far field ground conductances were based on a steady-state conductance. An energy balance was performed on all internal ground nodes at each integration time step based upon these steady-state conductances.




1 Btu/hr - °F= 0.525 J/s·K

FIGURE 9

RESULTS OF TWO NODE CONDUCTANCE MODEL

The heat pipe was assumed to be an isothermal device in which the net heat transfer to the pipe was forced to be zero at all times. The heat pipe was divided into sections (corresponding to nodes) which could individually have a high conductance when acting as either an evaporator or condenser, or zero conductance when shut off. The horizontal primary condenser section was connected to the upper primary condenser ground nodes through a steady-state conductance formula for a row of infinite circular holes in the mid-plane of an infinite plate (Reference 43) and allowed to be either a condenser or shut off (it was never allowed to be an evaporator).

The very bottom 0.3 m of the heat pipe was allowed to act only as an evaporator or be shut off. This bottom section corresponded to the liquid reservoir residing in the bottom of the pipe. Sections between the top condenser and the very bottom evaporator section were allowed to act either as an evaporator, condenser, or be shut off. Whether these sections were acting as an evaporator, condenser, or shut off was determined by the relative temperature difference between the heat pipe vapor temperature and the surrounding ground.

Any evaporator section, except at the very bottom one, had to receive condensate from sections above or reduce its conductance proportionally. This model does allow for heating of the ground throughout the entire length of heat pipe since intermediate sections may take on conductance values of both condensers and evaporators depending on relative temperature differences. The values of internal heat pipe transfer coefficients used were obtained experimentally.

The physical properties of weathered granite and bentonite were measured experimentally on samples obtained from the Sybille Canyon project in Southeastern Wyoming. The basic model used values of weathered granite and bentonite only, since values of the thermal diffusivities of granite and bitumen compared quite closely as seen in Table 10.

### 2.3.3 Results of Computer System Runs

For the average and worst years selected in Section 2.2 for New York City, Dodge City, Kansas, and Madison, Wisconsin, the following computer runs were made:

| MATERIAL | Specific Heat | | Density | | Thermal Conductivity | | Thermal Diffusivity | |
|---|---|---|---|---|---|---|---|---|
| | J/Kg-K | Btu/lb-°F | Kg/m³ | lb/ft³ | W/m-K | Btu/hr-ft-°F | cm²/s | ft²/hr |
| Bentonite | 2552 | 0.609 | 1466 | 91.5 | 6.90 | 4.00 | 0.018 | 0.072 |
| Weathered Granite | 824 | 0.197 | 2212 | 138 | 1.04 | 0.60 | 0.006 | 0.024 |
| Bitumen | -- | -- | -- | -- | 1.45 | 0.84 | 0.007 | 0.028 |
| Clay | -- | -- | -- | -- | 2.18 | 1.26 | 0.011 | 0.044 |

Note: Later measurements at the University of Wyoming indicate that bentonite thermal conductivity values used above are high. New values are 1.72 W/m-K, 1.0 Btu/hr-ft-°F.

TABLE 10

MATERIAL PROPERTIES

- The idealized surface was rerun. The surface has no thermal mass. It was maintained at $1^{o}C$ by energy additions throughout the winter. The energy dissipated, energy dissipated during all precipitation events, and peak power for each winter month were obtained.

- The idealized surface was thermally connected to infinite ground. It was maintained at $1^{o}C$ by energy additions during all precipitation events. The energy dissipated during all precipitation events and peak power for each winter month were obtained.

- The unaugmented West Virginia system was run. The energy dissipated for each winter month was obtained for only the average year for each city.

- The West Virginia system was run with required energy additions during all precipitation events to maintain the surface at $1^{o}C$. The heat pipe energy dissipated, the required augmentation energy during all precipitation events, and the peak augmentation power for each winter month were obtained.

- The West Virginia system was run assuming that the ground temperature at each city was increased by $5.55^{o}C$ ($10^{o}F$). Required energy additions were made to maintain the pavement surface at $1^{o}C$ during all precipitation events. The heat pipe energy dissipated, the required additional augmentation energy during all precipitation events, and the peak augmentation power for each winter month were obtained.

- A West Virginia valved heat pipe system was run for the average year at Dodge City. Two valve settings and normal and normal plus $5.55^{o}C$ earth temperature cases were investigated. The heat pipe energy dissipated, the required augmentation energy during all precipitation events, and the peak augmentation power for each winter month were obtained.

- A six year recovery experiment run was made for the average year at Dodge City. Energy additions were made to the West Virginia system as required during all precipitation events to maintain the surface at $1^{o}C$. The heat pipe energy dissipated, the required augmentation energy during all precipitation events, the peak augmentation power for each winter month, and the end of winter ground temperatures for each of the six years were obtained.

The results for New York City, Dodge City, and Madison for the idealized surface, the non-heat pipe pavement, the West Virginia system with normal and normal plus $5.55^{o}C$ ground temperatures are summarized in Tables 11, 12, and 13. In all cases,

| No. | SYSTEM DESCRIPTION | Parameter | Average Year | Worst Year |
|---|---|---|---|---|
| 1 | Idealized Surface | $Q_d$ | 17.1 | 42.5 |
| | | $Q_t$ | 133.7 | 215.9 |
| | | Peak Power | 0.584 | 1.336 |
| 2 | Standard Pavement with Demand Energy Only | $Q_d$ | 17.4 | 45.6 |
| | | Peak Power | 0.767 | 1.363 |
| 3 | West Virginia Heat Pipe System, No Demand Energy | $Q_t$ | 196.7 | -- |
| 4 | West Virginia Heat Pipe System, Demand Energy Added During All Precipitation Events to Maintain Surface at 1°C | $Q_d$ | 6.48 | 26.5 |
| | | $Q_t$ | 195.2 | 218.5 |
| | | Peak Power | 0.482 | 1.251 |
| 5 | Same as System #4 Except Starting Earth Temperature Increased 10°F | $Q_d$ | 4.75 | 21.7 |
| | | $Q_t$ | 314.9 | 335.6 |
| | | Peak Power | 0.436 J | 1.208 F |

$Q_d$, $Q_t$ Demand and Total energy in $Kw\text{-}hr/m^2$; Peak Power in $Kw/m^2$

TABLE 11

RESULTS OF COMPUTER RUNS FOR NEW YORK CITY

| No. | SYSTEM DESCRIPTION | Parameter | Average Year | Worst Year |
|---|---|---|---|---|
| 1 | Idealized Surface | $Q_d$ | 48.0 | 79.3 |
| | | $Q_t$ | 215.5 | 333.7 |
| | | Peak Power | 0.671 | 0.718 |
| 2 | Standard Pavement with Demand Energy Only | $Q_d$ | 46.9 | 84.5 |
| | | Peak Power | 0.673 | 0.977 |
| 3 | West Virginia Heat Pipe System, No Demand Energy | $Q_t$ | 186.2 | -- |
| 4 | West Virginia Heat Pipe System, Demand Energy Added During All Precipitation Events to Maintain Surface at 1°C | $Q_d$ | 21.6 | 56.6 |
| | | $Q_t$ | 181.0 | 200.3 |
| | | Peak Power | 0.519 | 0.679 |
| 5 | Same as System #4 Except Starting Earth Temperature Increased 10°F | $Q_d$ | 13.3 | 46.4 |
| | | $Q_t$ | 293.0 | 312.7 |
| | | Peak Power | 0.450 N | 0.626 J |

$Q_d$, $Q_t$ Demand and Total energy in Kw-hr/$m^2$; Peak Power in Kw/$m^2$

TABLE 12

RESULTS OF COMPUTER RUNS FOR DODGE CITY

| No. | SYSTEM DESCRIPTION | Parameter | Average Year | Worst Year |
|---|---|---|---|---|
| 1 | Idealized Surface | $Q_d$ | 68.7 | 92.0 |
| | | $Q_t$ | 343.5 | 417.7 |
| | | Peak Power | 0.839 | 0.803 |
| 2 | Standard Pavement with Demand Energy Only | $Q_d$ | 82.8 | 113.4 |
| | | Peak Power | 0.833 | 0.925 |
| 3 | West Virginia Heat Pipe System, No Demand Energy | $Q_t$ | 189.2 | -- |
| 4 | West Virginia Heat Pipe System, Demand Energy Added During All Precipitation Events to Maintain Surface at 1°C | $Q_d$ | 47.7 | 73.6 |
| | | $Q_t$ | 177.6 | 187.9 |
| | | Peak Power | 0.799 | 0.760 |
| 5 | Same as System #4 Except Starting Earth Temperature Increased 10°F | $Q_d$ | 33.4 | 54.0 |
| | | $Q_t$ | 282.5 | 298.3 |
| | | Peak Power | 0.760 M | 0.702 D |

$Q_d$, $Q_t$ Demand and Total energy in Kw-hr/m$^2$; Peak Power in Kw/m$^2$

TABLE 13

RESULTS OF COMPUTER RUNS FOR MADISON, WISCONSIN

$Q_t$ is the annual energy dissipated by either the idealized surface or the heat pipes, $Q_d$ is the annual demand energy that is required to maintain the surface at $1^{\circ}C$ during all precipitation events, and peak power represents the maximum required rate of demand energy that must be supplied. This maximum power occurs during some month of the winter.

For both New York City and Dodge City, the demand energy during precipitation for the idealized surface and non-heat pipe pavement is about the same for both average and worst years. For Madison, the demand energy for the non-heat pipe pavement is more than 20% higher than that for the idealized surface. These results are understandable when it is recognized that the pavement system in cold climates is below $0^{\circ}C$; and, therefore, when precipitation occurs, demand energy must be supplied to bring the pavement up to $0^{\circ}C$ before energy for melting becomes available.

It should also be noted that the annual dissipations for all three cities for unaugmented and demand augmented systems are approximately the same. Since the heat pipe driving temperature is the average ground temperature at each location and since the average ground temperature is taken as the average annual air temperature and, further, since the spread between wintertime average temperature and average annual temperature is about the same for all locations, these results are also understandable.

The results of the computer runs for various settings of the bimetallic valve shown in Figure 10 are summarized in Table 14. The valve performance was verified in laboratory experiments. The bimetallic element is operated by the heat pipe vapor temperature. The valve shuts off the flow of returning condensate to the condenser when the heat pipe vapor temperature reaches a given value and does not resume the flow of condensate until the vapor temperature drops to some preset lower value. For example, in Case #1 in Table 14, the heat pipe is shut off when the vapor temperature reaches $8^{\circ}C$ ($46.5^{\circ}F$) and is turned on when the vapor temperature drops to $2.5^{\circ}C$ ($36.5^{\circ}F$). The computer runs were made only for the average year at Dodge City.

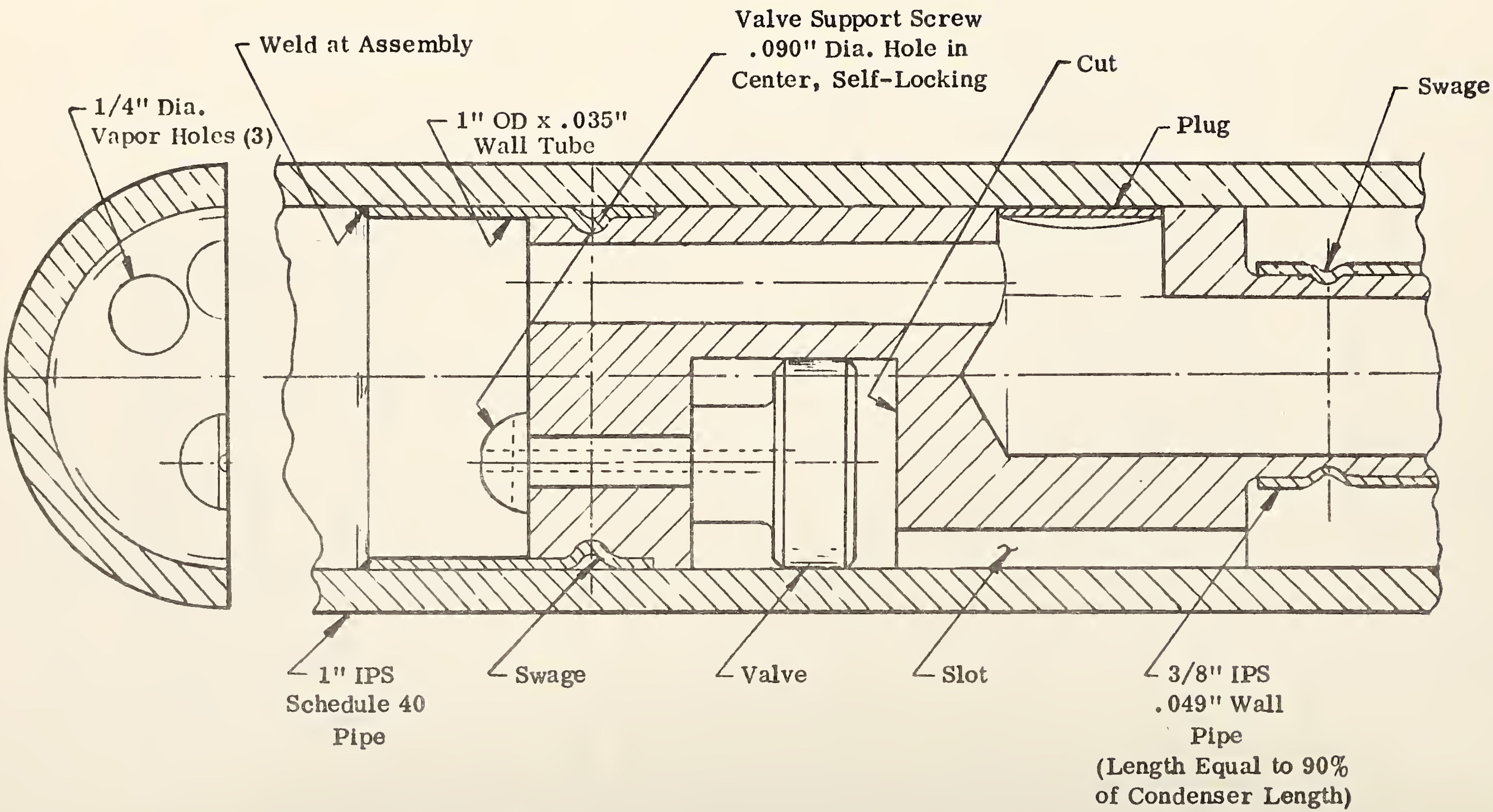



FIGURE 10

BIMETALLIC VALVE INSTALLED IN CONDENSER LEG
OF EARTH HEAT PIPE

| No. | SYSTEM DESCRIPTION | Parameter | Average Year Values |
|---|---|---|---|
| 1 | West Virginia Valved Heat Pipe System - Valve Setting 36.5°F - 46.5°F<br>2.5°C - 8.1°C | $Q_d$ | 22.9 |
| | | $Q_t$ | 124.7 |
| | | Peak Power | 627 |
| 2 | System #1 with Earth Temperature Increased 10°F<br>5.6°C | $Q_d$ | 32.5 |
| | | $Q_t$ | 78.2 |
| | | Peak Power | 614 |
| 3 | West Virginia Valved Heat Pipe System - Valve Setting 40.0°F - 46.0°F<br>4.4°C - 7.8°F | $Q_d$ | 20.5 |
| | | $Q_t$ | 149.9 |
| | | Peak Power | 568 |
| 4 | System #3 with Earth Temperature Increased 10°F<br>5.6°C | $Q_d$ | 18.1 |
| | | $Q_t$ | 139.3 |
| | | Peak Power | 559 |

Peak Power in $W/m^2$

TABLE 14

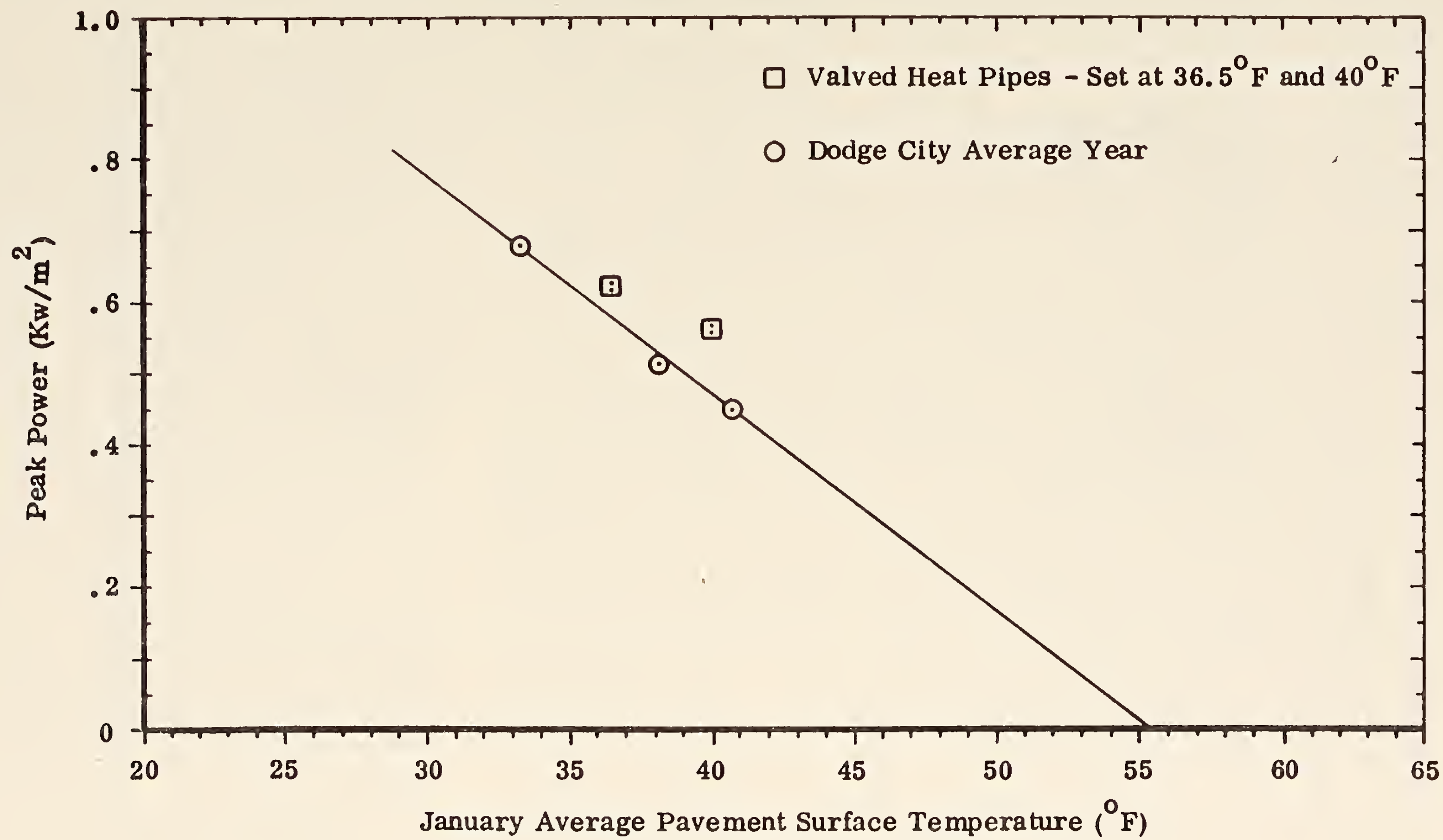
RESULTS OF COMPUTER RUNS FOR VALVED HEAT PIPE SYSTEMS LOCATED AT DODGE CITY

Note that Case #3 in Table 14 represents a system with a performance comparable to Case #4 in Table 12. The valved system, however, has 83% of the annual energy dissipation of the unvalved system. This energy saving feature is even more pronounced if Case #4 in Table 14 is compared with Case #5 in Table 12. This energy saving feature has significant performance and system cost implications for systems augmented by increasing heat pipe field earth temperature.

At the time that these computer runs were made, the temperature settings for the valve were selected randomly or from the data of valve tests. This explains the scatter of results reported in Table 14. Figure 11 shows a plot of peak augmentation power as a function of average January pavement surface temperature for Cases #2, #4, and #5 of Table 12 (average year). Plotted also are the four cases of Table 14 where the turn on heat pipe vapor temperature was taken as the pavement surface temperature (actually the vapor temperature is higher than the surface temperature). To significantly effect peak power and, as will be shown later, demand power, the cut in temperature setting of the valve must be set higher than indicated in Table 14.

The question of summer recovery of the heat pipe field has been raised by many Highway Engineers. The heat capacity in the volume of the earth surrounded by the adiabatic surfaces in the idealized model shown in Figure 8 is 155.7 Kw-hr/$m^2$-$^oC$. If only the volume to a depth of 18.29 m is taken, its heat capacity is 47.2 Kw-hr/$m^2$-$^oC$. At an annual energy dissipation of 200 Kw-hr/$m^2$, the average temperature drop in the large volume is 1.3$^oC$ (2.3$^oF$) and in the small volume it is 4.2$^oC$ (7.6$^oF$). Unfortunately, the construction of the model with adiabatic surfaces does not permit heat to flow into and out of the earth volume from the sides. With the understanding that the results would be pessimistic, a six year computer experiment was run for the average year for Dodge City.

The average year's weather of Dodge City was repeated six times. The final temperatures of the earth of one run became the initial temperatures for the following year run. Alternate energy was allowed to be supplied to the surface in order to maintain its temperature at 1$^oC$ during precipitation. The average temperature of the large volume Figure 8 dropped from an initial value of 11.15$^oC$ (52.07$^oF$) to 6.75$^oC$ (44.15$^oF$) over a six year period. The maximum temperature drop in the




$t_c = (t_F - 32) / 1.8$

FIGURE 11

PEAK POWER AS A FUNCTION OF JANUARY AVERAGE PAVEMENT SURFACE TEMPERATURE FOR VALVED AND UNVALVED HEAT PIPE SYSTEMS six years observed was 6.5$^{\circ}$C (11.7$^{\circ}$F) which occurred at a depth of 6 m (19.7 feet).

Energy delivered by the system decreased from 181 to 97 Kw-hr/m$^2$, corresponding to a 46% decrease. The additional alternate energy required to maintain the surface at 1$^{\circ}$C during all precipitation events increased from 21.6 Kw-hr/m$^2$ to 32 Kw-hr/m$^2$, or an increase of 48%.

W. B. Bienert (Reference 19) observed that, at the center of a field of 19 heat pipes, summer temperature recovery was within 1.9$^{\circ}$C (3.4$^{\circ}$F) of the temperature prior to winter operation. He extracted 189 Kw-hr/m$^2$ from the system. In his model, however, he neglected vertical heat conduction. The average earth temperature drop in the Figure 8 model after the first year summer recovery was 2$^{\circ}$C. It would appear that, if both vertical and horizontal conduction (and heat pipe contributions to conduction) were accounted for in the computer model, the average earth temperature drop after a six year period would be 50% of that computed.

The inner heat pipe selected for the model represents the heat pipe with the lowest heat capacity. Furthermore, the outermost heat pipes (Figure 3) which comprise one third of the field can be considered to be virtually isolated from the remaining heat pipes and, for these, 100% recovery can be assumed. It is estimated, therefore, for the entire heat pipe field, an 80% recovery can be assumed after six years of operation. Computer results show that, after six years, further decreases in performance can be expected to be minor.

The recovery efficiency $\eta_r$ has been thought to be equal to 100 - $\eta_s$, where $\eta_s$ is the storage efficiency. This reversible behavior is strictly true in idealized situations where only thermal conduction is present. This reversible behavior does not hold true for a heat pipe field because, even when the pavement surface heat flux is zero, the heat pipes continue to operate. In fact, the heat pipes continue to operate throughout the entire summer bringing thermal energy from deep earth into the heat pipe field. The computer model correctly accounts for this behavior.

## 2.4 Thermal Design of Earth Heating Systems

The conventional approach to the design of snow melting systems using heated coils is presented in the Snow Melting Design Guide of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (Reference 42) and is based on a decade of work by W. P. Chapman and his associates. The Guide advises that thermal energy is to be added to the pavement system in two distinctly separate modes. The first mode, called the idling mode, applies a low level amount of thermal energy continuously throughout the winter months when the air temperature is less than 32°F. The idling energy is intended to maintain the pavement surface temperature at 32°F during average conditions of temperature and wind speed. The second mode, called the melting mode, applies a higher power during the time of snowfall. The value of required power is determined from an analysis of several years of weather data for each location. Particular events are selected for detailed calculations using a conventional heat transfer equation. There seems to exist a rather general reluctance to rely heavily upon the standards presented in the Guide.

In the present study, a computer was used to perform continuous calculations. Actual weather data tapes were used. Most of the correlations used to calculate the various modes of heat transfer had been previously verified experimentally. The earth, heat pipes, and pavement system were analytically modeled and made part of the continuous calculations. Computer experiments were conducted to ascertain the effects of changing various parameters.

Despite the availability of modern computers, some simplifying assumptions in modeling the entire earth heating system were, nevertheless, required to permit continuous computation of system performance within reasonable computer run times. Where assumptions were required, caution was exercised to make sure that the resulting system performance calculations would be conservative.

The justification for this arduous evaluation of earth heating system performance using actual weather data was to establish, insofar as modern technology permits, an accurate benchmark of system performance in environments of varying severity. An engineering approach to the design of earth heating systems was formulated and tested against the benchmark results obtained using this scientific tool.

## 2.4.1 Augmentation by Increasing Earth Temperature

Because the earth is a low temperature source of thermal energy, earth systems are known as low power systems. The power supplied to the pavement surface, however, is not constant. Generally, it is the highest when snow is being melted and the lowest when the air is calm and warm, when the sun is shining, and when the pavement surface is dry. If the temperature of the earth is increased by additions of thermal energy, then the power at the pavement surface is correspondingly increased under all conditions.

The power that is supplied to the pavement surface by the system is determined by the resistance to heat flow between the earth and the air environments for a dry pavement surface, and by the resistance to heat flow between the earth and the pavement surface when snow is being melted. The resistance to heat flow causes temperature drops to occur all along the heat flow path much like the voltage drops that occur when electric current flows through resistances in an electrical circuit. All temperature drops along the heat flow path must equal the total temperature difference between the earth and the air environments for a dry pavement of between the earth environment and $32^{\circ}F$ on the pavement surface when snow is being melted.

Unfortunately, in the thermal design of earth heating systems, the resistances between the air and pavement surface and between the heat pipes and surrounding ground vary continuously because of varying weather conditions and energy demands on the system. The thermal conditions in the ground during a given snow event are determined by the history of power demand on the system prior to the event. A history of low power demand will permit the system to react with exuberance when confronted with a snow event. A history of high power demand will result in a sluggish response to a snow event. A snow event which lasts for many hours will result in a gradual increase in sluggishness. In view of these complex dynamic responses, it has been decided to characterize the system thermal performance by using average short (1 month) and long-term (5 months) resistances as determined from experiments and computer results.

The ground temperature is defined as the average temperature in the earth at the specified location and is taken as being equal to the annual average air temperature. If the ground temperature is augmented, then the augmentation temperature $\Delta T_g$ is added to the ground temperature $T_g$.

The total system thermal resistance $R_t$ is taken as the resistance between the above ground temperature (adjusted for the drop in temperature due to the earth energy extracted) and the air temperature $T_a$. This implies that over a sufficient period of time the incoming and outgoing radiations balance each other and convection losses dominate the heat transfer process for a dry pavement surface. The total system resistance consists of three separate resistances. (The resistance of the heat pipe itself is small in comparison and is lumped into the ground-to-pipe resistance.)

$$R_t = R_{g,p} + R_{p,s} + R_{s,a}$$

These individual resistances are the resistance between the ground and heat pipe $R_{g,p}$, the resistance between the heat pipe and the pavement surface $R_{p,s}$, and the resistance between the pavement surface and the air $R_{s,a}$. If the total resistance is to be determined for the five winter months, it is designated as $R_{t,5}$. Similarly, the resistance between the pavement surface and air for a given month is designated as $R_{s,aj}$ for January, etc.

As the winter progresses, the energy delivered to the pavement surface decreases the average heat pipe field earth temperature. Before the value of $R_{t,5}$ can be determined from the results of the computer runs, the decrease in earth temperature must be determined. For this, the product of the volume of earth coupled by the heat pipes and the specific heat of the earth (heat capacity) is required. For the reference West Virginia design, the volume of earth coupled by the heat pipes was taken as the volume within the area formed by the pavement surface, the outermost heat pipes, and an arc drawn through the tips of the heat pipes at the bottom. The value for the specific heat was that used in the computer calculations. A conservative value of heat capacity of the earth heat pipe field with respect to the pavement surface was determined to be:

$$C_{e,s} = 33.57 \text{ Kw-hr/m}^2\text{-}^{\circ}\text{C}$$

Using this heat capacity, the local value of ground temperature, the average five month value of winter air temperature, and the calculated five month energy losses, the value of $R_{t,5}$ for each of the three cities is:

| | $^oF-ft^2/W$ | $^oC-m^2/Kw$ |
|---|---|---|
| New York City | 2.432 | 125.5 |
| Dodge City | 2.321 | 119.8 |
| Madison | 2.788 | 143.9 |

Note that the above values are for 1 inch OD tube, whereas the West Virginia design utilized 1 inch IPS pipe. Corrections for this difference are made later.

Average values for the pavement and earth portions of the total resistance were determined experimentally for the initial Virginia heat pipe installation and are reported in Reference 1. Correcting for the physical differences between the Virginia design and the computer model, the value of the resistance from the ground to the pavement surface ($R_{g,p} + R_{p,s}$) is $71.28^oC-m^2/Kw$ ($1.381^oF-ft^2/w$). This value is assumed to remain the same for all three cities. Therefore, the average winter pavement surface-to-air resistance by difference is:

| | $^oF-ft^2/W$ | $^oC-m^2/Kw$ |
|---|---|---|
| New York City | 1.051 | 54.25 |
| Dodge City | 0.940 | 48.52 |
| Madison | 1.407 | 72.62 |

The above method was also used to obtain the average resistance between the pavement and air for January which is normally the month having the severest winter weather. The inverse ratio of this resistance to the total system resistance for the West Virginia design is plotted against average January wind velocity in Figure 12. This ratio is used in calculating the average January pavement surface temperature. In all resistance calculations, the pavement surface was assumed to be dry which introduces a small error because the hours during melting represent a small fraction of the total hours in a month.

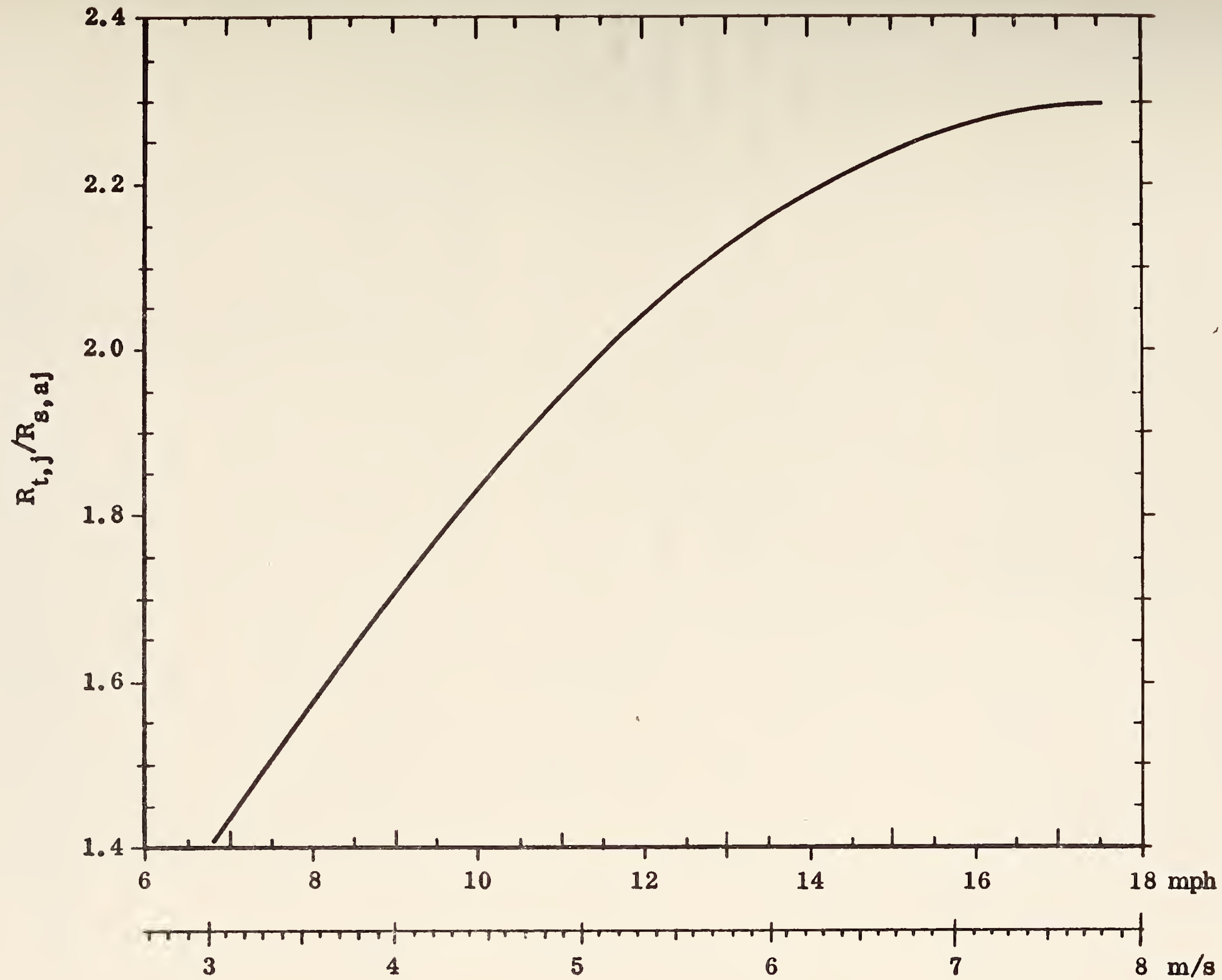


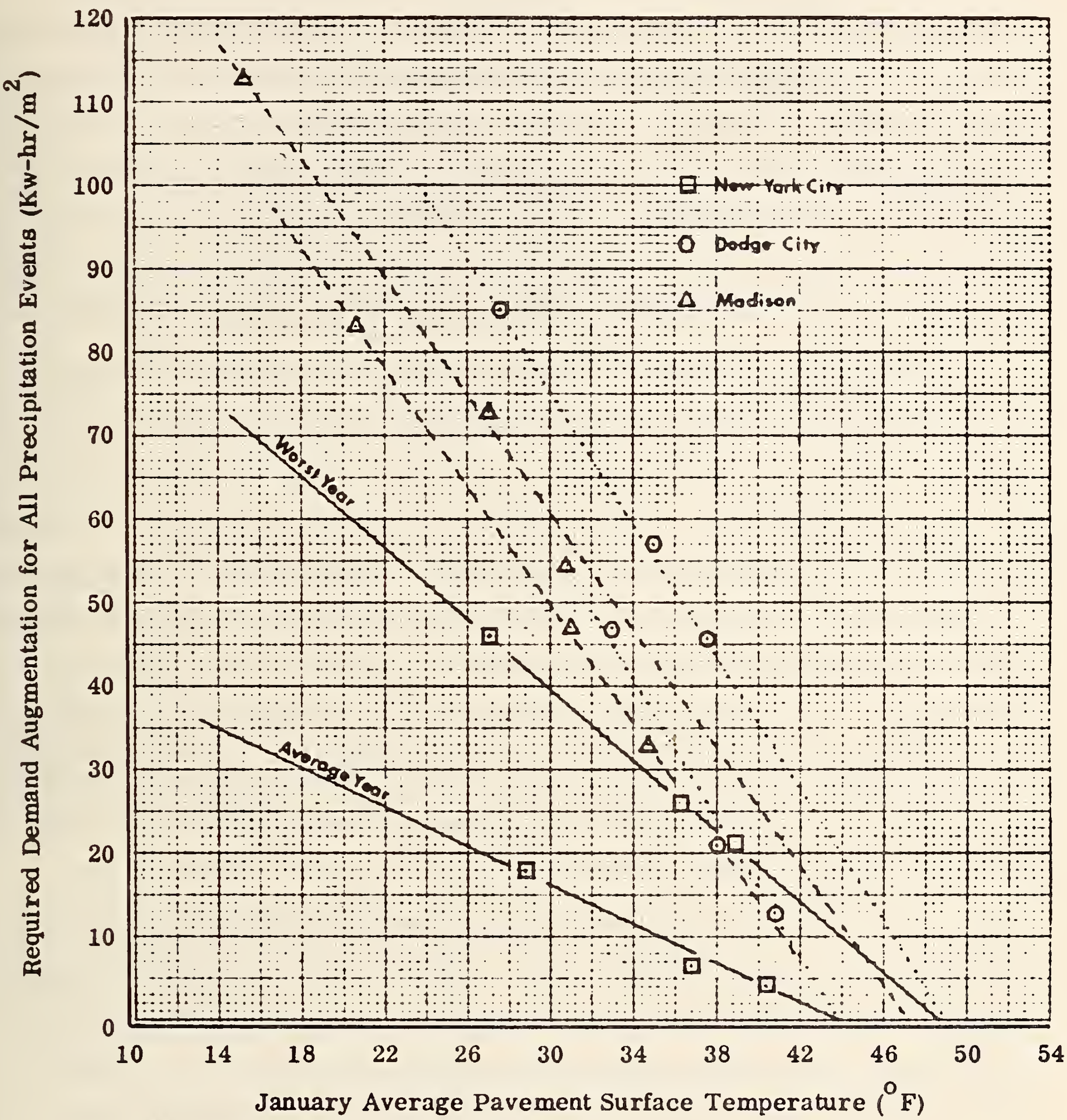

FIGURE 12

RESISTANCE RATIO FOR VARIOUS JANUARY AVERAGE WIND VELOCITIES

For earth heating systems to be effective, the pavement surface temperature must be above freezing during the severest weather month (January). The average surface temperature for January was calculated for the non-heat pipe demand system, the West Virginia heat pipe system, and the West Virginia heat pipe system with an increase of 5.56°C (10°F) in earth temperature at the beginning of the winter season. Actual January average wind velocities and air temperatures and calculated average January system resistances were used. This was done for all three cities and for both the average and worst years. The computer calculated annual augmentation requirements were plotted against the calculated January surface temperature and are shown in Figure 13.

In Figure 13, the annual augmentation ordinate is for all precipitation events, both measurable and non-measurable. This is conservative. The data is extrapolated to zero augmentation using straight lines. This extrapolation may not be conservative at low values of augmentation in some locations, and the implications of this are discussed later. The lower slope of New York City is due primarily to cloud cover effects (see Section 2.3.1). For design engineering purposes, a January surface temperature of 9.44°C (49°F) was selected for systems defined as full performance systems since this is the maximum surface temperature at which zero augmentation was achieved in these six case histories.

In order to make augmentation calculations more useful to practical Highway Engineers, some simplifications consistent with the recognized limited preciseness of available site data and good engineering judgment have been introduced. The first simplification concerns the value to be used for average January air temperature. The air temperature throughout the United States cycles about the ground temperature (average annual air temperature) in a more or less sinusoidal manner with a maximum in July and a minimum in January. A survey of over 60 cities located on the Interstate Highway system shows that the average January air temperature is between 11 to 14°C (19.8 to 25.2°F) below the local average ground temperature except for a group of midwestern cities formed by the boundary of Bismark, North Dakota; Sioux Falls, South Dakota; Omaha, Nebraska; Des Moines, Iowa; and Minneapolis, Minnesota, where the value is 16.7°C (30°F) and except for cities along the Pacific Coast




$t_C = (t_F - 32) / 1.8$

FIGURE 13

REQUIRED DEMAND AUGMENTATION OF WEST VIRGINIA SYSTEM FOR THREE STUDY CITIES AS A FUNCTION OF JANUARY AVERAGE PAVEMENT SURFACE TEMPERATURE where, typically for Salem, Oregon; Portland, Oregon; and Seattle, Washington, the value is 8°C (14.4°F). Further, a survey of the 50 to 70 year weather histories of a representative spectrum of cities shows that the lowest average January air temperature is about 4.5°C (8.1°F) lower than the above stated averages. In view of this information, a value of 16.7°C (30°F) below average ground temperature was selected as the average January air temperature applicable to most cities in the United States where augmented earth heating systems are likely to be used. A value of 13.9°C (25°F) was selected for the Pacific Northwest coastal region.

The amount of energy extracted from the earth during the winter season has a second order effect on the required augmentation. This is because, as energy is extracted, the temperature of the earth is decreased and this decrease in temperature reduces the performance of earth heating systems and must be accounted for. The amount of energy extracted is determined by the five month average winter air temperature, the total resistance for five winter months $R_{t,5}$, and the heat capacity of the earth coupled to the pavement surface.

The five winter months average air temperature was also determined for locations throughout the United States. The difference between local ground temperature and the five winter months average temperature is designated by $\delta T$. Values for $\delta T$ by region are shown in Figure 17.

Regions of high, medium, and low average January wind velocities throughout the United States are shown in Figures 58 and 59. Highway Engineers recognize that significant variation from regional averages may occur locally. Studies show that the five winter months average wind velocity also falls in the high, medium, and low regions shown in Figures 58 and 59. Since the effect of the five winter months average wind velocity is second order, it was decided to designate five winter months resistance $R_{t,5}$ by high, medium, and low regions of wind velocity. For the West Virginia design, these values are:

| Wind Region | °F-ft²/W | °C-m²/Kw |
|---|---|---|
| High | 2.10 | 108.4 |
| Medium | 2.25 | 116.1 |
| Low | 2.55 | 131.6 |

By incorporating these simplifications into heat transfer expressions, the following is obtained for the required temperature augmentation of the earth to achieve a full performance West Virginia system (in metric units):

$$\Delta T_g = \frac{R_{t,5} + 53.98}{R_{t,5}} \left( \frac{R_{t,j}}{R_{s,aj}} (26.11 - T_g) - 16.67 + \frac{53.98 \ \delta T}{R_{t,5} + 53.98} \right)$$

The required temperature augmentation in English units is given by:

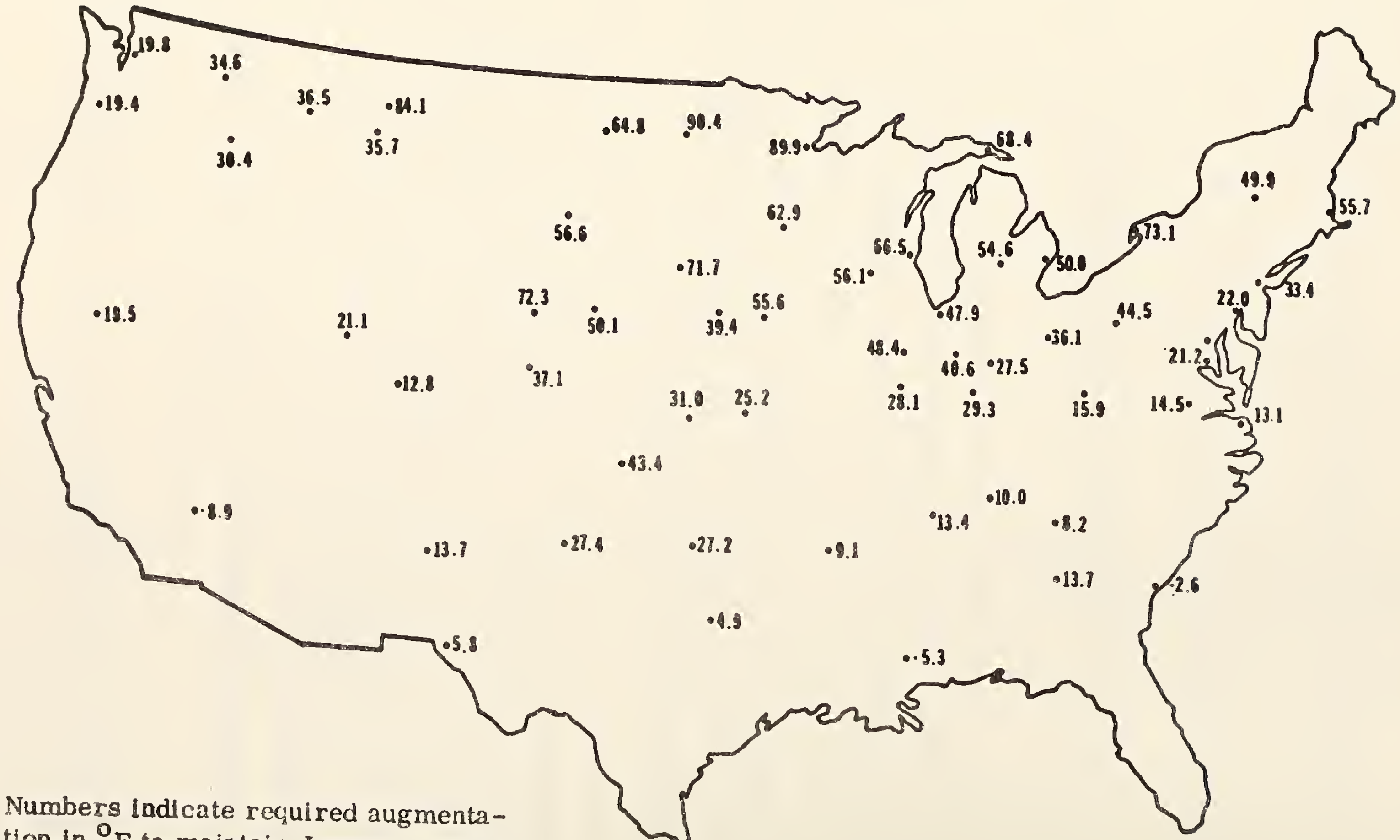
$$\Delta T_g = \frac{R_{t,5} + 1.05}{R_{t,5}} \left( \frac{R_{t,j}}{R_{s,aj}} (79 - T_g) - 30 + \frac{1.05 \ \delta T}{R_{t,5} + 1.05} \right)$$

The temperatures are in either $^{o}C$ or $^{o}F$ and the values of $R_{t,5}$ were given previously in English and Metric units. The ratio $R_{t,j}/R_{s,aj}$ is obtainedfrom Figure 12 for the average January wind velocity for the particular location under consideration. The average January wind velocities given in Figures 58 and 59 are usually obtained at weather stations located at airports. The Highway Engineer should use his judgment in selecting the wind velocity to use for the specific pavement site to be heated as this can have a considerable influence on the required augmentation.

For a nominal climate with average wind speeds ( $\delta T = 9.1^{o}C$, $V = 4.9$ m/s, $T_g = 12.8^{o}C$), the predicted increase in earth temperature needed to achieve a full performance system is $17.7^{o}C$ ($31.8^{o}F$). For the West Virginia system located in West Virginia ( $\delta T = 9.1^{o}C$, $V = 3.6$ m/s, $T_g = 13.1^{o}C$), the predicted increase in earth temperature needed to achieve a full performance system is $8.8^{o}C$ ($15.9^{o}F$). This calculation has been repeated for other cities on the Interstate Highway system and the results are shown in Figures 14 and 15.

The average January pavement surface temperature in metric units is given by:

$$T_{s,j} = T_g - 16.67 + \frac{R_{s,aj}}{R_{t,j}} \left( \Delta T_g + 16.67 - \frac{53.98 \ (\Delta T_g + \delta T)}{R_{t,5} + 53.98} \right)$$




Note: Numbers indicate required augmentation in $^{o}F$ to maintain January average pavement surface temperature at $49^{o}F$.

FIGURE 14

REQUIRED INCREASE IN EARTH TEMPERATURE TO ACHIEVE FULL PERFORMANCE WEST VIRGINIA DESIGN SNOW MELTING SYSTEM


Note: Numbers indicate required augmentation in $^{o}C$ to maintain January pavement surface temperature at 9.44 $^{o}C$

FIGURE 15

REQUIRED INCREASE IN EARTH TEMPERATURE TO ACHIEVE FULL PERFORMANCE
WEST VIRGINIA DESIGN SNOW MELTING SYSTEM

For the unaugmented West Virginia system located in West Virginia ($\Delta T_g = 0$), the calculated average January pavement surface temperature is $5.37^oC$ ($41.8^oF$). By using this surface temperature in place of the $9.4^oC$ ($49^oF$) January surface temperature for a full performance system, locations of equivalent performance throughout the country can be determined. This is shown in Figure 16.

### 2.4.2 Augmentation By Supplying Energy During Snowfall

Earth heating systems can be augmented by supplying energy from an external source during periods of snowfall (melting mode of the ASHRAE Guide). The required energy for all events as a function of average January pavement surface temperature is given in Figure 13 for the average and worst years for the three cities studied by computer techniques. The January average air temperature and wind speed and the calculated average January surface temperature along with the peak power and annual precipitation and precipitation hours are given in Table 15.

A conservative estimate of the amount of augmentation energy required may be obtained by calculating the average January surface temperature by the method discussed previously and choosing the particular set of data from Table 15 most closely corresponding to the selected location and using Figure 13 to read the melting energy for the calculated surface temperature. The rate of energy (power) that must be delivered to the pavement surface will be discussed later.

### 2.4.3 Annual Energy Dissipation

The annual energy dissipated from West Virginia earth heating systems during the five winter months is given in metric units by:

$$Q_t = \frac{3624\ (\Delta T_g + \delta T)}{R_{t,5} + 53.98}$$

For a full augmentation system, the value of $\Delta T_g$ is determined and the value of $Q_t$ becomes:


Note: Locations below the line will perform better than demonstrated and above the line will perform poorer.

FIGURE 16

LINE DESIGNATING LOCATIONS AT WHICH UNAUGMENTED SYSTEMS OF THE WEST VIRGINIA DESIGN WILL HAVE PERFORMANCE EQUAL TO THAT DEMONSTRATED AT WEST VIRGINIA

| CITY | Type Year | Average January Temperature | Average January Wind Velocity | Ground Temperature | Peak Power | Total Snowfall | Total Precipitation Time | January Average Surface Temperature |
|---|---|---|---|---|---|---|---|---|
| | | °C | m/s | °C | $W/m^2$ | cm $H_2O$ | Hours | °C |
| New York | A | -1.78 | 5.75 | 12.8 | 482 | 5.0 | 168 | 3.2 |
| | W | -2.40 | 5.74 | 12.8 | 1251* | 14.7 | 180 | 2.3 |
| Dodge | A | 0.67 | 6.25 | 10.0 | 519 | 3.9 | 425 | 3.4 |
| | W | -2.41 | 6.35 | 10.0 | 679 | 7.3 | 354 | 1.5 |
| Madison | A | -6.64 | 4.08 | 7.4 | 799 | 5.8 | 512 | -0.6 |
| | W | -9.29 | 4.62 | 7.4 | 760 | 8.5 | 678 | -2.7 |

*Represents 6.5 cm water equivalent snowfall in 37 measurable precipitation hours.

TABLE 15

ACTUAL COMPUTER MODEL JANUARY WEATHER DATA AND
COMPUTED JANUARY AVERAGE PAVEMENT SURFACE TEMPERATURES

$$Q_t = \frac{3624}{R_{t,5}} \left( (26.11 - T_g) \frac{R_{t,j}}{R_{s,aj}} - 16.67 + \delta T \right)$$

The energy dissipated, $Q_t$, is given in Kw-hrs/$m^2$ as related to the pavement surface and 3624 represents the number of hours in five winter months. Some adjustments in the number of hours can be made; however, $R_{t,5}$ and $\delta T$ have been determined for five months. Figure 17 gives the regional values for $\delta T$.

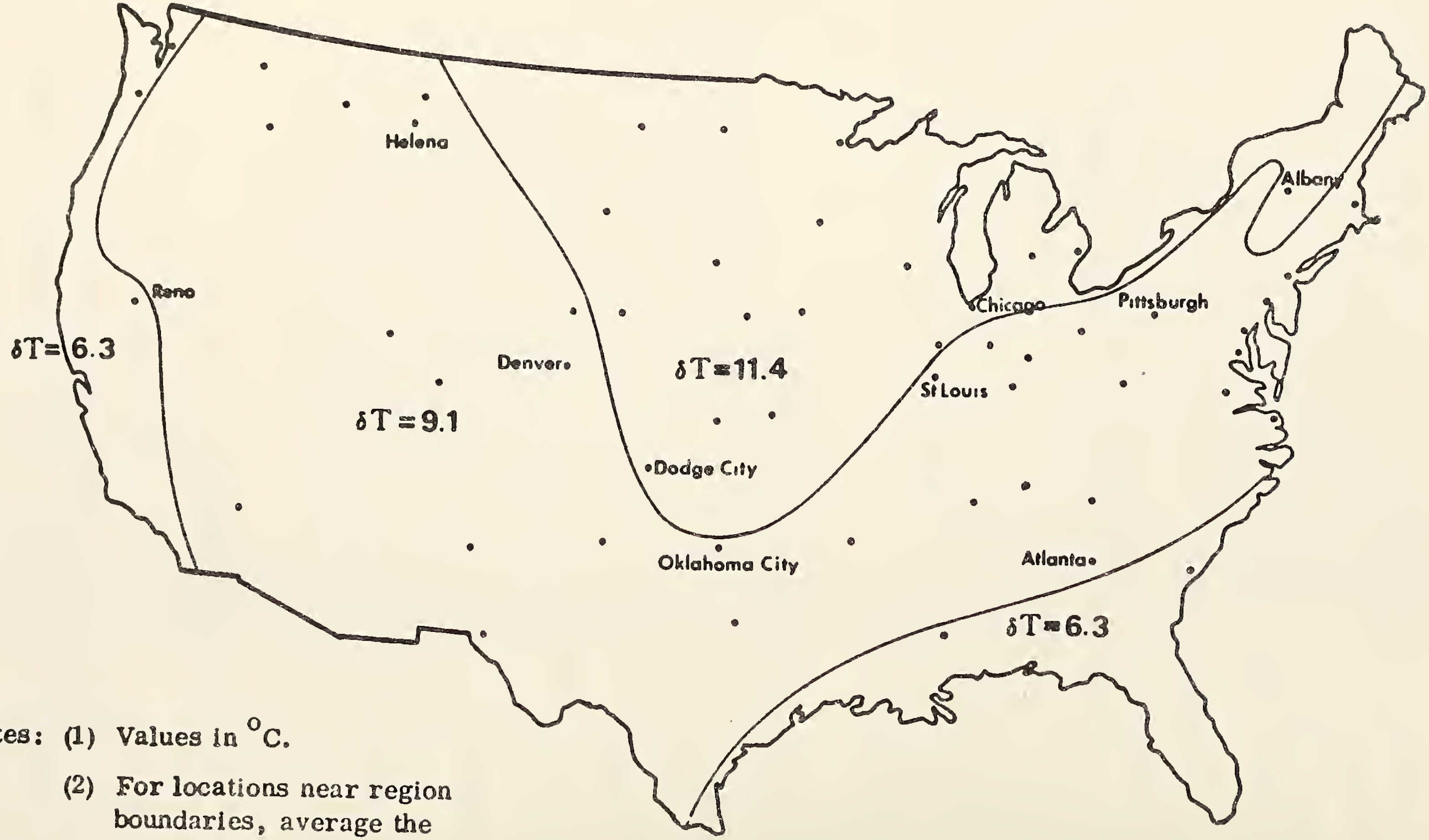
Without attempting to introduce refinements, the total energy dissipation for an augmented West Virginia system is given in Figure 18 for various locations in the United States. Because of the relationship between unaugmented ground temperature and climate severity, it is also possible to calculate $Q_t$ for various unaugmented ground temperatures. Figures 19 and 20 show the variation of $Q_t$ for a full performance system as a function of January average wind velocity for various values of unaugmented ground temperature.

### 2.4.4 System Performance as Related to Peak Power

The analysis heretofore assumes that a full performance system exists when the straight line extrapolations shown in Figure 13 intersect a surface temperature value at zero demand augmentation. Table 15 lists computer determined values of peak power for demand augmented earth heating systems for the three cities investigated. Because earth heating systems are nonlinear to short term changes, it is not possible to predict their power capability for single snow events by using averaging techniques. It is possible, however, to calculate January average power for a dry surface. It is assumed (confirmed by computer calculations) that one-half the total annual energy dissipation has occurred by the middle of January.

$$\dot{q}_j = \frac{\Delta T_g + 16.67 - Q_t/2\, C_{e,s}}{R_{t,j}}$$

The terms have been defined previously and $\dot{q}_j$ is in Kw/$m^2$. The value of the total January system resistance as a function of wind speed is given in Figure 21. The




Notes: (1) Values in $^{\circ}C$.

(2) For locations near region boundaries, average the values of both regions.

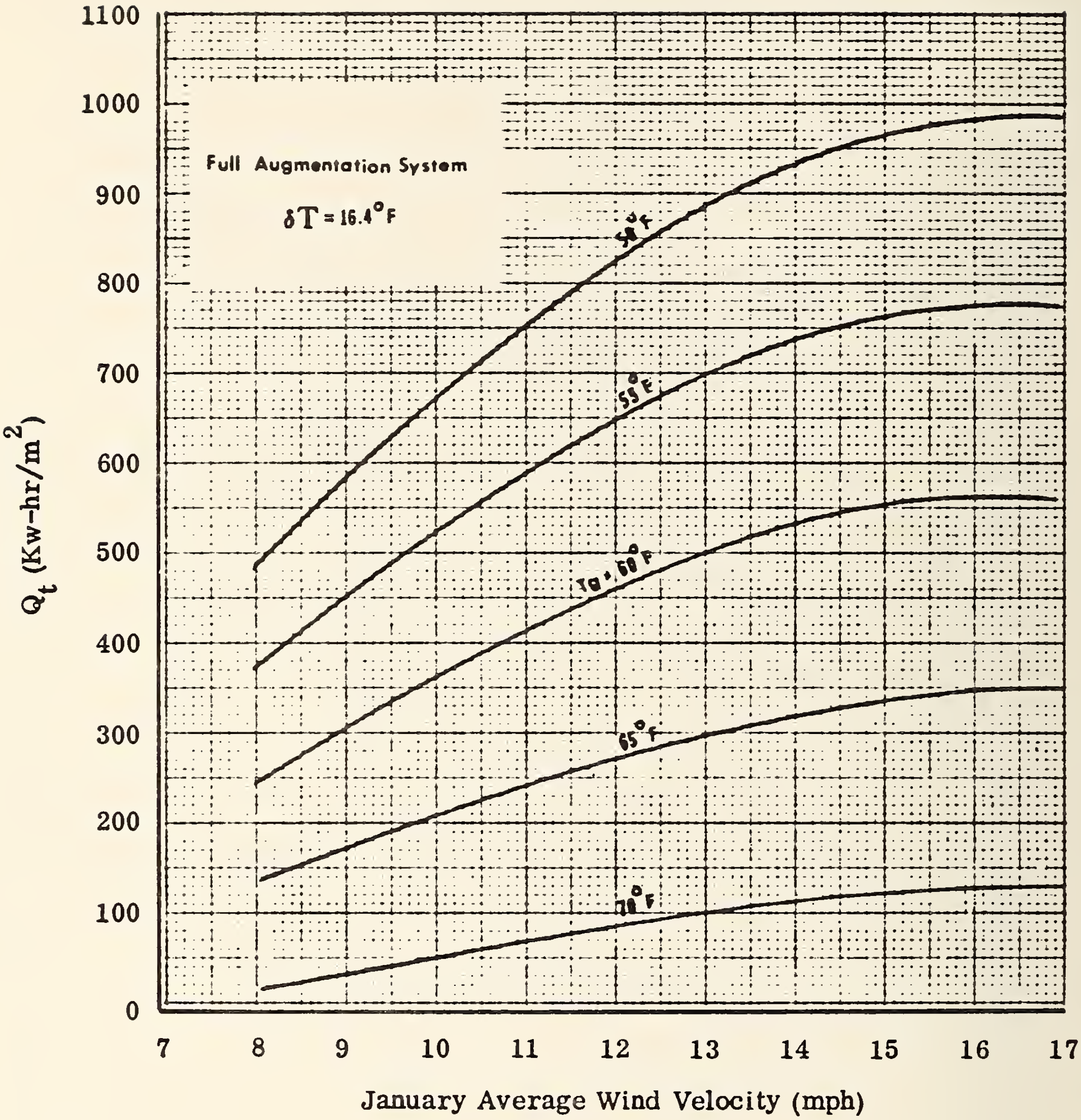
FIGURE 17

REGIONAL VALUES FOR THE DIFFERENCE BETWEEN UNAUGMENTED GROUND TEMPERATURE AND THE FIVE MONTH AVERAGE WINTER AIR TEMPERATURE


Note: Numbers indicate energy loss in Kw-hr/m$^2$.

FIGURE 18

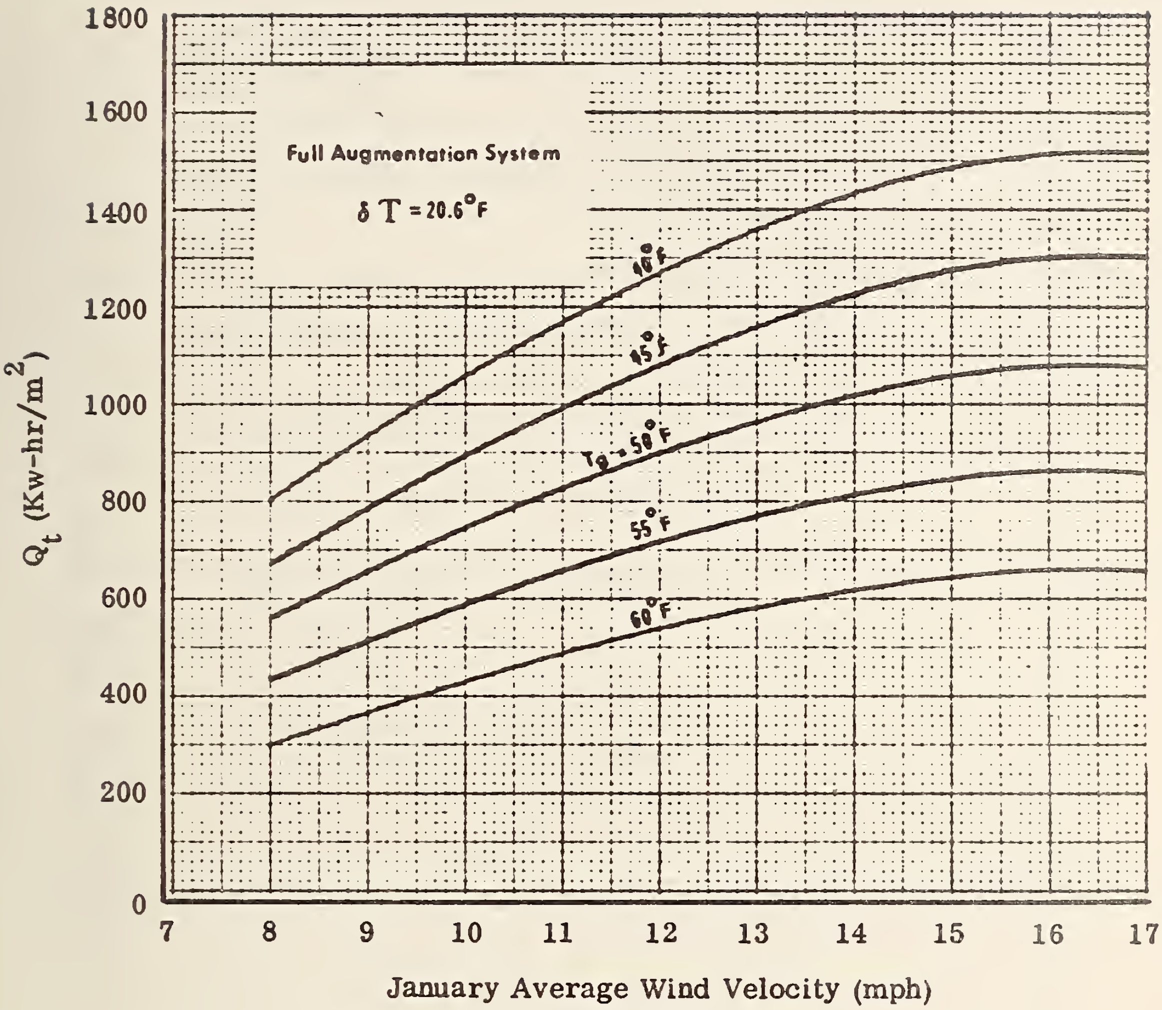
TOTAL ENERGY LOSS IN THE FIVE WINTER MONTHS FROM A FULL PERFORMANCE WEST VIRGINIA DESIGN SNOW MELTING SYSTEM




1 mph = 0.447 m/s

FIGURE 19

TOTAL ENERGY LOSS AS A FUNCTION OF
JANUARY AVERAGE WIND VELOCITY




1 mph = 0.447 m/s

FIGURE 20

TOTAL ENERGY LOSS AS A FUNCTION OF JANUARY AVERAGE WIND VELOCITY

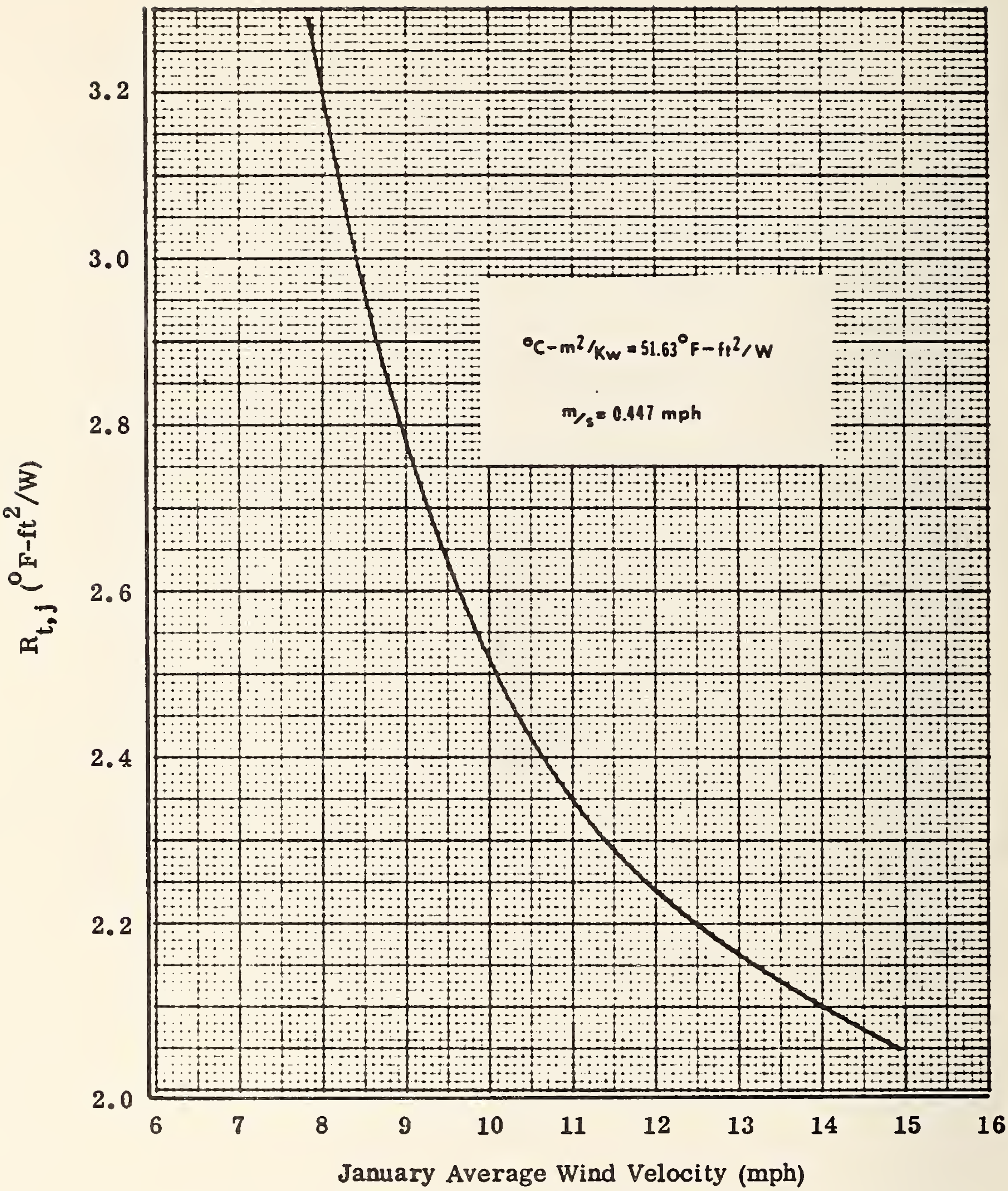



FIGURE 21

TOTAL SYSTEM RESISTANCE AS A FUNCTION OF JANUARY AVERAGE WIND VELOCITY above expression merely says that the average January power is equal to the difference between the augmented ground temperature and the January air temperature corrected for the ground temperature reduction due to energy extraction to January and this net total divided by the total January system resistance evaluated at the average January wind speed.

For example, the West Virginia design located in West Virginia dissipates 350 $Kw\text{-}hr/m^2$ when augmented $8.8^oC$. For an average January wind velocity of 3.6 m/s the $R_{t,j}$ from Figure 21 is $164.1^oC\text{-}m^2/Kw$. The value of the heat capacity of the earth related to the surface was given previously and is $33.57\ Kw\text{-}hr/m^2\text{-}^oC$. Substituting these values, $\dot{q}_j$ becomes $0.123\ Kw/m^2$ ($11.5\ W/ft^2$) which is the average January power when the pavement surface is dry. This power can be thought of as the idling power as defined by the ASHRAE Guide.

The average January power for a wet melting surface at a temperature $T_m = 0^oC$ ($32^oF$) is given by:

$$\dot{q}_{j,m} = \frac{\Delta T_g + T_g - T_m - Q_t/2\,C_{e,s}}{R_{g,p} + R_{p,s}}$$

For the augmented West Virginia design, the steady state value of $R_{g,p} + R_{p,s}$ is $59.05^oC\text{-}m^2/Kw$ ($1.144^oF\text{-}ft^2/W$). The unaugmented ground temperature in West Virginia is $13.1^oC$ ($55.6^oF$). The average melting power for the augmented system is $0.282\ Kw/m^2$ ($26.3\ W/ft^2$). Note that the average melting power is more than two times the idling power.

The augmented heating system has an average short-term power capability above this average melting power. This additional capability derives from the stored thermal energy in the pavement and the nonlinear response of the earth-to-heat pipe resistance to changes in power.

The average drop in pavement temperature during the transition from dry to wet conditions (represents energy which transiently contributed to melting power) is given by:

$$\Delta T_p = (0.282 - 0.123)\,(R_{p,s})$$

For the above case ($R_{p,s} = 37.1^{o}C\text{-}m^2/Kw$), this is $5.9^{o}C$ ($10.6^{o}F$). Averaged over a 10-hour period, this drop in temperature will contribute 0.060 $Kw/m^2$ to the average melting power.

As evident from Figure 9 and confirmed by Ingersoll (Reference 37), a sudden application of power demand on an earth heat pipe system will result in an initial ground-to-pipe resistance about 50% of the long-term resistance. Over the first 10 hours, the available power from the earth system due to this effect is 0.323 $Kw/m^2$ compared with the longer term value calculated for melting of 0.282 $Kw/m^2$. Adding the transient power due to pavement heat capacity to this transient melting power resulting from nonlinear system behavior yields a total 10-hour power capability for the West Virginia augmented system of 0.383 $Kw/m^2$ (35.6 $W/ft^2$). This is approximately the estimated power required to handle the incident described in Section 1.

The ASHRAE Guide (Reference 42) presents the results of a frequency analysis of the required melting powers for 33 representative United States cities. The analysis was made by selecting particular events from historical weather records and performing detailed calculations on an idealized surface to obtain melting power. Each event represents a definite number of hours of snowfall. The analysis permits an estimate to be made of the percentage of annual snowfall hours that an idealized pavement heating system can melt snowfall as rapidly as it falls. The ASHRAE results have been confirmed by the idealized surface analysis performed by the present study. The analysis has been shown to give pessimistic results for unaugmented earth heating systems. This pessimism can be partly offset by using the 10-hour transient power capabilities of earth heating systems in estimating snow melting performance using the idealized surface data. The time period of 10 hours was selected because this is the median duration of storm sizes ranging from 1.27 cm (0.5 inch) to 8.86 cm (3.49 inches) snowfall as determined by an analysis of 10 years of weather data for 10 representative locations throughout the United States (Reference 45).

The 10-hour capability for fully augmented earth heating systems was calculated for the 33 cities listed in the Guide. A comparison of the calculated power capability against the ASHRAE frequency analysis for each city shows that, for all cities except seven, the augmented earth system will melt snow as rapidly as it falls for more than 90% of the annual snowfall hours. The exceptions and the associated percentages are:

| | |
|---|---|
| Amarello, Texas | >80% |
| Cheyenne, Wyoming | >80% |
| Colorado Springs, Colorado | >80% |
| Memphis, Tennessee | >80% |
| Oklahoma City, Oklahoma | >75% |
| Rapid City, South Dakota | >75% |
| Salina, Kansas | >80% |

It should be noted that the ASHRAE Guide does not specify 100% melting capability but is based on melting frozen precipitation as rapidly as it falls in 98% of the events when there is measurable snowfall and that the system does not fail to melt all snow for two consecutive hours.

Of the seven exceptions, the ASHRAE data for Memphis is anomalous and must be disregarded. The remaining six cities are located in the Central Plains region. This region is generally characterized by high wind velocities and high ranges in daily temperature. The calculated 10-hour transient power capability is based on average January conditions and, therefore, may underestimate the power capability of the system for specific snow events.

A small unaugmented heat pipe earth heating system has been installed in a composite bridge deck located in Sybille Canyon, Wyoming. Climatic parameters of this location for this year are very similar to Cheyenne, Wyoming, except that about one-third as much snow fell during the 1977-1978 Winter (10.3 cm water equivalent) as generally in Cheyenne. The maximum power delivered to the pavement surface was estimated to be 0.20 $Kw/m^2$ which, in accordance with the ASHRAE frequency analysis for Cheyenne, is capable of maintaining a bare pavement 24% of the total snowfall hours. It was observed that for the Winter of 1977-1978 the heat pipe system successfully melted approximately 60% of all of the snow as rapidly as it fell during the daylight hours. (The pavement surface condition was recorded photographically at five minute intervals during daylight hours.) The average weather characteristics for the Sybille Canyon test year are thought to be more representative of the winter weather at Salina, Kansas. However, it should be noted that, during January of the test year, the average air temperature was $-4.5^{o}C$ ($23.9^{o}F$), the wind speed was 8.1 m/s (18.1 mph), and 60% of the total winter snowfall occurred. For Salina, Kansas, the ASHRAE frequency analysis predicts a bare pavement for 53.5% of the snowfall hours at a peak power of 0.20 $Kw/m^2$.

The average January 10-hour transient power capability for a fully augmented system located at Salina, Kansas, is 0.443 $Kw/m^2$. Using the ASHRAE frequency data for Salina, this power will maintain a bare pavement for 87% of the snowfall hours.

Experience with earth heating systems in the United States is only available at the West Virginia and Sybille Canyon sites. Both installations perform better than expected. However, in view of the Highway Engineer's desire to maintain a bare pavement in critical locations for more than 90% of the time and preferably for more than 95%, it appears prudent for the time being to install a backup augmentation system in the Central Plains region. This may later be eliminated as more operating experience is obtained.

## 2.5 Sources of Energy for Augmentation

A survey of solar, ambient air, and wind renewable energy sources and of energy from biodegradation of refuse for use in pavement heating has been made and the results are summarized in this section. The summertime collectable energy for solar and ambient air and the wintertime collectable energy for wind have been determined for the worst years for New York City, Dodge City, and Madison. All values are given in $Kw\text{-}hr/m^2$ where, in each case, the area refers to the area of the solar collectors, the face area of the ambient air heat exchanger, and the face area of the wind rotor.

### 2.5.1 Solar Energy

The commercialization of solar energy technology (Reference 18) for purposes of heating is rapidly becoming a reality. Increasing fuel costs, natural gas shortages, and U.S. Government demonstration programs have all contributed to this realization. Many companies, both large and small, have entered the market and are offering concentrating and nonconcentrating solar collectors of various designs. Foreign based companies are importing solar collector designs of proven service life for manufacture and sale in the United States.

A sufficient number of companies have standardized performance data for catalogue flat plate solar collectors to permit meaningful comparisons, although care must be taken to exclude data which is unsupported by sufficient test information. The performance is specified in terms of collection efficiency (for a constant wind velocity) as a function of the following loss factor:

$$L_f = \frac{\frac{T_o + T_i}{2} - T_a}{Q} \quad , \quad \frac{m^2 - {}^oC}{W} \quad \text{or} \quad \frac{hr\text{-}ft^2 - {}^oF}{Btu}$$

and quoted values range from zero to 0.17 in metric units and to 1 in English units. In the loss factor term, $T_i$ is the inlet water temperature and $T_o$ is the outlet water temperature to the collector, $T_a$ is the air ambient temperature, and Q is the insolation in $W/m^2$ ($Btu/hr\text{-}ft^2$). An independent consulting engineering firm, Dubin-Bloome

Associates of New York City, surveyed available solar collector performance data of a number of marketed collectors. For a loss factor value of zero, the efficiencies varied from 54 to 86%; for a $L_f$ value of 0.0875 $m^2$-$^oC/W$, efficiencies varied from 8 to 62%; and, for a $L_f$ value of 0.17 $m^2$-$^oC/W$, efficiencies for all except six collectors was zero.

For an augmentation system using ground water at a temperature of 10$^o$C (50$^o$F) and heating it to 37.8$^o$C (100$^o$F) the average value of the loss factor for January of the worst year for each of the three cities is:

| | Horizontal Orientation | 40$^o$ Inclination |
|---|---|---|
| New York City | 0.13 | 0.051 |
| Dodge City | 0.88 | 0.034 |
| Madison | 0.11 | 0.043 |

Most horizontally oriented nonconcentrating collectors will collect a negligible amount of energy during January of the worst year in each of the cities. Even under ideal inclinations, most commercially available collectors will have single glaze efficiencies varying from 55% for Dodge City to 45% for New York City. Double glazed collectors are 5 to 10% more efficient; however, they are correspondingly more expensive.

In each of the cities for both the average and worst years, the average monthly solar radiation falling on a horizontal surface maximizes during June and July and minimizes during December (Figures 22, 23, 24). The maximum/minimum ratio is about 4 for northern cities and is somewhat less in southern cities. The year-to-year variation of solar radiation does not deviate by more than 8% from the average of all the years surveyed for each of the three cities. Solar energy, therefore, represents a reasonably stable source. Its disadvantage is that storage must be provided to keep the area of the collectors and, therefore, system cost to a reasonable value. Previous studies of solar heating systems for pavement snow removal has shown this to be true (Reference 2).

Summertime collection efficiency at temperatures of 37.8$^o$C (100$^o$F) are high (about 75%) for even poorly constructed collectors because of high ambient tempera-

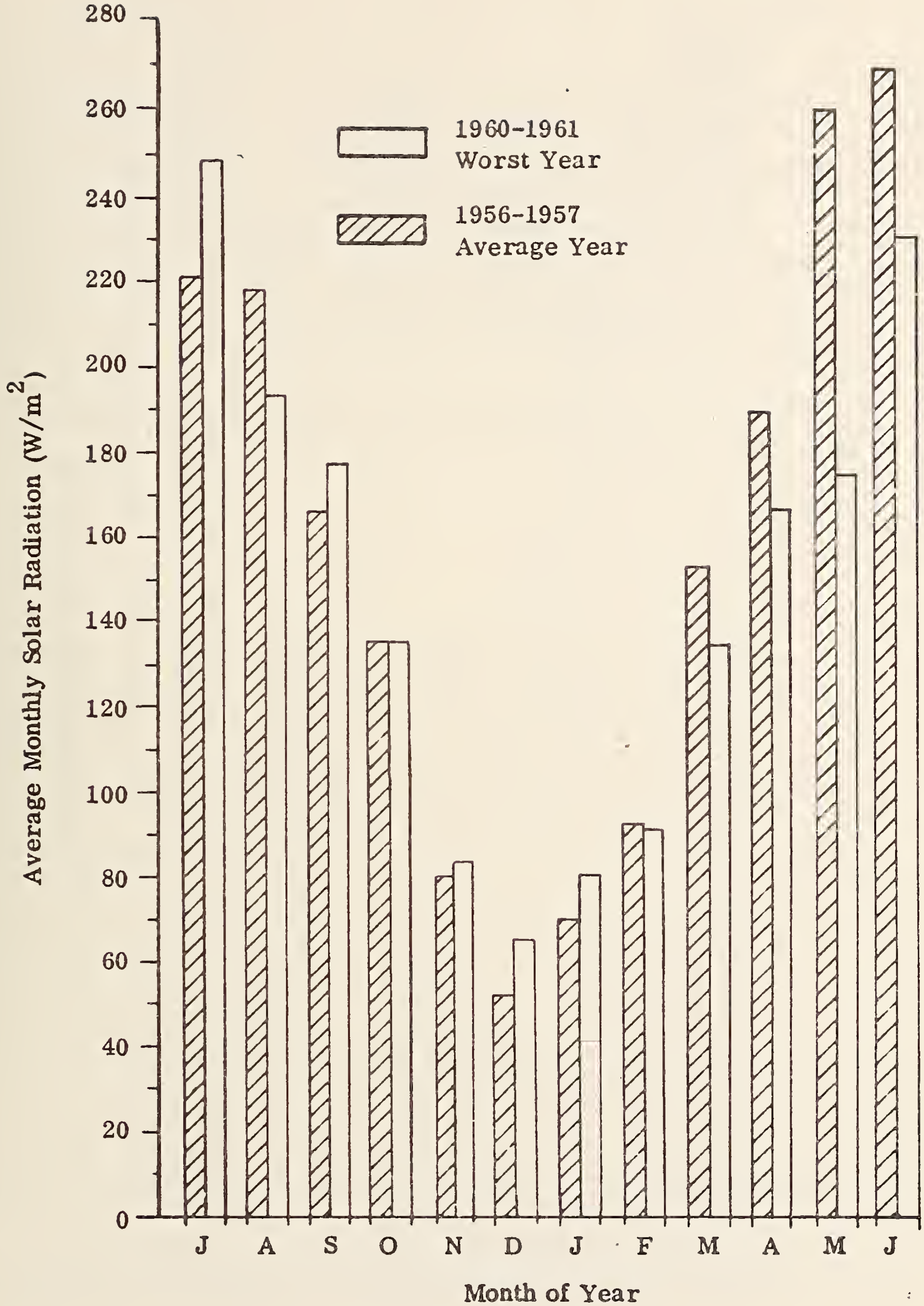



FIGURE 22

AVERAGE MONTHLY SOLAR RADIATION FOR
AVERAGE AND WORST YEARS FOR NEW YORK CITY

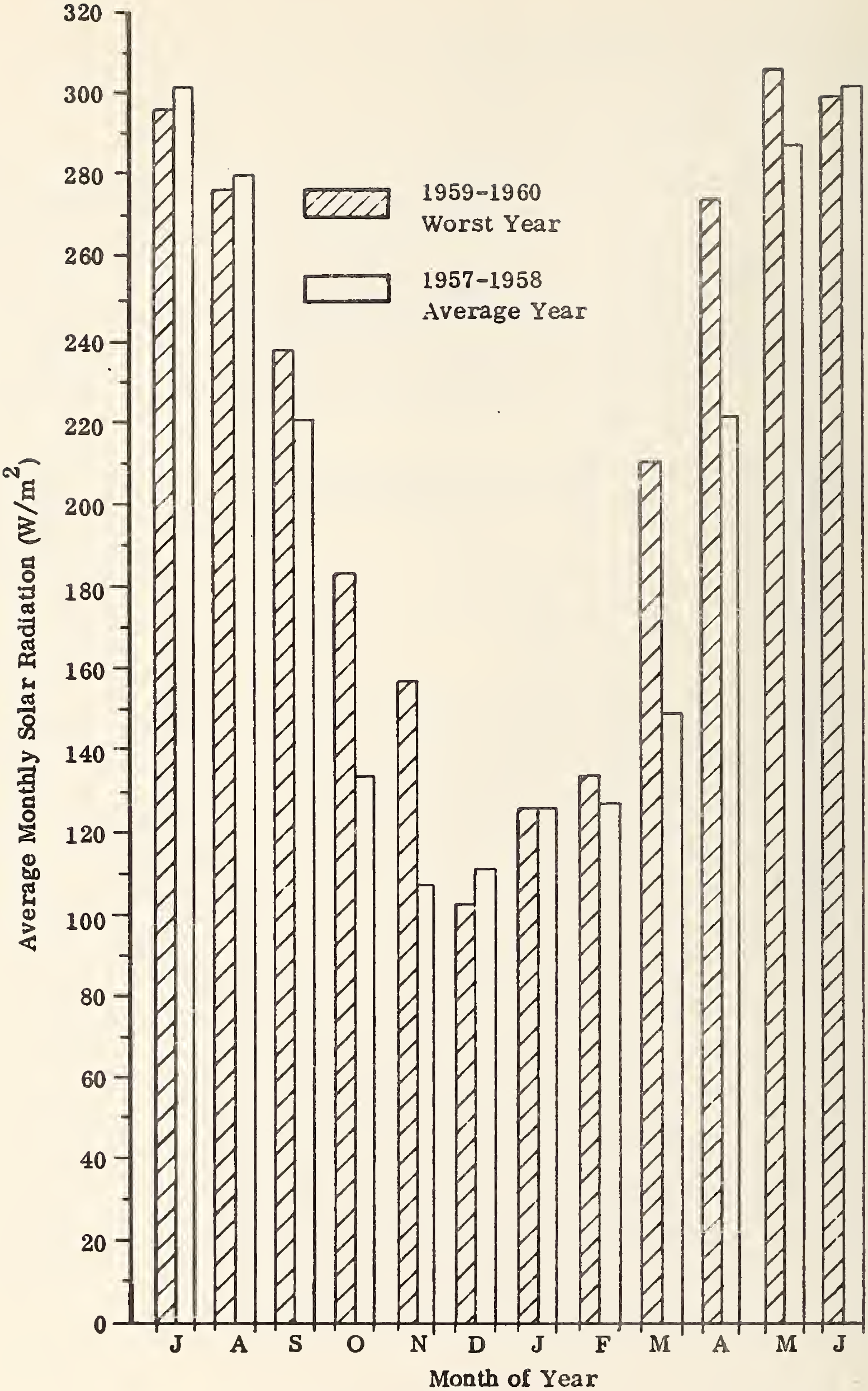



FIGURE 23

AVERAGE MONTHLY SOLAR RADIATION FOR AVERAGE AND WORST YEARS FOR DODGE CITY, KANSAS

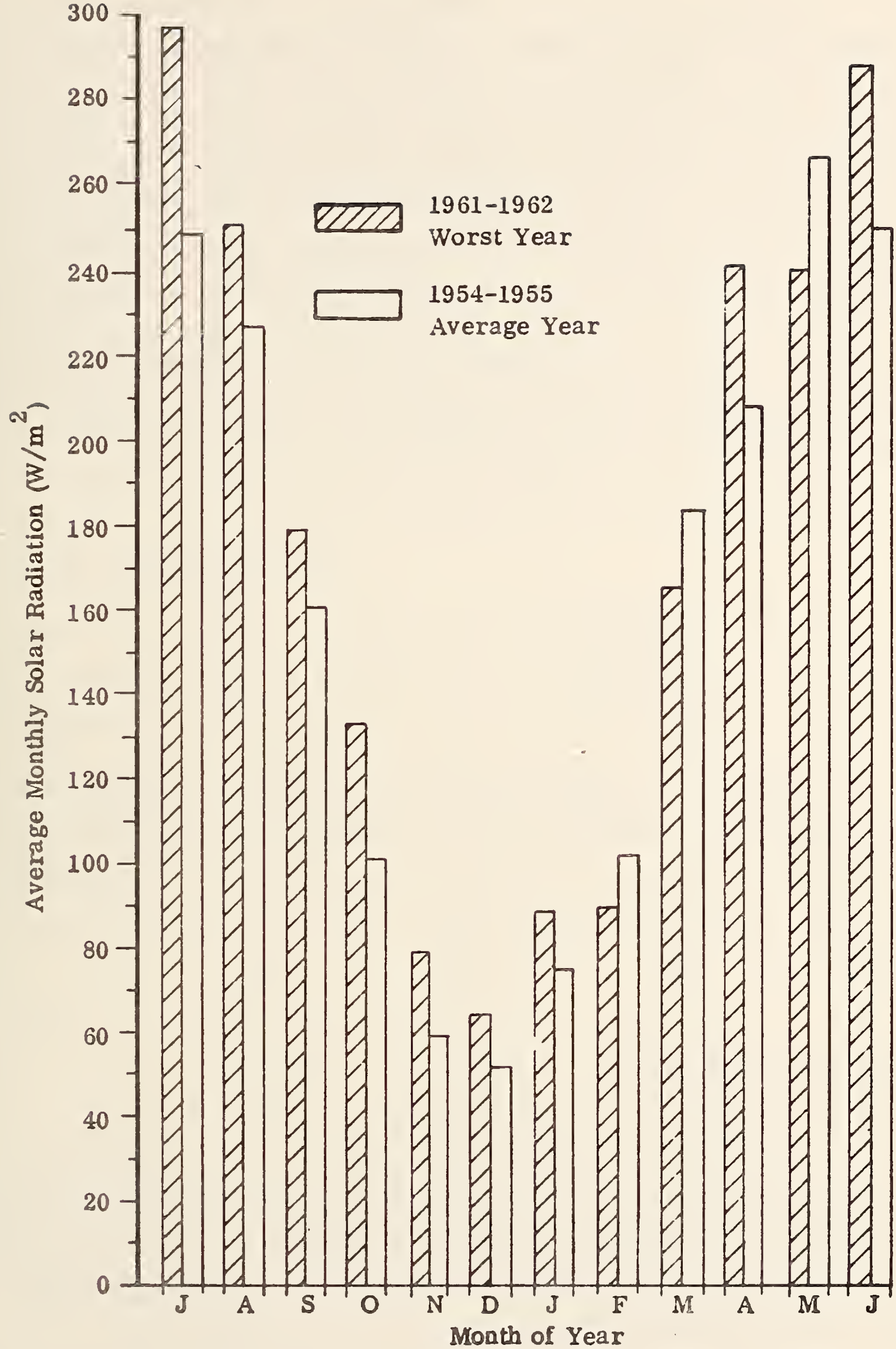



FIGURE 24

AVERAGE MONTHLY SOLAR RADIATION FOR
AVERAGE AND WORST YEARS FOR MADISON, WISCONSIN

tures. This coupled with the very high insolation can increase the collected energy on a horizontally positioned collector surface almost an order of magnitude over that obtainable during the midwinter. By orienting the collector at an angle from vertical of about equal to its latitude (for Oklahoma City, latitude $35^{o}$, optimum angle is $32.5^{o}$ per Reference 27), the power density on the surface of the collector can be made to vary only about 40% from midwinter to midsummer. However, wintertime collector efficiencies are a fraction of those of summertime in the northern latitudes.

Based on a system optimized to collect solar energy during the summer months of May, June, July, and August, the collectable energy in $Kw\text{-}hr/m^2$ for the worst year (where the area is that of the solar collectors) for the three cities is:

| | Collectable Energy |
|---|---|
| New York City | 493 |
| Dodge City | 626 |
| Madison | 629 |

A collector, infrequently considered, is the roadway pavement itself. Pavement temperatures, measured 1.3 cm (1/2 inch) below a bituminous surface, exceeded $50^{o}C$ ($122^{o}F$) during sunny summer days (Reference 19). The utilization of the pavement to perform a dual function offers potential economies and will be considered in Section 2.6.

### 2.5.2 Ambient Air Energy

The temperature of daytime summer ambient air is, on the average, about $15^{o}C$ above the average temperature of the earth for the three selected cities. The heat capacity of air at standard conditions is 0.279 $W\text{-}hr/kg\text{-}^{o}C$ (0.24 $Btu/lb\text{-}^{o}F$). The utilization of a good part of the daytime ambient air energy to heat the earth is technically feasible (Section 2.12).

Consider for example, a system wherein a closed loop water system is utilized to transfer heat to the earth beneath the pavement and an air-to-water heat exchanger is used to collect ambient air energy. Assume that, at the beginning of summer, the ground around the heat pipes has been cooled so that water in the closed loop enters the heat exchanger at 7.2°C (45°F). Assume further that the daytime air temperature is at 26.7°C (80°F) and that the air has a relative humidity of 60%. Some moisture condensation is inevitable. A standard ARI certified heat exchanger is commercially available which will raise the exiting water temperature to 16.1°C (61°F) at an airside face velocity of 3.56 m/s (700 ft/minute) resulting in an energy input to the water of 97.9 Kw-hr (334,000 Btu) for every square metre (10.76 $ft^2$) of heat exchanger face area and for each hour of operation. At an ambient air temperature of 33°C (91.4°F) under these same conditions, the input to the water becomes 151 Kw-hr (516,700 Btu). In this example, the electrical energy required for the water and airside pump and blower is 3 Kw-hr (10,242 Btu) for each hour of operation. No attempt has been made to optimize the expenditure of energy to achieve this rate of collection.

A review of the average monthly worst year temperatures for the three cities indicated that the ambient energy system can be operated effectively for varying daily hours during the months of April, May, June, July, and August for a total operating time of approximately 1780 daytime hours. The worst year average monthly temperatures in °C for four of these months for the three cities are (temperatures in brackets are in °F):

| | May | June | July | Aug |
|---|---|---|---|---|
| New York City | 15.9 (60.6) | 21.2 (70.2) | 23.0 (73.4) | 23.1 (73.6) |
| Dodge City | 18.8 (65.8) | 22.7 (72.9) | 24.3 (75.7) | 27.2 (81.0) |
| Madison | 12.8 (55.0) | 19.6 (67.3) | 21.3 (70.3) | 21.0 (69.8) |

Because ambient air is already a low temperature heat source, operation only during the daytime is necessary. Average daily maximum temperatures are between 11°C and 17°C higher than average daily minimum temperatures during the summer months throughout the climate zones under investigation. The exact value depends on elevation, nearby bodies of water, nearby mountains, etc. Therefore, for daytime operation, the above tabulated values can be increased by 5.5°C (10°F) for purposes of estimating the amount of energy that this ambient air system can capture over a summertime of operation.

The collectable energy in $Kw\text{-}hr/m^2$ for the ambient air system (where the area refers to the face area of the heat exchanger) during the worst year is estimated to be:

| | End of Summer Earth Temperature, $^oC$ | Collectable Energy |
|---|---|---|
| New York City | 15.5 | 57,000 |
| Dodge City | 18.3 | 60,000 |
| Madison | 21.1 | 34,000 |

For comparison, a commercial flat plate solar collector will collect no more than 500 $Kw\text{-}hr/m^2$ at $37.8^oC$ ($100^oF$) in New York City during the worst year and during the same summer months. For all practical purposes, solar and ambient air energy systems collect heat during the summer for use during the winter, although ambient air systems are obviously more dependent on efficient energy storage. Furthermore, solar systems have the advantage that they can collect heat at higher temperatures than ambient air systems. The system and cost implications of these comparisons are considered in Section 2.7.

### 2.5.3 Wind Energy

For many centuries, wind energy has been used to propel ships, pump water, and grind grain. In the last 75 years, the development of machines capable of converting the energy in fossil fuels to mechanical and electrical energy has resulted in significant reduction in the use of wind energy and the demise of many companies marketing wind machines. For example, in this country the Jacobs brothers manufactured and sold over 50 million dollars worth of their excellent 2 to 3 Kw, 32 to 110 volt, ac and dc wind machines before discontinuing their manufacture in 1956. Today, the U. S. Government is sponsoring development of large wind machines (1500 Kw and 3000 Kw) that can tie into utility systems (Reference 20).

The wind power contained in a moving air mass is the product of mass of air passing through an area in a unit of time and its kinetic energy which for standard air is expressed by:

$$P_w = 0.00064\ AV^3$$

where $P_w$ is the wind power in kilowatts, A is the rotor face area in square metres, and V is the wind velocity in metre/second. Ideally, the maximum machine power that can be extracted by a wind machine is 16/27 of the wind power contained in the moving air mass. Therefore, the machine power the ideal wind machine will generate in standard air is given by:

$$P_m = 0.000379\ AV^3$$

where the units are the same as in the previous expression. Because generated power varies as the velocity cubed, average wind velocities cannot be used to calculate energy generation from a wind machine. For the three cities under study, the University of Wyoming calculated wind power using hourly wind velocities. The results for the average and worst years for the three cities are given in Figures 25, 26, and 27.

Wind energy is much more variable than either solar or ambient air energy (References 21, 22). A 20% variation in any one year from the average obtained for the years studied is not uncommon, and in Dodge City during the year 7/62 to 6/63 the deviation from average was in excess of 50%. However, unlike solar and ambient air energies, maximum wind energy occurs during the winter months and, therefore, storage requirements are minimized. The power density of wind energy ($W/m^2$) is about the same as for solar energy in the cities studied (not necessarily true for other locations) but both are much less than that of ambient air energy systems. This is because ambient air systems draw through the face area of a heat exchanger a virtually infinite source of energy.

Much of the current research sponsored by the U. S. Government is directed at improving the durability and reducing the cost of wind generators (References 20, 23, 24). Because of the advantages of economics of scale, two machines having face areas of 2634 $m^2$ (28,353 $ft^2$) and rated capacities of 1500 Kw are designed and in the process of construction (Reference 24). The wind machine for the roadway application

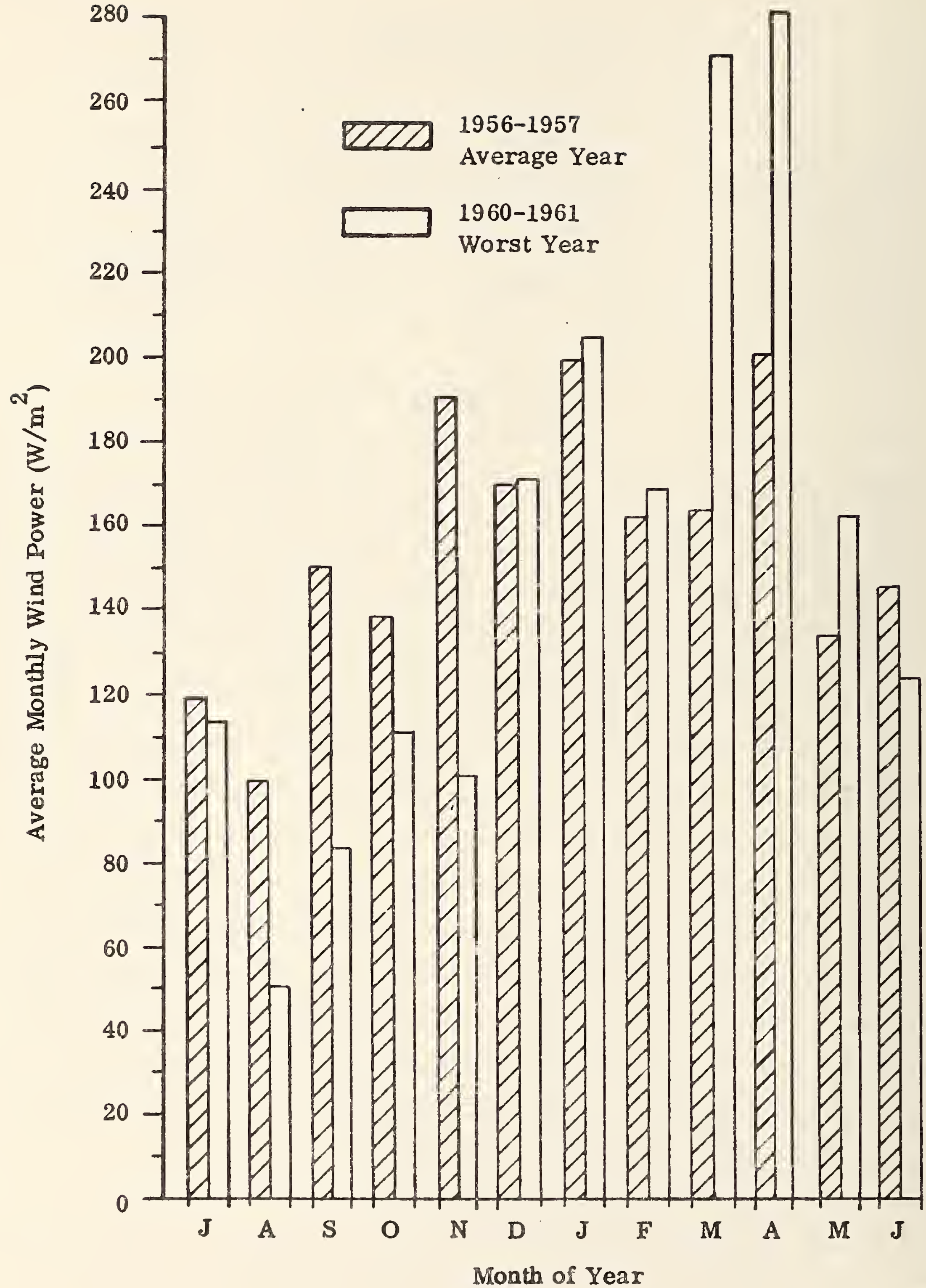



FIGURE 25

AVERAGE MONTHLY WIND POWER FOR
AVERAGE AND WORST YEARS FOR NEW YORK CITY

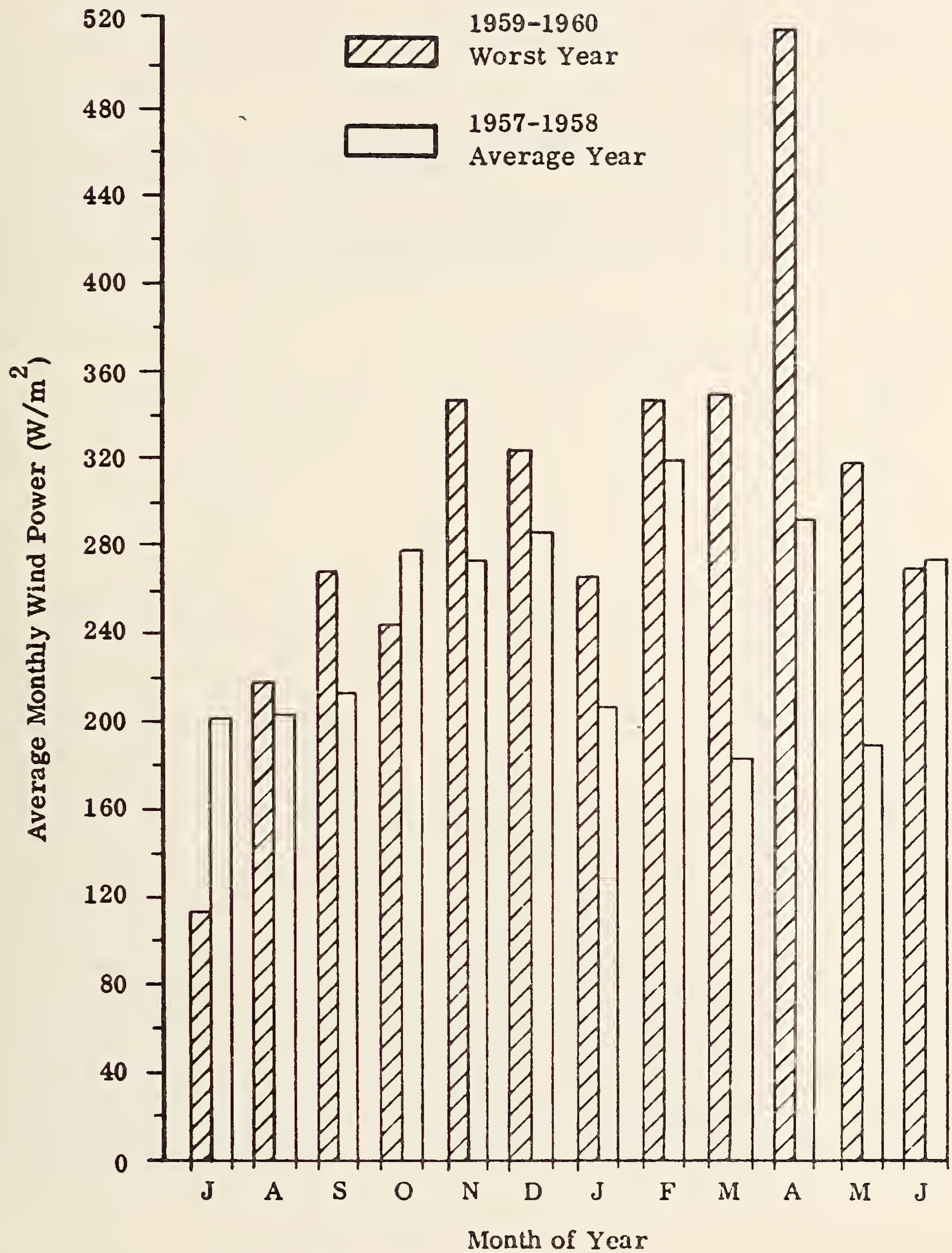



FIGURE 26

AVERAGE MONTHLY WIND POWER FOR
AVERAGE AND WORST YEARS FOR DODGE CITY, KANSAS

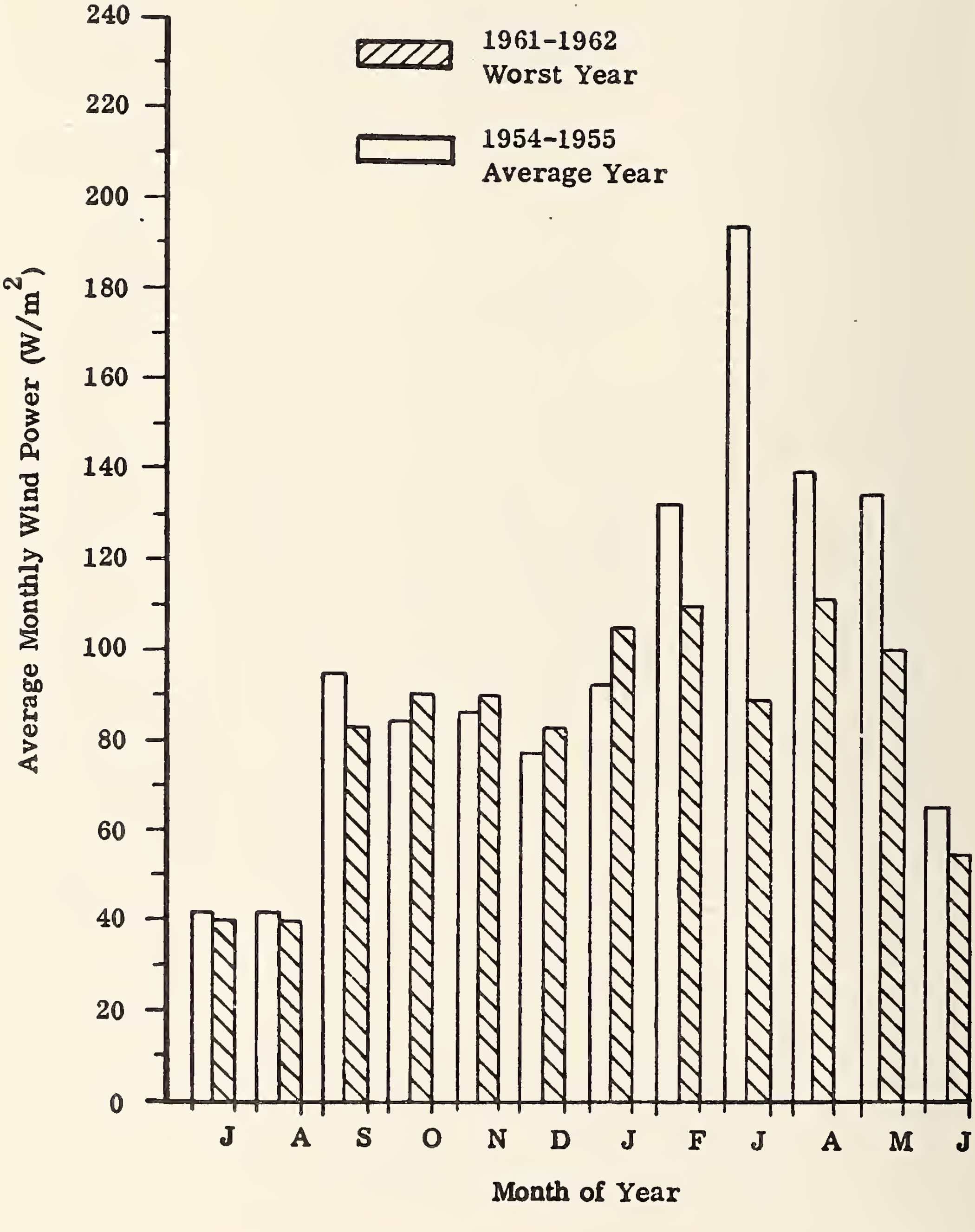



FIGURE 27

AVERAGE MONTHLY WIND POWER FOR
AVERAGE AND WORST YEARS FOR MADISON, WISCONSIN

is only required for demand heating and the operation and electrical design would, therefore, be simplified. A total conversion efficiency of 40% (wind power-to-electrical power) is a reasonable assumption for roadway demand heating applications (References 20, 24).

Using calculated monthly average values of wind power for the worst year for each of the cities, the estimated collectable energy in $Kw\text{-}hr/m^2$ (where the area is the rotor face area) for the months during which there is energy demand is:

| | Collectable Energy |
|---|---|
| New York City | 265 |
| Dodge City | 676 |
| Madison | 221 |

The above data is based on a wind machine having a rated capacity of 0.21 $Kw/m^2$ at a wind velocity of 10.7 m/s (24 mph) and a cut-in wind velocity of 3.5 m/s (8 mph).

Although the specific power of wind energy is about the same as that of solar energy (see Tables 7, 8, 9), the wind machines cannot convert it to low temperature heat energy as efficiently as solar collectors convert summer insolation to low temperature heat energy. However, for pavement snow melting applications, solar heat collected in the summer must be stored for use in the winter. Long-term thermal storage losses must, therefore, be included in the ultimate comparison of system economics. It should be noted that electrical energy can be converted to high temperature thermal energy without collection efficiency penalties, it can be used to provide the electrical requirements for thermal and other highway systems, and its convenience and simplicity at the systems level has been well demonstrated.

### 2.5.4 Biodegradation Energy

Biodegradation is the conversion of the organic components of refuse and sewage into methane by the action of microorganisms. The reaction occurs spontaneously in the absence of oxygen and at temperatures between 70°F and 120°F (Reference 28). Under ideal conditions (temperature, pH, cellulose concentration) a ton of refuse (from which glass and metals have been removed) will produce 283 $m^3$ (10,000 $ft^3$) methane and 122 $m^3$ (4,300 $ft^3$) of $CO_2$ under standard conditions. The heat content of this gas is 7.24 Kw-hr/$m^3$ (700 Btu/$ft^3$). A ton of refuse, therefore, will yield 2049 Kw-hr (7 x $10^6$ Btu) of energy in the form of a gas which can be stored under pressure and burned when thermal energy is required by the pavement heating system.

A number of cities are installing facilities to burn or pyrolyze refuse. Some of these installations are in successful operation. The Monsanto Landgard pyrolysis plant in Baltimore, although it appeared good on paper, has never operated properly. Both burning and pyrolysis require prior processing of the refuse.

Methane obtained by bioconversion, on the other hand, has not been commercialized and may require another 10 years to commercialize if U. S. Government support continues. A number of universities have experimented with bioconversion and the University of Pennsylvania will complete a feasibility study of a pilot plant in 1978.

There is unquestionably a large amount of energy in refuse. Baltimore City alone has a daily refuse output having an estimated energy content of 5.9 x $10^6$ Kw-hr (2 x $10^{10}$ Btu). It would appear that recovering energy from refuse can be more appropriately handled by constructing large facilities located near population centers, and it has not been pursued in this study.

## 2.6 Utilization of Roadway Pavements as Solar Collectors

The total annual solar radiation in $Kw\text{-}hr/m^2$ incident on a horizontal pavement for the worst year in each city is:

| | Incident Solar Radiation |
|---|---|
| New York City | 1296 |
| Dodge City | 1901 |
| Madison | 1542 |

The percentage of each city's incident solar radiation occurring during the worst year five summer months is 57.4 for New York City, 53.4 for Dodge City, and 59.0 for Madison. The incident radiation heats the surface of the pavement to a temperature at which the losses balance the incoming radiation. A typical time-temperature profile for a bituminous surface (measured 1.3 cm below the surface) located outside the Dynatherm plant in Cockeysville, Maryland, is given in Figure 28 for July 1975. The average pavement surface temperature is approximately $35^{o}C$ ($95^{o}F$) for this month. Note that the day-night variation in surface temperature during July was about $25^{o}C$ ($45^{o}F$) and that each day represents one cycle. Measurements of temperature were made at three hour intervals for a period of several months. Over a six month period, 170 such cycles occurred.

This cycling feature was used to thermally drive a patented device called a down-pumping heat pipe. A sketch of the device is shown in Figure 29. The principle of operation is quite simple. The pressure in Space A (Figure 29) is determined by the pavement temperature $T_p$, i.e., the vapor pressure of the working fluid at temperature $T_p$. The total pressure in Space B is determined by the ground temperature $T_g$, i.e., the partial pressure of the working fluid vapor at temperature $T_g$, and by the partial pressure of the noncondensible gas in this space. The amount of noncondensible gas in Space B can be adjusted such that when the ground temperature is $10^{o}C$ ($50^{o}F$) and the pavement temperature is $26.7^{o}C$ ($80^{o}F$), the total pressure in Space B is sufficient to force the working fluid up the down-pumping tube and into Space A. This would represent a normal night-time condition. During the day, the pavement temperature increases and the vapor pressure of the liquid in Space A increases until boiling occurs. The liquid is trapped in

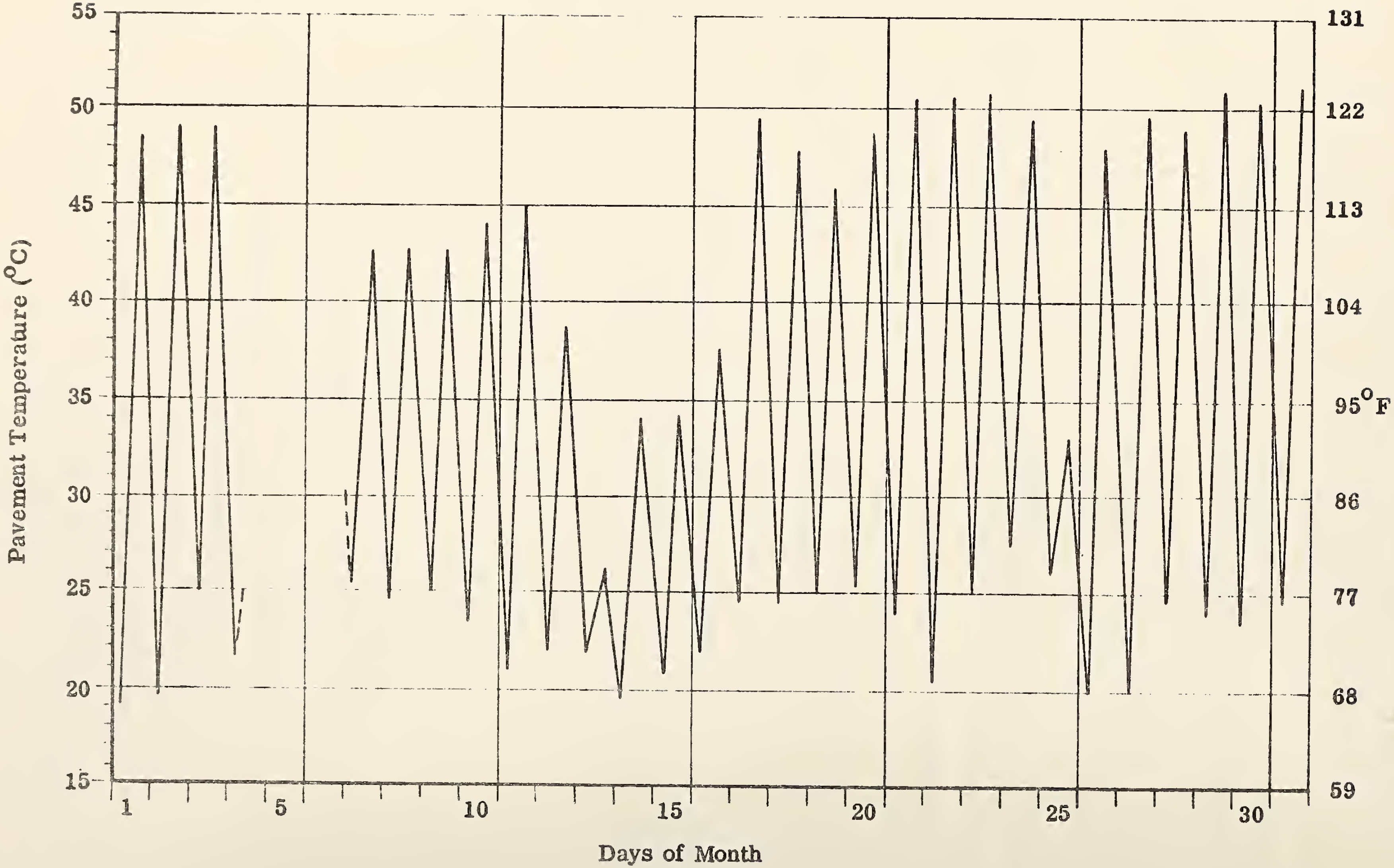



FIGURE 28

MEASURED PAVEMENT TEMPERATURE VARIATIONS DURING JULY 1975

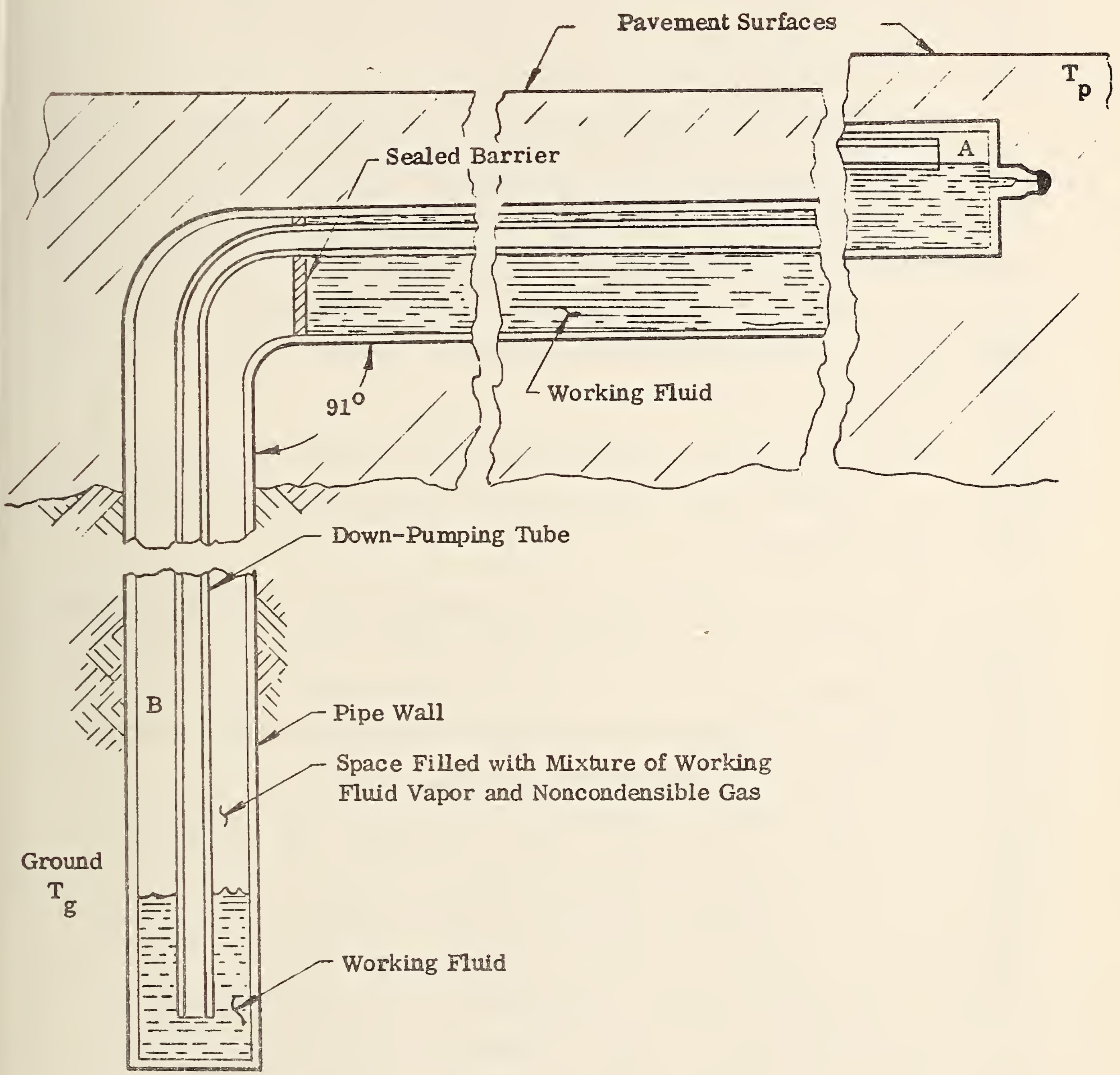



FIGURE 29

SCHEMATIC OF DOWN-PUMPING HEAT PIPE

Space A by the barrier so that it cannot be pushed back down through the down pumping tube (Figure 29) and can only be boiled out of Space A. The thermal energy carried down into the ground is determined by the quantity of working fluid contained in Space A and its specific heat and its heat of vaporization.

Table 16 shows the pumping performance as a function of Argon partial pressure of a down-pumping ammonia heat pipe extending into $10^{o}$C ($50^{o}$F) earth a vertical distance of 18.3 m (60 ft). Note that with no Argon in Space B, heat cannot be pumped down into the earth at a temperature exceeding the earth temperature. It may be possible to pump heat into the earth during warmer sunny winter days because measurements show that pavement temperatures (unheated pavements) are up to $7^{o}$C ($12.5^{o}$F) higher than air temperatures.

Figure 30 illustrates the construction configuration of a combined down-pumping and up-pumping heat pipe. The pipe is longer than a conventional heat pipe because of the tandem arrangement.

Under normal circumstances, the down-pumping heat pipe cycles once a day; therefore, the amount of heat pumped is a direct function of the volume of working fluid boiled. The linear length of pipe in a standard pavement section (Figure 2) is 295 m (969 ft). If the down-pumping part of the Figure 30 heat pipe is made equal to the up-pumping part, the internal volume of one-inch schedule 40 iron pipe in one section is 0.165 $m^3$ (5.82 $ft^3$). Because of vapor space requirements, only about 80% of this volume can be filled with working fluid. Ammonia has a heat of vaporization at $10^{o}$C ($50^{o}$F) of 0.34 Kw-hr/kg (527.3 Btu/lb) and a liquid density of 624.8 kg/$m^3$ (30 lb/$ft^3$). Therefore, each cycle in a standard pavement section will result in 28 Kw-hr of down-pumping. To this must be added the heat content of the liquid ammonia for say a $15^{o}$C ($27^{o}$F) temperature difference. The net collected heat is 30 Kw-hr per cycle or, for a summer season of 170 cycles, 5100 Kw-hr which is equivalent to a specific collection of 56.2 Kw-hr/$m^2$.

One method of improving the specific collection is to increase the volume of liquid vaporized during each cycle. For example, if the pipe size is increased to a two-inch schedule 40 size in only the down-pumping portion of the heat pipe shown in Figure 30, the specific collection becomes 218 Kw-hr/$m^2$. Note that in this case,

| Argon Partial Pressure | Ammonia Partial Pressure | Total Pressure | Roadway Temperature At Which Heat May Be Pumped Down | Roadway Temperature At Which Ammonia May Be Pumped Up |
|---|---|---|---|---|
| psia | psia | psia | $^{o}F$ | $^{o}F$ |
| 0 | 89.19 | 89.19 | 50 or More | 39 or Less |
| 10 | 89.19 | 99.19 | 56 or More | 46 or Less |
| 20.73 | 89.19 | 109.92 | 61 or More | 52 or Less |
| 31.10 | 89.19 | 120.29 | 66 or More | 58 or Less |
| 41.47 | 89.19 | 130.66 | 71 or More | 63 or Less |
| 51.83 | 89.19 | 141.02 | 75.5 or More | 68 or Less |
| 62.20 | 89.19 | 151.38 | 79.5 or More | 73 or Less |
| 72.56 | 89.19 | 161.75 | 83 or More | 77 or Less |
| 82.93 | 89.19 | 172.12 | 87 or More | 80 or Less |

$t_C = (t_F - 32)/1.8$    1psi= $6.89 \times 10^3$ Pa

TABLE 16

DOWN-PUMPING HEAT PIPE PUMPING TEMPERATURES
FOR VARIOUS ARGON PARTIAL PRESSURES

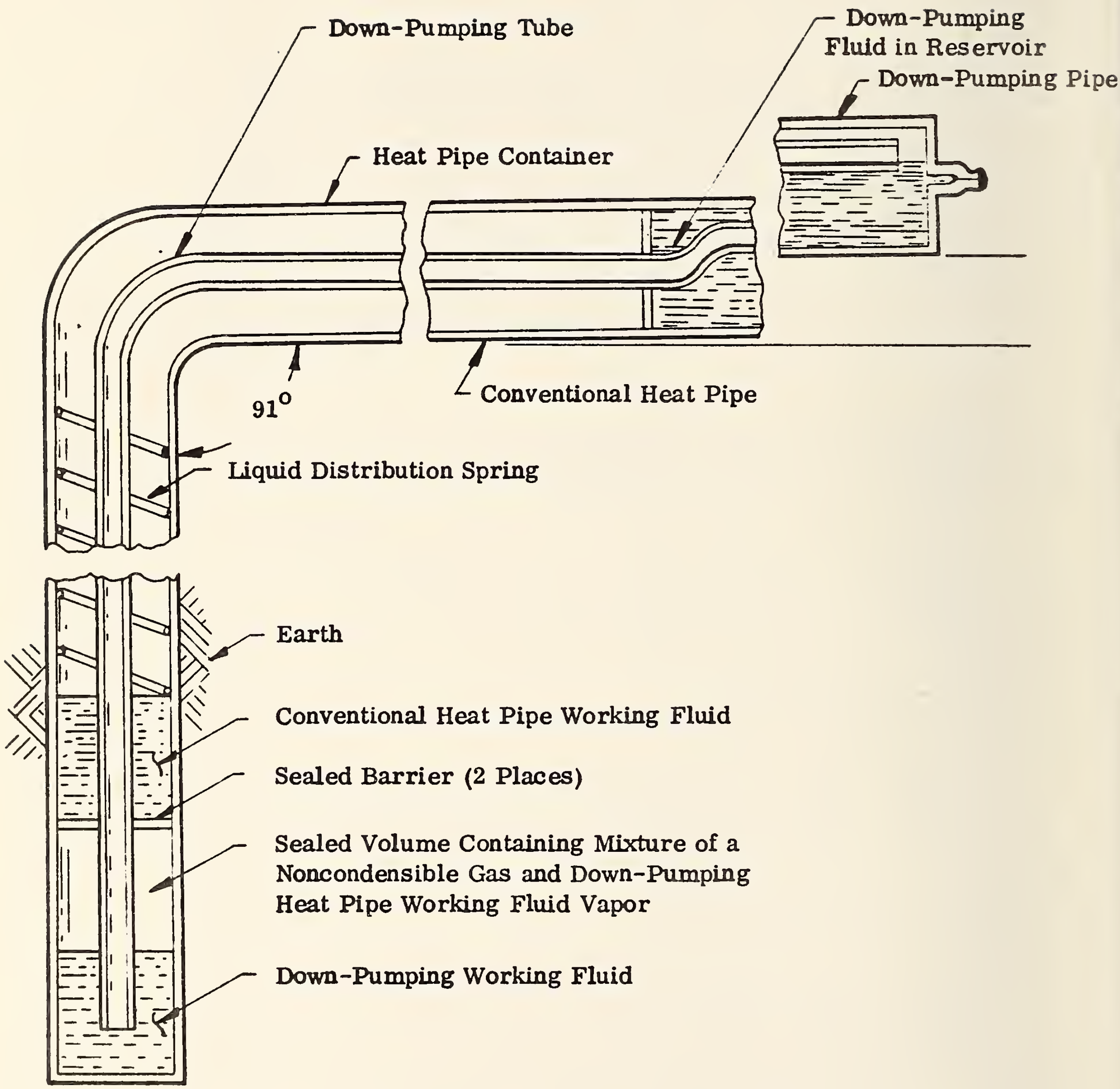



FIGURE 30

CONFIGURATION OF DOWN PUMPING AND CONVENTIONAL ROADWAY SNOW AND ICE REMOVAL HEAT PIPE the collector area is that of the pavement, whereas in solar energy it is the effective area of flat plate collectors, in wind energy it is the area swept by the blades of the wind machine, and in ambient air systems it is the face area of the air-to-water heat exchanger.

## 2.7 Energy Collection Cost Comparison

During the initial part of this study, a survey was made of the costs of the various equipments needed to collect solar, ambient air, wind electric, and roadway surface energy (Sections 2.5 and 2.6). A summary of the survey results follows.

The worst year collectable energy in $Kw\text{-}hr/m^2$ for the energy systems discussed in Sections 2.5 and 2.6 is summarized in the table below:

| | Solar Flat Plate | Ambient Air | Wind Electric | Roadway Surface |
|---|---|---|---|---|
| New York City | 493 | 57,000 | 265 | 56 |
| Dodge City | 626 | 60,000 | 676 | 56 |
| Madison | 629 | 34,000 | 221 | 56 |

where the surface area for each system is defined by the incident energy intercepted by the collector. The given values of collectable energy for flat plate, ambient air, and roadway surface collectors are for summer collection only and for wind machines are for winter collection only. In addition, the temperature of the collected energy is unlimited for wind machines, $37.8^{\circ}C$ ($100^{\circ}F$) for solar flat plate collectors (although this can be increased at the expense of efficiency), $37.8^{\circ}C$ ($100^{\circ}F$) for roadway down-pumping collectors, and $21.1^{\circ}C$ ($70^{\circ}F$) for ambient air collectors.

Determining collector costs proved difficult. The industrial base for solar flat plate collectors is now being established, what base existed for wind machines evaporated in the 1950's, and Dynatherm is the only manufacturer of roadway heat pipes and, thus far, only for experimental installations. A firm industrial base for air-to-water heat exchanger equipment costs has existed for many years. In view of this, judgment and experience was used in arriving at values for collector costs, all of which were assumed at a 1977 base.

Costs for single glaze flat plate collectors cluster between $\$140/m^2$ ($\$13/ft^2$) and $\$172/m^2$ ($\$16/ft^2$) when procured in 200 $m^2$ lots. For highway applications, mounting brackets and foundations must be provided. The estimated installed costs (investment costs) are between $285/m$^2$ ($26.5/ft$^2$) and $344/m$^2$ ($32/ft$^2$). A value of $300/m$^2$ ($27.9/ft$^2$) has been selected for use in making comparisons.

Cost for the most expensive ambient air-to-water heat exchangers is $1022/m$^2$ ($95/ft$^2$). To this must be added costs of the airside blower, blower mount, control box, electrical cables, foundations, and suitable ducting. Installed costs are estimated at $3600/m$^2$ ($344/ft$^2$) for installations of 5 m$^2$ or less and $2900/m$^2$ ($269/ft$^2$) for installations up to 25 m$^2$.

Costs for wind machines are also difficult to obtain. Rebuilt Jacobs machines including a 40-foot high guyed tower sell for $279.7/m$^2$ ($26/ft$^2$) and are rated at 10.7 m/s (24 mph). Installed cost is quoted at $305/m$^2$ ($28.3/ft$^2$). A 2000 Kw wind machine is to be installed on Howards Knob in North Carolina. Its projected installed cost, including instrumentation, is estimated to be about $3.5 million at a face area of 2918.6 m$^2$ or $1199/m$^2$ ($111.4/ft$^2$). The 1250 Kw Smith-Putnam, its predecessor, was installed on Grandpa's Knob, Rutland, Vermont, in the early 1940's at a cost of $286,673 (Reference 30). R. E. Wilson reestimated the Smith-Putnam cost based on 1971 prices at $1.05 million (Reference 25). Using Wilson's estimate and adding an inflation factor of 10%/year, the 1977 cost is estimated at $1.86 million or $832.4/m$^2$ ($77.3/ft$^2$). Subtracting out those items from Wilson's estimate that are not required for highway use, the 1977 cost becomes $670.9/m$^2$ ($62.3/ft$^2$). Many other estimates are being projected by interested parties (References 23, 24) for various designs and quantities of manufacture that calculate to be 1/2 of the 1977 Smith-Putnam cost. The estimate of wind machine installed cost for highway use is taken as $600/m$^2$ ($55.7/ft$^2$).

The collected energy of roadway surface collector is a function of the down-pumping heat pipe design. A simple 4.27 m pipe extension in the roadway was assumed in the reported collected energy. A 2 inch pipe, 3.1 m (10 ft) long, was assumed for the ammonia reservoir in the earth. The selling price of the 22.9 m (75 ft) long pipe F.O.B. West Virginia was $100 each in quantities of more than 1000. The estimate selling price of this down-pumping pipe combination is $140 each in quantities of more than 1000. To this must be added the cost of extending the hole into the earth an additional 3.1 m (10 ft) and the extra installation cost in the pavement. The total incremental cost/pipe is, therefore, \$50 or \$39.7/$m^2$ (\$3.69/$ft^2$). To put this on a basis comparable with the other collectors, the cost of extending the drilled hole must be subtracted out of this cost. The comparable installed cost becomes \$34.9/$m^2$ (\$3.2/$ft^2$).

To compare the various energy collection systems, the required capital investment for a unit quantity of energy collected in one year has been calculated. The values in the table below are given in \$/kW-hr:

| | Solar Flat Plate | Ambient Air | Wind Electric | Roadway Surface |
|---|---|---|---|---|
| New York City | 0.61 | 0.051 | 2.26 | 0.62 |
| Dodge City | 0.48 | 0.050 | 0.89 | 0.62 |
| Madison | 0.48 | 0.085 | 2.71 | 0.62 |

Remembering that the solar flat plate, ambient air, and roadway systems require long-term storage, the \$/Kw-hr values of these collection methods should be conservatively increased by a factor of 2. In addition, although wind electric demand systems do not require long-term storage, the efficiency of demand coupling is not likely to be higher than 50% in economically practical designs. Therefore, it is reasonable to multiply all the costs in the above table by a factor of 2 when evaluating the investment cost of usable energy delivered at the pavement surface.

For example, the required demand energies given for an otherwise unaugmented West Virginia system in the three cities for the worst year are New York City 26.5 Kw-hr/$m^2$, Dodge City 56.6 Kw-hr/$m^2$, and Madison 73.6 Kw-hr/$m^2$ (Case 4 Tables 11, 12, and 13). The investment costs for a wind demand machine are estimated to be \$120/$m^2$ for New York City, \$101/$m^2$ for Dodge City, and \$399/$m^2$ for Madison. These investment costs do not include the investment costs of storage and distribution.

Using the energy loss values for full performance systems for the three cities given in Figure 18, the investment cost can be determined for summer collection concepts in \$/$m^2$. These costs have been determined and are compared with the demand operated wind electric investment cost calculated in the previous paragraph:

| | Solar Flat Plate | Ambient Air | Wind Electric | Roadway Surface |
|---|---|---|---|---|
| New York City | 717 | 60 | 120 | 729 |
| Dodge City | 760 | 79 | 101 | 982 |
| Madison | 870 | 154 | 399 | 1123 |

Because of the National interest in wintertime collection of solar energy, collecting solar energy in the winter for use in a demand mode like that of the wind electric concept was investigated. Although the estimated normalized cost of solar collectors is one-half that of wind machines, solar energy densities during January are 40% of those of wind energy densities in New York, 55% in Dodge City, and 80% in Madison. Unfortunately, in the high wind areas such as Dodge City exemplifies, or in the very cold areas represented by Madison, wintertime collection of solar energy at temperatures necessary for demand operation is inefficient. More efficient solar collectors can be designed but their costs rapidly approach the estimated wind machine cost. Therefore, solar investment costs in $\$/m^2$ are projected to be above those for wind electric collection reported in the above table.

Although the ambient air collection concept is the most cost effective, it cannot supply sufficient energy to the earth in severe climates to achieve a full performance system of the West Virginia design. The alternatives are:

- Demand augment the ambient air system using wind electric as the next most cost effective renewable energy source.
- Demand augment the ambient air system using inexpensive modularized outdoor fossile fueled boilers recognizing that most of the energy requirements of the system will be supplied by a renewable energy source.
- Couple a greater volume of earth to the pavement surface so that a greater percentage of the required full augmentation energy can be supplied to the earth by the ambient air system operating under the temperature limitations at the particular location.
- Compromise on system performance to the extent that occasional severe storms will be beyond the system's melting capability.

## 2.8 Earth Energy Storage

The earth is variable in composition, temperature, compaction (density), and moisture content (Reference 31). In addition, augmentation introduces variabilities of artificial energy sources. A part of the heat pipe field may be below the water table and subjected to hydraulic gradients causing movement of water through the field. All of these conditions interrelate and determine how much heat the earth can store, how much heat can be extracted, and how long it will take for artificially added heat to naturally dissipate itself. Although the use of earth heat for heating buildings dates from the last century, until the recent ERDA interest not much had been done to establish the technology of using the earth as a renewable heat source. L. R. Ingersoll (Reference 37) integrates some theory with the experience gained in using the earth as an energy source and sink in connection with heat pump systems. However, a surprising amount of disconnected earth information is, nevertheless, available and reported in the literature by investigators whose objectives invariably were very specialized.

As a consequence of the above situation, designers of earth pavement heating systems have been forced to select data on a random basis for purposes of system analysis. This has led to varying performance estimates and conflicting opinions. It is beyond the scope of this study to resolve this dilemma. However, an attempt was made to establish a better basis for system design than previously existed. As Professor Sanger so aptly put the dilemma in dealing only with the moisture movement aspect of this entire problem, "No doubt the ultimate theory will follow from Physical Chemistry but at present it would appear that simple laboratory and field experiments will probably yield more useful results than highbrow theory with simplifying assumptions, no matter how brilliant the mathematics may be." (Reference 34)

In the present investigation, the treatment of the thermal behavior of earth was divided into the general categories of unsaturated earth (sometimes called the zone of aeration) and saturated earth (earth below the water table). Practically, earth heat pipes extend about 18.3 m (60 ft) into the ground. Water tables vary from a few feet below ground level to hundreds of feet below ground level. Consequently, an earth heat pipe system may encounter either all saturated or all unsaturated earth but most probably the system will encounter some variable combination of saturation and unsaturation. Consideration is given first to unsaturated soils.

## 2.8.1 Unsaturated Soils

The specific heats of a wide variety of dry soils vary from 795 J/kg-K (0.19 Btu/lb-$^{o}$F) at 60$^{o}$F to 670 J/kg-K (0.16 Btu/lb-$^{o}$F) at 0$^{o}$C (32$^{o}$F). The specific heat of soil-water mixtures may be calculated using the dry soil specific heat and the specific heat of water, each multiplied by the respective weight of soil and water in a given volume, added together, and the sum divided by the density of the soil-water mixture. A typical value for a soil with a 10% moisture content is 963 J/kg-K (0.23 Btu-lb-$^{o}$F). The value used in the computer model for weathered granite was 824 J/kg-K (0.197 Btu/lb-$^{o}$F).

The densities of dry earth materials vary from 2547 kg/m$^3$ (159 lbs/ft$^3$) for granite, 1762 kg/m$^3$ (110 lbs/ft$^3$) for sands, gravel, and Dakota sandy loam, 1442 kg/m$^3$ (90 lbs/ft$^3$) for clays, to 256 kg/m$^3$ (16 lbs/ft$^3$) for peats. By hard compaction, the dry densities of sands can be increased to 1922 kg/m$^3$ (120 lbs/ft$^3$) and, of course, the weight of the contained water must be added to this value to obtain the wet density.

The product of specific heat and wet density yields a value for the energy storage capability of soils. A typical value for dry sands at 60$^{o}$C is 1.4 x 10$^6$ J/m$^3$-K (20.9 Btu/ft$^3$-$^{o}$F). For saturated sands containing 30% moisture the value is 2.53 x 10$^6$ J/m$^3$-K (37.7 Btu/ft$^3$-$^{o}$F). A value commonly used in calculating the performance of unaugmented heat pipe pavement heating systems is 35 Btu/ft$^3$-$^{o}$F. The value used in the computer model was 27.15 Btu/ft$^3$-$^{o}$F which is a conservative value.

The thermal conductivity of most soils increases with density and moisture content up to 100% saturation. The amount of moisture at saturation decreases as soil density increases. For very dry sands, clay loams, silt loams, and sand loams, the thermal conductivity is very low and about 0.144 W/m-K (1 Btu-in/hr-ft$^2$-$^{o}$F). For highly compacted soils (density of 125 lbs/ft$^3$) at saturation, the thermal conductivity is about 2.88 W/m-K (20 Btu-in/hr-ft$^2$-$^{o}$F). The intelligent selection of a proper design value for conductivity of soils is difficult and designers are often forced to parametrically investigate the effects of using various values of conductivity (Reference 3). Conductivity is important in storage and storage loss calculations. The value used in the computer model was 1.04 W/m-K (7.22 Btu-in/hr-ft$^2$-$^o$F).

For thermal transient calculations, the thermal diffusivity of the soil is an important parameter. The thermal diffusivity due to conduction is defined by (Reference 33):

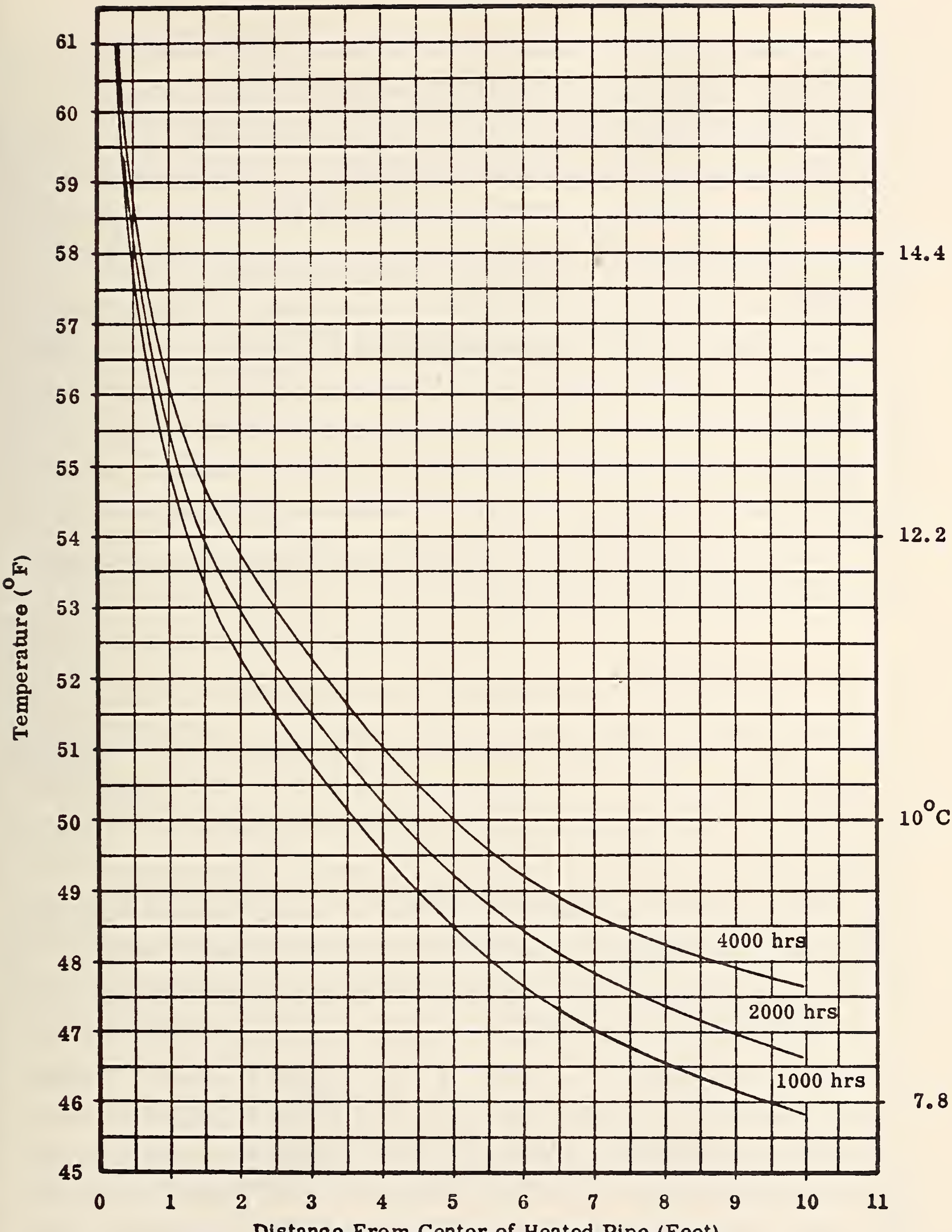
$$\alpha_{cond} = \frac{k}{\rho C_p}$$

and has the units of m$^2$/hr or ft$^2$/hr, and where (in consistent units) k is thermal conductivity, $\rho$ is the density, and $C_p$ is the specific heat of the soil. Thermal diffusivity varies slightly with density and temperature changes (Reference 31). Increases in moisture content increase diffusivity. Reference 31 gives the following expression for calculating diffusivity for various moisture contents. (Movement of moisture under the influence of temperature gradients is considered negligible.)

$$\alpha_{cond} = \frac{0.08333\ k}{\rho (C_p + \frac{w}{100})}$$

where $\alpha$ is in ft$^2$/hr, k is the soil conductivity in Btu-in/hr-ft$^2$-$^o$F, $\rho$ is the dry soil density in lb/ft$^3$, $C_p$ is the dry soil specific heat in Btu/lb-$^o$F, and w is the moisture content expressed as a percentage of the dry weight of the soil. Inserting experimental values into this expression for a range of soils and moisture contents, the diffusivity is found to vary from about $5.2 \times 10^{-7}$ m$^2$/s (0.02 ft$^2$/hr) to about $1.0 \times 10^{-6}$ m$^2$/s (0.04 ft$^2$/hr). For design purposes in the absence of moisture movement, a value of $7.7 \times 10^{-7}$ m$^2$/s (0.03 ft$^2$/hr) may be used in unsaturated soils. (A composite value of $6 \times 10^{-7}$ m$^2$/s (0.024 ft$^2$/hr) was used in the computer model to represent weathered granite.)

Using the design value of $7.7 \times 10^{-7}$ m$^2$/s for thermal diffusivity, the temperature profile in the earth around a 15.24 cm (6 inches) diameter buried heated pipe can be determined. This is shown in Figure 31 for times of 1000, 2000, and 4000 hours after heating is started and for the case of an ambient air system providing heat to 7.2$^o$C (45$^o$F) earth. The total energy added to the earth within a 2.4 m (8 ft)




1 foot= 0.305 m

FIGURE 31

TEMPERATURE DISTRIBUTION AROUND 15.24 CM DIAMETER HEAT PIPE IN UNSATURATED SOIL radius of the buried pipe in 1000 hours is 24.4 Kw-hr per metre of pipe length (a ground-to-pipe resistance for a 60-foot long pipe of $0.036^{o}F/W$) or for a 4.88 m (16 ft) wide pavement the equivalent surface power is 5.0 $Kw\text{-}hr/m^2$ (1586 $Btu/ft^2$). If the pipe were heated for four summer months, the input energy would only be 12 $Kw\text{-}hr/m^2$. Of course, as noted in Reference 3, increasing the pipe diameter can increase the stored energy but a six inch diameter pipe appears to be a practical limit.

The benefit to be derived from the movement of moisture in zones of aeration in the presence of thermal gradients was investigated. It is known that, during the summer, moisture travels downward into the ground under the influence of a positive temperature gradient and, during the winter, moisture travels upward towards the surface under the influence of a negative temperature gradient (Reference 35).

Professor Sanger (Reference 34) defines a term $k_t$ which he calls the coefficient of thermal moisture movement as:

$$V = k_t \; \Delta T/\Delta L$$

where V is the velocity of moisture movement and $\Delta T/\Delta L$ is the temperature gradient in the direction of flow. The direction of flow is from high to low temperatures. The value of $k_t$ varies from zero in saturated soils to maximum values in sands and gravels of low moisture content. Reference 34 reports an equilibrium value of $5.5 \times 10^{-7}$ $cm^2/sec\text{-}^{o}C$ for $k_t$ for a clay soil with an initial moisture content of 18%. The transient value of $k_t$ may be considerably higher. Moisture around a heated pipe will be gradually depleted and, consequently, soil conductivity will be decreased. It can be shown that the heat carried through the soil by water movement associated with temperature gradients is small compared to that of straight conduction. The negative effects of moisture depletion around a heated pipe more than negate any beneficial effects that arise from heat flow due to moisture movement. In cooled pipes, such as earth heat pipes, moisture flow in unsaturated soils is toward the pipe and increases in soil conductivity of about 50% around the pipe can be expected (Reference 37).

2.8.2 Saturated Soils

Saturated soils exist below the zone of aeration in the water table and contain what is termed free water. Free water below the zone of aeration can move in any direction under the influence of gravity and hydrostatic pressure, whereas free water above the water table must move downward under the influence of gravity.

The thermal conductivity of saturated soils is at a maximum and, in normal ranges of dry density, has values from about 1.15 W/m-K (8 Btu-in/hr-ft$^2$-$^o$F) to 2.88 W/m-K (20 Btu-in/hr-ft$^2$-$^o$F). A mean value for design purposes of 1.73 W/m-K (12 Btu-in/hr-ft$^2$-$^o$F) is commonly used. At this conductivity value, a saturation moisture content of 30% can be expected in normal soils at a dry density of about 1442 kg/m$^3$ (90 lbs/ft$^3$). Using the values of conductivity, density, and moisture content at saturation, the thermal diffusivity for design purposes is 5.9 x 10$^{-7}$ m$^2$/s (0.023 ft$^2$/hr). The effect of this is that the rate of heat extraction of the heat pipe embedded in earth which is at a fixed initial temperature is higher below the water table than it is above the water table.

The free water below the water table may not be stationary as assumed in the previous discussion. In this region, water flow is governed by Darcy's law which states:

$$Q = K A \Delta H / \Delta x$$

where K is termed the hydraulic conductivity and $\Delta H/\Delta x$ is the hydraulic gradient. This one dimensional expression is identical to that used to express one dimensional heat flow wherein the terms thermal conductivity and temperature gradient are used. The term intrinsic permeability is more frequently used and it is defined as:

$$k_i = \frac{Q}{A} \frac{\mu}{\rho g} \left( \frac{dH}{dx} \right)^{-1}$$

where $\mu$ is the water viscosity, $\rho$ is the water density, and g is the gravitational constant. The units of $k_i$ are either m$^2$ or ft$^2$ and in soil may have a vertical value different from its horizontal value. Values of $k_i$ for horizontal flow vary from 8.8 x 10$^{-20}$ m$^2$ for Pennsylvanian shale, 4.0 x 10$^{-11}$ m$^2$ for Pennsylvanian sandstone, 2.5 x 10$^{-7}$

$m^2$ for Ohio river alluvium, to $5.4 \times 10^{-7}$ $m^2$ for marine sand. For the 30% water content reference soil considered previously, an intrinsic permeability of $1 \times 10^{-8}$ $m^2$ is a reasonable estimate based on comparisons of experimental data (Reference 32).

Using an intrinsic permeability value of $1 \times 10^{-8}$ and water properties at $16^{o}C$, the value of Q/A (flow velocity) obtained is 321 dH/dx m/hr or 1054 dH/dx ft/hr where dH/dx is the hydraulic gradient. The hydraulic gradients depend on the amount of rainfall contributing to ground water recharge and local and regional disposition of the terrain. Locally, hydraulic gradients may vary from 0 to 0.01 in a generally rolling countryside terrain and are probably even higher in mountainous terrain. Regionally, as in the Maryland Piedmont (Reference 35) hydraulic gradients vary from about $10^{-6}$ to $10^{-3}$; however, local gradients within a region are determined by local terrain conditions. The presence of a spring fed lake in a locale suggests that relatively high hydraulic gradients are present in the vicinity. For the reference soil, local hydraulic gradients can result in ground water flows of from zero to 3 m/hr (10 ft/hr). Ingersoll (Reference 37) has investigated the effect of water movement on the heat transfer performance of a 5.1 cm (2 inch) diameter pipe buried in a soil having a water content of 30%. He concludes that a water flow of 0.003 m/hr (0.01 ft/hr) will effect the performance by 20% and a water flow of 0.03 m/hr (0.1 ft/hr) will effect the performance by 80%. Ground water flows of 0.013 m/hr (0.04 ft/hr) have been estimated for Long Island, New York, where the water table is within 3 to 5 feet of the ground surface (Reference 36).

In general, the water table varies throughout the year. Hydrographs recorded over a 20-year interval, at two widely separated locations in the Maryland Piedmont, show variations of water levels from 6.7 m (22 ft) to 4.9 m (16 ft) and from 23 m (76 ft) to 16.5 m (54 ft) with the lowest levels occurring in December and the highest levels occurring in late spring (Reference 35). These fluctuations occur because of seasonal variations in precipitation, seasonal differences in evapotranspiration, and ground water additions and withdrawals. This represents a variation of about 17% from the average annual level over the 20-year period of observation. These variations will obviously have more effect on the performance of a heat pipe system installed in a soil of high permeability than they will in a soil of low permeability. In the absence of ground water flow, local measurements of diffusivity will account for this effect.

### 2.8.3 Average Temperature of Earth

In addition to the soil properties, the location of the water table, and the movement of free water, the temperature of the earth system is an important parameter in the design of earth heat pipe systems. It has long been assumed that the temperature of the earth used in heat pipe system design is equal to the mean annual air temperature. This is not always true.

Pluhowski and Kantrowitz report that the mean annual ground water temperature in southwestern Long Island, New York, varies from about 11.7$^{o}$C (53$^{o}$F) at a depth of 4.6 m (15 ft) to 11$^{o}$C (52$^{o}$F) at a depth of 24.4 m (80 ft) in a wooded area and from about 12.8$^{o}$C (55$^{o}$F) at a depth of 4.6 m (15 ft) to 12$^{o}$C (53.5$^{o}$F) at a depth of 24.4 m (80 ft) in a cleared area (Reference 36). They attribute the difference to the difference in absorbed solar energy. The mean annual air temperature at the test site is 10.56$^{o}$C (51$^{o}$F).

The temperature profiles at 40 crystalline rock wells were measured in late fall and early spring down to depths of 61 m (200 ft) in the Maryland Piedmont (Reference 35). The mean temperatures determined were 12.3$^{o}$C (54.1$^{o}$F) at a depth of 15.2 m (50 ft), 11.8$^{o}$C (53.2$^{o}$F) at a depth of 30.4 m (100 ft), and 12.4$^{o}$C (54.3$^{o}$F) at a depth of 61 m (200 ft). The mean annual temperature as measured at the Baltimore-Washington Airport is 12.7$^{o}$C (54.9$^{o}$F), although a number of the wells were located in areas where the mean annual temperature is known to be lower.

### 2.8.4 Earth Storage and Storage Losses

Temperature measurements of the earth at various depths and throughout the year have been recorded at various locations throughout the United States. The temperature range at any depth is defined as the difference between the maximum and minimum temperatures recorded during the year. It is found that the range is the maximum at the surface and decreases until at depths of about 10 m (33 ft) the range becomes insignificant; that is, the temperature of the earth is constant throughout the year and its value approximates the average annual air temperature.

In addition to the reduction in range that occurs as depth is increased, a displacement in time also occurs. For example, while the maximum temperature recorded at the surface may occur in August, the maximum at a depth of 3.6 m (12 ft) may occur in November. Likewise, the minimum temperature recorded on the surface may occur in January and, at a depth of 3.6 m, the minimum temperature may occur in April. By measuring this time displacement at a given depth, the local soil diffusivity may be determined in statu quo.

This transient equilibrium condition is disturbed by adding or subtracting thermal energy. If the thermal disturbance thus created is local and does not persist, the earth will eventually return to its undisturbed transient equilibrium state. For example, it has been shown that large amounts of thermal energy can be extracted from the earth during the winter by heat pipes (a single heat pipe or a field of a few heat pipes) and that by the following August the earth has returned to its original equilibrium state. Regardless of whether energy is added or subtracted, local disturbances will be dissipated several months after the disturbance is removed.

In the absence of ground water flow, the larger the volume of earth thermally disturbed, the longer will be the time required for the earth to reach its original equilibrium once the disturbance is discontinued. In earth heat pipe systems, the disturbance occurs each winter and discontinues in the spring of the year. If the volume of earth disturbed is too large, the earth will not attain its original thermal state before the onset of the following winter. In this event, a gradual temperature drift will occur in the heat pipe field until a new equilibrium is established. To establish a new equilibrium may require a number of years.

Unaugmented earth heating systems depend upon natural replenishment of a substantial portion of the energy extracted during the winter. Systems augmented by adding energy to the heat pipe field during the summer depend on retaining a substantial portion of this added energy in the heat pipe field from which it can be extracted during the winter. When only normal conduction is considered, $\eta_r = 100 - \eta_s$ where $\eta_r$ is the recovery efficiency and $\eta_s$ is the storage efficiency. However, in a heat pipe field, even though storage follows the laws of normal conduction, recovery does not. As explained in Section 2.3.3, the heat pipes operate even in the summer to bypass normal conduction and increase the heat flow from deep earth into that part of the heat pipe field unaffected by heat flow from the surface.

In both the unaugmented and earth augmented systems, the addition and subtraction of heat from the earth is cyclic with a full cycle period of one year. Some insight into the significant parameters defining the ability of the earth to store and release energy can be obtained by considering the thermal behavior of a planar heat source or heat sink which is embedded in infinite earth consisting of homogeneous properties.

For a planar heat source/heat sink located within the earth at a temperature $T_o$ and varying sinusoidally in temperature $\pm \Delta T$ at a frequency f, the temperature at any distance x away from the source can be expressed by:

$$T_x = T_o + \Delta T \text{ e } \exp\left(-x\sqrt{\pi f/\alpha}\right) \sin\left(2\pi ft - x\sqrt{\pi f/\alpha}\right)$$

where:

$$T_{x=0} = T_o + \Delta T \sin 2\pi ft$$

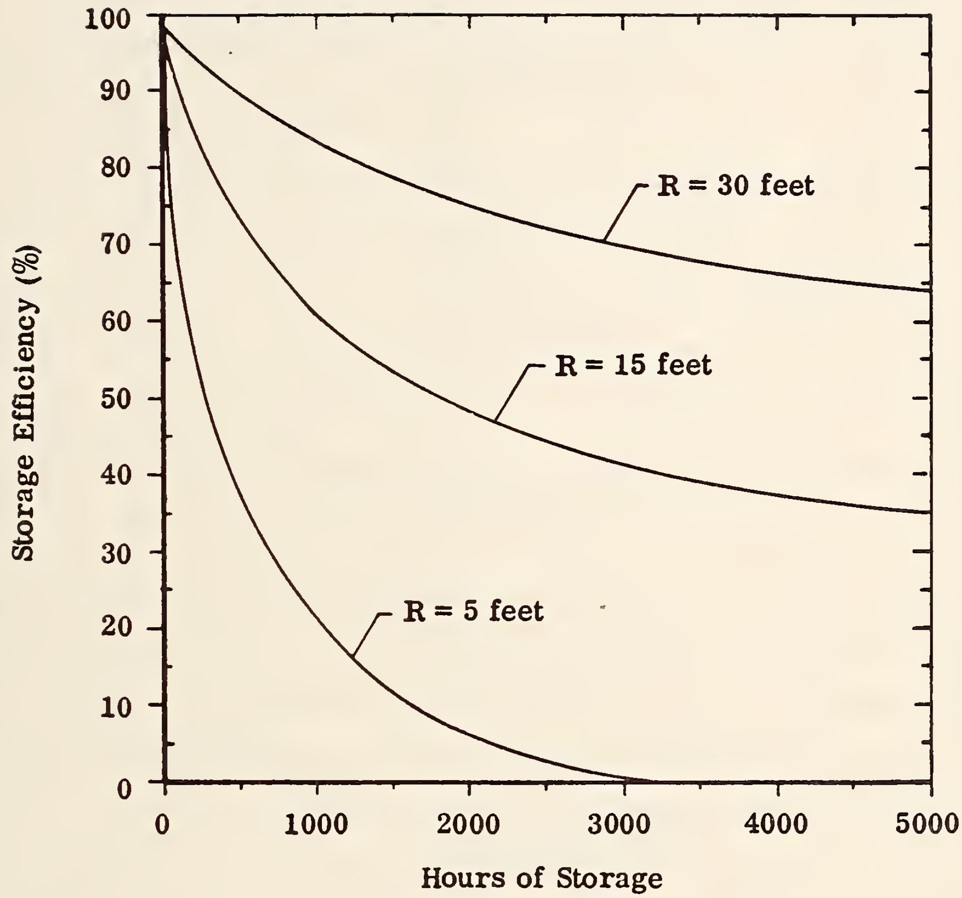
As the temperature wave proceeds in the direction x, it is attenuated and delayed in time. At a distance equal to $\sqrt{\pi \alpha/f}$, the temperature wave is 180 degrees out of phase with that of the heat source/heat sink and it is attenuated by $e^{-\pi}$ or (0.0432). This distance can be thought of as the characteristic earth system dimension and is 8.75 m (28.7 ft) for unsaturated earth and 7.67 m (25.2 ft) for saturated earth where the frequency is one cycle per year. It can be shown that for a heat source/heat sink varying sinusoidally in temperature $\pm \Delta T$ about a constant bulk earth temperature $T_o$, all the heat put into the earth on the up cycle can be extracted on the down cycle. The amount of heat which can be ideally stored and extracted by a planar source in saturated earth is 1.4 Kw-hr/$m^2$-$^oC$ (246 Btu/$ft^2$-$^oF$).

The volume of earth coupled to the pavement surface by the heat pipes can be represented by a long cylinder or a long block of rectangular cross section. If the radius of the cylinder or the distance from the center of the rectangle to the nearest face is greater than the characteristic dimension, then (if only normal conduction is assumed) summer recovery at the center will be small or, conversely, energy storage efficiency at the center will be large. It is evident that summer heat at the pavement surface will not benefit recovery at depths much beyond 6 m (20 ft). Also if the heat pipe did not operate to bypass normal conduction, deep earth heat would not benefit recovery much higher than 6 m (20 ft) from the bottom of the heat pipe. This would leave about 6 m of pipe length in poorly recovered earth. This region will have good storage efficiency because the heat pipe cannot remove this stored energy since it cannot pump heat downward.

The storage efficiency for three sizes of earth cylinders of very long length are given in Figure 32 as a function of storage hours. These efficiencies were determined using the conservative assumption that the surfaces of the cylinders were held at a constant temperature during the storage hours. The storage efficiency increases as cylinder size increases and as diffusivity and thermal conductivity of the earth in the cylinder decrease. The three cylinder sizes in Figure 32 have been superimposed on a scaled sketch of the cross section of the West Virginia system in Figure 33. Note that a cylinder size of 9.14 m (30 ft) radius can be positioned to give a reasonable coverage of the area of influence of the heat pipes. The winter storage period is 5000 hours. A conservative storage efficiency $\eta_s$ for the West Virginia system for this time period is 60%; that is, the required augmentation energy is 1.67 times the annual energy dissipation $Q_t$ of Section 2.4.3. Surface conduction losses are assumed to be a part of the idling energy.

### 2.8.5 Earth Storage in Confined Aquifiers

Under ERDA sponsorship, the storage of large amounts of thermal energy for periods of several months in confined and partly confined (leaky) aquifiers is being investigated. Experimental work of interest to this study is being conducted by the Water Resources Research Institute of Auburn University. The test site is near Mobile, Alabama. The initial experiment consisted of injecting 7570 $m^3$ (2,000,000 gallons) of heated water obtained from the effluent discharge canal of a power plant. Water at an average temperature of 37°C was injected into a confined




1 foot= 0.305 m

FIGURE 32

STORAGE EFFICIENCY OF AN EARTH CYLINDER

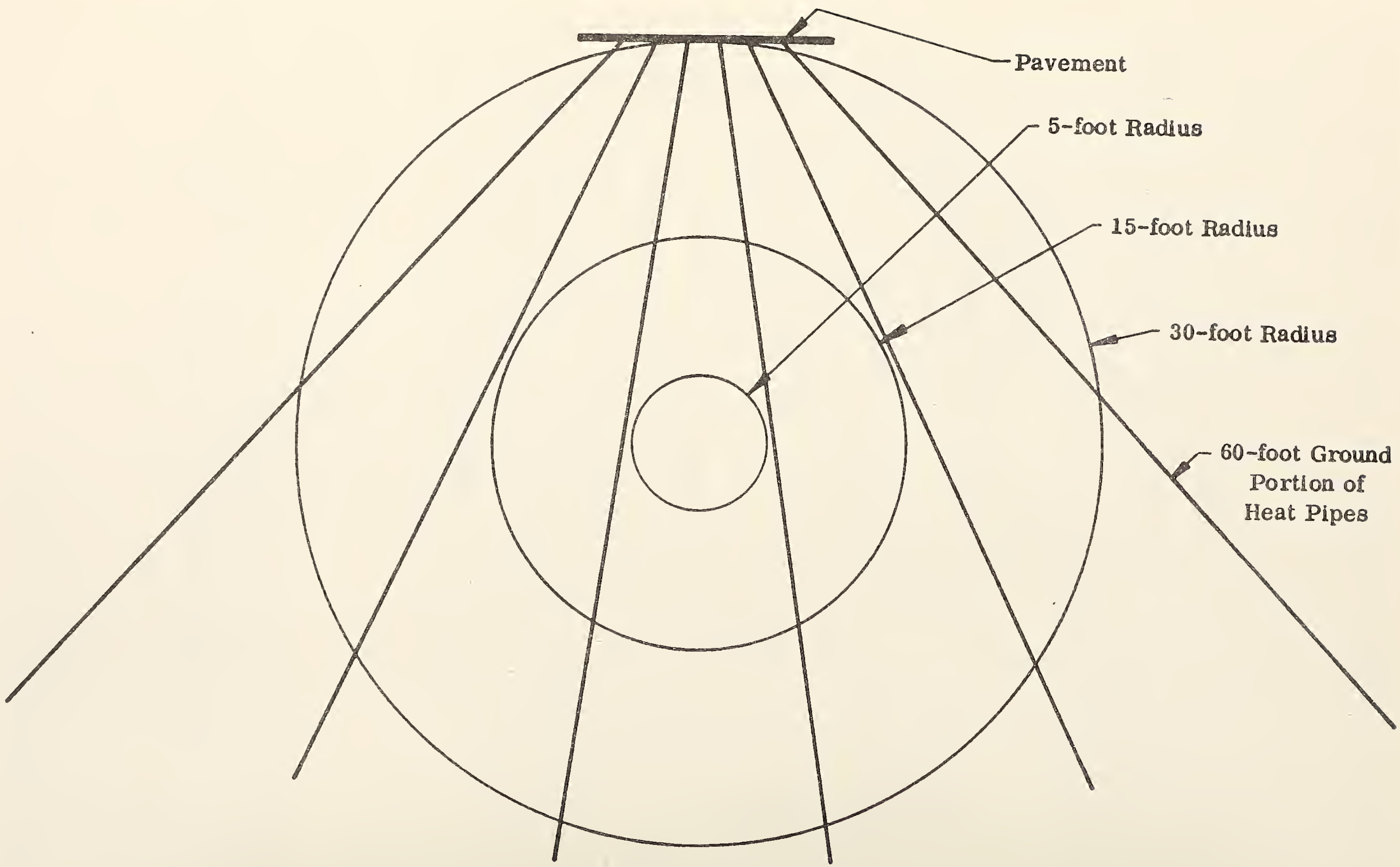



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FIGURE 33

SCALE SKETCH OF WEST VIRGINIA HEAT PIPE DISPOSITION AND VARIOUS CYLINDER SIZES aquifier 21.3 m (70 ft) thick (about equivalent to the 60-foot diameter cylinder in Section 2.8.4); the top of which was located 39.6 m (130 ft) below ground surface. The temperature in the aquifier before injection began was 20°C. The injection was accomplished over a period of 17.5 days (420 hours). After 59 days (1416 hours), water was then withdrawn from the aquifier through the same well hole used for the initial injection. The recovery period lasted 85 days (2042 hours) and was terminated when the water temperature reached 21°C. About 67% (100,000 Kw-hr) of the injected thermal energy was recovered.

In the second experiment, 54,900 $m^3$ (14.5 x $10^6$ gallons) of water obtained from an unconfined aquifier was heated to 55°C (131°F), injected over a period of 79 days (1900 hours), stored for a period of 50 days (1213 hours), and recovered over a period of 41 days (987 hours). Recovery was terminated when the water temperature fell to 33°C (91.4°F) at which time 65% (1.45 x $10^6$ Kw-hrs) of the initially injected energy was recovered. In both experiments, the ground water flow in the confined aquifier was estimated to be 0.002 m/hr (0.17 ft/day).

This experimental work demonstrates the capability of the earth to store large quantities of thermal energy at temperatures usable in earth heating systems. Furthermore, it suggests the possibility of storing thermal energy (collected during the summer months) inexpensively and efficiently in locations separate from the heat pipe field. This thermal energy, stored as heated water, can then be extracted from storage in aquifiers for use in the heat pipe field during melting mode periods described by ASHRAE. The coupling of this energy to the heat pipes by the method shown in Figure 51 is applicable.

## 2.9 Thermally Coupling an Energy Source to the Earth Heat Pipe System

The overall problem of thermally coupling an energy source to the earth heat pipe system can be subdivided as follows:

- For the energy sources which collect and separately store energy to be released to the earth heat pipe system on demand, the problem is one of achieving rapid and effective thermal coupling to the heat pipes.
- For those energy sources which collect energy during the summer and store it in the earth heat pipe matrix, the problem is one of retaining a reasonable percentage of the stored energy within thermal reach of the heat pipe matrix so that it can be extracted.
- For those energy sources which collect energy during the winter for use during the winter, the storage problems are minimal while the thermal coupling problems remain severe.

While one may envision a number of technical solutions to these problems, there are only a few which are economically practical. The type of collection system identifies with the problems of coupling and storage. The wind system collects energy during the winter for use in the winter, and the solar and ambient air systems collect energy during the summer for use in the winter. All collection systems can be combined with separate short or long-term storage wherein the energy is released on demand or all can use the existing earth for storage. The various combinations will be discussed separately under the subdivisions tilted storage-demand, summer collection, and winter collection.

### 2.9.1 Storage-Demand

The storage of thermal energy is receiving national attention as part of the Department of Energy charter. It has also been investigated in connection with heated pavement systems (References 2, 3, 4, 19). The storage of electrical energy is equally well documented. For now, it can be accepted that both electrical and thermal energy can be stored at reasonable storage efficiencies for the time periods required by pavement heating systems.

It has already been shown that for the case of the single heated pipe located in a field of earth heat pipes that, because of the low thermal diffusivity of earth soils, heat travels too slowly to be of practical significance in any augmentation system based upon the demand principle. On the other hand, if the demand augmentation system introduces heat directly around each heat pipe, the fact that heat travels slowly in earth soils turns out to be an advantage because heat is retained around the pipe.

One method of distributing heat more rapidly to the heat pipe field is to make use of the three-dimensional capillary properties of soils above the water table. The case of the flow of moisture under the influence of soil temperature gradients has already been discussed. The movement of held water, which is retained in the soil in a state of reduced pressure or suction, was shown to require very large temperature gradients to achieve rapid moisture and thermal movement. This technique for rapidly coupling the heated pipe to the earth heat pipe field has been discarded. In its place, a technique for percolating heated water through a porous pipe into unsaturated soil beneath the pavement has been investigated.

To describe the movement of moisture introduced into a stable zone of aeration, Darcy's equation must be written in three-dimensional form:

$$Q = K(\theta)\, A\, (\nabla H - \nabla \tau(\theta))$$

where $K(\theta)$ is termed the unsaturated conductivity and is always smaller than the saturated hydraulic conductivity. The symbol $\theta$ indicates that the unsaturated conductivity varies as the volumetric water content in the unsaturated soil. The term $\nabla H$ is the hydraulic gradient and $\nabla \tau(\theta)$ is the suction gradient which is also a function of $\theta$, the volumetric water content. Since both the conductivity K and suction $\tau$ are functions of $\theta$, Darcy's equation can be simplified.

$$Q/A = q = K(\theta)\, \nabla H + D(\theta)\, \nabla \theta$$

where $D(\theta)$ is called the soil-water diffusivity in $m^2/hr$ ($ft^2/hr$). The term $\nabla\theta$ is the concentration gradient. The soil-water diffusivity is defined by:

$$D(\theta) = K(\theta)\, (- d\tau/d\theta)$$

where $d\tau/d\theta$ is the suction gradient and is zero in saturated soils. Measurements of suction and water content are routine soil measurements (References 34, 38). As would be expected by capillary analogy, finer grained soils have high suction and coarse grained soils have low suction. Suction values of $1 \times 10^5$ kg/m$^2$ (150 lbs/in$^2$) are not uncommon in loamy soils at a 10% water content. If this soil is oven dried, suctions of $7 \times 10^7$ kg/m$^2$ ($10^5$ lbs/in$^2$) are obtainable.

To determine the practicality of quickly coupling a storage energy source to the earth heat pipe matrix, consider the case of a single 2 cm (0.8 inch) diameter porous pipe carrying heated water and located beneath the pavement in a Monoma silt loam soil. Assume that the initial water content of the soil is 30%, the soil porosity is 52%, and the porous pipe establishes at its surface water content of 45.5%. The diffusion of moisture under isothermal conditions is shown in Figure 34 as a function of time where the profiles establish the position of the advancing front of increased moisture content.

Because Darcy's equation contains both gravity and suction components, the movement of moisture in the vertical direction is asymmetrical. The amount of moisture introduced into the soil varies by a complex exponent from the surface of the porous pipe to the front of increasing moisture. Numerical methods are required to determine the quantity of water introduced into the soil as a function of time. To a first approximation, the horizontal front of moisture movement is proportional to the square root of time, after a few hours the downward movement is proportional to time, and the upward movement is inversely proportional to the square of the upward distance moved.

Incidentally, the performance of porous pipes carrying heated water has been investigated experimentally and analytically by D. L. Slegel in connection with subsurface irrigation and soil heating to improve plant growth and increase the duration of the growing season (Reference 41). His formulae for liquid and vapor flow were expressed in finite difference form and solved numerically using an implicit scheme on a CDC 3300 digital computer. His analytical results agree well with existing laboratory data.

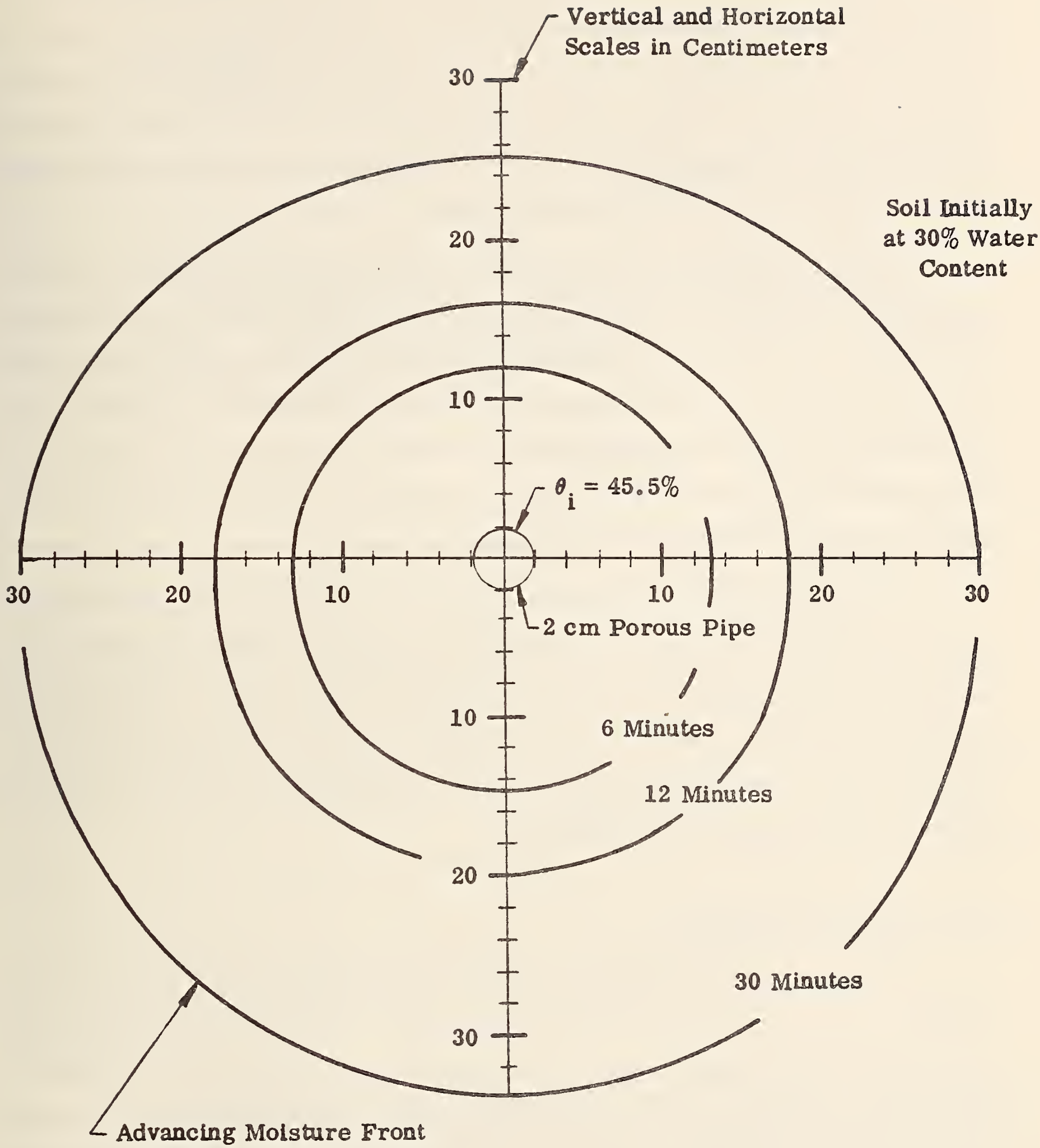



FIGURE 34

ISOTHERMAL MOISTURE MOVEMENT AROUND A POROUS PIPE
IN UNSATURATED MONONA SILT LOAM

In Figure 34, the calculated hourly quantity of water introduced into the soil by the porous pipe is 128 kg/m or 86 lbs/ft where the dimension refers to the linear length of the pipe beneath the pavement. For the temperatures represented by the ambient air collector example, $16^{\circ}C$ ($61^{\circ}F$) water and $7.2^{\circ}C$ ($45^{\circ}F$) earth, the power input to the earth is 1.32 Kw/m or 1376 Btu/hr-ft. A larger porous pipe will obviously increase the power input to the earth.

The more significant observation to be made from this analysis is that the movement of moisture and, concomitantly, thermal energy extends through the heat pipe matrix in a time period reasonable for consideration in demand systems. The movement upward in 10 hours is about 0.6 m (2 ft), horizontally 1.2 m (4 ft), and downward 2.4 m (8 ft). In addition, Highway Engineers need not fear adverse effects on the resilient modulus of subpavement soil if the porous pipe is located at a depth below the subgrade of about 1.8 m (6 ft) (Reference 41).

In order to apply this method of energy distribution, the soil beneath the pavement (to a depth of 4 m) must have the proper properties. Clays, unweathered slate, marble, mica schist, quartzite, chert are unsuitable earth media. Furthermore, the water table should be at least 6 m (19.7 ft) below the pavement subgrade during the winter months. Fortunately, for most interchange applications (Figure 1) these conditions either prevail or can be controlled.

## 2.9.2 Summer Collection

The pavement and ambient air collection systems are both committed to summertime collection and, for all practical purposes, to earth storage of the collected energy within the heat pipe matrix. It is instructive to calculate the heat capacity which must be coupled to the pavement's surface for a full performance air ambient system located in Madison, Wisconsin. The more general expression for the required temperature augmentation in metric units is:

$$\Delta T_g = \frac{R_{t,5} + \psi}{R_{t,5}} \left( (26.11 - T_g) \frac{R_{t,j}}{R_{s,aj}} - 16.67 + \frac{\psi \delta T}{R_{t,5} + \psi} \right)$$

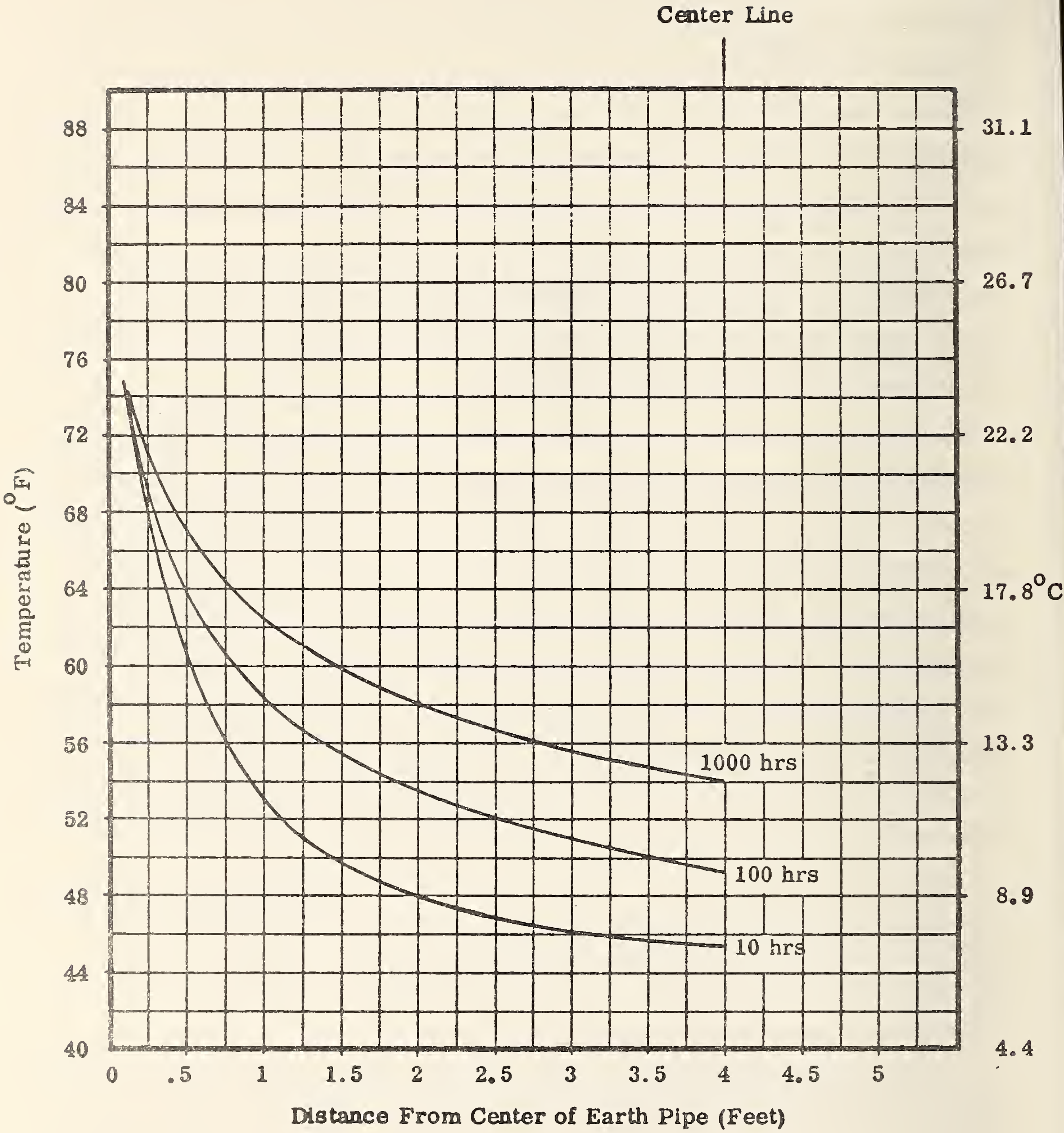
where $\psi$ is defined by:

$$\psi = \frac{3624}{2\ C_{e,s}}$$

If an 80% efficient system is assumed, the heat capacity $C_{e,s}$ for a full performance system, assuming perfect ground coupling, is calculated to be 160.7 Kw-hr/m$^2$-$^o$C. When it is realized that the heat capacity used for the West Virginia system is 33.57 Kw-hr/m$^2$-$^o$C, it becomes immediately obvious that the Madison full performance ambient air system is economically impractical and that some demand augmentation will be required in very cold climate regions.

The pavement collector using down-pumping heat pipes places collected energy at a higher temperature directly around the heat pipes than does an ambient air system. This is because the pavement collects solar energy directly and, thereby, achieves temperatures 10$^o$C to 15$^o$C higher than those available using ambient air. Since the heat pipe operates in a cyclic mode, an accurate representation of the resulting earth temperature profile requires computer analysis. If it is assumed that heat is supplied to the earth continuously from a one inch IPS pipe which operates at 23.9$^o$C (75$^o$F) to an earth sink at 7.2$^o$C (45$^o$F), the temperature profile around a single pipe in a field of pipes will be as shown in Figure 35. At 1000 hours, the energy input to a 2.44 m (8 ft) diameter earth cylinder 18.3 m (60 ft) long is 95 Kw-hr which is somewhat greater than the 71 Kw-hr reference collection capability stated in Section 2.6. Therefore, because heat is supplied over a period of time in excess of 3000 hours, the actual temperature profile around the pipe will be somewhat flatter than indicated.

W. B. Bienert (Reference 19) analyzed the case of a field of 19 down-pumping pipes. Using Ingersoll's approach (Reference 37), he developed a model and derived a line source equation which describes the temperature profile as a function of time and distance from each pipe. He first analyzed the unaugmented case assuming that each pipe was embedded in a pavement section of 0.93 m$^2$ (10 ft$^2$) area and that annual losses from this pavement section were 189 Kw-hr/m$^2$ (60,000 Btu/ft$^2$). To simplify the analysis, vertical heat conduction was assumed to be zero. The results are pre-




1 foot= 0.305 m

FIGURE 35

TEMPERATURE PROFILES AROUND A ONE INCH IPS HEATED PIPE IN UNSATURATED SOIL sented in Figure 36. The temperature in the center of the heat pipe field drops 9.1°C (16.3°F) during the first winter and recovers to within 1.9°C (3.4°F) during the subsequent summer. He then analyzed the same case with augmentation assuming that the heat supplied to the earth during the summer exactly compensated the heat extracted during winter operation. The results are presented in Figure 37. The average ground temperature at the center of the field during the second winter is 3.9°C (7°F) higher than in the field without augmentation.

In contrast to the natural disposition of summer energy in the earth inherent in the down-pumping concept, the ambient air system must employ a secondary system. It is obvious that, to deploy thermal energy into the earth by conduction with the same efficiency as a heat pipe system, the secondary system must essentially duplicate the existing heat pipe system in both disposition and linear pipe length.

### 2.9.3 Winter Collection

As indicated in Section 2.5.3, wind energy collection is a maximum during the winter months and solar energy collection is a maximum during the summer months. The discussion here concerns itself with the collection and short-term storage of wind energy for use in demand augmentation of an earth heat pipe system.

Electrical energy has the advantages that it is easy to transport from one location to another by means of relatively small diameter flexible wires and, by passing electric current through resistance elements, it can be converted to thermal energy at any desired temperature. It has the disadvantages that it is expensive to store and electrical cables, located in the ground and in pavements, are subject to premature failure unless adequately protected.

An electrical heating cable, which is buried longitudinally in the soil under the highway pavement, will dissipate thermal energy generated by its $I^2R$ losses. The cable will operate at the temperature required to dissipate these losses without the need for controls. This is an advantage because moisture moves away from heat sources located in unsaturated soils. This moisture movement causes a local dryout of the soil around the heat source and a significant decrease in soil thermal conductivity, which results in an increase in heat source temperature for a constant

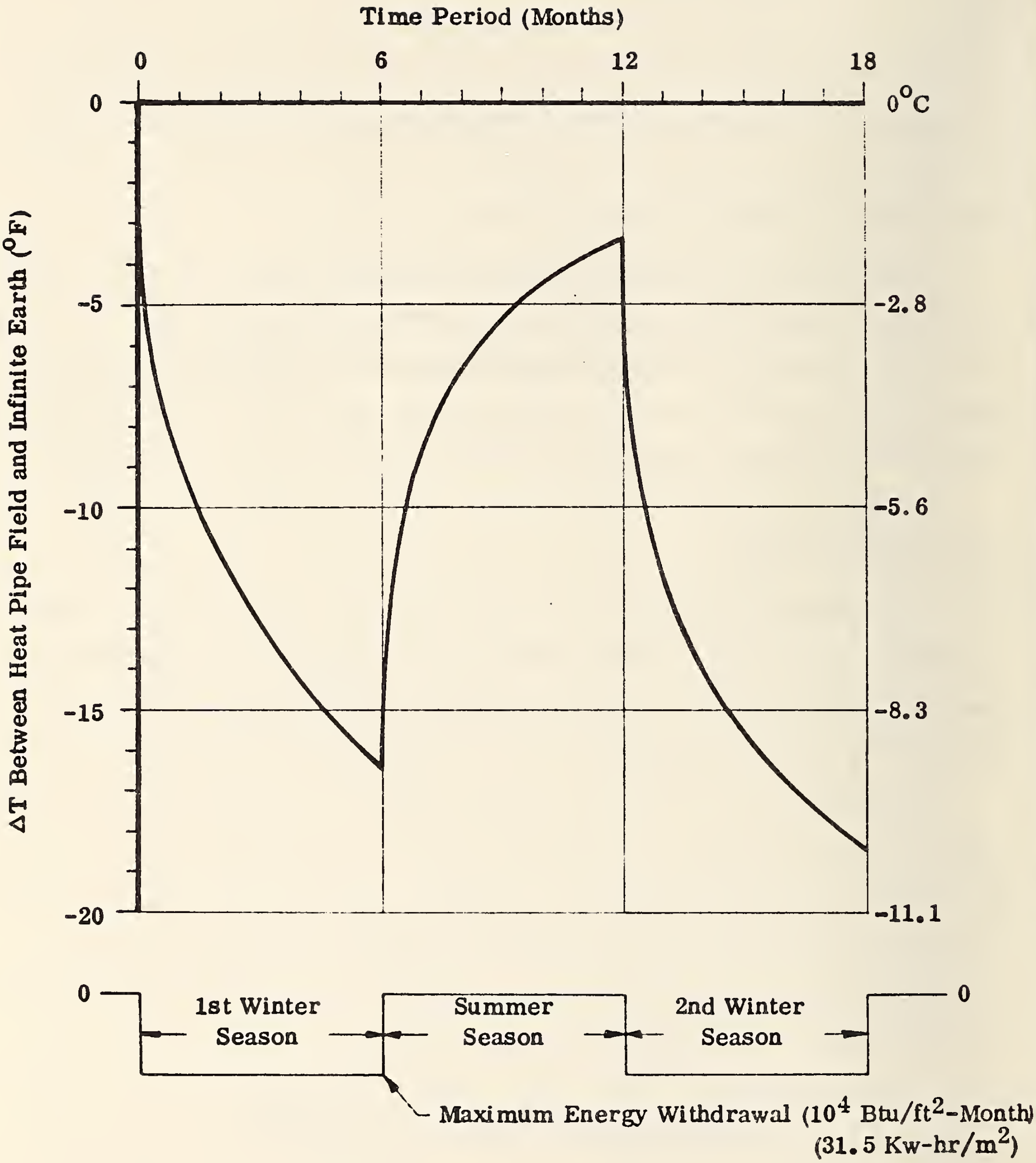



FIGURE 36

SEASONAL TEMPERATURE CHANGES IN CENTER OF AN UNAUGMENTED HEAT PIPE FIELD

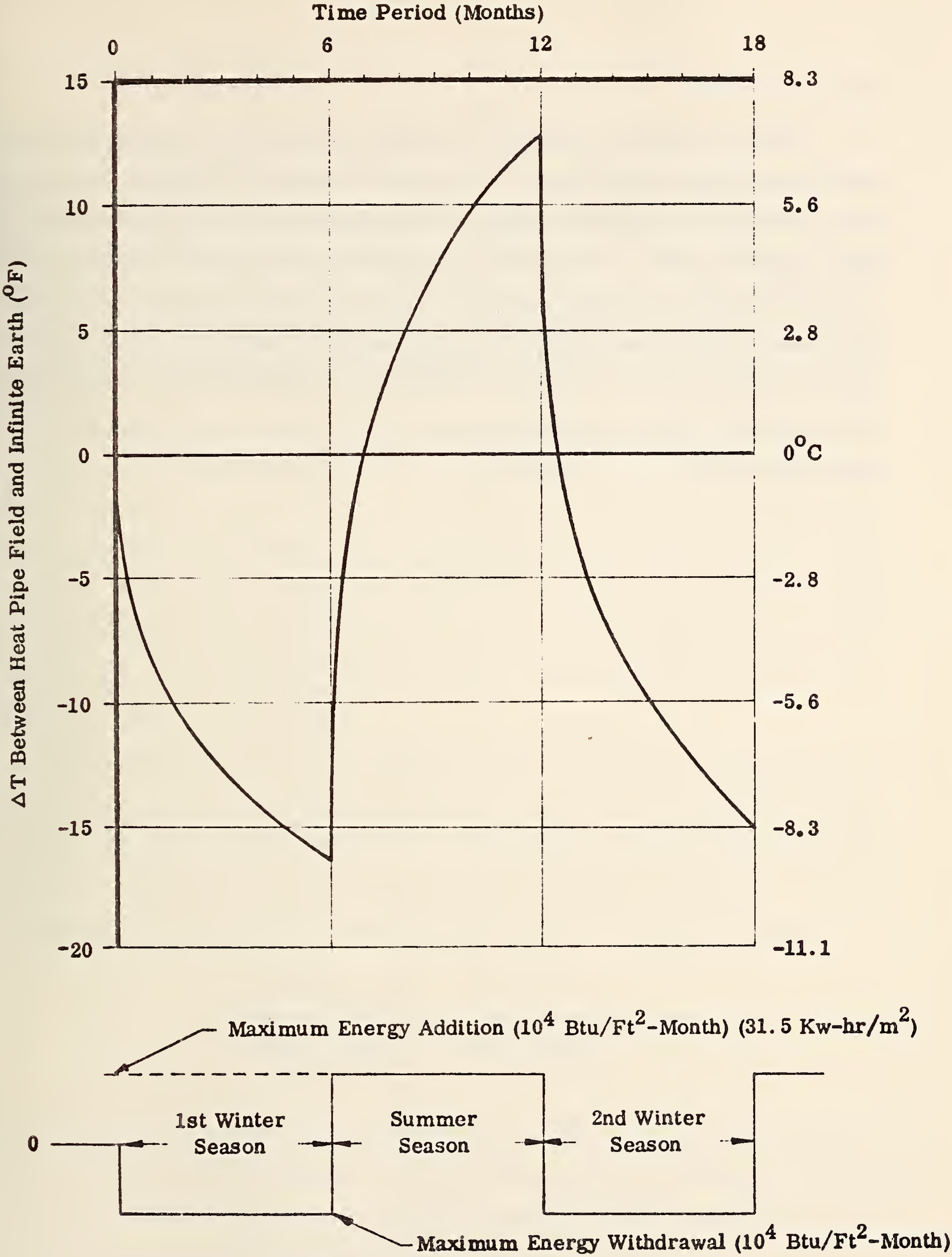



FIGURE 37

SEASONAL TEMPERATURE CHANGES IN CENTER OF AN AUGMENTED HEAT PIPE FIELD heat source output.

The best method of coupling an electrical heat source to an earth heating system is determined by economics. An electrical resistance wire may be wrapped around each ground portion of the earth heat pipes and connected to a feed cable leading to the wind machine system. Alternately, the liquid distribution system described in Section 2.12 may be utilized. The latter would require the use of an electrical liquid heater which would be energized whenever demand energy was required. If lead $H_2SO_4$ storage batteries were not employed, the electrical liquid heater could be reduced in capacity because it would operate more or less continuously to heat liquid in the thermal storage tank

## 2.10 Earth Heat Pipe Testing

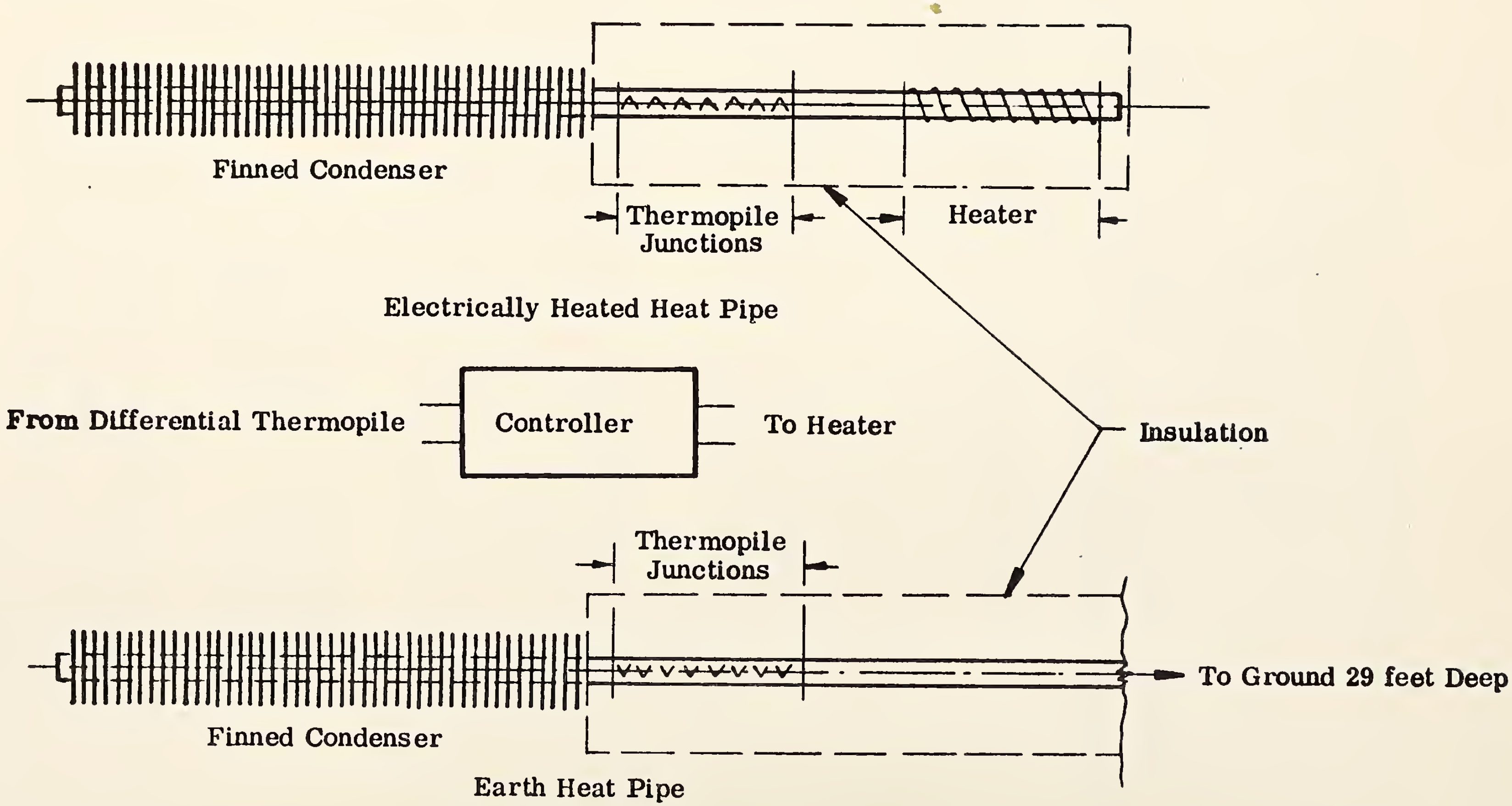
In order to obtain data on the energy extraction capability of a heat pipe embedded in what is expected to be typical earth conditions, a pipe that had been embedded in weathered Cockeysville marble (Reference 35) for four years was reactivated as a heat pipe. A schematic of the test setup is shown in Figure 38. A finned section was added to the horizontal leg of the heat pipe, and the pipe was recharged with ammonia. The finned section was exposed to the environment and, whenever the ambient air temperature was lower than the effective ground temperature, energy was extracted from the earth.

In order to measure the amount and rate of energy removed from the earth, a second electrically heated heat pipe was installed adjacent to the earth heat pipe as a control. Its finned section was identical to that of the earth heat pipe. The electrical energy input to this control pipe was automatically adjusted such that its vapor temperature was equal to that of the earth heat pipe. By measuring the instantaneous and integrated power and energy inputs to the control pipe, the power and energy output of the earth heat pipe was determined.

The test was initiated in late November 1976 and continued through March 1977. During the first two months of operation, the heat pipe was allowed to extract energy from the ground only during working days. (It was covered with insulation during the weekends.) During January, February, and March, the system was operated almost continuously. The average heat output rates during the months of testing were:

| | |
|---|---|
| December 1976 | 93.9 watts |
| January 1977 | 135.1 watts |
| February 1977 | 106.1 watts |
| March 1977 | 48.7 watts |

The heat output rates reflect the seasonal changes in ambient temperature since the system is coupled to the environment. The cumulative energy extracted from the earth is given in Figure 39. By the end of the severe winter, a total of about 180 Kw-hr of energy had been extracted from the earth.




1 foot= 0.305 m

FIGURE 38

SCHEMATIC OF TEST SETUP FOR DETERMINING HEAT REMOVAL FROM THE GROUND

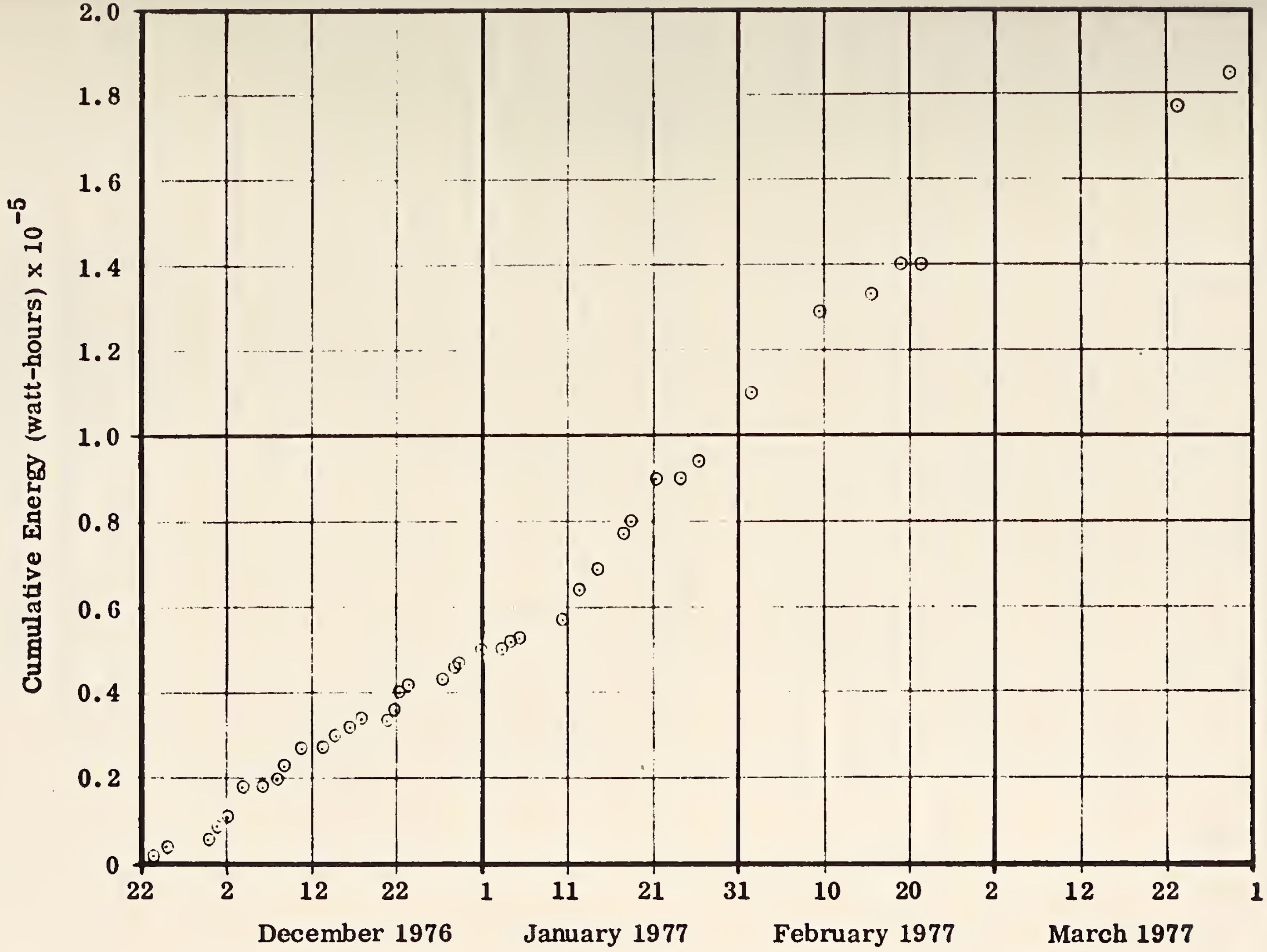



FIGURE 39

VARIATION OF CUMULATIVE ENERGY EXTRACTED FROM THE GROUND

As the winter progressed, the effective ground temperature decreased. At the start of testing, the ground temperature was approximately 14.33°C (57.8°F). Using this temperature, measured power extracted, and measured heat pipe vapor temperature, an effective ground resistance of $1.85 \times 10^{-2}$ °C/W ($3.33 \times 10^{-2}$ °F/W) was calculated using:

$$R_{g,p} = \frac{T_g - T_v}{\dot{q}_p}$$

Maintaining the effective ground resistance constant, the variation of effective ground temperature was obtained as a function of testing time and the values are plotted in Figure 40. The solid curve in Figure 40 was obtained using line source theory. The fluctuations of effective ground temperature shown are to be expected because of the variations of the rate of energy extraction; however, the long-term trend correlated well with the theory.

In this report, $R_{p,g}$ is defined as the resistance between faraway ground and the heat pipe at midwinter. The value of $R_{p,g}$ at the end of February for this (in Virginia) test pipe is 0.06°C/W (0.11°F/W). This value compares with 0.07°C/W (0.13 °F/W) determined for a field of pipes 8.84 m (29 ft) long of the same in-ground length as the present test pipe (Reference 1). It compares with the value of 0.025°C/W (0.045 °F/W) used herein for the 18.3 m (60 ft) long West Virginia heat pipes.

In addition, the test heat pipe was periodically deactivated and ground temperature profiles were thus obtained. The heat pipe condenser section was insulated to prevent heat loss. This permitted the heat pipe to reach equilibrium after a few days. By the middle of June, the earth temperatures were showing the characteristic recovery as shown in Figure 41.

In addition to the testing of an individual heat pipe, the performance of a field of 9 heat pipes located at the University of Wyoming's Sybille Canyon test site was monitored (Reference 46). The heat pipes were originally installed in October 1976, and the upper portions were left exposed to the environment until January 1977. Subsequently, 4.9 m (16 ft) of the upper portion of the heat pipes were installed in a

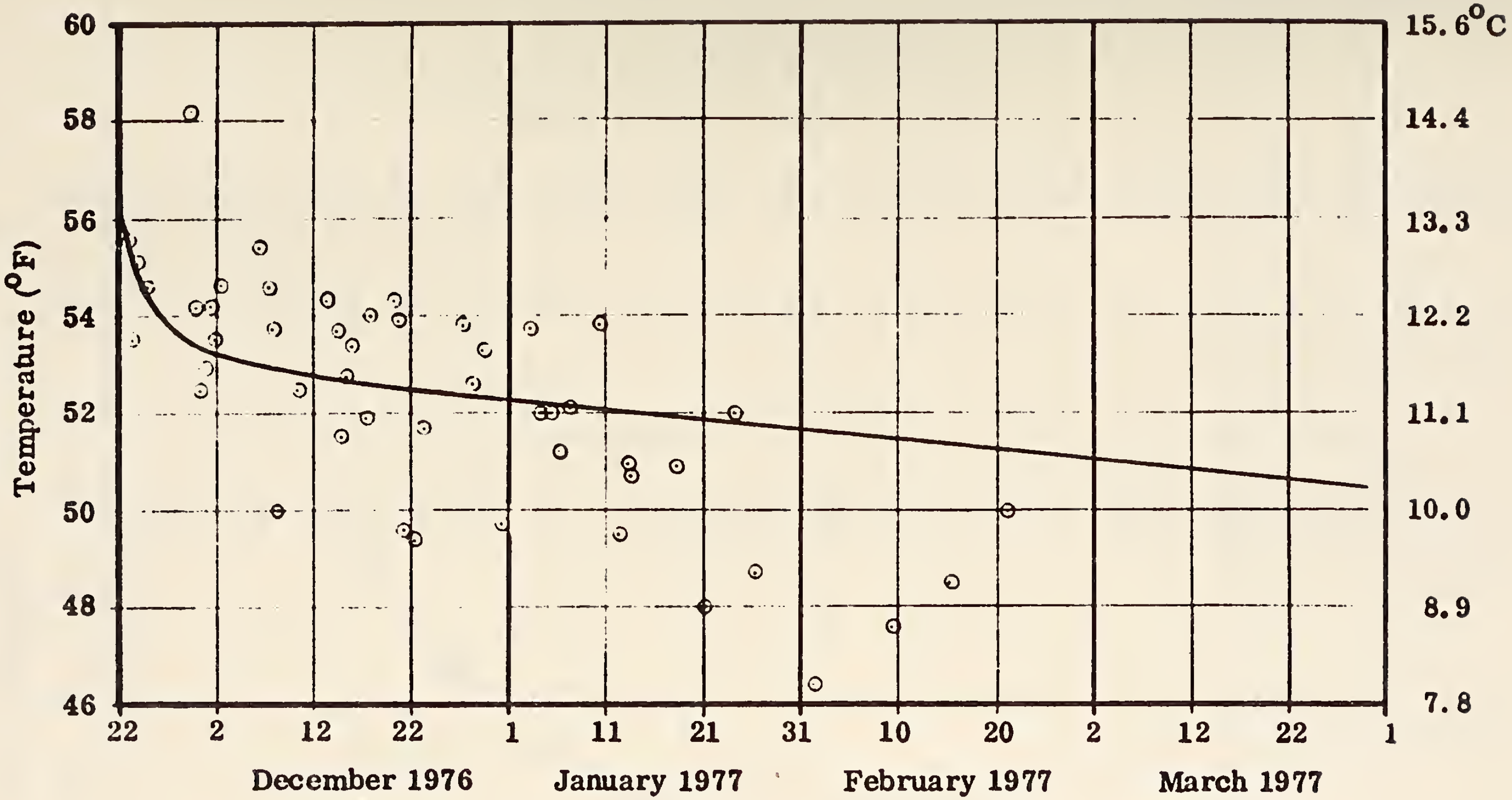
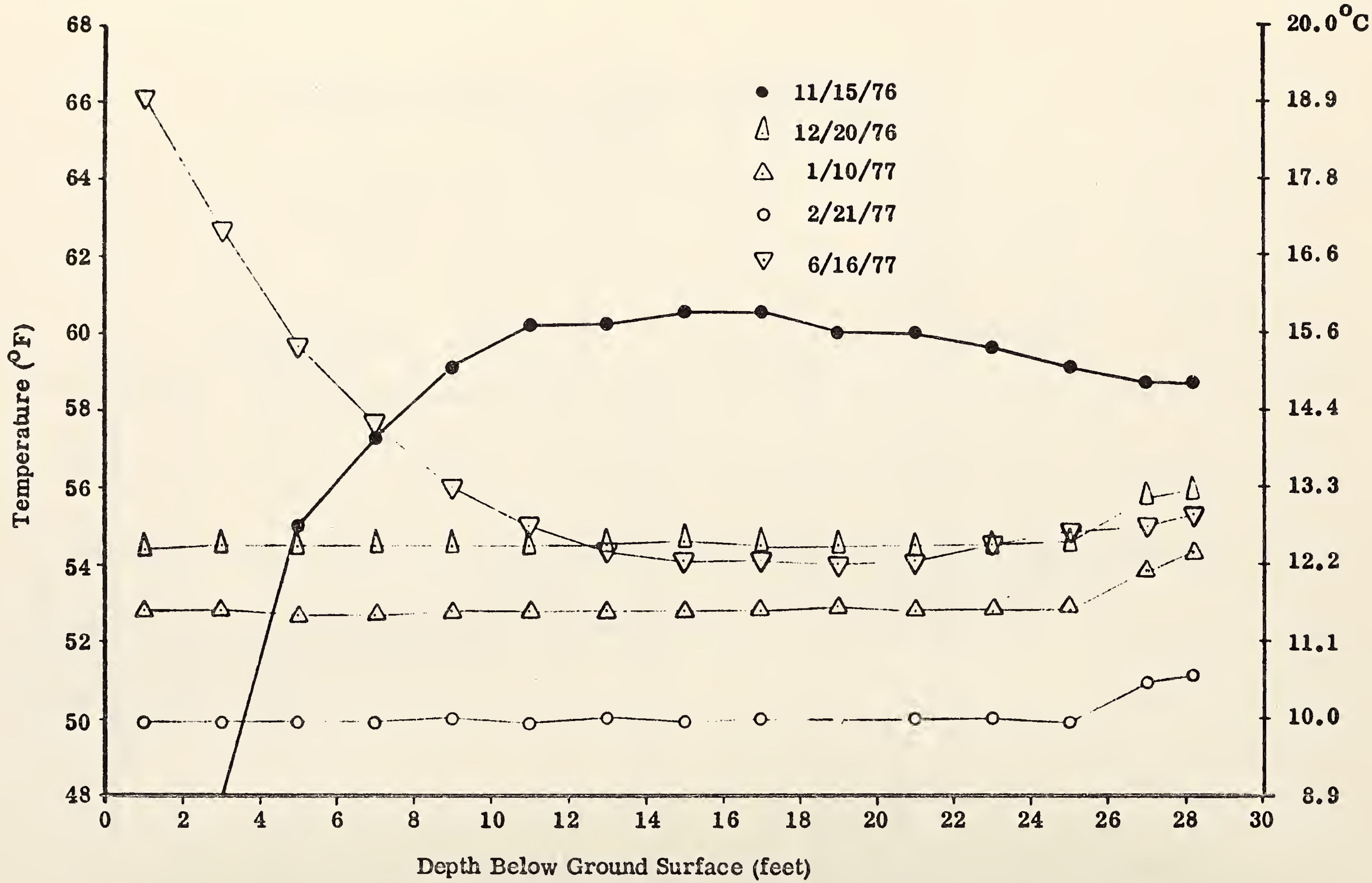



FIGURE 40

VARIATION OF EFFECTIVE GROUND TEMPERATURE




1 foot= 0.305 m

FIGURE 41

EARTH TEMPERATURE PROFILES

bridge deck and the remaining exposed portion was insulated. During the Winter of 1977-1978 the heat pipes supplied approximately 350 $Kw\text{-}hr/m^2$ of energy to the bridge deck. The heat pipes began to supply energy to the bridge deck in September and the temperature on the heat pipe takes on a negative slope in October, whereas the earth is still increasing in temperature as shown in Figure 42. The heat pipe temperature begins to recover in February and is fully recovered by July. Because the heat pipe field is relatively small (center-to-center pipe spacing was 1.2 m (4 ft) and there was one row of 4 pipes and one row of 5 pipes), good recovery is expected. Note that the depth at which the temperature measurements were taken is 16.2 m (53 ft).

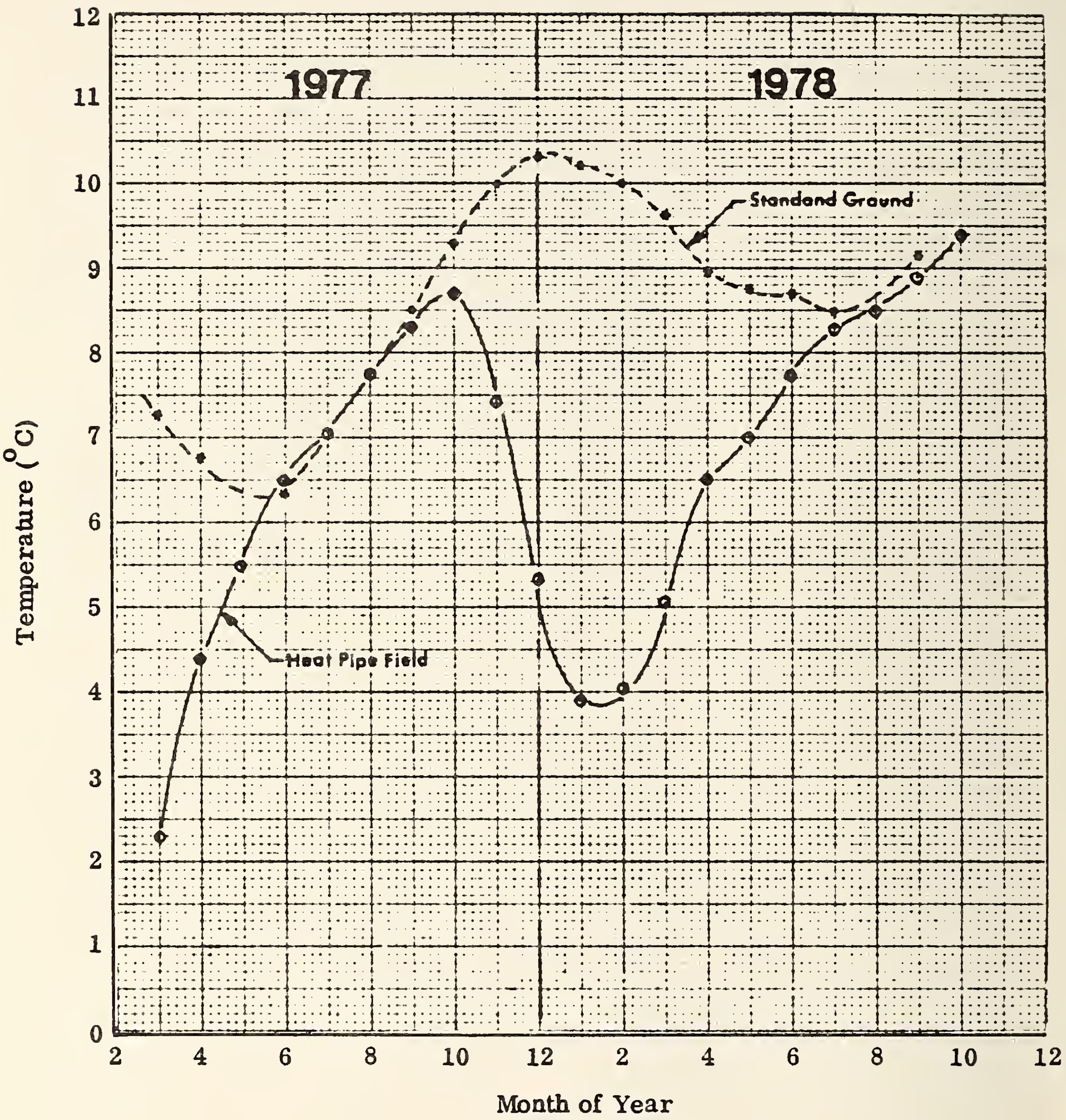



FIGURE 42

GROUND TEMPERATURE AT DEPTH VERSUS
HEAT PIPE FIELD TEMPERATURE

## 2.11 Augmentation System Concepts

Before a reference augmentation system design was selected, a study was made of the technical and economic implications of several suggested augmentation methods using solar, ambient air, and wind energy sources. The study of demand systems was carried forward, although they detract from the fundamentally passive nature of earth heating systems. This was done because this is basically the ASHRAE approach to snow melting systems; that is, an idling mode which is consonant with the part played by the unaugmented earth heating system, and a melting mode which can theoretically be assigned to wind or solar energy source augmentation systems. As evidenced by the ASHRAE recommendations, the annual energy requirements for the melting mode are a small fraction of those required for the idling mode and this is economically favorable to combat the initial high capital investment required for wind and solar collection systems.

### 2.11.1 Solar Energy Systems

A schematic of a flat plate solar collection system is shown in Figure 43. The system uses summer collection at the specific collection values reported previously for the three cities for the worst year. The collected energy is stored in heated water contained in an insulated underground tank. A water temperature rise 27.8°C (50°F) was assumed to determine the specific volume of water required for each square metre of collector area. The installed tank cost is given in parenthesis following each volume and is estimated using the information from Reference 4. The storage efficiency is 60.6% over a 6-month period for the 37.8°C (100°F) water temperature and a ground temperature of 12.8°C (55°F). The cost of delivered energy neglecting size dependent piping, pumps, and valving can be calculated. For all three cities, the ratio of initial capital outlay to energy distributed in one year is slightly in excess of $6/Kw-hr. The normalized cost represented by this ratio is very high, and the system can only be economically practical if the energy is used solely to satisfy demand requirements.

A demand system uses less energy because the energy is applied to the pavement surface only during precipitation events. Tables 11, 12, and 13 give values of the required demand energy for the West Virginia system (Case 4). The initial capi-

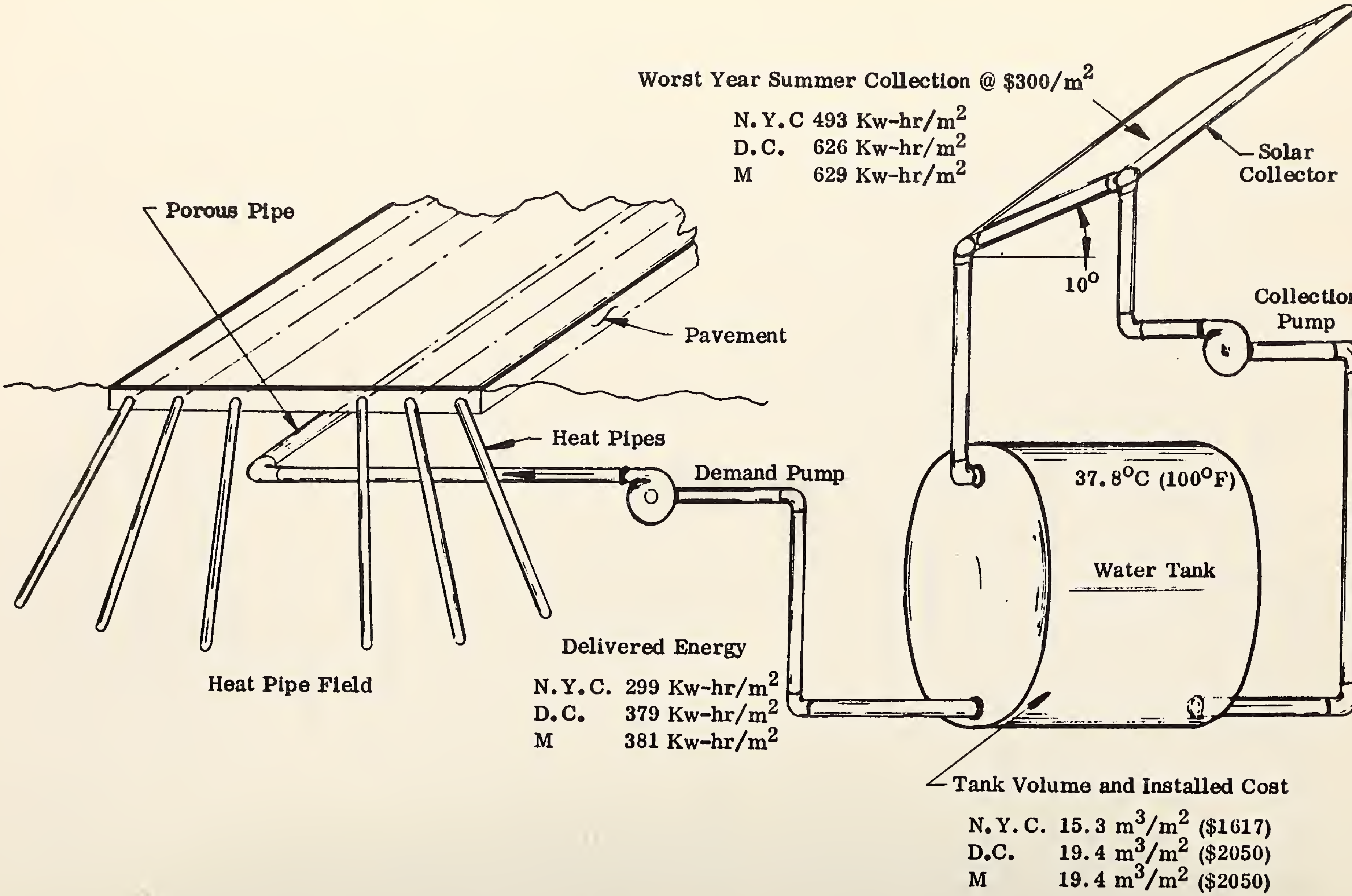



FIGURE 43

**FLAT PLATE SOLAR COLLECTION DEMAND SYSTEM**

tal investment at an energy cost of \$6/Kw-hr delivered on a demand basis for the worst year for New York is $\$159/m^2$, Dodge City is $\$340/m^2$, and for Madison is $\$442/m^2$. These costs do not include the pumps, valves, and distribution piping.

The above costs are higher than the results of previous studies. Reference 2 explored the use of solar collectors, water thermal storage, in-pavement heat pipes transverse to the pavement, and a water trough for coupling the heat pipes with the heat source. The installed costs for a 5574 $m^2$ (60,000 $ft^2$) airport ramp area were reported as $\$125/m^2$ ($11.6/ft^2$) for Chicago and $\$108.6/m^2$ ($\$10.1/ft^2$) for New York City. Although simpler in design, the Reference 2 system is not practical for highway use for two reasons:

- The highway system must be applicable to hill, curve, and ramp locations where substantial grades exist.
- The airport system can justify a part time operator, whereas a highway system cannot.

The alternate solar system concept utilizes the pavement as a solar energy receiver and down-pumping heat pipes (Figure 30) as energy collectors. The integration of the up-pumping/down-pumping heat pipe into the pavement system follows the pattern established in the Oak Hill facility. The plan of a standard pavement with this heat pipe installed is shown in Figure 44.

### 2.11.2 Ambient Air Energy Systems

During the summer months, the thermal energy in air at an acceptable augmentation temperature is virtually infinite. In contrast to solar and wind energy system collectors, the size of the ambient air collector is not determined by nature but is determined by design. This is an important distinction because:

- The aesthetics of large areas of solar collectors or large wind machines may not be acceptable in certain congested locations.
- The cost of any machine is related to its size, and there is not much a system designer can do if mother nature controls the major ingredients determining size.

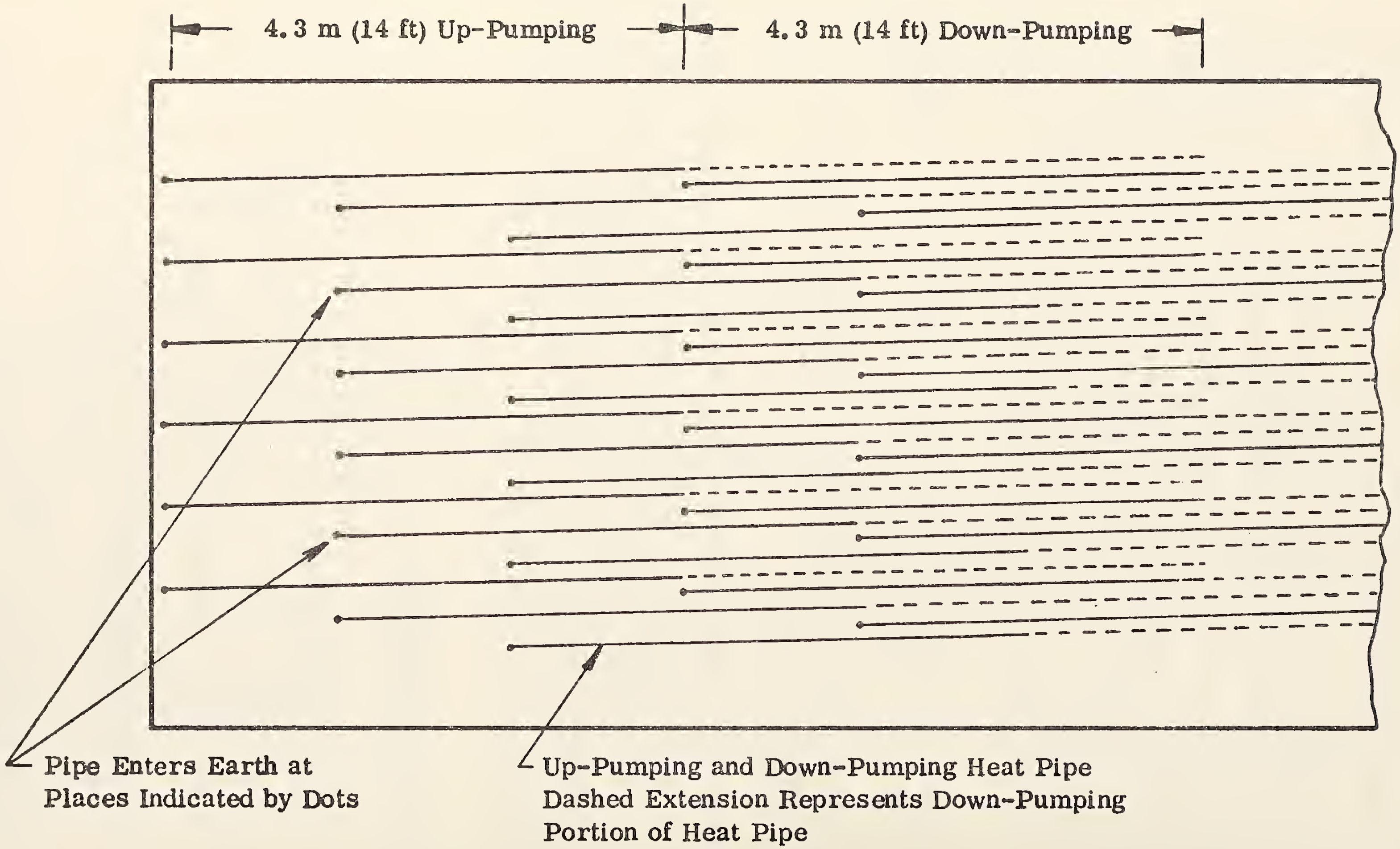



FIGURE 44

UP-PUMPING AND DOWN-PUMPING HEAT PIPE ARRANGEMENT
IN STANDARD PAVEMENT SECTION

Because ambient air energy is collected at low temperatures during the summer, earth storage is the only economically feasible method of storage. Great quantities of inexpensive energy are available. The problem is to couple this energy to the earth beneath the pavement in a technically and economically acceptable manner. Three basic approaches to accomplish this coupling have been investigated:

- The use of one or more pipes located beneath the pavement and carrying heated water in a closed loop system.
- The use of porous pipes located beneath the pavement and carrying heated water in an open loop system.
- Passing heated liquid through plastic tubing wrapped around each earth heat pipe (see Section 2.12).

Figure 31 shows the temperature distribution around a 15.2 cm (6 inch) diameter heated pipe embedded in unsaturated earth. The adverse effects of moisture movement away from a heated pipe were not accounted for. The pipe would be placed in a 1.83 m (6 ft) deep ditch dug down the approximate centerline of the heated pavement section. The calculated input energy as related to a 4.88 m (16 ft) wide pavement for a four month summer heating period was reported in Section 2.8 to be 12 $Kw\text{-}hr/m^2$. This could be improved by surrounding the pipe with a material (such as bentonite) having a conductivity higher than that of unsaturated earth. In this way, equivalent surface energy may be increased to 25 $Kw\text{-}hr/m^2$.

By December, the temperature front will have moved into the ground an additional distance of 8 m (26 ft) at which point it will be dissipated (Section 2.8). Because only conduction mechanisms of heat transfer are operating, the thermal involvement of the heat pipe matrix is obviously minimal. The situation could be materially improved at the expense of wasting some energy by placing two additional pipes under the pavement and locating them at the pavement edges. The collectable energy estimates reported in Section 2.5.2 were obtained using this as the reference system.

The porous pipe distribution system for low temperature energy sources using earth storage has some problems of its own. On the average, the energy transportable by water in these systems is between 11.6 W/kg (150 Btu/gallon) and 15.5 W/kg (200

Btu/gallon). This requires between 5 and 10 times the water usage of the demand system concept of Figure 43. This higher water usage may trouble some Highway Engineers concerned with exceeding the plastic limit in the subpavement soil structure, and there may be some concern regarding the availability of the required amount of water at the roadway site.

The concept envisioned is shown in Figure 45. The collection rates shown for the three cities for the worst years are based on using dry air thermal properties and local well water temperatures. To put the water usage requirements into perspective, the annual average rainfall is also shown for each location (Reference 21). Using the calculated collectable energy values, the water requirement for each square metre of collector area for New York City is 3.33 $m^3$/hr (14.6 gal/min), for Dodge City 3.15 $m^3$/hr (13.9 gal/min), and for Madison 2.42 $m^3$/hr (10.6 gal/min). This flow is required for about 1200 hours during the summer months of May, June, July, and August.

The annual energy dissipation from the pavement surface for a nondemand full performance West Virginia system located in Madison, Wisconsin, is calculated to be 907 Kw-hr/$m^2$ (Figure 18). If we assume a storage efficiency of 50% and collected energy of 43,136 Kw-hr/$m^2$, then a pavement area of 23.8 $m^2$ can be served. The amount of water needed to serve this pavement area is 2.42 $m^3$/hr or for 1200 hours of operation the total quantity of water required is 2904 $m^3$. Related to the pavement surface, the water usage is 122 $m^3/m^2$ or more than 150 times the average annual rainfall. Comparatively, this is a large amount of water addition to the soil and, even though it is being pumped out of and returned back to the acquifier, it may, nevertheless, result in soil instabilities beneath the pavement.

### 2.11.3 Wind Energy Systems

One form of a wind energy system is illustrated in Figure 46. The electric generator can supply electric energy to the buried resistance cable at any suitable voltage and frequency as determined by wind velocities ranging from cut-in to cut-out. The surface temperature of the resistance cable is variable. The system shown in Figure 46 is not particularly suitable for a demand system.

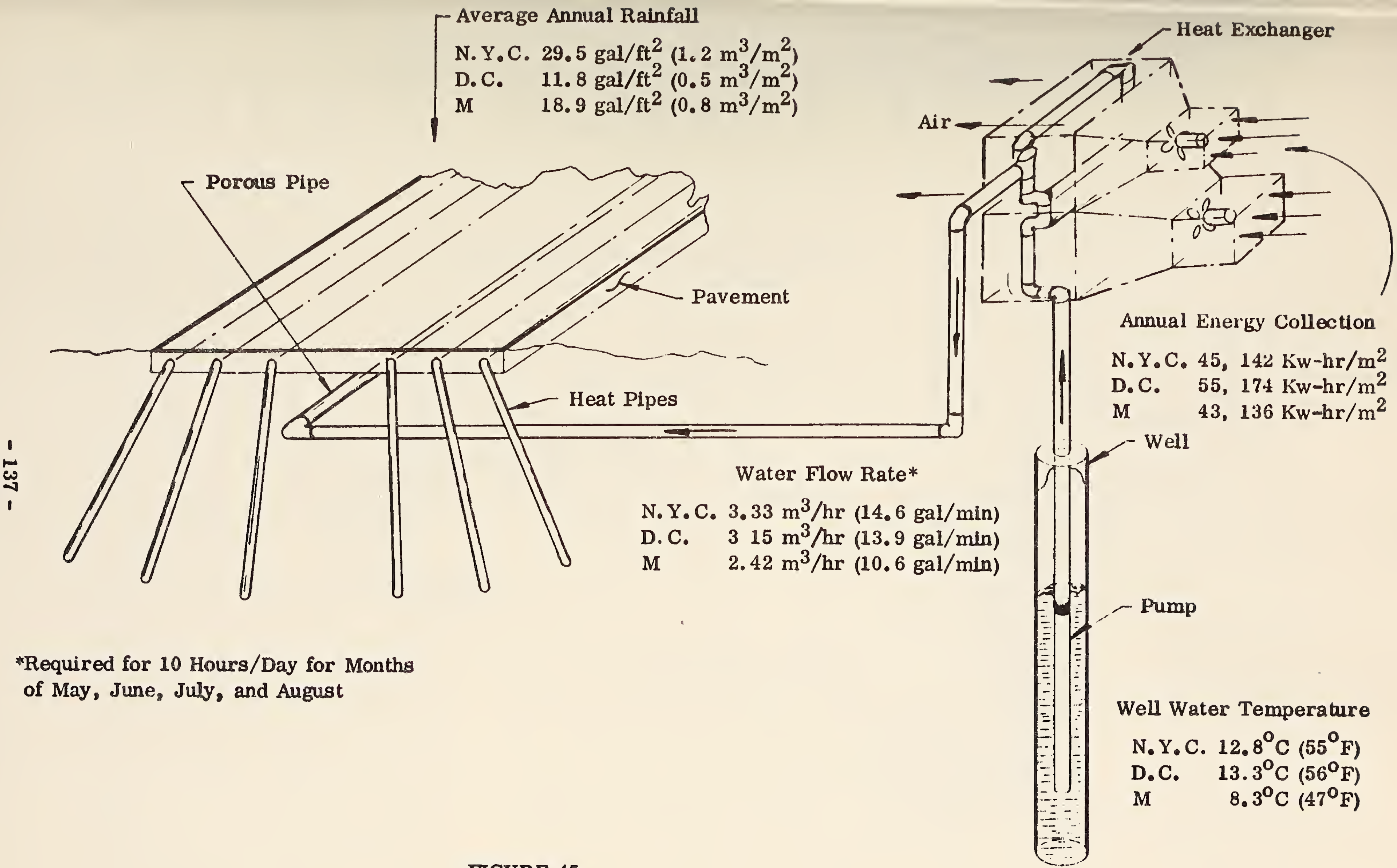



FIGURE 45

AMBIENT AIR AUGMENTATION SYSTEM

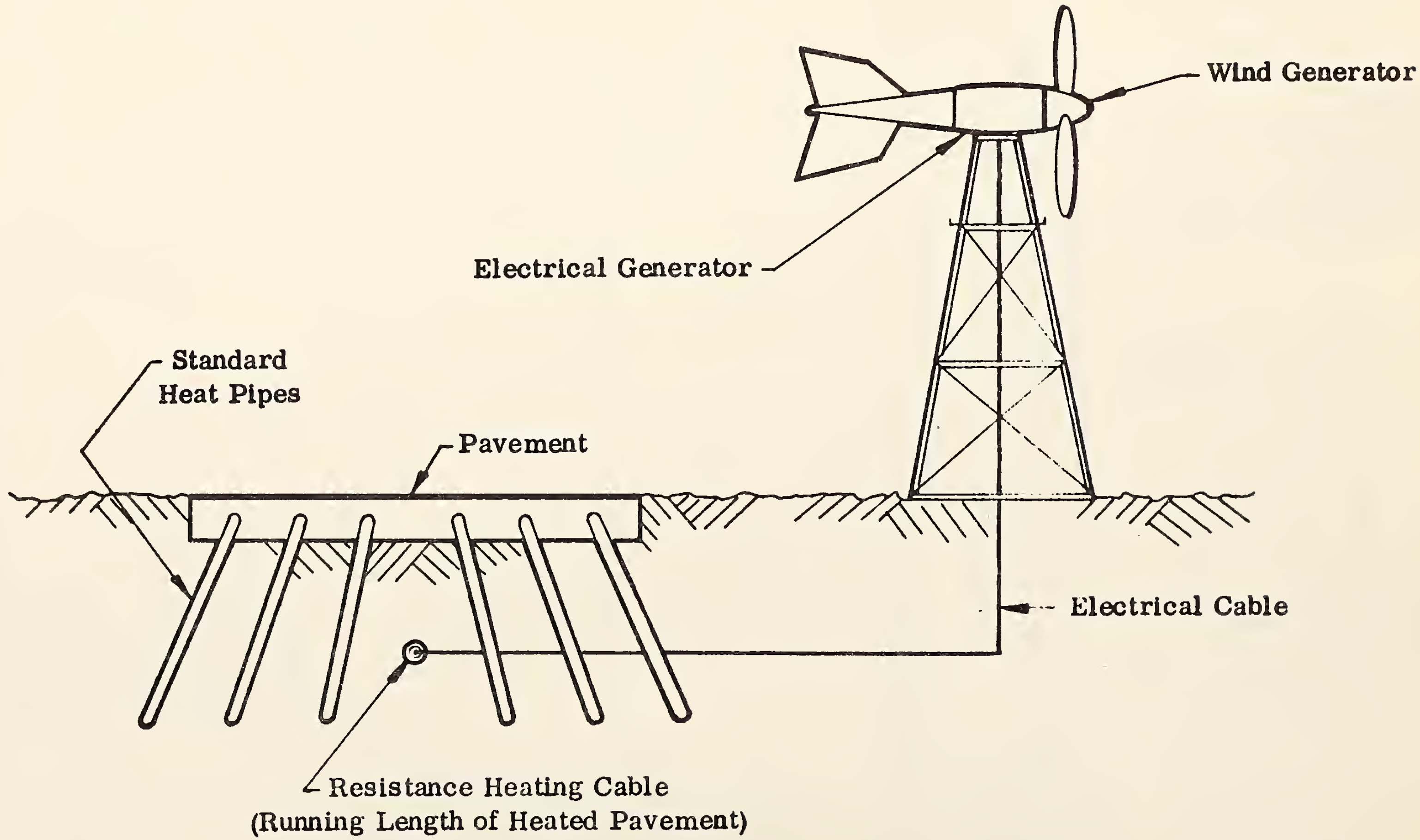



FIGURE 46

AUGMENTATION BY MEANS OF ELECTRICAL WIND MACHINE
FEEDING SUBPAVEMENT RESISTANCE HEATING CABLE

Figure 47 illustrates the design of a demand operated wind electric system. The electric heating cables are wrapped directly around each heat pipe and battery storage is provided. During the Spring, Summer, and Fall seasons, wind energy is dissipated in the earth heat pipe field and the battery storage is maintained at full charge by means of a trickle charge.

Because of the high capital investment required for battery storage (about $20/Kw-hr), the performance of a heat pipe system augmented with the demand wind system shown in Figure 47 was investigated. In this computer study, the heat pipe system was considered capable of supplying 150 $W/m^2$ for any event requiring power. When the power requirement was above 150 $W/m^2$, the wind system was made operative and the earth heat pipe system was made inoperative.

The capability of the wind generation system to ultimately deliver the kinetic wind energy that crosses rotor area $A_r$ to the pavement area $A_p$ can be characterized by an efficiency factor $\eta$, and the parameter $\alpha = \eta A_r/A_p$ was used to characterize the overall wind generation system. Similarly, the maximum energy storage capability of the system per unit heated pavement surface area can be specified and this parameter was denoted by S. The energy necessary to melt snow as rapidly as it falls was designated as $Q_{prec}$, and the energy provided by the earth heat pipe system was designated as $Q_{ren}$ (renewable energy). The results of this study are presented in Figures 48, 49, and 50 for various ratios of $Q_{ren}/Q_{prec}$, values of $\alpha$, and values of S and for the worst years in the three cities.

For the wind system shown in Figure 47, practical values for $\eta$ are 0.2 and, at an installed cost of $600/$m^2$ for wind machines, economically justifiable ratios of $A_r/A_p$ are 0.1 or less. Values of $\alpha$ of interest are, therefore, 0.02 or less. Although the battery storage investigated did not exceed values of S beyond one Kw-hr/$m^2$, it is evident that, at reasonable values of $\alpha$, wind system augmentation of the basic West Virginia system is not capable of economically providing a full performance system in any of the three cities regardless of the amount of battery storage provided. However, it should be observed that, by augmenting the West Virginia system using the ambient air technique, the required energy during precipitation can be reduced significantly and, in this case, a wind energy system appears attractive.

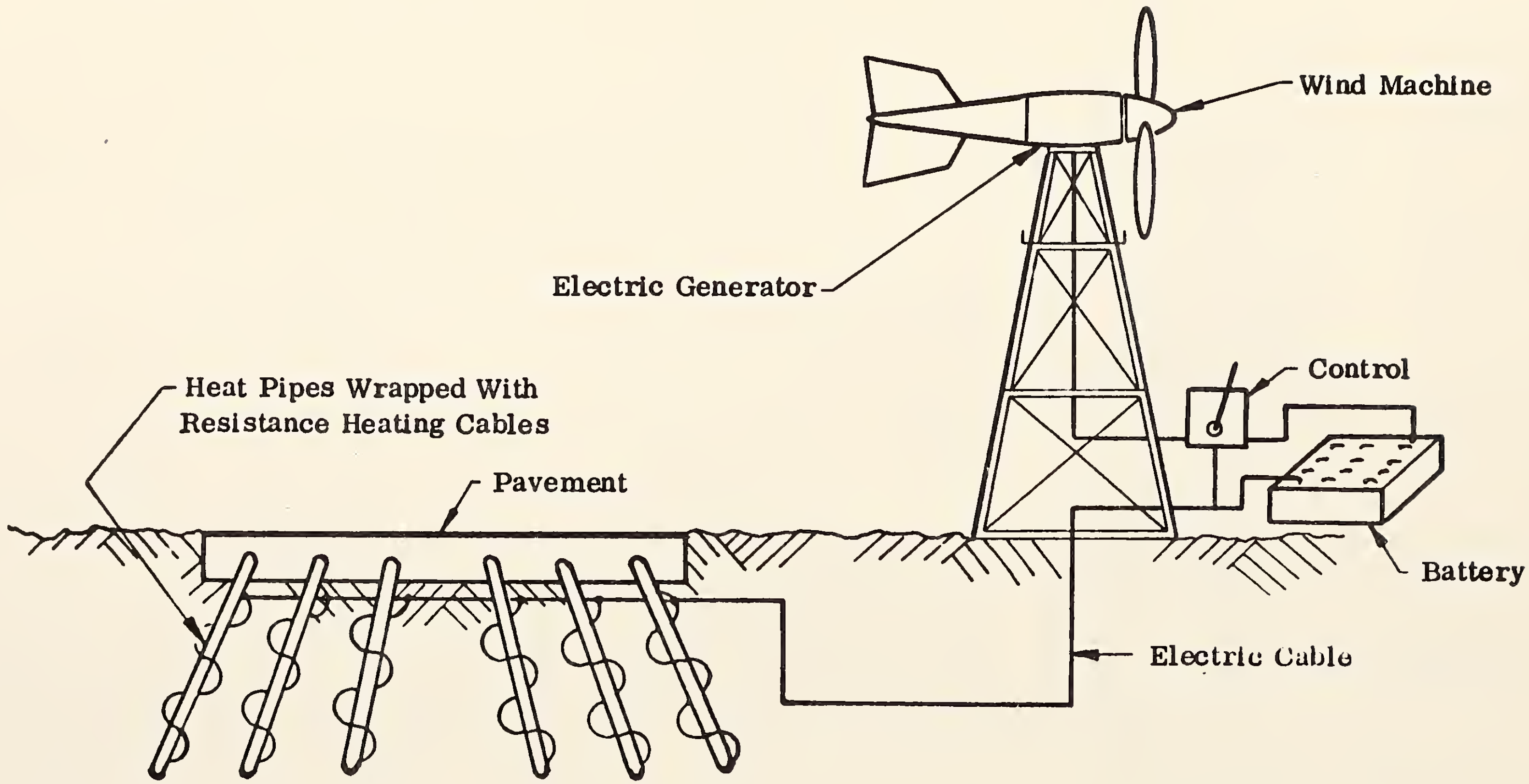



FIGURE 47

AUGMENTATION BY MEANS OF ELECTRICAL WIND MACHINE
FEEDING RESISTANCE HEATING CABLES AROUND EACH HEAT PIPE EVAPORATOR SECTION

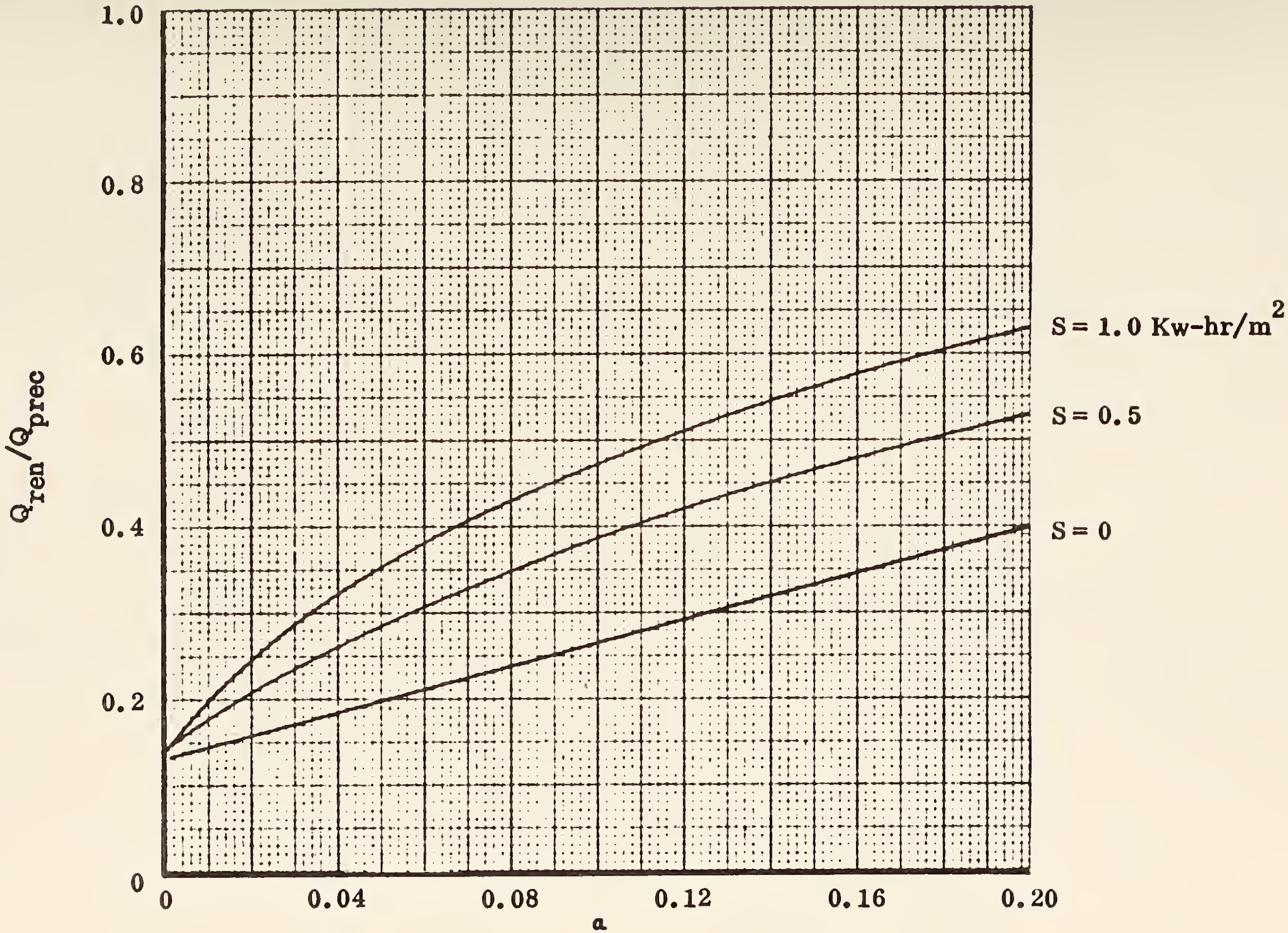



FIGURE 48

SNOW MELTING CAPABILITY AS A FUNCTION OF STORAGE AND WIND MACHINE SIZE FOR NEW YORK CITY

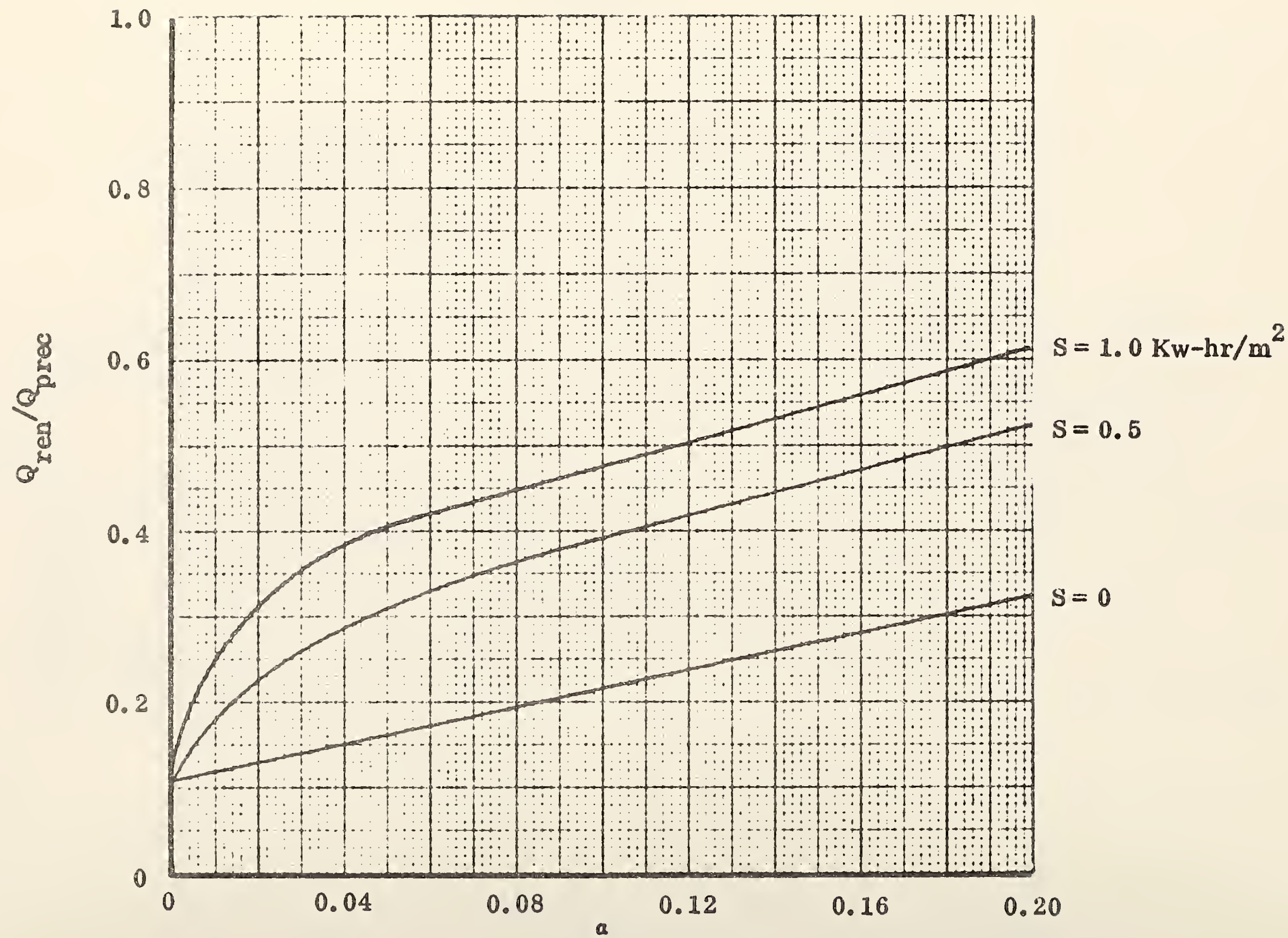



FIGURE 49

SNOW MELTING CAPABILITY AS A FUNCTION OF STORAGE AND WIND MACHINE SIZE FOR DODGE CITY

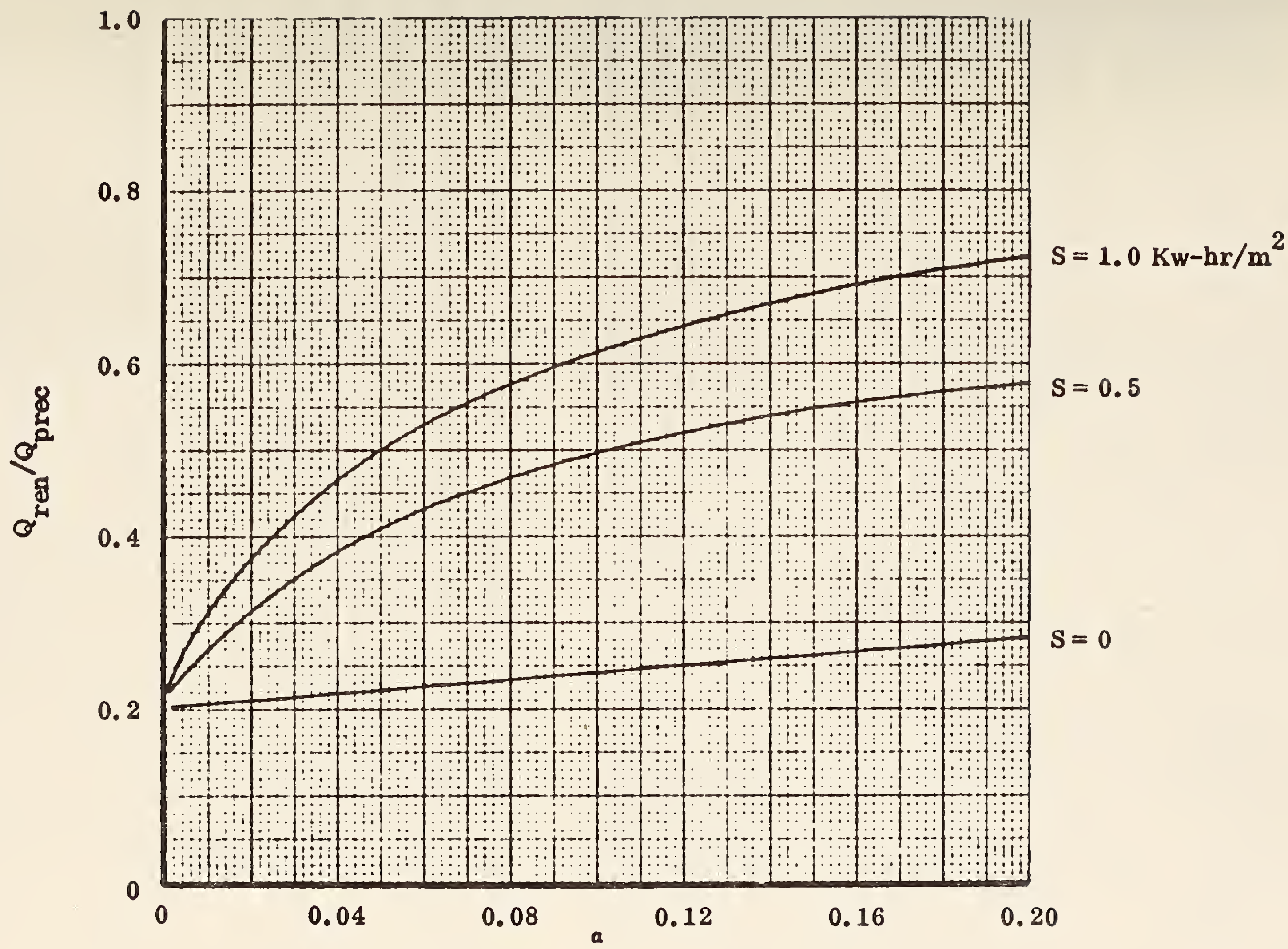



FIGURE 50

SNOW MELTING CAPABILITY AS A FUNCTION OF STORAGE AND WIND MACHINE SIZE FOR MADISON

Although the above results were obtained using wind energy input data, similar results would have been obtained if solar energy input data had been used. During January of the worst year, the average solar radiation for New York is one-third of the average wind power, for Dodge City it is one half of the average wind power, and for Madison it is about equal to the average wind power. The efficiency factor $\eta$ for a solar winter collection system is about equal to that for a wind system. The cost of collecting solar energy is about one-half of that for collecting wind energy as measured in $\$/m^2$. Therefore, for Dodge City, values of interest for $\alpha$ for solar energy are 0.02 which is the same as for wind energy; for New York the comparable value for $\alpha$ is 0.013; and for Madison the comparable value for $\alpha$ is 0.04. The conclusions regarding winter collection of solar energy are, consequently, the same as those reached for winter collection of wind energy.

Combining a solar collection system with an ambient air system is less attractive than combining a wind collection system with an ambient air system. This is because, during the summer, the wind collection system can provide the necessary electrical energy to drive blowers and liquid circulating pumps needed by the ambient air system.

The thermal energy that must be added to bridge decks to prevent preferential freezing is about 10% of that required to remove snow and ice from pavement surfaces. Because of this minimal energy requirement and the ease of integrating an electrical energy source into a bridge deck heating system, a wind energy source is economically and technically attractive. This subject is treated separately in the appendix beginning on Page 189.

## 2.12 Reference Augmented System

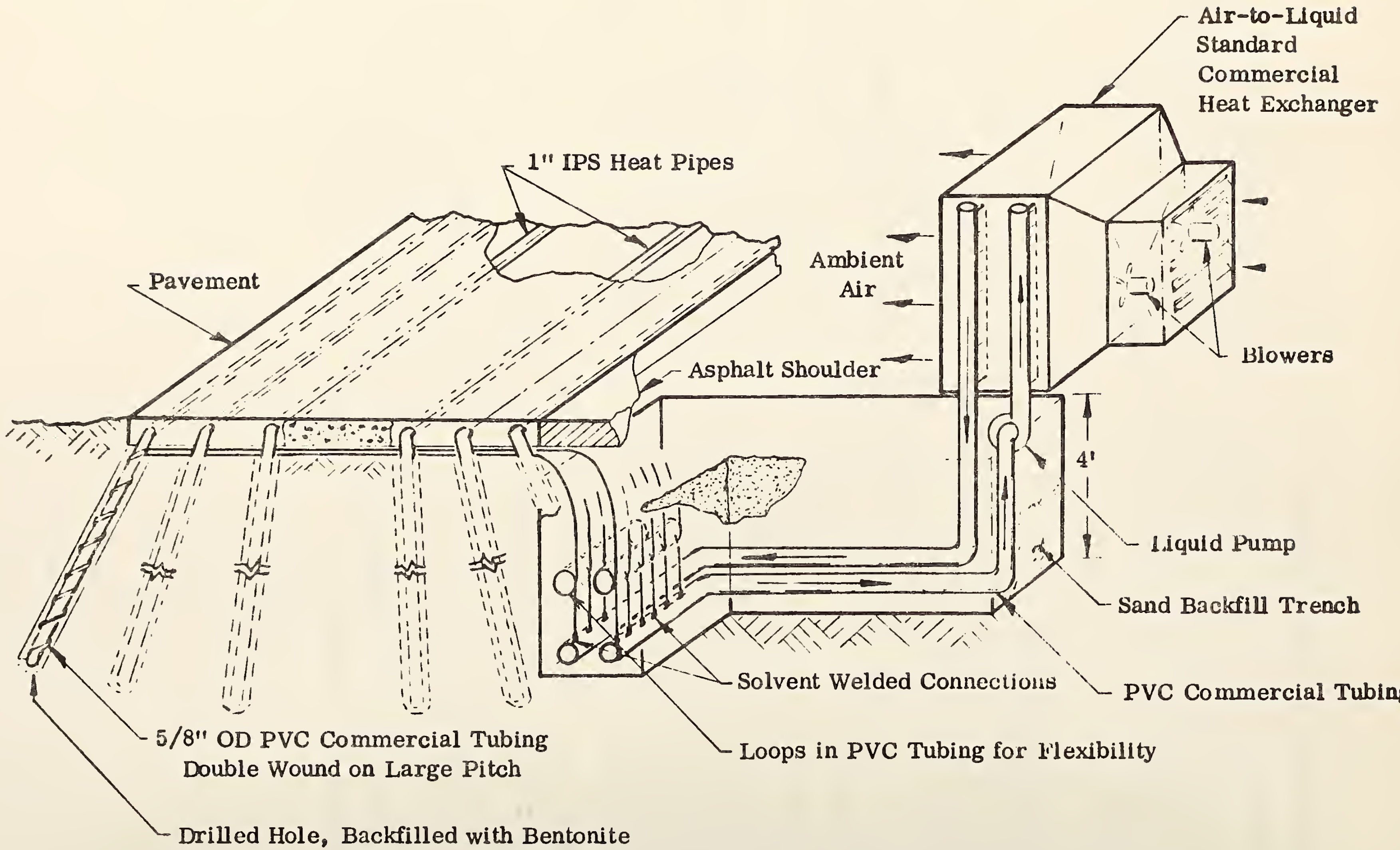
The design of the reference augmented systems consists of the basic West Virginia system described in Section 1 and an ambient air energy source and associated interconnecting plastic piping. The integrated system is shown schematically in Figure 51.

### 2.12.1 Design Description

A standard commercial air-to-liquid heat exchanger transfers the heat contained in warm summer air to a heat transfer fluid. The airside heat transfer is enhanced by using either plate fins or spiral fins made from either copper or low alloy aluminum. Both types have been used for over 50 years, and many innovative features have been incorporated in these fin designs to maximize airside heat transfer coefficients. The tubes which carry the heat transfer fluid are normally made from copper because of its good corrosion resistance. The thermal contact between the fins and tubes is achieved either by tension winding the spiral fins onto the tubes or by expanding the tubes into holes punched into plates. Each technique of manufacture has been demonstrated to give reliable service for many years in outdoor environments and is, therefore, considered state-of-the-art equipment and technology.

The warm summer air is blown across the fin surfaces by using standard blowers or fans. The higher the summer air velocity passing across the fins, the smaller is the required heat exchanger for a given amount of heat transferred. Of course, the higher velocities require more powerful blowers which use more electrical energy. Since the blowers will be used only about 15% of the time in any given year, it is preferred to reduce the size and therefore the cost of the heat exchanger by using larger blowers. The manufacturer should be consulted for his recommendation with regard to the best design compromise for his particular equipment.

As the air passes through the heat exchanger, it gives up energy to the fins being cooled by the heat transfer fluid and, thereby, the air temperature is reduced. By arranging the flow of heat transfer fluid such that the entering fluid (which is the coldest) is in contact with the coldest fins (exiting side of the air stream), a crossflow arrangement of heat transfer is established which gives the maximum overall




1 inch= 25.4 mm

FIGURE 51

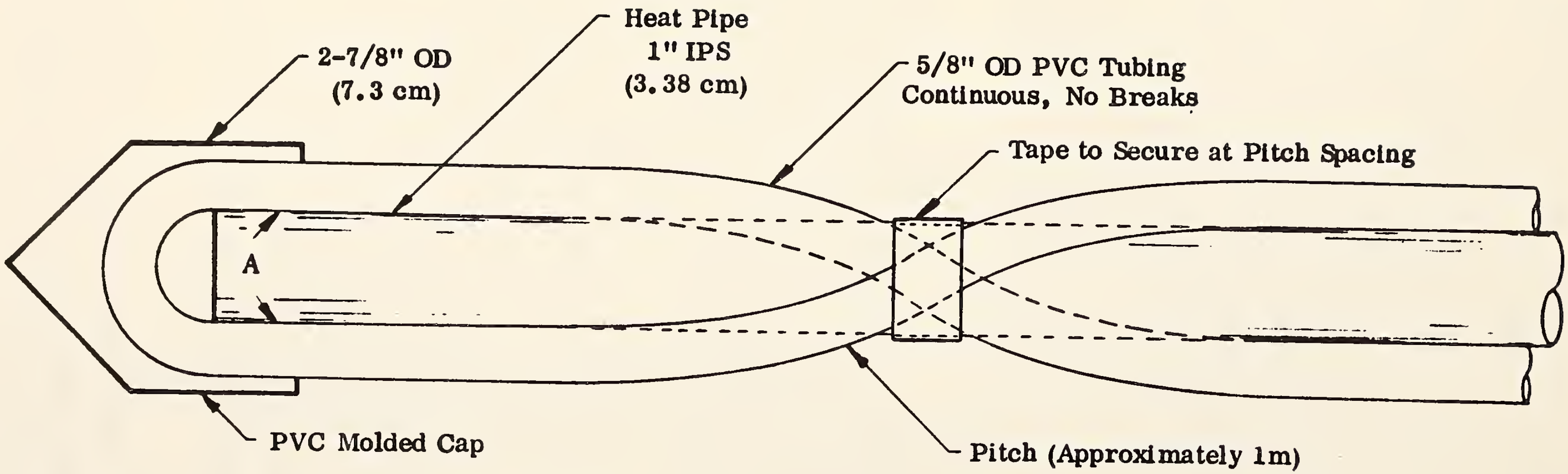
AUGMENTATION SYSTEM FOR WEST VIRGINIA DESIGN heat exchanger efficiency. Each manufacturer has his own techniques for providing the best cross-flow arrangement in the heat transfer fluid flow path.

The velocity of the heat transfer fluid in the tubes in the heat exchanger also is important in determining the efficiency of the heat exchanger. At higher velocities, the heat transfer between the fluid and the tube wall are higher. Practical velocity limits exist not only because of considerations of pumping power but because of metal erosion problems. Velocities of 3 m/s (10 ft/sec) are common but the manufacturer should be consulted because the selection of the heat transfer fluid may influence the velocity that he is willing to warrant.

The ASHRAE Guide (Reference 42) includes a section on fluid selection and hydraulic design for heated coil snow melting systems and should be consulted in the design of the fluid heat transfer system for this augmented system.

The augmented heat pipe is the other unique component in the augmentation system. Figure 52 shows the details of construction. The construction begins with a standard epoxy coated West Virginia heat pipe. A 46 m (150 ft) length of standard commercial PVC tubing (PVC pipe and solvent welding were used by Frank Winters in his earth heating installation) is cut from a commercial roll (1.59 cm (5/8 inch) diameter, 0.159 cm (1/16 inch) thick wall). At its midpoint length it is bent around the end of the pipe which is to be inserted into the ground. A die molded PVC plastic cap is fitted over the end of the heat pipe and the bent PVC tubing as shown and is secured in place by plastic welding. Each of the two free ends are wound around the pipe on a 1 m pitch and secured each metre as shown. The process continues for that length of pipe to be inserted into the ground 18.3 m (60 ft) at which point the remaining ends of the PVC tubing are temporarily attached to the remaining length of the heat pipe. The PVC tubing is pressure tested to 150 psig using clean filtered water, and the ends are plastic welded without removing the water. This procedure assures that the tubing will remain clean for installation. At this stage of assembly, the heat pipe is ready to ship to the construction site.

The construction contractor receives the prepackaged air-to-liquid heat exchanger assembly and the assembled augmented heat pipe. The only unique installation that he is required to perform, other than what was required at West Virginia, is to inter-




Note: Plastic Weld PVC Molded Cap to Heat Pipe at "A" Locations.

FIGURE 52

DETAILS OF CONSTRUCTION OF AUGMENTED HEAT PIPE connect these components as indicated in Figure 51. It is envisioned that one heat exchanger package can practically service about 400 $m^2$ (4300 $ft^2$) of pavement area and still provide the necessary redundancy and aesthetic quality. It may be desirable to space the ambient air packages on concrete slabs at the same spacing as the light poles and, thereby, provide the electric service to both using the same underground electric cables. This would be cost effective.

## 2.12.2 Thermal Design of Augmentation System

The ambient air augmentation system is required to store large amounts of energy in the heat pipe field. The amount of energy to be collected and introduced into the heat pipe field must be sufficient to supply the required Kw-hr/$m^2$ pavement energy after accounting for storage losses; and this energy must be stored at the proper augmentation temperature, $\Delta T_g + T_g$.

Essentially, the source of ambient air energy is infinite. The heat capacity of a cubic mile of air is $2.6 \times 10^9$ Btu/$^o$F ($1.37 \times 10^6$ Kw-hr/$^o$C). With respect to the average ground temperature (about 25$^o$F below summer air temperatures), the energy content in a cubic mile of air is $6.6 \times 10^{10}$ Btu ($1.9 \times 10^7$ Kw-hr). Because the temperature of this energy is limited, the augmentation system must collect and store this energy efficiently. This requires that the system design be optimized. Optimization of air ambient systems is beyond the scope of this study.

The engineering approach to the thermal design of a system to insert energy into the earth is the same as that of a system used to extract energy. Instead of the three resistances involved in extracting energy (Section 2.4.1), the augmentation system shown in Figure 51 can be specified by two resistances.

$$R_{t,au} = K\, R_{g,p}/N + R_{p,a}/A_{hx}$$

The total augmentation resistance $R_{t,au}$ equals the ground-to-pipe resistance $R_{g,p}$ multiplied by a storage constant K and divided by the number N of pipes in parallel for a given heat exchanger plus the resistance between the pipe and the air $R_{p,a}$ divided by the face area of the heat exchanger. As before, incidental resistances are lumped into these major resistances.

During the summer, the heat pipe is passive. In the augmentation system for summer operation, the 1-inch IPS pipe is replaced by two PVC tubes, each of which is approximately one-half the diameter of the heat pipe. Therefore, the value of $R_{g,p}$ for energy insertion is taken as the same value as that used for energy extraction. This value is $21.93^{o}C-m^{2}/Kw$ as related to the pavement surface and $25.3^{o}C/Kw$ as related to the pipe. The value of K is determined by the method of inserting energy in accordance with techniques outlined in Reference 37. For steady insertion over a five to six month time interval, the value of K is 1. For a short time insertion of say one day, the value of K is 0.40. For a 12-hour on, 12-hour off inserting sequence for a period of five to six months, the value of K is 0.9.

The value of $R_{p,a}$ is determined by the selection of the heat exchanger, the airflow velocity through the heat exchanger, the liquid flow velocity through the tubes of the heat exchanger, and by the ratio of the normalized heat capacities of the air and liquid flows. To identify the design which would collect the most energy for a minimum size and minimum expenditure of collection energy would require a rather extensive study.

As might be expected, as the efficiency of collection increases, the energy required for collection also increases. As a target for collection energy it was decided to use the estimated 7.5 to 15 $Kw-hr/m^{2}$ annually expended for high intensity ramp lighting. This permits consideration of using installed lighting utilities because the ambient air system will only operate during the daytime, and the concept visualizes multiple collection modules spaced the length of the ramp or highway section at more or less the interval used for the lighting poles.

The above objective dictates a low face velocity heat exchanger and a low heat capacity ratio. A two-row, 12-fin/inch, industrial heat exchanger at a face velocity of 2.3 m/s (450 ft/min) was selected as a representative design. The heat capacity of the airside is less than one-third of the heat capacity of the liquid side. This heat exchanger will remove two-thirds of the available air energy at the selected face velocity. The resistance of this heat exchanger $R_{p,a}$ is $0.55^{o}C-m^{2}/Kw$ where the area refers to the face area of the heat exchanger. The augmentation energy for the West

Virginia system is given by:

$$Q_{au} = 1.15\, t \left( \frac{T_{sa} - T_g}{K\, R_{g,p} + N\, R_{p,a} / A_{hx}} \right)$$

The augmentation energy is $Q_{au}$ in Kw-hr/m$^2$ (as related to the pavement surface) which is collected during the summer where t is the actual hours of operation, $T_{sa}$ is the average daytime August air temperature, $T_g$ is the unaugmented average ground temperature, $R_{g,p}$ is the ground-to-pipe resistance (as related to the pipe), N is the number of pipes in parallel with a heat exchanger having a pipe-to-air resistance $R_{p,a}$ and a face area $A_{hx}$. The annual energy dissipation in terms of the augmentation energy is given by:

$$Q_t = \eta_s\, Q_{au}$$

The value of $Q_t$ is the energy dissipated by the system during the winter and is given in Section 2.4.3 and $\eta_s$ is the storage efficiency. The benefits of natural summer recovery are neglected.

A survey of the daytime temperatures throughout the United States indicates that energy collection can begin in April and continue through September. The possible hours of operation increase to a maximum in July. In July the average daytime temperature is between 1 and 2$^{\circ}$C higher than in August and the permissible hours of operation average 16 hours per day. During April and May, the system is operated to correct the local temperature depressions around the heat pipes resulting from the end of winter operation of the system. As the hours per day of system operation decrease, the temperature at which energy is collected approaches the maximum daytime temperature. For example, 6 hours per day operation permits collection at an average temperature equal to 97% of the difference between the maximum daytime temperature and the daily average temperature plus the daily average temperature. The percentage for 12 hours per day operation is 67%. By the simple expedient of adjusting the permissible hours of daily operation, the driving temperature difference for energy insertion can be held relatively constant.

To be conservative, the value of $T_{sa}$ is taken as 50% of the sum of the August average maximum and average daily temperature. The difference between this value of August daily average temperature and average ground temperature for various locations in the United States is given in Figures 53 and 54. The permissible hours of operation are: April 180, May 279, June 360, July 496, and August 465, for a total annual hours of operation of 1780. Operation in September can be conducted on a sustaining basis and no credit for this operation is taken. For the West Virginia system, the collectable energy related to the pavement surface and for the selected heat exchanger is shown in Figure 55 as a function of the number of heat pipes in parallel with the collecting surface.

For the case where the driving temperature allocated to the heat exchanger collection is equal to that for the heat pipe, the following must be satisfied:

$$\frac{K R_{g,p}}{N} = \frac{R_{p,a}}{A_{hx}}$$

The value of N (the number of pipes paralleled with the heat exchanger) for the West Virginia system design is about 42 for every 1 $m^2$ heat exchanger face area and 42 heat pipes service 36.3 $m^2$ of pavement area. The collectable energy is 44.4 Kw-hr/$m^2$-$^oC$. From Figure 53, the available driving temperature at the West Virginia location is 14.4$^oC$; therefore, the collectable energy is 639 Kw-hr/$m^2$ at a ratio of pavement area to heat exchanger face area of 36 to 1. The energy loss $Q_t$ from Figure 18 for this location for a fully augmented system is 350 Kw-hr/$m^2$. At a storage efficiency of 60%, the augmentation energy $Q_{au}$ must be 583 Kw-hr/$m^2$.

A suitable compact heat exchanger package can be designed with a face area of 10 $m^2$. This package will service 363 $m^2$ of pavement at West Virginia which is equivalent to about 250 feet of West Virginia ramp length (four such packages are required for this installation). The total motor power (blower and liquid pump) is about 4 Hp (2.98 Kw). The total electrical energy for each package for a collection season is 5312 Kw-hr or 14.6 Kw per $m^2$ of pavement area. A large fraction of this energy is used to provide the face velocity of 450 ft/min (5.1 mph) and may be reduced by


FIGURE 53

DIFFERENCE IN °C BETWEEN AVERAGE DAYTIME AUGUST AIR TEMPERATURES AND GROUND TEMPERATURES THROUGHOUT THE UNITED STATES


FIGURE 54

DIFFERENCE IN °F BETWEEN AVERAGE DAYTIME AUGUST AIR TEMPERATURES AND GROUND TEMPERATURES THROUGHOUT THE UNITED STATES

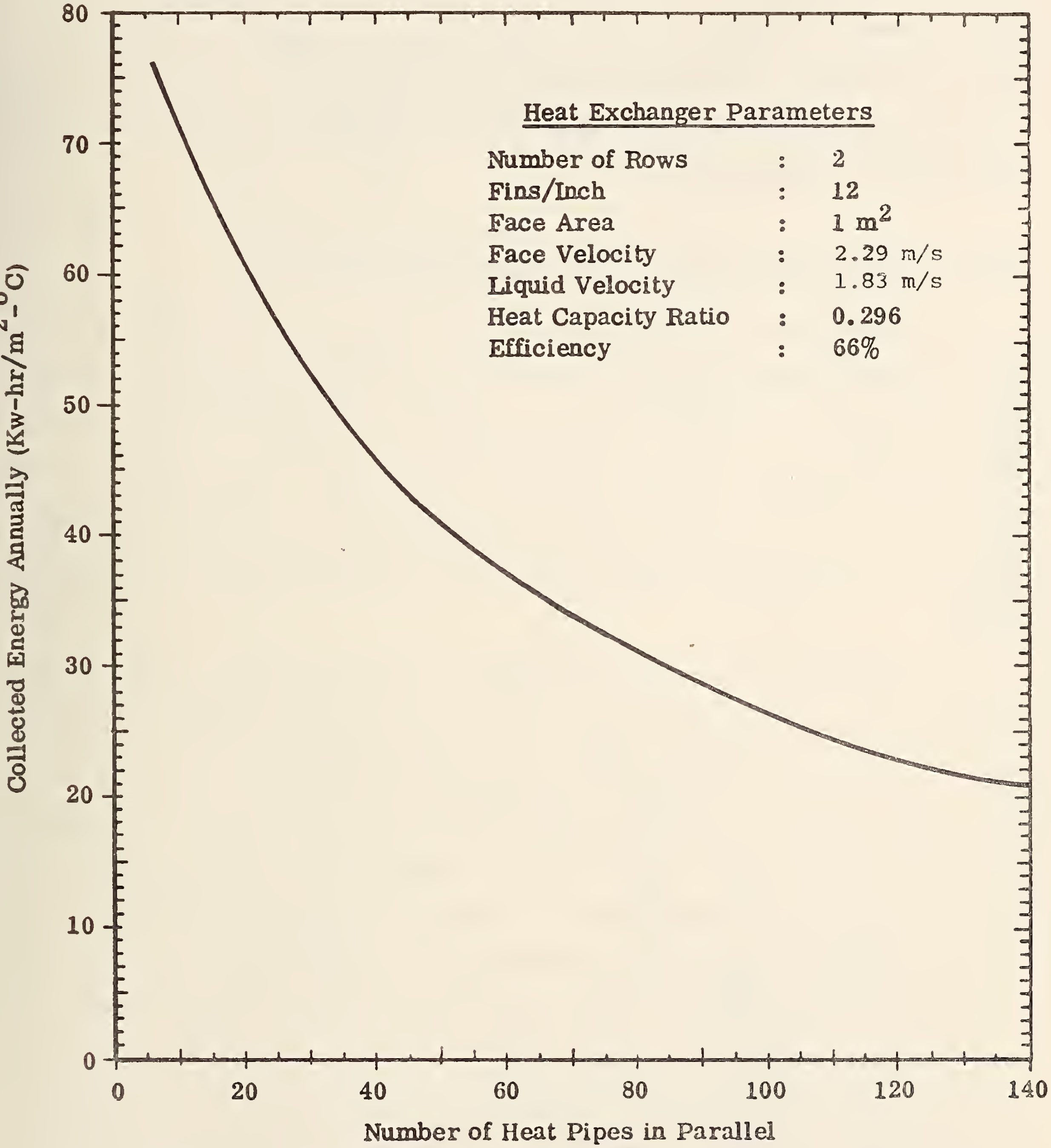



FIGURE 55

COLLECTED ENERGY RELATED TO PAVEMENT SURFACE AS A FUNCTION OF THE NUMBER OF HEAT PIPES PARALLELED positioning the heat exchanger favorably with respect to the prevailing winds. Incidentally, in many locations the average summertime wind speeds exceed 5.1 mph. Although the efficiency of collection decreases for a given heat exchanger design as the face velocity increases, the total energy collected increases. In the Central Plains, the energy collected for a given heat exchanger size could be increased 25% by favorable placement and the area ratio could be increased to 60 to 1 for the above West Virginia system design.

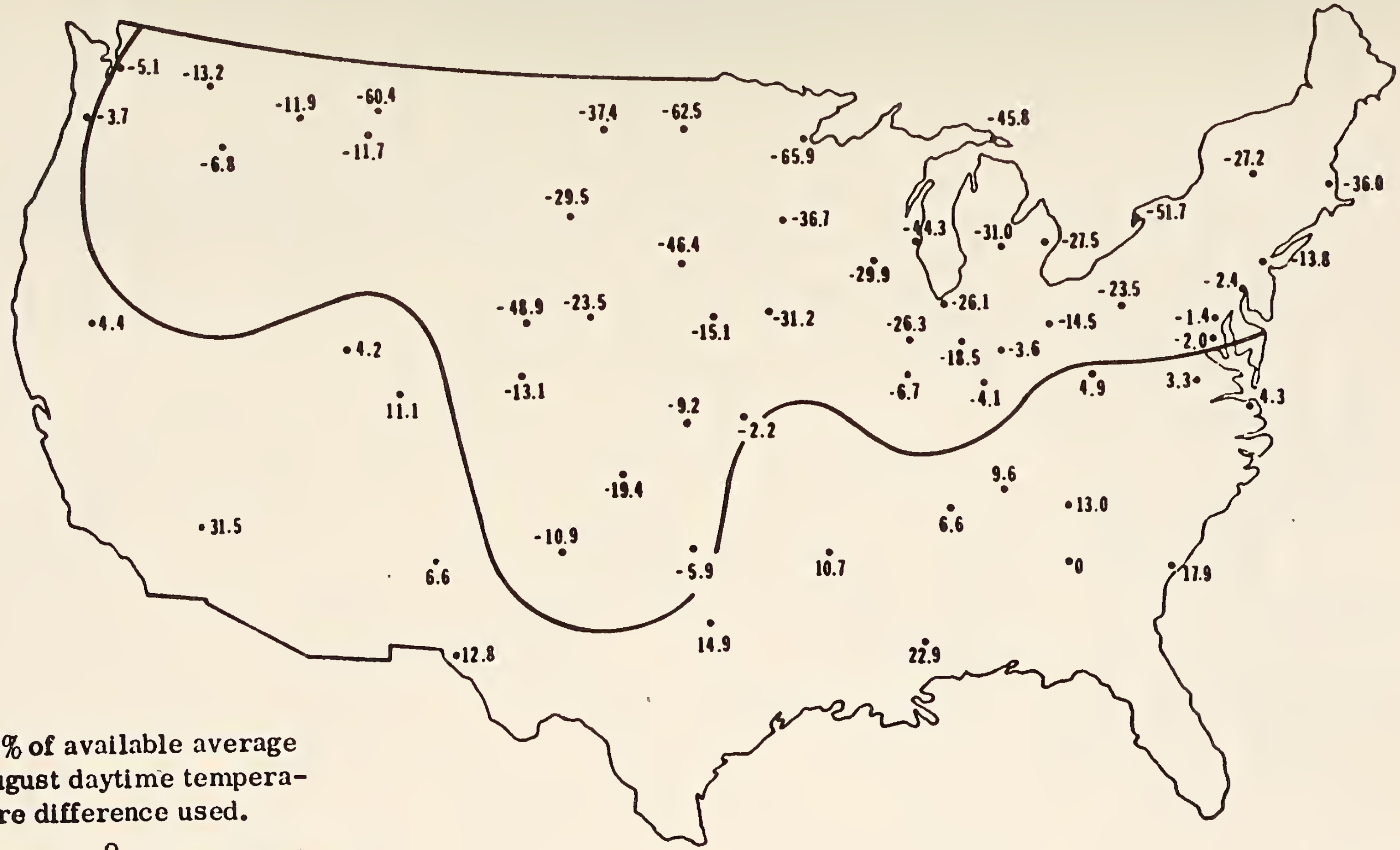
### 2.12.3 System Performance in Other United States Locations

Without addressing the question of cost, it can be seen from Figure 55 that, at small ratios of pavement area to heat exchanger area, large quantities of energy can be collected and stored. The total energy loss $Q_t$ for full performance West Virginia system designs throughout the United States is given in Figure 18. At some values of area ratios, the reference augmented system can provide these values of $Q_t$ plus the storage losses (except in the North Central Plains and Northeastern locations).

In Section 2.4 it was determined that, for full performance systems, the average pavement surface temperature during January is $9.44^{O}C$ ($49^{O}F$) and that, for a system having a performance equal to that of the unaugmented West Virginia system at West Virginia, the average pavement surface temperature during January is $5.37^{O}C$ ($41.8^{O}F$). Figure 56 shows a line designating locations in the United States at which an ambient air augmented West Virginia system will have full performance. Figure 57 shows a line designating locations in the United States at which an ambient air augmented West Virginia system will have performance equivalent to that of the unaugmented system located in West Virginia. For locations above these lines, demand augmentation is required. This reference system can be employed; however, during periods of snowfall, heated liquid must be pumped through the PVC system.

### 2.12.4 Augmentation System Costs

The estimated installed cost of the West Virginia heat pipe installation based on the cost elements given in Reference 1 was $\$269/m^2$ ($\$25/ft^2$) which compares with




Notes: (1) 80% of available average August daytime temperature difference used.

(2) Values in °F indicate either excess or deficient augmentation temperatures.

FIGURE 56

LINE DESIGNATING LOCATIONS AT WHICH AN AIR AUGMENTED WEST VIRGINIA DESIGN SYSTEM WILL CLEAR ALL SNOW AND ICE FROM PAVEMENT SURFACES


Note: Locations below the line will perform better than demonstrated, and above the line will perform poorer.

FIGURE 57

LINE DESIGNATING LOCATIONS AT WHICH AMBIENT AIR AUGMENTED SYSTEMS OF THE WEST VIRGINIA DESIGN WILL HAVE PERFORMANCE EQUAL TO THAT DEMONSTRATED BY THE UNAUGMENTED WEST VIRGINIA DESIGN AT WEST VIRGINIA the actual cost for this experimental installation of \$236.8/$m^2$ (\$22/$ft^2$) given in Reference 5. Drilling holes in rock proved to be less expensive than anticipated in spite of the angular disposition of the drilled holes. Correcting the estimating procedure for the actual known drilling costs, the revised estimated cost (1975 dollars) is \$208.5/$m^2$ (\$19.4/$ft^2$). It is judged that this installed cost represents a reasonable baseline value for the West Virginia reference design in sizes less than 1500 $m^2$ and in quantities of a few per year. In sizes an order of magnitude larger (such as the size of the Louisville, Kentucky, electrical installation) the installed cost is estimated to be \$173.7/$m^2$ (\$16.2/$ft^2$).

To the above baseline cost must be added the cost of those features unique to the augmentation system shown in Figure 51. The energy collection package is the single most expensive component in terms of cost per square metre of pavement area. Conservatively, energy dissipation for full performance systems appear to be about 500 Kw-hr/$m^2$. The augmentation energy for a 60% storage efficiency is, therefore, 833 Kw-hr/$m^2$. Assuming an available driving temperature of 15$^o$C for an ambient air collection system, the heat exchanger will be required to collect 56 Kw-hr/$m^2$-$^o$C. From Figure 55, the number of heat pipes that can be paralleled to each square metre of heat exchanger face area is 26. If the benefit of wind is accounted for (since at this dissipation, the wind velocities are above normal), the number of pipes which can be paralleled to each square metre of surface area is between 40 and 50.

Instead of selecting a 2-row heat exchanger, the more expensive 8-row heat exchanger can be considered. Although this would increase the blower size and, therefore, the energy required for collection, the value of $R_{p,a}$ would decrease from 0.55 to 0.34$^o$C/Kw-$m^2$ at a face velocity of 2.3 m/s and would further decrease $R_{p,a}$ to 0.2$^o$C/Kw-$m^2$ at a face velocity of 5.1 m/s (1000 ft/min). At the larger face velocity, the 8-row heat exchanger efficiency is 80% and 70 heat pipes could be paralleled with each square metre of heat exchanger face area.

The optimization of capital and operating costs for an air augmentation system is beyond the scope of this study. To determine capital costs, a ratio of pavement area to heat exchanger area of 50 was selected for the more expensive 8-row heat exchanger. In installations with a pavement area of 1500 $m^2$, the ambient air collection package will cost $\$58/m^2$ ($\$5.39/ft^2$) installed; and, for installations 10 times larger, the cost is $\$48.3/m^2$ ($\$4.49/ft^2$) installed.

The remaining components of the augmentation system are the PVC tubing around the earth portion of the heat pipe, the PVC header tubing, trenching, solvent welding, assembly, and pressure testing. The incremental cost of these items has been estimated at $\$64.0/m^2$ ($\$5.95/ft^2$) for small systems and $\$53.3/m^2$ ($\$4.96/ft^2$) for large systems.

The total incremental capital cost for the ambient air collection and distribution system is $\$122/m^2$ ($\$11.34/ft^2$) for small systems and $\$101.6/m^2$ ($\$9.45/ft^2$) for large systems. The small system will inject $1.25 \times 10^6$ Kw-hr/year of thermal energy into the earth for an incremental capital investment of $183,000 or 15 cents/Kw-hr for one year or 1.5 cents/Kw-hr over a 10 year period. The large system will inject $1.25 \times 10^7$ Kw-hr/year for a capital investment of $1,524,000 or 12 cents/Kw-hr for one year or 1.2 cents/Kw-hr over a 10 year period.

Current cost of thermal energy derived from burning fuel oil is 1.3 cents/Kw-hr; and, in Baltimore, the cost of thermal energy derived from electricity, not including demand charges, is 5.4 cents/Kw-hr. It has been suggested that the reference ambient air system can be designed to operate in the ASHRAE designated idling mode and that supplemental energy for melting be provided on a demand basis. This would certainly permit the system to be used in very severe climates. Since the annual melting energy for systems that continuously idle is $10 \pm 5\%$ of the idling energy, this supplemental energy that must be supplied by fossile fuels may be justified. As seen from Figure 13 in Section 2.4.1, if the ambient air system can maintain the average January pavement surface temperature at $2^oC$ ($35.6^oF$), the worst case melting energy requirement is about 60 $Kw\text{-}hr/m^2$ (all precipitation events included).

Oil fired swimming pool heaters suitable for outdoor installation are commercially available. These prepackaged units are easy to install and are capable of automatic operation. It is envisioned that these heaters could be made a part of the air handling package and connected in parallel with the air-to-liquid heat exchanger. The installed cost of a unit capable of supplying additional energy to the pavement at the rate of 0.5 $Kw/m^2$ is $\$20/m^2$. The annual fuel cost to supply 60 $Kw\text{-}hr/m^2$ to the pavement surface at current oil prices is $\$0.78/m^2$ without losses and above $\$1/m^2$ with losses. For less severe environments, the fuel cost would be less; however, the installation cost which is determined by capacity will not be reduced significantly.

# 3. EARTH HEATED PAVEMENT SYSTEM DESIGN PROCEDURES FOR HIGHWAY ENGINEERS

This design procedure applies to unaugmented (passive) and ambient air augmented (semipassive) earth heated pavements of the West Virginia design as described in Section 1 of this report. A procedure is also included for the design of demand augmentation systems. The basic design has been demonstrated to be within the capabilities of the manufacturing and construction industries. The specification for unaugmented heat pipes is given in Reference 1. Consult the ASHRAE Guide for the design of fluid systems.

## 3.1 Definition of Terms

### Energy

$Q_{au}$ — The amount of energy annually injected into the earth by an ambient air system always given with respect to the pavement surface. Units in either Kw-hr/m$^2$ or Kw-hr/ft$^2$ where 1 Kw-hr/m$^2$ = 10.76 Kw-hr/ft$^2$.

$Q_d$ — The amount of demand energy that is annually added to the pavement surface only during precipitation events. Units are the same as $Q_{au}$.

$Q_t$ — The total amount of energy annually dissipated from the pavement surface by the heating system. Units are the same as $Q_{au}$. $Q_t$ is related to $Q_{au}$ by $Q_t = \eta_s Q_{au}$ where $\eta_s$ is the earth storage efficiency.

### Resistance

$R_{p,a}$ — Heat exchanger resistance between the heat exchanger pipes and the air. Used in the design of ambient air augmentation systems. Units are in either $^oC$-m$^2$/Kw or $^oF$-ft$^2$/W where 1$^oC$-m$^2$/Kw = 51.6$^oF$-ft$^2$/W.

$R_{g,p}$ — Resistance between the ground and the heat pipe. The value of this resistance is determined by the diameter of the heat pipe in the ground, the length of pipe coupled to the ground, properties of bentonite or other backfill meadia, drilled hole size, and properties of the soil in which the pipe is embedded. A conservative value for the West Virginia design is 25.3°C/Kw or 0.0455°F/W.

$R_{s,aj}$ — Resistance between the dry pavement surface and air during January. Units are the same as in $R_{p,a}$.

$R_{t,au}$ — Total ambient air augmentation resistance equal to $K R_{g,p}/N + R_{p,a}/A_{hx}$. Units are in °C/Kw or °F/W.

$R_{t,j}$ — Total system resistance between the ground and the air during January. Units are the same as in $R_{p,a}$.

$R_{t,5}$ — Average five months total system resistance between the ground and the air. The five winter months are November, December, January, February, and March for a total number of hours of 3624. Units are the same as $R_{p,a}$.

## Temperature

$T_g$ — Ground temperature at a depth of more than 9 m (30 ft). Equal to the average annual air temperature at each location. Units are in °C or °F, where °F = 1.8 (°C) + 32.

$\Delta T_g$ — Increase in the effective ground temperature in the heat pipe field above the ground temperature $T_g$ resulting from injecting energy into the earth less the decrease due to storage losses. Units are in °C or °F where °F = 1.8 (°C).

$\delta T$ — The difference between the average ground temperature and the five winter month average air temperature. Units are the same as those for $\Delta T_g$.

$T_{sa}$ — Average daytime August air temperature. The units are the same as for $T_g$.

$T_{s,j}$ — Average pavement surface temperature during January. Units are the same as for $T_g$.

## Miscellaneous Terms

$A_{hx}$ — Face area of the air-to-liquid heat exchanger. Units in $m^2$ or $ft^2$ where $1\ m^2 = 10.76\ ft^2$.

$C_{e,s}$ — Heat capacity of the earth effectively coupled by the heat pipe and given with respect to the pavement surface. Units in Kw-hr/$m^2$-$^oC$ or Kw-hr/$ft^2$-$^oF$ where 1 Kw-hr/$m^2$-$^oC$ = 19.37 Kw-hr/$ft^2$-$^oF$. Heat capacity for West Virginia system 33.57 Kw-hr/$m^2$-$^oC$.

K — Storage constant. Unitless.

N — Number of heat pipes in parallel with one air-to-liquid heat exchanger in ambient air augmentation system. Unitless.

$\eta_s$ — Storage efficiency. Unitless.

t — Time, nominal summer augmentation time equals 1780 hours.

$V_{aj}$ — Average January wind velocity, m/s, mph.

## Definitions of Trade Usage

Face Area — Used to designate the free airflow area of air handling heat exchangers.

Heat Capacity Ratio — Dimensionless number less than unity formed by the ratio of the heat capacity of the smallest heat transfer medium (air or liquid) to the heat capacity of the largest heat transfer medium (air or liquid) flowing through a heat exchanger.

Face Velocity — Refers to the average air velocity as measured immediately upstream of the face area of a heat exchanger.

Rows — In air handling heat exchangers, tubes are arranged in planes transverse to the airflow. A group of tubes in a plane is given the name row. A heat exchanger may have several rows of tubes; each located downstream a short distance from the adjacent row. The efficiency of the heat exchanger increases with increasing number of rows; however, the airflow pressure drop and the capacity of the air blower also increase.

Fins — Refers to the extended surfaces secured to liquid carrying tubes in air handling heat exchangers. Because

| | |
|---|---|
| | air heat transfer coefficients are normally small, extended surfaces on the air side must be used to obtain useful efficiencies in reasonable equipment sizes. |
| Passive System | A system which has no moving mechanical parts as typified by the unaugmented West Virginia system. |
| Semipassive System | A system which is passive only during the winter. |
| Demand System | A system which requires the application of energy during precipitation events. |

## 3.2 Required Site Information

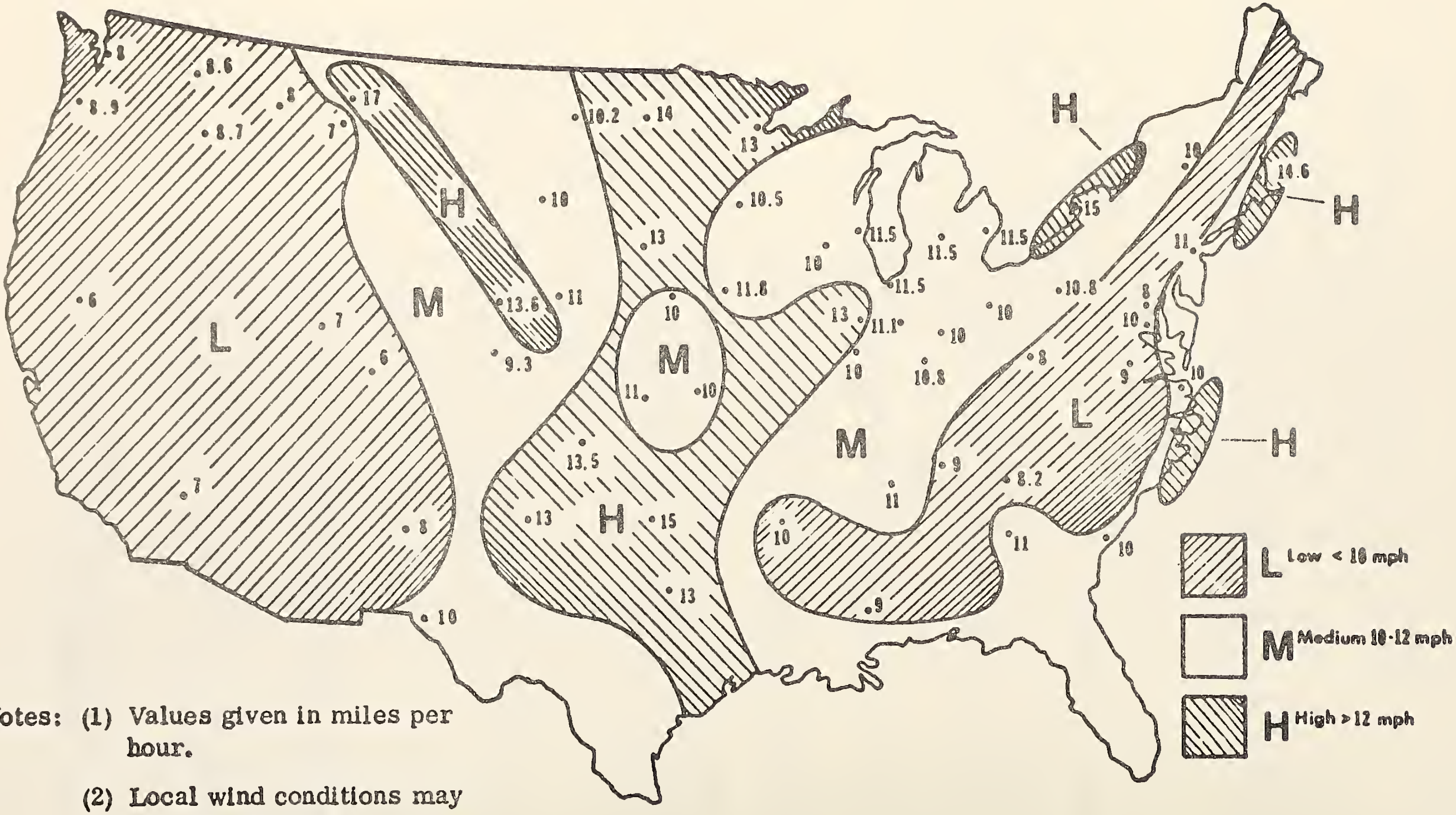
This simplified procedure requires that four items of site information be obtained to an accuracy consistent with good engineering practice. If it is determined that augmentation is not required, then the number of required items is reduced to two. These items are described below in Sections 3.2.1 to 3.2.4.

### 3.2.1 Average Ground Temperature, $T_g$

The average ground temperature may be obtained by boring a hole 9 m (30 ft) or more into undisturbed ground at the proposed installation site. Boring can also be used to develop information on ground structure for use in the bid package. Temperature measurements at the 9 m level can be made using a null-balance, portable, battery-operated temperature device, using a thermistor probe, or similar equipment. Care should be taken to obtain stable readings especially if the bottom of the hole is above the water table.

### 3.2.2 Average January Wind Velocity, $V_{aj}$

The average January wind velocity (speed) refers to the velocity at 2 m (6.56 ft) elevation above ground level at the proposed installation site. Figures 58 and 59 give the average January wind velocities for various locations in the United States. This information, in most cases, was obtained from weather stations situated at the local airport and is acceptable for use for proposed installation sites having similar terrain features and elevation.

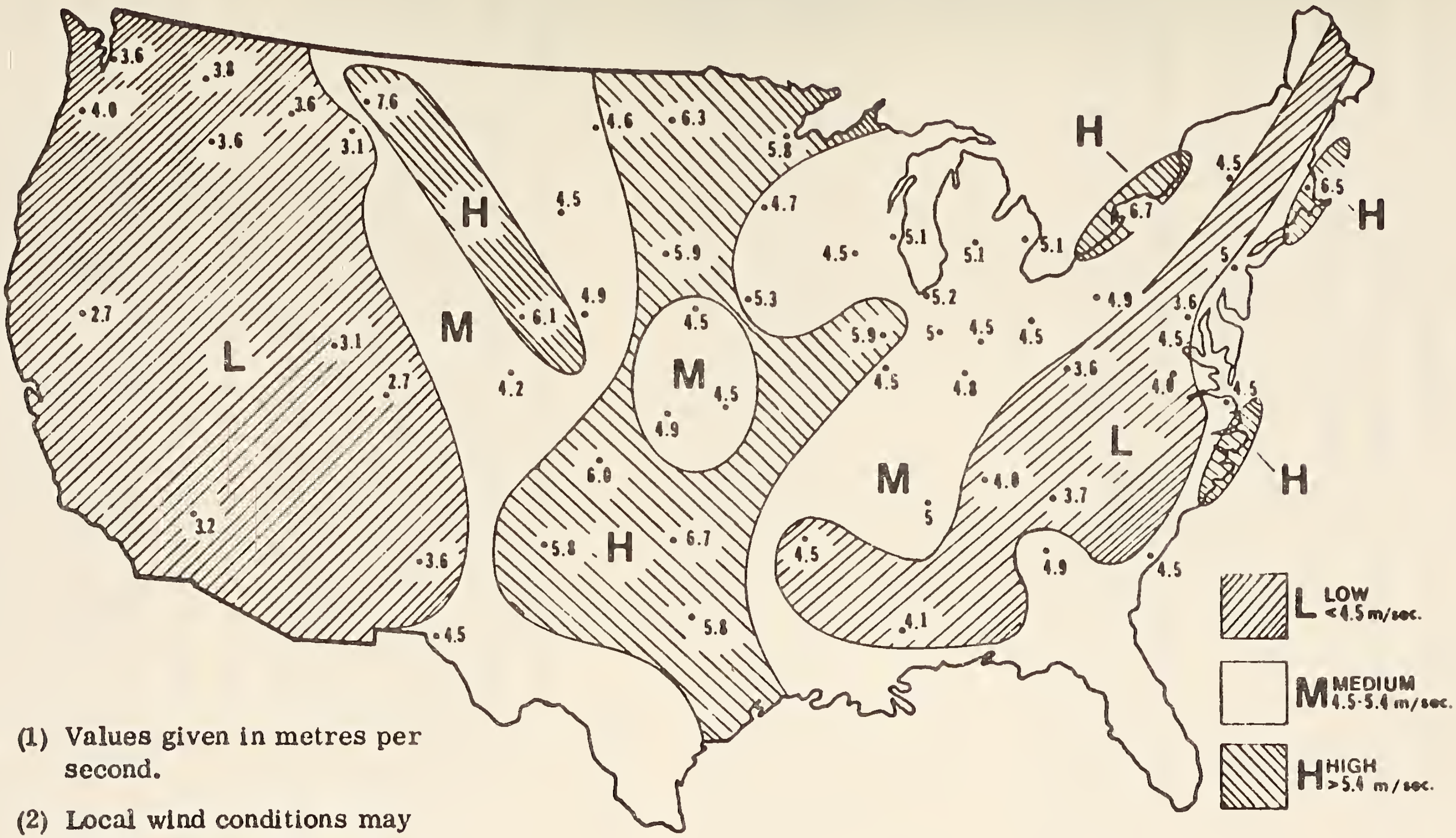



Notes: (1) Values given in miles per hour.

(2) Local wind conditions may vary considerably from regional values.

FIGURE 58

REGIONS OF AVERAGE JANUARY WIND VELOCITIES IN THE UNITED STATES




Notes: (1) Values given in metres per second.

(2) Local wind conditions may vary considerably from re-tional values.

FIGURE 59

REGIONS OF AVERAGE JANUARY WIND VELOCITIES
IN THE UNITED STATES

Because it is known that obstructions (trees, buildings), elevation (hills and elevated sites), and type of terrain (lakes, broken ground) over which the prevailing winds have traveled all affect wind velocity, it is preferred to obtain actual site data. This needs to be done for only one January month. The average wind velocity thus obtained should be compared with the value obtained at the nearby U. S. weather station and should then be adjusted either upward or downward depending how the weather station's January average data compares with its historical average.

If the wind velocity cannot be measured at the 2 m reference elevation above ground level, the actual measured wind velocity $V_{mea}$ at elevation $h_{mea}$ in metres may be converted into the desired velocity by:

$$V_{aj} = 1.13\, V_{mea} \left(\frac{1}{h_{mea}}\right)^{0.17}$$

In deciding the need for making wind velocity measurements, the Highway Engineer should note that the wind velocity on the crest of a hill devoid of obstructions will be between 50 and 75% higher than the wind velocity on flat ground in the same region.

### 3.2.3 Ground Water Flow

Ground water flow needs to be determined only if augmentation is definitely required. If the need for augmentation is marginal, ground water flowing through the heat pipe field will probably improve performance sufficiently to obviate the expense of augmentation. If the boring made to measure earth temperature shows a static water level, during late spring, below the expected penetration of the deepest pipe, ground water flow measurements are not required.

To determine the ground water flow at the proposed installation site, the hydraulic gradient and hydraulic conductivity of the earth (also referred to as the coefficient of permeability) must be determined. Ground water flow determinations at the test site should be assigned to either State or U. S. Department of Interior Geologists. Standard procedures within the expertise of Geologists are available for this determination. Care should be exercised to determine whether artesian or water table conditions prevail at each boring in the survey. If the static water level in each boring as referenced to a constant elevation datum is the same, the hydraulic gradient can be assumed to be negligible and soil permeability measurements will not have to be made. For purposes of this procedure, ground water flow of less than 0.25 ft/day (7.5 cm/day) are considered negligible.

### 3.2.4 Average Daytime August Air Temperature, $T_{sa}$

This determination is only required for the design of augmented systems. The local U. S. Weather Bureau measurements may be used if the approximate elevations are equal. The U. S. Weather Bureau compiles daily maximum, daily minimum, and monthly average air temperatures. The value of $T_{sa}$ is the sum of the daily maximum monthly average and monthly average air temperatures divided by 2.

If the elevation of the proposed installation is within 1000 m (3281 ft) of the elevation of the local weather station, a linear correction of $6^oC$ ($10.8^oF$) per 1000 m should be made to the average August daytime air temperature. If the proposed installation is at a higher elevation, the correction is subtracted from the average August air temperature; and, if lower, the correction is added. These procedures should not be used in regions where Chinook winds are likely to occur.

## 3.3 Procedure for Determining Augmentation Requirements

The augmentation method proposed herein is based on storing energy in the earth heat pipe field during the summer. The storing of energy less losses increases the effective earth temperature by an amount $\Delta T_g$. The expressions for the $\Delta T_g$ required (on the assumption that storage losses are zero) to achieve a full performance snow melting system of the West Virginia design are given in metric and English units by:

$$\Delta T_g = \frac{R_{t,5} + 53.98}{R_{t,5}} \left( (26.11 - T_g) \frac{R_{t,j}}{R_{s,aj}} - 16.67 + \frac{53.98\ \delta T}{R_{t,5} + 53.98} \right)$$

$$\Delta T_g = \frac{R_{t,5} + 1.05}{R_{t,5}} \left( (79 - T_g) \frac{R_{t,j}}{R_{s,aj}} - 30 + \frac{1.05\ \delta T}{R_{t,5} + 1.05} \right)$$

Note that for cities located along the Northwestern U. S. coast replace 26.11 by 23.3 and 16.67 by 13.9 in the first expression and 79 by 74 and 30 by 25 in the second expression.

The values yet to be determined are $\delta T$, the January resistance ratio, and $R_{t,5}$. The regional values of $\delta T$ are given in Figure 60 in $^{o}F$. These values may converted to $^{o}C$ by dividing by 1.8. For locations near the boundary between two wind regions, use an average value for $\delta T$. The January resistance ratio is dimensionless and is given in Figure 61 for various values of average January wind speed. The value of $R_{t,5}$ depends upon the wind region (Figures 58 and 59) and is as follows:

| Wind Region | $^{o}F\text{-}ft^2/W$ | $^{o}C\text{-}m^2/Kw$ |
|---|---|---|
| High | 2.10 | 108.4 |
| Medium | 2.25 | 116.1 |
| Low | 2.55 | 131.6 |

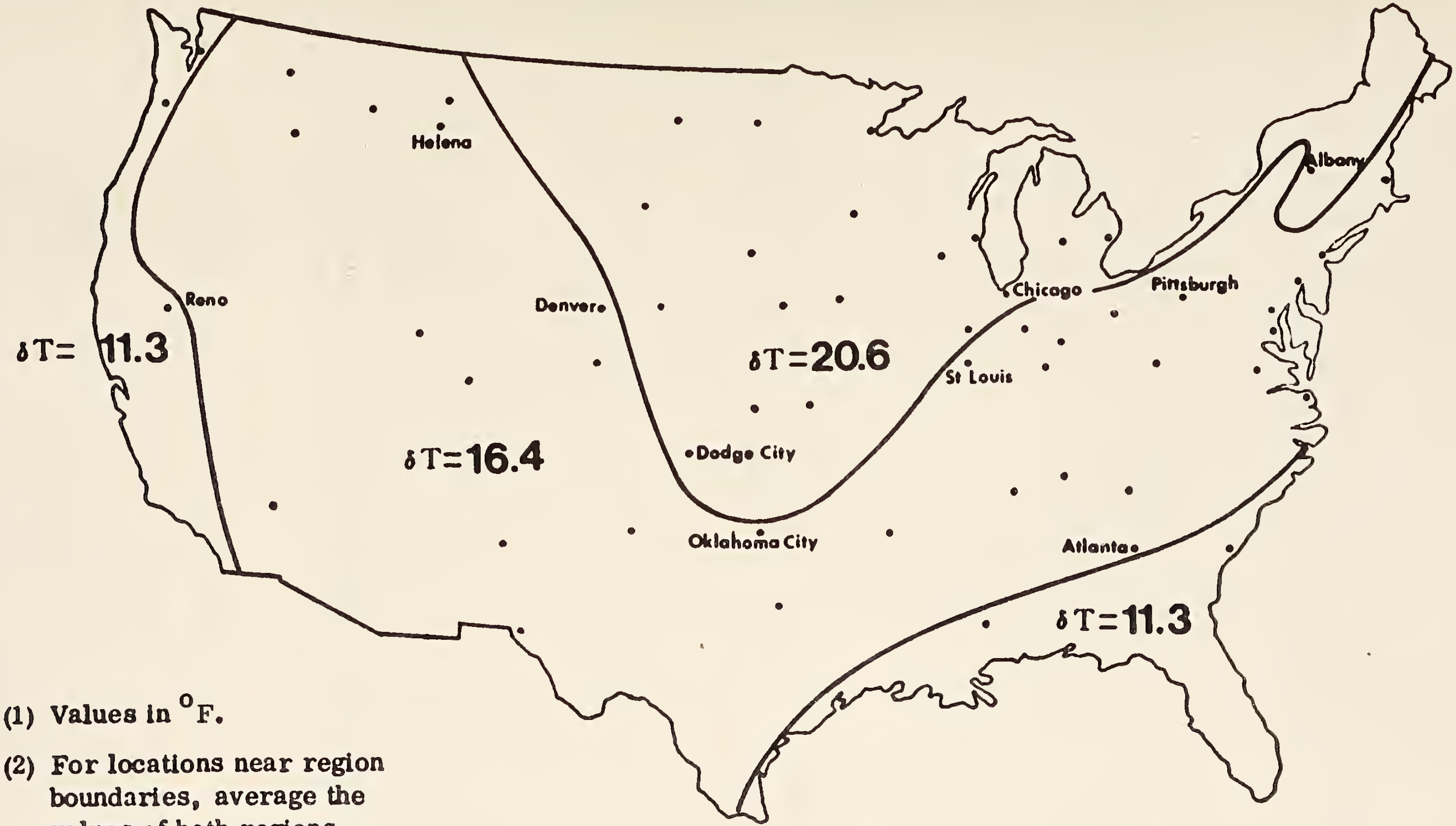
### 3.3.1 Example of Temperature Augmentation Calculation

Determine the amount of earth temperature augmentation required for a full performance system located in Washington, D. C. The following has been determined from measurements and U. S. Weather Bureau data (ground water flow has been judged to be negligible):

$$T_g = 57.0^{o}F\ (13.9^{o}C)$$

$$V_{aj} = 9.6\ \text{mph}\ (4.3\ \text{m/s})$$

This is judged to be a low wind region and $R_{t,5} = 131.6^{o}C\text{-}m^2/Kw$ ($2.55^{o}F\text{-}ft^2/W$). From Figure 61, the resistance ratio $R_{t,j}/R_{s,aj}$ is 1.78. From Figure 60, the value of $\delta T$ is $16.4^{o}F$ ($9.1^{o}C$). Substituting these values in the appropriate equation in




Notes: (1) Values in $^{o}$F.

(2) For locations near region boundaries, average the values of both regions.

$$t_C = (t_F - 32)/1.8$$

FIGURE 60

REGIONAL VALUES FOR THE DIFFERENCE BETWEEN UNAUGMENTED GROUND TEMPERATURE AND THE FIVE MONTH AVERAGE WINTER AIR TEMPERATURE

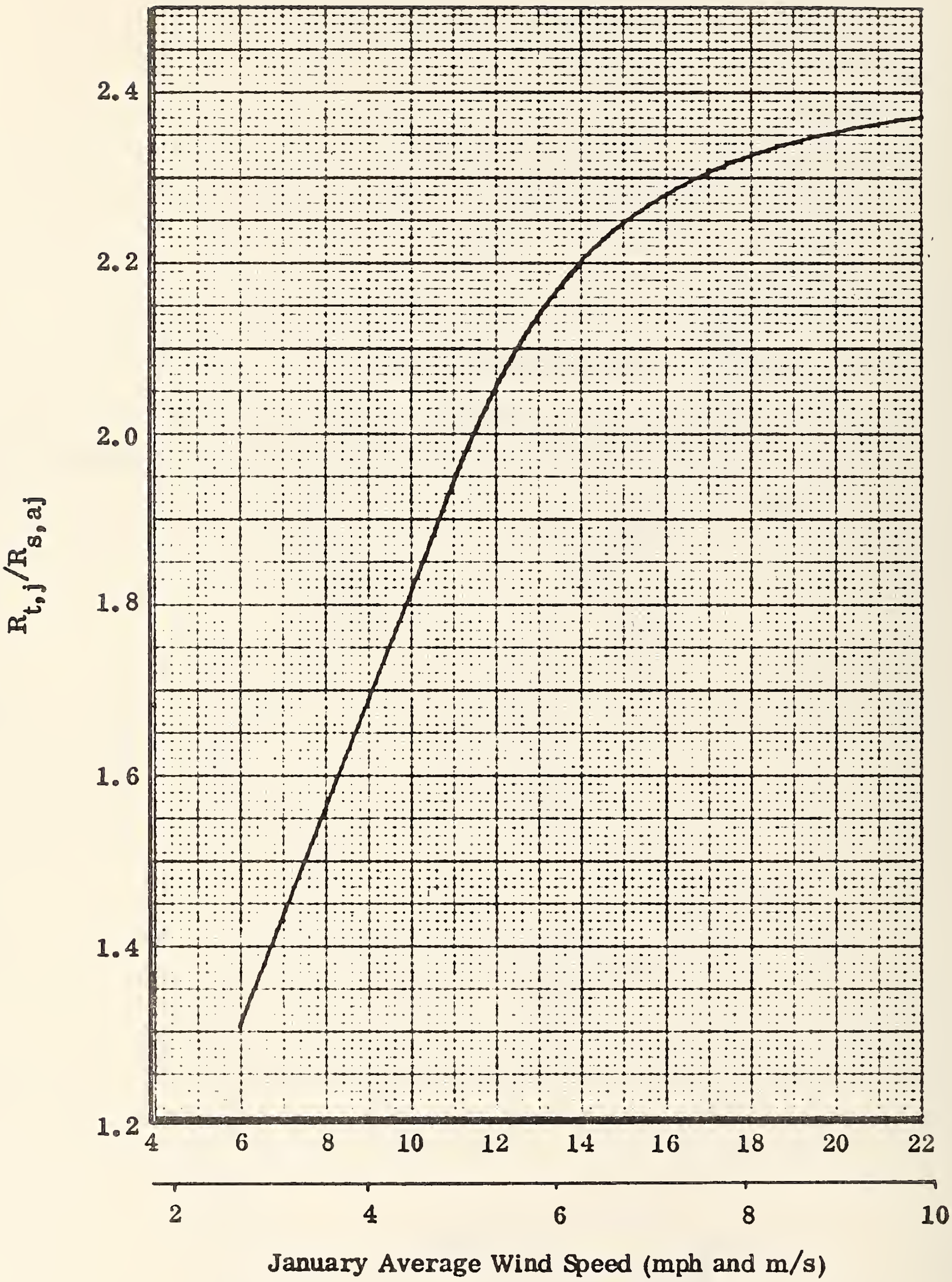



**FIGURE 61**

RESISTANCE RATIO FOR VARIOUS
JANUARY AVERAGE WIND VELOCITIES

Section 3.3, the value of $\Delta T_g$ is calculated to be 19.7°F (10.9°C) for a full performance West Virginia system located in the outskirts of Washington, D. C. Note that the significance in determining $\Delta T_g$ is that it permits system energy dissipation $Q_t$ and average January pavement surface temperature $T_{s,j}$ to be calculated. If $\Delta T_g$ is zero, no augmentation is required. If $\Delta T_g$ is negative, the West Virginia system is overdesigned for the selected site.

## 3.4 Procedure for Designing Augmentation Systems

The ambient air augmentation system collects the thermal energy in summer air and injects it into the heat pipe field where it is stored for use in the winter. To size the system it is necessary to first determine the energy dissipated by the augmented system during winter operation. The energy dissipated in metric and English units is given by:

$$Q_t = \frac{3624\ [\Delta T_g + \delta T]}{R_{t,5} + 53.98} \qquad (\text{Kw-hr/m}^2)$$

$$Q_t = \frac{3.62\ [\Delta T_g + \delta T]}{R_{t,5} + 1.05} \qquad (\text{Kw-hr/ft}^2)$$

Secondly, it is necessary to determine the size of the heat exchanger and the number of heat pipes which are to be supplied by it. The augmentation energy must be large enough to supply both the dissipated energy $Q_t$ and the storage losses. The storage losses are defined by the storage efficiency $\eta_s$, or:

$$Q_t = \eta_s Q_{au}$$

Figure 62 gives the collectable energy in Kw-hr/°C for each m² of pavement surface area for varying numbers of heat pipes paralleled with each m² of face area for standard commercial heat exchangers having various numbers of tube rows. This collectable energy has been determined for one °C difference between ground temperature $T_g$ and average daytime August air temperature $T_{sa}$. Figure 63 gives typical values

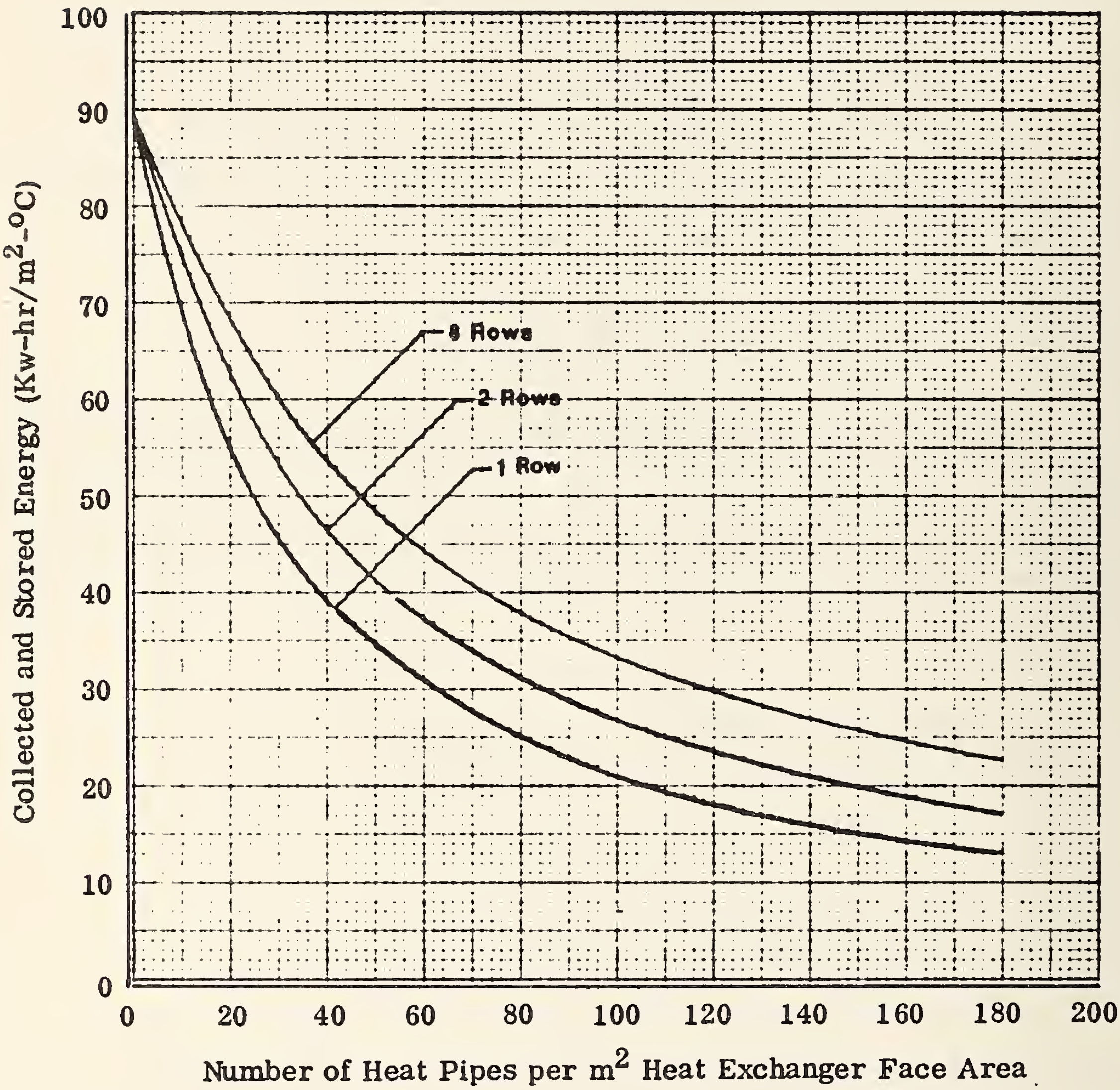



FIGURE 62

COLLECTED ENERGY RELATED TO PAVEMENT SURFACE
AS A FUNCTION OF THE NUMBER OF HEAT PIPES PARALLELED
AND NUMBER OF HEAT EXCHANGER TUBE ROWS


FIGURE 63

DIFFERENCE IN °C BETWEEN AVERAGE DAYTIME AUGUST AIR TEMPERATURES AND GROUND TEMPERATURES THROUGHOUT THE UNITED STATES of $T_{sa} - T_g$ in $^oC$ for various locations throughout the United States.

The size of the blower required for a 10 $m^2$ heat exchanger is given in Figure 64 for various numbers of tube rows at a face velocity of 500 ft/min (2.54 m/s).

### 3.4.1 Example of System Calculation

For the example of Section 3.3.1, determine the energy loss of an augmented earth heating system located in Washington, D. C. Determine the size of the heat exchanger, number of heat pipes connected to the heat exchanger, and the required blower size.

For a $\Delta T_g$ of 10.9$^oC$ (19.7$^oF$), a $\delta T$ of 9.1$^oC$ (16.4$^oF$), and $R_{t,5}$ of 131.6$^oC$-$m^2$/Kw (2.55$^oF$-$ft^2$/W), the value of $Q_t$ is calculated to be 390.6 Kw-hr/$m^2$ (36.3 Kw-hr/$ft^2$). At a storage efficiency of 60%, the system must put energy equal to 651 Kw-hr/$m^2$ into the earth heat pipe field.

As determined from U. S. Weather Bureau records, the average August day-time air temperature is 81$^oF$ (27.2$^oC$). The difference between this temperature and the ground temperature of 57$^oF$ (13.9$^oC$) is 24$^oF$ (13.3$^oC$). The amount of energy that must be collected for each one $^oC$ driving temperature is 651/13.3 or 48.9 Kw-hr/$^oC$. From Figure 62, this amount of energy can be collected by heat exchangers consisting of one or more tube rows. If advantage is not to be taken of prevailing winds, select a one row heat exchanger. The number of heat pipes that can be paralleled with each $m^2$ of this heat exchanger face area is 26 (from Figure 62).

It is desired to locate the ambient air modules on a 150-foot spacing consistent with the light pole spacing at a 16-foot wide ramp. Therefore, one heat exchanger module must service 16 x 150 or 2400 $ft^2$ (223 $m^2$) of pavement surface area. For the West Virginia design, one heat pipe services 0.867 $m^2$ of pavement area; therefore, 26 heat pipes service 22.5 $m^2$ of pavement area. The heat exchanger size satisfying this spacing has a face area of 223/22.5 or 10 $m^2$.

The blower size for a 10 $m^2$ heat exchanger is obtained from Figure 64 and is 2½ horsepower for a one row heat exchanger. For other heat exchanger areas, ratio this power up or down.

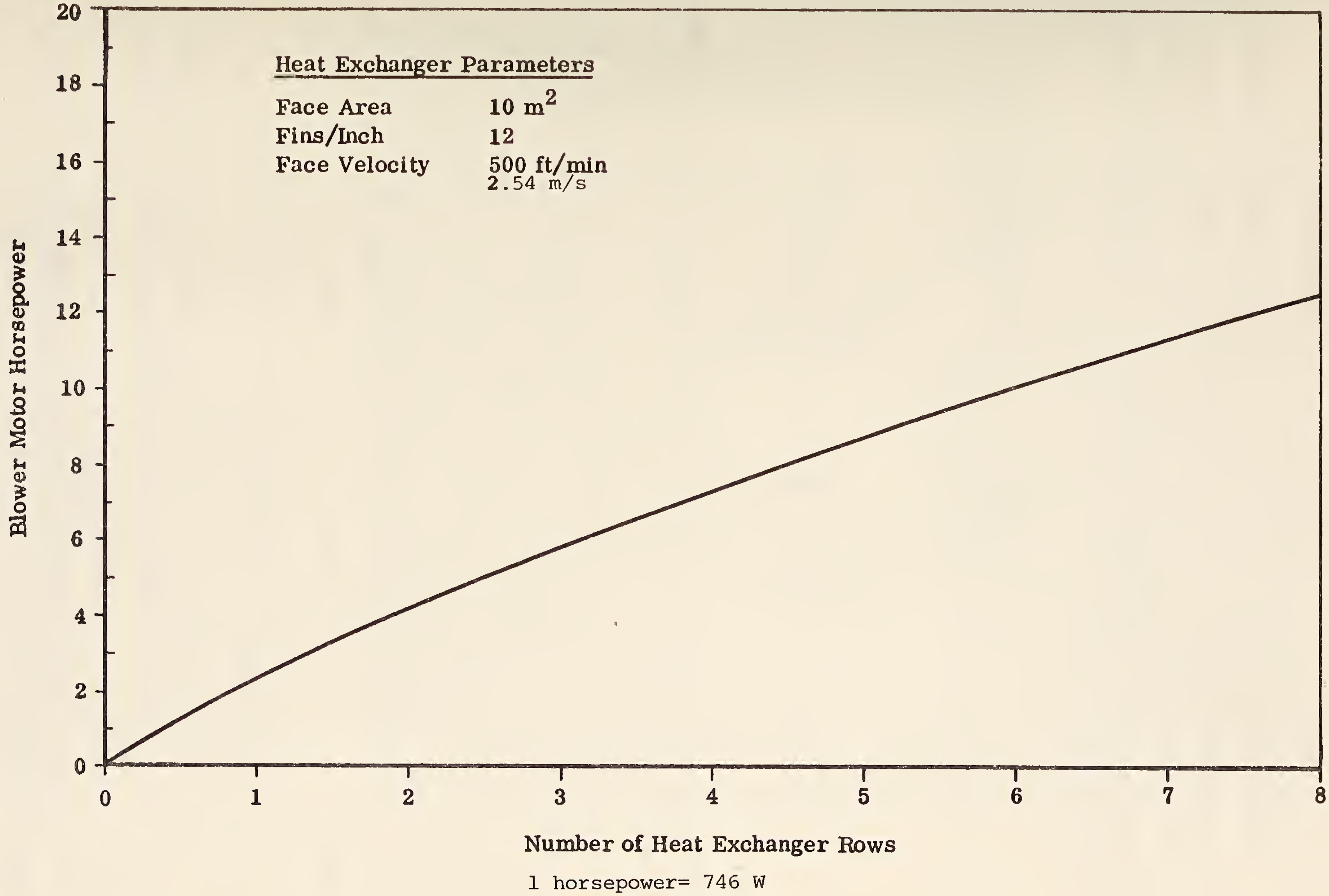



FIGURE 64

BLOWER POWER FOR HEAT EXCHANGER OF VARIOUS NUMBER OF TUBE ROWS

## 3.5 Procedure for Designing a Demand Augmentation System

A earth pavement heating system may be augmented by supplying thermal energy to the heat pipes in the earth only during precipitation events. To design a demand system by the methods employed here, it is first necessary to determine the average pavement surface temperature during January. The applicable expressions in metric and English units are:

$$T_{s,j} = T_g - 16.67 + \frac{R_{s,aj}}{R_{t,j}} \left( \Delta T_g + 16.67 - \frac{53.98\,(\Delta T_g + \delta T)}{R_{t,5} + 53.98} \right)$$

$$T_{s,j} = T_g - 30 + \frac{R_{s,aj}}{R_{t,j}} \left( \Delta T_g + 30 - \frac{1.05\,(\Delta T_g + \delta T)}{R_{t,5} + 1.05} \right)$$

For cities along the Northwestern coast replace 16.67 by 13.3 in the first expression and 30 by 25 in the second expression.

Figure 65 gives the required maximum annual demand augmentation in Kw-hr/$m^2$ for various values of average January pavement surface temperature when determined from the above expressions. The figure gives worst and average year values of demand energy for coastal and inland cities and includes all precipitation events which are necessary to provide adequate margin for false starts. For systems which do not store summer heat in the heat pipe field, $\Delta T_g$ is set equal to zero in the above expressions.

### 3.5.1 Example of a Demand System Calculation

It has been determined that the earth heating system located in Washington, D. C., will not be ambient air augmented but will be demand augmented. Determine the required capacity of an automatic outdoor oil-fired liquid heater required to demand service 223 $m^2$ (2400 $ft^2$) pavement sections and determine the maximum annual demand energy.

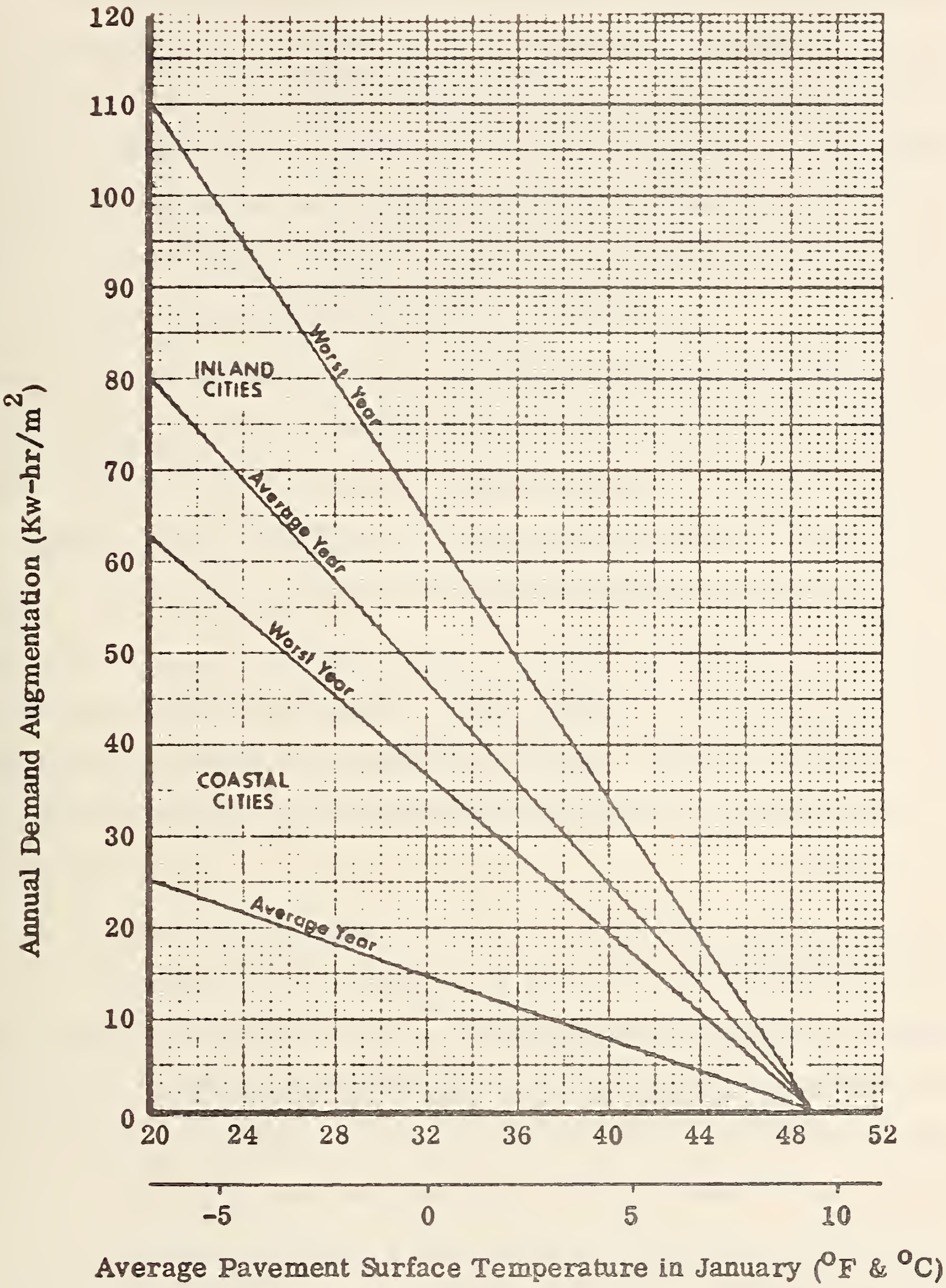



FIGURE 65

REQUIRED DEMAND ENERGY FOR VARIOUS VALUES OF AVERAGE PAVEMENT SURFACE TEMPERATURE

In this example, $\Delta T_g$ is zero. Using the same values for $T_g$, the resistance ratio, and $\delta T$ previously determined, the value of $T_{s,j}$ is calculated to be 5.1°C (41.2°F). From Figure 65 (coastal city), the maximum annual energy $Q_d$ that must be supplied to the pavement is 17 Kw-hr/$m^2$ or, for the 223 $m^2$ pavement section, 3791 Kw-hr. This value must be doubled because approximately one-half of the input energy is used to heat the earth surrounding the heat pipe during periods of demand energy addition.

To determine the capacity of the oil-fired heater, refer to Table 3, Chapter 49, of the ASHRAE Guide. For a Class III snow melting system located in Washington, D. C., the Guide specifies a pavement surface power of 144 Btu/hr-$ft^2$ (0.454 Kw/$m^2$). The size of the oil-fired heater is 0.454 x 233 x 2 = 212 Kw (725,000 Btu/hr) where the factor of 2 makes provision for earth heating losses.

Experience with the West Virginia system, located in a more severe climate than that of Washington, D. C., suggests that demand augmentation may only be required once a year at the most. For an average year, the system will only be required to supply 6 Kw-hr/$m^2$ to the surface or, with losses, 2680 Kw-hr to the 223 $m^2$ pavement section.

### 3.6 System Variations

System performance can be improved by decreasing the in-pavement spacing of heat pipes limited to a practical minimum of 6 inches (15.24 cm). In the West Virginia design, 14-foot (4.27 m) long heat pipes were placed in the pavement on 8-inch (20.32 cm) centers. One heat pipe was coupled to 0.867 $m^2$ (9.33 $ft^2$) of pavement surface. By placing pipes on 6-inch centers, one heat pipe would couple 0.651 $m^2$ (7 $ft^2$) of pavement surface. For the Washington, D. C., example, this change would reduce $\Delta T_g$ from 19.7°F to 17.1°F and increase $Q_t$ from 391 Kw-hr/$m^2$ to 436 Kw-hr/$m^2$. In this case, the improvement in performance is not sufficient to justify the additional installation cost; but closer spacing may be employed in marginal cases.

System performance can also be improved by augmenting with ambient air to the extent practical in the given location and then demand augmenting as discussed in

Section 3.5. In this case, $\Delta T_g$ is retained at the calculated value in the determination of average January pavement surface temperature. In cold climates, reasonable volumes of earth cannot be sufficiently augmented using available air temperatures. Combinations of ambient air and demand augmentation may be experimented with to define the design which is most economical in cost and fuel.

## 3.7 Installations with High Ground Water Movement

When water movement through a substantial portion of the heat pipe field occurs (0.3 m/day or 1 ft/day), earth augmentation is not practical. Demand augmentation as defined herein, however, is practical.

Thermal degradation of the heat pipe field will not occur when water moves through a substantial fraction of the field at a large enough rate. The last terms (representing earth temperature degradation) in the equations in Section 3.3 are eliminated. The resistance between the heat pipe and the ground will decrease significantly, but estimates for this beneficial behavior are difficult to make. At the best, calculations show that augmentation for West Virginia systems located in Washington, D. C., is not required.

If the last term discussed above is eliminated, the $\Delta T_g$ value for the Washington, D. C., example becomes 12.9°F (7.2°C); and, if it is recognized that the heat capacity of the system now becomes very large, the value of $\Delta T_g$ is calculated to be 9.2°F (5.1°C). The January pavement temperature under the latter condition is 44°F, and based on Figure 65 the maximum demand energy is less than 11 Kw-hr/$m^2$ during the worst winter year and the average is less than 4 Kw-hr/$m^2$.

The Highway Engineer who is uncertain of his site ground conditions can, at a small additional expense, buy performance insurance by specifying a backup demand system as part of the energy package. It may not be used in which case it can be dismantled after the Highway Engineer has obtained his desired degree of assurance.

## 3.8 Snow Fences

The use of snow fences should be considered by the Highway Engineer in the design of thermal snow and ice control systems (References 47, 48). The performance of the West Virginia system could have been improved if snow fences had been installed. They were deliberately not installed in West Virginia in order to permit evaluation of system performance under pristine conditions.

## 3.9 Precautions

In most locations throughout the United States, pavement heating systems engineered in accordance with these procedures and good weather and earth data will keep the pavement clear of snow and ice except during infrequent blizzard conditions. The Highway Engineer is cautioned that adding additional design margin will not improve performance commensurate with the additional investment required.

Because of the variability of weather in the Great Plains region, pavement heating systems engineered in accordance with these procedures will permit snow and ice to form on the pavement occasionally and for short periods of time. It is believed that under normal traffic conditions this condition will be acceptable. However, no assurance can be given that this will be so until more experience is obtained with systems installed in the Great Plains region of the United States. The Highway Engineer, at a small additional investment, can provide a demand system to insure against unacceptable performance should this occur. Simultaneously, this will permit obtaining the needed experience for future system design.

The Highway Engineer is also aware that pavements shaded from the winter sun by obstructions or on severe north-facing grades will require more energy to clear snow and ice. For complete shading without, at the same time, obstructing the view of the pavement to nighttime sky, the value of $Q_t$ must be increased between 250 and 400 $Kw\text{-}hr/m^2$ depending upon the amount of wintertime sun that the pavement would normally receive.

Finally, these procedures are equally applicable to asphalt pavements, either original or overlays on concrete pavements. However, installations in asphalt pavements are not recommended where severe braking is required such as at the bottom of steep grades where traffic lights or stop signs are sometimes located.

## 4. CONCLUSIONS

The Donald C. Long design of the earth heated ramp at the Oyler Avenue Interchange on the Oak Hill Expressway in West Virginia is well conceived from the viewpoints of Highway, Thermal, and Geotechnical Engineers. The construction and first year performance of this installation is the subject of an excellent FHWA documentary film.

Solar thermal, wind electric, and summertime air thermal renewable energy sources, techniques for storing energy from these sources, and methods of coupling this energy to the West Virginia earth system were investigated for three climate regions of varying severity with the objective of extending the usefulness of this unaugmented system.

The selected semipassive augmentation system collects the thermal energy contained in summertime air and stores it in the earth below the pavement from where it can be passively extracted by the heat pipes for wintertime use. The selection was based on the following reasoning:

- The passive feature of the basic system is retained during wintertime operation.
- This system is the least expensive to install and maintain.
- Aprehensions regarding earth recovery in deep drawdown cases are eliminated.
- The usefulness of the selected system may be extended to more severe climates by employing demand augmentation using wind, sun, fossile fuel, or waste heat energy sources.
- The selected system may be demand augmented at a small additional expense. This feature can be employed by Highway Engineers to provide performance margin as a contingency to cover uncertainties in site data.
- The aesthetics of highway systems are least affected by the selected system.

The ambient air augmentation system extends the capability of the basic West Virginia design to an additional one million square miles of continental United States territory. By using a nominal amount of demand augmentation, the system can be used in virtually all regions of the Country.

At the limit of its nondemand capability, the total installed cost of the basic augmented pavement heating system is estimated to be 58% higher than an unaugmented West Virginia heat pipe system. This percentage incremental increase in cost appears to be independent of system size. The total installed cost per unit of pavement area obviously decreases as size increases.

Using the amount of energy collected for earth storage, the ambient air system installation cost will equal the present cost of the equivalent amount of electric energy used in three years of operation, and it will equal the present cost of the equivalent amount of fuel oil energy used in 10 years of operation. Of the renewable energy systems considered, the ambient air system is by far the most cost effective.

The augmented West Virginia snow melting system can be modified and employed in such places as airport runways and ramps or wherever snow and ice interrupt the availability of important facilities.

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## PREVENTION OF PREFERENTIAL BRIDGE ICING USING WIND ENERGY

In many parts of the United States, the preferential icing of bridges occurs several times during a typical winter season. The input thermal energy to the bridge deck required to avoid this condition is a fraction of that needed to thermally remove snow and ice from a highway pavement.

Investigations have been made into the feasibility of using earth and solar energy inputs to bridge decks to prevent preferential icing (References 3, 4). These studies show that the integration of these energy sources into even relatively simple bridge structures is difficult and may be impractical for more complex and extensive structures. The cost estimate for a 5,000 $ft^2$ solar heated bridge deck located in New York City is reported in Reference 4 as $12.7/$ft^2$. Heat is distributed in the deck by means of 1/2 inch IPS heat pipes located on 18-inch centers.

As stated in the body of this report, the use of wind energy to prevent preferential bridge icing is attractive because the energy requirements are minimal and the transmission of electrical energy to the bridge deck is simpler than the transmission of thermal energy. To permit a comparison, a 5,000 $ft^2$ bridge deck located in New York City was selected. The worst year weather data (Reference 39) was used.

Figure 66 illustrates the system concept. It consists of 3/4 inch IPS heat pipes located on 9-inch centers within the bridge deck. The pipes are oriented transversely, running from each side of the bridge toward the bridge centerline. Two heat of fusion thermal storage troughs run lengthwise along each side of the deck. The heat pipes are bent 90 degrees at the edges of the deck so as to dip into these thermal storage troughs.

Energy is supplied to the thermal storage troughs by means of an electric wind machine. The electrical generator is direct connected to resistance heating elements which are located in the troughs and run the full length of the troughs. The wind machine can be located at a convenient site near the bridge deck.

Further details of the heat pipe and thermal storage trough are illustrated in Figure 67. The heat pipes are the standard West Virginia ammonia design except that

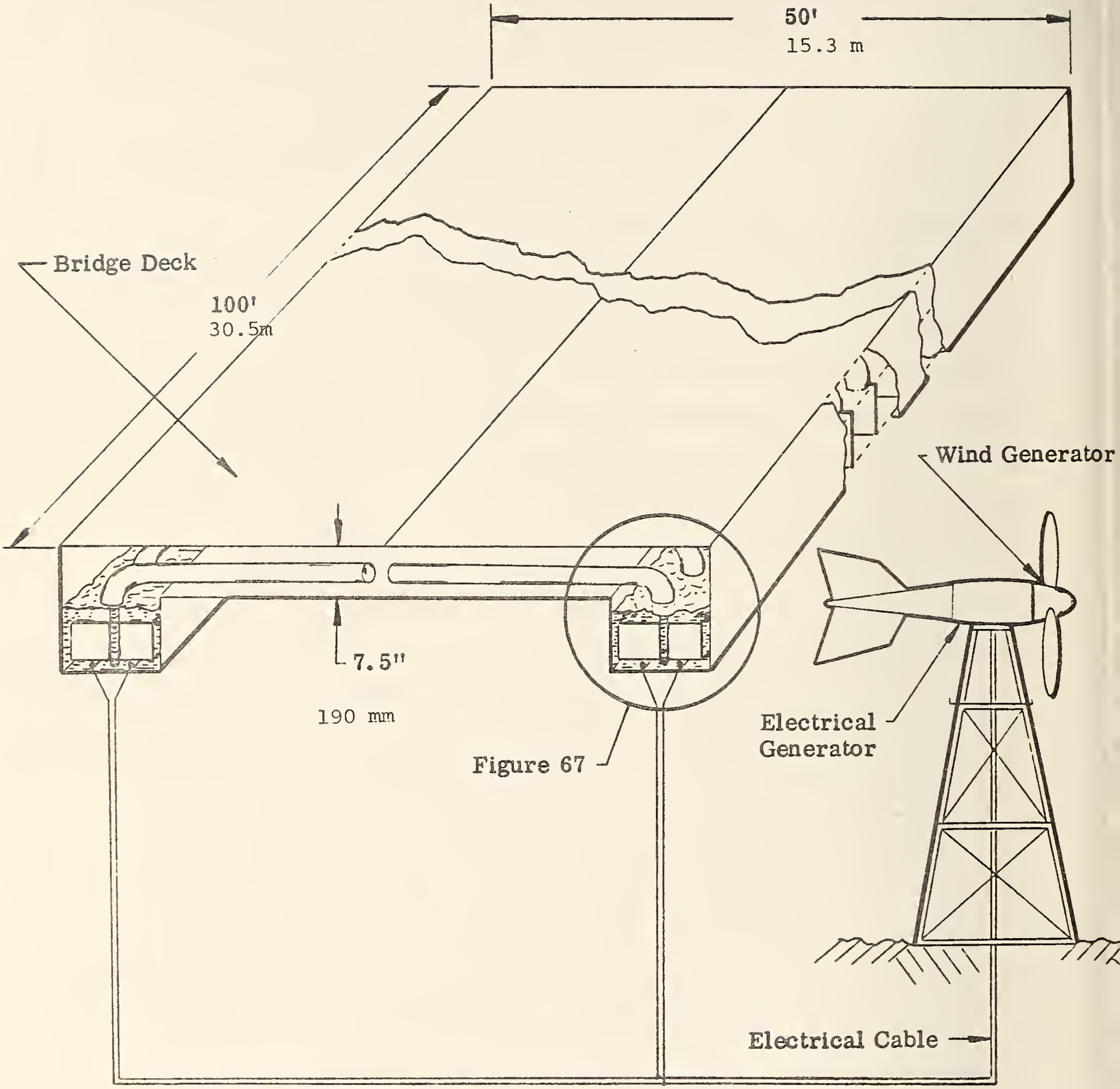


FIGURE 66

HEATING SYSTEM USING WIND POWER FOR
PREVENTION OF PREFERENTIAL BRIDGE ICING

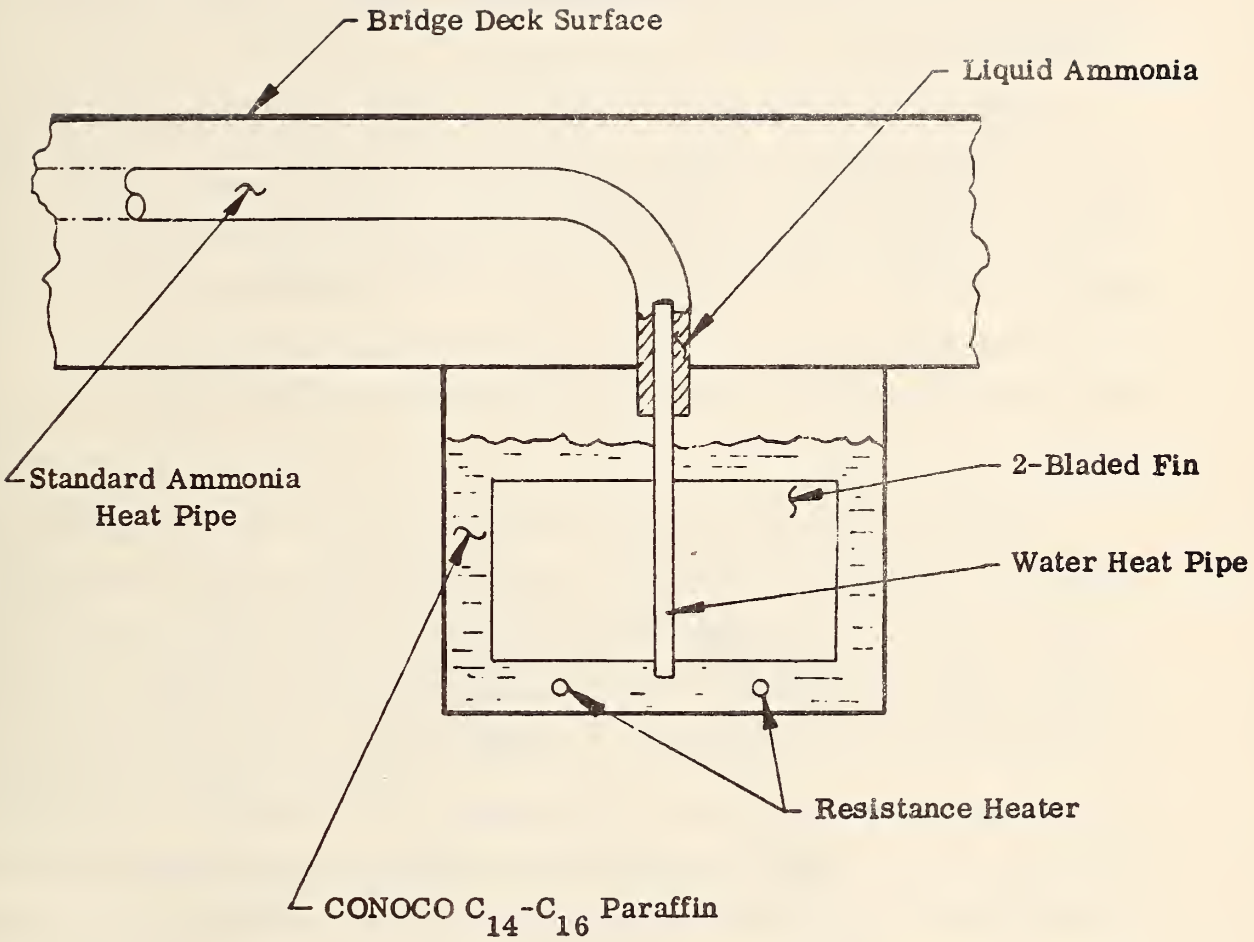


FIGURE 67

DETAILS OF THERMAL STORAGE AND HEAT PIPE SYSTEM INTERFACE the size is 3/4 inch IPS instead of 1 inch IPS. In addition, a separate short length water heat pipe is connected to the trough end of the deck heat pipe as illustrated in Figure 67. Two fins are connected to the water heat pipe. These fins transfer heat from the phase change paraffin to the water heat pipe.

The selected phase change material is CONOCO $C_{14}$-$C_{16}$ which is relatively inexpensive and has a phase change (melting) temperature of 42$^{o}$F. The thermal energy required to melt this paraffin is 85.4 Btu/lb which is also the energy released during its freezing.

The combination of the 42$^{o}$F melting temperature of the selected paraffin and the 32$^{o}$F freezing point of water creates a passive thermal switch. Using computer determined pipe-to-surface resistance and making the paraffin-to-pipe resistance equal to this value, the maximum bridge deck surface heat flux is 2.8 watts/ft$^2$ at a heat pipe temperature of 37$^{o}$F and a pavement surface temperature of 32$^{o}$F. At pavement surface temperatures of less than 27$^{o}$F, the system ceases to transfer heat.

Based on a cycling heat transfer analysis similar to the one conducted in Reference 3, a constant power input to the bridge deck of 2 watts/ft$^2$ is required to prevent preferential freezing in New York City when the ambient air temperature is cycled between 28 and 40$^{o}$F. Without a thermal switch, a 5,000 ft$^2$ deck would require 7,440 Kw-hr of energy for a typical winter month. For New York City for January of the worst year, the ambient temperature varies between 27$^{o}$F and 42$^{o}$F for 60% of the time. The average input to the bridge deck (during this interval) for the passive thermal switch design of Figure 67 is about 1.4 watts/ft$^2$ giving a monthly energy consumption of 3125 Kw-hr. For an on-off system, the monthly energy consumption is given as 1740 Kw-hr (Reference 4).

The sizing of the required electric wind machine and energy storage is determined by the January energy winds. A study of winter wind velocities shows that for New York City there is rarely a day when winds do not exceed the minimum wind machine velocity of 8 mph during at least some part of the day. In view of the nature of energy utilization and energy generation, thermal storage of four days of mean January usage is considered conservative. This requires an energy storage capability

480 Kw-hr ($1.64 \times 10^6$ Btu) which is satisfied by 19,200 pounds of paraffin $C_{14}$-$C_{16}$. This amount of paraffin is less than 5% of the dead weight of the bridge deck. The trough size in Figure 67 will be 2 feet wide, 1.5 feet high, and 100 feet long. This size can be easily contained within the existing slab support beam structure.

The overall efficiency of two-bladed wind machines is about 40% when direct connected to the load. For New York City for January of the worst year, the average wind power is 0.219 Kw/$m^2$. This wind power is exceeded 30% of the time. The wind machine will extract 65.2 Kw-hr/$m^2$ of energy during January. In order to collect 3125 Kw-hr of energy for the 5,000 $ft^2$ bridge deck, a wind machine with a face area of 48 $m^2$ is required. This can be realized by a two-bladed propeller which has a tip-to-tip dimension of 7.8 m (25.6 ft). This requirement can be satisfied by a standard 10 m, 10 Kw wind machine of which a few thousand have been manufactured in Germany.

A cost analysis of the entire system was performed. For the small wind machine required here, pricing (such as is available) is quoted on the basis of the cost per installed Kw. W. L. Hughes of Oklahoma State University has used a cost of $250 per installed Kw in economic analysis performed by him and his associates, although he admits pressure to use up to $600 per installed Kw. A 5 metre, 5 Kw Swiss made wind machine has sold for $1900 in 1973. Pricing for the wind machine of German manufacture could not be obtained. To be conservative, a cost of $1250 per installed Kw has been selected.

The 1972 cost of $C_{14}$-$C_{16}$ paraffin was $0.05/lb. Heat pipe costs were obtained using Dynatherm's West Virginia heat pipe manufacturing experience. The total cost of the installed system less bridge peculiar construction is estimated at $50,071 or $10/$ft^2$.



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## FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

### *FCP Category Descriptions*

**1. Improved Highway Design and Operation for Safety**

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

**2. Reduction of Traffic Congestion and Improved Operational Efficiency**

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

**3. Environmental Considerations in Highway Design, Location, Construction, and Operation**

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

**4. Improved Materials Utilization and Durability**

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

**5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety**

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

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This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

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Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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