# EVAPORATION OF WASTEWATER FROM MOUNTAIN CABINS

by

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# EVAPORATION OF WASTEWATER FROM MOUNTAIN CABINS

Completion Report
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by

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ACKNOWLEDGEMENTS

Originally it had been planned to use test sites on land under the control of the U.S. Forest Service. However, it quickly became clear that such arrangements would take years to complete, and there was a good chance that they would never be completed. Consequently this idea was abandoned completely and instead all but one of the test sites were located on private property where the arrangements took only minutes (versus years). The only test site not located on private land was the Fort Collins Site which was located on Colorado State University property. The other test sites were located as follows:

| Location | Owners |
|---|---|
| Red Feather Site | Dr. and Mrs. Gerald Schmidt<br>Mr. and Mrs. Gus Schmidt |
| Storm Mountain Site | Dr. John C. Ward |
| Breckenridge Site | Dr. George O.G. Löf |
| Fort Collins Site | Colorado State University |

All of these owners assisted with the project by making some of the observations. In addition, both a covered unit and the only full scale unit were located on the Schmidt property. Without the complete and wholehearted cooperation of the Schmidt families, the usefulness of this project would have been greatly impaired.

It should be noted then in summary, that if private land owners had not been willing to allow these test sites to be constructed on their property, this project could not have been completed.

Two graduate research assistants worked on this project: E. C. Frein (25) and W. C. Kuse (29). These 2 men constructed the covered units at the Red Feather, Storm Mountain, and Breckenridge Sites. Mr. Kuse designed the covered units, all of which were identical. In addition to making many of the experimental observations, both completed theses on this project which are referred to throughout the text.

## LIST OF SYMBOLS

a = household use of water for a household of 1 person, gal/(person)(day).

A = horizontal surface area of the water body, $ft^2$.

$\overline{A}$ = average water surface area during interval, $ft^2$.

$A_b$ = area of the bottom of the surface water body, $ft^2$.

$A_c$ = cross-sectional area of a stream, $ft^2$.

b = empirical constant with a numerical value of about 1/2.

c = specific heat of water at constant pressure = 1 Btu/(lb)(°F) at 1 atm and for $32 \leq T_w \leq 212$°F.

C = Thermal conductivity of wet soil, Btu/(hr)(ft)(°F).

D = effective depth at the surface water body, ft.

E = water evaporation rate, ft/day.

$\overline{E}$ = average annual water evaporation rate, ft/day.

365E = water evaporation rate, in./month or ft/year.

$E_o$ = water evaporation rate when T = 0, ft/day.

F = fraction of the incident solar radiation transmitted, dimensionless.

$F_o$ = F when $\rho_A = 0$, dimensionless (for glass, $F_o = 0.93$).

h = convection heat transfer coefficient, Btu/(hr)($ft^2$)(°F).

H = depth of water at the deepest part of a surface water body, ft.

$H_a$ = absolute humidity, $\frac{\text{lb water vapor}}{\text{lb dry air}}$.

$H_R$ = relative humidity, %.

i = constant that depends on the time of year.

I = % increase of solar radiation intensity compared to sea level, %.

$I_1$ = I when z = 1, %.

k = mass transfer coefficient, lb/(hr)($ft^2$).

K = constant, $ft^2$/lb (for glass, K = -0.0462 $ft^2$/lb).

m = constant (the indicated magnitude of m is about 3).

$M_a$ = molecular weight of air = 29, dimensionless.

$M_v$ = molecular weight of water = 18, dimensionless.

n = constant

N = number of persons per household.

°N = degrees north latitude.

p = vapor pressure of water at temperature $T_w$, atm.

$p_a$ = partial pressure of the water vapor in the air, atm.

$p_b$ = vapor pressure of water at the wet-bulb temperature $T_{wb}$, °F.

$p_s$ = vapor pressure of water at the air temperature, atm.

P = atmospheric pressure, atm.

q = average household use of water, gal/(person)(day).

$q_b$ = rate at which a surface water body gains heat from the earth, Btu/(hr)(ft$^2$).

$q_c$ = rate at which a surface water body loses heat by convection, Btu/(hr)(ft$^2$).

$q_e$ = rate at which a surface water body loses heat by water evaporation, Btu/(hr)(ft$^2$).

$q_r$ = rate at which a surface water body loses heat by long wave radiation, Btu/(hr)(ft$^2$).

$q_s$ = rate at which a surface water body gains heat from solar (short wave) radiation, Btu/(hr)(ft$^2$).

$q_w$ = rate at which the heat content of a surface water body decreases, Btu/(hr)(ft$^2$).

Q = total water use per household, gal/day.

s = solar radiation, Btu/(ft$^2$)(day).

t = time interval, hr.

T = air temperature, °F.

$\overline{T}$ = average annual air temperature, °F.

$T_o$ = average annual air temperature at sea level, 0°N, and 0°W, °F.

$T_A$ = absolute air temperature
= 460°F + T, °R.

$T_{Aa}$ = absolute average temperature of the atmosphere, °R.

$T_{AK}$ = absolute air temperature, °K.

$T_{Aw}$ = absolute water temperature
= 460°F + $T_w$, °R.

$T_b$ = soil temperature, °F.

$T_{max}$ = maximum air temperature during an interval, °F.

$T_{min}$ = minimum air temperature during an interval, °F.

$T_S$ = absolute clear sky temperature (the temperature to which an object on the earth's surface radiates long wave radiation), °R.

$T_w$ = water temperature, °F.

$\bar{T}_w$ = average water temperature, °F.

$\frac{dT_w}{dt}$ = rate of change of water temperature, °F/hr.

$\frac{\Delta T_w}{\Delta T}$ = rate of change of water temperature with air temperature, dimensionless.

$T_{wo}$ = water temperature when the air temperature T = 0°F, °F.

$T_{wb}$ = wet-bulb temperature, °F.

V = volume of water in the surface water body, $ft^3$.

ΔV = change in water volume, $ft^3$.

w = surface width of a stream, ft.

W = wind velocity, miles/hr.

°W = degrees west longitude.

x = effective thickness of heat conducting soil layer, ft.

z = elevation, ft.

α = absorptivity of the atmosphere, dimensionless.

ε = water surface emissivity = 0.97, dimensionless.

$\rho$ = weight density of water = 62.4 $lb/ft^3$ at 1 atm and for $32 \leq T_w \leq 212°F$.

$\rho_A$ = area density, $lb/ft^2$.

$\sigma$ = Stefan-Boltzman constant
= $1.73 \times 10^{-9}$ $Btu/(ft^2)(hr)(°R^4)$.

$\tau$ = latent heat of vaporization of water at temperature $T_w$, Btu/lb.

$\tau_b$ = heat of vaporization at the wet-bulb temperature $T_{wb}$, Btu/lb.

# INTRODUCTION

Extensive and intensive development of mountain properties and lands has brought with it many of the pressing problems of environmental degradation. Expectedly, pollution of mountain waters, both surface supplies and groundwaters, is one such problem.

A major contributor of such pollution to mountain waters is domestic wastewater. The problem arises when these wastewaters are inadequately treated or improperly disposed of.

Currently, there are several disposal systems and devices available on the commercial market. Many of these, however, are expensive to install and to maintain. Some of these systems and devices suffer further from the handicaps of requiring an external energy source, usually electricity, and the necessity of the owner providing frequent attention, maintenance, and servicing.

At the present time, four types of home disposal systems are most commonly utilized. These include: (1) a wastewater holding tank or vault; (2) the septic tank and leach field; (3) septic tank and evaporation-transpiration bed; and (4) aerobic treatment units with surface discharge or discharge into leach fields. Each of these types of systems incorporates special design and operational considerations into their successful application.

## Typical Rural Wastewater Disposal Systems

### Holding Tank or Vault

The holding tank or vault is a large tank designed to receive directly, the wastewaters of the user. Surfaces of the tank are coated to make them impervious. In any event, all of the wastewater discharged must eventually be transported by truck to a place where it can be treated.

### Septic Tank and Leachfield

A septic tank and leach field system is intended to dispose of wastewater through sub-surface percolation and evapotranspiration with retention of the setteable solids in the septic tank and their subsequent reduction in volume through anaerobic decomposition. The purpose of the septic tank is to settle particulate matter and provide flotation for greases and fats. Description of the design, construction, and operation of these systems is given in (1).

In mountainous areas numerous special problems arise when one attempts to dispose of wastewater with a septic tank-leach field system. In addition to the obvious climate severities, there are difficulties of shallow depths of earth (usually only a few feet) underlain by fractured rock, and deep frost depths in excess of 6 feet and ranging to 10-11 feet (2).

Evapo-transpiration Systems

In this system the septic tank is followed by an evaporation-transpiration bed (evapotranspiration bed) rather than a leach field. This system has been used as an alternative where conditions will not permit use of the leach field. The system is designed as shown in Figure 1 and in most cases in accordance with the criteria of Bernhart (3). If the unit is to be successfully employed as an evaporation-transpiration system, medium-fine sand (1/2-2mm) and gravel (5-20mm) must be transported to the site for use as the bed media.

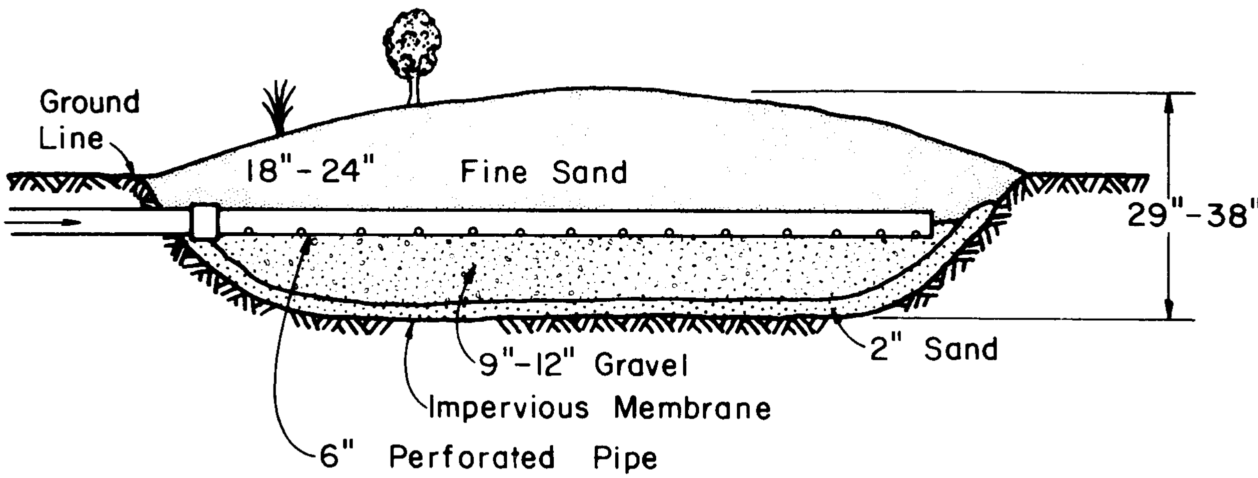



Figure I - Evaporation-Transpiration Bed (6)

Experience with these systems is limited and as a result firm performance evaluation of advantages and disadvantages are not readily available. According to Bernhart, by designing the evapobed for maximum plant growth, for aerobic biological conditions, with sandy bed material and for shallow bed depth (about 18-21 inches), the evapotranspiration rate can be increased by about 200% to 250% over "lake evaporation." Based on Bernhart's work, an evapobed of 1,000 sq. ft. can totally evapotranspirate the daily 200 U.S. gallons of wastewater from an average household, if the bed is actively aerobic, well ventilated, well planted, and well crowned.

However, other authorities state that evaporation from land areas is only about 1/3 to 1/2 of the evaporation from water surfaces. Evaporation loss from turf or grassland is 0.6 to 0.8 times that from an open water surface.

The normal loss of water from the soil by evaporation and plant transpiration is the consumptive use. The largest proportion of consumptive use is transpiration. Consumptive use of crops in California ranges from 0.034 to 0.052 gal/(ft$^2$)(day) which is substantially less than the rate of 0.2 gal/(ft$^2$)(day) claimed by Bernhart above.

Salvato (4) provides a discussion of various types of evapotranspiration systems. Among the things, he presents a graphical relationship between transpiration rate (in inches per month) versus mean monthly air temperature (no transpiration occurs at mean monthly air temperatures of less than 40°F). Using this graphical relationship and mean monthly air temperatures for Denver, Colorado (5), Table 1 was constructed (the maximum transpiration rate of 3.7 inches per month occurs at a mean monthly air temperature of 85°F).

Table 1. Transpiration for Denver, Colorado.

| Month | Mean monthly air Temperature, °F | Transpiration rate, inches per month |
|---|---|---|
| January | 28 | 0 |
| February | 31 | 0 |
| March | 36 | 0 |
| April | 46 | 0.6 |
| May | 56 | 1.4 |
| June | 66 | 2.2 |
| July | 73 | 2.7 |
| August | 71 | 2.3 |
| September | 63 | 1.6 |
| October | 51 | 0.6 |
| November | 48 | 0 |
| December | 32 | 0 |
| Annual Average | 49 | 0.9 |
| Total, inches per year | | 11.4 |

Even at Denver's elevation of only 5,280 feet, the annual precipitation exceeds the annual transpiration. Because air temperature decreases at the rate of 3.6°F per 1,000 feet, the situation becomes even worse at higher elevations where the annual precipitation is even greater. Table 2 shows the transpiration rate as a function of elevation in the mountains west of Denver. Above about 12,300 feet, there is no transpiration at all.

Table 2. Transpiration Rate as a Function of Elevation.

| Month | Elevation in feet | | | | | |
|---|---|---|---|---|---|---|
| | 6,000 | 7,000 | 8,000 | 9,000 | 10,000 | 11,000 |
| April | 0.3 | 0 | 0 | 0 | 0 | 0 |
| May | 1.2 | 1.0 | 0.6 | 0.2 | 0 | 0 |
| June | 2.0 | 1.8 | 1.5 | 1.2 | 0.9 | 0.5 |
| July | 2.5 | 2.3 | 2.0 | 1.8 | 1.4 | 1.1 |
| August | 2.1 | 1.8 | 1.4 | 1.3 | 0.8 | 0.6 |
| September | 1.4 | 1.1 | 0.8 | 0.6 | 0.2 | 0 |
| October | 0.4 | 0.2 | 0 | 0 | 0 | 0 |
| Total transpiration inches per year | 9.9 | 8.2 | 6.3 | 5.1 | 3.3 | 2.2 |

## Aerobic Treatment Units

Aerobic treatment units have also been proposed as an alternative for applications where septic tank leach fields are deemed to be unsuitable. These systems normally incorporate discharge directly onto the ground surface or into shallow, rock filled trenches.

The typical aerobic unit, shown in Figure 2 is usually constructed to function in a manner similar to a small activated sludge treatment plant. Aeration is generally provided with compressed air, aided by mechanical stirring. Studies at the University of Colorato (6) have indicated that the average performance of operational units is below discharge standards for effluents released on the ground surface.

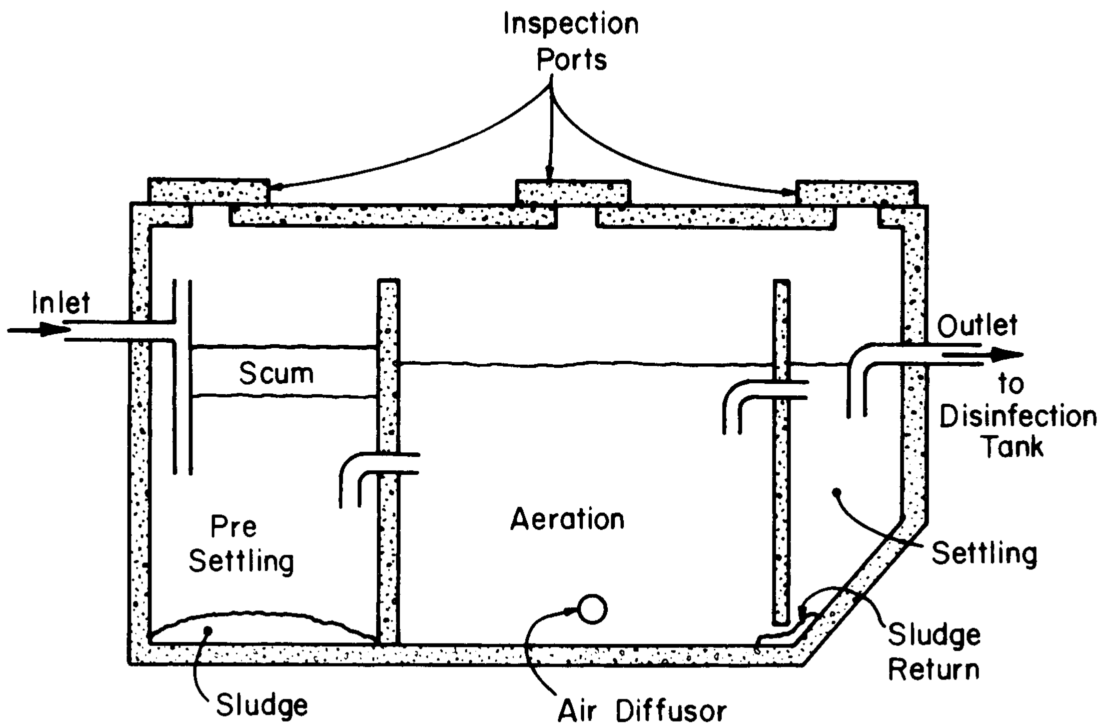



Figure 2 - Typical Aerobic Unit (6)

Two reasons have been identified in these studies (6) which account for the disappointing performance. One important factor is neglect by the homeowner. Many owners will not accept any maintenance responsibility related to a sewage disposal system. Another consideration is the system's high degree of sensitivity to surge flows which are common to the small home system.

## Wastewater Evaporation

Because of the unsuitability of all of the 4 forgeoing wastewater disposal systems for individual mountain homes, the concept of wastewater evaporation will be explored in this report. This system utilizes a conventional septic tank for settling out settleable suspended solids followed by evaporation of the effluent wastewater. Mountain regions often experience annual precipitation amounts in excess of annual evaporation. For an evaporator to work at all some sort of precipitation interceptor must be employed.

In order to design an evaporation system of this kind, it will be necessary to know the evaporation rate as a function of elevation. Also it will be necessary to know how wastewater evaporation rates compare to water evaporation rates.

The ultimate objective of this entire three year investigation is to develop a practical workable system for wastewater disposal and volume reduction. With respect to ground and surface waters, this system will be entirely closed. The design is simple enough for the average layman to construct and install, and it is economically competitive with existing disposal alternatives. Therefore, these features of simplicity and economy are strongly reflected in all design components, including the experimental small scale prototype evaporator units.

## WASTEWATER STORAGE REQUIREMENTS

A breakdown of domestic water consumption apportions the various uses as follows (7):

| | % |
|---|---|
| Flushing toilets | 41 |
| Washing and bathing | 37 |
| Kitchen use | 6 |
| Drinking water | 5 |
| Washing clothes | 4 |
| General household cleansing | 3 |
| Garden watering | 3 |
| Washing the family car | 1 |
| Total | 100 |

Clearly the maximum % that must be evaporated is 96%. The volumes of water used under rural conditions and the resulting wastewaters vary downward in magnitude from values common for urban areas. Table 3 lists representative values (8).

Table 3. Rates of Water Use

| | gallons per person per day |
|---|---|
| troops in combat (absolute minimum) | 0.5 |
| troops on the march or in bivouac | 2-5 |
| restaurants (on a patronage basis) | 10 |
| troops in temporary camps | 15 |
| minimum use of piped water in dwellings | 20 |
| rural schools, overnight camps, and factories (excluding manufacturing uses) | 25 |
| work on construction camps | 45 |
| average use of piped water in dwellings and troops in permanent military installations | 50 |
| resort hotels | 100 |
| rural sanatoria or hospitals | 200 |

Wastewaters are of the same order of magnitude, but with some loss.

It has been found that the amount of water used per person per unit time declines as the number in the household increases (9) as follows:

| Number in Household | | Gallons per day per person |
|---|---|---|
| 1 | | 44 |
| 2 | | 57 |
| 3 | | 47 |
| 4 | | 39 |
| 5 | | 37 |
| 6 | | 33 |
| 7-9 | | 27 |
| 3.6 | Average | 41 |

Equations that have been proposed for this relationship usually take the following form (10):

$$q = a\ N^{-b} \qquad (1)$$

where $q$ = average household use in gallons per person per day,
$N$ = total number of persons per dwelling unit,
$a$ = gallons per person per day for $N = 1$ and,
$b$ is an empirical constant. A least squares fit of the foregoing data using equation 1 gives for $N \geq 2$, $a = 80$, and $b = 0.49 \cong 0.5$ with a correlation coefficient of $-\bar{0}.994$. Therefore, the total use per household in gallons per day, $Q$, is

$$Q = N\ q = a\ N^{1-b} \cong 80\ \sqrt{N} \quad \text{for} \quad N \geq 2 \quad . \qquad (2)$$

From the data presented in this section, it is clear that the largest single use of water is for flushing toilets (41%). However, this use can be reduced enormously or even entirely eliminated by means of commercially available products. For example, a human waste combustion unit completely eliminates the wastewater that would ordinarily be generated by toilet flushing.

In a conventional flush toilet, with a water tank closet, 5 to 5.5 gallons are used per flush. Even a flush toilet with a flushmeter valve will consume 4 to 4.5 gallons of water per flush (11). However, a recirculating flushing toilet discharges only 0.0875 gallons per flush reducing the volume of wastewater discharged from toilet flushing to only 1.6 to 2.2% of what it would be without recirculation. Clearly then, use of either of the foregoing devices would reduce wastewater flows by 40 to 41%.

As a consequence, the remaining wastewater that must be disposed of is about

$$0.55Q = 44\ \sqrt{N} \text{ gallons per day.} \qquad (3)$$

## Annual Distribution of Wastewater Production

While the average wastewater flow rate from cottages and small dwellings with seasonal occupancy is 50 gallons per person per day, the annual distribution of this flow varies with the time of year, and is especially important in determining the requisite storage capacity for evaporation units. At the Red Feather experimental site (which will be described in detail later) the water consumption of a vacation, holiday, and weekend cabin was monitored over a 2 year period. The results are given in Table 4.

It will be noted that the total wastewater discharged from this cabin was 19,850 liters per year or an average of only 14.4 gallons per day.

## Annual Distribution of Water Evaporation

Dalinsky (12) has observed that the average relative evaporation in each month can be expressed as a sinusoidal function whose points of intersection with the annual arithmetic average are in October and April, the minimum being in January and the maximum being in July. His data is reproduced in Table 5 along with equivalent data for Denver, Colorado. It will be noted that the % distribution of water evaporation for Denver differs slightly from that for Israel.

Nevertheless, Dalinsky's point is that for a large region (Israel as a whole), the annual distribution of water evaporation expressed as a % per month is essentially the same despite the fact that climatic conditions ranged from subhumid to arid, and the stations he studied were located at the seashore, in the desert, in valleys and plains, and in mountains. In other words, monthly average relative evaporation was uniform throughout Israel despite large differences in evaporation rates. Dalinsky concluded that the annual distribution of solar radiation differed from the annual distribution of water evaporation by half a month (the minimum of the latter occurs a half month after the mininum of the former) although he stated that even this small difference may be the result of computing evaporation by calendar months. He expressed the % annual distribution of solar radiation by a sinusoidal function also.

## Wastewater Storage Requirement

Table 6 contains the necessary calculations for determining wastewater storage requirements. Fortunately the annual distribution of wastewater production (from Table 4) resembles the annual distribution of water evaporation (from Table 5) which reduces storage requirements substantially. Table 6 is for the case where all of the wastewater is to be evaporated.

It is clear from Table 6 that the greatest difference between wastewater production and water evaporation is in June, and because wastewater production exceeds water evaporation in June, it is also the month requiring the greatest carryover storage. Starting with June then, column 5 of Table 6 shows the cumulative storage required on an annual basis in order to carry over the excess wastewater

Table 4. Annual Distribution of Wastewater Production from a Second Home (in liters per month).

| Year | 1973 | 1974 | 1975 | Average | % of |
|---|---|---|---|---|---|
| Month | liters | liters | liters | liters | Annual |
| January | | 600 | 1,000 | 800 | 4.0 |
| February | | 500 | 1,000 | 750 | 3.8 |
| March | | 600 | 1,100 | 850 | 4.3 |
| April | | 400 | 900 | 650 | 3.3 |
| May | | 2,300 | 1,100 | 1,650 | 8.3 |
| June | 4,200 | 3,000 | | 3,600 | 18.1 |
| July | 4,700 | 2,900 | | 3,800 | 19.2 |
| August | 2,100 | 2,400 | | 2,250 | 11.3 |
| September | 2,100 | 2,200 | | 2,150 | 10.8 |
| October | 2,200 | 1,100 | | 1,650 | 8.3 |
| November | 1,000 | 900 | | 950 | 4.8 |
| December | 400 | 1,100 | | 750 | 3.8 |
| Total | | | | 19,850 | 100.0 |
| Average | | | | 1,654 | 8.3 |

Table 5. Annual Distribution of Water Evaporation.

| | Israel (12) | | | Denver, Colorado (5) | | |
|---|---|---|---|---|---|---|
| Month (1) | % of annual solar radiation (2) | % of annual water evaporation (3) | % of annual water evaporation (4) | Average air tempera- ture, °F (5) | Water eva- poration, inches per month (6) | Solar radiation, $\frac{\text{Btu}}{(\text{ft}^2)(\text{day})}$ (7) |
| Jan. | 4.3 | 3.7 | 2.9 | 28.5 | 1.6 | 959 |
| Feb. | 5.4 | 4.3 | 3.2 | 31.5 | 1.8 | 1,255 |
| March | 7.7 | 6.1 | 4.5 | 36.4 | 2.5 | 1,568 |
| April | 9.5 | 8.2 | 6.7 | 46.4 | 3.7 | 1,937 |
| May | 11.1 | 11.0 | 9.0 | 56.2 | 5.0 | 2,140 |
| June | 12.1 | 13.1 | 13.4 | 66.5 | 7.4 | 2,435 |
| July | 12.1 | 13.2 | 15.9 | 72.9 | 8.8 | 2,362 |
| Aug. | 11.2 | 12.2 | 15.2 | 71.5 | 8.4 | 2,140 |
| Sept. | 9.5 | 10.4 | 12.1 | 63.0 | 6.7 | 1,808 |
| Oct. | 7.3 | 8.0 | 8.3 | 51.4 | 4.6 | 1,384 |
| Nov. | 5.4 | 5.7 | 5.4 | 37.7 | 3.0 | 996 |
| Dec. | 4.4 | 4.1 | 3.4 | 31.6 | 1.9 | 812 |
| Total | 100.0 | 100.0 | 100.0 | | 55.4 | |
| Average | 8.3 | 8.3 | 8.3 | 49.5 | 4.6 | 1,650 |

Table 6. Wastewater Storage Requirements for Second Homes Using Wastewater Evaporation.

| Month (1) | % of Annual: Wastewater production (from Table 4) (2) | % of Annual: Water evaporation (from Table 5 (3) | Wastewater production minus evaporation (2-3) (4) | Storage required (Σ4) (5) |
|---|---|---|---|---|
| June | 18.1 | 13.4 | 4.7 | 4.7 |
| July | 19.2 | 15.9 | 3.3 | 8.0 |
| August | 11.3 | 15.2 | -3.9 | 4.1 |
| September | 10.8 | 12.1 | -1.3 | 2.8 |
| October | 8.3 | 8.3 | 0 | 2.8 |
| November | 4.8 | 5.4 | -0.6 | 2.2 |
| December | 3.8 | 3.4 | 0.4 | 2.6 |
| January | 4.0 | 2.9 | 1.1 | 3.7 |
| February | 3.8 | 3.2 | 0.6 | 4.3 |
| March | 4.3 | 4.5 | -0.2 | 4.1 |
| April | 3.3 | 6.7 | -3.4 | 0.7 |
| May | 8.3 | 9.0 | -0.7 | 0.0 |
| Total | 100.0 | 100.0 | 0.0 | |

produced to months where water evaporation exceeds wastewater production. It is clear that the greatest storage requirement is 8% of the annual wastewater volume. For the second home whose wastewater production is given in Table 4, the storage required then is

$$\frac{19{,}850 \text{ liters}}{3.785 \text{ ℓ/gal}} \times 0.08 = 420 \text{ gallons or } 56 \text{ cubic feet.}$$

## WATER SURFACE HEAT BALANCE

The rate at which the heat content of a surface water body decreases, $q_w$, in Btu/(hr)(ft$^2$), is

$$q_w = q_c + q_r + q_e - q_s - q_b \quad \text{where} \tag{4}$$

$q_c$ = rate of heat loss by convection, Btu/(hr)(ft$^2$),

$q_r$ = rate of heat loss by long wave radiation, Btu/(hr)(ft$^2$),

$q_e$ = rate of heat loss by water evaporation, Btu/(hr)(ft$^2$),

$q_s$ = rate of heat gain by solar (short wave) radiation, Btu/(hr)(ft$^2$),

$q_b$ = rate of heat gain from the earth, Btu/(hr)(ft$^2$).

Equation 4 may be rewritten

$$q_c + q_r + q_e = q_s + q_w + q_b \tag{5}$$

where the left side of equation 5 may be considered to be the rate of heat depletion of the reservoir, and the right side, the heat input.

The 3 terms on the left side of equation 5 can be evaluated as follows:

$$q_c = h\ (T_w - T) \tag{6}$$

$$q_r = \sigma\ (\varepsilon T_{Aw}^4 - \alpha T_A^4) \tag{7}$$

$$q_e = \frac{E}{24}\ \tau\rho \tag{8}$$

where:

$h$ = heat transfer coefficient, $\frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(°\text{F})}$

$T_w$ = water temperature, °F,
$T$ = air temperature, °F,
$\sigma$ = Stefan-Boltzman constant
= $1.73 \times 10^{-9}$ Btu/(ft$^2$)(hr)(°R$^4$)
$\varepsilon$ = water surface emissivity = 0.97, dimensionless
$T_{Aw}$ = absolute water temperature
= 460°F + $T_w$, °R
$\alpha$ = absorptivity of the atmosphere, dimensionless
$T_A$ = absolute air temperature
= 460°F + T, °R
$E$ = water evaporation rate, ft/day,
$\tau$ = latent heat of vaporization of water at temperature $T_w$, Btu/lb
$\rho$ = weight density of water
= 62.4 lb/ft$^3$ at 1 atm and for $32 \le T_w \le 212$°F.

In like fashion the terms on the right side of equation 5 can be evaluated as follows:

$$q_w = -\ c\,\rho\,D\ d\ T_w/dt \tag{9}$$

$$q_b = \frac{C}{x}\ (\frac{A_b}{A})\ (T_b - T_w) \tag{10}$$

where

$c$ = specific heat of water at constant pressure = 1 Btu/(lb)(°F) at 1 atm and for $32 \le T_w \le 212$°F,
$D$ = effective depth of the surface water body, ft,
$\frac{dT_w}{dt}$ = rate of change of water temperature, °F/hr,

$C$ = thermal conductivity of wet soil, (Btu)(ft)/(hr)($ft^2$)(°F),
$x$ = effective thickness of heat conducting soil layer, ft,
$A$ = horizontal surface area of the water body, $ft^2$,
$A_b$ = area of the bottom of the surface water body, $ft^2$,
$T_b$ = soil temperature, °F.

## Long Wave Radiation

Clear sky temperature is needed to calculate long-wave radiation heat losses from surface water bodies. During cloudy weather, the water surface radiates directly to the clouds which substantially reduces the proportion of the total heat lost by this mechanism. If the clear sky temperature is known, then equation 7 simplifies to

$$q_r = \sigma(\varepsilon T_{Aw}^4 - T_s^4) \qquad (11)$$

where $T_s$ is the absolute clear sky temperature, °R.

Ward (13) derived from first principles an equation that predicts the absolute average temperature of the air in the atmosphere as a function of surface air temperature and the average rate of change of air temperature with altitude in the overlying atmosphere. Using the average rate of change of air temperature with altitude for the U.S. standard atmosphere, the average atmospheric air temperature is given by the following equation:

$$T_{Aa} = 0.914\ T_A \qquad (12)$$

where $T_{Aa}$ = absolute average temperature of the atmosphere, °R.

Using published experimental data (15 observations) collected at 4 different locations in the conterminous U.S. with elevations ranging from 30 to 6,257 feet above mean sea level, Ward showed that

$$T_{Aa} \cong T_s \qquad (13)$$

The experimental observations were made at surface air temperatures ranging from -1.2°C up to 32°C, with relative humidity ranging from 10 up to 71%. % sunshine ranged from 90 to 99%. Therefore,

$$T_s = 0.914\ T_A \qquad (14)$$

and

$$T_s^4 = 0.70\ T_A^4 \qquad (15)$$

Consequently, it appears that, for clear skies, a comparison of equations 7, 11, and 15 give $\alpha = 0.7$. Previously reported values for $\alpha$ given by 3 other authors reported in (14) average 0.7 for clear skies.

Equation 7 can be written

$$q_r = \sigma\ \varepsilon\ (T_{Aw}^4 - \frac{\alpha}{\varepsilon} T_A^4) \qquad (16)$$

Assuming $T_{Aw} \cong T_A$, then

$$q_r = \sigma\ \varepsilon\ T_A^4\ (1 - \frac{\alpha}{\varepsilon}) \qquad (17)$$

Assuming a temperature of 32°F, equation 17 reduces to

$$q_r \cong 27.4\ \text{Btu/(hr)(ft}^2\text{)}.$$

## Rate of Water Evaporation

The rate of water evaporation is

$$E = \frac{24k}{\rho}\ (\frac{M_v}{M_a})(\frac{p-p_a}{P}) \qquad (18)$$

where $k$ = mass transfer coefficient, lb/(hr)(ft$^2$),
$M_v$ = molecular weight of water = 18, dimensionless
$M_a$ = molecular weight of air = 29, dimensionless,
$p$ = vapor pressure of water at temperature $T_w$, atm,
$p_a$ = partial pressure of the water vapor in the air, atm,
$P$ = atmospheric pressure, atm.

As long as air flow conditions are turbulent, the ratio $h/k$ = 0.24 Btu/(°F)(lb) is independent of the air velocity. The numerical value given for this ratio is for air-water systems under a total pressure of 1 atm.

$k$ is usually related to wind velocity, $W$, in miles per hour, by the following empirical relationship (14):

$$k = 0.61\ W\ . \qquad (19)$$

Average annual wind velocities are shown in Figure 3.

Values of $p$ can be found in (15). $p_a$ can be calculated from the following equation (16):

$$p_a = p_b - \frac{0.386P}{\tau_b}(T - T_{wb}) \qquad (20)$$

$p_b$ = vapor pressure of water at the wet-bulb temperature $T_{wb}$, °F,
$\tau_b$ = heat of vaporization at the wet-bulb temperature $T_{wb}$, Btu/lb,
$T_{wb}$ = wet-bulb temperature, °F.

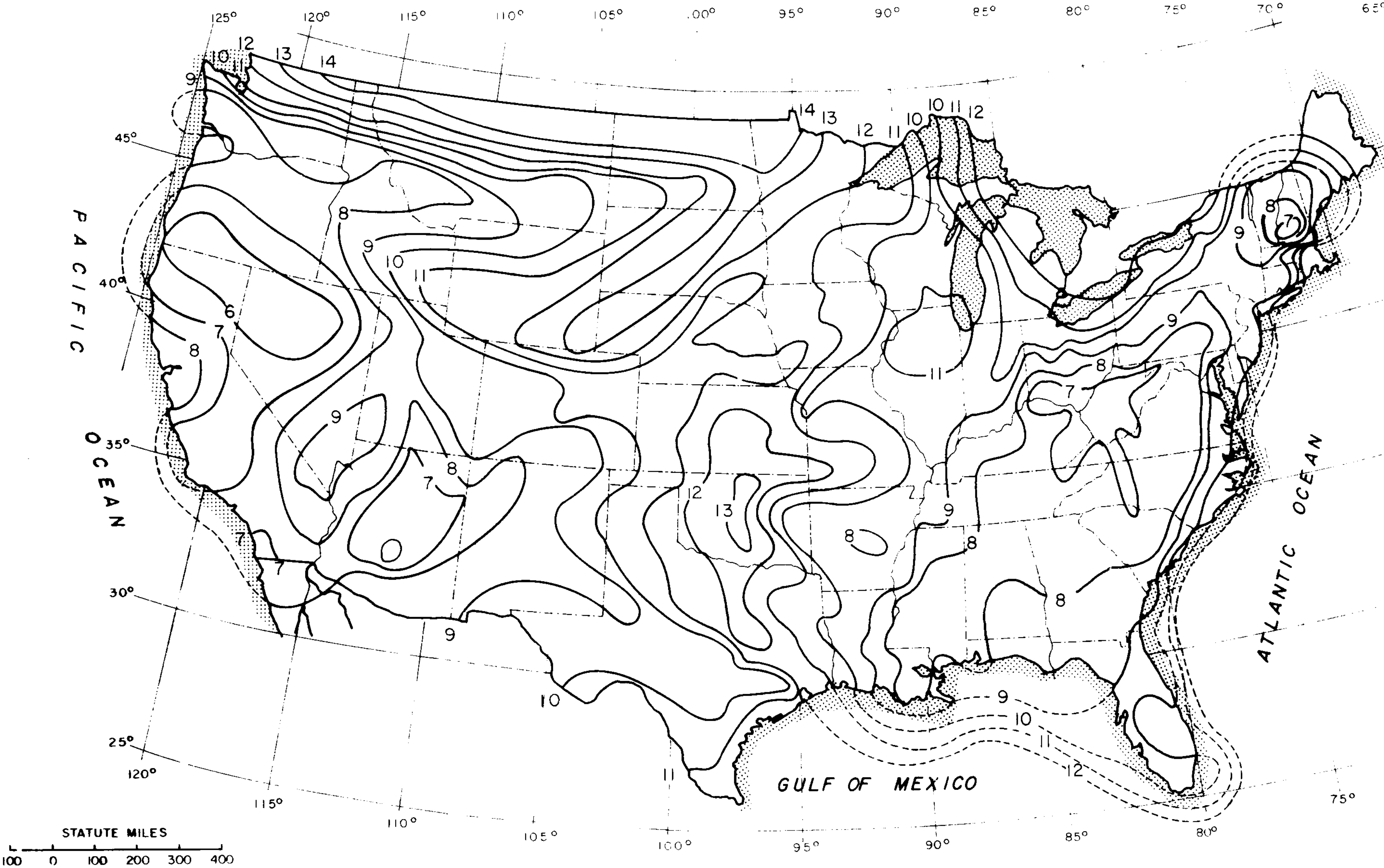



Figure 3 - Annual Average Wind Velocity in miles per hour

If $T_{wb} \leq 32°F$, then $\tau_b$ = 1,076 Btu/lb and equation 20 reduces to

$$p_a = p_b - 3.59 \times 10^{-4} P (T - T_{wb}) \qquad (21)$$

Substituting in the values of the constants in equation 18, one obtains,

$$E = 0.24 k \left(\frac{p - p_a}{P}\right) \qquad (22)$$

If the temperature of the surface water body is at the wet-bulb temperature, then equations 20 and 22 can be combined to obtain

$$E = \frac{0.093k}{\tau} (T - T_w) \qquad (23)$$

or

$$E = \frac{0.093k}{\tau_b} (T - T_{wb}) \qquad (23A)$$

## Solar Radiation

The value of the solar constant is 442 Btu/(ft$^2$)(hr) ± 2%, but the value of $q_s$ is almost always less than this (17). In addition, only 94% of the incoming solar radiation is absorbed by the water.

Table 7 contains representative solar radiation data for latitudes ranging from 32 to 48°N taken from (18). It will be noted that the solar radiation minimum occurs in December and the maximum occurs in June or July. On the other hand, minimum air temperatures are experienced in January and maximum air temperatures are observed in July. Clearly air temperatures are approximately 1 month out of phase with solar radiation.

The wavelength of solar radiation extends from 0.1 to 4 microns, and the wavelength of long wave radiation extends from 4 to 100 microns (19). The peak solar radiation intensity occurs at a wavelength of 0.5 microns and the peak long wave radiation intensity occurs at a wavelength of 10 microns for objects at the mean temperature of the earth (57°F).

As altitude increases, the length of the path of the sun's rays through the atmosphere decreases and atmospheric transmission increases. The percentage increase of solar-radiation intensity with altitude has been calculated by Becker and Boyd (20) for June 21 and December 21 at 40°N latitude. Their results are as follows:

Table 7. Representative Solar Radiation and Air Temperature Data
Part I - Data Location Description

| Lat. °N | Elevation in feet | Location |
|---|---|---|
| 32 | 3,916 | El Paso, Texas |
| 33 | 1,112 | Phoenix, Arizona |
| 34 | 1,020 | Riverside, California |
| 35 | 5,314 | Albuquerque, New Mexico |
| 36 | 2,440 | Inyokern,California |
| 37 | 331 | Fresno, California |
| 38 | 2,592 | Dodge City, Kansas |
| 39 | 6,262 | Ely, Nevada |
| 40 | 8,389 | Grand Lake, Colorado |
| 41 | 1,189 | Lincoln, Nebraska |
| 42 | 1,329 | Medford, Oregon |
| 43 | 5,370 | Lander, Wyoming |
| 44 | 3,218 | Rapid City, South Dakota |
| 45 | 339 | Ottawa, Ontario |
| 46 | 1,034 | St. Cloud, Minnesota |
| 47 | 3,664 | Great Falls, Montana |
| 48 | 2,277 | Glasgow, Montana |

The solar radiation and air temperature data for the above locations are given in Parts II and III of this table.

Table 7. - Continued - Part II - Representative Solar Radiation Data in Btu/(day)(ft$^2$)

| Lat. °N | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 1248 | 1613 | 2049 | 2447 | 2673 | 2731 | 2391 | 2350 | 2077 | 1705 | 1325 | 1052 |
| 33 | 1127 | 1515 | 1967 | 2388 | 2710 | 2782 | 2451 | 2300 | 2131 | 1689 | 1290 | 1041 |
| 34 | 100 | 1335 | 1751 | 1943 | 2282 | 2493 | 2443 | 2264 | 1955 | 1510 | 1169 | 980 |
| 35 | 1151 | 1454 | 1925 | 2343 | 2561 | 2757 | 2561 | 2388 | 2120 | 1640 | 1274 | 1052 |
| 36 | 1149 | 1554 | 2137 | 2595 | 2925 | 3109 | 2909 | 2759 | 2409 | 1819 | 1170 | 1094 |
| 37 | 713 | 1117 | 1653 | 2049 | 2409 | 2642 | 2512 | 2301 | 1898 | 1415 | 907 | 617 |
| 38 | 953 | 1186 | 1566 | 1976 | 2126 | 2460 | 2401 | 2211 | 1842 | 1421 | 1065 | 874 |
| 39 | 872 | 1255 | 1750 | 2103 | 2322 | 2649 | 2417 | 2308 | 1935 | 1473 | 1079 | 815 |
| 40 | 735 | 1135 | 1579 | 1877 | 1975 | 2370 | 2103 | 1708 | 1716 | 1212 | 776 | 660 |
| 41 | 712 | 956 | 1300 | 1588 | 1856 | 2041 | 2011 | 1903 | 1543 | 1216 | 773 | 643 |
| 42 | 435 | 804 | 1260 | 1807 | 2216 | 2440 | 2607 | 2262 | 1672 | 1043 | 559 | 346 |
| 43 | 786 | 1146 | 1638 | 1988 | 2114 | 2492 | 2438 | 2121 | 1713 | 1302 | 837 | 695 |
| 44 | 688 | 1032 | 1504 | 1807 | 2028 | 2194 | 2236 | 2020 | 1628 | 1179 | 763 | 590 |
| 45 | 539 | 852 | 1250 | 1507 | 1857 | 2084 | 2045 | 1752 | 1327 | 827 | 459 | 408 |
| 46 | 633 | 977 | 1383 | 1598 | 1859 | 2003 | 2088 | 1828 | 1369 | 890 | 545 | 463 |
| 47 | 524 | 869 | 1370 | 1621 | 1971 | 2179 | 2383 | 1986 | 1536 | 985 | 575 | 421 |
| 48 | 573 | 966 | 1438 | 1741 | 2127 | 2262 | 2415 | 1984 | 1531 | 997 | 575 | 428 |

The Solar radiation data given above is for the locations given in Part I of this table.

Table 7. - Continued - Part III - Representative Air Temperatures in °F

| Lat. °N | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 47 | 53 | 59 | 67 | 76 | 84 | 85 | 83 | 78 | 69 | 56 | 48 |
| 33 | 54 | 59 | 65 | 72 | 81 | 89 | 95 | 92 | 87 | 76 | 64 | 57 |
| 34 | 55 | 57 | 61 | 65 | 69 | 74 | 81 | 81 | 78 | 71 | 63 | 57 |
| 35 | 37 | 43 | 50 | 60 | 69 | 79 | 83 | 81 | 74 | 62 | 48 | 39 |
| 36 | 47 | 54 | 59 | 66 | 73 | 81 | 87 | 85 | 79 | 69 | 57 | 49 |
| 37 | 47 | 54 | 59 | 66 | 73 | 81 | 87 | 85 | 79 | 69 | 57 | 49 |
| 38 | 34 | 39 | 46 | 58 | 67 | 77 | 84 | 82 | 74 | 62 | 46 | 37 |
| 39 | 27 | 32 | 39 | 48 | 57 | 65 | 74 | 72 | 64 | 52 | 40 | 31 |
| 40 | 18 | 23 | 28 | 39 | 49 | 57 | 63 | 61 | 55 | 45 | 30 | 23 |
| 41 | 28 | 32 | 42 | 56 | 66 | 76 | 83 | 80 | 71 | 60 | 43 | 32 |
| 42 | 39 | 45 | 51 | 56 | 63 | 69 | 77 | 76 | 70 | 59 | 47 | 40 |
| 43 | 20 | 26 | 35 | 45 | 56 | 65 | 75 | 72 | 61 | 48 | 33 | 24 |
| 44 | 25 | 27 | 35 | 48 | 58 | 67 | 76 | 75 | 65 | 53 | 39 | 29 |
| 45 | 15 | 16 | 28 | 43 | 57 | 67 | 72 | 70 | 61 | 49 | 35 | 20 |
| 46 | 14 | 17 | 30 | 46 | 59 | 68 | 74 | 72 | 62 | 50 | 32 | 18 |
| 47 | 25 | 28 | 36 | 48 | 57 | 64 | 74 | 71 | 61 | 51 | 38 | 29 |
| 48 | 13 | 17 | 31 | 48 | 59 | 67 | 76 | 73 | 61 | 49 | 31 | 19 |

The air temperature data given above is for the locations given in Part I of this table.

| Altitude feet | % increase of solar radiation intensity compared to sea level | |
|---|---|---|
| | December 21 | June 21 |
| 2,000 | 3 | 7 |
| 3,000 | 7 | 12 |
| 4,000 | 9 | 15 |
| 5,000 | 11 | 18 |
| 6,000 | 13 | 21 |
| 7,000 | 14 | 23 |
| 8,000 | 15 | 24 |

% increases for other times of the year can be estimated by interpolating between paired values.

The foregoing data can be empirically represented by an equation of the form

$$I = I_1 + i \ln z \tag{24}$$

where

$I$ = % increase of solar radiation intensity compared to sea level, %,
$I_1$ = $I$ when $z = 1$, %,
$i$ = constant that depends on the time of year,
$z$ = elevation, feet.

Equation 24 was fitted to the foregoing data by the method of least squares with the following results:

| | December 21 | June 21 |
|---|---|---|
| Correlation coefficient | 0.999 | 0.998 |
| $I$, % | -62.64 | -88.74 |
| $i$ | 8.658 | 12.57 |

## Heat Capacity

The effective depth of a surface water body, $D$, is

$$D = V/A = A_c/w \tag{25}$$

where

$V$ = volume of water in the surface water body, $ft^3$,
$A_c$ = cross-sectional area of a stream, $ft^2$,
$w$ = surface width of a stream, ft.

On an annual basis, the water temperature in streams varies about 36°F (21), so that the average rate of change of water temperature per month is about 6°F or about 0.2°F per day. As a result, the magnitude of $q_w$ in equation 9 per foot of depth is roughly

$$\frac{q_w}{D} = -\ (1)\ (62.4)\ (-0.01) \cong 0.6\ \frac{\text{Btu/(hr)(ft}^2)}{\text{ft}}$$

which is clearly negligible when compared to the long wave radiation heat loss of 27 $\frac{\text{Btu}}{\text{(hr)(ft}^2)}$. Of course, in deep water bodies, $q_w$ is much larger.

## Heat Transfer Between Surface Water Bodies and the Earth

The normal heat flux from the center of the earth is 0.02 Btu/(ft$^2$)(hr), which is clearly negligible. For concrete tanks, rough over-all values of the ratio $C/x$ in equation 10 are 0.1 and 0.3 Btu/(ft$^2$)(hr)(°F) for exposures to dry earth and wet earth respectively (22). Therefore, for a surface water body with vertical walls, $A_b/A$ = 1, and the rate at which a surface water body gains heat from dry earth per °F temperature difference between the water and the soil is

$$\frac{q_b}{T_b - T_w} = (0.1)(1) = 0.1\ \text{Btu/(hr)(ft}^2)$$

which is clearly also negligible.

## Water Evaporation Rate from Water Surface Heat Balance

Substitution of equation 8 into equation 5 gives

$$E = \frac{24}{\tau\rho}\ (q_s + q_w + q_b - q_c - q_r) \qquad (26)$$

It has already been shown that for the kinds of surface water bodies of concern to this project that $q_w$ and $q_b$ are negligible and that $q_r \cong 27.4$ Btu/(hr)(ft$^2$). Therefore, equation 26 may be reduced to

$$E = \frac{24}{\tau\rho}\ (q_s - q_c - q_r) \qquad (27)$$

Substituting equation 6 into equation 27, one obtains

$$E = \frac{24}{\tau\rho}\ (q_s - q_r - h\ T_w) + \frac{24h}{\tau\rho}\ T \qquad (28)$$

Now if $h/\tau\rho$ is relatively constant, plots of E versus T should be straight lines if $\frac{(q_s - q_r - h\ T_w)}{\tau\rho}$ is relatively constant. It seems likely that as $q_s$ increases, $T_w$ will increase and vice versa. Because $q_r$ appears to be relatively constant, it is at least conceivable that the ratio $(q_s - q_r - hT_w)/\tau\rho$ might be roughly constant.

It appears that, for a given location, E is a straight line function of T. Table 8 gives the results of least squares correlations for 6 cities scattered throughout the United States. For Denver, Colorado, equation 28 becomes

Table 8. Water Evaporation Rate and Air Temperature

| City and State | Latitude, °N | Elevation, feet | Average solar radiation, Btu/(ft$^2$)(day) | Average air temperature, °F | Average water evaporation, inches/month | least squares fit* intercept, inches/month | slope, inches/(month)(°F) | correlation coefficient | slope/intercept |
|---|---|---|---|---|---|---|---|---|---|
| Oklahoma City, Okla. | 35 | 1,304 | 1,631 | 63.5 | 5.50 | -6.64 | 0.191 | 0.971 | -0.03 |
| Nashville, Tenn. | 36 | 605 | 1,396 | 63.2 | 3.30 | -4.01 | 0.116 | 0.997 | -0.03 |
| Columbus, Ohio | 40 | 833 | 1,200 | 55 | 2.74 | -2.99 | 0.104 | 0.991 | -0.03 |
| Denver, Colorado | 40 | 5,280 | 1,650 | 49.5 | 4.62 | -3.27 | 0.159 | 0.992 | -0.05 |
| Seattle, Wash. | 47 | 386 | 1,011 | 53.2 | 2.04 | -3.77 | 0.109 | 0.969 | -0.03 |
| Bismark, N. Dak. | 47 | 1,660 | 1,375 | 45.2 | 3.28 | -1.79 | 0.112 | 0.958 | -0.06 |

*The least squares fit was to a straight line of the form:
Water evaporation (inches/month) = intercept + (slope)(T). The temperature at which evaporation is zero is - intercept/slope. These temperatures for the cities listed above were 35, 35, 29, 21, 35, and 16°F, respectively.

$$E = -0.00868 + 0.000431\ T \tag{29}$$

Using $\tau$ = 1,076 Btu/lb, then $h$ = 1.21 Btu/(hr)(ft$^2$)(°F) and $k$ = 5.04 lb/(hr)(ft$^2$). Using equation 19, this value of $k$ corresponds to a wind velocity of 8.3 miles per hour. Comparing equations 28 and 29, one obtains

$$q_s - q_r - h\ T_w = -\ 24.3 \tag{30}$$

for Denver, Colorado. Solving equation 30 for $T_w$, one obtains

$$T_w = \frac{q_s}{h} + \frac{2.43 - q_r}{h} \tag{31}$$

Using the values of $h$ and $q_r$ previously obtained, equation 31 reduces to

$$T_w = 0.826\ q_s - 2.6 \tag{32}$$

Equation 32 indicates a correlation between water temperature and solar radiation. An empirical correlation was made using monthly average values of $q_s$ and $T_w$ for the Arkansas River at Little Rock Arkansas, which gave the following result (correlation coefficient = 0.89):

$$T_w = 0.58\ q_s + 30 \tag{33}$$

Solar radiation and water temperature data are given in Table 9 for Cheney Reservoir. A least squares analysis of the data in columns 2 and 3 gave the following result (correlation coefficient = 0.86):

$$T_w = 0.612\ q_s + 18.5 \tag{34}$$

However, a least squares analysis of the data in columns 2 and 4 gave the following result (correlation coefficient = 0.994):

$$T_w = 0.709\ q_s + 12.3 \tag{35}$$

Apparently for Cheney Reservoir the water temperature lags behind solar radiation about one month which would put it in phase with air temperature.

Equations 31, 32, 33, 34, and 35 indicate that water temperature is related to solar radiation by an equation of the form

$$T_w = \frac{q_s}{h} - \frac{(q_r + E_o\ \tau\rho/24)}{h} \tag{36}$$

where

$E_o$ = water evaporation rate when $T = 0$, ft/day.

Table 9. Cheney Reservoir Solar Radiation and Water Temperature

| Month (1) | Data corresponding to column 1: Solar Radiation, $\frac{Btu}{(hr)(ft^2)}$ (2) | Data corresponding to column 1: Water Temperature, °F, (3) | Data corresponding to column 5, water temperature, °F (4) | Month (5) |
|---|---|---|---|---|
| Jan. | 36.7 | 36.8 | 37.8 | Feb. |
| Feb. | 46.2 | 37.8 | 44.1 | Mar. |
| Mar. | 61.1 | 44.1 | 53.9 | Apr. |
| Apr. | 76.4 | 53.9 | 64.7 | May |
| May | 79.7 | 64.7 | 73.5 | June |
| June | 93.1 | 73.5 | 78.0 | July |
| July | 92.0 | 78.0 | 77.0 | Aug. |
| Aug. | 82.4 | 77.0 | 70.7 | Sept. |
| Sept. | 69.7 | 70.7 | 60.9 | Oct. |
| Oct. | 53.7 | 60.9 | 50.1 | Nov. |
| Nov. | 39.6 | 50.1 | 41.3 | Dec. |
| Dec. | 32.8 | 41.3 | 36.8 | Jan. |

## Solar Distillation

For solar radiation above about 1,000 Btu/$(ft^2)$(day), the following equation estimates fairly well the production rate of solar stills (23):

$$E = -5.45 \times 10^{-3} + (8.9 \times 10^{-6})(24\ q_s) \quad (37)$$

where

$E$ = solar distillation rate, ft/day,
$24\ q_s$ = solar radiation intensity, Btu/$(ft^2)$(day).

In Table 10 is given the solar radiation, calculated solar distillation, and water evaporation rates for Miami, Florida, located at latitude 26°N (elevation 9 feet). It will be noted that despite relatively high year round solar radiation intensities, the solar distillation rate is always less than the water evaporation rate, and, on an annual basis, averages 82% of the water evaporation rate.

The following cost data is about 10 years old and is taken from 23. The costs of solar stills in the United States range from about $2/$ft^2$ for a 3,000 $ft^2$ pilot plant to about $1/$ft^2$ for a 20-acre distiller of the same materials and design as the pilot plant. For the latter figure, about 72% is material cost and the remaining 28% is labor cost assuming an unskilled labor rate of $2/hr (0.135 man-hours of labor are required per $ft^2$). These latter figures do not include contractor fee or profit.

Table 10. Solar Radiation, Water Evaporation, and Solar Distillation Rates for Miami, Florida.

| Month | Solar Radiation Intensity, $\frac{\text{Btu}}{(\text{ft}^2)(\text{day})}$ | Solar Distillation Rate, ft/day | Days per Month | Solar Distillation Rate, $\frac{\text{inches}}{\text{month}}$ | Water Evaporation, Rate, $\frac{\text{inches}}{\text{month}}$ |
|---|---|---|---|---|---|
| Jan. | 1,292 | 0.0060 | 31 | 2.2 | 3.0 |
| Feb. | 1,555 | 0.0084 | 28 | 2.8 | 3.4 |
| Mar. | 1,829 | 0.0108 | 31 | 4.0 | 4.1 |
| Apr. | 2,021 | 0.0125 | 30 | 4.5 | 4.9 |
| May | 2,069 | 0.0130 | 31 | 4.8 | 5.0 |
| June | 1,991 | 0.0123 | 30 | 4.4 | 4.8 |
| July | 1,993 | 0.0123 | 31 | 4.6 | 5.3 |
| Aug. | 1,891 | 0.0114 | 31 | 4.2 | 5.1 |
| Sept. | 1,647 | 0.0092 | 30 | 3.3 | 4.3 |
| Oct. | 1,436 | 0.0073 | 31 | 2.7 | 4.1 |
| Nov. | 1,321 | 0.0063 | 30 | 2.3 | 4.3 |
| Dec. | 1,183 | 0.0051 | 31 | 1.9 | 2.7 |
| Total | | | 365 | 41.7 | 51.0 |
| Average | 1,686 | 0.0095 | 30.4 | 3.5 | 4.3 |

Estimates of construction costs of plastic-covered solar stills range from about 50¢ to nearly $\$1/\text{ft}^2$, depending on the type of plastic film used, the structural design, etc. These costs are about 50% of the costs of the glass-covered distillers previously discussed. On the other hand, along with these lower construction costs of plastic-covered solar stills, one must take into account the shorter life of plastic materials. Some plastic films have undergone several years of exposure testing, under conditions similar to those encountered in a solar still. The better films exhibited maximum lives of about 4 years. However, in experimental solar distillers, no plastic films have survived longer than 1 year.

## TRANSPARENT MATERIALS

The transparent material used as the precipitation interceptor should be transparent to solar radiation and should be opaque to long wave radiation. All transparent covers will reduce, to some extent, the solar radiation incident on the water surface under them.

### Published Solar Radiation Transmittance Data for Glass

Table 11 contains solar radiation transmittance data for glass taken from (24). The solar radiation transmittance is related to the glass thickness as follows:

$$\ln F = \ln F_o + K \rho_A \tag{38}$$

or

$$F = F_o \exp (K \rho_A) \tag{39}$$

Table 11. Approximate Solar Radiation Transmittance of Sheet and Plate Glass.

| Type | Nominal Thickness in. | Weight lb/ft$^2$ | Direct 90° Solar Energy, % |
|---|---|---|---|
| Sheet | 1/16 | 0.81 | 89 |
| Sheet | 5/64 | 1.00 | 88 |
| Sheet | 3/32 | 1.22 | 87 |
| Sheet | 1/8 | 1.64 | 86 |
| Sheet | 3/16 | 2.47 | 84 |
| Sheet | 7/32 | 2.85 | 82 |
| Plate or Float | 1/8 | 1.64 | 86 |
| Plate or Float | 1/4 | 3.28 | 79 |
| Plate or Float | 5/16 | 4.09 | 77 |
| Plate or Float | 3/8 | 4.91 | 74 |
| Plate or Float | 1/2 | 6.55 | 70 |
| Plate or Float | 5/8 | 8.18 | 65 |
| Plate or Float | 3/4 | 9.83 | 60 |
| Plate or Float | 7/8 | 11.45 | 55 |
| Plate or Float | 1 | 13.13 | 49 |

Note: Many types of glass are available, including tempered heat-strengthened glass, laminated shatter-proof glass, conductive-coated glass, reflective-coated glass. Several double-pane combinations are offered.

Direct 90° transmittance of solar ultraviolet radiation through non-tinted window glass is about 85 percent as high as the values for total solar energy transmittance. Ultraviolet transmittance of gray or bronze glass is lower.

Infrared transmittance is considerably lower than visual transmittance. This is significant in view of the large percentage of infrared radiation from most sources.

Visible reflectance of untinted glass is about 8 percent.

where

$F$ = fraction of the incident solar radiation transmitted, dimensionless,

$F_o$ = F when $\rho_A = 0$, dimensionless

$K$ = constant for glass, $ft^2/lb$,

$\rho_A$ = area density of glass, $lb/ft^2$,

A least squares analysis of the data in Table 11 gave the following results (correlation coefficient = - 0.997): $K = - 0.0462\ ft^2/lb$, and $F_o = 0.93$.

Solar Radiation Transmittance Data for Several Transparent Materials

Solar radiation transmittance data was experimentally determined for several transparent materials.

An Epply Black and White Pyranometer (in which the detector is a differential thermopile with the hot junction receiver blackened and the cold junction receivers whitened with Barium Sulphate) was used for the measurement of global (total sun and sky) radiation. The emf produced by the temperature difference measured at the thermojunctions gave low-level signals to a Leeds and Northrop Model 10896 Electronic Integrator which registered the number of counts. From the number of counts per hour, the millivolt output from the pyranometer can be determined. Knowing the output in millivolts, solar radiation in $cal/(cm^2)(min)$ can be calculated from the constant for the instrument.

For automatic printing of the counts at desired intervals of time, the output from the electronic integrator was connected to a General Electric Company PD-57-F Printing Demand Meter. The 69 foot chemically treated record tape can be adjusted for 15, 30, or 60 minute demand intervals. When the integrator and the demand meter are used simultaneously, there is a multiplying factor of two for the latter, i.e., two counts on the printing demand meter will be equal to one count on the electronic integrator.

Measurements of solar radiation transmittance of various transparent materials (these same materials were tested for long wave transmittance) was accomplished. Generally, a second Eppley Pyranometer similar to the one described above was used for precise determination of solar and sky radiation. The apparatus set up is shown in Figure 4. The pyranometer was mounted in a box in which the interior had been blackened. The box had a 45° sloping open face which was prepared to hold an 8 inch by 10 inch sample of the material to be tested between the pyranometer and the sky. Observations were carried out between 2 hours before and 2 hours after solar noon so that maximum solar and diffuse sky radiation would be available. The surface of the sample was oriented as nearly as possible to be perpendicular to the incident solar radiation during data collection. The pyranometer was connected to a potentiometric strip chart recorder which recorded the millivolt output.

Experimental procedure was generally to record the incident solar radiation intensity with no sample in place, then with a sample in place, and finally with the sample removed again. The differences in intensity for the sample in place versus the average of the before and after (without sample) readings then allowed calculation of the percent transmission.

The results of the experimental measurements are given in Table 12 taken from (25). Also given in Table 12 are the results of another series of experiments which will be discussed presently (column 6). The last 6 materials listed in Table 12 are glass.

Column 4 of Table 12 lists the actual experimentally determined solar transmittance of the various materials, while column 5 shows the calculated solar transmittance (using equation 39) of glass with the same area density. It should be noted, however, that the actual minimum thickness of glass commonly used is 1/16 inch corresponding to an area density of 0.81 $lb/ft^2$ and a calculated solar transmittance of 0.9. From this standpoint, the K-Clear Plastic offers a solar transmittance as good as that of ordinary glass.

Clearly the Kalwall Longlife material has a lower solar transmittance than the Kalwall Sunlite material which in turn has a substantially lower solar transmittance than ordinary glass. On the other hand, the Uvex material has a solar transmittance only slightly less than that obtainable with ordinary glass.

Three tests were made on Fourco Clearlite Glass. One sample was untreated, a second sample was partially treated, and the third sample

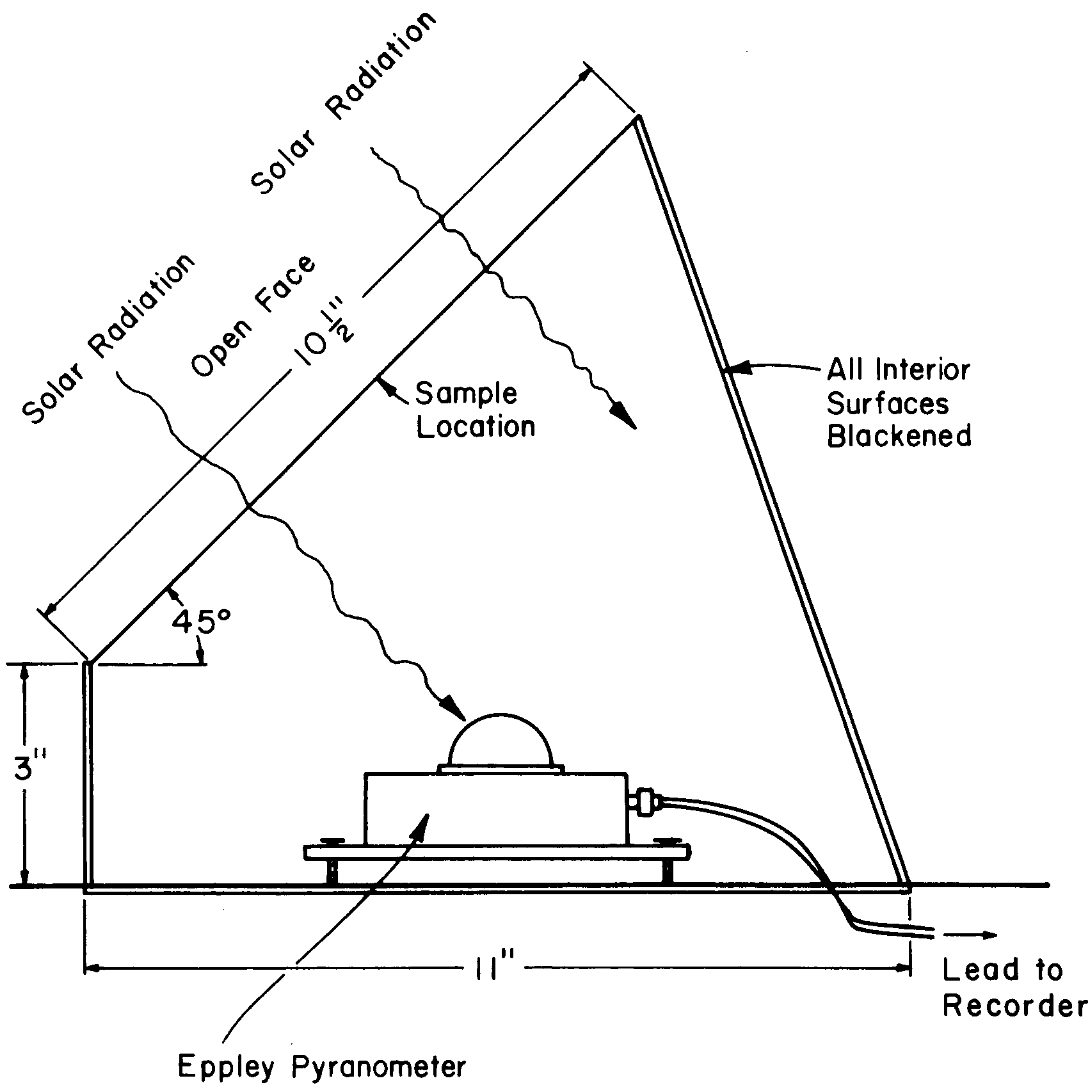



Figure 4 - Apparatus Used in Determining Solar Radiation Transmittance (25)

Table 12. Solar Radiation Transmittance of Various Materials.

| Material (1) | | Thickness, inches (2) | Area density, $lb/ft^2$ (3) | % Transmittance Solar Radiation | | % Transmittance long wave radiation from (25) (6) |
|---|---|---|---|---|---|---|
| | | | | Observed (4) | Ordinary glass (equation 39) (5) | |
| K-Clear Plastic | | 0.008 | 0.05 | 90.1 | 92.8 | 43.1 |
| K-Clear Plastic | | 0.012 | 0.09 | 90.3 | 92.6 | 35.5 |
| Kalwall Longlife | | 0.030 | 0.17 | 76.8 | 92.3 | 23.4 |
| Kalwall Sunlite | | 0.027 | 0.18 | 83.5 | 92.2 | 21.6 |
| Kalwall Sunlite | | 0.030 | 0.19 | 83.7 | 92.2 | 22.7 |
| Kalwall Sunlite | | 0.037 | 0.23 | 80.3 | 92.0 | 22.2 |
| Kalwall Longlife | | 0.037 | 0.24 | 77.9 | 92.0 | 22.3 |
| Kalwall Sunlite | | 0.045 | 0.24 | 81.9 | 92.0 | 19.3 |
| Uvex | | 1/8 | 0.39 | 88.7 | 91.3 | 20.2 |
| Fourco Clear-lite Glass* | Treated | 3/32 | 1.13 | 91.1 | 88.3 | 22.6 |
| | Partially Treated | 3/32 | 1.13 | 90.4 | 88.3 | 22.6 |
| | Untreated | 3/32 | 1.13 | 87.3 | 88.3 | 22.6 |
| LOF Glass | | 3/32 | 1.19 | 85.5 | 88.0 | 22.7 |
| ASG Crystal 76 | | 3/16 | 2.32 | 90.3 | 83.5 | 27.3 |
| ASG Crystal 76 | | 7/32 | 2.71 | 88.9 | 82.1 | 24.5 |

| | |
|---|---|
| K-Clear Plastic<br>Jerlee Products Coproration<br>Brooklyn, New York | Uvex<br>Kodak Eastman Plastics<br>(Cellulose Acetate<br>Butyrate Sheet)<br>Eastman Chemical Products<br>Kingsport, Tennessee 37662 |
| Kalwall Corporation<br>(fiberglass reinforced)<br>Manchester, N. H. 03105 | |
| LOF Glass<br>Libby-Owen-Ford | ASG Crystal 76 Glass<br>ASG Industries, Inc.<br>Kingsport, Tennessee 37662 |

*Treatment is solar low reflectivity coating.

was treated with a low reflectivity (to solar radiation) coating. Clearly this low reflectivity coating increases solar transmittance. While the ASG Crystal 76 glass has much better solar transmittance than ordinary glass of the same thickness, its somewhat excessive thickness to some extent outweighs this advantage, unless other requirements dictate a thicker than normal glass.

Long Wave Radiation Transmittance Data for Several Transparent Materials

This work was done using the experimental setup shown in Figure 5. The experimental apparatus used included a net all wave radiation exchange radiometer, a Bristol strip chart recorder for the net all wave radiation exchange radiometer output, and another strip chart recorder for temperature.

A temperature compensated Net Exchange Radiometer (Packard Bell Model TCN-188), based on a design by J. T. Gier and R. V. Dunkle of the University of California, was used to sense net radiation by means of a thermopile whose output is proportional to the difference between the incident radiation on each side of the sensing element. Measurements were carried out in a darkened laboratory so that essentially the only radiation input to the upper side of the sensing element was a constant long wave radiation from the ceiling. A Corning PC-35 hot plate with a blackened heating surface (3-M "NEXTEL" Brand Velvet Coating) was placed below the net radiometer sensor. With the hot plate control on heat, readings were made, after equilibrium was reached, without a sample and then with a sample of material to be tested between the hot plate and the net radiometer sensor. The difference between the two readings then allowed calculation of the percentage transmittance of long wave radiation by the sample.

Copper-constantan thermocouples were attached to the blackened surface of the hot plate and the material sample being tested. The temperatures allowed calculation of the long wave radiation emitted by the sample due to heating so that the true value of long wave radiation could be determined.

The results of these experiments are given in Column 6 of Table 12. Glass is opaque to long-wave radiation. Apparently both the Kalwall and Uvex are also opaque to long-wave radiation. On the other hand, the K-Clear Plastic is not entirely opaque to long-wave radiation; the percent transmission appears to increase with decreasing area density.

A statistical analysis of the values listed for all materials except K-Clear plastic gives a mean % transmittance to long wave radiation of 22.6% (with a standard deviation of ±1.9%). Therefore it appears that the previously calculated value of $q_r$ for water surfaces exposed to the atmosphere of 27.4 Btu/(hr)(ft$^2$) will be reduced to [(0.226) (27.4)=] 6.2 Btu/(hr)(ft$^2$) for outdoor water surfaces covered with a precipitation interceptor.

## Transparent Material Durability

Plastic film displays a rather large thermal coefficient of expansion. Consequently, at colder temperatures, the plastic stiffens and

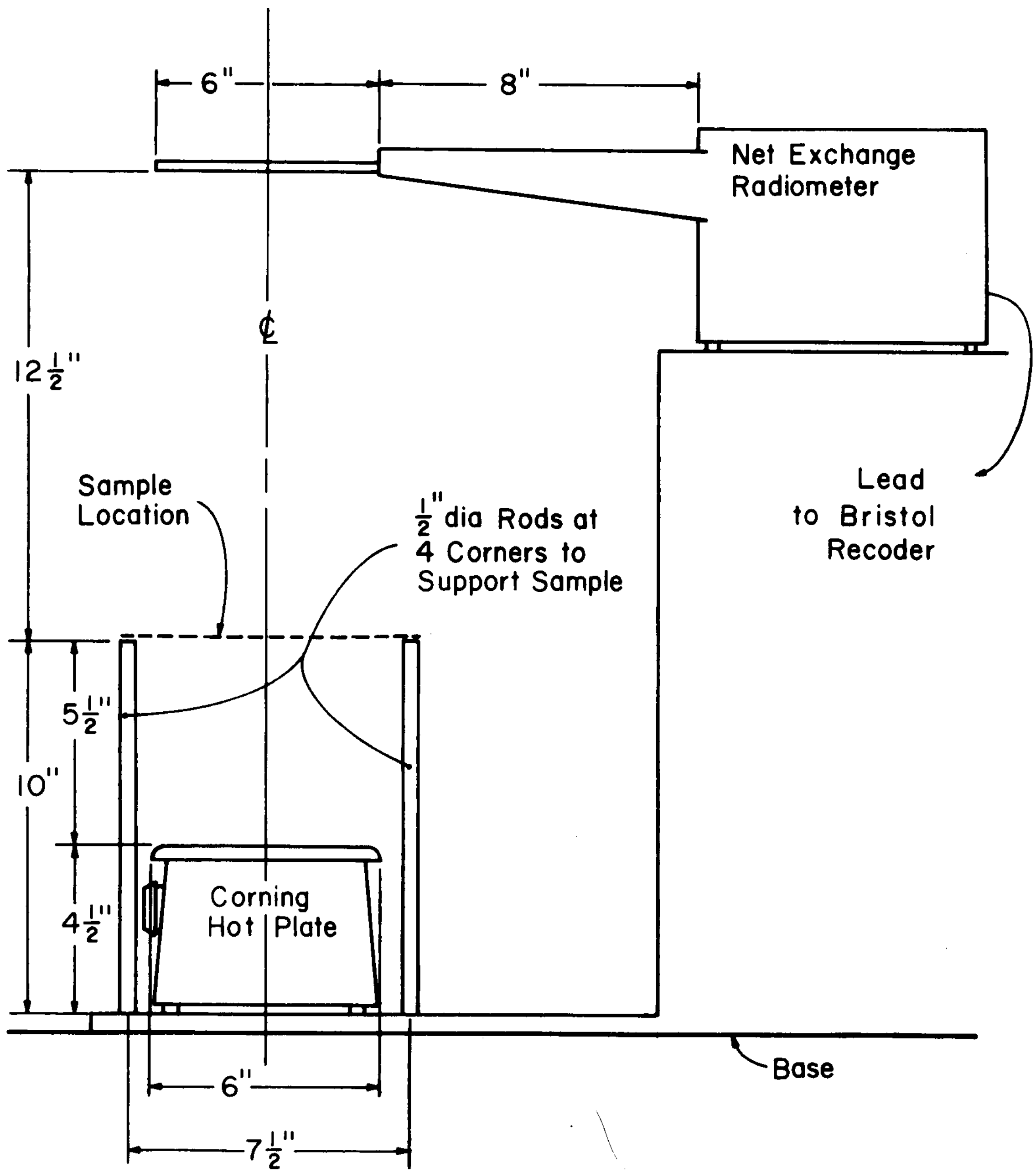



Figure 5 - Longwave Radiation Transmittance Determination Apparatus Diagram (25)

becomes more difficult to handle while at higher temperatures it expands and droops. It is recommended that any film material be installed during relatively warm weather. As the temperatures cool, the film will contract, producing a good tight cover. If the film is not tight, the cover will, of course, sag. This condition in turn may permit the wind to flutter and tear the slackened film.

It was observed that the plastic film provides reasonably good resiliancy and load bearing strength. Impact loads, however, can cause considerable damage. If the impact area is small, i.e., from BB to marble size, the resulting puncture or rip remains relatively small with mean tear diameters of only about 1-3 inches. Larger impact cross-sectional areas, however, produce shock stresses so high that the resultant attempted energy dissipation in effect shatters a large area surrounding the point of impact. Such an impact may destroy the entire panel as well as several neighboring panels depending upon the magnitude and size of the load and the energy transfer properites of the film structure. It is also suspected that such damage is more extensive at colder temperatures due to the added thermal contraction stresses already present in the film. While such damage is objectionable, it is neither as extensive nor as hazardous as would be encountered if glass were the cover material.

The Kalwal "Sunlite" fiberglass reinforced material proved to be superior to the plastic films used in terms of durability. In fact, after its installation on the full scale unit, which has a roof slope of 22 degrees, the snow load was sloughed well. The plastic material comes in roll form 54 inches wide by a variety of lengths (150 feet was used in this case). The material proved to be very easy to install using roofing nails directly into the truss top cords. No nailing strips were required as with the plastic film.

The final material tested was "UVEX" which proved to be totally inadequate for cold weather application at least by the securing techniques used in this experiment, i.e., direct nailing or nailing strips. As soon as the air temperatures dropped to below freezing, stress cracks appeared in this material and ultimately complete shattering of the material occurred.

## ELEVATION, LATITUDE, LONGITUDE, AND TEMPERATURE

### Atmospheric Pressure

Ward (16) has shown that the variation of atmospheric pressure with elevation and air temperature is given by the following equation:

$$P = [1 + \frac{1.98 \times 10^{-3} z}{T_{AK}}]^{-5.29} \qquad (40)$$

where

$T_{AK}$ is the air temperature in °K at elevation $z$. If one uses the air temperatures corresponding to the U.S. Standard atmosphere (26), then equation 40 reduces to

$$P = (1 - 6.87 \times 10^{-6} z)^{5.29} \qquad (41)$$

At a given elevation, atmopsheric pressure does not vary more than ±4% at the most, and therefore, for the purposes of this work, may be considered constant at a given elevation.

## Air Temperature

### Time Variations of Air Temperature

As mentioned earlier, air temperature lags behind solar radiation by about one month. Consequently, in the United States, January is usually the coldest month and July the warmest. However, at oceanic stations, this lag is nearer 2 months, and the temperature difference between warmest and coldest months is much less (26).

The daily variation of air temperature lags somewhat behind the daily variation of solar radiation. Air temperature begins to rise shortly after sunrise, reaches a peak 1 to 3 hr (about 1/2 hr at oceanic stations) after solar noon, and falls through the night to a minimum about sunrise (26). On cloudy days, the maximum air temperature is lower because of reduced solar radiation, and the minimum air temperature is higher because of reduced outgoing long wave radiation. The daily range in air temperature is also smaller over oceans.

### Geographic Distribution of Air Temperature

Forested areas have higher daily minimum and lower daily maximum air temperatures than do barren areas. Air temperatures in a forested area may be 2 to 4°F lower than that in comparable open country, the difference being greater in the summer (26).

The heat from a large city, which may be roughly 1/3 of the solar radiation, causes the average annual air temperatures of cities to be about 2°F higher than that of the surrounding region, and most of this difference results from higher daily minimum air temperatures in cities (26). On still, clear nights, when long wave radiation cooling is especially important, ground air temperatures may be as much as 15°F lower than air temperatures 100 feet above the ground, but a slight gradient in the opposite direction is observed on windy or cloudy nights (26).

### Air Temperature and Elevation

On the average, air temperature decreases at the rate of 3.6°F per 1,000 feet increase in elevation. The greatest variations in lapse rate are found in the layer of air just above the land surface. The earth radiates heat energy to space at a relatively constant rate that is a function of its absolute temperature (see equation 17 and the following discussion).

Under optimum surface heating conditions, the air near the ground may be heated sufficiently so that the lapse rate in the lowest layers becomes super - adiabatic (>5.4°F per 1,000 feet). On the other hand, the saturated-adiabatic lapse rate is about 3°F per 1,000 feet in the lower layers. At very low temperatures or at high altitudes, there is little difference between these 2 lapse rates because of the very small amounts of water vapor available (26).

## Elevation and Latitude

An increase in elevation of 1,000 feet is equivalent to a 300 mile movement North. Because 1°N latitude is about 69 miles, it appears that an increase in elevation of 1,000 feet is equivalent to an increase in latitude of about 4.35°N.

Average annual precipitation increases roughly 3.7 inches per year per 1,000 feet increase in elevation. According to the Brueau of Reclamation, the annual evaporation rate varies with elevation as follows (for the oil shale area of Colorado):

| Altitude, ft | Evaporation Rate, ft/yr |
|---|---|
| 4,000 | 4.6 |
| 5,000 | 4.0 |
| 6,000 | 3.5 |
| 7,000 | 3.25 |

This data can be represented by the following equation:

$$365E = 25 - 2.46 \ln z \qquad (42)$$

where

365E is the water evaporation rate, ft/yr,

z = elevation, ft.

The correlation coefficient for equation 42 is -0.995.

Using the average annual precipitation for Denver, Colorado as a base, the excess of evaporation over precipitation as a function of elevation is given in Table 13. It will be noted that at an elevation of 9,400 feet, evaporation equals precipitation. Below this elevation, evaporation exceeds precipitation and above this elevation, precipitation exceeds evaporation.

Table 13. Water Evaporation Excess and Elevation.

| | Inches per year | | |
|---|---|---|---|
| Elevation, feet | Precipitation | Evaporation (Equation 42) | Evaporation Minus Precipitation |
| 4,000 | 10.1 | 55.3 | 45.2 |
| 5,000 | 13.8 | 48.7 | 34.9 |
| 6,000 | 17.5 | 43.4 | 25.9 |
| 7,000 | 21.2 | 38.8 | 17.6 |
| 8,000 | 24.9 | 34.9 | 10.0 |
| 9,000 | 28.6 | 31.4 | 2.8 |
| 10,000 | 32.3 | 28.3 | - 4.0 |
| 11,000 | 36.0 | 25.5 | -10.5 |
| 12,000 | 39.7 | 22.9 | -16.8 |
| 13,000 | 43.4 | 20.6 | -22.8 |
| 14,000 | 47.1 | 18.4 | -28.7 |

Figure 6 is an elevation classification for Colorado. The equivalent latitude in Figure 6 is based on a latitude of 38.5°N at an elevation of 5,000 feet. Using this same basis, Table 14 gives an illustration of the climates at different elevations by listing cities at the equivalent latitude given in Figure 6. However, it should be noted that this equivalence is not completely exact from the standpoint of solar radiation.

Table 14. Latitude and Elevation Equivalents.

| Elevation, feet | City located at the equivalent latitude given in Figure 6 |
|---|---|
| 0 | Acapulco, Mexico |
| 1,000 | Guadalajara, Mexico |
| 2,000 | Brownsville, Texas |
| 3,000 | Apalachicola, Florida |
| 4,000 | Los Angeles, California |
| 5,000 | Davis, California |
| 6,000 | Lander, Wyoming |
| 7,000 | Great Falls, Montana |
| 8,000 | Calgary, Alberta, Canada |
| 9,000 | Annette Island, Alaska |
| 10,000 | Bethel, Alaska |
| 11,000 | Fairbanks, Alaska |
| 11,600 | Artic Circle |

## Air Temperature, Elevation, Latitude, and Longitude

Several least squares regressions were run on the computer using data for the cities listed in Table 15. The average annual air temperature, latitude, longitude, and elevation of these 31 cities were correlated by means of the following empirical equation:

$$T = T_o + \left(\frac{\partial T}{\partial °N}\right)(°N) + \left(\frac{\partial T}{\partial °W}\right)(°W) + \left(\frac{\partial T}{\partial z}\right)(z) \qquad (43)$$

where

$T$ = average annual air temperature, °F,

$T_o$ = average annual air temperature at 0 feet elevation, 0°N, 0°W, °F,

°N = degrees north latitude,

°W = degrees west longitude,

$z$ = elevation, feet.

The results of these least squares fits are given in Table 16. It should be noted that for the cities listed in Table 15,

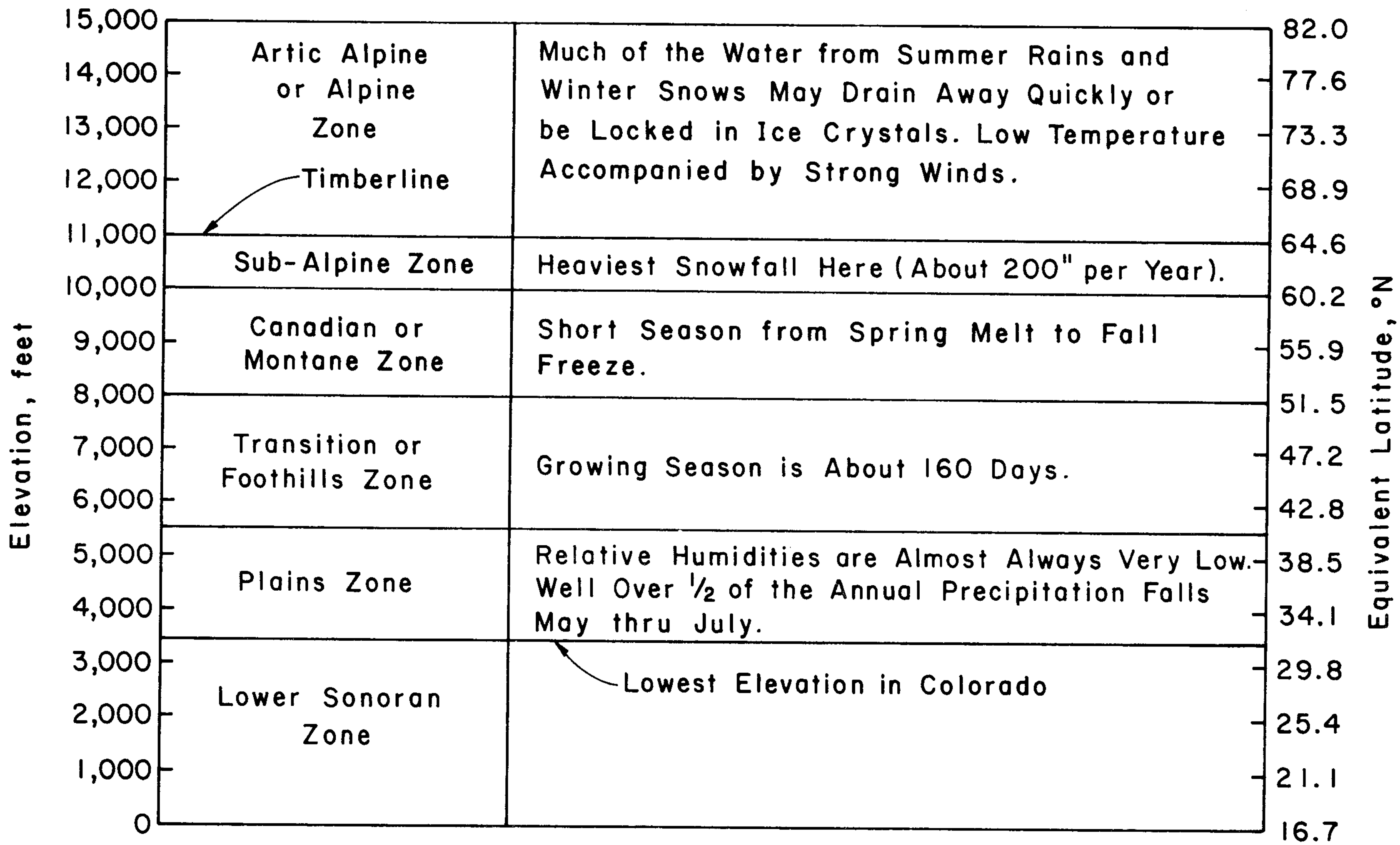
$40.1 \leq T \leq 75.1°F$

$25.80 \leq °N \leq 58.37°$

$70.32 \leq °W \leq 134.58°$

$3 \leq z \leq 6{,}126$ feet.

From the previous discussion, it appears that the ratio $\partial T/\partial °N$ should have a value of about (3.6/4.35=) 0.83 °F/°N, whereas all the values given in Table 16 are greater than this. Also from the foregoing narrative, one would expect that




This Figure is Based on a Latitude of 38.5° N at an Elevation of 5000'

Figure 6- Elevation Classification for Colorado.

Table 15. Cities Used in Least Squares Analysis.

| | |
|---|---|
| Juneau, Alaska | Sault Ste. Marie, Michigan |
| Phoenix, Arizona | Kansas City, Missouri |
| Los Angeles, California | Reno, Nevada |
| San Francisco, California | Albuquerque, New Mexico |
| Washington, D. C. | Buffalo, New York |
| Jacksonville, Florida | New York, New York |
| Miami, Florida | Bismark, North Dakota |
| Atlanta, Georgia | Oklahoma City, Oklahoma |
| Boise, Idaho | Portland, Oregon |
| Chicago, Illinois | Pittsburgh, Pennsylvania |
| Indianapolis, Indiana | Nashville, Tennessee |
| Des Moines, Iowa | El Paso, Texas |
| Louisville, Kentucky | Salt Lake City, Utah |
| New Orleans, Louisana | Seattle-Tacoma, Washington |
| Portland, Maine | Spokane, Washington |
| | Cheyenne, Wyoming |

$- 3 \times 10^{-3} \leq \partial T/\partial z \leq - 5.4$ °F/ft with an average value of $\partial T/\partial z = = - 3.6 \times 10^{-3}$ °F/ft, but all the values listed in Table 16 are less than expected.

Nevertheless, equation 43 can do a good job of predicting T from °N, °W, and z. For example, for Cheyenne, Wyoming, z = 6,126 feet, °N = 41.15°, °W = 104.82°, and the value of T computed from equation 43 using the results of trial 1 in Table 16 is 45.9°F compared with the observed value of T = 45.9°F. As a consequence, the trial 1 values listed for $\partial T/\partial°N$ and $\partial T/\partial°W$ will be used to correct for slight differences in experimental site location. Therefore the following equation will be utilized in this report:

$$T = 107.3 - 1.352°N + 0.142°W - 3.6 \times 10^{-3} z \qquad (44)$$

## Predicting the Date of Ice Breakup

Williams (27) presented data that may be useful in estimating the end of ice cover in wastewater evaporation ponds. His data is presented in columns 1-4 of Table 17. Column 5 corresponds to the date given in column 4 (January 1 = 1). Column 6 is 105 minus column 2. Because there are 360° longitude total and 365 days in a calendar year, then 1° longitude ≅ 1 day. Column 7 is column 5 minus column 6. The values in column 7 are the dates at which ice breakup should occur at a longitude of 105°W and the given latitude. A least squares analysis was made of the data in columns 1 and column 7 with the following result (correlation coefficient = 0.98):

$$\text{day of the year at } 105°W = - 195 + 6.07°N \qquad (45)$$

In other words, for a longitude of 105°W, equation 45 will give the date of ice breakup for a given latitude. In order to obtain this date for other longitudes, one should subtract 1 day for each °W of

Table 16. Regression Coefficients for Equation 43.

| Trial (1) | $T_o$, °F (2) | $\frac{\partial T}{\partial °N}$, °F/°N (3) | $\frac{\partial T}{\partial °W}$, °F/°W (4) | $\partial T/\partial z$ °F/foot (5) | Correlation coefficient (6) | Cities listed in Table 15 that were not included in the given trial (7) |
|---|---|---|---|---|---|---|
| 1 | 96.3 | -1.352 | 0.142 | $-1.59 \times 10^{-3}$ | 0.96 | all 31 were used |
| 2 | 95.2 | -1.482 | 0.218 | $-2.12 \times 10^{-3}$ | 0.98 | Los Angeles San Francisco |
| 3 | 94.5 | -1.495 | 0.230 | $-1.96 \times 10^{-3}$ | 0.98 | Los Angeles San Francisco Reno, Nevada |
| 4 | 104.0 | -1.212 | 0 | $-1.1 \times 10^{-3}$ | 0.92 | all 31 were used |
| Values that will be used in this report | 107.3 | -1.352 | 0.142 | $-3.6 \times 10^{-3}$ | | The value of $T_o$ corresponds to that of Denver, Colorado located at 39.7°N, 105°W |

Table 17. Location, Elevation, and Date of Lake Ice Breakup.

| Latitude, °N (1) | Longitude, °W (2) | Elevation, feet (3) | Average date of Lake ice Breakup (4) | Day of the year (5) | 105-°W (6) | day of the year at 105°W (5-6) (7) |
|---|---|---|---|---|---|---|
| 45.6 | 77 | 571 | April 25 | 115 | 28 | 87 |
| 45.6 | 71 | 1,362 | April 30 | 120 | 34 | 86 |
| 46.1 | 65 | 248 | April 25 | 115 | 40 | 75 |
| 46.5 | 81 | 850 | April 27 | 117 | 24 | 93 |
| 48.4 | 71 | 335 | May 9 | 129 | 34 | 95 |
| 53.2 | 71 | 1,759 | June 13 | 164 | 34 | 130 |
| 53.8 | 101 | 890 | May 12 | 132 | 4 | 128 |
| 54.9 | 67 | 1,681 | June 11 | 162 | 38 | 124 |
| 54.9 | 99 | 764 | May 26 | 146 | 6 | 140 |
| 57.9 | 102 | 1,150 | June 5 | 156 | 3 | 153 |
| 60.1 | 129 | 2,248 | May 25 | 145 | -24 | 169 |
| 61.1 | 101 | 1,065 | July 8 | 189 | 4 | 185 |
| Average | | 1,077 | | | | |

105°W from the value given by equation 45. This result is qualitatively in agreement with equation 44.

In summary then, equation 45 can be rewritten as follows:

$$\text{Date of Ice Breakup (day of the year)} = (105 - {}^\circ\text{W}) - 195 + 6.07^\circ\text{N} \quad (46)$$

The Fort Collins site is located at 40.6°N, 105.15°W. Substituting these values into equation 46 gives a day of the year of 51 or February 20. It was actually observed at this site that the ice thickness on the uncovered unit became zero on this date.

The average elevation for the observations listed in Table 17 is 1,000 feet, while the elevation of the Fort Collins site is 5,200 feet. Therefore, it appears that equation 46 is applicable for elevations up to at least 5,200 feet. However, observations made at higher elevations indicate that some correction for elevations above 5,200 feet is in order. Therefore, using the data from columns 3 and 5 of Table 16 (Trial 1), it appears that one should add to the actual latitude 1.18°N per 1,000 feet in excess of 5,200 feet. Therefore, equation 46 can be rewritten

$$\text{Date of Ice Breakup (day of the year)} = (105 - {}^\circ\text{W}) - 195 + 6.07\left[{}^\circ\text{N} + 1.18\left(\frac{z - 5{,}200}{1{,}000}\right)\right] \quad (47)$$

In summary then, equation 46 is used for elevations below 5,200 feet, and equation 47 is used for elevations above 5,200 feet.

## EXPERIMENTAL SITE DESCRIPTIONS

4 experimental sites were used to obtain the data for this project. A description of each site follows.

### Engineering Research Center (ERC), Foothills Campus, Colorado State University (CSU), Fort Collins, Colorado

Elevation 5,200 feet
Latitude 40.6°N
Longitude 105.15°W

This site will be referred to as the Fort Collins site. 4 experimental scale wastewater evaporators were constructed at this location about 15 feet apart:

1. Experimental wastewater evaporator (this will be referred to as the covered unit).
2. Same as 1 except sides were also enclosed with transparent material (this will be referred to as the enclosed unit).
3. Same as 1 except that while it is also covered by the same structure as in all the other experimental wastewater evaporators, no transparent material was used. This will be referred to as the structural unit.
4. Same as 1 except that it is not covered at all. This will be referred to as the uncovered unit.

Unit 1 (the covered unit) is the same as the experimental wastewater evaporators constructed at the other 3 experimental sites. Unit 2 (the enclosed unit) was constructed to determine the effects of totally enclosing the experimental wastewater evaporator. Unit 3 (the structural unit) was constructed to observe the effects of structural shading on performance. Unit 4 (the uncovered unit) was built to establish a base with which to compare evaporation rates from the other units.

The centerline orientation of the roof peak of these units was 13° South of East. Continuous recording instrumentation was installed at this site which is adjacent to the CSU Atmospheric Science Department weather station which includes a standard 4 foot diameter evaporation pan.

Figure 7 is a photograph of the Fort Collins site looking Southwest. The trailer housed the continuous recording equipment. Elements of the CSU weather station are visible including the wind velocity tower. From left to right, the units shown are the structural unit (#3), the covered unit (#1), and the enclosed unit (#2).

### Red Feather Lakes, Colorado

Elevation: 8,180 feet
Latitude: 40.8°N
Longitude: 105.56°W

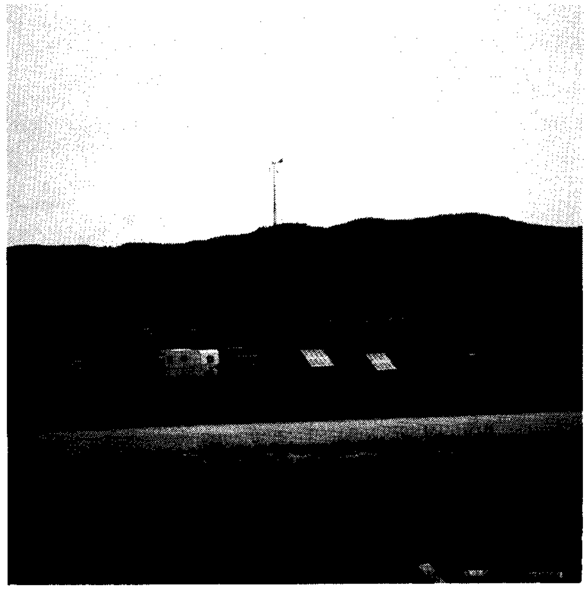


Figure 7. Fort Collins Site Experimental Wastewater Evaporators.

This site will be referred to as the Red Feather site. In addition to the experimental wastewater evaporator, a full scale wastewater evaporator was constructed at this site, and it will be referred to as the full scale unit. Orientation of the roof peak centerlines at this site was 27° East of North for the experimental unit and 21° East of North for the full scale unit.

Figure 8 is a sketch of the full scale unit. Figure 9 is the cabin served by the full scale unit (the cabin was used by 2 families). Figure 10 is a view of the full scale unit looking west from the cabin balcony. Figure 11 is a picture of the full scale unit during construction and before the transparent material in the roof was changed. Pond liner is actually black (although it appears white in the photograph) nylon reinforced Butyl rubber liner 1/32 inch thick (the seams in this liner failed after the experimental observations were completed). The structural members supporting the roof covered with transparent material were standard house roof trusses that have an angle of 22.5° with the horizontal. An extra roof truss (upside down) appears in the foreground. View is looking southwest. Figure 12 is the same view after changing the transparent material (chlorinator tubes are visible in the lower left side of the photograph). Figure 13 is a picture of the full scale unit looking Northwest. Figure 14 is the experimental unit at the Red Feather site.

<u>Storm Mountain Near Drake, Colorado</u>

Elevation: 8,570 feet
Latitude: 40.4°N
Longitude: 105.39°W

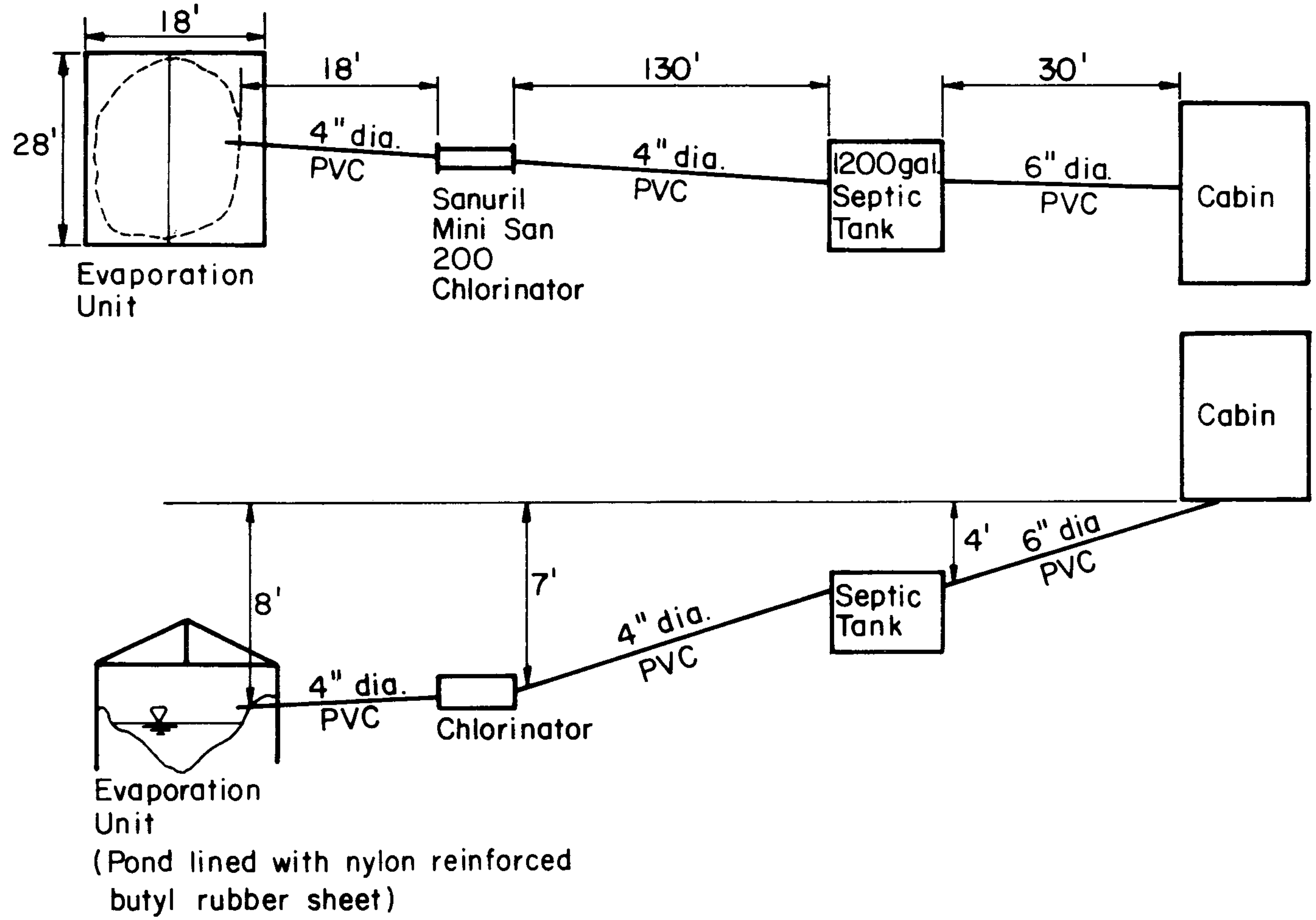



Figure 8 - Full Scale Unit at Red Feather Site.

Figure 9. Cabin Served by the Full Scale Unit.

Figure 10. View of Full Scale Unit from Cabin.

Figure 11. Full Scale Unit During Construction.

Figure 12. Full Scale Unit after Changing Transparent Material.

Figure 13. Full Scale Unit Looking Northwest.

Figure 14. Experimental Unit at the Red Feather Site.

This will be referred to as the Storm Mountain Site. The unit's roof peak centerline has an orientation of 15° East of North. Figure 15 is a photograph of this unit looking East.

Figure 15. Storm Mountain Site.

Near Breckenridge, Colorado

Elevation: 10,665 feet
Latitude: 39.5°N
Longitude: 106.05 °W

This site was about 4 miles east of Breckenridge, Colorado, and will be referred to as the Breckenridge site. The orientation of the roof peak centerline is 17° East of North. Figure 16 is a picture of this unit.

## Comparison of Experimental Sites

With the exception of the Fort Collins site, it is clear from the photographs in Figures 10, 11, 12, 13, 14, 15, and 16 that the units at all the other 3 sites were partially shaded from the sun at certain times of the day, and, as a result, the evaporation rates observed at these sites will be less than would be observed if the units were completely unshaded by surrounding trees and rocks like the experimental units at the Fort Collins Site. On the other hand, the conditions at these higher 3 sites are probably relatively typical of the conditions that will actually be encountered.

Perhaps the best way to summarize the climate at these 4 sites is by the annual average air temperature. Equation 44 and the values in columns 2, 3, and 4 were used to calculate the annual average air

Figure 16. Breckenridge Experimental Unit.

temperatures given in column 5 of Table 18. Equation 40 and columns 2 and 5 were used to calculate the average annual atmospheric pressure values given in column 6 of Table 18. Equation 47 and the values in columns 2, 3, and 4 were used to calculate the date of ice breakup given in columns 7-9.

Table 18. Comparison of Experimental Sites.

| Site (1) | Z, ft (2) | °N (3) | °W (4) | T, °F (5) | P, atm (6) | Date of Ice Breakup (day of the year) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Day of the year (7) | Date: Month (8) | Date: Day of the Month (9) |
| Fort Collins | 5,200 | 40.6 | 105.15 | 48.6 | 0.827 | 51 | Feb. | 20 |
| Red Feather | 8,180 | 40.8 | 105.56 | 37.7 | 0.740 | 73 | March | 14 |
| Storm Mountain | 8,570 | 40.4 | 105.39 | 36.8 | 0.729 | 74 | March | 15 |
| Breckenridge | 10,665 | 39.5 | 106.05 | 30.6 | 0.674 | 83 | March | 24 |

## EXPERIMENTAL SITE INSTALLATIONS

Standard steel stock watering tanks constructed of galvanized steel and circular in shape were used to contain the water to be evaporated in every case except for the full scale unit at the Red Feather site. These tanks were 6 feet in diameter and 2 feet deep. Evidence has been presented that indicates that the water evaporation rate is almost independent of depth for depths greater than about one inch, at least for uninsulated solar stills (28). In addition, insulation appears to be of little value for depths greater than about 6 inches. All of these 6 foot tanks were placed on ground leveled for that purpose, and the sides were above ground level.

These tanks were covered with a square roof structure 10 feet by 10 feet, providing a minimum of 2 feet overhang on all sides. 6 supporting posts were used to support the roof structure. Standard W trusses were used in the roof on 24 inch centers. The top of the trusses made an angle of 45° with the horizontal. Additional details on these units are available elsewhere (29).

### Full Scale Unit at the Red Feather Site

A pond was excavated at this site, and following installation of an impermeable liner, the contour map shown in Figure 17 was developed. The volume of water contained in this pond is related to the depth of the pond by an equation of the form,

$$V = n\,H^{m} \tag{48}$$

where $n$ and $m$ are constants (the indicated magnitude of $m$ is about 3),

$H$ = depth of water at the deepest part of the wastewater evaporation pond, feet.

Clearly,

$$\frac{dV}{dH} = A = n\,m\,H^{m-1} \tag{49}$$

and

$$D = \frac{V}{A} = \frac{H}{m} \tag{50}$$

Equation 49 can be written

$$\ln A = \ln (nm) + (m-1) \ln H \tag{51}$$

A least squares analysis using equation 51 and the data contained in Figure 17 gave a correlation coefficient of 0.9999 with values for the constants in equations 48, 49, 50, and 51 of $n = 43.1$ and $m = 1.869$. Consequently, equations 48, 49, and 50 for the full scale unit at the Red Feather Site become

$$V = 43.1\,H^{1.869} \tag{52}$$

$$A = 80.6\,H^{0.869} \tag{53}$$

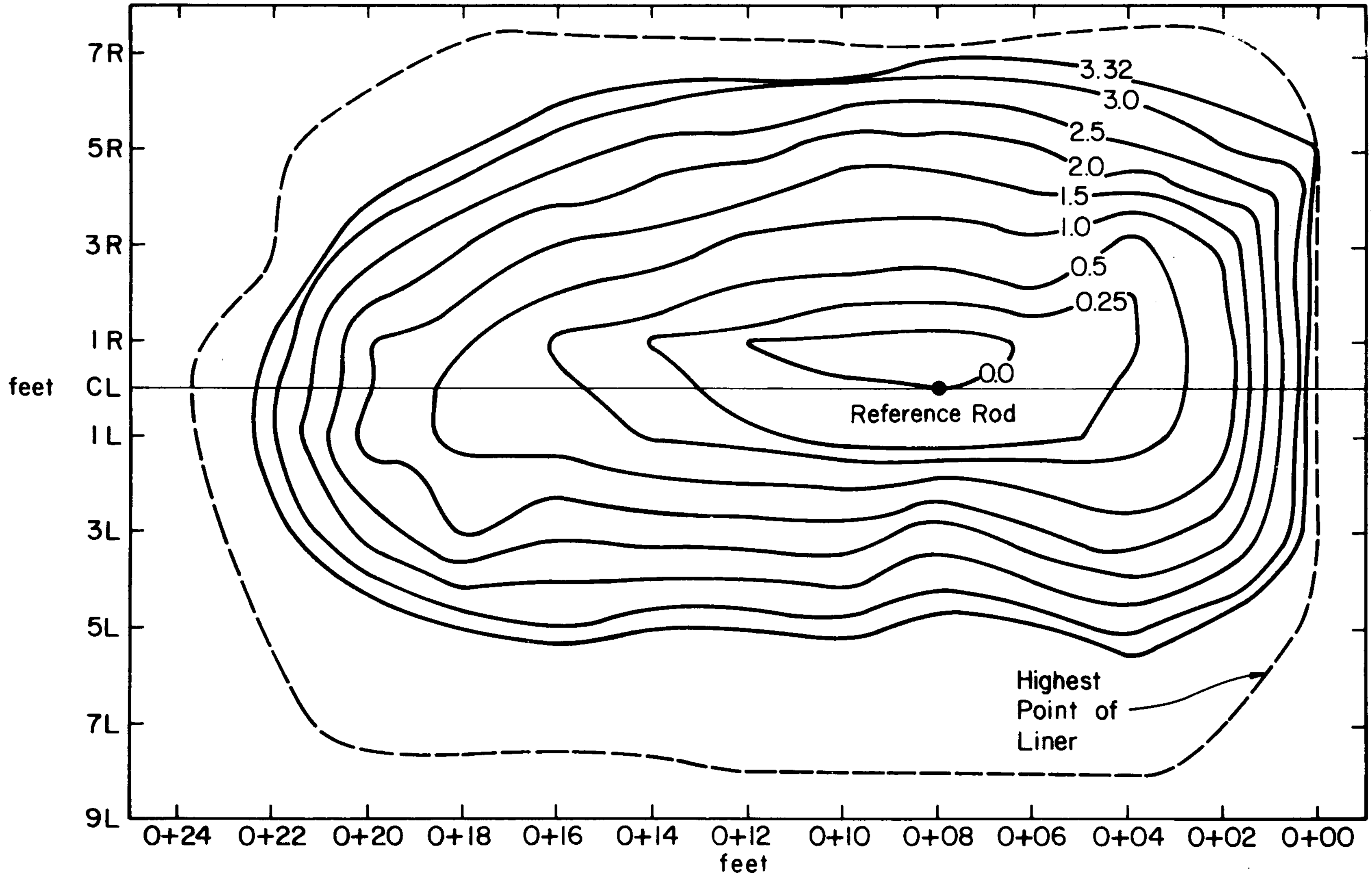



Figure 17 - Contour Map of the Full Scale Unit at the Red Feather Site (25)

$$D = H/1.869 \qquad (54)$$

From these 3 equations and Figure 17, it is clear that at the maximum pond depth of H = 3.32 feet, the volume is 406 $ft^3$ (3,037 gallons), the surface area is 229 $ft^2$, and the effective depth is 1.78 feet.

The impermeable pond liner used was 1/32 inch thick nylon reinforced butyl rubber which proved completely satisfactory during the period of this project. However, a few months following completion of the experimental observations, the seams in this liner failed.

The roof covering this pond was 18 feet wide by 28 feet long. Commercially available roof tursses were used on 2 foot centers. The roof had a slope of 5 vertical to 12 horizontal (22.5° was the angle between the horizontal and the roof).

Summary of Experimental Site Installations

A summary of the 8 experimental site installations is given in Table 19. Units 1, 6, 7, and 8 were identical. With the exception of unit 5, the steel water tank in the remaining 7 units were identical.

Table 19. Summary of Experimental Site Installations.

| |
|---|
| Fort Collins Site |
| 1. Covered Unit |
| 2. Enclosed Unit |
| 3. Structural Unit |
| 4. Uncovered Unit |
| Red Feather Site |
| 5. Full Scale Unit |
| 6. Covered Unit |
| Storm Mountain Site |
| 7. Covered Unit |
| Breckenridge Site |
| 8. Covered Unit |

## OBSERVED WATER EVAPORATION DATA

Table 20 is a blank data form used for recording observed data. Columns 1-4 are self explanatory. Observations in columns 5 and 6 are from a maximum-minimum thermometer located at the bottom of the water. The date and time corresponds to the date and time that the maximum-minimum thermometer was read. Data appears in columns 7, 8, 12, and 13 only during those periods when the unit was enclosed. Columns 7 and 8 are air temperatures also taken from a maximum-minimum thermometer. Columns 9 and 10 are outdoor air temperatures taken from a maximum-minimum thermometer. Column 11 is the water temperature at the date and time indicated. Columns 12 and 14 are dry bulb air temperatures, and columns 13 and 15 are wet bulb temperatures. Column 16 is the atmospheric pressure in inches of Mercury. Column 17 is the actual water depth (for the full scale unit, it is H). Columns 18 and 19 are the

Table 20. Observed Data Form Used.

| | | | | BEFORE ADDING WATER | | | | | | | | | | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | | | TIME OF DAY | WATER | | INSIDE | | AIR | | | INSIDE | | AIR | | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | | SNOW DEPTH |
| | MONTH | DAY | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | T, °F, WATER | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | | | | T, WATER, °F | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
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LOCATION:

same as columns 17 and 11, respectively, except that columns 18 and 19 report observations made after water is added to replace that lost to evaporation. The observations reported in columns 1 through 17 were made before any water was added. If no water was added, then the values in columns 18 and 19 will be identical to those in columns 17 and 11, respectively. Column 20 was used for various other observations such as snow depth, ice thickness, miles of wind, water meter readings, etc.

The data form illustrated in Table 20 was developed at the outset of the project, about 4 years before this report was written. Consequently some minor changes have been made in the symbols during this time interval. Table 21 lists these changes.

Table 21. Symbols Used on Data Form and in This Report.

| Columns | Symbol used on Data Form (Table 20) | | Symbol used in this report | |
|---|---|---|---|---|
| | Symbol | Units | Symbol | Units |
| 11 and 19 | $T$ | °F | $T_w$ | °F |
| 12 and 14 | $T_a$ | °F | $T$ | °F |
| 13 and 15* | $T_w$ | °F | $T_{wb}$ | °F |
| 16 | P | in. Hg | P | atm |
| 17 and 18 | D | feet | ** | feet |

* Wet-bulb temperature, °F
**For all but the full scale unit, the water depth is actually the effective depth of the surface water body, D. For the full scale unit, the water depth is H.

Tables 22 through 32 contain observed data from the 8 units at the 4 sites. Table 33 was constructed using the data in column 16 of Tables 24, 30, 31, and 32. The coefficient of variation is the ratio of the standard deviation to the mean, column 4 divided by column 3. Column 6 was obtained by dividing column 3 by 29.92 In. Hg. It will be noted that both the standard deviation and coefficient of variation appear to increase with elevation. The calculated values of atmospheric pressure are, on the average, about 1% below the average of the observed atmospheric pressure values.

Values of the surface water temperature after adding water are not reported in Table 23 because the mixing that took place when water was added to replace that lost by evaporation resulted in uniform water temperatures throughout the steel water tanks.

As the data in Table 24 (page 4) shows, the sides of the enclosed unit at the Fort Collins Site were opened on February 28, 1975, so that water evaporation with a Kalwall transparent roof cover could be directly compared with that from a Uvex transparent roof cover. The results of this comparison show that during this time period February 28, 1975, through June 19, 1975, the water evaporation from the Kalwall unit was

Table 22. Observed Data.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | BEFORE ADDING WATER: WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 5 | 19 | 15:15 | | | | | 87 | 12 | 65 | | | 74 | 57 | 24.86 | 1.612 | 1.612 | 65 | 0 |
| 1973 | 5 | 25 | 17:39 | 66 | 55 | | | 86 | 44 | 60 | | | 70 | 51 | 24.42 | 1.477 | 1.477 | 60 | 0 |
| 1973 | 6 | 28 | 9:30 | 78 | 44 | | | 102 | 44 | 68 | | | 77 | 63 | 24.95 | 0.763 | 1.95 | 64 | 0 |
| 1973 | 7 | 25 | 13:40 | 80 | 58 | | | 107 | 50 | 68 | | | 80 | 61 | 25.21 | 1.26 | 1.26 | 68 | 0 |
| 1973 | 8 | 7 | 10:40 | 77 | 62 | | | 90 | 56 | 66 | | | 73 | 62 | 24.86 | 1.06 | 1.06 | 66 | 0 |
| 1973 | 8 | 10 | 11:10 | 75 | 64 | | | 94 | 54 | 69 | | | 84 | 66 | 24.92 | 1.00 | 1.76 | 68 | 0 |
| 1973 | 8 | 17 | 8:45 | 76 | 64 | | | 100 | 52 | 68 | | | 73 | 62 | 24.97 | 1.59 | 1.59 | 68 | 0 |
| 1973 | 9 | 4 | 13:47 | 78 | 52 | | | 100 | 39 | 66 | | | 79 | 59 | 25.08 | 1.15 | 1.93 | 64 | 0 |
| 1973 | 10 | 23 | 9:15 | 70 | 42 | | | 89 | 32 | 52 | | | 57 | 43 | 24.79 | 1.19 | 1.90 | 51 | 0 |
| 1973 | 11 | 13 | 15:40 | 58 | 39 | | | 83 | 22 | 53 | | | 56 | 47 | 24.64 | 1.61 | 1.61 | 53 | 0 |
| 1973 | 11 | 28 | 9:20 | 52 | 34 | | | 63 | 18 | 39 | | | 39 | 34 | 24.91 | 1.48 | 1.48 | 39 | 1.75 |
| 1973 | 12 | 3 | 11:40 | 45 | 38 | | | 63 | 23 | 40 | | | 40 | 33 | 24.78 | 1.46 | 1.46 | 40 | 0.125 |
| 1973 | 12 | 11 | 14:52 | 42 | 36 | | | 61 | 2 | 41 | | | 50 | 40 | 24.65 | 1.40 | 1.40 | 41 | 0 |

LOCATION: Fort Collins Site, Covered Unit (page 1 of 4 pages).

Table 22. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 12 | 17 | 10:00 | 43 | 34 | | | 57 | 21 | 40 | | | 47 | 33 | 24.72 | 1.34 | 1.34 | 40 | 0.06 |
| 1973 | 12 | 21 | 14:00 | 41 | 35 | | | 56 | 3 | 37 | | | 44 | 37 | 24.66 | 1.33 | 1.33 | 37 | 2.5 |
| 1974 | 1 | 14 | 14:00 | 32 | 32 | | | 50 | -14 | 32 | | | 42 | 34 | 24.78 | 1.32 | 1.32 | 32 | 15.84 |
| 1974 | 1 | 21 | 13:00 | 40 | 32 | | | 71 | 27 | 35 | | | 35 | 32 | 24.63 | 1.20 | 1.20 | 35 | 7.5 |
| 1974 | 2 | 11 | 15:40 | 45 | 33 | | | 62 | 10 | 42 | | | 60 | 43 | 24.65 | 1.05 | 1.05 | 42 | 0.75 |
| 1974 | 2 | 19 | 9:45 | 46 | 37 | | | 61 | 19 | 40 | | | 39 | 33 | 24.35 | 0.99 | 0.99 | 40 | 0.125 |
| 1974 | 3 | 1 | 10:00 | 50 | 37 | | | 66 | 11 | 43 | | | 62 | 44 | 24.67 | 0.88 | 1.82 | 44 | 0 |
| 1974 | 4 | 15 | 12:30 | 58 | 34 | | | 76 | 14 | 45 | | | 60 | 44 | 24.92 | 1.12 | 1.12 | 45 | 0 |
| 1974 | 4 | 22 | 9:15 | 62 | 40 | | | 74 | 26 | 42 | | | 47 | 39 | 24.99 | 1.01 | 1.01 | 42 | 0 |
| 1974 | 4 | 26 | 9:30 | 68 | 42 | | | 85 | 37 | 62 | | | 68 | 58 | 24.71 | 0.95 | 0.95 | 62 | 0 |
| 1974 | 5 | 2 | 14:00 | 70 | 45 | | | 83 | 34 | 64 | | | 75 | 53 | 24.69 | 0.84 | 1.64 | 58 | |
| 1974 | 5 | 10 | 11:00 | 68 | 47 | | | 84 | 39 | 61 | | | 71 | 55 | 24.54 | 1.48 | 1.48 | 61 | |

LOCATION: Fort Collins Site, Covered Unit (page 2 of 4 pages).

Table 22. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Miles of Wind |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 5 | 17 | 10:00 | 64 | 46 | | | 82 | 37 | 58 | | | 58 | 55 | 24.74 | 1.29 | 1.29 | 58 | 2,264.6 |
| 1974 | 5 | 28 | 14:30 | 71 | 50 | | | 92 | 40 | 67 | | | 88 | 59 | 24.71 | 1.06 | 1.81 | 62 | 3,062.9 |
| 1974 | 6 | 29 | 11:30 | 77 | 43 | | | 99 | 39 | 68 | | | 91 | 61 | 24.88 | 1.07 | 1.71 | 67 | 5,444.6 |
| 1974 | 7 | 16 | 10:30 | 79 | 65 | | | 99 | 50 | 71 | | | 82 | 66 | 24.92 | 1.25 | 1.68 | 70 | 6,489.7 |
| 1974 | 7 | 29 | 10:00 | 82 | 62 | | | 95 | 52 | 64 | | | 72 | 62 | 25.18 | 1.38 | 1.38 | 64 | 7,215.5 |
| 1974 | 8 | 8 | 11:30 | 77 | 60 | | | 89 | 47 | 65 | | | 74 | 58 | 24.84 | 1.19 | 1.19 | 65 | 7,754.1 |
| 1974 | 9 | 9 | 11:55 | 77 | 48 | | | 98 | 38 | 64 | | | 90 | 64 | 25.0 | 0.63 | 1.84 | 66 | 9,675.7 |
| 1974 | 10 | 19 | 12:10 | 72 | 43 | | | 97 | 29 | 57 | | | 72 | 54 | 25.1 | 1.16 | 1.96 | 62 | 1,872.3 |
| 1974 | 12 | 15 | 14:30 | 62 | 38 | | | 80 | 4 | 40 | | | 41 | 31 | 24.7 | 1.40 | 1.40 | 40 | 5,308.4 |
| roof gone during this interval. It was replaced with Uvex. | | | | | | | | | | | | | | | | | | | |
| 1975 | 2 | 28 | 17:00 | 50 | 32 | | | 68 | - 6 | 50 | | | 57 | 43 | 24.9 | 1.00 | 1.00 | 50 | 2,114.6 |
| 1975 | 4 | 13 | 11:00 | 58 | 33 | | | 77 | 0 | 42 | | | 45 | 40 | 24.8 | 0.68 | 1.64 | 44 | 6,432.3 |
| 1975 | 5 | 17 | 8:00 | 77 | 39 | | | 86 | 30 | 58 | | | 65 | 53 | 24.75 | 1.01 | 1.21 | 64 | 9,919.4 |

LOCATION: Fort Collins Site, Covered Unit (page 3 of 4 pages).

Table 22. Continued

| | | | | BEFORE ADDING WATER | | | | | | | | | | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | MONTH | DAY | TIME OF DAY | WATER | | INSIDE | | AIR | | T, °F, WATER | INSIDE | | AIR | | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | T, WATER, °F | Miles of Wind |
| | | | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | | | | | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1975 | 6 | 19 | 15:30 | 73 | 42 | | | 89 | 37 | 67 | | | 72 | 56 | 24.8 | 0.77 | 0.77 | 67 | 2,197.4 |

LOCATION: Fort Collins Site, Covered Unit (page 4 of 4 pages).

Table 23. Water Surface Temperatures, Fort Collins Site, Covered Unit.

| Year | Month | Day | Time of day | Water surface temperature, °F | water surface temperature during period between dates shown, °F max | min |
|---|---|---|---|---|---|---|
| 1973 | 12 | 11 | 14:52 | 44 | | |
| | | | | | 65 | 38 |
| 1974 | 4 | 22 | 9:15 | 47 | | |
| | | | | | 72 | 44 |
| 1974 | 4 | 26 | 9:30 | 60 | | |
| | | | | | 70 | 43 |
| 1974 | 5 | 2 | 14:00 | 63 | | |
| | | | | | 68 | 45 |
| 1974 | 5 | 10 | 11:00 | | | |
| | | | | | 67 | 42 |
| 1974 | 5 | 17 | 10:00 | 57 | | |
| | | | | | 73 | 47 |
| 1974 | 5 | 28 | 14:30 | 66 | | |
| | | | | | 79 | 42 |
| 1974 | 6 | 29 | 11:30 | 69 | | |
| | | | | | 79 | 61 |
| 1974 | 7 | 16 | 10:30 | 71 | | |
| | | | | | 80 | 58 |
| 1974 | 8 | 8 | 11:30 | 66 | | |
| | | | | | 82 | 45 |
| 1974 | 9 | 9 | 11:55 | 70 | | |
| | | | | | 75 | 40 |
| 1974 | 10 | 19 | 12:10 | 70 | | |
| | | | | | 65 | 26 |
| 1974 | 12 | 15 | 14:30 | 31 | | |

Table 24. Observed Data.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 2 | 2 | 12:10 | 40 | 40 | 52 | 52 | 43 | 43 | 40 | 51 | 43 | 42 | 36 | 25.00 | 1.685 | 1.685 | 40 | 0 |
| 1973 | 2 | 8 | 13:35 | 44 | 38 | 66 | 9 | 56 | 8 | 40 | 33 | 29 | 24 | 23 | 25.11 | 1.662 | 1.662 | 40 | 0.5 |
| 1973 | 2 | 15 | 13:31 | 42 | 38 | 65 | 12 | 56 | 10 | 40 | 48 | 37 | 44 | 35 | 24.99 | 1.651 | 1.651 | 40 | 0 |
| 1973 | 2 | 22 | 14:05 | 46 | 39 | 71 | 18 | 61 | 15 | 46 | 60 | 44 | 51 | 39 | 24.92 | 1.594 | 1.594 | 46 | 0 |
| 1973 | 3 | 1 | 10:50 | 50 | 42 | 77 | 27 | 61 | 25 | 47 | 63 | 48 | 57 | 45 | 24.87 | 1.548 | 1.548 | 47 | 0 |
| 1973 | 3 | 9 | 9:19 | 50 | 40 | 70 | 24 | 62 | 21 | 42 | 47 | 41 | 38 | 35 | 24.77 | 1.499 | 1.499 | 42 | 0 |
| 1973 | 3 | 21 | 9:09 | 53 | 40 | 78 | 22 | 63 | 20 | 43 | 42 | 38 | 40 | 36 | 24.66 | 1.429 | 1.429 | 43 | 0 |
| 1973 | 4 | 3 | 9:22 | 50 | 40 | 72 | 25 | 58 | 26 | 40 | 39 | 33 | 37 | 31 | 25.14 | 1.334 | 1.334 | 40 | 0 |
| 1973 | 5 | 19 | 15:00 | 72 | 40 | 94 | 15 | 87 | 12 | 72 | 77 | 58 | 74 | 57 | 24.86 |  | 1.683 | 72 | 0 |
| 1973 | 5 | 25 | 17:40 | 73 | 63 | 95 | 48 | 86 | 44 | 68 | 72 | 55 | 70 | 51 | 24.42 | 1.607 | 1.607 | 68 | 0 |
| 1973 | 6 | 28 | 9:30 | 84 | 56 | 110 | 44 | 102 | 44 | 77 | 92 | 68 | 77 | 63 | 24.95 | 1.169 | 1.86 | 75 | 0 |
| 1973 | 7 | 25 | 13:40 | 86 | 64 | 118 | 53 | 107 | 50 | 78 | 89 | 67 | 80 | 61 | 25.21 | 1.43 | 1.43 | 78 | 0 |
| 1973 | 8 | 7 | 10:40 | 81 | 68 | 102 | 55 | 90 | 56 | 73 | 85 | 68 | 73 | 62 | 24.86 | 1.26 | 1.26 | 73 | 0 |

LOCATION: Fort Collins Site, Enclosed Unit (page 1 of 4 pages).

Table 24. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 8 | 10 | 11:10 | 80 | 71 | 121 | 57 | 94 | 54 | 75 | 90 | 69 | 84 | 66 | 24.92 | 1.22 | 1.91 | 70 | 0 |
| 1973 | 8 | 17 | 8:45 | 84 | 69 | 108 | 57 | 100 | 52 | 76 | 75 | 65 | 73 | 62 | 24.95 | 1.73 | 1.73 | 76 | 0 |
| 1973 | 9 | 4 | 13:47 | 83 | 61 | 111 | 43 | 100 | 39 | 72 | 90 | 65 | 79 | 59 | 25.08 | 1.45 | 1.84 | 71 | 0 |
| 1973 | 10 | 23 | 9:15 | 76 | 47 | 98 | 34 | 89 | 32 | 60 | 64 | 50 | 57 | 43 | 24.79 | 1.38 | 1.48 | 60 | 0 |
| 1973 | 11 | 13 | 15:40 | 62 | 40 | 91 | 22 | 83 | 22 | 56 | 59 | 49 | 56 | 47 | 24.64 | 1.36 | 1.36 | 56 | 0 |
| 1973 | 11 | 28 | 9:20 | 55 | 39 | 75 | 20 | 63 | 18 | 38 | 51 | 40 | 39 | 34 | 24.91 | 1.29 | 1.29 | 38 | 0.125 |
| 1973 | 12 | 3 | 11:40 | 45 | 39 | 75 | 27 | 63 | 23 | 42 | 52 | 43 | 40 | 33 | 24.78 | 1.28 | 1.28 | 42 | 0 |
| 1973 | 12 | 11 | 14:52 | 44 | 39 | 69 | 5 | 61 | 2 | 42 | 54 | 43 | 50 | 40 | 24.65 | 1.24 | 1.76 | 43 | 0 |
| 1973 | 12 | 17 | 10:00 | 44 | 40 | 58 | 24 | 57 | 21 | 40 | 48 | 34 | 47 | 33 | 24.72 | 1.73 | 1.73 | 40 | 0 |
| 1973 | 12 | 21 | 14:00 | 41 | 39 | 68 | 8 | 56 | 3 | 40 | 46 | 39 | 44 | 37 | 24.66 | 1.72 | 1.72 | 40 | 0.25 |
| 1974 | 1 | 14 | 14:00 | 41 | 32 | 62 | -10 | 50 | -14 | 32 | 49 | 38 | 42 | 34 | 24.78 | 1.70 | 1.70 | 32 | 7.25 |
| 1974 | 1 | 21 | 13:00 | 46 | 33 | 64 | 29 | 71 | 27 | 40 | 38 | 34 | 35 | 32 | 24.63 | 1.66 | 1.66 | 40 | 0.25 |
| 1974 | 2 | 11 | 15:40 | 48 | 38 | 110 | 14 | 62 | 10 | 48 | 68 | 48 | 60 | 43 | 24.65 | 1.56 | 1.56 | 48 | 0 |

LOCATION: Fort Collins Site, Enclosed Unit (page 2 of 4 pages).

Table 24. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 2 | 19 | 9:45 | 51 | 42 | 75 | 19 | 61 | 19 | 43 | 53 | 33 | 39 | 33 | 24.35 | 1.52 | 1.52 | 43 | 0 |
| 1974 | 3 | 1 | 10:00 | 50 | 40 | 79 | 15 | 66 | 11 | 49 | 69 | 49 | 62 | 44 | 24.67 | 1.45 | 1.72 | 48 | 0 |
| 1974 | 4 | 15 | 12:30 | 58 | 40 | 89 | 14 | 76 | 14 | 48 | 62 | 45 | 60 | 44 | 24.92 | 1.40 | 1.40 | 48 | 0 |
| 1974 | 4 | 22 | 9:15 | 65 | 47 | 87 | 31 | 74 | 26 | 51 | 61 | 49 | 47 | 39 | 24.99 | 1.33 | 1.33 | 51 | 0 |
| 1974 | 4 | 26 | 9:30 | 72 | 52 | 102 | 40 | 85 | 37 | 67 | 72 | 59 | 68 | 58 | 24.71 | 1.29 | 1.29 | 67 | 0 |
| 1974 | 5 | 2 | 14:00 | 74 | 52 | 99 | 37 | 83 | 34 | 70 | 70 | 60 | 75 | 53 | 24.69 | 1.21 | 1.74 | 54 | |
| 1974 | 5 | 10 | 11:00 | 73 | 54 | 98 | 43 | 84 | 39 | 68 | 79 | 59 | 71 | 55 | 24.54 | 1.65 | 1.65 | 68 | |
| 1974 | 5 | 17 | 10:00 | 74 | 60 | 96 | 39 | 82 | 37 | 64 | 60 | 56 | 58 | 55 | 24.74 | 1.54 | 1.54 | 64 | |
| 1974 | 5 | 28 | 14:30 | 76 | 61 | 103 | 44 | 92 | 40 | 74 | 97 | 64 | 88 | 59 | 24.71 | 1.40 | 1.40 | 74 | |
| 1974 | 6 | 29 | 11:30 | 85 | 50 | 112 | 40 | 99 | 39 | 80 | 98 | 68 | 91 | 61 | 24.88 | 0.96 | 1.79 | 72 | |
| 1974 | 7 | 16 | 10:30 | 84 | 72 | 113 | 56 | 99 | 50 | 75 | 92 | 73 | 82 | 66 | 24.92 | 1.50 | 1.50 | 75 | |
| 1974 | 7 | 29 | 10:00 | 88 | 69 | 110 | 56 | 95 | 52 | 70 | 83 | 68 | 72 | 62 | 25.18 | 1.31 | 1.31 | 70 | |
| 1974 | 8 | 8 | 11:30 | 83 | 68 | 105 | 51 | 89 | 47 | 70 | 81 | 64 | 74 | 58 | 24.84 | 1.17 | 1.17 | 70 | |

LOCATION: Fort Collins Site, Enclosed Unit (page 3 of 4 pages).

Table 24. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 9 | 9 | 11:45 | 82 | 53 | 116 | 39 | 98 | 38 | 69 | 100 | 71 | 89 | 64 | 25.0 | 0.77 | 1.86 | 71 | |
| 1974 | 10 | 19 | 12:10 | 77 | 49 | 109 | 34 | 97 | 29 | 64 | 61 | 82 | 72 | 54 | 25.1 | 1.43 | 1.89 | 62 | 0 |
| 1974 | 12 | 15 | 14:30 | 65 | 39 | 85 | 9 | 80 | 4 | 40 | 43 | 33 | 41 | 31 | 24.7 | 1.55 | 1.55 | 40 | 0.3 |
| Roof replaced with Kalwall fiberglass reinforced plastic. | | | | | | | | | | | | | | | | | | | |
| 1975 | 2 | 28 | 17:00 | 48 | 32 | | | 68 | -6 | 48 | | | 57 | 43 | 24.9 | 1.20 | 1.20 | 48 | |
| 1975 | 4 | 13 | 11:00 | 57 | 32 | | | 77 | 0 | 41 | | | 45 | 40 | 24.8 | 0.88 | 1.64 | 47 | |
| 1975 | 5 | 17 | 8:00 | 64 | 35 | | | 86 | 30 | 60 | | | 65 | 53 | 24.75 | 1.05 | 1.63 | 63 | |
| 1975 | 6 | 19 | 15:30 | 71 | 40 | | | 89 | 37 | 65 | | | 72 | 56 | 24.8 | 1.11 | 1.11 | 65 | |

LOCATION: Fort Collins Site, Enclosed Unit (page 4 of 4 pages).

Table 25. Water Surface Temperatures, Fort Collins Site, Enclosed Unit.

| Year | Month | Day | Time of day | Water surface temperature, °F | Water surface temperature during period between dates shown, °F | |
|---|---|---|---|---|---|---|
| | | | | | max | min |
| 1973 | 11 | 28 | 9:20 | | | |
| | | | | | 57 | 36 |
| 1973 | 12 | 3 | 11:40 | 47 | | |
| | | | | | 54 | 32 |
| 1973 | 12 | 11 | 14:52 | 47 | | |
| | | | | | 52 | 34 |
| 1973 | 12 | 17 | 10:00 | 44 | | |
| | | | | | 45 | 30 |
| 1973 | 12 | 21 | 14:00 | 33 | | |
| 1974 | 3 | 1 | 10:00 | 58 | | |
| | | | | | 72 | 32 |
| 1974 | 4 | 15 | 12:30 | 55 | | |
| | | | | | 74 | 47 |
| 1974 | 4 | 22 | 9:15 | 56 | | |
| | | | | | 82 | 54 |
| 1974 | 4 | 26 | 9:30 | 70 | | |
| | | | | | 79 | 51 |
| 1974 | 5 | 2 | 14:00 | 72 | | |
| | | | | | 81 | 55 |
| 1974 | 5 | 10 | 11:00 | 71 | | |
| | | | | | 79 | 60 |
| 1974 | 5 | 17 | 10:00 | 65 | | |
| | | | | | 84 | 60 |
| 1974 | 5 | 28 | 14:30 | 79 | | |
| | | | | | 91 | 49 |
| 1974 | 6 | 29 | 11:30 | 82 | | |
| | | | | | 93 | 70 |
| 1974 | 7 | 16 | 10:30 | 81 | | |
| | | | | | 110 | 55 |
| 1974 | 8 | 8 | 11:30 | 73 | | |
| | | | | | 90 | 52 |
| 1974 | 9 | 9 | 11:45 | 77 | | |
| | | | | | 84 | 48 |
| 1974 | 10 | 19 | 12:10 | 74 | | |
| | | | | | 77 | 31 |
| 1974 | 12 | 15 | 14:30 | 41 | | |

Table 26. Observed Data.

| | | | | BEFORE ADDING WATER | | | | | | | | | | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | | | TIME OF DAY | WATER | | INSIDE | | AIR | | | INSIDE | | AIR | | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | | Ice Thickness, inches |
| | MONTH | DAY | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | T, °F, WATER | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | | | | T, WATER, °F | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 5 | 2 | 14:00 | | | | | | | | | | 75 | 53 | 24.69 | 0 | 1.73 | 51 | |
| 1974 | 5 | 10 | 11:00 | 68 | 44 | | | 84 | 39 | 60 | | | 71 | 55 | 24.54 | 1.58 | 1.58 | 60 | |
| 1974 | 5 | 17 | 10:00 | 65 | 43 | | | 82 | 37 | 57 | | | 58 | 55 | 24.74 | 1.40 | 1.40 | 57 | |
| 1974 | 5 | 28 | 14:30 | 72 | 47 | | | 92 | 40 | 67 | | | 88 | 59 | 24.71 | 1.19 | 1.79 | 64 | |
| 1974 | 6 | 29 | 11:30 | 79 | 49 | | | 99 | 39 | 71 | | | 91 | 61 | 24.88 | 1.29 | 1.29 | 71 | |
| 1974 | 7 | 16 | 10:30 | 79 | 60 | | | 99 | 50 | 69 | | | 82 | 66 | 24.92 | 0.94 | 1.68 | 68 | |
| 1974 | 7 | 29 | 10:00 | 80 | 58 | | | 95 | 52 | 62 | | | 72 | 62 | 25.18 | 1.47 | 1.47 | 62 | |
| 1974 | 8 | 8 | 11:30 | 76 | 58 | | | 89 | 47 | 63 | | | 74 | 58 | 24.84 | 1.31 | 1.31 | 63 | |
| 1974 | 9 | 9 | 11:35 | 76 | 44 | | | 98 | 38 | 62 | | | 89 | 64 | 25.0 | 0.76 | 1.89 | 69 | |
| 1974 | 10 | 19 | 12:10 | 73 | 38 | | | 97 | 29 | 57 | | | 72 | 54 | 25.1 | 1.41 | 1.93 | 62 | |
| 1974 | 12 | 15 | 14:30 | 68 | 32 | | | 80 | 4 | 38 | | | 41 | 31 | 24.7 | 1.57 | 1.57 | 38 | 3 |
| 1975 | 2 | 28 | 17:00 | 44 | 24 | | | 68 | -6 | 44 | | | 57 | 43 | 24.9 | 1.24 | 1.24 | 44 | 1 |
| 1975 | 4 | 13 | 11:00 | 57 | 30 | | | 77 | 0 | 42 | | | 45 | 40 | 24.8 | 1.11 | 1.61 | 58 | |

LOCATION: Fort Collins Site, Structural Unit (Page 1 of 2 pages).

Table 26. Continued.

| | | | | BEFORE ADDING WATER | | | | | | | | | | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | | | TIME OF DAY | WATER | | INSIDE | | AIR | | | INSIDE | | AIR | | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | | Ice Thickness, inches |
| | MONTH | DAY | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | T, °F, WATER | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | | | | T, WATER, °F | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1975 | 5 | 17 | 8:00 | 68 | 34 | | | 86 | 30 | 58 | | | 65 | 53 | 24.75 | 1.16 | 1.77 | 62 | 0 |
| 1975 | 6 | 19 | 15:30 | 71 | 38 | | | 89 | 37 | 65 | | | 72 | 56 | 24.8 | 1.69 | 1.69 | 65 | 0 |

LOCATION: Fort Collins Site, Structural Unit (Page 2 of 2 pages).

Table 27. Soil Temperatures, Fort Collins Site, Structural Unit.

| Year | Month | Day | Time of day | Temperature °F | Soil temperature at depth indicated, °F | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | underneath water tank | | in shade | in sun |
| | | | | | 3" | 9" | 3" | 3" |
| 1974 | 5 | 2 | 14:00 | | 59 | 56 | | |
| 1974 | 5 | 10 | 11:00 | 60 | 56.5 | 55 | 60 | 64 |
| 1974 | 5 | 17 | 10:00 | 57 | 56 | 54.5 | 56 | 62 |
| 1974 | 5 | 28 | 14:30 | 67 | 61 | 58 | 68 | 103 |

Table 28. Observed Data.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 6 | 28 | 9:30 | 98 | 48 | | | 102 | 44 | 74 | | | 77 | 63 | 24.95 | | 1.708 | 72 | 0 |
| 1973 | 7 | 25 | 13:40 | 90 | 59 | | | 107 | 50 | 76 | | | 80 | 61 | 25.21 | 1.292 | 1.292 | 76 | 0 |
| 1973 | 8 | 7 | 10:40 | 86 | 64 | | | 90 | 56 | 68 | | | 73 | 62 | 24.86 | 1.16 | 1.16 | 68 | 0 |
| 1973 | 8 | 10 | 11:10 | 86 | 66 | | | 94 | 54 | 74 | | | 84 | 66 | 24.92 | 1.13 | 1.53 | 72 | 0 |
| 1973 | 8 | 17 | 8:45 | 86 | 66 | | | 100 | 52 | 70 | | | 73 | 62 | 24.97 | 1.37 | 1.37 | 70 | 0 |
| 1973 | 9 | 4 | 13:47 | 87 | 50 | | | 100 | 39 | 74 | | | 79 | 59 | 25.08 | 0.95 | 1.68 | 68 | 0 |
| 1973 | 10 | 23 | 9:15 | 80 | 42 | | | 89 | 32 | 51 | | | 57 | 43 | 24.79 | 1.20 | 1.20 | 51 | 0 |
| 1973 | 11 | 13 | 15:40 | 62 | 38 | | | 83 | 22 | 54 | | | 56 | 47 | 24.64 | 1.26 | 1.26 | 54 | 0 |
| 1973 | 11 | 28 | 9:20 | 54 | 36 | | | 63 | 18 | 38 | | | 39 | 34 | 24.91 | 1.20 | 1.20 | 38 | 3 |
| 1973 | 12 | 3 | 11:40 | 44 | 35 | | | 63 | 23 | 40 | | | 40 | 33 | 24.78 | 1.18 | 1.18 | 40 | 0.5 |
| 1973 | 12 | 11 | 14:52 | 44 | 38 | | | 61 | 2 | 42 | | | 50 | 40 | 24.65 | 1.14 | 1.14 | 42 | 3 |
| 1974 | 12 | 17 | 10:00 | 45 | 37 | | | 57 | 21 | 42 | | | 47 | 33 | 24.72 | 1.11 | 1.11 | 42 | 2.75 |
| 1973 | 12 | 21 | 14:00 | 43 | 37 | | | 56 | 3 | 39 | | | 44 | 37 | 24.66 | 1.13 | 1.13 | 39 | 5.5 |

LOCATION: Fort Collins Site, Uncovered Unit (page 1 of 3 pages).

Table 28. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice Thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 1 | 14 | 14:00 | 32 | 32 | | | 50 | -14 | 32 | | | 42 | 34 | 24.78 | 1.29 | 1.29 | 32 | 15.48 |
| 1974 | 1 | 21 | 13:00 | 33 | 32 | | | 71 | 27 | 32 | | | 35 | 32 | 24.63 | 1.25 | 1.25 | 32 | 10 |
| 1974 | 2 | 11 | 15:40 | 44 | 32 | | | 62 | 10 | 43 | | | 60 | 43 | 24.65 | 1.01 | 1.01 | 43 | 4.5 |
| 1974 | 2 | 19 | 9:45 | 48 | 38 | | | 61 | 19 | 42 | | | 39 | 33 | 24.35 | 1.00 | 1.00 | 42 | 0.375 |
| 1974 | 3 | 1 | 10:00 | 51 | 35 | | | 66 | 11 | 42 | | | 62 | 44 | 24.67 | 0.90 | 1.71 | 44 | 0 |
| 1974 | 4 | 15 | 12:30 | 62 | 38 | | | 76 | 14 | 48 | | | 60 | 44 | 24.92 | 1.31 | 1.31 | 48 | 0 |
| 1974 | 4 | 22 | 9:15 | 66 | 42 | | | 74 | 26 | 44 | | | 47 | 39 | 24.99 | 1.19 | 1.19 | 44 | 0 |
| 1974 | 4 | 26 | 9:30 | 73 | 44 | | | 85 | 37 | 62 | | | 68 | 58 | 24.71 | 1.13 | 1.13 | 62 | 0 |
| 1974 | 5 | 2 | 14:00 | 76 | 45 | | | 83 | 34 | 66 | | | 75 | 53 | 24.69 | 1.03 | 1.71 | 64 | 0 |
| 1974 | 5 | 10 | 11:00 | 75 | 50 | | | 84 | 39 | 62 | | | 71 | 55 | 24.54 | 1.54 | 1.54 | 62 | 0 |
| 1974 | 5 | 17 | 10:00 | 74 | 46 | | | 82 | 37 | 62 | | | 58 | 55 | 24.74 | 1.33 | 1.33 | 62 | 0 |
| 1974 | 5 | 28 | 14:30 | 84 | 51 | | | 92 | 40 | 74 | | | 88 | 59 | 24.71 | 1.08 | 1.78 | 67 | 0 |
| 1974 | 6 | 29 | 11:30 | 88 | 45 | | | 99 | 39 | 76 | | | 91 | 61 | 24.88 | 1.15 | 1.15 | 76 | 0 |

LOCATION: Fort Collins Site, Uncovered Unit (Page 2 of 3 pages).

Table 28. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 7 | 16 | 10:30 | 88 | 63 | | | 99 | 50 | 72 | | | 82 | 66 | 24.92 | 0.77 | 1.46 | 71 | |
| 1974 | 7 | 29 | 10:00 | 90 | 62 | | | 95 | 52 | 66 | | | 72 | 62 | 25.18 | 1.19 | 1.19 | 66 | |
| 1974 | 8 | 8 | 11:30 | 85 | 61 | | | 89 | 47 | 66 | | | 74 | 58 | 24.84 | 0.99 | 0.99 | 66 | |
| 1974 | 9 | 9 | 11:20 | 86 | 47 | | | 98 | 38 | 68 | | | 89 | 64 | 25.0 | 0.45 | 1.78 | 73 | |
| 1974 | 10 | 19 | 12:10 | 77 | 43 | | | 97 | 29 | 58 | | | 72 | 54 | 25.1 | 0.95 | 1.92 | 63 | |
| 1974 | 12 | 15 | 14:30 | 66 | 39 | | | 80 | 4 | 40 | | | 41 | 31 | 24.7 | 1.55 | 1.55 | 40 | 3.25 |
| 1975 | 2 | 28 | 17:00 | 50 | 34 | | | 68 | -6 | 50 | | | 57 | 43 | 24.9 | 1.30 | 1.30 | 50 | 0 |
| 1975 | 4 | 13 | 11:00 | 65 | 33 | | | 77 | 0 | 47 | | | 45 | 40 | 24.8 | 1.11 | 1.11 | 47 | |
| 1975 | 5 | 17 | 8:00 | 77 | 39 | | | 86 | 30 | 58 | | | 65 | 53 | 24.75 | 0.64 | 1.46 | 65 | |
| 1975 | 6 | 19 | 15:30 | 82 | 44 | | | 89 | 37 | 74 | | | 72 | 56 | 24.8 | 1.33 | 1.33 | 74 | |

LOCATION: Fort Collins Site, Uncovered Unit (page 3 of 3 pages).

Table 29. Observed Data.

| | | | | BEFORE ADDING WATER | | | | | | | | | | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | | | TIME OF DAY | WATER | | INSIDE | | AIR | | | INSIDE | | AIR | | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | | Water meter reading, liters |
| | MONTH | DAY | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | T, °F, WATER | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | | | | T, WATER, °F | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| Water meter reading just before installation | | | | | | | | | | | | | | | | | | | 52,198.0 |
| 1973 | 5 | 19 | water meter reading just after filling septic tank | | | | | | | | | | | | | | | | 56,973.75 |
| 1973 | 6 | 3 | 15:40 | | | | | | | 49 | | | 43 | 40 | | | | | 60,299.25 |
| 1973 | 6 | 7 | 13:22 | | | | | 72 | 30 | | | | 71 | 49 | 22.57 | | | | 60,550.25 |
| 1973 | 6 | 17 | 15:48 | | | | | 75 | | 64 | | | 82 | 52 | | | | | 61,979 |
| 1973 | 7 | 1 | 16:05 | | | | | 89 | 34 | 78 | | | 89 | 55 | | | | | 64,170 |
| 1973 | 7 | 6 | 11:45 | | | | | 88 | 48 | 64 | | | 86 | 55 | 22.50 | 1.97 | 1.97 | 64 | |
| Hail destroyed K-Clear Plastic transparent roof covering | | | | | | | | | | | | | | | | | | | |
| 1973 | 7 | 22 | 17:35 | 77 | 55 | | | 87 | 42 | 62 | | | 58 | 50 | | 2.28 | 2.28 | 62 | 67,350 |
| 1973 | 7 | 25 | 10:45 | 58 | 55 | | | 70 | 43 | 56 | | | 58 | 47 | 22.74 | 2.40 | 2.40 | 56 | 68,200.9 |
| Destroyed transparent roof covering replaced with Uvek | | | | | | | | | | | | | | | | | | | |
| 1973 | 8 | 18 | 12:05 | 60 | 54 | | | 84 | 39 | 56 | | | 68 | 53 | 22.57 | 2.44 | 2.44 | 56 | |
| 1973 | 10 | 21 | 12:16 | | | | | 84 | 24 | 40 | | | 60 | 44 | 22.43 | 2.96 | 2.96 | 40 | |

LOCATION: Red Feather Site, Full Scale Unit (Page 1 of 3 pages).

Table 29. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Water meter reading, liters |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 10 | 23 | 14:14 | 56 | 42 | | | 68 | 33 | 44 | | | 68 | 44 | 22.26 | 3.00 | 3.00 | 44 | |
| 1973 | 11 | 9 | 14:17 | 43 | 40 | | | 66 | 6 | 43 | | | 62 | 58 | | 2.98 | 2.98 | 43 | 75,633.4 |
| 1973 | 12 | 12 | 11:30 | Several Uvex roof panels broken | | | | | | | | | | | | 3.06 | 3.06 | | |
| All Uvex roof panels were replaced with Kalwall roof material | | | | | | | | | | | | | | | | | | | |
| 1974 | 4 | 19 | 13:30 | | | | | 62 | 4 | 38 | | | 44 | 37 | 22.72 | 2.95 | 2.76 | 36 | |
| 1974 | 5 | 10 | 14:30 | 58 | 40 | | | 70 | 29 | 54 | | | 57 | 43 | 22.03 | 2.74 | 2.74 | 54 | 78,693 |
| 1974 | 5 | 22 | 9:45 | 71 | 38 | | | 80 | 28 | 43 | | | 50 | 35 | | 2.76 | 2.76 | 43 | 79,679 |
| 1 of 2 toilets in cabin replaced with chemical toilet; chlorinator installed. | | | | | | | | | | | | | | | | | | | |
| 1974 | 6 | 27 | 14:00 | 55 | 43 | | | 89 | 32 | 54 | | | 82 | 54 | 22.49 | 3.05 | 2.96 | 54 | |
| 1974 | 7 | 26 | 12:30 | 57 | 51 | | | 90 | 39 | 55 | | | 74 | 54 | 22.60 | 3.02 | 3.02 | 55 | 86,359 |
| 1974 | 8 | 9 | 12:30 | 57 | 52 | | | 86 | 36 | 52 | | | 66 | 53 | 22.52 | 3.13 | 0.54 | 52 | |
| 1974 | 9 | 7 | 8:50 | 65 | 40 | | | 84 | 31 | 46 | | | 60 | 43 | 22.5 | 1.05 | 1.06 | 46 | |
| 1974 | 9 | 15 | 17:10 | 52 | 41 | | | 80 | 27 | 46 | | | 58 | 41 | | 1.10 | 1.10 | 46 | 90,127.5 |

LOCATION: Red Feather Site, Full Scale Unit (Page 2 of 3 pages).

Table 29. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Water meter reading, liters |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 10 | 6 | 13:40 | 52 | 42 | | | 80 | 28 | 44 | | | 50 | 37 | | 1.40 | 1.40 | 44 | 91,753 |
| 1974 | 10 | 19 | 16:40 | 52 | 40 | | | 78 | 28 | 45 | | | 64 | 47 | | 1.40 | 1.40 | 45 | 92,261.2 |
| 1974 | 11 | 10 | 14:20 | 44 | 33 | | | 74 | 13 | 33 | | | 28 | | | 1.52 | 1.52 | 33 | 92,593.5 |
| 1974 | 11 | 17 | 14:35 | 43 | 30 | | | 48 | 14 | 32 | | | 44 | 33 | 22.23 | 1.55 | 1.12 | 32 | 92,834 |
| 1975 | 6 | 26 | 12:00 | 58 | 17 | | | | | 49 | | | 65 | 44 | 22.4 | 1.49 | 1.49 | 49 | 100,405 |

LOCATION: Red Feather Site, Full Scale Unit (page 3 of 3 pages).

Table 30. Observed Data.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1972 | 9 | 25 | 17:33 | | | | | | | 55 | | | 49 | 42 | 22.35 | 2.002 | 2.002 | 55 | |
| 1972 | 11 | 16 | 8:30 | | 32 | | | 65 | 3 | 32 | | | 27 | 23 | 22.34 | 1.570 | 1.570 | 32 | 4 |
| 1973 | 5 | 25 | 16:22 | 42 | 2 | | | 51 | -19 | 52 | | | 57 | 46 | 22.04 | 1.167 | 1.745 | 52 | |
| 1973 | 6 | 7 | 13:22 | 52 | 46 | | | 72 | 30 | 52 | | | 71 | 49 | 22.57 | 1.610 | 1.610 | 52 | |
| 1973 | 7 | 1 | 16:10 | | 54 | | | 83 | 34 | 68 | | | 86 | 54 | | 1.30 | 1.30 | 68 | |
| 1973 | 7 | 6 | 11:45 | 70 | 61 | | | 88 | 48 | 66 | | | 86 | 55 | 22.50 | 1.22 | 1.82 | 70 | |
| 1973 | 7 | 22 | 17:35 | 72 | 50 | | | 87 | 42 | 64 | | | 58 | 50 | | 1.65 | 1.65 | 64 | |
| 1973 | 7 | 25 | 10:45 | 58 | 52 | | | 70 | 43 | 53 | | | 58 | 47 | 22.74 | 1.63 | 1.63 | 53 | |
| 1973 | 8 | 18 | 12:05 | 64 | 51 | | | 84 | 39 | 60 | | | 68 | 53 | 22.57 | 1.39 | 1.39 | 60 | |
| 1973 | 10 | 21 | 12:16 | 64 | 40 | | | 84 | 24 | 44 | | | 60 | 44 | 22.43 | 0.90 | 0.90 | 44 | |
| 1973 | 10 | 23 | 14:14 | 47 | 42 | | | 68 | 33 | 45 | | | 68 | 44 | 22.26 | 0.88 | 0.88 | 45 | |
| 1973 | 11 | 9 | 14:30 | 46 | 36 | | | 66 | 6 | 42 | | | 62 | 58 | | 0.80 | 0.80 | 42 | |
| 1973 | 12 | 12 | 11:30 | 32 | 32 | | | 59 | 10 | 32 | | | 26 | 32 | 22.02 | 0.75 | 0.75 | 32 | 9 |

LOCATION: Red Feather Site, Covered Unit (Page 1 of 2 pages).

Table 30. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1974 | 4 | 19 | 13:30 | 54 | 8 | | | 62 | 4 | 42 | | | 44 | 37 | 22.72 | 0.32 | 1.74 | 40 | |
| 1974 | 5 | 10 | 14:30 | 52 | 38 | | | 70 | 29 | 50 | | | 57 | 43 | 22.03 | 1.56 | 1.56 | 50 | |
| 1974 | 5 | 22 | 9:45 | 62 | 38 | | | 80 | 28 | 41 | | | 50 | 35 | | 1.43 | 1.43 | 41 | |
| 1974 | 6 | 27 | 14:00 | 64 | 39 | | | 89 | 32 | 62 | | | 82 | 54 | 22.49 | 1.05 | 1.74 | 58 | |
| 1974 | 7 | 26 | 12:30 | 64 | 55 | | | 90 | 39 | 60 | | | 74 | 54 | 22.60 | 1.40 | 1.40 | 60 | |
| 1974 | 8 | 9 | 12:30 | 62 | 52 | | | 86 | 36 | 54 | | | 66 | 53 | 22.52 | 1.28 | 0.06 | 54 | |
| 1974 | 11 | 17 | 14:35 | | | | | 48 | 14 | | | | 44 | 33 | 22.23 | 0 | 1.84 | 40 | |
| 1975 | 6 | 26 | 12:00 | 57 | 4 | | | | | 46 | | | 65 | 44 | 22.4 | 0.84 | 0.84 | 46 | 0 |

LOCATION: Red Feather Site, Covered Unit (Page 2 of 2 pages).
All data on this page is for evaporation of concentrated sewage.

Table 31. Observed Data.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1972 | 9 | 1 | 11:30 | | | | | 74 | 39 | 50 | | | 39 | 39 | 22.3 | 1.737 | 1.737 | 50 | |
| 1972 | 9 | 14 | 13:27 | 56 | 45 | | | 80 | 36 | 61 | | | 65 | 53 | 22.3 | 1.658 | 1.658 | 61 | |
| 1972 | 10 | 1 | 11:30 | 59 | 44 | | | 81 | 31 | 50 | | | 65 | 47 | 22.1 | 1.602 | 1.602 | 50 | |
| 1972 | 10 | 8 | 14:13 | 54 | 44 | | | 74 | 27 | 49 | | | 48 | 46 | 22.1 | 1.435 | 1.890 | 50 | |
| 1972 | 10 | 14 | 14:17 | 52 | 45 | | | 68 | 28 | 43 | | | 30 | 30 | 22.3 | 1.772 | 1.772 | 43 | |
| 1972 | 11 | 5 | 9:45 | 52 | 34 | | | 60 | 6 | 37 | | | 41 | 34 | 21.68 | 1.605 | 1.605 | 37 | * |
| 1972 | 11 | 14 | 8:00 | 40 | 32 | | | 53 | 16 | 32 | | | 27 | 24 | 21.98 | 1.802 | 1.802 | 32 | 2 |
| 1973 | 3 | 4 | 15:04 | | | | | 59 | -18 | 32 | | | 28 | 33 | 21.66 | 1.333 | 1.333 | 32 | * |
| 1973 | 6 | 1 | 11:55 | 52 | 31 | | | 72 | - 8 | 52 | | | 69 | 51 | 21.88 | 1.000 | 1.875 | 52 | |
| 1973 | 7 | 7 | 13:00 | 72 | 42 | | | 96 | 32 | 68 | | | 75 | 59 | 22.15 | 1.40 | 1.98 | 68 | |
| 1973 | 8 | 12 | 11:30 | 66 | 48 | | | 85 | 40 | 62 | | | 73 | 63 | | 1.60 | 1.88 | 65 | 0 |
| 1973 | 9 | 5 | 16:50 | 65 | 56 | | | 83 | 36 | 57 | | | 60 | 50 | 22.37 | 1.56 | 1.56 | 57 | 0 |
| 1973 | 10 | 14 | 9:37 | 60 | 38 | | | 80 | 22 | 45 | | | 59 | 44 | 22.26 | 1.30 | 1.30 | 45 | 0 |

LOCATION: Storm Mountain Site (page 1 of 3 pages)
*floating ice

Table 31. Continued.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER °F, max | WATER °F, min | INSIDE °F, max | INSIDE °F, min | AIR °F, max | AIR °F, min | T, °F, WATER | INSIDE $T_a$, °F | INSIDE $T_w$, °F | AIR $T_a$, °F | AIR $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | AFTER ADDING WATER: WATER DEPTH, feet, D | T, WATER, °F | Ice thickness, inches |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1973 | 10 | 16 | 15:40 | 52 | 44 | | | 69 | 34 | 50 | | | 62 | 48 | 22.15 | 1.27 | 1.97 | 55 | 0 |
| 1973 | 11 | 21 | 16:00 | 55 | 33 | | | 62 | 6 | 38 | | | 33 | 32 | 21.51 | 1.69 | 1.69 | 38 | 1.5 |
| 1973 | 12 | 11 | 11:20 | 43 | 36 | 71 | 2 | | | 39 | 47 | 35 | 46 | 32 | 21.90 | 1.64 | 1.64 | 39 | 0 |
| 1974 | 2 | 11 | 13:40 | 41 | 33 | 60 | -4 | 49 | -11 | 40 | 56 | 40 | 45 | 32 | 21.82 | 1.53 | 1.53 | 40 | 0.9 |
| 1974 | 4 | 18 | 10:15 | 48 | 34 | 80 | 7 | 62 | 2 | 44 | 65 | 53 | 52 | 41 | 21.96 | 1.34 | 1.34 | 44 | 0 |
| 1974 | 5 | 27 | 11:30 | 64 | 40 | 96 | 26 | 82 | 26 | 63 | 90 | 63 | 75 | 54 | 22.09 | 1.07 | 1.91 | 62 | 0 |
| 1974 | 6 | 27 | 10:15 | 68 | 39 | | | 88 | 30 | 64 | | | 73 | 57 | 22.11 | 1.57 | 1.90 | 65 | 0 |
| 1974 | 7 | 7 | 11:12 | 68 | 58 | | | 89 | 46 | 63 | | | 69 | 54 | 21.98 | 1.71 | 1.71 | 63 | 0 |
| 1974 | 8 | 10 | 9:00 | 67 | 49 | | | 86 | 36 | 49 | | | 55 | 44 | 21.96 | 1.36 | 1.36 | 49 | |
| 1974 | 9 | 11 | 13:00 | 66 | 41 | | | 85 | 30 | 55 | | | 44 | 41 | 21.86 | 1.01 | 1.92 | 57 | |
| 1974 | 10 | 6 | 8:22 | 56 | 40 | | | 72 | 24 | 42 | | | 28 | 28 | 22.08 | 1.68 | 1.68 | 42 | |
| 1974 | 11 | 3 | 8:40 | 53 | 34 | | | 68 | 22 | 34 | | | 27 | 27 | 21.92 | 1.54 | 1.54 | 34 | 0.5 |
| 1974 | 12 | 15 | 13:19 | | | | | 65 | 5 | 32 | | | 28 | 22 | 21.62 | 1.38 | 1.38 | 32 | 5 |

LOCATION: Storm Mountain Site (page 2 of 3 pages).

Table 31. Continued

| | | | | BEFORE ADDING WATER | | | | | | | | | | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | MONTH | DAY | TIME OF DAY | WATER | | INSIDE | | AIR | | | INSIDE | | AIR | | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | | Ice thickness, inches |
| | | | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | T, °F, WATER | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | | | | T, WATER, °F | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| half of roof had holes through which precipitation could fall into tank | | | | | | | | | | | | | | | | | | | |
| 1975 | 4 | 7 | 13:55 | 43 | 30 | | | 57 | -12 | 34 | | | 41 | 33 | 21.18 | 1.20 | 1.20 | 34 | * |
| half of roof gone during this interval. Reparied on following date. | | | | | | | | | | | | | | | | | | | |
| 1975 | 4 | 17 | 11:24 | 41 | 32 | | | 55 | 10 | 36 | | | 46 | 35 | 21.50 | | 1.96 | 42 | * |
| 1975 | 6 | 8 | 10:16 | 60 | 33 | | | 80 | 16 | 54 | | | 50 | 49 | 21.86 | 1.51 | 1.51 | 54 | |
| 1975 | 6 | 15 | 14:53 | 60 | 38 | | | 76 | 30 | 60 | | | 70 | 50 | 21.86 | 1.45 | 1.45 | 60 | |
| 1975 | 6 | 25 | 13:40 | 63 | 44 | | | 74 | 38 | 63 | | | 74 | 51 | 21.82 | 1.37 | 1.37 | 63 | |

LOCATION: Storm Mountain Site (page 3 of 3 pages).
*floating ice.

Table 32. Observed Data.

| YEAR | MONTH | DAY | TIME OF DAY | BEFORE ADDING WATER: WATER | | INSIDE | | AIR | | | INSIDE | | AIR | | | | AFTER ADDING WATER | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | °F, max | °F, min | °F, max | °F, min | °F, max | °F, min | T, °F, WATER | $T_a$, °F | $T_w$, °F | $T_a$, °F | $T_w$, °F | P, In. Hg | WATER DEPTH, feet, D | WATER DEPTH, feet, D | T, WATER, °F | Ice thickness, inches |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) | (17) | (18) | (19) | (20) |
| 1972 | 9 | 26 | 12:30 | | | | | | | 44 | | | 49 | 38 | 20.5 | 1.920 | 1.920 | 44 | |
| 1972 | 10 | 15 | 11:30 | 47 | 41 | | | 71 | 24 | 42 | | | 39 | 37 | | 1.646 | 1.646 | 42 | |
| 1972 | 11 | 20 | 16:22 | | | | | 52 | 3 | | | | 16 | 16 | 20.2 | | | | solid ice |
| 1973 | 5 | 30 | 10:55 | 55 | 4 | | | 62 | -19 | 42 | | | 40 | 35 | 20.5 | 1.00 | 1.86 | 42 | |
| 1973 | 6 | 10 | 10:00 | 62 | 40 | | | 76 | 18 | 54 | | | 66 | | | 1.77 | 1.77 | 54 | |
| 1973 | 10 | 28 | | | | | | | | | | | | | | 0.72 | 0.72 | | 1 |
| 1973 | 12 | 29 | 9:00 | | | 84 | -13 | | | | | | 22 | 32 | | 0.68 | 0.68 | | ice |
| 1974 | 8 | 16 | 14:10 | | | | | | | | | | 68 | 49 | | 0 | 0 | | |
| 1974 | 9 | 5 | 13:00 | | | | | | | | | | 57 | 47 | 20.58 | 0 | 1.62 | 61 | |
| 1974 | 10 | 18 | 14:00 | 63 | 38 | | | 71 | 24 | 44 | | | 61 | 44 | 20.8 | 1.34 | 1.92 | 46 | |
| 1974 | 12 | 1 | 16:00 | | | | | 56 | - 5 | | | | 33 | 29 | 21.31 | 1.92 | 1.92 | | ice |
| 1975 | 6 | 24 | 15:30 | 61 | 6 | | | 73 | -10 | 61 | | | 74 | 50 | 20.5 | 1.37 | 1.37 | 61 | |
| 30% of roof gone | | | | | | | | | | | | | | | | | | | |

LOCATION: Breckenridge Site

Table 33. Observed Average Atmospheric Pressure at the 4 Sites.

| Site Name (1) | Number of Observations (2) | In. Hg | | Coefficient of Variation (5) | Atmospheric pressure, atm. | |
|---|---|---|---|---|---|---|
| | | Average Observed Atmospheric Pressure (3) | Standard Deviation (4) | | Average Observed (6) | Calculated (from Table 18) (7) |
| Fort Collins | 46 | 24.83 | 0.187 | 0.0075 | 0.830 | 0.827 |
| Red Feather | 17 | 22.40 | 0.226 | 0.010 | 0.749 | 0.740 |
| Storm Mountain | 30 | 21.94 | 0.272 | 0.012 | 0.733 | 0.729 |
| Breckenridge | 7 | 20.63 | 0.349 | 0.017 | 0.690 | 0.674 |
| 1 atm. = 29.92 In. Hg | | | | | | |

1.43 feet, while the water evaporation from the Uvex unit was 1.39 feet, or essentially no significant difference. These results were obtained despite the fact that Kalwall has a lower transmittance to solar radiation and a higher transmittance to long wave radiation. Apparently small difference in these 2 characteristics do not significantly affect water evaporation rates.

Tables 26 and 28 permit a direct comparison of the effect of the roof structure on water evaporation rates. During the period May 2, 1974, through June 19, 1975, the net evaporation from the structural unit was 4.13 feet while the net evaporation from the uncovered unit was 4.89 feet (these results are the evaporation that took place in excess of precipitation). Clearly the massive nature of the roof structure reduced the water evaporation rate to 84% of what it would have been if the roof structure had not blocked some of the solar radiation.

Tables 22 and 28 permit a direct determination of how much more a covered unit will evaporate compared to an uncovered unit. During the time period from June 28, 1973, through June 19, 1975, the net evaporation from the uncovered unit was 7.51 feet, while the evaporation from the covered unit was 10.16 feet. The difference of 2.65 feet or 31.8 inches is greater than the precipitation of about 29.4 inches that would ordinarily fall in a 2 year period despite the fact that the solar radiation reaching the covered unit was about 84% that reaching the uncovered unit. In fact the water evaporation from the covered unit of about 5.1 feet per year is more than the average annual evaporation from lakes of about 4.6 feet per year. If a roof structure is used such that solar shading is insignificant, then the water evaporation from the covered unit could conceivably be increased to (5.1 ÷ 0.84=) 6.1 feet per year or 1.33 times lake evaporation.

Tables 22 and 24 permit one to make a direct comparison between covered and enclosed units. During the period from May 19, 1973, through December 15, 1974, the water evaporation from the covered unit was 9.21 feet compared with 5.71 feet from the enclosed unit. As a very rough approximation, one can probably say that water evaporation from a covered unit will be 1.6 times that of a solar still under the same conditions.

The observed data in Table 29 bears some discussion. The capacity of the septic tank was obviously 4,776 liters or 1,262 gallons. In July, 1973, hail destroyed the K-Clear plastic transparent roof covering. This was replaced with Uvex transparent roof covering which self-destructed in December, 1973. The destroyed Uvex material was replaced with Kalwall roof material which has survived intact to the present. In May, 1974, one of the 2 toilets in the cabin was replaced with a chemical toilet in an attempt to reduce wastewater volume by about 40%. However, the families using the cabin did not like the chemical toilet, and used the other one instead. Consequently, it is believed that the chemical toilet in this instance had no effect on wastewater volumes.

The chlorinator was installed in June, 1974, in an attempt to reduce alleged odors. The alleged odor situation will be discussed later in this report.

On August 9, 1974, liquid was pumped out of both the full scale and the covered units at the Red Feather Site, and this liquid was hauled away by truck.

It should be noted that all the data on page 2 of Table 30 is for concentrated wastewater. Beginning with April, 1974, all the liquid required for replacement of the water evaporated by this unit was taken from the full scale unit.

From page 2 of Table 31, it is apparent that the covered unit at this site was temporarily converted to an enclosed unit. The unit was enclosed November 21, 1973, until May 27, 1974, a period of 187 days. This can be compared with the previous year data for the period November 14, 1972, through June 1, 1973, a period of 199 days. During these intervals, the enclosed unit evaporated 0.62 feet of water at a rate of 0.0033 ft/day while the covered unit evaporated 0.802 feet of water at a rate of 0.0040 ft/day, so once again the covered unit out performed the enclosed unit.

The transparent roof covering that eventually failed (page 3 of Table 31) at this site was K-Clear Plastic.

The covered unit at the Breckenridge site was also temporarily enclosed from October 28, 1973, to December 29, 1973. However, the results are inconclusive because of ice formation not only during this period but also during the corresponding time periods in 1972 and 1974.

Of course, anytime that a zero depth is recorded means that all the water was evaporated at the time of the observation, but when it was actually all evaporated is unknown. This circumstance occurred on August 16, 1974, at the Breckenridge site and on November 17, 1974, at the Red Feather Site (covered unit only).

## WATER EVAPORATION DATA ANALYSIS

### Summary of Previous Developments

It has been established that water evaporation rate is related to air temperature (see Table 8). Specifically this relationship is expressed analytically by equation 28 which can be written as

$$E = \text{intercept} + (\text{slope})\, T \qquad (55)$$

where $E$ - ft/day and $T$ = °F. For Denver, Colorado, equation 55 becomes

$$E = -\ 0.00868 + 0.000431\, T \qquad (29)$$

### Interpretation of Maximum and Minimum Temperature Data

During the course of this project it was determined (by continuously recording temperature data) that the average temperature $\bar{T}$ during an interval was given by the following equation:

$$T = \frac{T_{max} + T_{min}}{2} \tag{57}$$

where $T_{max}$ = maximum temperature during the interval, °F,

$T_{min}$ = minimum temperature during the interval, °F.

This result means that the Uniform Probability Law (30) governs the temperature distribution over the interval $T_{min}$ to $T_{max}$. Consequently, the standard deviation of $T$ is $\frac{(T_{max} - T_{min})}{\sqrt{12}}$. Also the probability density function is

$$f_T(t) = \frac{1}{T_{max} - T_{min}} \quad \text{for} \quad T_{min} < t < T_{max} \tag{58}$$

and $f_T(t) = 0$ otherwise. The probability distribution function is

$$F_T(t) = P[T \leq t] = \int_{T_{min}}^{t} f_T(t)dt$$

$$= \int_{T_{min}}^{t} \frac{dt}{T_{max} - T_{min}} = \frac{t - T_{min}}{T_{max} - T_{min}} \quad . \tag{59}$$

It was experimentally observed that equation 57 is valid for the data in columns 5, 6, 7, 8, 9, and 10 of Table 20. As a result, the average temperature during an interval is related to the maximum and minimum temperatures observed during that interval by equation 57.

<u>Fort Collins Site, Covered Unit</u>

Using the data in columns 1, 2, 3, 9, 10, 17, and 18 of Table 22, the results corresponding to equation 29 are

$$E = - 0.00580 + 0.000381\ T \tag{56}$$

with a correlation coefficient of 0.824. These results are plotted in Figure 18 along with equations 56 and 29. It is clear that equations 29 and 56 are practically the same (they are exactly the same at an air temperature of 57.6°F) within the temperature range of interest, and that both represent the experimental data adequately. This is a very important result because it means that despite the fact that the solar radiation reaching the covered unit was reduced to 84% by structural roof shading, it still evaporated water at about the same rate as a lake. Consequently, equation 29 will be used as a basis of comparison for the data obtained at the other sites.

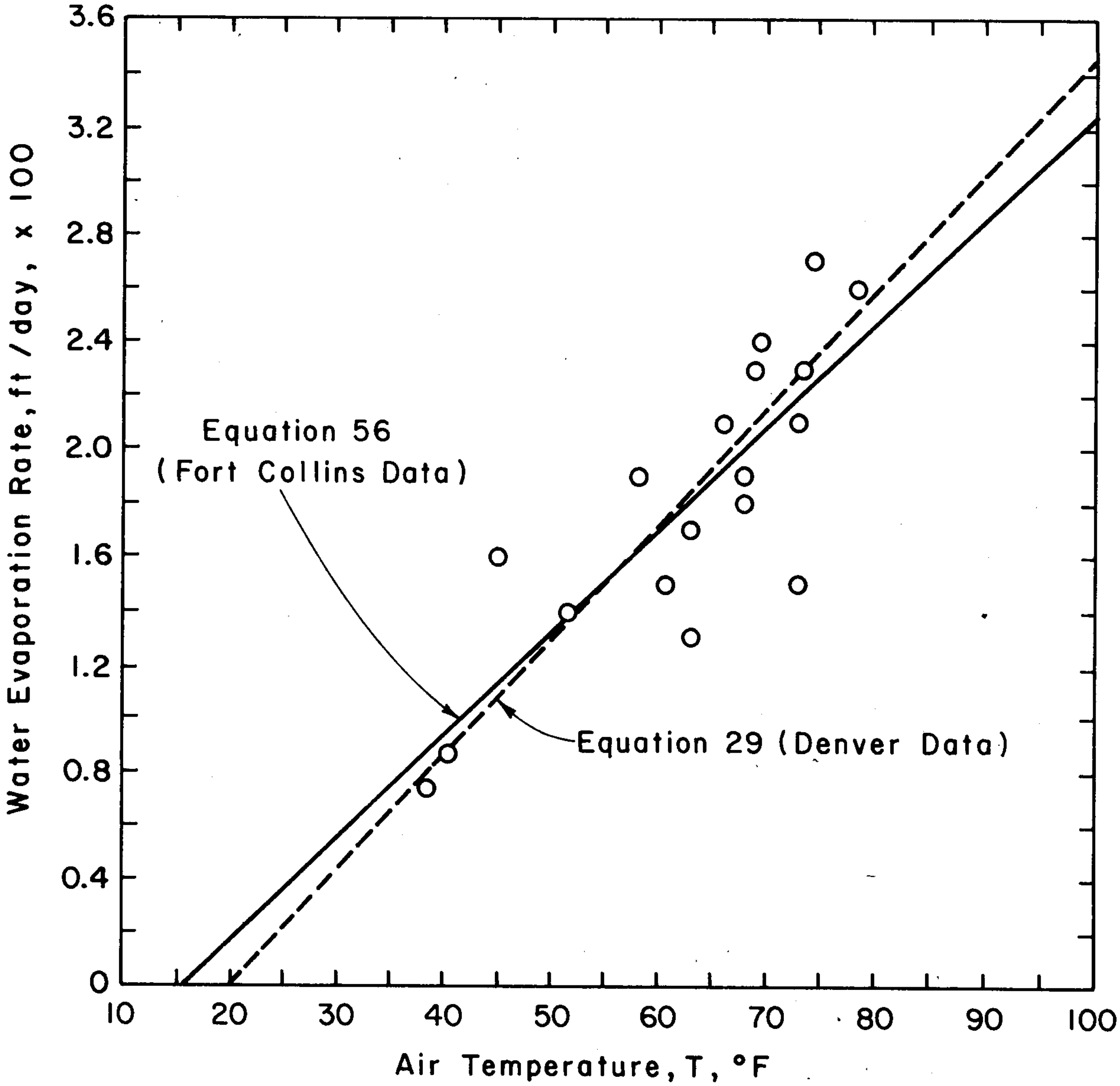


Figure 18 - Water Evaporation Rate and Air Temperature, Fort Collins Site, Covered Unit

The results of Figure 18 are not especially surprising when one considers Figure 19. The data for Figure 19 was obtained from columns 5, 6, 9, and 10 of Table 22. The equation of the least squares line shown is (correlation coefficient = 0.94)

$$T_w = 14.2 + 0.72T \qquad (60)$$

For air temperatures below 51°F, water temperature is greater than air temperature, and the opposite is true for air temperatures greater than 51°F. It will be noted that 51°F is quite close to the average annual air temperature of 49°F given in Table 18. Equation 60 can be written in more general form as follows:

$$T_w = T_{wo} + \frac{\Delta T_w}{\Delta T} T \qquad (61)$$

where

$T_{wo}$ = water temperature when $T = 0$, °F,

$\frac{\Delta T_w}{\Delta T}$ = rate of change of water temperature with air temperature, dimensionless.

Equation 61 can be written

$$T - T_w = T\left(1 - \frac{\Delta T_w}{\Delta T}\right) - T_{wo} \qquad (62)$$

Substituting equation 62 into equation 23 gives

$$E = -\frac{0.093\ k}{\tau} T_{wo} + \frac{0.093\ k}{\tau}\left(1 - \frac{\Delta T_w}{\Delta T}\right) T \qquad (63)$$

which has the same form as equations 29 and 56. The ratio of the slope to the intercept in equation 63 is

$$\frac{\left(1 - \frac{\Delta T_w}{\Delta T}\right)}{-T_{wo}} = \frac{\text{slope}}{\text{intercept}} \qquad (64)$$

For equation 29 this ratio is - 0.0497 ≅ - 0.05 and for equation 56 this ratio is - 0.0657.

Equation 63 provides an understanding of why equations of the form of equations 29 and 56 work so well despite their unexpected simplicity. It is interesting to note that the ratio of equation 64 has essentially the same numerical value for 4 of the 6 cities listed in Table 8.

The water evaporation rate in inches per month is 365E. Using the data in Table 8, the following least squares results were obtained (correlation coefficient = 0.95):

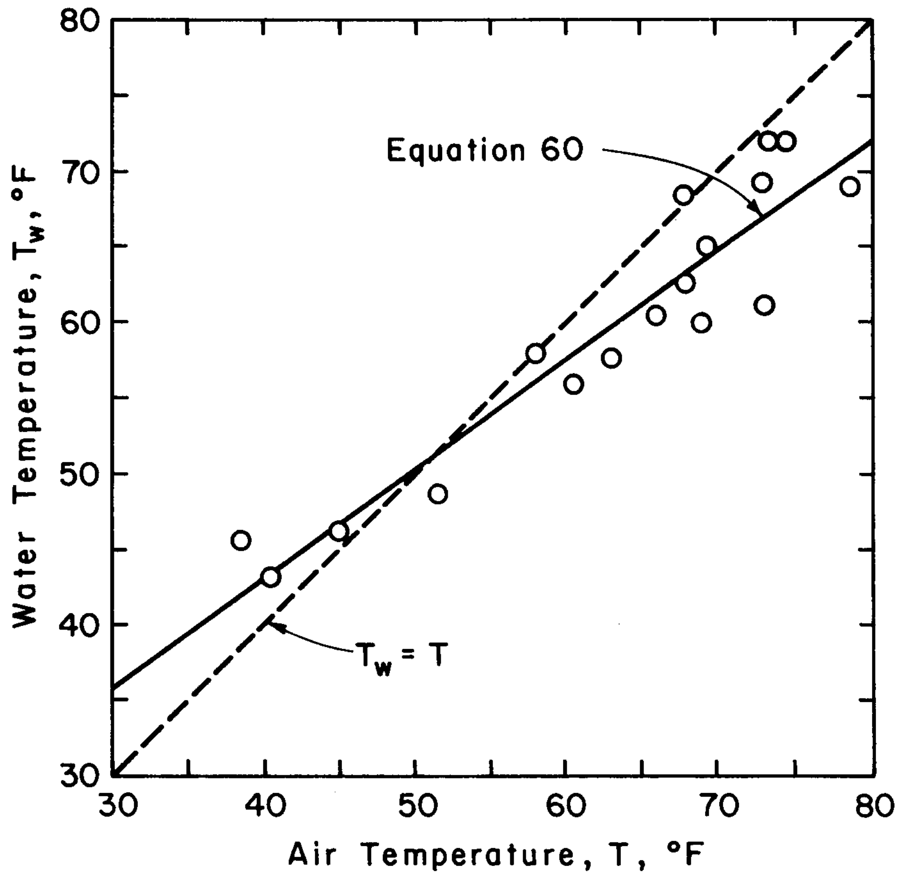


Figure 19 - Water and Air Temperature, Fort Collins Site, Covered Unit

$$365\ \bar{E} = -3.11 + 0.00485s \qquad (65)$$

where $\bar{E}$ = average annual water evaporation rate, feet/day,

$s$ = solar radiation, $\frac{\text{Btu}}{(\text{ft}^2)(\text{day})}$ .

Clearly the average solar radiation has a profound effect on the average water evaporation rate.

Also from Table 8, it will be noted that the average air temperature plus the ratio intercept/slope has the following values respectively: 28.7, 28.6, 26.3, 28.9, 18.6, and 29.2. With the exception of the 18.6 value for Seattle, Washington, the rest of these values are practically the same with an average of 28.3, a standard deviation of 1.2, and a coefficient of variation of 0.04.

In order to develop equations similar to those in Table 8 for other locations, the following procedure is used. Equation 63 can be written

$$365\ E = \text{intercept} + (\text{slope})T \qquad (66)$$

and

$$365\ \bar{E} = \text{intercept} + (\text{slope})\bar{T} \qquad (67)$$

From the foregoing discussion it is known that

$$\bar{T} + \frac{\text{intercept}}{\text{slope}} = 28.3 \qquad (68)$$

Substituting equations 65 and 68 into equation 67, one obtains

$$\text{slope} = -\ 0.11 + 0.000171s \qquad (69)$$

and

$$\text{intercept} = -3.11 + 0.11\bar{T} + 0.00484s\ - 0.000171s\bar{T}\ . \qquad (70)$$

Apparently the slope is determined primarily by the amount of solar radiation while the intercept is a function of both solar radiation and average air temperature. Substitution of equations 69 and 70 into equation 66 gives

$$365\ E = -\ 3.11 + 0.00484s + (\bar{T}\text{-}T)(0.11\ -\ 0.000171s) \quad (71)$$

Comparison of the data in Tables 23 and 22 shows that the water evaporation tanks were not temperature stratified in that the bottom and top water temperatures were identical. Inspection of Table 27 indicates that the soil temperature at a depth of 3 inches and shielded from the sun is approximately the same as the water temperature.

Table 34 shows the relative performance of 3 of the Fort Collins Site units at a time of year when ice cover is relatively common. Column

Table 34. Fort Collins Site Ice Data

| Date | Uncovered Unit liquid water depth, ft (1) | Uncovered Unit ice thickness in feet (2) | Uncovered Unit equivalent water depth, feet (3) | Uncovered Unit water evaporation, feet (4) | Covered Unit liquid water depth, feet (1) | Covered Unit ice thickness in feet (2) | Covered Unit equivalent water depth, feet (3) | Covered Unit water evaporation, feet (4) | Enclosed Unit liquid water depth, feet (1) | Enclosed Unit ice thickness in feet (2) | Enclosed Unit equivalent water depth, feet (3) | Enclosed Unit water evaporation, feet (4) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11-28-73 | 0.95 | 0.25 | 1.18 | 0 | 1.33 | 0.15 | 1.47 | 0.01 | 1.28 | 0.01 | 1.29 | 0.01 |
| 12-3-73 | 1.14 | 0.04 | 1.18 | 0.06 | 1.45 | 0.01 | 1.46 | 0.06 | 1.28 | 0 | 1.28 | 0.04 |
| 12-11-73 | 0.89 | 0.25 | 1.12 | 0.03 | 1.40 | 0 | 1.40 | 0.06 | 1.24 1.76 | 0 | 1.24 1.76 | 0.03 |
| 12-17-73 | 0.88 | 0.23 | 1.09 | 0 | 1.33 | 0.01 | 1.34 | 0.03 | 1.73 | 0 | 1.73 | 0.01 |
| 12-21-73 | 0.67 | 0.46 | 1.09 | -0.09 | 1.12 | 0.21 | 1.31 | 0.10 | 1.70 | 0.02 | 1.72 | 0.07 |
| 1-14-74 | 0 | 1.29 | 1.18 | 0 | 0 | 1.32 | 1.21 | 0.06 | 1.10 | 0.60 | 1.65 | -0.01 |
| 1-21-74 | 0.42 | 0.83 | 1.18 | 0.21 | 0.58 | 0.62 | 1.15 | 0.10 | 1.64 | 0.02 | 1.66 | 0.10 |
| 2-11-74 | 0.63 | 0.38 | 0.97 | -0.03 | 0.99 | 0.06 | 1.05 | 0.06 | 1.56 | 0 | 1.56 | 0.04 |
| 2-19-74 | 0.97 | 0.03 | 1.00 | | 0.98 | 0.01 | 0.99 | | 1.52 | 0 | 1.52 | |
| Total average | | 0.42 | | 0.18 | | 0.27 | | 0.48 | | 0.07 | | 0.29 |

1 is the depth of liquid water. Column 2 is the depth of solid water (ice). Column 3 is column 1 + (0.917)(column 2) = water depth if all the ice were melted. Column 4 is the actual water evaporation.

It is interesting to note that the water evaporation from the covered unit (0.48 feet) was about 1.7 times the water evaporation from the enclosed unit (0.29 feet), while the water evaporation from the uncovered unit (in excess of precipitation) was only 0.18 feet. These results were obtained despite the fact that there was always more ice in the covered unit than in the enclosed unit. Comparison of the data for the uncovered and covered units shows the effectiveness of the transparent roof cover in reducing long wave radiation heat losses in that the average ice thickness in the covered unit was only 64% that of the uncovered unit.

## Red Feather Site

### Full Scale Unit

Because the analysis of the data from the full scale unit is not perfectly straight forward, detailed calculations are shown in Table 35. The data in columns 1-3, 6, 7, and 10 of Table 35 was obtained from columns 1-3, 9, 10, 17, 18, and 20 of Table 29. Column 4 in Table 35 was determined from columns 1-3 and Table 36. Column 5 was determined from column 4. Column 8 was calculated using equation 52 and column 7. Column 9 was calculated using equation 53 and column 7. Column 11 is the time weighted average of the values in column 9. Column 12 was calculated from the values listed in column 8. Column 13 = column 10 minus column 12. Column 14 is column 13 divided by column 11. Column 15 is column 14 divided by column 5.

Because the water meter was located inside the cabin, and because none of the project personnel had a key to this cabin, it was not always possible to obtain a water meter reading everytime that the other readings were made. As a result, some of the values listed in columns 6 and 11 are time weighted average values.

During the period November 17, 1974, to June 26, 1975, the maximum-minimum thermometer recording air temperature broke, so the time weighted average air temperature for the period November 9, 1973, to June 27, 1974, was used to get the value listed in column 6.

The values in columns 6 and 15 of Table 35 are plotted in Figure 20. The 2 points designated by arrows were determined during periods when part of the roof was gone and consequently had significantly lower evaporation rates than that predicted by equation 29. The point corresponding to an average air temperature of 43°F indicates a negative rate of evaporation which could have been caused by different ice thicknesses and consequently probably has no real meaning.

Table 37 illustrates the quantitative approach taken to compare the results obtained with those predicted by equation 29. The time weighted average value of the ratio $\frac{\text{Observed E}}{\text{Calculated E}}$ is 1.03, so that equation 29

Table 35. Red Feather Site, Full Scale Unit

| Year (1) | Month (2) | Day (3) | Day of the year (4) | days, t/24 (5) | T, °F (6) | Water depth, H, ft (7) | Water volume V, $ft^3$ (8) | Water area, A, $ft^2$ (9) | Water added, $ft^3$ (10) | Average area, $\bar{A}$, $ft^2$ (11) | ΔV, $ft^3$ (12) | Water evaporation, $ft^3$ (13) | Evaporation depth, ft (14) | Water evaporation rate, E, ft/day (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 73 | 7 | 22 | 203 | | | 2.28 | 201.12 | 165 | | | | | | |
| | | | | 3 | 56 | | | | 30.05 | 168.5 | 20.24 | 9.81 | 0.0582 | 0.0194 |
| 73 | 7 | 25 | 206 | | | 2.40 | 221.36 | 172 | | | | | | |
| | | | | | | | | | | | | | | |
| 73 | 7 | 25 | 206 | | | 2.40 | 221.36 | 172 | | | | | | |
| 73 | 8 | 18 | 230 | | | 2.44 | -- | 175 | | | | | | |
| | | | | 107 | 53 | | | | 262.45 | 190 | 110.37 | 152.08 | 0.800 | 0.00748 |
| 73 | 10 | 21 | 294 | | | 2.96 | -- | 207 | | | | | | |
| 73 | 10 | 23 | 296 | | | 3.00 | -- | 209 | | | | | | |
| 73 | 11 | 9 | 313 | | | 2.98 | 331.73 | 208 | | | | | | |
| | | | | | | | | | | | | | | |
| 73 | 11 | 9 | 313 | | | 2.98 | 331.73 | 208 | | | | | | |
| 74 | 4 | 19 | 109 | | | 2.95 | 325.52 | 206 | | | | | | |
| | | | | 182 | 35 | | | | 108.04 | 206 | -10.09 | 118.13 | 0.573 | 0.00315 |
| 74 | 4 | 19 | 109 | | | 2.76 | 287.43 | 195 | | | | | | |
| 74 | 5 | 10 | 130 | | | 2.74 | 283.55 | 194 | | | | | | |

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Table 35. Continued.

| Year (1) | Month (2) | Day (3) | Day of the year (4) | days, t/24 (5) | T, °F (6) | Water depth, H, ft (7) | Water volume, V, $ft^3$ (8) | Water area, A, $ft^2$ (9) | Water added, $ft^3$ (10) | Average area $\bar{A}$, $ft^2$ (11) | $\Delta V$, $ft^3$ (12) | Water evaporation, $ft^3$ (13) | Evaporation depth, ft (14) | Water evaporation rate, E, ft/day (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74 | 5 | 10 | 130 | | | 2.74 | 283.55 | 194 | | | | | | |
| | | | | 12 | 54 | | | | 34.82 | 194.5 | 3.88 | 30.94 | 0.159 | 0.01325 |
| 74 | 5 | 22 | 142 | | | 2.76 | 287.43 | 195 | | | | | | |
| | | | | | | | | | | | | | | |
| 74 | 5 | 22 | 142 | | | 2.76 | 287.43 | 195 | | | | | | |
| 74 | 6 | 27 | 178 | | | 3.05 | 346.44 | 212 | | | | | | |
| | | | | 65 | 62 | | | | 235.88 | 206 | 71.53 | 164.35 | 0.798 | 0.0123 |
| 74 | 6 | 27 | 178 | | | 2.96 | 327.58 | 207 | | | | | | |
| 74 | 7 | 26 | 207 | | | 3.02 | 340.10 | 211 | | | | | | |

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Table 35. Continued.

| Year (1) | Month (2) | Day (3) | Day of the year (4) | days, t/24 (5) | T, °F (6) | Water depth, H, ft (7) | Water volume, V, $ft^3$ (8) | Water area A, $ft^2$ (9) | Water added, $ft^3$ (10) | Average area $\bar{A}$, $ft^2$ (11) | ΔV, $ft^3$ (12) | Water evaporation, $ft^3$ (13) | Evaporation depth, ft (14) | Water evaporation rate, E, ft/day (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74 | 7 | 26 | 207 | | | 3.02 | 340.10 | 211 | | | | | | |
| 74 | 8 | 9 | 221 | | | 3.13 | 363.62 | 217 | | | | | | |
| 74 | 8 | 9 | 221 | | | 0.54 | 13.62 | 47 | | | | | | |
| | | | | 51 | 57 | | | | 133.91 | 110 | 61.40 | 72.51 | 0.659 | 0.0129 |
| 74 | 9 | 7 | 250 | | | 1.05 | 47.22 | 84 | | | | | | |
| 74 | 9 | 7 | 250 | | | 1.06 | 48.06 | 85 | | | | | | |
| 74 | 9 | 15 | 258 | | | 1.10 | 51.50 | 88 | | | | | | |
| | | | | | | | | | | | | | | |
| 74 | 9 | 15 | 258 | | | 1.10 | 51.50 | 88 | | | | | | |
| | | | | 21 | 54 | | | | 57.40 | 98 | 29.33 | 28.07 | 0.286 | 0.0136 |
| 74 | 10 | 6 | 279 | | | 1.40 | 80.83 | 108 | | | | | | |
| | | | | 13 | 53 | | | | 17.94 | 108 | 0.00 | 17.94 | 0.166 | 0.0128 |
| 74 | 10 | 19 | 292 | | | 1.40 | 80.83 | 108 | | | | | | |
| | | | | 22 | 43 | | | | 11.73 | 112 | 13.43 | -1.70 | -0.015 | -0.0007 |
| 74 | 11 | 10 | 314 | | | 1.52 | 94.26 | 116 | | | | | | |
| | | | | 7 | 31 | | | | 8.49 | 117 | 3.51 | 4.98 | 0.043 | 0.0061 |
| 74 | 11 | 17 | 321 | | | 1.55 | 97.77 | 118 | | | | | | |

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Table 35. Continued.

| Year (1) | Month (2) | Day (3) | Day of the year (4) | days, t/24 (5) | T, °F (6) | Water depth, H, ft (7) | Water volume, V, $ft^3$ (8) | Water area A, $ft^2$ (9) | Water added, $ft^3$ (10) | Average area $\bar{A}$, $ft^2$ (11) | $\Delta V$, $ft^3$ (12) | Water evaporation, $ft^3$ (13) | Evaporation depth, ft (14) | Water evaporation rate, E, ft/day (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74 | 11 | 17 | 321 | | | 1.12 | 53.27 | 89 | | | | | | |
| | | | | 221 | 40 | | | | 267.34 | 101.5 | 37.55 | 229.79 | 2.26 | 0.0102 |
| 75 | 6 | 26 | 177 | | | 1.49 | 90.82 | 114 | | | | | | |

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Table 36. Day of the Year.

| 1 Jan. | 2 Feb. | 3 Mar. | 4 April | 5 May | 6 June | 7 July | 8 Aug. | 9 Sept. | 10 Oct. | 11 Nov. | 12 Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 32 | 60 | 91 | 121 | 152 | 182 | 213 | 244 | 274 | 305 | 335 |
| 2 | 33 | 61 | 92 | 122 | 153 | 183 | 214 | 245 | 275 | 306 | 336 |
| 3 | 34 | 62 | 93 | 123 | 154 | 184 | 215 | 246 | 276 | 307 | 337 |
| 4 | 35 | 63 | 94 | 124 | 155 | 185 | 216 | 247 | 277 | 308 | 338 |
| 5 | 36 | 64 | 95 | 125 | 156 | 186 | 217 | 248 | 278 | 309 | 339 |
| 6 | 37 | 65 | 96 | 126 | 157 | 187 | 218 | 249 | 279 | 310 | 340 |
| 7 | 38 | 66 | 97 | 127 | 158 | 188 | 219 | 250 | 280 | 311 | 341 |
| 8 | 39 | 67 | 98 | 128 | 159 | 189 | 220 | 251 | 281 | 312 | 342 |
| 9 | 40 | 68 | 99 | 129 | 160 | 190 | 221 | 252 | 282 | 313 | 343 |
| 10 | 41 | 69 | 100 | 130 | 161 | 191 | 222 | 253 | 283 | 314 | 344 |
| 11 | 42 | 70 | 101 | 131 | 162 | 192 | 223 | 254 | 284 | 315 | 345 |
| 12 | 43 | 71 | 102 | 132 | 163 | 193 | 224 | 255 | 285 | 316 | 346 |
| 13 | 44 | 72 | 103 | 133 | 164 | 194 | 225 | 256 | 286 | 317 | 347 |
| 14 | 45 | 73 | 104 | 134 | 165 | 195 | 226 | 257 | 287 | 318 | 348 |
| 15 | 46 | 74 | 105 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 |
| 16 | 47 | 75 | 106 | 136 | 167 | 197 | 228 | 259 | 289 | 320 | 350 |
| 17 | 48 | 76 | 107 | 137 | 168 | 198 | 229 | 260 | 290 | 321 | 351 |
| 18 | 49 | 77 | 108 | 138 | 169 | 199 | 230 | 261 | 291 | 322 | 352 |
| 19 | 50 | 78 | 109 | 139 | 170 | 200 | 231 | 262 | 292 | 323 | 353 |
| 20 | 51 | 79 | 110 | 140 | 171 | 201 | 232 | 263 | 293 | 324 | 354 |
| 21 | 52 | 80 | 111 | 141 | 172 | 202 | 233 | 264 | 294 | 325 | 355 |
| 22 | 53 | 81 | 112 | 142 | 173 | 203 | 234 | 265 | 295 | 326 | 356 |
| 23 | 54 | 82 | 113 | 143 | 174 | 204 | 235 | 266 | 296 | 327 | 357 |
| 24 | 55 | 83 | 114 | 144 | 175 | 205 | 236 | 267 | 297 | 328 | 358 |
| 25 | 56 | 84 | 115 | 145 | 176 | 206 | 237 | 268 | 298 | 329 | 359 |
| 26 | 57 | 85 | 116 | 146 | 177 | 207 | 238 | 269 | 299 | 330 | 360 |
| 27 | 58 | 86 | 117 | 147 | 178 | 208 | 239 | 270 | 300 | 331 | 361 |
| 28 | 59 | 87 | 118 | 148 | 179 | 209 | 240 | 271 | 301 | 332 | 362 |
| 29 | | 88 | 119 | 149 | 180 | 210 | 241 | 272 | 302 | 333 | 363 |
| 30 | | 89 | 120 | 150 | 181 | 211 | 242 | 273 | 303 | 334 | 364 |
| 31 | | 90 | | 151 | | 212 | 243 | | 304 | | 365 |

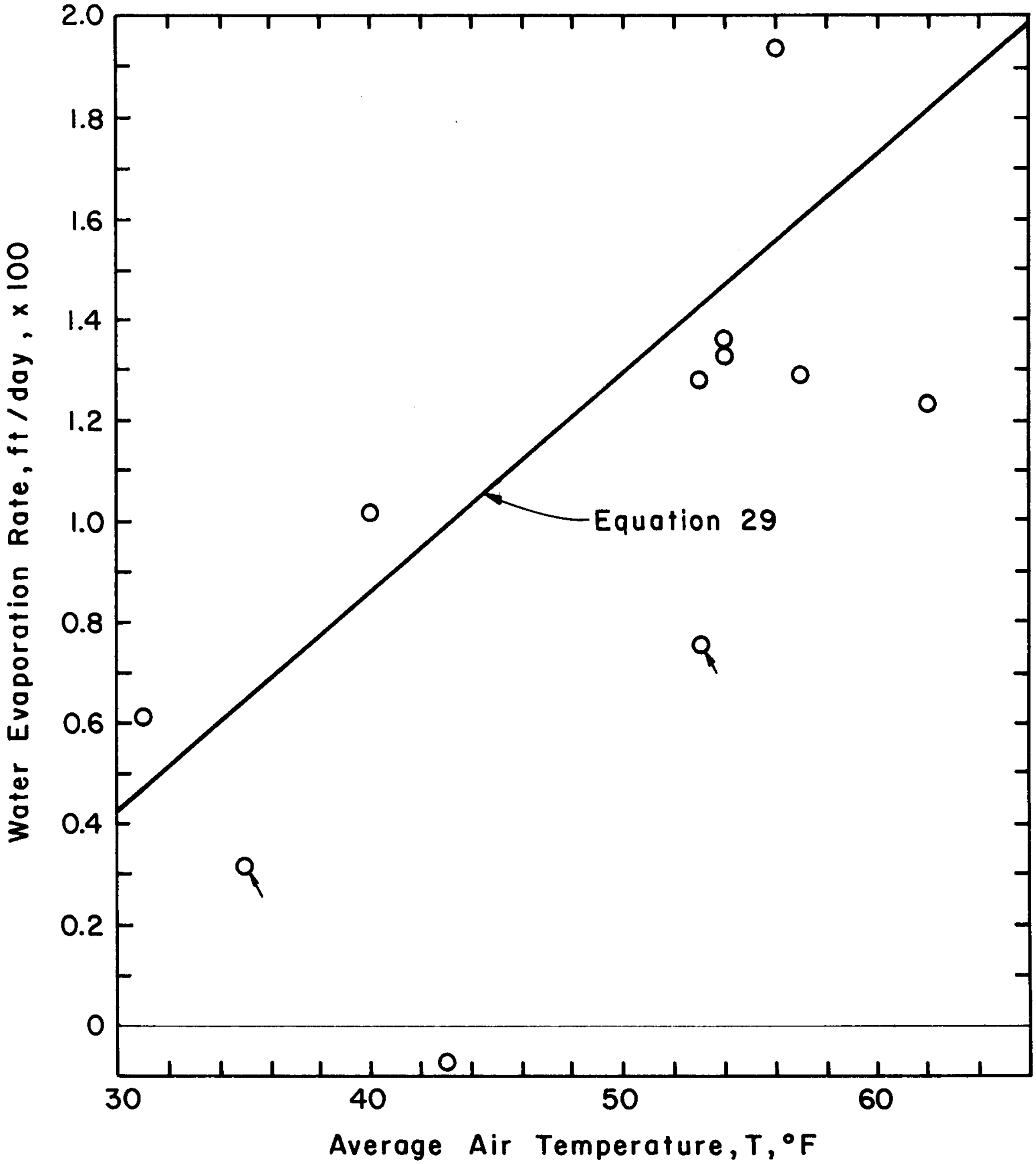


Figure 20 - Water Evaporation Rate (E) and Air Temperature, Red Feather Site, Full Scale Unit.

Table 37. Comparison of Results for the Full Scale Unit at the Red Feather Site with Equation 29.

| From Table 35 | | E x 100 from Eq. 29 (3) | Ratio, Observed/Calculated (4) | Days (5) | Ratio times Days (6) |
|---|---|---|---|---|---|
| T, °F (1) | E x 100 (2) | | | | |
| 56 | 1.94 | 1.55 | 1.252 | 3 | 4 |
| 54 | 1.325 | 1.46 | 0.908 | 12 | 11 |
| 62 | 1.23 | 1.81 | 0.680 | 65 | 44 |
| 57 | 1.29 | 1.59 | 0.811 | 51 | 41 |
| 54 | 1.36 | 1.46 | 0.932 | 21 | 20 |
| 53 | 1.28 | 1.42 | 0.901 | 13 | 12 |
| 31 | 0.61 | 0.46 | 1.326 | 7 | 9 |
| 40 | 1.02 | 0.85 | 1.200 | 221 | 265 |
| Σ | | | | 393 | 406 |
| | Average | | | 49 | 51 |

is apparently satisfactory for predicting the water evaporation rate from a full scale wastewater evaporation unit.

Covered Unit

The results are shown in Table 38, and these results are plotted in Figure 21. The time weighted average value of the ratio $\frac{\text{Observed E}}{\text{Calculated E}}$ is 0.65, while the value of this ratio for the full scale unit at the same site was 1.03. Therefore it appears that the water evaporation from a full scale unit will be (1.03 ÷ 0.65=) 1.58 times that observed from a covered unit.

Storm Mountain Site, Covered Unit

The observed data for this site is shown in Table 39, and this data is plotted in Figure 22. During part of the period of observation at this site, the experimental evaporation unit was completely enclosed from November 21, 1973, to May 27, 1974, during which time 0.62 feet of water was evaporated. During the period November 14, 1972, to June 1, 1973, 0.802 feet of water were evaporated from the covered unit. The average evaporation rate when the unit was enclosed was 0.0033 feet per day and while covered was 0.0040 feet per day. Once again, the covered unit out performed the enclosed unit.

Table 38. Comparison of Results for the Covered Unit at the Red Feather Site with Equation 29.

| From Table 30 | | E x 100 from Eq. 29 (3) | Ratio, Observed/Calculated (4) | Days (from Table 30) (5) | Ratio times Days (6) |
|---|---|---|---|---|---|
| T, °F (1) | EX100 (Observed) (2) | | | | |
| 34 | 0.831 | 0.59 | 1.408 | 52 | 73 |
| 16 | 0.212 | 0 | ∞ | -- | -- |
| 51 | 1.038 | 1.33 | 0.780 | 13 | 10 |
| 58.5 | 1.292 | 1.65 | 0.783 | 24 | 19 |
| 64.5 | 1.06 | 1.92 | 0.552 | 16 | 9 |
| 61.5 | 1.000 | 1.78 | 0.562 | 24 | 13 |
| 54 | 0.766 | 1.45 | 0.528 | 64 | 34 |
| 33 | 0.336 | 0.54 | 0.622 | 128 | 80 |
| 49.5 | 0.857 | 1.26 | 0.680 | 21 | 14 |
| 54 | 1.08 | 1.45 | 0.745 | 12 | 9 |
| 60.5 | 1.06 | 1.74 | 0.609 | 36 | 22 |
| 64.5 | 1.17 | 1.92 | 0.609 | 29 | 18 |
| 61 | 0.857 | 1.76 | 0.487 | 14 | 7 |
| 40 | 0.452 | 0.85 | 0.532 | 221 | 118 |
| Σ | | | | 654 | 426 |
| Average | | | | 50 | 33 |

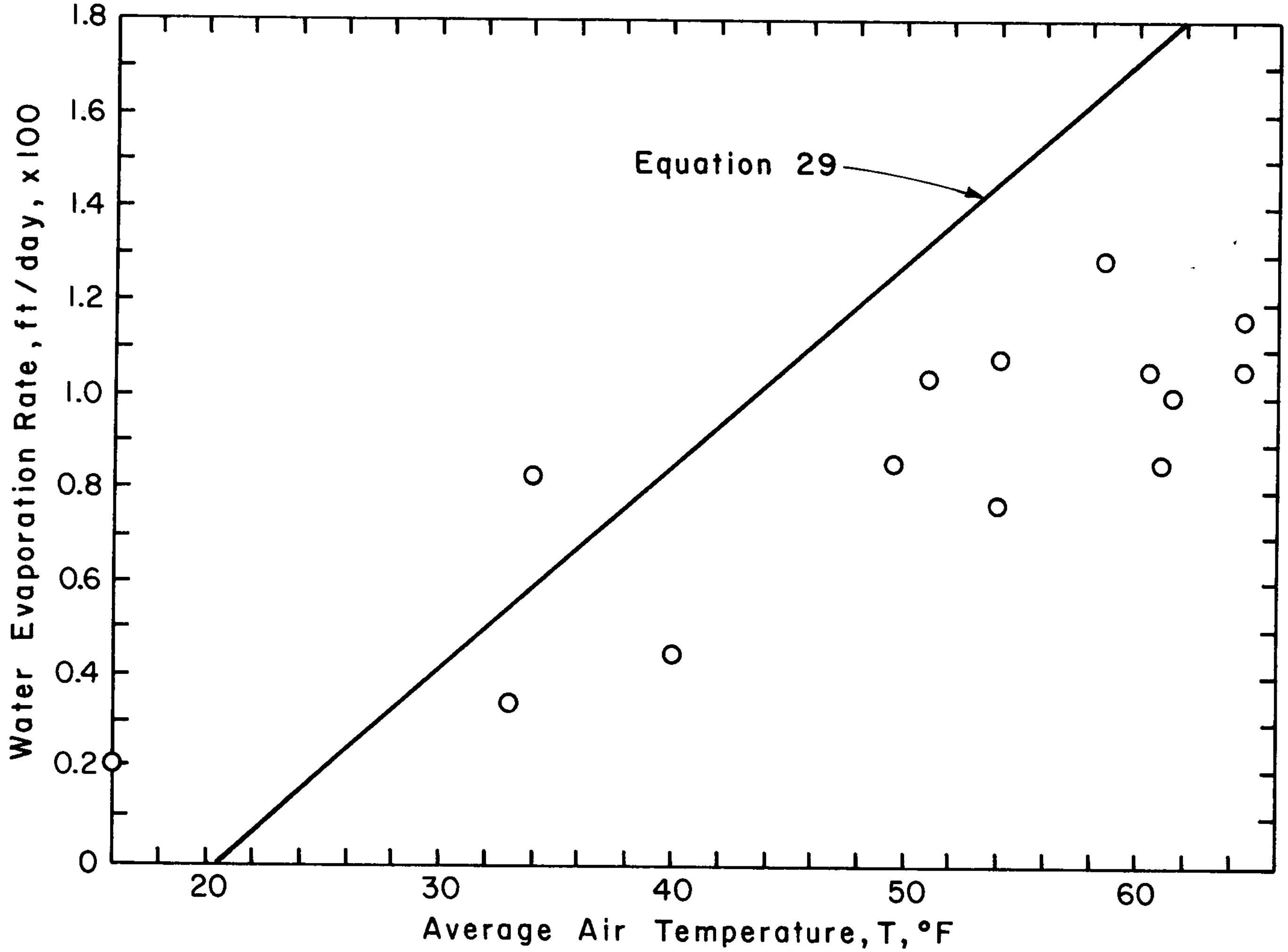


Figure 21 - Water Evaporation Rate (E) and Air Temperature, Red Feather Site, Covered Unit

Table 39. Comparison of Results for the Covered Unit at the Storm Mountain Site with Equation 29.

| | From Table 31 T, °F (1) | E x 100 (Observed) (2) | E x 100 from Eq. 29 (3) | Ratio, Observed/Calculated (4) | Days (from Table 31) (5) | Ratio times Days (6) |
|---|---|---|---|---|---|---|
| | 33 | 0.76 | 0.54 | 1.41 | 22 | 31 |
| | 20.5 | 0.43 | 0 | ∞ | 110 | -- |
| | 32 | 0.37 | 0.50 | 0.74 | 89 | 66 |
| | 64 | 1.32 | 1.89 | 0.70 | 36 | 25 |
| | 62.5 | 1.06 | 1.82 | 0.58 | 36 | 21 |
| | 59.5 | 1.33 | 1.69 | 0.79 | 24 | 19 |
| | 51 | 0.67 | 1.32 | 0.51 | 39 | 20 |
| | 34 | 0.78 | 0.58 | 1.34 | 36 | 48 |
| * | 19 | 0.18 | 0 | ∞ | (62) | -- |
| * | 32 | 0.29 | 0.50 | 0.58 | (66) | (38) |
| * | 54 | 0.69 | 1.45 | 0.48 | (39) | (19) |
| | 59 | 1.10 | 1.67 | 0.66 | 31 | 20 |
| | 67.5 | 1.90 | 2.04 | 0.93 | 10 | 9 |
| | 61 | 1.03 | 1.76 | 0.59 | 34 | 20 |
| | 57.5 | 1.09 | 1.60 | 0.68 | 32 | 22 |
| | 48 | 0.96 | 1.19 | 0.81 | 25 | 20 |
| | 45 | 0.50 | 1.06 | 0.47 | 28 | 13 |
| | 35 | 0.38 | 0.62 | 0.61 | 42 | 26 |
| ** | 22.5 | 0.16 | 0.09 | 1.78 | 113 | 201 |
| | 48 | 0.87 | 1.19 | 0.73 | 52 | 38 |
| | Σ (excluding values in parentheses) | | | | 649 | 599 |
| | Average (excluding values in parentheses) | | | | 41 | 37 |

* Results obtained while unit was enclosed.
**Half of roof had holes through which precipitation could fall into tank.

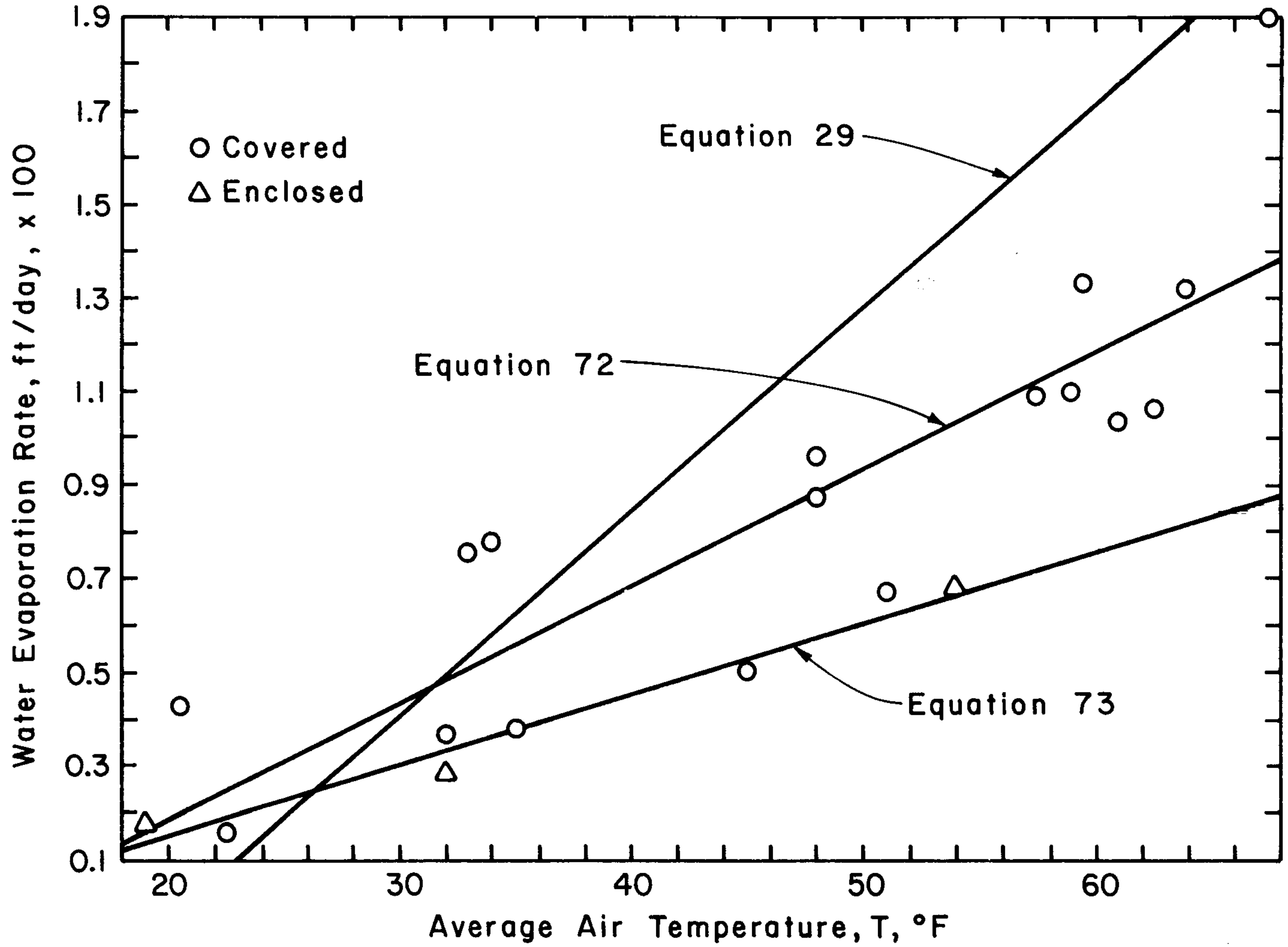


Figure 22 - Water Evaporation Rate (E) and Air Temperature, Storm Mountain Site, Covered Unit

The data for the covered unit in Figure 22 was fitted by least squares (correlation coefficient = 0.86) to obtain

$$E = - 0.00306 + 0.000249\ T \quad . \tag{72}$$

The data in Figure 22 for the enclosed unit was also fitted by least square (correlation coefficient = 0.99) to obtain

$$E = - 0.00137 + 0.000150\ T \tag{73}$$

Table 40 illustrates how equations 29 and 72 were compared. From Table 18 it is clear that the average annual air temperature at the Storm Mountain Site is 36.8°F, which is 12.7°F less than the annual average air temperature for Denver, Colorado. Therefore, in Table 40, column 3 = column 2 minus 12.7°F. The values listed in column 3 were then used to calculate the values listed in columns 4 and 5. It is clear from the totals of columns 4 and 5 that water evaporation from the covered unit at the Storm Mountain site was [(0.609)(100%)/0.734=] 83% of that predicted by Equation 29 on an annual average basis.

Table 40. Comparison of Equations 29 and 72 for the Storm Mountain Site.

| | Air temperature, °F | | E x 100 | |
|---|---|---|---|---|
| Month (1) | Denver, Colorado (2) | Storm Mountain Site (3) | From Eq. 72 (4) | From Eq. 29 (5) |
| January | 28.5 | 15.8 | 0.087 | 0 |
| February | 31.5 | 18.8 | 0.162 | 0 |
| March | 36.4 | 23.7 | 0.284 | 0.137 |
| April | 46.4 | 33.7 | 0.533 | 0.571 |
| May | 56.2 | 43.5 | 0.777 | 0.997 |
| June | 66.5 | 53.8 | 1.033 | 1.444 |
| July | 72.9 | 60.2 | 1.192 | 1.722 |
| August | 71.5 | 58.8 | 1.157 | 1.662 |
| September | 63.0 | 50.3 | 0.946 | 1.292 |
| October | 51.4 | 38.7 | 0.657 | 0.788 |
| November | 37.7 | 25.0 | 0.316 | 0.193 |
| December | 31.6 | 18.9 | 0.165 | 0 |
| Annual Average | 49.5 | 36.8 | 0.609 | 0.734 |

## Breckenridge Site, Covered Unit

The water evaporation data for this site is given in Table 41 and this data in turn is plotted in Figure 23. Water evaporation at this site was at least (498 x 100% ÷ 919=) 54% of that predicted by Equation 29.

Table 41. Comparison of Results for the Covered Unit at the Breckenridge Site with Equation 29.

| From Table 32 | | E x 100 from Eq. 29 (3) | Ratio, Observed/Calculated (4) | Days (from Table 32) (5) | Ratio times Days (6) |
|---|---|---|---|---|---|
| T, °F (1) | E x 100 (observed) (2) | | | | |
| 47.5 | 1.44 | 1.17 | 1.23 | 19 | 23 |
| 40.5 | 0.29 | 0.86 | 0.34 | 227 | 77 |
| 47 | 0.82 | 1.15 | 0.71 | 11 | 8 |
| 46 | 0.75 | 1.1 | 0.68 | 140 | 95 |
| 16.5 | 0.06 | 0 | ∞ | 62 | -- |
| 31 | ≥0.30 | 0.45 | ≥0.67 | 230 | ≥154 |
| 47.5 | 0.65 | 1.17 | 0.56 | 43 | 24 |
| 25.5 | 0 | 0.21 | 0 | 44 | 0 |
| 31.5 | 0.27 | 0.47 | 0.57 | 205 | 117 |
| Total | | | | 919 | ≥498 |
| Average | | | | 115 | ≥ 71 |

## Summary of Water Evaporation Data Analysis

With the single exception of the Fcrt Collins Site, all 3 of the remaining sites were at least partially shaded from the sun by surrounding trees. Despite this fact, the full scale unit still performed slightly better than was predicted from Equation 29. From the results obtained at the Red Feather Site, it is clear that one could expect the evaporation from a full scale unit to be (1.03/0.65=) 1.58 times that of a covered unit. With this in mind, Table 42 shows the observed water evaporation at the altitudes of the 4 experimental sites.

Table 42. Water Evaporation versus Altitude.

| Altitude, feet | Ratio, Observed Evaporation Rate / Calculated Evaporation Rate* | |
|---|---|---|
| | Covered Unit | Full Scale Unit |
| 5,200 | 1.11 | 1.03 |
| 8,180 | 0.65 | |
| 8,570 | 0.83 | |
| 10,665 | 0.54 | |

*Calculated Evaporation Rate using Equation 29.

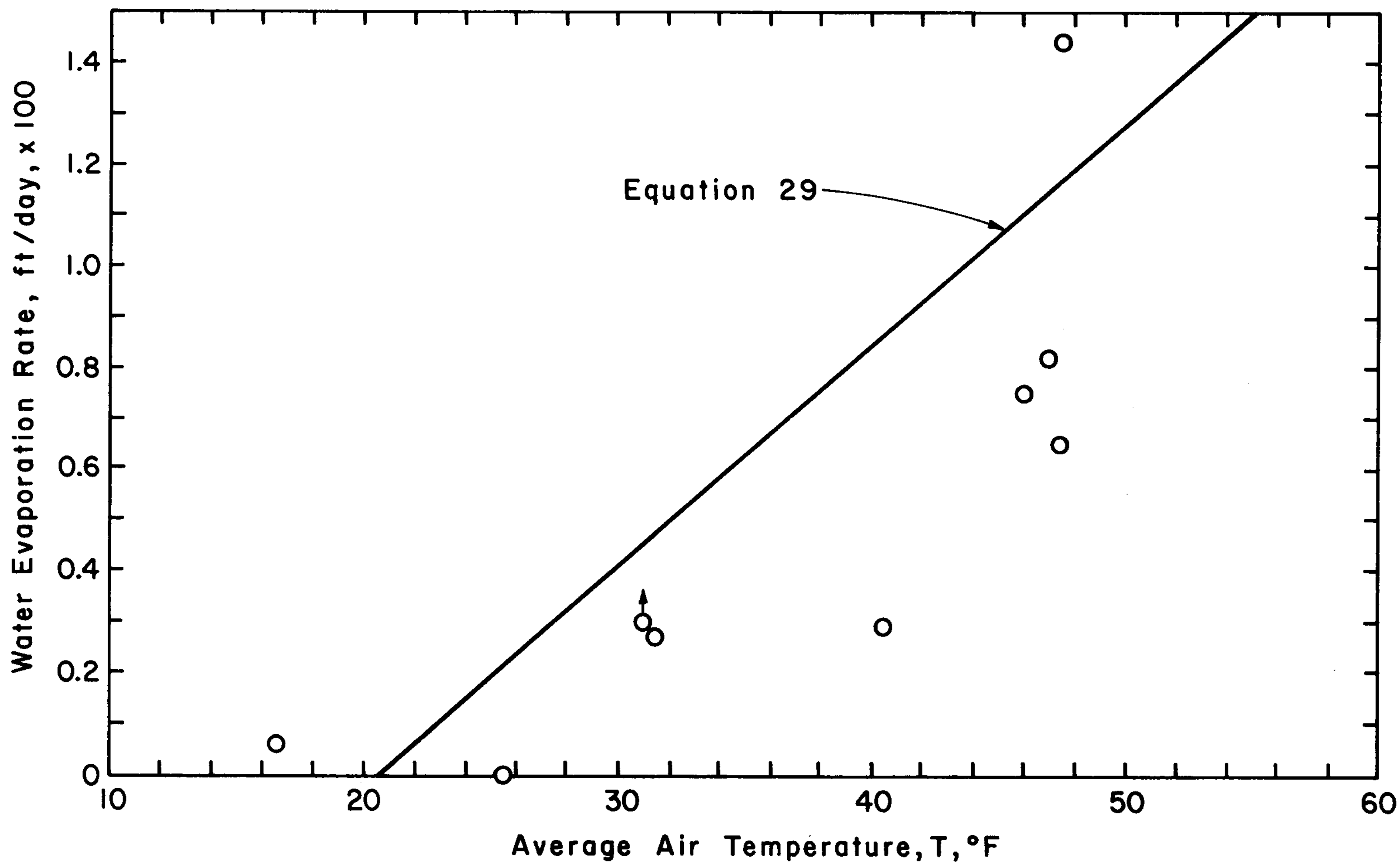


Figure 23 - Water Evaporation Rate (E) and Air Temperature, Breckenridge Site, Covered Unit

Denver, Colorado, is located at 39.7°N, 105°W. Substituting these values into equation 44 gives

$$T = 68.5 - 3.6 \times 10^{-3} z \qquad (74)$$

Combining equations 29 and 74 gives

$$.365E = 7.51 - 0.565 \times 10^{-3} z \qquad (75)$$

Substituting into equation 75 the elevation of Denver (5,280 feet) gives an annual average evaporation rate of 4.53 ft/year compared to an observed rate of 4.62 ft/year. Substituting this same elevation into equation 42 gives 3.91 ft/year. Clearly water evaporation in the oil shale area at an elevation of 5,280 feet is (3.91/4.62=) 0.85 that of Denver.

Having established the factor of 0.85, the results using equation 75 can be directly compared to the Bureau of Reclamation data as in Table 43.

Table 43. Comparison of Equation 75 with Bureau of Reclamation Data.

| Altitude feet (1) | Evaporation Rate, ft/yr | | |
|---|---|---|---|
| | Bureau of Reclamation (2) | from Equation 75 (3) | column 3 times 0.85 (4) |
| 4,000 | 4.6 | 5.25 | 4.5 |
| 5,000 | 4.0 | 4.69 | 4.0 |
| 6,000 | 3.5 | 4.12 | 3.5 |
| 7,000 | 3.25 | 3.56 | 3.0 |

Comparison of columns 2 and 4 in Table 43 shows that agreement is good and consequently that equation 75 is an accurate prediction equation when differences in location are taken into account.

Using the equations given in the section entitled, "Water Surface Heat Balance," Frein (25) calculated the quantity of solar radiation received by the covered unit at each of the 4 sites and the amount received by the full scale unit at the Red Feather Site. In addition he calculated the quantity of solar radiation that would have been received at each site during the time period of its operation if the site had had an elevation of 5,200 feet, taking into account structural shading and the solar radiation transmittance of the precipitation interceptor. Frein's results are given in columns 4 and 5 of Table 44.

The values in column 3 were calculated using equation 24 and were used to estimate the increased amount of solar radiation at higher altitudes. The values in column 6 were obtained by multiplying the values in column 5 by these factors in column 3. Column 7 is the ratio of the observed solar radiation (determined by heat balance) to the calculated solar radiation and therefore is a quantitative measure of the amount of shading caused by surrounding trees, rocks, and topography. It is clear from these values that (with the single exception of the Fort Collins site) significant solar shading occurred at the 3 higher elevation sites. This shading appears to be essentially the same for both the covered and full scale units at the Red Feather site.

The data from Tables 42 and 44 are compared in Figure 24. With the single exception of the full scale unit, it is clear that any reduction in water evaporation rate is directly proportional to the amount of solar shading. Consequently, with the exception of the full scale unit, the ratios in Table 42 were determined by the amount of solar shading. Therefore, if there had been no solar shading (there was none at the Fort Collins site), all of the values given for the covered units in Table 42 would have been near 1. This means that Equation 29 can be used to calculate water evaporation rates at all elevations.

In Table 42 it will be noted that the actual evaporation rate of the Fort Collins Site Covered Unit was 1.11 times that calculated by Equation 29. In addition, it is known that the water evaporation rate from a full scale unit will be 1.58 times that of a covered unit. Therefore it appears that the water evaporation rates that can be expected from full scale units will be (1.11 x 1.58=) 1.75 times that predicted by Equation 29. Therefore, in order to predict water evaporation rates from full scale units, equation 29 should be multiplied by 1.75 to obtain

$$E = -\ 0.0152 + 0.000754\ T \qquad (76)$$

In order to convert equation 76 to a more convenient equation, multiplying by 365 will give the water evaporation rate in either inches per month or feet per year:

$$365\ E = -\ 5.55 + 0.275\ T \qquad (77)$$

The maximum probable water evaporation rate can be <u>roughly</u> estimated by assuming that all of the incoming solar radiation is converted to evaporated water. If the solar radiation is reported in terms of Btu/(ft$^2$)(day, then

$$\frac{\text{Btu}}{(\text{ft}^2)(\text{day}} \left| \frac{365\ \text{days}}{\text{year}} \right| \frac{\text{ft}^3}{62.43\ \text{lb}} \left| \frac{\text{lb}}{1{,}075.8\ \text{Btu}} \right.$$

= ft/year or inches per month or

$$\frac{\text{Btu}}{(\text{ft}^2)(\text{day})} \div 184 = \text{ft/year or inches/month.}$$

Table 45 was constructed using the above conversion and the data in Table 5. It will be noted that during the months of July through October, the evaporation rate predicted by using equation 77 is greater than would be obtained if all the incoming solar energy was converted

Table 44. Effect of Solar Shading on Water Evaporation.

| Unit (1) | Altitude, feet (2) | From Eq. 24 (3) | Solar Radiation, $\frac{Btu}{(hr)(ft^2)}$ | | | Ratio, $\frac{Observed}{Calculated}$ column 4 divided by column 6 (7) |
|---|---|---|---|---|---|---|
| | | | From heat balance (4) | Calculated | | |
| | | | | (at 5,200 feet elevation) (5) | (at site elevation) column 3 times column 5 (6) | |
| Covered | 5,220 | 1 | 49.2 | 50.7 | 50.7 | 0.97 |
| Covered | 8,180 | 1.04 | 36.0 | 60.0 | 62.4 | 0.58 |
| Full Scale | 8,180 | 1.04 | 32.1 | 51.6 | 53.7 | 0.60 |
| Covered | 8,570 | 1.05 | 47.2 | 53.6 | 56.3 | 0.84 |
| Covered | 10,665 | 1.07 | 32.4 | 54.1 | 57.9 | 0.56 |

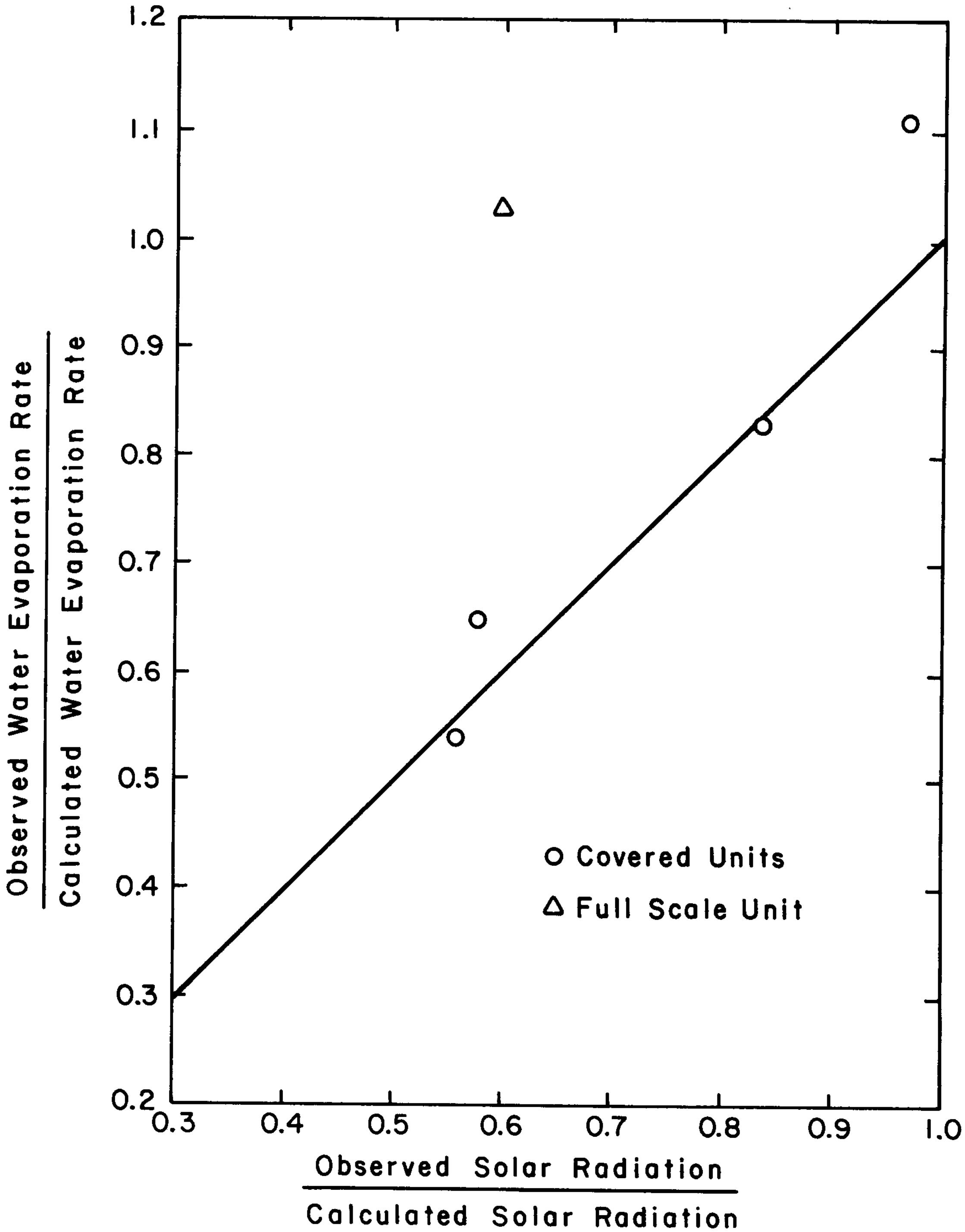


Figure 24 - Effect of Solar Shading on Water Evaporation Rate.

to evaporated water. This could be caused by 1 or more of the following 2 phenomena:

1. If the air temperature is greater than the water temperature, then this will constitute an additional energy input.
2. Water evaporation rates tend to depend on the solar radiation received the previous month. Therefore the water evaporation rates in July through October will depend on the solar radiation received in June through September.

Table 45. Water Evaporation Rates for Denver, Colorado (inches/month).

| Month (1) | Lake evaporation rate (from Table 5) (2) | For full scale wastewater evaporation unit (calculated by equation 77) (3) | If all solar energy is converted to evaporated water (4) |
|---|---|---|---|
| January | 1.6 | 2.3 | 5.2 |
| February | 1.8 | 3.1 | 6.8 |
| March | 2.5 | 4.5 | 8.5 |
| April | 3.7 | 7.2 | 10.5 |
| May | 5.0 | 9.9 | 11.6 |
| June | 7.4 | 12.7 | 13.2 |
| July | 8.8 | 14.5 | 12.8 |
| August | 8.4 | 14.1 | 11.6 |
| September | 6.7 | 11.8 | 9.8 |
| October | 4.6 | 8.6 | 7.5 |
| November | 3.0 | 4.8 | 5.4 |
| December | 1.9 | 3.1 | 4.4 |
| Total | 55.4 | 96.6 | 107.3 |
| Average | 4.6 | 8.1 | 8.9 |

To better illustrate this latter point, consider the fact that as a consequence of equation 17, the daily long wave radiation heat loss from an uncovered water surface is

$$\left[\frac{24 \text{ hours}}{\text{day}} \times \frac{27.4 \text{ Btu}}{(\text{hr})(\text{ft}^2)} = \right] 658 \ \frac{\text{Btu}}{(\text{day})(\text{ft}^2)} .$$

Using the solar radiation data in column 7 of Table 5, column 2 in Table 46 is constructed by subtracting 658. It will be noted that the total of column 2 of Table 45 is 85.6% of the total of column 3 of Table 46. Therefore the actual lake evaporation can be estimated by using 85.6% of the previous month's estimate in column 3 of Table 46. In other words, the values in column 4 of Table 46 are 0.856 times the values listed in column 3 for the previous month. The figure 85.6% indicates that apparently 14.4% of the annual net radiation heat gain is lost by means of convection and that the rest is lost by water evaporation. Finally column 5 is the observed lake evaporation. It will be noted that the figures in columns 4 and 5 of Table 46 are highly correlated (correlation coefficient = 0.975) in that the calculated value in column 4 is related to the actual value in column 5 as follows:

Table 46. Estimation of Lake Evaporation from Net Radiation Data for Denver.

| Month (1) | Net Radiation Heat Gain, $\frac{\text{Btu}}{(\text{day})(\text{ft}^2)}$ [solar radiation - 658] (2) | Evaporation if net radiation is converted to evaporated water, $\frac{\text{inches}}{\text{month}}$, (2)÷184 (3) | Estimated lake evaporation, $\frac{\text{inches}}{\text{month}}$ (0.856 x previous month value in column 3) (4) | Actual lake evaporation, $\frac{\text{inches}}{\text{month}}$ (from column 2 of Table 45) (5) |
|---|---|---|---|---|
| January | 301 | 1.6 | 0.7 | 1.6 |
| February | 597 | 3.2 | 1.4 | 1.8 |
| March | 910 | 4.9 | 2.7 | 2.5 |
| April | 1,279 | 7.0 | 4.2 | 3.7 |
| May | 1,482 | 8.1 | 6.0 | 5.0 |
| June | 1,777 | 9.7 | 6.9 | 7.4 |
| July | 1,704 | 9.3 | 8.3 | 8.8 |
| August | 1,482 | 8.1 | 8.0 | 8.4 |
| September | 1,150 | 6.3 | 6.9 | 6.7 |
| October | 726 | 3.9 | 5.4 | 4.6 |
| November | 338 | 1.8 | 3.3 | 3.0 |
| December | 154 | 0.8 | 1.5 | 1.9 |
| Σ | | 64.7 | 55.3 | 55.4 |
| Average | 992 | 5.4 | 4.6 | 4.6 |

$$\text{column 4} = 0.03 + (0.99)\ \text{column 5} \qquad (78)$$

The information contained in the section entitled, "Long Wave Radiation Transmittance Data for Several Transparent Materials" indicates that the long wave radiation heat loss from a covered unit should be about 6.2 Btu/(hr)(ft$^2$) or 149 Btu/(day)(ft$^2$). From Table 5, the average annual solar radiation in Denver, Colorado, is 1,650 Btu/(ft$^2$)(day). Therefore the predicted water evaporation from a water surface covered with a precipitation interceptor is (1,650-149) ÷ 184 = 8.16 ft/year compared to 8.05 ft/year from column 3 of Table 45.

## Water Surface Heat Balance Results

On a long term basis, the value of $q_b$ in equation 5 will have a net value of zero. Therefore equation 5 may be simplified to

$$q_c + q_r + q_e = q_s + q_w \qquad (79)$$

Also the value of $q_w$ in equation 79 should also have a net value of zero over a long term basis. A value of $q_w$ different from zero indicates a short term experiment that did not end at the same time of year that it was initiated. The greater the difference between the value of $q_w$ and zero, the less representative is the experimental data on an annual basis.

Of the 5 terms in equation 79, $q_s$ and $q_r$ are always positive. $q_e$ is also always positive, at least on an annual basis. However, the values of $q_c$ and $q_w$ may be either positive or negative. Accordingly, Table 47 provides 2 columns each for $q_c$ and $q_w$ depending on whether they represent a heat loss or a heat gain. Table 47 shows the % distribution of the quantities contributing to both heat gain and heat loss. For 6 of the 8 experimental units, $q_w$ is zero, and is only slightly greater than zero for the 2 others. Therefore, even the % distribution given for these latter 2 sites is close to what would have been observed if the period of observation had been longer and/or had been initiated and terminated at the same time of year. The data in Table 47 is based on data presented in (25).

Comparing the data in column 7 of Table 5 and the results listed in Table 46, it is clear that water evaporation accounts for only about 51% of the annual heat loss and this corresponds closely with the value of 50% reported in Table 47 for an uncovered unit. Solar radiation is by far the most important source of heat gain with heat gain from convection being either zero or at least relatively insignificant. The major source of heat loss is water evaporation except at very high elevations. Long wave radiation heat loss is the next most important mechanism of heat loss except at very high elevations where it is the most important. The importance of convection heat loss appears to roughly increase with elevation.

These qualitative observations are shown quantitatively in Figure 25. This figure was constructed from the covered unit data given in Table 47. It is interesting to note that the % heat loss by water evaporation consistently decreases with increasing elevation, while the % heat loss by long wave radiation consistently increases with increasing elevation. The % convective heat loss increases with elevation up to about 14% at 11,000 feet.

## Additional Experimental Site Observations

The absolute humidity $H_a$ is (31)

$$H_a = \frac{M_v}{M_a} \left(\frac{p_a}{p-p_a}\right) \quad (80)$$

where $H_a$ is the absolute humidity, $\frac{\text{lb water vapor}}{\text{lb dry air}}$. Because $p_a$ is generally small in comparison with $P$, equation 80 can be simplified to

$$H_a \cong \frac{M_v}{M_a} \left(\frac{p_a}{P}\right) = 0.621 \frac{p_a}{P} \quad (81)$$

Table 47. % Distribution of Heat Gain and Loss.

| | heat loss | | | | heat gain | | |
|---|---|---|---|---|---|---|---|
| | $q_e$ | $q_r$ | $q_c$ | $q_w$ | $q_c$ | $q_w$ | $q_s$ |
| Fort Collins Site: | | | | | | | |
| Covered Unit | 84 | 16 | | | 10 | | 90 |
| Enclosed Unit | 73 | 27 | | | 12 | 3 | 85 |
| Structural Unit | 64 | 35 | | 1 | 13 | | 87 |
| Uncovered Unit | 50 | 47 | 3 | | | | 100 |
| Red Feather Site: | | | | | | | |
| Full Scale Unit | 82 | 18 | | | 6 | | 94 |
| Covered Unit | 56 | 39 | 5 | | | | 100 |
| Storm Mountain Site | 43 | 32 | 25 | | | | 100 |
| Breckenridge Site | 40 | 46 | 14 | | | | 100 |
| Table 5 and Table 46 | 51 | 40 | 9 | | | | 100 |

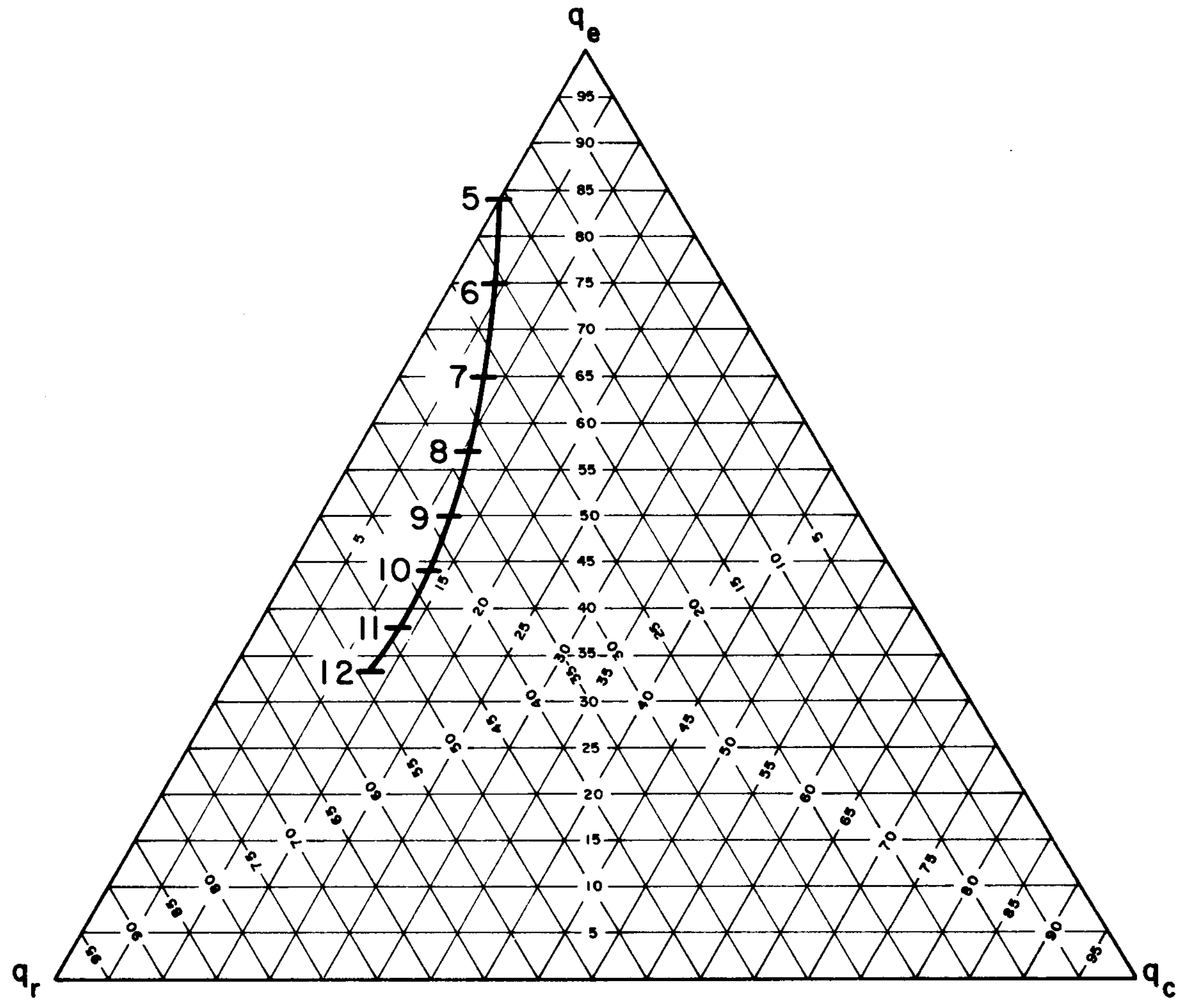


Figure 25- Percent Distribution of Heat Loss from a Water Surface versus Elevation (Numbers Indicate Elevation in thousands of feet). This Graph was Constructed from Table 47 Using the Data for Covered Units.

The relative humidity $H_R$ is

$$H_R = 100 \frac{p_a}{p_s} \tag{82}$$

where $H_R$ = relative humidity, %

$p_s$ = vapor pressure of water at the air temperature, atm.

Frein (25) observed that the value of $k$ is approximately constant throughout the year. In addition, while the value of $H_a$ fluctuates throughout the year, it shows no readily apparent seasonal pattern. Consequently, representative values of these 2 parameters are given in Table 48 for the various units and sites. Values of $H_R$ are also given. The standard deviations of both $H_a$ and $H_R$ are also listed.

The values of $p_a$ in column 8 of Table 48 were calculated using equation 81 and the values listed in columns 3 and 4. It is worth noting that none of the parameters listed in columns 4 through 9 of Table 48 show any consistent trend with elevation. Average values of $k$ were determined for the Red Feather and Fort Collins sites (the average for the Fort Collins site does not include the enclosed unit). The overall average value of $k$ is the average of the 4 sites.

## Average Air and Water Temperatures

The wet-bulb temperature, $T_{wb}$, can be related to air temperature, $T$, as follows:

$$T_{wb} = \text{intercept} + (\text{slope})\ T \tag{83}$$

where $T_{wb}$ = wet-bulb temperature, °F. Table 49 gives the values of the intercepts and slopes obtained at the 4 sites using the data from columns 14 (T) and 15 ($T_{wb}$) of Tables 22, 30, 31, and 32. There appears to be no consistent variation in either slope, intercept, or correlation coefficient with elevation. However, there is a correlation between the slope and intercept values (correlation coefficient = -0.973):

$$\text{intercept} = 38.6 - 46.9\ \text{slope} \tag{84}$$

For example, a slope of 0.587 gives an intercept value of 11.0 and it is believed that these 2 latter values can be used at all elevations. Therefore,

$$T_{wb} = 11 + 0.587\ T \tag{85}$$

Consequently the difference $T - T_{wb}$ in equations 20 and 23 becomes

$$T - T_{wb} = -11 + 0.413\ T \tag{86}$$

Table 48. Representative Values of k, $H_a$, $p_a$, and $H_R$.

| Site and Unit (1) | Z, ft (from Table 18) (2) | P, atm (from Table 18) (3) | $H_a$ x $10^3$ (4) | Standard Deviation of $H_a$ x $10^3$ (5) | Standard Deviation of $H_R$, % (6) | $H_R$, % (7) | $p_a$, atm x $10^3$ (8) | k, $\frac{lb}{(hr)(ft^2)}$ (9) |
|---|---|---|---|---|---|---|---|---|
| Fort Collins | 5,200 | 0.827 | 6.79 | 3.23 | | | 9.04 | 8.20 ave. |
| Covered | 5,200 | 0.827 | | | | | | 9.10 |
| Enclosed | 5,200 | 0.827 | | | 17.7 | 45.8 | | 4.36 |
| Structural | 5,200 | 0.827 | | | | | | 10.08 |
| Uncovered | 5,200 | 0.827 | | | | | | 5.41 |
| Red Feather | 8,180 | 0.740 | 5.95 | 2.29 | 15.7 | 36.0 | 7.09 | 6.34 ave. |
| Full Scale | 8,180 | 0.740 | | | | | | 7.98 |
| Covered | 8,180 | 0.740 | | | | | | 4.69 |
| Storm Mountain | 8,570 | 0.729 | 7.22 | 2.64 | 27.0 | 54.9 | 8.48 | 8.25 |
| Breckenridge | 10,665 | 0.674 | 6.82 | 3.24 | 26.4 | 54.6 | 7.40 | 7.47 |
| Average | ---- | ----- | 6.70 | 2.85 | ---- | ---- | ---- | 7.57 |

Table 49. Slopes and Intercepts for Equation 83.

| Site | intercept for equation 83 | slope for equation 83 | correlation coefficient |
|---|---|---|---|
| Fort Collins | 7.38 | 0.666 | 0.942 |
| Red Feather | 16.2 | 0.486 | 0.871 |
| Storm Mountain | 10.1 | 0.621 | 0.935 |
| Breckenridge | 10.4 | 0.574 | 0.969 |
| Average | 11.0 | 0.587 | 0.929 |

and equation 23 becomes

$$E = \frac{0.093\ k}{\tau}\ (-11 + 0.413\ T) \tag{87}$$

Substituting into equation 87 an average $k$ value of 7.57 lb/(hr)(ft$^2$) from Table 48 and a value of $\tau$ = 1,075.8 Btu/lb at 32°F, one obtains

$$E = -0.00719 + 0.00027\ T \tag{88}$$

which is comparable to equation 29.

Examination of Table 20 indicates that there are 2 ways to establish a relationship between $T$ and $T_w$: (1) correlate column 11 ($T_w$) with column 14 (T), both of which represent instantaneous values, or (2) correlate $\overline{T}$ (obtained from columns 9 and 10 using equation 57) with $\overline{T}_w$ (obtained from columns 5 and 6 in the same manner), where $\overline{T}_w$ is the average water temperature in °F. The latter of these 2 possibilities was chosen because of the thermal capacity of the water. Consequently, the data from columns 5, 6, 9, and 10 of Tables 22, 30, 31, and 32 were used to determine the slope and intercept at each of the 4 sites for the following equation:

$$\overline{T}_w = \text{intercept} + (\text{slope})\ \overline{T}\quad . \tag{89}$$

The results are given in Table 50. Once again, there is no clear relationship with elevation. However, there is a relationship between slope and intercept (correlation coefficient = -0.999):

$$\text{intercept} = 51.6 - 52.1\ (\text{slope}) \tag{90}$$

For example, if the slope is 0.614, then equation 90 says that the intercept is 19.6, so these two values will be used in equation 89 to get

$$\overline{T}_w = 19.6 + 0.614\ \overline{T} \tag{91}$$

Table 50. Slopes and Intercepts for Equation 89.

| Site | Elevation, Z, feet (from Table 18) | Intercept for Equation 89 | Slope for Equation 89 | Correlation coefficient for Equation 89 |
|---|---|---|---|---|
| Fort Collins | 5,200 | 13.4 | 0.725 | 0.954 |
| Red Feather | 8,180 | 26.7 | 0.479 | 0.865 |
| Storm Mountain | 8,570 | 26.8 | 0.475 | 0.948 |
| Breckenridge | 10,665 | 11.4 | 0.777 | 0.946 |
| Average | | 19.6 | 0.614 | 0.928 |

Again if we substitute equation 91 into equation 23 one obtains

$$E = \frac{0.093\ k}{\tau} (0.386T - 19.6) \qquad (92)$$

Again substituting in the values of $k$ and $\tau$, one obtains

$$E = -0.0128 + 0.000252\ T \qquad (93)$$

which is comparable to equation 88.

If one combines equation 85 with equation 91, the result is

$$T_w = 8.1 + 1.05\ T_{wb} \qquad (94)$$

If $T_{wb} = 32°F$, then $T_w = 41.7°F$, or a difference of about 10°F.

For comparison the relationship between $T_w$ (column 11 of Table 28) and $T$ (column 14 of Table 28) is (correlation coefficient = 0.929)

$$T_w = 5.15 + 0.813\ T \qquad (95)$$

## OPERATION OF WASTEWATER EVAPORATION UNITS

A brief description of the overall system for handling and evaporating wastewater follows. The wastewater will be piped from the household to a conventional septic tank. Sufficient detention time will be allowed for the settleable solids to settle out of suspension. Additionally, floatable materials are trapped within the tank by baffle placement at the effluent opening. The effluent, which contains few materials in suspension, then flows to the evaporator basin where the volatile components, principally water, are evaporated.

Solids removal will be occasionally necessary from both the septic tank and the evaporation basin. Materials removed from the septic tank will be sewage sludges in various stages of anaerobic decomposition. Frequency of cleaning should be the same as that of a conventional septic tank.

Cleaning of the evaporation basin is somewhat different from cleaning the sedimentation tank. First, the "solids" will generally be salts and other compounds in dissolved form. Precipitation of these salts and other compounds may occur, but probably rather infrequently. Occasional removal of the wastewater residue from the evaporator basin might be required to prevent dissolved solids buildup from significantly interfering with the evaporation rate. The effect of salinity increase is to reduce the vapor pressure of the water solution and hence the evaporation rate. Occasional removal of the high dissolved solids content water will maintain conditions favorable to continued high evaporation rates. In this situation, liquid and solids removal will actually be necessary.

Higher dissolved solids concentrations, however, also lower the freezing point somewhat. This effect will aid in delaying or reducing possible winter freezing of the basin water. From this standpoint, salts accumulation may be advantageous especially because the deleterious incremental effect upon retarding evaporation is substantially smaller than its beneficial incremental effect upon retarding freezing.

It is very possible, indeed probable, that microbial growth will also occur in the basin. If such populations are allowed to develop, their periodic destruction may be necessary. For this reason, it may be advantageous to maintain an aquatic environment toxic to microorganisms. Chemical treatments such as lime treatment, chlorination, etc. will create the desired toxicity. Such treatments however are not simple, and require careful determination of such parameters as toxicity levels, dose rates, feed concentrations, etc. This problem is further complicated by the fact that it is quite likely that these parameters will change rather frequently with changes in microbial types and numbers.

It has been found in this study that the best results are obtained by using formaldehyde. Five gallons of 37 percent formaldehyde solution added to the full-scale unit at the Red Feather Site stopped all odors and appeared to destroy all aquatic life leaving a water surface with no algae growth.

## Odors and Microbial Growth

Any standing body of wastewater may produce disagreeable odors. Naturally, the magnitude of this problem is diminished if the water body is kept aerobic and it is worsened if the wastewater is allowed to become anaerobic. Because the influent to the evaporation basin is the effluent liquid from an anaerobic septic tank system, it is expected that, while some facultative behavior will undoubtedly occur, the basin may exhibit a tendency toward anaerobiosis. Obviously, basin depth will largely determine which biosis condition will establish domination.

Shallower basin depths will favor aerobic populations of microorganisms while relatively deeper basins will generally produce anaerobic conditions, unless, of course, aeration is provided.

The solids removal feature of this system will diminish this problem by reducing the amount of putrescible matter available for odor production. Admittedly, however, this will not reduce the levels of dissolved organic materials which will still be very high. If aerobic conditions can prevail in a top layer of sufficient depth within the basin, i.e., if facultative conditions develop, this top layer will reduce the amount of odors which escape into the atmosphere.

Because the higher temperatures that accompany the warmer months of the year increase the rates of microbial metabolism, the problem of odor production will, of course, be more severe during the summer than during the winter.

A related problem to biosis predomination is massive microbial colony growth. If the microbial population grows sufficiently large to produce significant turbidity in the water or if the growths reach macroscropic proportions such as to cause a bulking type of growth (such as that caused by Spherotilus in aerobic waters and Thiothrix where anaerobic conditions are rapidly introduced to oxygen), the evaporation rate may change because of different solar reflection caused by the organisms. Algal growth, such as diatoms, can cause such a significant turbidity development, and hence change solar radiation reflection.

Because domestic wastewaters are usually rather high in nutrients (phosphorus and nitrogen) partly due to the household usage of cleaning compounds, and generally have an adequate carbon source supply for microbial usage, environmental conditions are good for stimulating bacterial and algal growth. If other environmental conditions are adequate (such as nutrient concentrations, aerobic conditions, lack of toxins, etc.), algal synthesis is directly proportional to solar intensity and exposed surface area. Hence, measures designed to increase solar intensity also work in favor of stimulating algal growth. It can be seen, then, that aquatic growth may become a significant factor. Because it is microbial action that produces the obnoxious odors commonly associated with sewage, growth of microbes becomes a two-pronged problem.

One common solution to the growth of microorganisms is to regularly dose the water with a mixture of copper sulphate (1 mg/ℓ), copper citrate (2 mg/ℓ), and calcium hypochlorite (10 mg/ℓ). This mixture, of course, is toxic to most microorganisms commonly encountered in wastewaters, and as such should prevent significant population development.

During the first portion of operation of the full scale unit, batch treatment of the basin with copper sulfate and calcium hypochlorite was accomplished. This treatment, applied approximately every two months from April, 1974, through September, 1974, and only once during the remaining months, appeared to adequately control the microbial growth and reduce odors to a generally acceptable level. Toward the end of each dosage period odors did become objectionable near the unit.

During the last summer of operation, in order to reduce the batch dosage requirements and provide continuous treatment of the influent to the evaporation basin, a Mini-San Model 200 chlorinator was installed in the influent line. This unit utilizes chlorine tablets instead of gas and is manufactured by the Diamond Shamrock Corporation, Cleveland, Ohio. Based on average flow conditions, this unit provided a dosage of 17 to 32 mg/ℓ of available chlorine. In addition to this chlorine treatment, the copper sulfate treatment was continued. Again, microbial growth was held to a minimum and odors were held to acceptable levels during most of the period.

From actual experience, it is felt that both microbial growth and odors can be held to acceptable levels with continuous chlorination of the influent, copper sulfate dosages, and occasional additional batch dosages of calcium hypochlorite during the summer months.

Formaldehyde, which is generally used quite successfully in "so-called" chemical toilets as a holding agent to prevent odors and microbial growth, proved to be the best solution. Based on its successful use in the "chemical toilet" industry, the basin was treated with this chemical once, and, so far there have been no more odors.

## Insects

Another possible problem is insect nuisance. The quiescent water surface provided by the evaporator basin as well as the possible food source availability supplied by the wastewater components may produce an environment favorable to the habitation and propagation of various insect species. Certainly, the most probable insect type expected under these conditions is the mosquito, but fly and gnat breeding as well as other insect types may also be responsive to this environment. Obviously a floating oil film or other water surface monolayer cannot be used to combat this problem because of their deleterious effects upon the evaporation rate.

Insect nuisance was minimized during the operational period of the full scale unit by the chlorine and copper sulfate treatment utilized. If the problem should prove to be of concern in further operations the solution will probably be insecticide treatment or an anti-insect measure such as enclosing sides with common window screen material. Unfortunately, insecticides would float on the water surface and thus would reduce evaporation rates. Such enclosure would also help to alleviate any animal or human intrusion problems that may be encountered.

At no time during the period of this study did any of the units display any insect problem.

## Animal and Human Intrusion

One anticipated problem involves those measures required to keep animals and children out of the evaporator basin. The obvious problems related to the interaction of people and animals around any contained body of water are directly applicable to these evaporator basins. Because these evaporators will probably be at least mildly unpleasant to be within due to odors and other factors, general animal instinct will substantially discourage animal intrusion. Enclosure with screen wire and perhaps fencing the perimeter of the evaporator site will give added protection. Fencing the evaporator will help protect children, and any generally interest-discouraging feature will probably prove beneficial.

It is of significance to note that during the period of this experiment a total of three chipmunks and two birds drowned in the evaporation basins of all units. There was no sign of any other animal or human intrusion at any sites even though there were no fences or enclosures provided. It is highly recommended, however, that any future construction of these units include safety fencing probably directly applied to the unit's exterior perimeter.

## Internal Water Condensation

At the beginning of this study there was some conern that because of the generally poor wetting properties of plastic films that these film covered evaporators might develop considerable fogging on the inside of the precipitation interceptors. This concern was further supported by similar problems reported by solar distillation investigators. No fogging or internal condensation of any form has been observed in these evaporators, however. It is felt that this has been avoided by providing for good internal air circulation. Additionally, in this respect, the enclosed evaporator seems to be as trouble-free as the open units. Should such fogging occur, of course, its presence would severely reduce the amount of solar radiation reaching the water surface.

## Salinity Buildup

Salinity (or total dissolved solids) was monitored by measuring the specific conductance of the water in the evaporation basin of the full scale unit at the Red Feather site. Laboratory measurements of both specific conductance and dissolved solids concentrations on samples of water taken from this unit showed that the dissolved solids was directly proportional to the specific conductance:

$$\text{dissolved solids} = (0.541)(\text{specific conductance}) \tag{96}$$

where dissolved solids = mg/ℓ and specific conductance = micromhos/cm at 25°C. Dissolved solids were determined using a drying temperature of 103°C following procedures outlined in (32).

Eventually an excessively high dissolved solids concentration can be expected to reduce water evaporation rates somewhat, but the freezing point will also be reduced. However, no detectible decline in evaporation rate attributable to high dissolved solids concentration was observed in any unit at any site during the course of this project.

Table 51 contains the results observed at the full scale unit of the Red Feather site. The total dissolved solids in the inflow to the full scale unit was determined to be about 540 mg/ℓ. From Table 29 it is clear that some precipitation entered the unit between 7-6-73 and 7-22-73, between 7-25-73 and 8-18-73, and between 12-12-73 and 4-19-74. This accounts for the 2 reductions in dissolved solids concentration apparent in Table 51.

Table 51. Dissolved Solids Accumulation, Full Scale Unit, Red Feather Site.

| Date (1) | Days of Operation (2) | Days (3) | Dissolved Solids Concentration mg/ℓ (4) | Water volume, liters (28.32 V) (5) | Dissolved Solids Mass, grams (6) | Change in Mass, grams (7) | Grams/day (8) |
|---|---|---|---|---|---|---|---|
| 5-19-73 | 0 | | 520 | 0 | 0 | | |
| | | 49 | | | | 2,557 | 52.2 |
| 7-6-73 | 49 | | 590 | 4,334 | 2,557 | | |
| | | 16 | precipitation entered unit | | | 787 | 49.2 |
| 7-22-73 | 65 | | 587 | 5,696 | 3,344 | | |
| | | 3 | | | | 762 | 254 |
| 7-25-73 | 68 | | 655 | 6,269 | 4,106 | | |
| | | 88 | precipitation entered unit | | | 1,961 | 22.3 |
| 10-21-73 | 156 | | 654 | 9,277 | 6,067 | | |
| | | 2 | | | | 792 | 396 |
| 10-23-73 | 158 | | 721 | 9,513 | 6,859 | | |
| | | 178 | precipitation entered unit | | | 1,143 | 6.42 |
| 4-19-74 | 336 | | 868 | 9,219 | 8,002 | | |
| | | 0 | | | | -936 | -- |
| 4-19-74 | 336 | | 868 | 8,140 | 7,066 | | |
| | | 21 | | | | 522 | 24.9 |
| 5-10-74 | 357 | | 945 | 8,030 | 7,588 | | |
| | | 12 | | | | 715 | 59.6 |
| 5-22-74 | 369 | | 1,020 | 8,140 | 8,303 | | |
| | | 36 | | | | 1,586 | 44.1 |
| 6-27-74 | 405 | | 1,008 | 9,811 | 9,889 | | |
| | | 0 | | | | -538 | -- |
| 6-27-74 | 405 | | 1,008 | 9,277 | 9,351 | | |
| | | 29 | | | | 551 | 19.0 |
| 7-26-74 | 434 | | 1,028 | 9,632 | 9,902 | | |
| Average | | | | | | | 26.2 |

The data in column 5 of Table 51 was obtained using the data in columns 17 and 18 of Table 29 along with equation 52. Also, in Table 51, column 6 = $\frac{\text{column 4 times column 5}}{\text{1,000 mg/g}}$ , and column 8 = column 7 divided by column 3.

According to (33), the average discharge of dissolved inorganic solids is 80 grams per person per day, so that it appears that, on the average, the cabin was occupied about 1/3 of the time by one person. This observation corresponds closely with the previously determined flow rate from this cabin of about 14.4 gallons per day, which is about 1/3 the flow rate from one person. In summary, the occupancy of the cabin can be determined both from the standpoint of mass of dissolved inorganic solids discharged and volume of wastewater discharged as follows:

$$\frac{\text{14.4 gallons/day from the cabin}}{\text{44 gallons/(day)(person)}} = 0.327 \text{ Persons}$$

$$\frac{\text{26.2 grams/day from the cabin}}{\text{80 grams/(day)(person)}} = 0.327$$

This exact agreement clearly shows that there was no leakage from the evaporation basin during the period of these observations and that the recorded flow volumes are accurate. The average concentration in the wastewater discharged from this cabin was

$$\frac{26.2 \text{ g}}{\text{day}} \Big| \frac{\text{day}}{14.4 \text{ gal}} \Big| \frac{1{,}000 \text{ mg}}{\text{g}} \Big| \frac{\text{gal}}{3.785 \ \ell} = 481 \text{ mg}/\ell$$

of inorganic dissolved solids.

## ECONOMICS

The cost of removing wastewater by truck from mountain cabin wastewater vaults is about 10¢ per gallon. Consequently, the cost of hauling off the wastewater from the cabin at the Red Feather site would be about ($\frac{\$0.1}{\text{gal}}$ x 14.4 gal/day x 365 days/year=) \$526 per year.

In order to obtain an estimate of the unit costs involved, one can use the actual costs of the full scale unit at the Red Feather Site. Regardless of whether or not a wastewater evaporation device is used, it will be necessary to have a septic tank or concrete (leakproof) vault to hold the wastewater until it can be hauled to treatment facilities. The cost of the 1,262 gallon septic tank was \$750 which included excavation, grading, installation, and backfill, or about 60¢ per gallon of actual liquid capacity.

The 0.06 inches thick Uvex transparent material cost 46¢ per $ft^2$, but even at this relatively high price proved completely unsatisfactory because it was destroyed by cold weather. The thin plastic film used (which was destroyed by hail on the full scale unit) cost 12¢ per $ft^2$. Finally the material that appears satisfactory is the Kalwall Sun-Lite transparent material (0.03 inches thick) which costs 28¢ per $ft^2$.

The roof trusses were wooden, 18 ft long with a slope of 5" vertical to 1' horizontal and were about $15 each. 15 were used for a total cost of $225. The area covered was 18 ft wide by 28 ft long (504 $ft^2$).

The nylon reinforced Butyl rubber liner (0.03125 inches thick) was 25 ft long by 35 feet wide. The pond depth was 3.32 feet, so about 3 1/2 feet was necessary on each side (7 feet in each dimension) to allow for depth. The liner cost was 22¢ per $ft^2$ of liner. In addition, a 4 inch diameter Butyl rubber pipe clamp was purchased for $5.20 so that the inlet pipe could enter the pond through the liner wall.

The cost of digging the trench (148 feet) from the septic tank to the evaporation pond, installing the 4 inch diameter plastic pipe in this trench, and digging the evaporation pond was $250. This resulted in a pond with a volume of 406 $ft^3$ (3,037 gallons) and a surface area of 229 $ft^2$ (effective depth = 1.78 feet). The storage requirement was (0.08 x 14.4 gal/day x 365 days/year=) 420 gallons.

Other costs were:

| | $\$/ft^2$ |
|---|---|
| additional lumber | 0.45 |
| support posts | 0.10 |
| bolts and washers | 0.06 |
| linseed oil | 0.16 |
| nails | 0.04 |
| miscellaneous | 0.15 |
| subtotal other costs | $0.96 |

Table 52 contains a summary of these costs as well as unit costs based on both roof area and pond area. The unit costs are based on a ratio of roof area to pond area of 2.2.

It will be noted that the total unit cost of the full scale unit (including optional unskilled labor costs) is $3.70 per $ft^2$ of roof which compares with present day costs of solar stills of about $4 per $ft^2$, but the wastewater evaporation unit will evaporate (1.75 ÷ 0.82=) 2.13 times as much water as a solar still. Therefore, for the same evaporation capacity, the cost of the solar still would be ($4 x 2.13=) $8.52 per unit compared to $8.13 per $ft^2$ of pond area.

It should be noted that if the cabin owner performs the unskilled labor himself with ordinary tools, then his cost is only 72% of what it would be otherwise.

From equation 77 and Table 18, the evaporation rate at the Red Feather site for a full scale unit not shaded from the sun would be 4.82 ft per year. The annual volume of wastewater is

$$\frac{14.4 \text{ gal}}{\text{day}} \Big| \frac{365 \text{ days}}{\text{year}} \Big| \frac{ft^3}{7.481 \text{ gal}} = 703 \ ft^3/\text{year} .$$

Table 52. Cost of Full Scale Unit, Red Feather Site.

| Item | Cost, $ | $ per $ft^2$ of roof | $ per $ft^2$ of pond |
|---|---|---|---|
| transparent roof material | 141.12 | 0.28 | 0.62 |
| wooden roof trusses | 225.00 | 0.45 | 0.99 |
| nylon reinforced Butyl rubber liner | 192.50 | 0.38 | 0.84 |
| 4" diameter Butyl rubber pipe clamp | 5.20 | 0.01 | 0.02 |
| excavation of trench and pond | 250.00 | 0.50 | 1.10 |
| additional lumber | 226.80 | 0.45 | 0.99 |
| wooden support posts | 50.40 | 0.10 | 0.22 |
| steel bolts and washers | 30.24 | 0.06 | 0.13 |
| linseed oil | 80.64 | 0.16 | 0.35 |
| steel nails | 20.16 | 0.04 | 0.09 |
| miscellaneous | 75.60 | 0.15 | 0.33 |
| subtotal material costs | 1,297.66 | 2.58 | 5.68 |
| Colorado state sales tax (3%) | 38.93 | 0.08 | 0.17 |
| subtotal materials and sales tax | 1,336.59 | 2.66 | 5.85 |
| unskilled labor costs (optional) | 520.07 | 1.04 | 2.28 |
| Total Cost | 1,856.66 | 3.70 | 8.13 |

Therefore the required evaporation area is (703 ÷ 4.82=) 146 $ft^2$. However the annual carryover storage requirement is (420 ÷ 7.481=) 56 $ft^3$. Therefore, at times, the liquid volume should not exceed (406 - 56=) 350 $ft^3$, and the evaporation area corresponding to this depth of (from equation 52) 3.07 ft would be 214 $ft^2$ (from equation 53). Clearly then, if the full scale unit at the Red Feather Site was not partially shaded from the sun, it would have been oversize by a factor of (214 ÷ 146=) 1.5.

For a full scale unit at the Red Feather Site not partially shaded by the sun, the required evaporation area of 146 $ft^2$ corresponds to a depth of 1.98 ft (from equation 53) and a volume of 155 $ft^3$. Adding 56 $ft^3$ for storage, the total volume (liquid + storage) should be 211 $ft^3$ corresponding to a depth of 2.34 ft (from equation 52) and a total pond area of 169 $ft^2$ (from equation 53) that could be constructed at a total cost of $1,374 (including optional unskilled labor). Clearly then the full scale unit would pay for itself in (1,374 ÷ 526=) 2.6 years or (0.72 x 2.6=) 1.9 years if the cabin owner performed the optional unskilled labor himself.

Because the full scale unit at the Red Feather site received only 60% of the solar energy that it would have received if it had not been partially shaded, the required pond area in the absence of shading of 169 $ft^2$ would have had to be increased to (169 ÷ 0.6=) 282 $ft^2$ to completely evaporate all the wastewater discharged. Because the pond area was only 229 $ft^2$, only 81% of the wastewater discharged could be evaporated.

## Optional Costs

Formaldehyde costs \$2.60 per gallon. If a wastewater chlorinator is installed (\$96), the cost of the chemical tablets is \$1.16 per pound. The cost of recirculating chemical toilets range from \$115 to \$579, and the cost of liquid is \$6 per gallon. However the cost of flushing an ordinary toilet is 40 to 55¢ per flush (if the wastewater must be hauled out of the mountains to a wastewater treatment facility) whereas the cost of flushing a recirculating chemical toilet is 0.225¢ per flush.

The installation of a recirculating chemical toilet reduces wastewater flows about 40%. Therefore, even if the most expensive (\$579) recirculating chemical toilet had been used at the Red Feather site, the reduction in the cost of the wastewater evaporation unit would have been (0.4 x \$1,374=) \$550.

## Economics Summary

The cost of removing wastewater by truck from mountain cabin wastewater vaults is about 10¢ per gallon, so for the typical cabin flow of about 14.4 gal/day, the cost is about \$526 per year. Furthermore, this cost can be expected to greatly increase at a rate greater than even the current double digit rate of inflation as the cost of gasoline triples or quadruples in price.

The annual carryover storage requirement is 56 $ft^3$. The evaporation area depends on elevation because the evaporation rate depends on air temperatures (equation 77 on page 100):

$$\text{feet/year} = -5.55 + 0.275T \tag{77}$$

The mountainous area of Colorado falls within the following area (approximately): 37 to 41°N and 105 to 109°W. Taking average coordinates of 39°N and 107°W, equation 44 on page 34 becomes

$$T = 69.8 - 3.6 \times 10^{-3} z \quad . \tag{44A}$$

Combining equations 77 and 44A gives

$$\text{feet/year} = 13.7 - \frac{z}{1,000} \quad . \tag{97}$$

Equation 97 states that this method of wastewater disposal will not work at elevations in excess of 13,700 feet.

The annual volume of wastewater to be evaporated is 703 $ft^3$/year. Therefore, the required pond area is

$$ft^2 = \frac{703}{13.7 - z/1,000} \quad . \tag{98}$$

From Table 52 on page 119, the cost per $ft^2$ of pond area is \$8.13 (\$5.85 if the owner constructs the unit himself), so the initial cost as a function of elevation is

$$\$ = 5,715/(13.7 - z/1,000) \tag{99}$$

or if the owner constructs the unit himself, the initial cost is

$$\$ = 4{,}113/(13.7 - z/1{,}000) \quad . \tag{100}$$

Finally, the number of years required for the wastewater evaporation pond to pay for itself is

$$\text{years} = 10.9/(13.7 - z/1{,}000) \quad , \tag{101}$$

or if the owner furnishes the optional unskilled labor, the time required for the unit to pay for itself is

$$\text{years} = 7.82/(13.7 - z/1{,}000) \quad . \tag{102}$$

The minimum elevation in the area lying within 37 to 41°N and 105 to 109°W is about 5,000 feet. Consequently, Table 53 gives, as a function of elevation, the required wastewater evaporation pond area, cost, and payback time for the mountainous areas of Colorado. Column 2 is calculated from equation 98. Column 3 is \$8.13 times column 2 and column 4 is column 3 ÷ \$526 per year.

Table 53. Required Wastewater Evaporation Pond Area, Cost, and Payback Time as a Function of Elevation

| Elevation, Feet (1) | Evaporation Pond Area, $ft^2$ (2) | Initial Construction Cost of Wastewater Evaporation Pond, \$ (3) | Payback Time, Years (4) |
|---|---|---|---|
| 5,000 | 81 | 659 | 1.3 |
| 6,000 | 91 | 740 | 1.4 |
| 7,000 | 105 | 854 | 1.6 |
| 8,000 | 123 | 1,000 | 1.9 |
| 9,000 | 150 | 1,220 | 2.3 |
| 10,000 | 190 | 1,545 | 2.9 |
| 11,000 | 260 | 2,114 | 4.0 |
| 12,000 | 414 | 3,366 | 6.4 |
| 13,000 | 1,004 | 8,163 | 15.5 |

As noted on page 6, wastewater flows can be reduced by 40% by using any one of the following 3 devices: (1) a human waste combustion unit, (2) a recirculating flushing toilet, or (3) a concrete-vault privy (\$221 installed). Consequently, the area shown in column 2 of Table 53 could be reduced by 40%. In addition, if the owner constructs the wastewater evaporation unit himself, this cost could be reduced to \$5.85 per $ft^2$ of pond area. These results are tabulated in Table 54. Column 2 is 0.6 times the corresponding values in column 2 of Table 53. Column 3 is \$5.85 per $ft^2$ of pond times column 2. Column 4 is column 3 divided by (\$526 x 0.6=) \$316 per year.

Table 54. Minimum Wastewater Evaporation Pond Area, Minimum Cost, and Minimum Payback Time as a Function of Elevation

| Elevation, feet (1) | Minimum Wastewater Evaporation Pond Area, $ft^2$ (2) | Minimum Cost of Wastewater Evaporation Pond, $ (3) | Minimum Payback Time, Years (4) |
|---|---|---|---|
| 5,000 | 49 | 287 | 0.9 |
| 6,000 | 55 | 322 | 1.0 |
| 7,000 | 63 | 369 | 1.2 |
| 8,000 | 74 | 433 | 1.4 |
| 9,000 | 90 | 527 | 1.7 |
| 10,000 | 114 | 667 | 2.1 |
| 11,000 | 156 | 913 | 2.9 |
| 12,000 | 248 | 1,451 | 4.6 |
| 13,000 | 602 | 3,522 | 11.1 |

Examination of Tables 53 and 54 reveals that above elevations of about 11,000 (timberline) or 12,000 feet, wastewater evaporation may not be economically attractive. However, there are very few cabins above 12,000 feet.

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16. Abstract

This report gives the results of a study of wastewater evaporation and a comparison of this technique with other alternatives for the disposal of wastewater from second homes located in mountainous areas. The wastewater evaporation unit is covered with a transparent (to solar radiation) precipitation interceptor that also serves to reduce long wave radiation heat losses.

Several experimental and 1 full scale wastewater evaporators were installed at 4 elevations ranging from 5,200 to 10,665 feet. These units were observed for a period of 3 years. Following this observational period, the experimental data obtained was analyzed to obtain design and cost data as a function of elevation, latitude, and longitude. Analysis of the experimental data showed that wastewater evaporation is a technical and economically viable alternative for elevations up to about 11,000 or 12,000 feet in Colorado.

Because of the manner in which the design equations were developed, the results of this report can be applied anywhere in the conterminous United States, although the design and cost data developed for Colorado as an example may not be applicable. The design and cost data for other states can be derived using the equations in this report.



17a. Descriptors *Evaporators, *Elevation, *Air Temperature, *Solar Radiation, *Thermal Radiation, *Heat Balance, *Wastewater Disposal, *Water Temperature, Mountains, Colorado.

17b. Identifiers *Wastewater Evaporators, *Second Homes, *Long Wave Radiation, Average Temperature, Latitude, Longitude

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