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A PASSIVE COOLER FOR A HUMID CLIMATE

BY

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RESEARCH REPORT

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ABSTRACT

This paper will examine a passive cooling system for a humid climate. This system will be divided into two parts, a radiative system and an evaporative system combined into a roof pond system. Performance of the radiative system will be enhanced through the use of a selective cover which will make use of an atmospheric window between 8 and 13um. An attempt will also be made to thermally isolate the radiative system from convective gains with the evaporative system. The evaporative system will consist of a water, solvent and dye layer over the selective cover of the radiative system. The performance of the evaporative system will be enhanced by virtue of the increased vapor pressure made available through the use of solvents. The main solvent to be examined shall be methanol. The increased vapor pressure shall sufficiently increase the rate of evaporative cooling to a point where useful cooling is obtained even under high humidity conditions.

It was found that a solution with a 0.8 mole fraction of methanol in the evaporative system could cool a sufficiently large water storage to 45^{o}F using a 300 m^2 roof pond. This is a heat sink which, if used to provide cooling and dehumidification, will provide 576000 BTU of cooling. This is the equivalent of a 3 ton unit operating 16 hours a day.

It was found that a water layer thicker than 0.1 mm would radiatively isolate the selective cover, making the concept of a liquid thermal protection useless as a means of providing only convective protection. However, as a selective cover, teflon was found to make the best use of the 8-13um window. As a result, this would provide 33 BTU/ft^2-night as compared to 11 BTU/ft^2-night for a black cover. It was also found that a green or blue and yellow or red dye mixture, when dissolved in water, would provide a blace surface throughout the visual and infared range.

CONTENTS

Chapter

INTRODUCTION

Radiation to the night sky and evaporative cooling have been in use for centuries. In the Middle East, these systems not only provided comfortable houses bur also ice for kings and peasants alike. These systems of cooling have been largely overlooked in this country in favor of mechanical means of cooling. Now that the energy to power these devices is becoming short in supply, radiative and evaporative cooling are again being investigated.

The most extensive example of passive cooling can be found in Iranian architecture. Radiation effects were utilized through the use of thick earthern walls which absorbed much of the radiation during the day and then reradiated it during the cool nights. Wind towers were built which created temperature and density gradients in a tunnel which ran underground to the house. The drafts which were produced in the tunnel were sensible cooled by the walls of the tunnel. This same air was then brought over a cistern or fountain and evaporatively cooled. The resultant air was then drawn through the residence, providing almost complete comfort to the residents at no cost.[1]

Here in the United States, the most extensive use of passive cooling has been done in the south west. The Sky Therm project in Phoenix, Arizona was a successful attempt to provide complete summer comfort through the use of roof ponds. During the night the ponds were cooled by radiation to the night sky and by evaporation. During the day, insulation panels were placed over the ponds to limit heat gains from the sun. Interior comfort was maintained during the day by fans whcih brought the interior air into thermal contact with the now cool roof pond.[2]

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[1] Mehdi Bahadori, "Passive Cooling Systems in Iranian Architecture," Scientific American 238 (February 1978):144-154.

[2] J.I. Yellott and H.R. Hay, "Natural Air Conditioning With Roof Ponds and Movable Insulation," ASHRAE Transactions 75 (1969): 165-177.

What all of these systems have in common, is that they operate in a very dry climate. Both radiative and evaporative cooling are adversely affected by humidity. Radiation exchange decreases because the sky acts less and less like a black body and more like a grey body as humidity increases. Evaporation is directly dependent on the difference between the vapor pressure of the pond and the sky; as the humidity approaches 100%, evaporation approaches zero.

This paper will examine a system, of vapor pressure and radiosity control, which can make passive cooling possible in humid climates.

STATEMENT OF THE PROBLEM

Here in Central Florida we are faced with the problem of providing cooling under relatively high humidity conditions. In most areas where evaporative cooling is used, this is accomplished with direct evaporative units. However, this procedure adds moisture to the air and would be inappropriate for this area. So, we must design an indirect evaporative cooler for humid climates. This has two advantages; first, no moisture will be added to the air; second, we may enhance evaporative loss through means which would be unacceptable in a direct process. This second advantage is due to the fact that any odors or chemicals in the evaporant will be transferred to the interior air in a direct process, but not in the indirect process.

A further problem associated with high humidity is a decrease in radiative exchange with the night sky. The more humid the sky, the greyer, and warmer, it appears. At sea level and 100% humidity, radiative heat loss is essentially zero. However, an atmospheric window exists between 8 and 13 um due to the fact that water vapor does not absorb in this range. So, if a selective surface can be found which radiates only within this range, then radiation loss will be essentially independant of humidity, and in fact superior to what can be obtained by a black surface under these conditions. This will be further explored in the radiation chapter.

The physical system which will be examined in this paper is envisioned as shown in figures 1 and 2. Figure 1 shows a north facing roof built in steps. The horizontal portion of each step represents a liquid pond. Construction in this manner means that these ponds will be shielded from direct sunlight and so will only be subject to diffuse radiation during the day. During the summer the solar angle of incidence is about 9°. This means that if adequate shading is to be provided, the ratio between the horizontal and

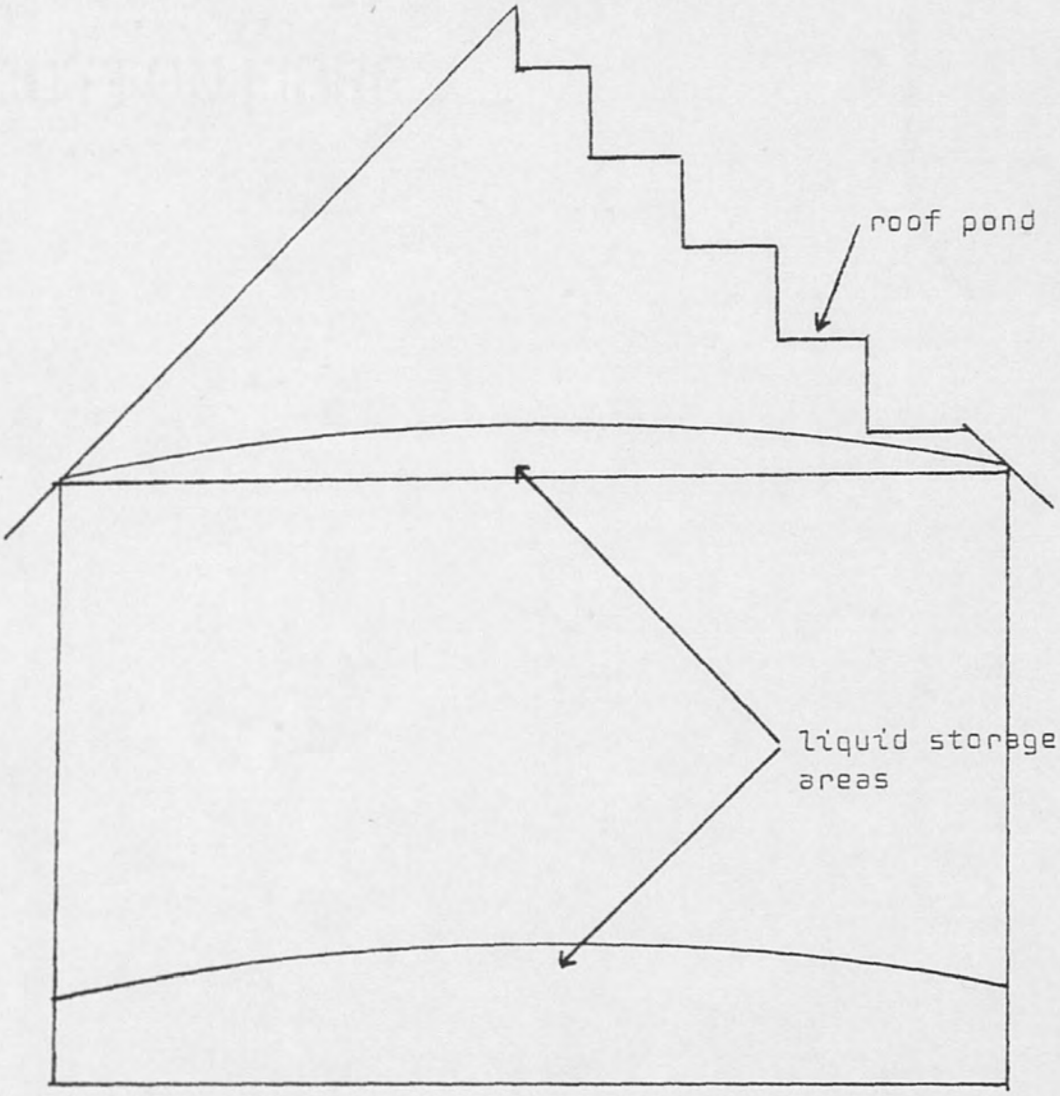

Fig. 1. System configuration on a residence

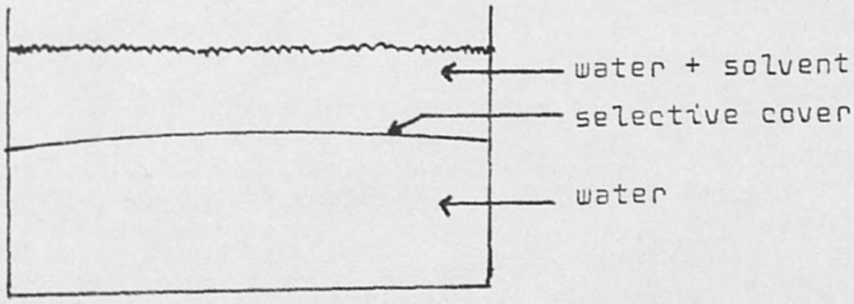

Fig. 2. Roof pond cross section

vertical portions will be the arc tan of 9^0 or 84. Should it turn out that this system needs only night time operation, then this difficult angle need no longer be achieved, and the roof ponds can be used during the day as a seperate insulation system to absorb direct and diffuse radiation. For the purposes of this paper it is assumed that the projected area of the north facing roof is 30 x 10 meters, providing $300m^2$ of pond area. It is anticipated that the cool liquid produced in these ponds will be held in storage areas over the ceiling and under the floor. Air conditioning of interior air would then be accomplished through the use of heat exchangers connected with the storage areas.

Figure 2 shows a cross section of the roof pond system to be examined. It shows a bottom layer of water contained by a selective plastic cover. This cover is insulated from the atmosphere by a liquid layer which will be cooled by evaporation. Since there will be common storage areas it will be assumed that there is no thermal interaction between the two liquid layers. Further it will be assumed that all convective, conductive, and evaporative interactions with the atmosphere are confined to the top layer of liquid. This means that the lower layer has only radiative contact with the atmosphere. Evaporation and transmissivity of the upper layer will be controlled through the use of dyes and solvents.

For design purposes it was necessary to construct an average summer day in the Orlando area. To this end, monthly summaries of weather data were obtained for the summer of 1978 from the weather station at the Orlando International Airport. The monthly averages for the months of May through September were averaged to arrive at the graph shown as figure 3. This graph shows the relative variation of humidity, temperature and wind speed over a twenty four hour period. Table one, below, shows the extremes of each month used.[1]

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[1] U.S. Department of Commerce-NOAA, Local Climatological Data, May-September 1978. (Ashville, NC: National Climatic Center 1978).

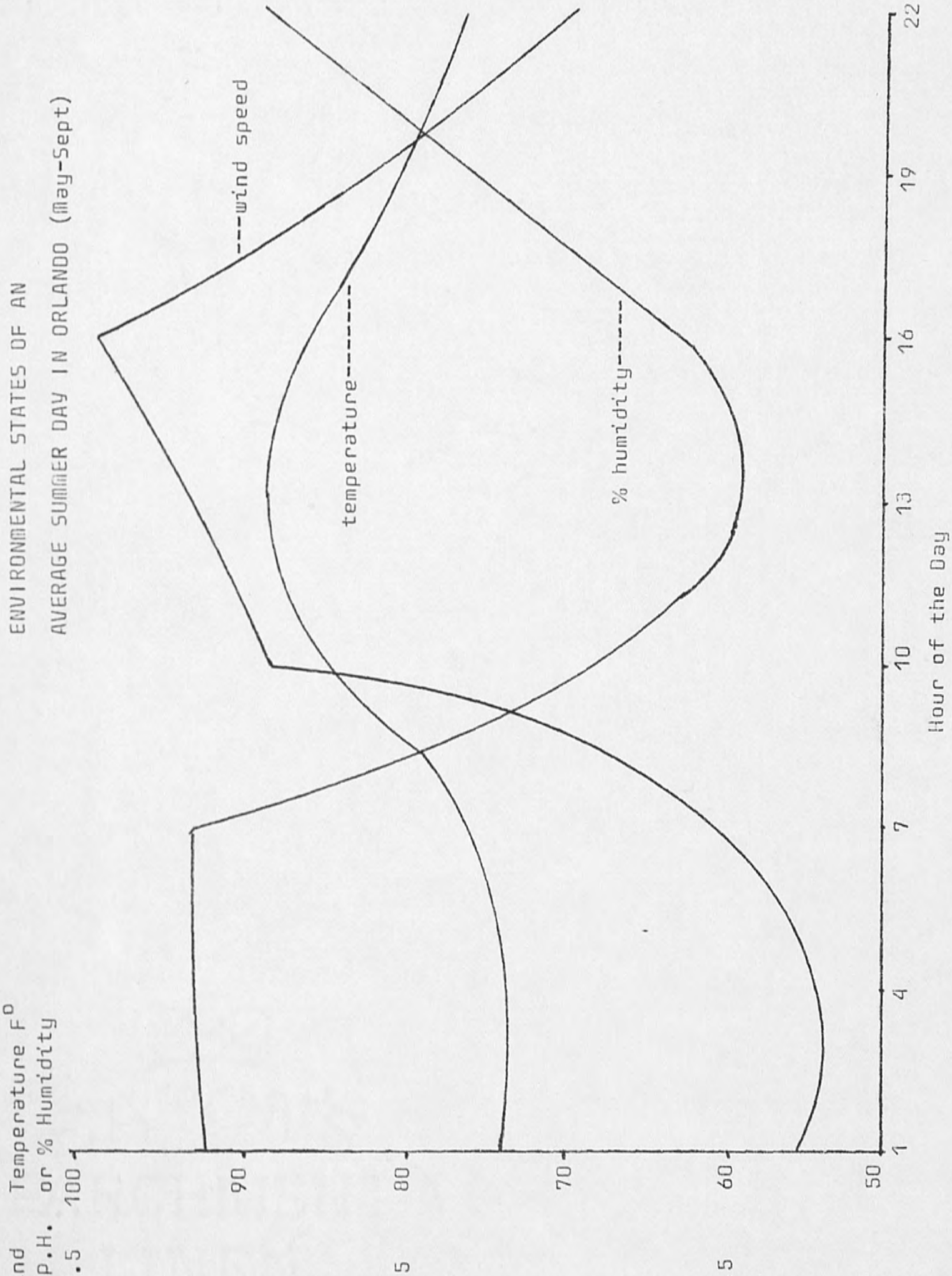

Fig. 3. The design day

TABLE 1

MONTH	DRY BULB TEMP. F°	DEW POINT F°	%HUMIDITY	WIND SPEED MPH
May	96	67	39	4.0
June	96	75	51	6.6
July	97	74	49	4.3
August	94	73	52	6.0
September	95	74	52	7.5

Compiled from figures in U.S. Department of Commerce-NOAA, Local Climatological Data May-September 1978.

THE EVAPORATION SYSTEM

Evaporation is a complex system of heat, mass and momentum transfer, and a number of different models have been proposed to deal with it. What all of these models have in common is an energy balance. A pond receives energy as direct and indirect radiation from the atmosphere. The first interaction takes place at the liquid surface where energy is reflected, absorbed, or transmitted to the bottom. At the bottom of the pond, the radiation if reflected (most likely to be absorbed by the liquid) or is absorbed by the bottom material and conducted away. Of course, at night, when the bottom is warmer than the sky, this energy will be conducted from the bottom back to the pond. The liquid loses energy by reradiation to space. Finally, there is the energy exchange with the atmosphere due to conduction and convection. Whether this exchange will be a gain or a loss is a function of several factors; including temperature, wind speed, and humidity. Evaporation and changes in temperature account for the difference between energy gain and loss.

Yellot presents an equation derived by Carrier for evaporation.[1]

$$q_e = 0.093 \times h_{fg}(1.0 + 0.38V)\Delta p_v + A(\phi)$$

where: q_e= evaporation heat loss - BTU

h_{fg}= latent heat of pond - BTU/lb

Δp_v= difference between pond and air vapor pressures- in.Hg

V= Wind speed

$A(\phi)$= a function of incident radiation relating temp. and vapor changes to energy gained from the sun

As can be seen from this equation there are two means by which

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[1] J.I. Yellott and H.R. Hay, "Thermal Analysis of a Building With Natural Air Conditioning," <u>ASHRAE Transactions</u> 75 (1969): 178-190.

evaporative losses can be increased. The first is by using volatile solvents to increase Δp_v. The second is through the use of dyes to increase $A(\phi)$. The use of dyes will be covered in the chapter on the radiation system. Further, this chapter on evaporation will assume night time operation so that $A(\phi)$ can be neglected.

The choice of volitile solvents is somewhat limited. The primary limitations are due to health and safety considerations. Secondly, the solvent should be miscible with water and inexpensive. For the purposes of this paper it was decided to base the analysis on methanol. Methanol fits most of the criteria listed above. It is relatively safe, infinitely soluable in water and if not sufficiently inexpensive, can be produced via a biomass conversion. Once the analysis procedure has been established, ethanol will also be evaluated. Although these are the two most likely choices for commercial use, another reason for this choice is that the thermophysical data is available on methanol, ethanol-water mixtures which is not available on more exotic choices.

Solution Vapor Pressure

The calculation of the solution vapor pressure at different concentrations of methanol was performed using Raoult's law.[1]

$p = p_1^o\, p_2^o \,/\, p_1^o + (p_2^o - p_1^o)\, y_1$

$p = p_1^o\, x_1 + p_2^o\, x_2$

where: p_n^o = the vapor pressure of the pure substance n

p = total pressure

x_n = mole fraction of n in the liquid

y_n = mole fraction of n in the vapor

The results of these calculations have been graphed for 55°F and are shown as Fig. 4. Once the pressure is known at one temperature, it can be found at other temperatures by the ideal gas law. From this chart it is possible to find the vapor pressure of any given concentration of methanol and the resulting concentration in the

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[1] Gilbert W. Castellan, Physical Chemistry, 2nd ed. (Reading: Addison-Wesley, 1971), pp. 305-308.

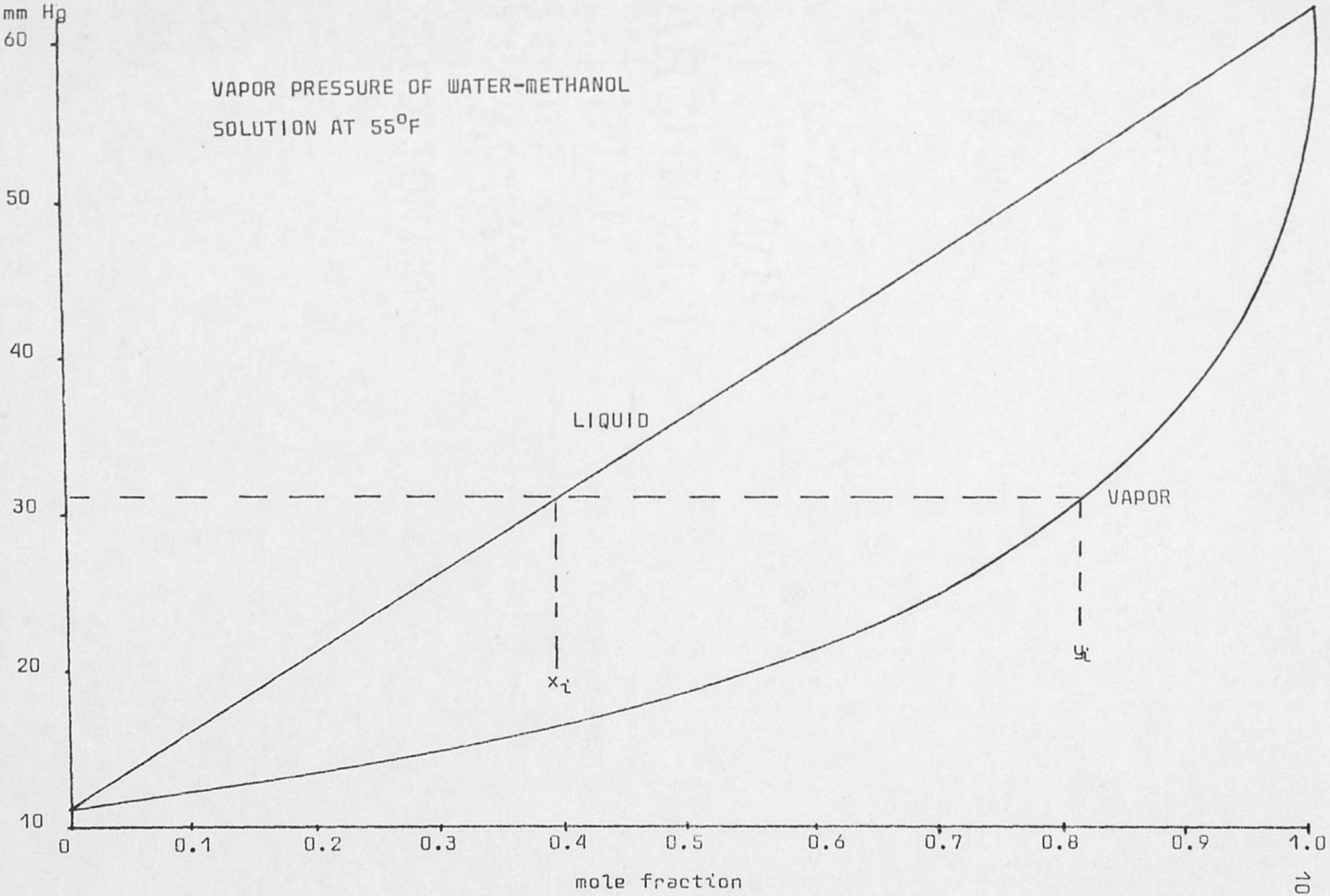

Fig. 4. Pond vapor pressure

vapor. An example of the relationship between x_i and y_i is shown by dotted lines on the graph.

Evaporation Heat Flow

The equation, as was expressed earlier, to be used for evaporation is, $q_e = 0.093 \times h_{fg}(1.0 + 0.38V)\Delta p_v$.[1]
Using the general properties of mixtures, it will be assumed that,[2]
$h_{fg} = x_1\, h_{fg1} + x_2\, h_{fg2}$.
At 55^oF, h_{fg} for H_2O = 1062 BTU/lb
h_{fg} for methanol (CH_3OH) = 519 BTU/lb .[3]
The reason for the choice of 55^oF will become apparent later in this chapter, Table 2 summarizes the changes in the equation of evaporation for different mole fractions of methanol.

TABLE 2

x_i of methanol	h_{fg}	$q_e/\Delta p_v =$
0.2	953.4	(88.6 + 33.7V)
0.3	899.1	(83.6 + 31.8V)
0.4	845.0	(78.6 + 29.9V)
0.5	790.0	(73.5 + 29.7V)
0.6	736.0	(68.4 + 26.0V)
0.7	681.9	(63.4 + 24.1V)
0.8	627.6	(58.3 + 22.2V)
0.9	573.3	(53.3 + 20.3V)

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[1] Yellott and Hay, "Thermal Analysis," p. 183

[2] Gordon Van Wylen and Richard Sonntag, Fundamentals of Classical Thermodynamics, 2nd ed. (New York: John Wiley and Sons, 1973), pp. 431-476.

[3] Richard Perry and Charles Chilton, eds., Chemical Engineer's Handbook, 5th ed. (New York: McGraw-Hill Book Co., 1973), p.3-136.

An examination of these equations reveals the trade off inherent in the use of solvents. The higher the vapor pressure, the lower the heat of vaporization. However, it will be seen in a later comparison of methanol and ethanol that within certain limitations, the increase in vapor pressure is more important than the decrease in the heat of vaporization.

Convection Heat Flow

The convection heat transfer is of course governed by

$$q_{conv} = \bar{h}(T_{pond} - T_{air}).$$

Now $\bar{h}$ must be obtained. To do this the Nusselt number, $Nu_l = \bar{h}L/k$, must be found, where L= 30m and k= 0.392 W/mC° for air.[1] The following relations were also used to obtain the convection heat transfer in a turbulent flow over a flat plate.[2]

$Nu_l = Pr^{.33}(0.037Re_l^{.8} - 850)$

$Re_l = VL\rho/\mu$

$Pr = C_p\mu/k$ which for air is 0.708 at 300°K

Figure 5 shows the calculated variation of $\bar{h}$ with time over our average day.

Solvent Evaporative Losses

It was shown by Holman that the use of the diffusion equations in predicting the evaporation losses in the environment gave answers which were several orders of magnitude in error.[3] Several different methods of approximating the actual loss were tried until two different methods were found to agree within five percent. One method which failed was based on the following method. First, the volume of one mole of gas at S.T.P. was found using a 1'x1' base. The resulting height was then multiplied by the area described by the pond width times the distance traveled by the wind. Using vapor pressure

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[1] Douglas A. Kaminski, ed., Heat Transfer Data Book (Schenectady: General Electric, 1977), p. G514.2.3.

[2] J.P. Holman, Heat Transfer, 4th ed. (New York: McGraw-Hill Book Co., 1976), p. 181.

[3] Ibid., p. 483.

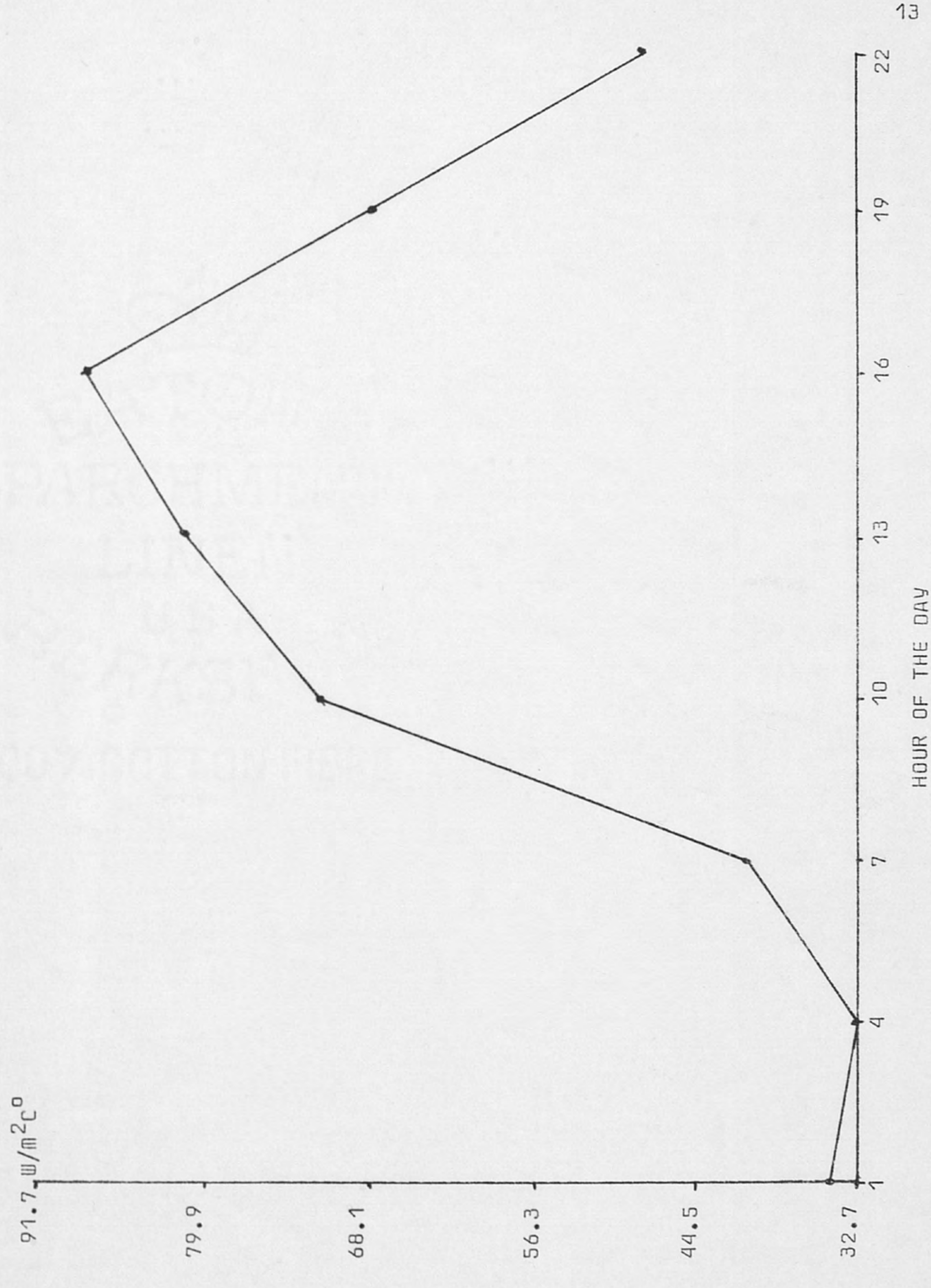

Fig. 5. Variation of $\bar{h}$ during the average day

and mole fraction data, it was then calculated how many moles of methanol were present. The reason that this method fails is that it assumes that the air over the pond is there for a sufficient time to establish the equilibrium vapor pressure in any given volume.

Holman presents an empirical relation which has been shown to be fairly accurate for evaporation from a pond of water.[1]

$E_{lp} = 0.7(0.37 + 0.0041\bar{U})(P_s - P_w)^{.88}$

where: E_{lp} = land pan evaporation- in/day

$\bar{U}$ = daily wind movement- mi/day

P_s = saturation pressure of air- in.Hg

P_w = actual vapor pressure of air- in.Hg

then: $m_w/A = E_{lp}\ w/12$, where m_w/A is the mass evaporated per area.

Since a methanol molecule is essentially the same size and shape as a water molecule, we can probably assume that the surface area of the pond which represents water is the same as its mole fraction. So, if we assume that we are using a 0.8 solution of methanol, then 20% of the pond surface area is water. Using this assumption and the above equations it was found that the amount of methanol evaporation predicted was slightly less than that obtained by the following relationship:

$m_w/A = Q_t/h_{fg}$

where: $Q_t = Q_{conv} + Q_{evap}$

h_{fg}= latent heat of vaporization of the pond

m_w/A = lb. of water per area.

Since this latter relation predicted a slightly higher rate of evaporation, it was the one used in the evaluation of the ponds thermodynamic performance. Although there are some obvious errors possible, such as when Q_t is 0 or negative, it is felt that this gives a fair approximation to what the actual losses would be. Of course the proof of this statement will only come from experimental observation, which is at present lacking.

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[1] Ibid., pp. 482-485.

Storage Size

A basic equation in heat transfer is $Q = mC(T_2 - T_1)$. If it is assumed that it is necessary to provide two tons of air conditioning twenty four hours a day, then Q = 576000 BTU. Put into other terms, this is the same as a three ton unit operating for 16 hours a day or a 48 ton unit running for an hour. It shall also be assumed that there is a 10^oF difference between T_2 and T_1. From available data it was determined that the C_p at 55^oF for a 45 mole percent solution of methanol is 0.8 BTU/lb_mF^o.[1] This means that a storage of 72000 lb_m or about 60000 gal. is required. If all this liquid was stored under the floor it would be about 1.25 ft. in depth. Although this size of storage will present some minor but well known construction problems, it also has a major hidden problem. It would cost well over 30000 dollars to buy enough alcohol to start the system. Clearly this is unacceptable. Fortunately, there is a solution. A small tank can circulate the methanol solution onto the roof, then the cooled solution can go through a heat exchanger system with a water storage area before returning to its tank. The sizing of this alcohol tank will depend on the loss of methanol and will be determined after this is known, in the overall performance section. An examination of the effect of different heat exchange efficiencies will also be done in the performance section.

Using the equation given at the beginning of this section, the required storage of water is 6519 KG/½ton of air conditioning desired. So, two continuous tons requires 26074 KG of water. The only other change this makes in our calculations is that the change in storage temperature will now be determined from the C_p of water and not that of the pond.

Thermodynamic Performance of the Evaporative System

For the purposes of this section it will be assumed that the

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[1] Perry and Chilton, Chemical Engineer's Handbook, p. 3-136.

radiation losses of the pond are offset by conduction into the storage from the ground and conduction into the ponds from the sky. Although it will not be calculated here, it will be seen in a later chapter on the radiation system that radiation produces about 10600 W of cooling during the night. This allows for a continuous loss of about 0.13 tons per hour during the entire day.

A computer program was written to compare a number of different factors and is listed in the appendix. This program varies the mole fraction of methanol, the number of tons or storage size available, and the efficiency of heat transfer between the ponds and storage. From this, the environmental data and the necessary equations, the program calculates the various Q's, the change in storage temperature and the number of gallons of methanol which are evaporated. An examination of the psychrometric chart reveals that the dew point for interior air at 78°F, 50% relative humidity is 58°F. It was therefore decided that the storage temperature could not be allowed to rise above 55°F. For this reason 55°F or 12.78°C is used as the starting point in the program. For the system to succeed it must lower the storage temperature to 45°F or 7.22°C during the typical night. Although various storage sizes can be examined in the program, it is anticipated that two tons must work for the system to be feasible. This is because two tons represents a three ton unit for two eight hour days, or two days of normal use, and so is the minimum size which will allow for a night of rain.

The results of the program showed that a 0.7 solution of methanol could only achieve a 2 ton storage if the heat transfer efficiency was 100%. Therefore it was decided to center our analysis on a 0.8 solution of methanol. An abridged form of the program output can be seen in the appendix as table 3. This table shows the results of a 0.8 solution at a few different heat exchange efficiencies and the results for pure ethanol at 100% heat exchange efficiency. A number of graphs have also been prepared which show further relationships found in the complete data. Figure 6 shows the relationship between temperature and the number of night time hours used to lose heat, or store cool. Further it shows how the change in storage size effects the performance of a 0.8 solution of methanol. This graph is based on 100% efficiency of heat transfer between the ponds and storage. Under these conditions it will take seven hours of operation (until 4AM) to cool 26075 KG of water (2 tons storage) from 55° to 45°F. Figure 7 shows the relationship between the mole fraction of methanol and the time necessary to achieve cool down, 45°F, for different efficiencies of heat exchange between the pond and storage. It can be seen from this chart that the heat exchange must occur with at least 70% efficiency for a 0.8 solution to be used. Of course a higher concentration of methanol could be used, but this will probably be hard to maintain in actual practice. Practically, the storage tank of methanol could be at 0.9 or 0.95. However, once in the environment it will experience evaporation and condensation of water into the solution. Under these conditions a 0.8 solution is probably the best which can be maintained.

The higher the heat exchange efficiency, the less methanol that is evaporated. Since methanol represents our fuel cost it is necessary to keep its use as low as possible. Figure 8 shows the extent of cooling which can be achieved with different heat exchange efficiencies and the number of gallons of methanol which will be evaporated per day to produce the desired 10°F change in the given storage. The full use of the two ton storage, ie. 3 tons for 16 hours a day, represents the evaporation of 2500 gal/mo. However, in actual use it is likely that less than half of the potential storage will be used in a day. So, the actual figure for methanol use is about 1250 gal/mo. Even this lower figure is to much methanol to buy each month. Methanol is currently priced at 51¢/gal. Its price would have to be reduced to about 8¢/gal for the purchase of methanol to be comparable to the present cost of an electric air conditioner at 5¢/KWH. Fortunatly, methanol can be produced via a biomass process. This means that a small biomass reactor will have to be incorporated into the house plan to turn all organic waste into methanol. Since the air conditioning is only needed about 5 months per year, this

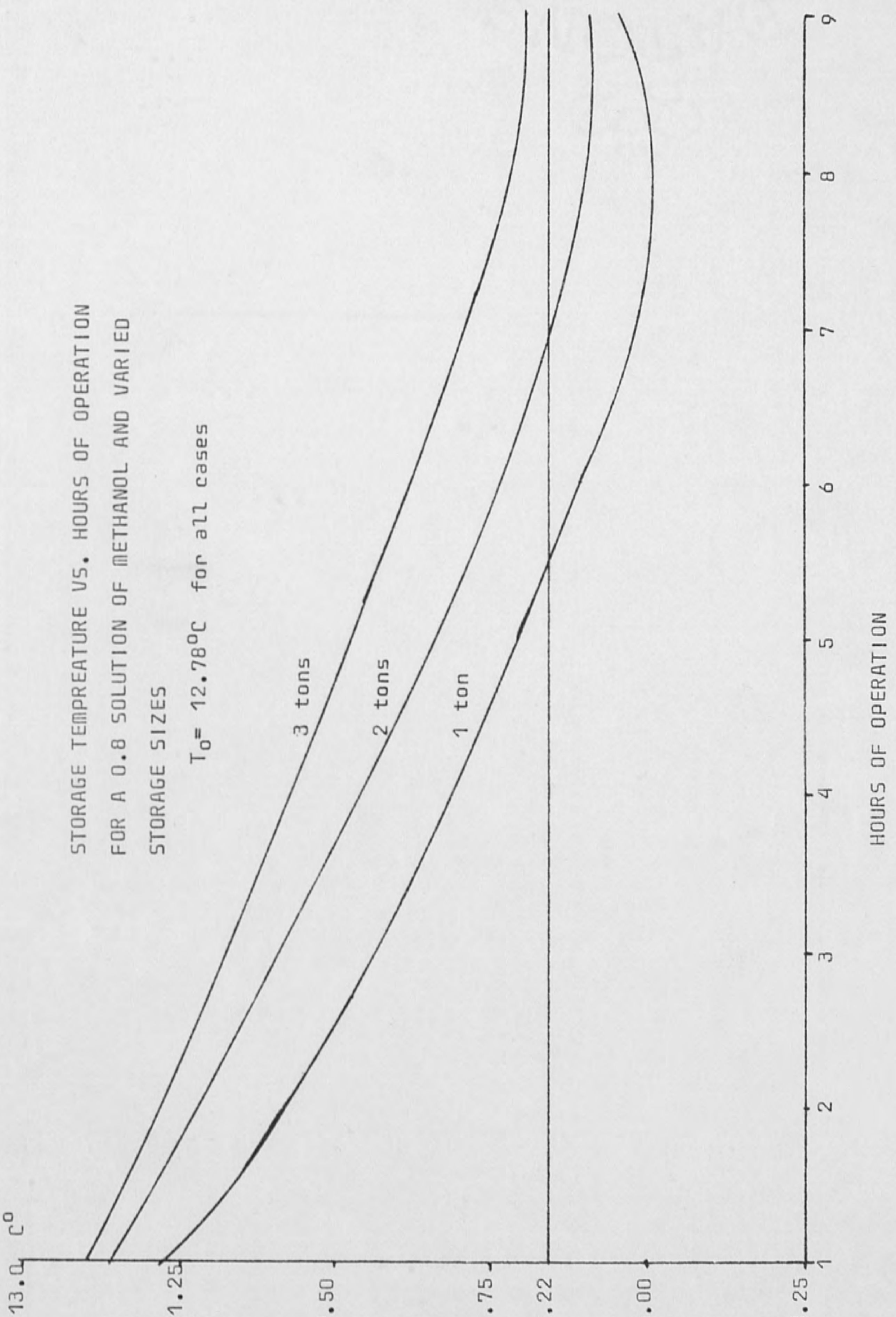


Fig. 6. Hours to cool storage

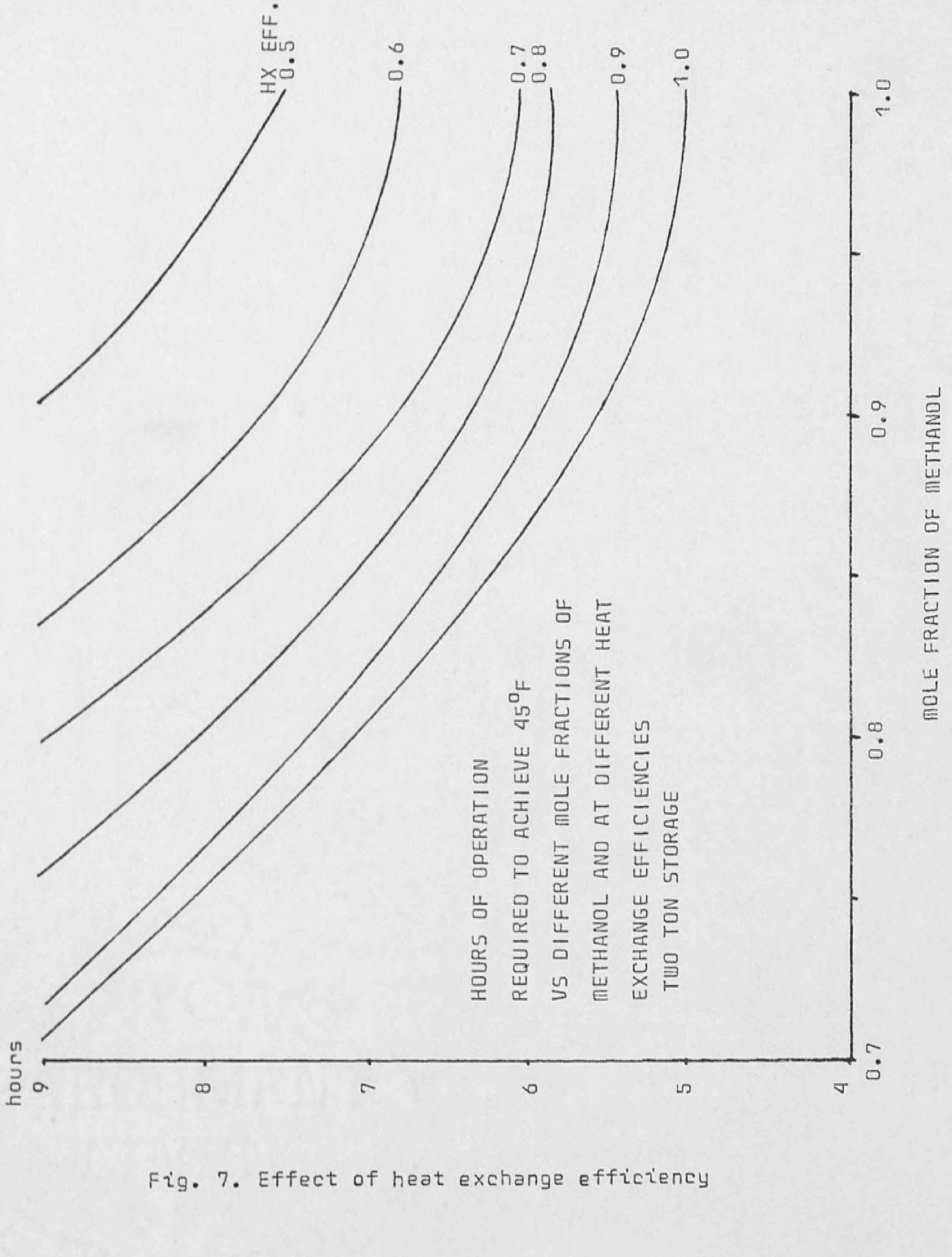
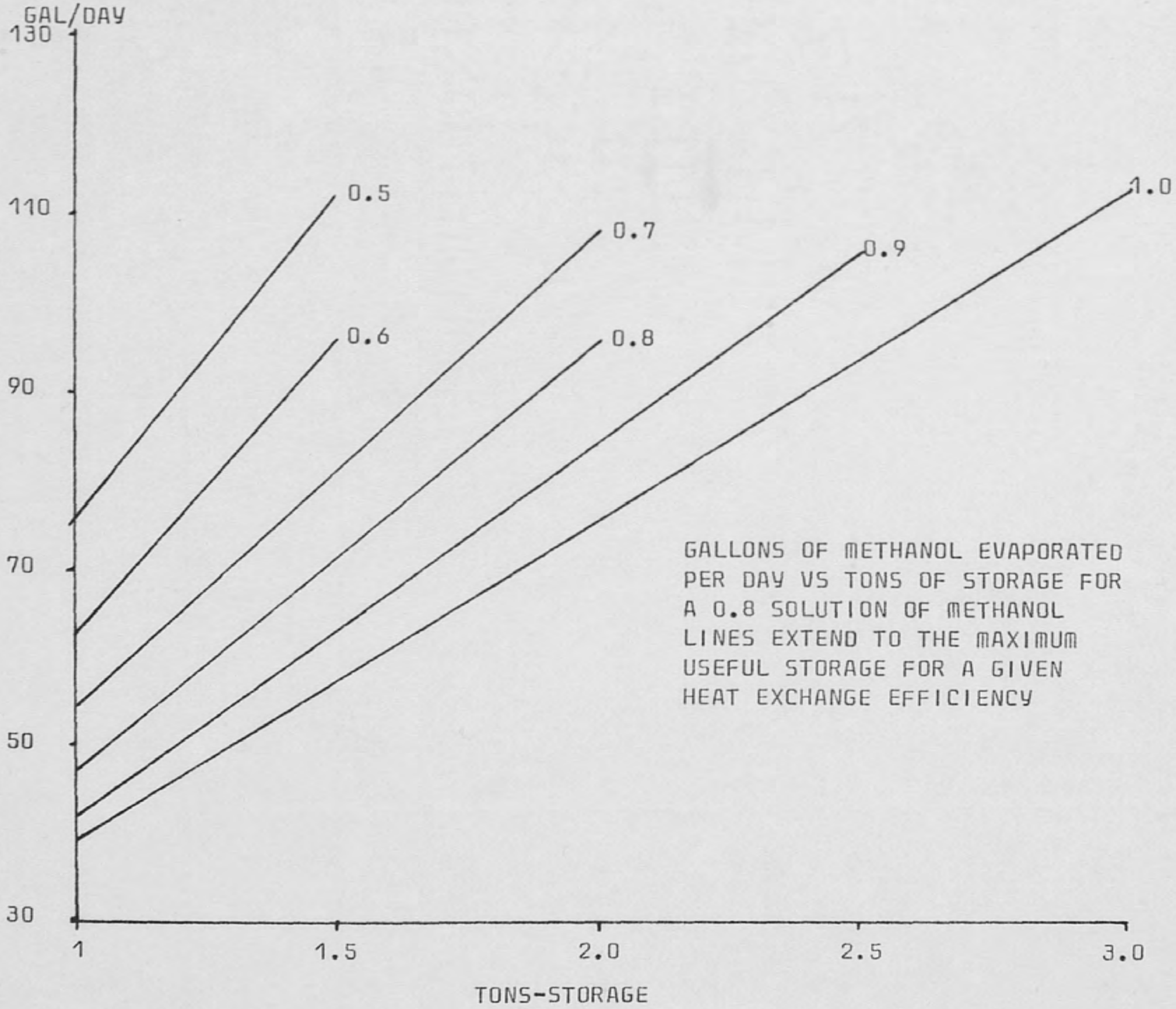


Fig. 7. Effect of heat exchange efficiency



GALLONS OF METHANOL EVAPORATED PER DAY VS TONS OF STORAGE FOR A 0.8 SOLUTION OF METHANOL LINES EXTEND TO THE MAXIMUM USEFUL STORAGE FOR A GIVEN HEAT EXCHANGE EFFICIENCY

Fig. 8. Evaporation of methanol

means that the maximum necessary output will be 520 Gal/mo, corresponding to the 1250 Gal/mo figure in use. Another feature is that the distillation apparatus of the biomass reactor can be used to redistill our storage of methanol as its concentration falls below 0.8.

Summary and Operation of the Evaporation System

The following relationships:

$QE = 0.093 \times h_{fg}(1.0 + 0.38V)\Delta p_v$ and

$QC = \bar{h}(T_{storage} - T_{air})$,

along with the necessary atmospheric and solution data have been used to describe an evaporative cooling system which will provide three tons of cooling sixteen hours a day at a temperature low enough to also provide dehumidification in a humid environment. This is possible due to the greatly increased vapor pressure and only slightly decreased heat of vaporization made possible through the use of methanol. Ethanol, another common product of biomass, was also studied via the same program as methanol. Ethanol was not able to even maintain the starting temperature of 55^{0}F and heated up to 61^{0}F or beyond during the night. It was found that a 0.8 solution of methanol would cool to 45^{0}F during the night with heat exchange efficiencies as low as 70%.

The operation of the system will be as follows after initial start up. The biomass system, which includes a still for purifying methanol, will deliver 0.9 to 0.95 methanol to storage. This methanol will be pumped onto the roof to be cooled in the pond. Sensors will detect methanol concentration, pond inlet and outlet temperatures, as well as storage temperatures and weather conditions. When the alcohol system falls below 0.8 concentration due to evaporation losses and condensation gains, it will be reconcentrated in the solar stills. Operation of the alcohol system will be stopped when the storage system cools to 45^{0}F, the pond outlet temperature is greater or equal to the inlet temperature, or if it rains. The cooled methanol will cool the storage via heat exchangers. If we assume a ΔT_m of 1°C then we shall need a heat exchanger with approximately $100 m^2$ of surface area. The stored water will then be pumped through heat exchangers where it will cool and dehumidify the interior air of the house.

THE RADIATIVE SYSTEM

In the statement of the problem, the pond cross section showed a lower radiation system covered by the evaporative system. It was thought that since water vapor is transparent in the 8-13um range, that liquid water would be transparent within this same range. If this is so, then a selective radiatior can be built which could be thermally protected by water and still have radiation losses during the night as well as the day. Further, these losses would be greater than those possible from a black surface. To further enhance this prospect, it was thought that dyes placed in the upper layer would absorb the 35% of light in the visible region which normally passes through water. Although liquid water does absorb less strongly in the 8-13um band, it must be kept to a thickness of about 0.1mm for this system to be effective. Obviously, this can not be achieved on a roof. However, some interesting and worthwhile information was obtained and will be presented here.

A review was made of the infrared spectra of 192 polymers to determine which were the best suited to our purpose.[1] The plastics reviewed can be broken down into seven groups; aliphatic polyhydrocarbons (polyethylene), aromatic polyhydrocarbons (polystyrene), halogenated polyhydrocarbons (teflon), acrylics and polyvinyl esters (polyvinyl acetate), cellulose derivatives, polyethers (polyvinyl butyral) and polyamides. Of these, only the halogenated polyhydrocarbons exibit the desired properties. This group can be further divided into chlorinated and fruorinated compounds. Of these, it was found that the flourinated compounds, the teflons (Teslar, Tedlar,Kynar,Houstaflon TF-14, Kel-F 827, and Houstaflon C2) were

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[1] Dieter O. Hummel, Infrared Spectra of Polymers, (New York: Interscience Publishers, 1966), pp. 91-187.

most appropriate. The infrared spectra of these compounds indicate that Teslar, Tedlar and Houstaflon C2 are essentially equivalent for our purpose. Figure 9 shows approximate infrared spectra of these compounds.[1] Examination of these spectra shows that these plastics are highly reflecting outside the desired band, while being highly absorbing within the 8-13um band. Tests done for this purpose on Tedlar showed that reflectivity outside of the band was 0.85 and 0.15 within the band.[2]

The reason that a selective surface is superior to a black surface in this application is that a black surface will absorb radiation a selective radiator will reflect, but will only emit as much radiation within the desired atmospheric window, as a selective surface. As an example, diffuse radiation during the day is within a band less than or equal to 4um. A black surface will absorb this radiation, which can amount to 94.6 W/m^2 in this area.[3] The emission spectra which corresponds to the black body temperature of our radiator, peaks within the 8-13um range. The night sky radiates on both sides of this range but has a transparency window within this range. So, a black radiator which will absorb all radiation will be at a disadvantage to a selective radiator which reflects all radiation except that which is within the range at which it can be effectively emitted back to the sky. Experiments done on a Tedlar radiator in a situation where convective gains were eliminated, showed that a selective surface would be from 15-20°C colder than a black surface and that even during the day a 15°C temperature change from room could be achieved with the surface. These experiments were done in Naples, Italy which has a climate very similar to ours here in Florida.[4]

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[1] Ibid.

[2,4] S. Catalanotti et al., "The Radiative Cooling of Selective Surfaces," Solar Energy 47 (1975):83-89.

[3] John Duffie and William Beckman, Solar Energy Thermal Processes, (New York: John Wiley and Sons, 1974), pp. 25-52.

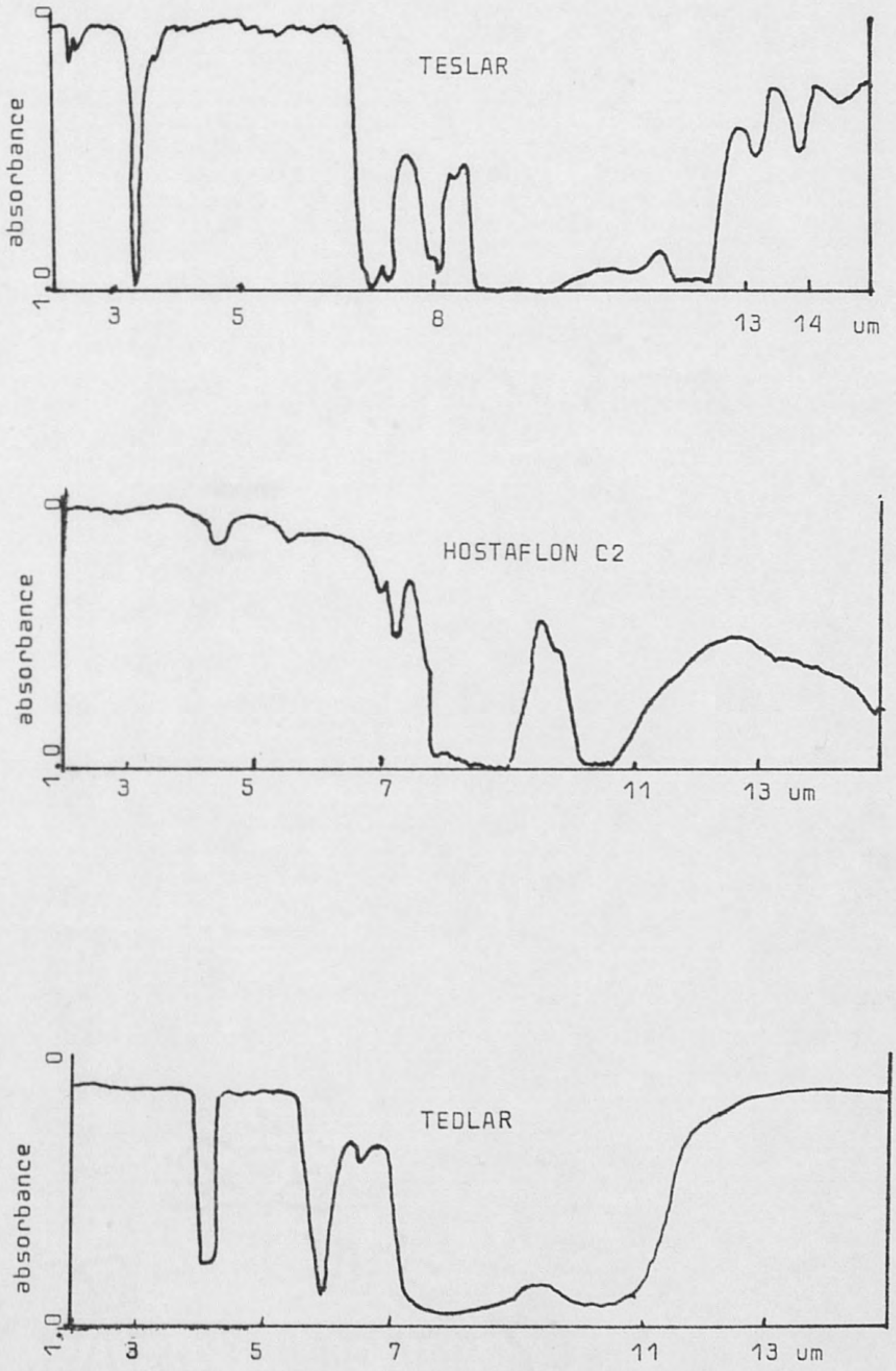

Fig. 9. I.R. spectra of teflons

Calculations were done to determine the radiation losses using the following equations.[1]

$T_{sky} = 0.0552T_{air}^{1.5}$

$Q_{selective} = 0.26T_{sky}^{4} - 0.36T_{radiator}^{4}$

where 0.26 = emissivity of sky at Cocoa Beach, FL

0.36 = emissivity of Tedlar

$Q_{black} = 0.26(T_{sky}^{4} - T_{radiator}^{4})$

The results obtained from these equations confirmed the temperature differences given earlier and showed that for a black surface (or the exposed water in the evaporative system) it would obtain an average of 4081 BTU/hr cooling, or about 3 tons/night. Compared to this a selective surface would yield 41661 BTU/hr or about 9 tons/night.

The Use of Dyes

It was seen in the previous section that water in any appreciable thickness will absorb virtually 100% of all incoming I.R. radiation. However, water is transparent to visual wavelenghts, 35% of the solar spectrum. The addition of a dye which will absorb the visible light will make water an ideal black surface for low temperature solar work. During the day this solution can be used in the roof ponds and south facing collectors to absorb all incoming radiation. It can be cooled during the day by providing hot water and by passing it through coils under the ground. It can be further cooled to ground temperature, 72°F, by conduction and radiation at night. In this way a large percentage of the daily radiation gains would be eliminated, thereby reducing the cooling load.

This dye water solution would have other advantages during the winter, or in flat plate collector design in general. Instead of heating a flat metal plate which then transmits a percentage of the heat to the water, the water can be heated directly. Plus, the

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[1] Duffie and Beckman, Solar Energy, p. 76.

water dye solution provides a blacker surface than a painted or plated surface.

It has been reported by M.R. Bloch that the addition of Napthol Green to brine greatly enhances the absorption and thereby the evaporation of salt solutions. The Palestine Potash Co, has had their salt production rise 20% as a result of this small process change.[1]

A review was made of the spectral transmission factors of a large number of dyes in the visual range. It was found that as individual color groups, the green and blues were most effective, and Napthol Green was one of the best. However, as table 4 reveals, Napthol Green as well as the other greens and blues, transmits some light between 0.45 and 0.57um. The remainder of table 4 lists some yellow and red dyes which absorb within this range and would eliminate the transmission of any visible light if mixed with one of the green or blue dyes. So, the mixture of dyes in water provides a surface which is black throughout the visible and infared spectrum. While this surface may be more directional than a painted surface, this could be controlled through the proper use of cover glass.

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[1] M.R. Bloch, Ladislaus Farkas and K.S. Speigler, "Solar Evaporation of Salt Brines," <u>Industrial and Engineering Chemistry</u> 7 (1950):1544-1553.

TABLE 4

Spectral Transmission Factors

Dye Name	Wave Length-um												
	.44	.46	.48	.50	.52	.54	.56	.58	.60	.62	.64	.68	.70
napthol green	.00	.00	.02	.06	.10	.15	.09	.02	.00	.00	.00	.00	.00
neptune green	.00	.19	.36	.18	.02	.00	.00	.00	.00	.00	.00	.00	.02
prussian blue	.06	.09	.09	.05	.02	.01	.00	.00	.00	.00	.00	.00	.00
patent blue	.15	.25	.17	.05	.00	.00	.00	.00	.00	.00	.00	.00	.12
red													
rapid filter	.00	.00	.00	.00	.00	.01	.10	.47	.86	.95	.96	.96	.96
carmen ruby	.00	.00	.00	.00	.00	.00	.00	.00	.00	.04	.18	.37	.49
yellow													
chrysoidin	.00	.00	.00	.00	.00	.00	.00	.00	.02	.23	.50	.79	.79
methyl orange	.00	.00	.00	.00	.00	.00	.01	.31	.70	.79	.80	.81	.81

Compiled from figures in M. Luckiesh, "Physical Basis of Color-Technology," Journal of the Franklin Institute, (1917) 184: 73-93.

5

CONCLUSION AND POTENTIAL DEVELOPMENT

This paper has shown that a passive cooler can be designed for a humid climate which can completely replace conventional air conditioners. This is done through the use of solvents which increase the evaporative losses from a roof pond by increasing the vapor pressure above those which can be achieved even at zero humidity with water alone. This system is effective enough that a temperature can be achieved in storage to provide latent as well as sensible cooling. At the mid point temperature of the storage, 50^{0}F, air can be supplied to a room at 65^{0}F, 60% humidity, which will result in very comfortable conditions.

It has also been shown that while radiation cooling has limited use in a humid climate, and can not be thermally protected by a useful water layer, its effect can be maximized through the use of selective covers. The most effective covers found for this purpose were shown to be of the teflon family. It has also been seen that through the use of dyes in a water solution, a black absorbing surface can be provided to limit radiation gains during summer days and provide hot water and or heat year round. Industrial uses of dyes have been limited to the use of one dye in solution, probably due to later separation considerations. We have seen that a more effective absorbing solution can be had by a mixture of dyes.

The most obvious next step which must be taken to make this design a reality, is the biomass reactor. It has been found that little experimental data exists for such a system. Data which does exist is for single element, homogenous, reaction mixtures; wood, paper, sewage,etc. In this system we must be able to react a number of different organic wastes which are common to a household. This means we are faced with a varying cellulose concentration, which inhibits the reaction, as well as a number of different elements which will react at different rates. This will require the funding of an experimental program to determine reaction rates and efficiency as well as those conditions which must be maintained to make optimal use of the enzymes under such diverse conditions.

The next development is a modification of the ponds. There is no reason that the evaporation must take place on the roof where we lose so much methanol to the atmosphere. There are many health dangers associated with methanol and the evaporation of so much of it into the atmosphere would be banned by the E.P.A. As a result the entire roof pond concept can be abandoned or modified to a single large roof pond which would only make use of the water dye solution. What must be designed is a closed spray evaporator, cooling tower, which would provide a cold solution to be heat exchanged with the storage while also providing a combustable mixture of methanol vapor and air. This mixture can then be led off to a combustion chamber where it can be converted to electrical power for the dwelling. If enough methanol can be produced to make possible year round operation of the system, the waste heat from the combustion can also be use for heating the dwelling. If we assume that as an average we evaporate 50 gal/day during the cooling months then at a 30% conversion efficiency, the methanol will provide 52650 KWH to an electrical storage. This is more than enough to provide total electric power for over a year.

APPENDIX

A PROGRAM TO PREDICT EVAPORATION SYSTEM PERFORMANCE

```
C     P= TOTAL PRESSURE            HFG = HEAT OF VAPORIZATION
C     T = INITIAL STORAGE TEMP   T2 = CHANGED STORAGE TEMP
C     QE,QC,QT = HEAT TRANSFER DUE TO EVAPORATION, CONVECTION AND
C     TOTAL
C     KG = KILOGRAMS OF WATER IN STORAGE
C     TONS = CONTINUOUS COOLING AVAILABLE
C     GAL = GALLONS OF METHANOL LOST PER HOUR
C     TA = AIR TEMP               PA= AIR VAPOR PRESSURE
C     H = CONVECTION HEAT TRANSFER COEFFICIENT
C     V = WIND SPEED
      REAL P,HFG,T2,QE,QC,QT,T,KG,TONS,GAL
      DIMENSION TA(9),PA(9),H(9),V(9)
C     READ INPUT DATA
      DO 2 I=1,9
      READ(5,100) TA(I),PA(I),H(I),V(I)
    2 CONTINUE
      WRITE(6,200)
C     SET INITIAL CONDITIONS AND AND PARAMETERS TO STEP THROUGH
C     ½ TON COOLING CHANGES
      DO 6 J=5,10
      Y=0.1*J
      T=12.78
      TONS=0.5
      KG=6518.69
      DO 5 I=1,5
      KG=KG+6518.69
      TONS=TONS+0.5
      DO 3 N=7,10
      T2=12.78
```

```
      X=0.1*N
C     CALCULATE HFG AND P FROM STEPPED MOLE FRACTIONS AND CALCULATED
C     CHANGES DUE TO TEMPERATURE CHANGES IN STORAGE
      HFG=519*X+(1-X)*1062
      P=(X*2.44+(1-X)*.44)*((T2+273.15)/(T+273.15))
C     CALCULATE QE,QC,QT IN WATTS/ M^2
      DO 4 M=1,9
      QE=.293*HFG*(1.0+.38*V(M))*(P-PA(M))
      QC=H(M)*(T2-TA(M))
C     CALCULATE GAL USING  NECESSARY MOLE FRACTION AND CONVERSION
C     DATA TO ARRIVE AT A FIGURE OF GAL/300M**2/hr
      GAL=(QT*X*3114.67)/(HFG*(X32.04+(1-X)*18))
C     ADJUST QT FOR HEAT EXCHANGE EFFICIENCY
C     CALCULATE T2 BASED ON ADJUSTED QT
      QT=QT*Y
      T2=T2-(257.75QT/KG)
      WRITE(6,250) M,QE,QC,QT,T2,X,TONS,KG,Y,GAL
    4 CONTINUE
    3 CONTINUE
    5 CONTINUE
    6 CONTINUE
  100 FORMAT(F4.2,F4.3,F4.2,F3.2)
  200 FORMAT(///3X,4HTIME,5X,2HQE,10X,2HQC,10X,2HQT,10X,2HT2,10X,
     C2HXI,6X,4HTONS,3X,10HKG STORAGE,5X,3HEFF,8X,3HGAL)
  250 FORMAT(/5X,I2,6(3X,F8.3),3X,F9.2,2(3X,F8.3))
      STOP
      END
```

An earlier version of the same program was also run for ethanol. This earlier program did not account for heat transfer efficiency or the gallons of solvent evaporated. The reason that ethanol was not run in the final version, is that it was shown not to work as a viable solvent. Its results will be seen in the following table. Since only two lines were varied to account for the different solvent properties in the earlier program, these two lines for ethanol are shown below.

```
HFG=400*X+(1-X)*1062
P=(X*1.54+(1-X)*.44)*((T2+273.15)/(T+273.15))
```

TABLE 3

TIME	QE-W/m^2	QC	QT	T2-C^o	XI	TONS	KG STORAGE	EFF	GAL
22	783.764	-715.296	47.927	12.306	0.800	2.000	26074.77	0.700	9.299
23	723.976	-597.467	88.556	11.431	0.800	2.000	26074.77	0.700	17.182
24	663.116	-552.438	77.474	10.665	0.800	2.000	26074.77	0.700	15.032
01	614.180	-513.657	70.366	9.969	0.800	2.000	26074.77	0.700	13.653
02	561.772	-461.474	70.209	9.275	0.800	2.000	26074.77	0.700	13.623
03	564.094	-465.538	68.989	8.593	0.800	2.000	26074.77	0.700	13.386
04	566.311	-472.553	65.630	7.945	0.800	2.000	26074.77	0.700	12.734
05	553.013	-484.817	47.737	7.473	0.800	2.000	26074.77	0.700	9.262
06	579.635	-549.507	21.090	7.264	0.800	2.000	26074.77	0.700	4.092
									108.2
22	783.764	-715.296	54.774	12.239	0.800	2.000	26074.77	0.800	9.299
23	723.976	-600.799	98.541	11.264	0.800	2.000	26074.77	0.800	16.730
24	663.116	-559.816	82.640	10.448	0.800	2.000	26074.77	0.800	14.030
01	614.180	-522.285	73.516	9.721	0.800	2.000	26074.77	0.800	12.481
02	561.772	-470.060	73.370	8.996	0.800	2.000	26074.77	0.800	12.456
03	564.094	-475.030	71.252	8.291	0.800	2.000	26074.77	0.800	12.097
04	566.311	-482.620	66.953	7.629	0.800	2.000	26074.77	0.800	11.367
05	553.013	-495.120	46.314	7.172	0.800	2.000	26074.77	0.800	7.863
									96.4

This table is an extract of information provided by the computer program and shows that information which was most extensively used throughout the paper.

TIME	QE-W/m^2	QC	QT	T2-C^o	XI	TONS	KG STORAGE	EFF	GAL
22	783.764	-715.296	61.621	12.171	0.800	2.000	26074.77	0.900	9.299
23	723.976	-604.132	107.859	11.105	0.800	2.000	26074.77	0.900	16.277
24	663.116	-566.901	86.594	10.249	0.800	2.000	26074.77	0.900	13.068
01	614.180	-530.176	75.604	9.501	0.800	2.000	26074.77	0.900	11.409
02	561.772	-477.641	75.718	8.753	0.800	2.000	26074.77	0.900	11.427
03	564.094	-483.262	72.749	8.034	0.800	2.000	26074.77	0.900	10.979
04	566.311	-491.197	67.603	7.366	0.800	2.000	26074.77	0.900	10.202
05	553.013	-503.746	44.340	6.927	0.800	2.000	26974.77	0.900	6.691
									89.4
				ETHANOL					
22	293.963	-715.296	-421.333	16.945	1.000	2.000	26074.77		
23	282.578	-369.060	-86.481	17.800	1.000	2.000	26074.77		
24	254.924	-270.042	-15.118	17.949	1.000	2.000	26074.77		
01	234.869	-224.622	10.247	17.848	1.000	2.000	26074.77		
02	214.827	-189.353	25.475	17.596	1.000	2.000	26074.77		
03	217.420	-183.302	34.118	17.259	1.000	2.000	26074.77		
04	219.947	-183.912	36.035	16.903	1.000	2.000	26074.77		
05	213.698	-192.075	21.623	16.689	1.000	2.000	26074.77		
06	223.985	-223.353	0.632	16.683	1.000	2.000	26074.77		

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