Enhancing the Cooling Capacity of Roof Ponds Using Polyethylene Band Filter

by

Mohd. Aqdus Siddiqui

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2013 by the
Graduate Supervisory Committee:

Harvey Bryan, Chair
T Agami Reddy
Michael Kroelinger

ARIZONA STATE UNIVERSITY

May 2013

ABSTRACT

With the desire of high standards of comfort, huge amount of energy is being consumed to maintain the indoor environment. In US building consumes 40% of the total primary energy while residential buildings consume about 21%. A large proportion of this consumption is due to cooling of buildings. Deteriorating environmental conditions due to excessive energy use suggest that we should look at passive designs and renewable energy opportunities to supply the required comfort.

Phoenix gets about 300 days of clear sky every year. It also witnesses large temperature variations from night and day. The humidity ratio almost always stays below the 50% mark. With more than six months having outside temperatures more than 75 ^{o}F, night sky radiative cooling promise to be an attractive means to cool the buildings during summer. This technique can be useful for small commercial facilities or residential buildings.

The roof ponds can be made more effective by covering them with Band Filters. These band filters block the solar heat gain and allow the water to cool down to lower temperatures. It also reduces the convection heat gain. This helps rood ponds maintain lower temperatures and provide more cooling then an exposed pond. 50 μm Polyethylene band filter is used in this study. Using this band filter, roof ponds can be made up to 10% more effective. About 45% of the energy required to cool a typical residential building in summer can be saved.

To

My Family

ACKNOWLEDGMENTS

I would like to thank Prof. Harvey Bryan for his guidance and steering this thesis to the right path. I would also like to thank Prof. T. Agami Reddy for his invaluable inputs and all the time and effort he put in to make this thesis happen. I am also thankful to Prof. Michael Kroelinger for his attempts to make this a success. I take this opportunity to thank Prof. Muthukumar Ramalingam for providing me with the lab instruments and helping me throughout the process.

TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

Figure Page

Chapter 1

INTRODUCTION

Overview

Passive cooling techniques have always been there is some form or the other. People developed smart techniques to meet their need of comfort. Their techniques steered nature's forces to their benefit.

Passive techniques have gradually developed over time but they have been largely ignored throughout the world. The reason could be lack of knowledge or people's interest in new and latest technology. Climate responsive design has been limited to HVAC sizing. Some passive techniques like evaporation, ventilation have been worked upon more than others. On the other hand phenomenon of Radiation attracted fewer researchers.

Passive cooling techniques have found its place in research and theory but when it comes to practice it is very rare to find. The passive approaches require considerable amount of knowledge about climate. Thus it's difficult to design systems which can achieve desired level of comfort level and work universally. This is not the case in active systems. Another reason for popularity of active systems is commercialization. There are more experts for active systems then passive ones. Also active systems are easily available in the market which makes them more accessible.

Problem Statement

Cooling takes the highest share of energy in a building in the hot and dry climate of Phoenix. Big variation in temperature between nights and days and low humidity are ideal conditions for radiative cooling phenomenon. This technique is used to in the form of roof ponds to provide cooling to the buildings. However the technique has not been perfected yet and still needs to be made more effective. Band filter like polyethylene films are cheap and effective ways to improve the performance of the roof ponds. Further investigation is required to establish the behavior of the pond when covered with a band filter and its effectiveness to provide cooling to the buildings.

Research Objective

The first objective of this study was to experimentally understand the phenomenon radiative cooling using of sky window (8-13µm wavelength). It involved studying how a roof pond behaves when it is covered by a 50µm thick polyethylene band filter.

The second objective was to determine the time of the year and duration for which it is useful to operate such a pond and how much energy it can save.

Scope and Limitations

This study is limited to geographic location of Phoenix due to suitable climatic conditions; however the results can be applied to the areas with similar climate and building cooling loads. Also this study looks at only residential building type and does not cover other building types. It is focused on only the sensible cooling loads of a typical residential building in Phoenix area. Effects of roof pond on heating and other purpose were not analyzed. Also it is restricted to performance of a 50µm polyethylene band filter.

Chapter 2

BACKGROUND

Terms and definitions

Conduction: Heat transfer is a result of molecular-level kinetic energy transfer in solids, liquids and gases. Conduction heat flow occurs in the direction of decreasing temperature.

Convection: when a moving fluid contacts a surface at a different temperature the resulting heat transfer is called Convection. Convection heat transfer is always associated with a large scale (i.e., not molecular-scale) motion of a fluid – either liquid or gas – over a warmer or cooler surface. The higher the velocity of fluid flow, the higher the rate of convection heat transfer (Kreider, 2010).

Radiation: heat transfer is the transport of energy by electromagnetic waves. No material other than the surface exchanging energy need tobe present for radiation to occur. The sole requirement for radiation heat transfer to occur is the presence of two surfaces at different temperatures. Radiation must be absorbed by matter to produce internal energy (Kreider, 2010).

Reflectivity, Absorptivity and transmissivity: When thermal radiation is incident on a surface it must be reflected, absorbed or transmitted.

Incident = Absorbed + Reflected + Transmitted

Or

$$1 = \frac{\text{Absorbed}}{\text{Incident}} + \frac{\text{Reflected}}{\text{Incident}} + \frac{\text{Treansmitted}}{\text{Incident}}$$

Three terms in the equation above are called Absorptivity α, the reflectivity ρ, and the transmissivity τ. Thus above equation can also be rewritten as (Mahan, 2002).

$$1 = \alpha + \rho + \tau \qquad \text{Eq. 1}$$

Stefan-Boltzmann law of radiation heat transfer: The heat flux emitted from a blackbody at absolute temperature T_b is given by

$$q_{rad} = \sigma T_b^4 \qquad \text{Eq. 2}$$

Blackbody: A blackbody is defined as a perfect absorber of thermal radiation; that is, it absorbs all incident radiation from all directions and at all wavelengths (Mahan, 2002).

Graybody radiation: An energy radiator which has a blackbody energy distribution, reduced by a constant factor, throughout the radiation spectrum or within a certain wavelength interval. The designation "gray" has no relation to the visual appearance of a body but only to its similarity in energy distribution to a blackbody. Most metals have a constant emissivity within the visible region of the spectrum and thus are gray bodies in that region. The gray body concept allows the calculation of the total radiation intensity of certain substances by multiplying the total radiated energy (as given by the Stefan-Boltzmann law) by the emissivity. The concept is also quite useful in determining the true temperatures of bodies by measuring the color temperature (McGraw-Hill Science & Technology Encyclopedia, 2005).

Radiosity: it is defined as the radiation heat flux leaving a surface. It is defined with regards to direction or wavelength such that when multiplied by the area or a surface the result is the radiative power leaving the surface. It includes both emitted and reflected power (Mahan, 2002).

Departure of real surfaces from blackbody behavior

Surfaces of practical engineering interest, such as metals paints and plastics generally do not absorb all incident radiation, nor do they generally emit as much radiation as a blackbody at the same temperature. Furthermore, their departure from blackbody behavior usually depends on the wavelength interval of interest as well as on the direction of emission or incidence (Mahan, 2002).

Thermal radiation is electromagnetic radiation emitted by a material substance solely due to its temperature. The part of electromagnetic spectrum considered to be thermal is not clearly bounded. Note that the part of the electromagnetic spectrum visible to human eye occupies only about 0.3 μm out of the spectrum that ranges over more than seventeen orders of magnitude (Mahan, 2002).

The spectral distribution of radiation emitted from a source is the variation with wavelength (per unit wavelength) of the source strength. It is interesting to note that the spectral distribution of radiation emitted by the sun peaks at about 0.55 μm, or in the center of the visible spectrum. The human eye has evidently to be optimally suited to exploit the earth's natural light source (Mahan, 2002).

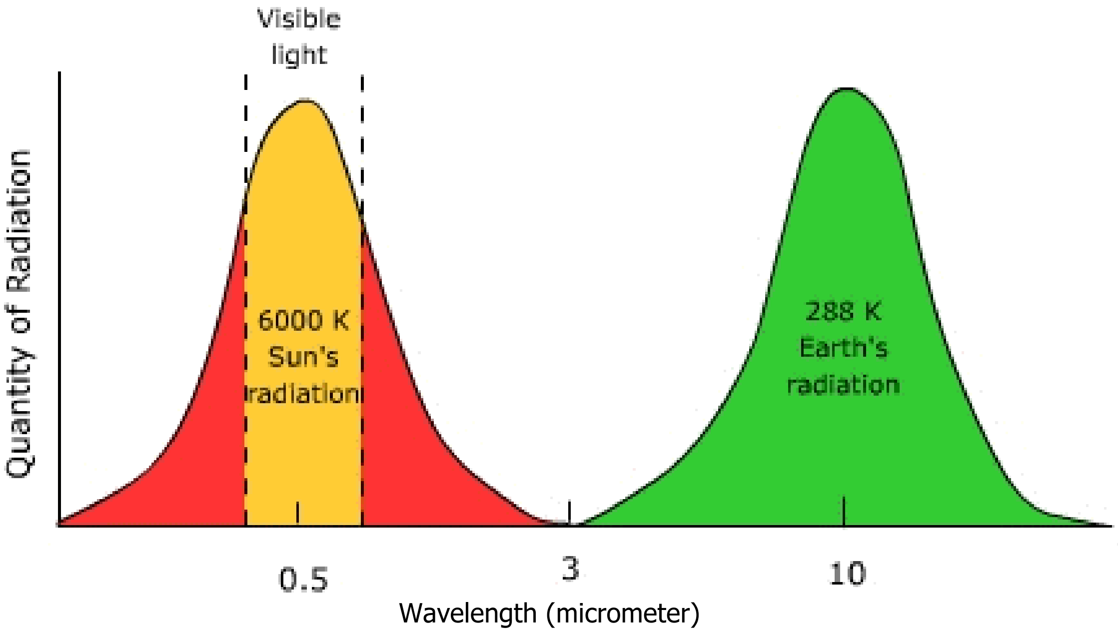

Figure 1 : Comparison of Solar and Earth radiation spectra

Figure 1 shows the Sun and the Earth spectrum. Sun radiates high energy radiations hence their wavelength is short. Earth radiates long wavelength radiations. Solar radiation peaks at around 0.55 μm whereas earth radiation peaks at around 10 μm. Most of the earth radiation falls between 8-13 μm wavelengths range. This range is also called sky window. Sky window can be defined as a window in the radiation spectrum where earth looses its energy to maintain its temperature.

Earth energy balance

Earth is a close loop system where no external matter or energy enters the system. The exception to this statement is the energy transferred from the Sun to the Earth. Everyday Sun supplies enormous amount of energy to the earth in the forms of radiations. This raises the temperature of the earth. In order to maintain its temperature earth has to get rid of this excess energy. Earth losses this energy in the form of long wave radiations.

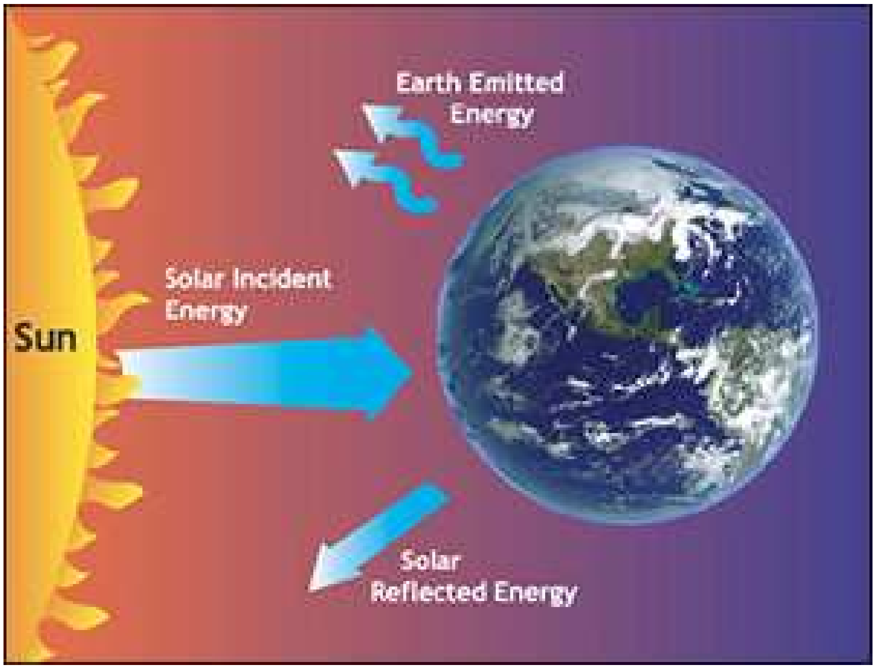

Figure 2: Solar and Earth radiations. (Nasa)

Earth maintains its temperature by losing heat to the cold sky by radiative heat transfer process.

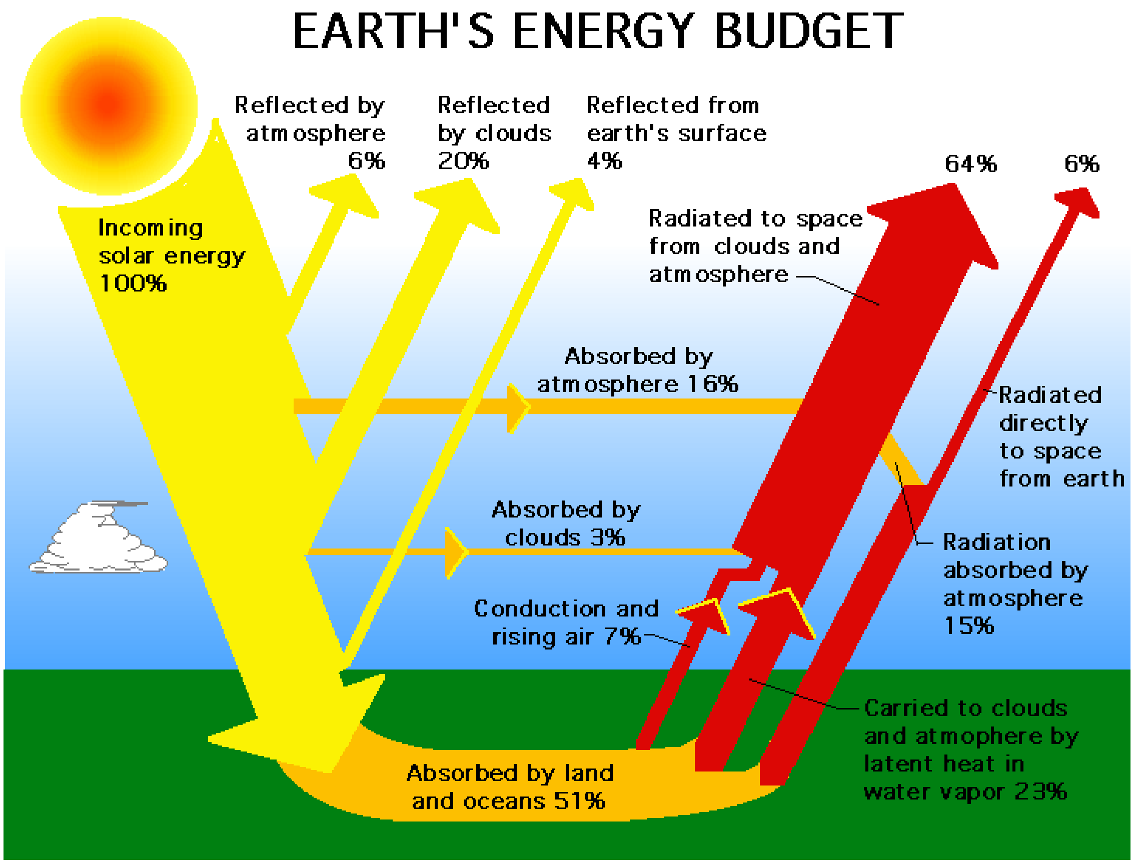

Figure 3: Earth energy balance. (Rutgers)

Figure 3 explains that about 30% of the solar radiations that are directed towards the earth are reflected back to the sky. Most of these radiations are reflected by the atmosphere and clouds. A small amount of these radiations are reflected by the earth surface. About 70% of the solar radiations are absorbed by the earth and its atmosphere. This Huge amount of energy raises the temperature of the earth during the day time. Earth constantly losses this heat by radiating it towards the sky. This phenomenon is more prominent at night time when sky temperature is very low and there is no solar heat gain happening.

Heat Transfer Process in Radiant Cooling

All systems for radiant cooling of building involve five processes of heat transfer that affect the performance of the system

1) Long-wave radiation emitted by the radiator
2) Radiation emitted by the atmosphere and absorbed by the radiation surface.
3) Convective heat exchange between the radiator and the ambient air.
4) Cold energy transfer from radiator to the building, either by conduction (with concrete roof radiators) or by forced air flow in the case of specialized lightweight (metallic) radiators.
5) Convective heat exchange between the radiator and the heat transfer medium, namely air (in the case of a light weight radiator). (Givoni, 1994)

The system's performance depends in part on climatic conditions and in part on its design details. The balance between the two first processes yields the net radiant heat loss, which represents the climatic potential for radiant cooling. The balance between the net radiant loss and the convective exchange with the ambient air yield the stagnation temperature of the radiator, the heat exchange between the radiator and the air flowing underneath, and the air flow rate, determining the temperature of the air exiting from the radiator and the cooling energy delivered to the building (Givoni, 1994).

Every surface emits radiation with a spectrum of wavelengths, which depends on its temperature. At the ordinary temperature found on earth the emitted radiation is in the long wave range. When a given surface faces other surfaces at similar temperature (for example, the ground around the building or the walls of other buildings) the net gain or loss is rather small. However, when a given surface such a roof of a building, is exposed to the sky, the situation is different. The downward flux of atmospheric long wave radiation is weaker than the radiation emitted upward by the ordinary surfaces. The results are a net long-wave radiant heat loss and a cooling of surfaces exposed to the sky (Givoni, 1994)

Emission of long-wave radiation takes place continuously, day and night. However, during the day time the surface radiation in the long-wave part of the spectrum are exposed to solar radiation. The solar radiation absorbed at the surface (which depends on its solar absorptivity; that is, its color) produces heating, which in most cases outweighs the cooling effect produced by the emission of long-wave radiation. Therefore, net radiant cooling can be obtained only during the night hours. For this reason radiant cooling is often referred to as nocturnal radiation (Givoni, 1994).

The long-wave radiation emitted by the building occures over the range of 5 to 30 microns μ, with peak radiation at about 10μ (gray-body radiation) the spectrum of the radiation emitted by the atmosphere, however may or may not follow a similar pattern, its spectrum pattern depends on the moisture content of the air (measured, among other ways, by the vapor pressure or the dew-point temperature) and especially on cloud conditions (Givoni, 1994).

The net radiant heat loss from a radiator placed on the roof of a building is the balance between the energy flux emitted by the radiator and the incoming atmospheric radiation absorbed by the radiator. It can be about 70 W/m^2, or even more, from a radiator with an "ordinary" surface under clear night sky in a desert, and it decreases with cloudiness and the humidity of the ambient air. It drops to about 40 to 50 W/m^2 under clear sky in humid areas and is negligible under cloudy sky, the net radiation loss provides the potential for radiant cooling (Givoni, 1994).

In calculating the net radiant heat loss two optional concepts can be used: the "effective sky temperature" and the "sky emissivity". The effective sky temperature is defined as the temperature of a black body that radiates towards the ground with a continuous spectrum at the same energy flux as the measured atmospheric radiation under given climatic condition (Givoni, 1994).

Not all the radiant net loss can always be utilized as a cooling energy for a building. A nocturnal radiator at a temperature below the ambient air gains heat by convection, some cold energy is also lost during the process of transfer from the radiator to the building. In this case the effective cooling of the building is less than the radiant net loss (Givoni, 1994).

Design Options of Radiant Cooling Systems

Several design options can be considered for utilizing the physical process of radiant heat loss as a cooling source for buildings. They involve three basic types of nocturnal radiators:

(a) A high mass roof with movable insulation serving as a combined radiator/cold storage element;

(b) A lightweight, usually a metallic radiator that cools ambient air below its initial temperature

(c) Unglazed water-type solar collectors.

Each one of these radiators can be developed onto several radiant cooling systems.

A high mass roof can be a structural concrete roof or a steel deck with water-filled bags over it. Movable insulation panels expose the roof mass to the sky during the night and insulate it during the day time (Givoni, 1994).

A lightweight radiator with an air space and ambient air flow underneath can cool the flowing air by several degrees. The cool air then is directed in to the building to provide instantaneous cooling during the night and to cool the interior mass of the building by convection, thus creating a cold storage for the following day (Givoni, 1994).

Unglazed solar collector can be used during the night to cool water. The cooled water can be circulated in pipes embedded with a concrete roof (or walls) and using the building mass as a cold energy reservoir (heat sink) for absorbing the heat penetrating in to the building during the day time. Alternatively the circulated water can cool a pond over the roof that, together with the roof mass, forms a combined heat sink (Givoni, 1994).

Design Issues in Radiant Cooling System

Actually applicability and choice of type and design detail of a radiant cooling system depends on the type of roof (for example, flat or pitched, load bearing or non load-bearing), the type of the building (single story or multistory, lightweight or high mass) and the climatic conditions, this choice also may be influenced by the desired period of indoor cooling. For example, residents may need the building cooled only during the evening and night hours, or cold storage for the following day may be necessary. Another issue is the desired mode of heat transfer between the storage medium and the indoor space-conductive or convective- and the resulting indoor air speed and temperature swings, this last point effects the comfort sensation of the occupants because it determines the relative roles of radiative and convective heat exchange between the human body and the indoor environment (Givoni, 1994).

Several issues should be considered when choosing a cooling system that uses nocturnal long wave radiation. The issues should also be considered when design details are decided.

1) The application of radiant cooling under the specific climatic condition of the site should be checked.
2) The applicability of radiant cooling for the specific building type in question should be checked.
3) The specific system should be chosen. Sub issues involve deciding whether to use the roof itself as a radiator/storage/transfer unit, whether to apply a specialized lighting weight metallic radiator, or whether to use unglazed solar collectors as nocturnal radiators. (Givoni, 1994).

Radiation Emitted by Long-Wave Radiator

The intensity R_{emit} of long-wave radiation emitted by a specialized radiator or by the roof itself when it serves as the radiating surface, depends on only two factors: the (absolute) temperature of the radiating surface, T_r and its emissivity E_r (Givoni, 1994).

$$\mathbf{R_{emit} = \sigma \; X \; E_r \; X \; T_r^4} \qquad \text{Eq 3}$$

$$\mathbf{\sigma = 0.567 \; X \; 10^{-8} \; (w/m^2K^4)}$$

$$\mathbf{\sigma = 0.1714 \; X \; 10^{-8} \; (Btu \; hr^{-1}ft^{-2}R^{-4})}$$

The emissivity of a given radiating surface is a physical property and represents the potential of the surface to emit radiation relative to a perfect "black" surface. Most common materials (except metals) have an emissivity of about 0.9 (Givoni, 1994).

The temperature of the radiator, and specially its relation to ambient air temperature, depends on its mass and on the way in which it is utilized. Therefore it is one of the system design factors affecting its performance (Givoni, 1994). If the mass of the radiator is high like concrete slab it will have a lag in both cooling and heating in comparison to the ambient air. This will result in temperature difference between the radiator and the air. This will lead to convection losses. In case of the light weight radiator like a metal radiator, the radiator will heat up or cool down very fast. The radiator will be at lower temperature at night with respect to ambient air. Hence the radiative heat loss will be balanced by convective heat gain.

Thus the radiator type is very significant in determining total energy loss from the radiator (combined net radiant loss and convective heat exchange). The thermal contact between the radiator and the building to be cooled can also affect the temperature of the radiator and its overall efficiency (Givoni, 1994).

Atmospheric Radiation

Any surface exposed to the sky receives long-wave radiation, which is emitted by the atmosphere. The atmosphere consists mainly of nitrogen (about 78%) and oxygen (about 21%), with only minute quantities of the other constituents, mainly water vapor, CO_2 and dust. Oxygen and nitrogen are mostly transparent to this part of the radiation spectrum. However, water vapor emits and absorbs radiation at wavelengths around 6.6 and 18 μ while CO_2 emits and absorbs radiation around 15 µ. Clouds, in particular, greatly increase the incoming atmosphere radiation. The radiation emitted by the atmosphere downward toward the earth is defined as "atmospheric back radiation" (Givoni, 1994).

Atmospheric back radiation depends mainly on cloud conditions and to some extent also on the water vapor content of the ambient air. Under clear sky conditions and low humidity and atmosphere radiation is concentrated in distinct wavelength bands – the 3 to 8 µ and the 13 to 20 µ bands. Between the 8 and 13 µ atmospheric back radiation is weak, and the 8 to 13 µ band therefore is called the "atmospheric window". As the water vapor content of the air increase, the intensity of the atmosphere back radiation in the 8 to 13 µ band also increase, resulting in the stronger total atmospheric back radiation towards the earth (Givoni, 1994).

Clouds especially low clouds emit radiation through the long-wave spectrum, so that under an overcast sky the phenomenon of the sky window practically disappears. Thus, under cloudy sky conditions atmospheric radiation reaches its maximum (Givoni, 1994).

Convective Heat Exchange with Ambient Air

In practically all cases of radiant cooling there is also a convective component of heat exchange interacting with the radiative processes. For exposed long-wave radiators the convective exchange is a function of the convective coefficient, which depends on the wind speed near the radiator. It is proportional to the temperature difference between the radiator and the ambient air (Givoni, 1994).

The convective coefficient however is one of the most difficult factors to estimate accurately. It depends on wind speed next to the radiating surface and on whether the airflow above the surface is laminar or turbulent. In reality any value assumed for air speed should be considered only as rough estimate. The only known wind parameters relevant to the building are usually the wind speed and direction at same meteorological station, which at best is close, but usually may be at some distance or even remote, from the building in question (Givoni, 1994).

Techniques to Increase the Net Heat Loss

The techniques can be considered, separately or jointly, for increasing the rate of the net heat loss from radiators:

a) Applying a windscreen, transparent to long-wave radiation, to reduce convective heat gain from the ambient air.

b) Applying a selective surface to the radiator, which emits mainly in the spectrum of the sky window (between 8 and 13 μ) and is reflective in the rest of the long-wave spectrum and preferably also in the short wave (solar) spectrum (Givoni, 1994).

Convective Gain Suppression by Wind-Screen

At night the temperature of lightweight radiator drops well below the ambient air temperature. The radiator then gains head from the ambient air by convection. A higher wind speed increases the heat fain and reduces the temperature drop of the radiator. Therefore, when it is desired to lower a radiator's temperature well below the ambient level it would be desirable to minimize convection without interfering too much with the emission of long wave radiator. This is always the case when a specialized lightweight nocturnal radiator is used (Givoni, 1994).

A windscreen could consist of an open honeycomb covering that reduces convection. Air motion in a space above the emitter plate produces a pocket of cool stagnant air, thus limiting heat intrusion from the warm ambient air above. Glazings have been used experimentally, but are difficult to implement since few materials are sufficiently transparent over the infrared wavelength corresponding to atmospheric window (8-13 μm) (Martin, 1988).

An inexpensive material that is about 75% transparent to long-wave radiation (infrared transparent) is polyethylene film without ultraviolet inhibitors. If a thin film of polyethylene is stretched firmly over a radiator, supported by either air pressure or tension so that it does not flutter in the wind, stagnant cold air layer is formed over the radiator. The stagnant air layer and the film serve as transparent insulation, minimizing convective heat gain and lowering the temperature of the radiator below the temperature drop of an exposed radiator (Givoni, 1994). Commercially available polyethylene having a thickness of 50 μm(2 mil) has adequate transparency properties (Martin, 1988).

Radiative properties of polyethylene film (without ultraviolet inhibitors) were measure by Clark and Blanpied (1979). They studied the film infrared transmissivity, its reflectivity, and its emissivity. Typical weighted averages (for different angles of incidents) are:

Transmissivity = 0.75

Reflectivity = 0.10

Emissivity = 0.15

If a thicker film of same material is used, the infrared optical transparency is greatly reduced (Martin, 1988). Even single layer of polyethylene reduces emitted radiation by about 25 percent because of its imperfect transmissivity. However convective heat gain, when the radiator's temperature is below that of the ambient air, is reduced to a much greater extent, especially under windy condition. Thus the net effect is to increase the net heat loss and the temperature depression of the radiator below ambient air temperature (Givoni, 1994).

If a glazing material were completely transparent and had a low index of refraction so that surface reflections were negligible, then its only function would be to produce a stagnant insulating layer of air between itself and the radiator. In actuality, the glazing material is capable of emitting and absorbing a fraction of the infrared radiation incident on it from the sky and from the radiator surface below. Thus, the glazing itself becomes a real radiator, as well as convectively coupled to the ambient air.

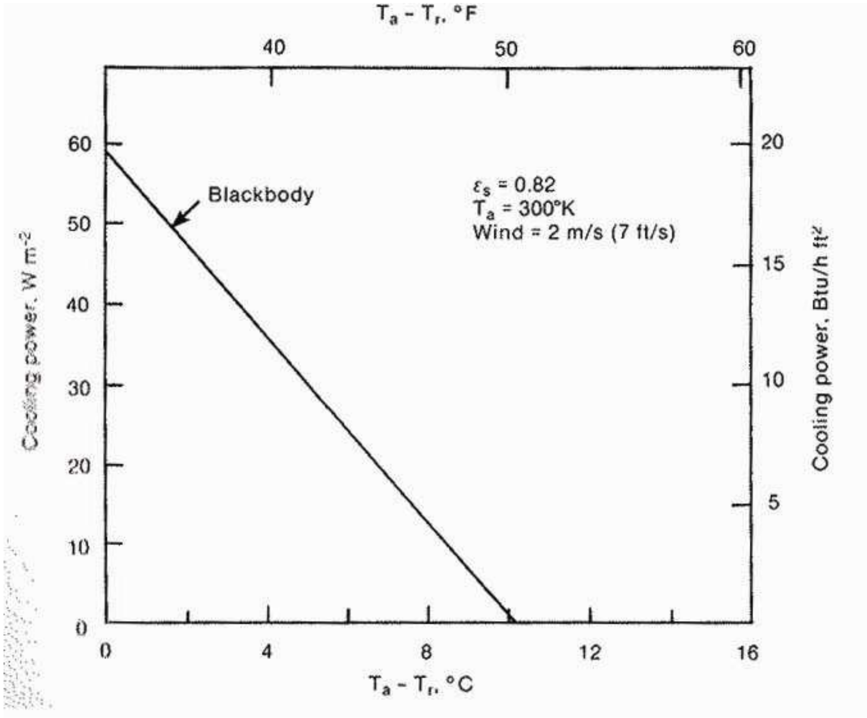

Figure 4: Calculated net cooling from a blackbody covered by a 50 µm polyethylene gazing. Source Berdahl,Martin, and Sakkal (1983)

Detail of this process have been presented in the literature (Johnson, 1975) and Figure 4 shows the calculated cooling power from the blackbody radiator under 50 µm polyethylene windscreen at a wind speed of 2 m/s (7 mph) (Berdahl, Martin and Sakkal, 1983). The conditions shown correspond to a sky temperature 14.5 ^{o}C (26 ^{o}F) below that of the ambient air. The stagnation temperature is obtained as the zero cooling power intercept of the horizontal temperature axis and under the stated conditions is approximately 10.2 ^{o}C (18.4 ^{o}F) below that of the ambient air. The vertical axis intercept shows that proximately 60 W/m^{2} (19 Btu/ft^{2}h) is radiated to the sky when the radiator is at the ambient temperature of 300 ^{o}K (27 ^{o}C) (Martin, 1988).

The main drawback encountered in the use of polyethylene films is that they rapidly undergo degradation when exposed to air and sunlight. This photochemical degradation process increases the infrared Absorptivity and decrease the mechanical strength of the film. Black polyethylene film is a more stable material, and would suffice for nighttime glazing applications. It is desirable, however, to make the upper glazing surface highly reflective in the visible and near region. Such an optically reflective glazing would be capable of maintaining a lower surface temperature than a black surface, and would permit effective radiative cooling during daylight hours as well as at night (Martin, 1988).

Selective long-wave radiators

To maximize net long-wave radiant heat loss the radiative surface should reflect away incoming atmospheric radiation from water, CO_2, and dust particles in the air while strongly emitting at the long-wave spectrum of the atmospheric window. An ideal long-wave radiator should have high Absorptivity (and, therefore, high emissivity) in the 8 and 13 μ spectral band and high reflectivity (and, therefore, low Absorptivity) above and below this band. In particular, it would be desirable to have surface with high reflectivity also in the solar spectrum (0.4 to 3 μ) so that radiant cooling will continue during the daytime (Givoni, 1994).

Experimental comparison of radiant cooling obtainable by a gray-body emitter and a selective emitter have been made by Mitchell in Australia, Sakkal, Martin, and Berdahl of the Lawrence Berkeley Laboratory, Miller and Breadly of the Desert Research Institute in Nevada, and Landro and McCormick in Australia. The results of all the studies mentioned demonstrate that, with the selective surface tested, no distinct advantage in the radiant cooling potential was observed in the selective surface over radiator with ordinary surface. Taking into account the fact that the small effects of selectivity that have been observed in these studies were seen under stagnation conditions, without any utilization of cooling, the practicality of using selective surface (always more expensive than ordinary surface) is questionable, at least given present technology.

When the roof itself serves as a combined radiator and cold-storage element, and the radiating surface temperature is closer to ambient air temperature, a selective radiator might even be less effective than an ordinary surface (Givoni, 1994).

Another point that should not be overlooked is the probable effect of condensation on the performance of selective surface. Even if a lower temperature were attained by such surface it might increase the likelihood of condensation over the selective surface itself. Once the selective surface has been covered by a water film, it would lose its selective radiative properties (Givoni, 1994).

The study in Institute of Desert Research, Sede Boqer revealed a phenomenon that had not yet been taken into account in estimating the effect of a polyethylene windscreen: the dependence of the effect of the polyethylene wind screening on dew formation, even in arid regions. When an exposed radiator is cooled, during clear nights, by about 5 to 8 ^{o}K below the ambient dry bulb temperature, it may also drop below the dew point temperature. However, dew formation over an exposed radiator does not affect its performance because water has a very high emissivity (Givoni, 1994).

The temperature of radiator with a wind screen, during clear dry night, are much lower than those of the exposed ones, are more likely to drop even below the ambient dew point temperature. The polyethylene film, itself, being mostly transparent to infrared radiation, has low emissivity and thus would not cool significantly by radiant heat loss, however, when the radiator, under the windscreen, is cooled sufficiently below ambient dew point temperature, a layer of stagnant cold air is formed between the radiator and the windscreen (Givoni, 1994).

The underside of the polyethylene film is then cooled by conduction and its temperature may also drop below the ambient dew-point temperature, when the film's temperature drops below this level, dew may begin to condense over the film. Once condensation starts over the polyethylene, the process is self accelerating: water absorbs and emits long-wave radiations, and therefore the film attains high emissivity. When dust particles settle over the film they enhance the initiation of dew formation (Givoni, 1994).

Design Consideration for Radiative Cooling System

The amount of heat that can be rejected by the radiator to the sky depends on the thermal load to be dissipated and on the intensity of the incident sky radiation. A designer can first determine the approximate radiator area required to dissipate a known heat load, or calculate the amount of heat that can be dissipated by a roof surface of a given area (Martin, 1988).

The most important system-dependent criterion is the radiator temperature, since it limits the rate of the heat rejection to the sky. If thermal comfort is to be maintained in the building interior, the radiator must remain below the upper comfort temperature. For heat to flow from the interior to the radiator, a temperature gradient must exist. A small temperature gradient may suffice if only a small amount of heat needs to be rejected, Or if thermal resistance is low between the interior space and the radiator. The price paid for poor thermal coupling is that a lower radiator temperature must be maintained to achieve the required heat removal rate, thus reducing overall system performance. To achieve good thermal coupling, large heat transfer area must be used. The ceiling or walls are excellent candidates for this as they provide for radiator as well as convective heat transfer. A major advantage of the roof pond system is that it uses the ceiling area effective for this purpose; similarly hollow core masonry wall looks promising for use as heat transfer and storage elements with a variety of natural technologies (Martin, 1988).

Effect of Aging, Thickness and Color on Performance of Polyethylene Film

Aging of polyethylene films leads to substantial degradation in its transmissivity from average values of 0.72, 0.69, 0.57 and 0.42 corresponding to a new one, 5, 30 and 100 days aging in the wavelength range of 8-13 µm. Also neither thickness of the film nor their new colors have significant effects on the transmittance. It has been found that the effect of aging of the polyethylene film by 100 day led to the reduction in performance of night cooling by 33%. The decrease in thickness of the polyethylene films from 50 to 25 μm lead to an increase in its radiative properties (transmittance) and the performance of the night sky radiation unit by 8.6% approximately (Ahmad Hamza H, 1996).

Angle of the radiator

Since the coolest part of the sky dome is directly overhead, a radiator surface should be positioned horizontally to achieve its maximum cooling power. If the radiator is tilted, it's exposed more to the warmer region of the sky near the horizon. The radiator no longer sees a full hemisphere of the sky, but only an amount determined by its view factor. In addition, the radiator picks up even more of the warmer radiations emitted by the ground (Martin, 1988).

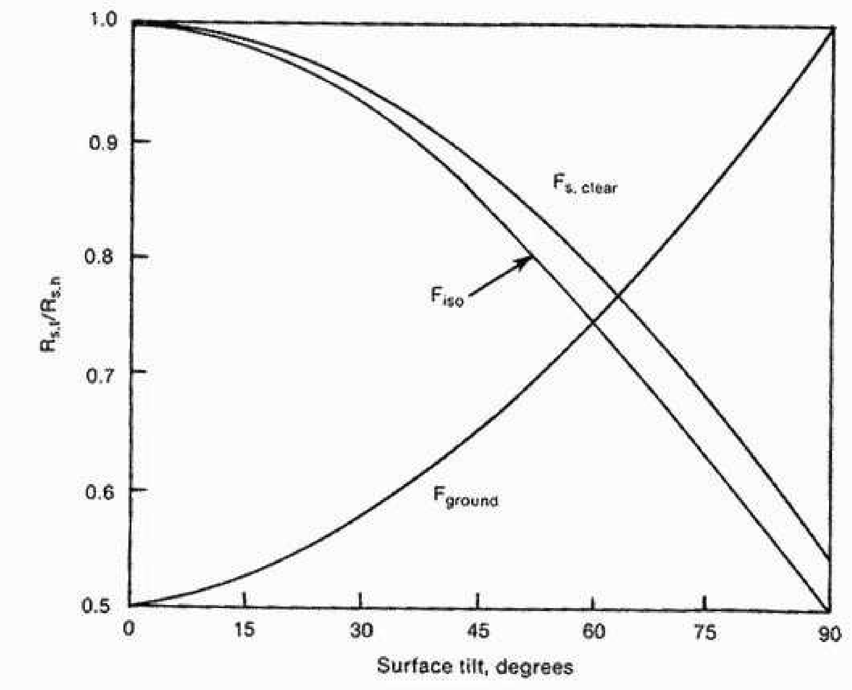

Figure 5: Sky factor for the clear sky and overcast sky within the range of view of a tilted radiator. Fground is the geometrical view factor of the ground for the same tilted surface. Adapted from Blanpied, Clark, and Cummings (1982)

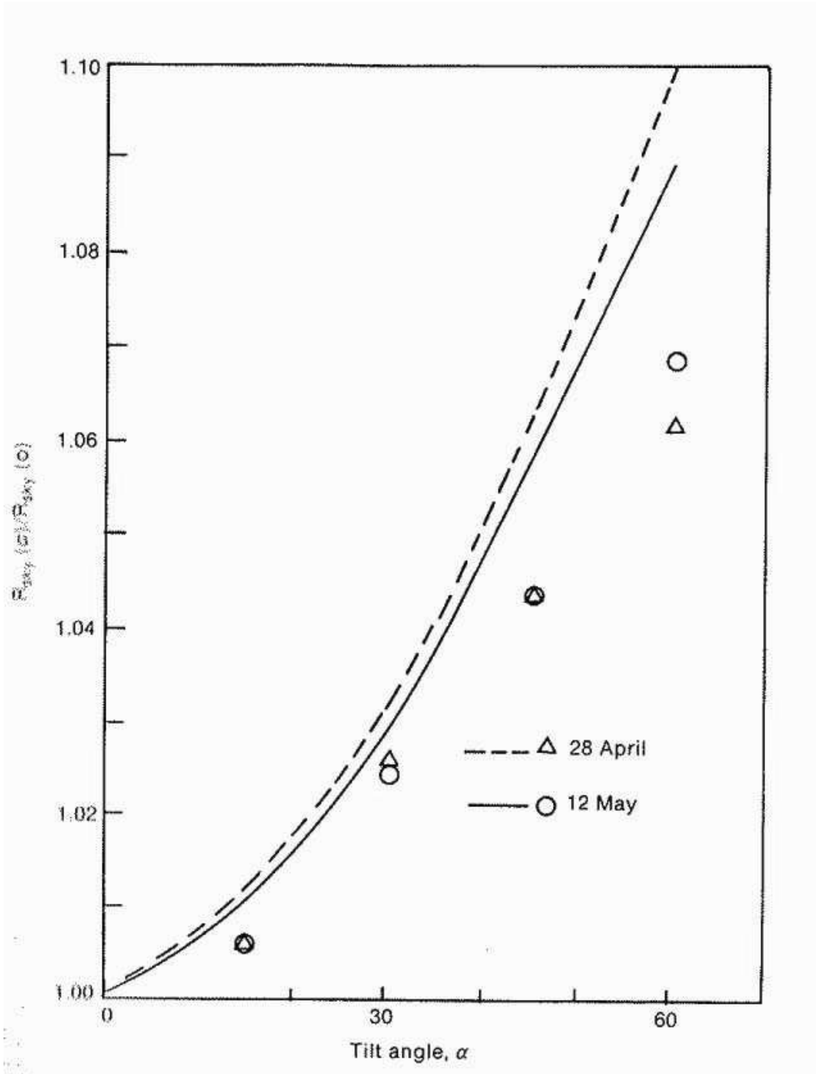

Figure 6: Ration of incident radiation on a surface tilted through an angle a from the horizontal. The data points are reported in Sweat and Carroll (1983) and the curves are calculated by the method of Blanpied, Clark, and Cummings (1982) using ambient weather at the time of measurements

Advantages of a Roof Pond as Compared to Conventional Residence

- Fuel costs for a roof pond residence will be minimal due to the decreased fuel demand.
- In some area of the country, local building codes may not require the installation of a backup heating system (if the roof pond is sized to provide 100 % of the heating load). Therefore, the additional cost for this item is eliminated.

- A roof pond residence will save a substantial amount of energy for heating and cooling and hence help to reduce the total energy demand of the country.
- A Roof pond system provides even temperature throughout the residence than do conventional residences, which may have unit wall heaters or air conditioners.
- Because air motion is not required for heating and cooling a roof pond home, the noise from furnace blower and air conditioners is eliminated.
- Roof pond residences are less of a fire hazard than conventional residences.
- Because of the decreased fire hazard, insurance rates for roof pond homes will be lower.
- Because heat transfer by radiation is the dominant mechanism in a roof pond residence, no excessive air movement due to fans or blowers is present.
- Roof pond systems can conserve water in comparison with conventional homes using evaporative coolers.
- Roof pond homes provide a measure of self-sufficient, both for the occupants and the country in general. Resource decentralization is also furthered by the self sufficient nature of a roof pond home.
- Conventional homes are heated or cooled by convection; temperature stratification between the ceiling and flow can be significant. Since roof pond homes are radiantly heated or cooled, stratification is of much less importance in terms of comfort.
- Roof pond occupants are able to increase their overall thermal comfort for no additional energy use or cost.
- With the higher relative humidity normally found in roof pond residences, the internal air temperature can be lower and still provide adequate comfort.
- Social costs (such as pollution, strip mining, transportation of hazardous waste, etc) are reduced with a roof pond residence. (William P. Marlatt, 1984)

Disadvantages of a Roof Pond as Compared to Conventional Residence

- Because of the lack of standardization of roof pond components, roof pond homes have higher initial component costs than conventional homes.
- Maintenance requirements of the roof pond systems are greater than those of convectional systems.
- To provide optimum performance, the operation of a roof pond system requires more occupant interaction and awareness about the basic principles involved.
- Unlike conventional systems, the performance of a roof pond system is a direct function of weather conditions; abnormal weather may cause undesirable changes in performance.
- Because the roof pond system technology is not yet fully developed, trained architects, installers and repairmen are few and available design tools are limited in their accuracy, applicability and adequacy.
- Even though the performance of existing roof pond residences is know, the actual performance of any individual residence cannot be reliably predicted.
- The lifetime if a roof pond system components, maintenance requirements, and total life cycle costs for roof pond residences are unknown, since many of the existing homes were built recently.
- Development work on some roof pond system components is necessary in order to provide a system as reliable as a conventional system.
- Public acceptance of roof pond residences is currently low, due to a lack of reliable information and a general resistance to change.
- Roof pond homes, in general, are limited to one story, because of the nature of the radiant heating and cooling mechanism.
- Roof pond residences have a greater potential for water leakage into the living space than conventional residences.

- Due to the metal ceiling in a roof pond home, the noise level and eco effects may be more pronounced than in a conventional home.
- Due to the slower response time of a roof pond system, desired internal temperature changes may occur at a slower rate.
- Local zoning ordinances or building codes may be difficult to interpret in relation to a rood pond home, hence design and construction schedules may be extended.
- The resale value of a roof pond home may be less than that of a conventional home, since the number of potential buyers will be lower.

Chapter 3

METHODOLOGY

Overview

In order to test the phenomenon of sky window and the performance of the roof pond covered with a band filter, some experimentation was required. Objective of this experiment was to understand how a band filter affects the temperature of water in the roof pond. This experiment was done also to know the exact relationship between the different weather conditions like wind speed, humidity, ambient air temperature and irradiance with the water temperature in the roof pond. For this purpose 2 tanks were made and filled with water. One of them was covered with a thin and transparent Polyethylene sheet. Unlike the popular concept of covering the roof ponds during the day time these ponds were left exposed for about 7 days and nights.

The study was conducted in winter months of November and December but the focus of the study was reducing the cooling load. Hence it was necessary to make a very accurate thermal model which could predict the performance of the roof pond in summer. It was expected to be able to extrapolate the temperature of water for the whole year based on the weather data. This would later be used to calculate the amount of cooling a pond can provide. The aim of this study was also to understand the thermodynamic processes like conduction, convection etc individually. For this purpose the thermal model was even more important. Thermal model was a spreadsheet based calculation of thermodynamics of the roof pond.

An alternate approach to thermal model was also taken to ensure the accuracy of the result. With the help of regression technique a relation between the weather conditions and the water temperature was developed. This relation was in the form of an equation which could be used to extrapolate the temperature of water in the pond based on the weather data.

All the experiments were done in stagnation condition. The ponds were not coupled to any space hence the heat gain or loss to the space was not incorporated. To understand the performance of the pond, a real building was required to be coupled to it. A typical single story, 2500 ft^2 was modeled in eQuest and hourly cooling loads of the building were procured from it. This building was modeled with a flat concrete roof but not with a roof pond. Later on an hourly calculation for heat transfer was done.

Experimentation

2 rectangular tanks of inner dimensions of 32 in X 68 in 6 in were made. Both the tanks were made out of 2 in thick polystyrene with an R value of 11.

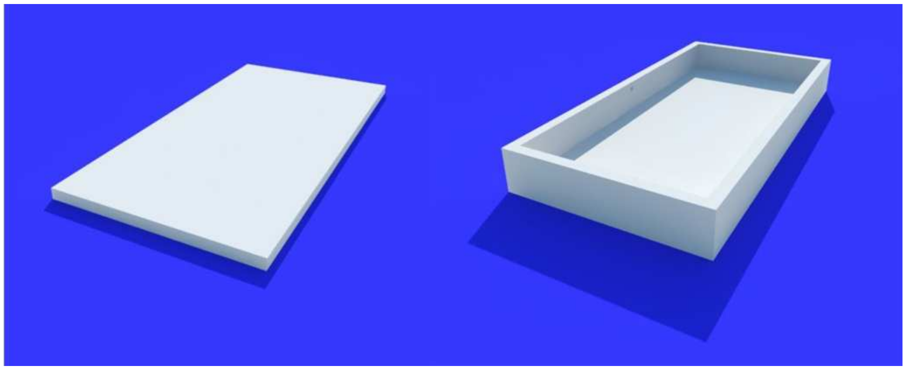

Figure 7: Step 1 & 2, base and sides of the Experimental setup

The tanks had a polystyrene base and were open from the top. All the sides of the tanks were joined together with a sealant. To make sure that the tanks are properly sealed and no heat is entering from the sides, continues and uniform spread of the sealant was ensured. To be doubly sure all the joints ware sealed both from inside and outside by heavy duty tape. The tanks had to contain water in them so they had to be waterproof. A plastic sheet generally used as a drape cloth for covering the floor or furniture for painting applications was used. This sheet comes in large sizes so a proper side of plastic was cut. This sheet was then spread inside the tanks covering the base as well as the sides all the way to the top. The side of the sheet was taped to stop them from falling back onto the base.

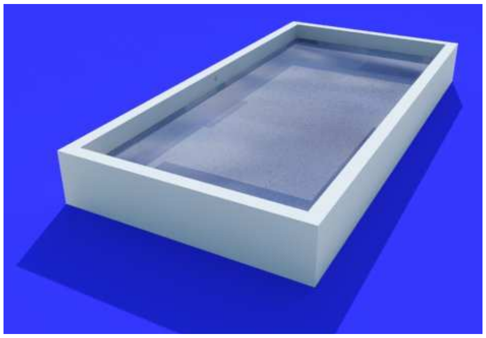

Figure 8: Step 3, waterproofing

Now both the tanks were half filled i.e. 3 inches with tap water. The floor on which tanks were kept has a slight tilt so depth of water was measure at the center of the tanks.

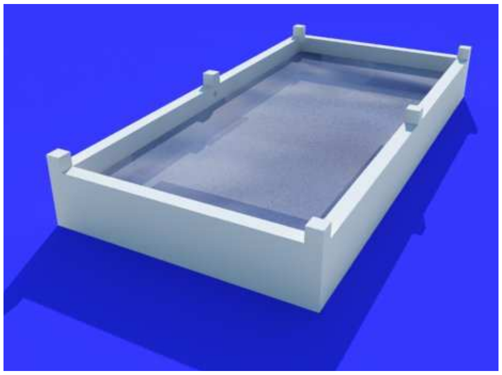

Figure 9: Step 4, Two inch cubes

Six blocks of 2 in X 2 in X 2 in were cut. Four of them were placed on the four corners of one of the tanks. The other two blocks were placed in the center of the longer side of the same tank. These blocks were then secured in their position with the help of a sealant. This formed a frame on which a band filter can be stretched.

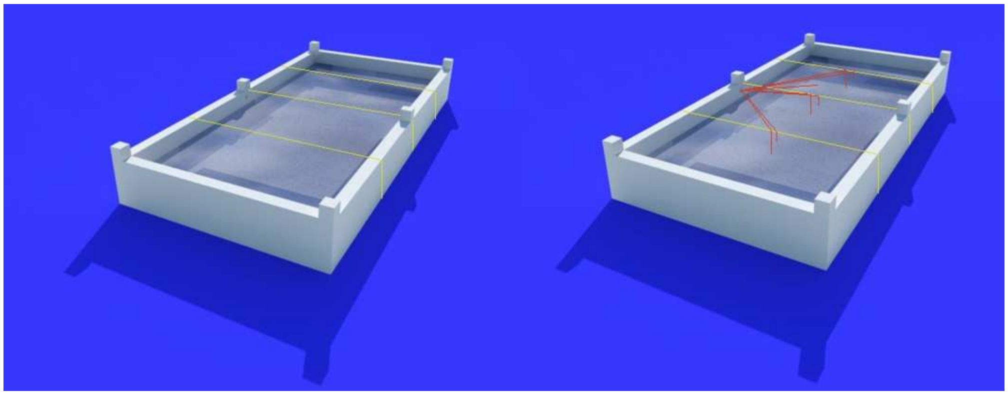

Figure 10: Step 5 &6, setting up Thermocouples

Both tank had six thermocouples measuring the temperature of the water. Three of them measured the temperature of water close to the bottom of the tank. Rest three measured the temperature of water near the surface of water. Three strings were tied along the length of each tank to hang these thermocouple wires. A whole was punched into the wall of the tank to bring in the wires. These wires were hanged along the longitudinal axis of the tanks. This was done to capture any irregularity in the temperature of water throughout the tank. Another thermocouple wire was placed near one corner of each tank to check for any edge effects.

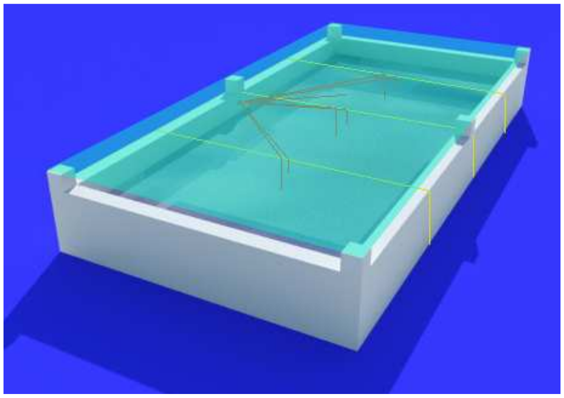

Figure 11: stretching Polyethylene Sheet

Now a Polyethylene Band filter sheet was stretched over the frame which was prepared earlier. The sheet was of size 3 ft X 6 ft. Thickness of the sheet was 50 micrometer. The band filter was secured to the frame with the help of a heavy duty tape. While installing the band filter it was kept in mind that it just covers the tank outer edges. An air gap of 2 inches was formed due to the frame which allowed the air to pass through. Another thermocouple wire was attached to center of the band filter on the bottom face. This was to measure its temperature.

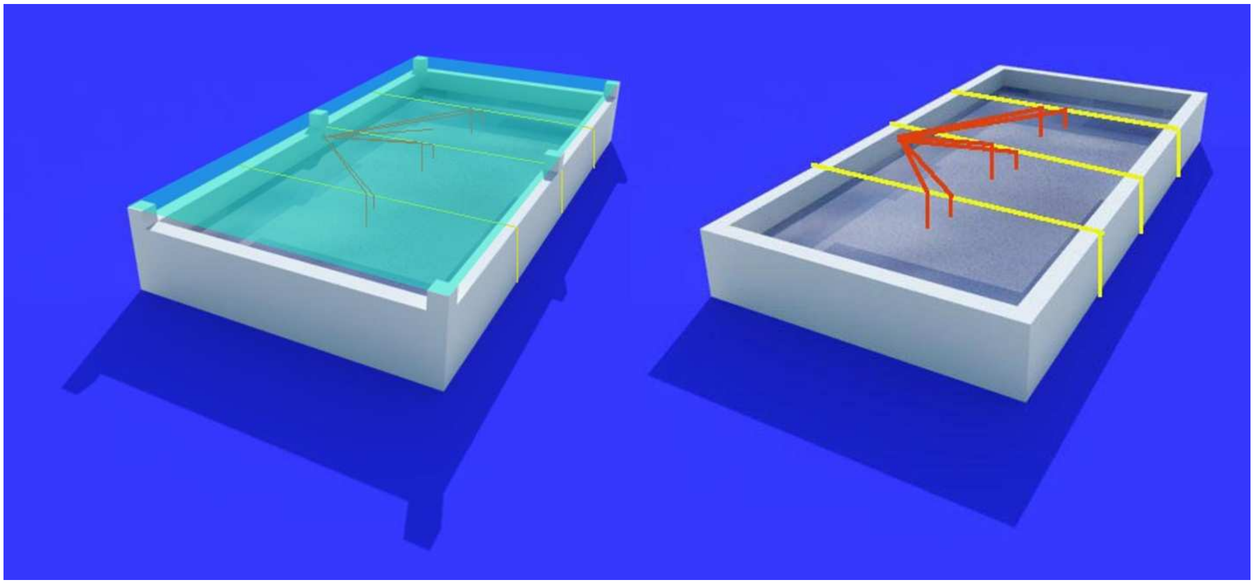

Figure 12: Completed Experimental Setup - Both Tanks

Data Collection

During the experiment two data logging devices where used namely

1) Agilent data logger
2) Whether station

Agilent data logger was used to measure the following parameters

I. Temperature near the top and bottom surfaces of the water.
II. Band filter surface temperature
III. Total solar irradiance

The weather station was used to measure the following

I. Wind speed
II. Gust speed
III. Ambient air temperature

IV. Relative humidity

The setup was brought to its completion and experiment was started. The ponds were left exposed to the environment for about 7 days and nights. Unlike general trend of covering the ponds during the day time, these ponds were never covered or shaded by any means. Data loggers logged every minute. Later on the data was averaged for every hour. Experiment was stopped everyday between 10am and 11am to collect data from the data loggers. Weather station was quick in transferring data and was only stopped for 2-5 minutes between the sessions. On the other hand the Agilent data logger took much longer to transfer data and had to be stopped up to an hour every day.

After the data collection it was felt necessary for the authentication of the research to validate the data with external reference. For this purpose Weather data period was procured from Phoenix Sky Harbor airport weather station. The data was procured through National Oceanic and Atmospheric Administration's (NOAA) website. The followings graphs were drawn to be assured that the data collected through the experiment was consistent with the Sky harbor weather station reading.

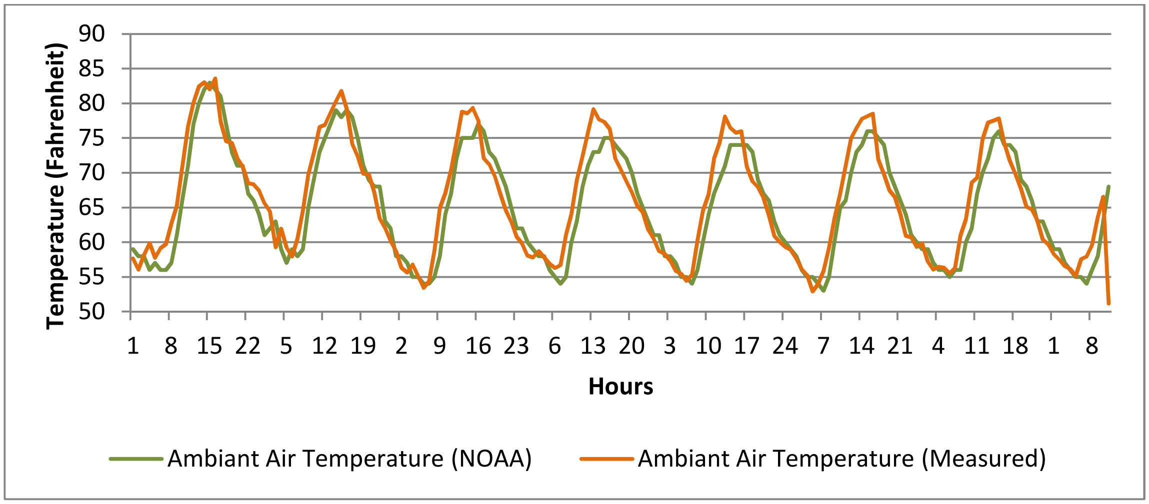

Figure 13: Comparison of Measured and NOAA data for ambient air temperature

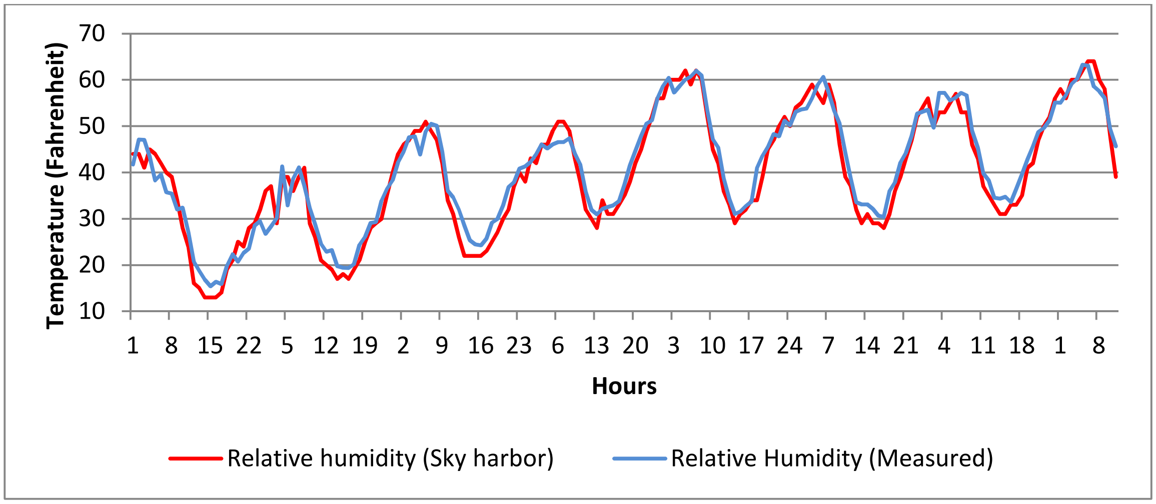

Figure 14: Comparison of Measured and NOAA data for Relative humidity

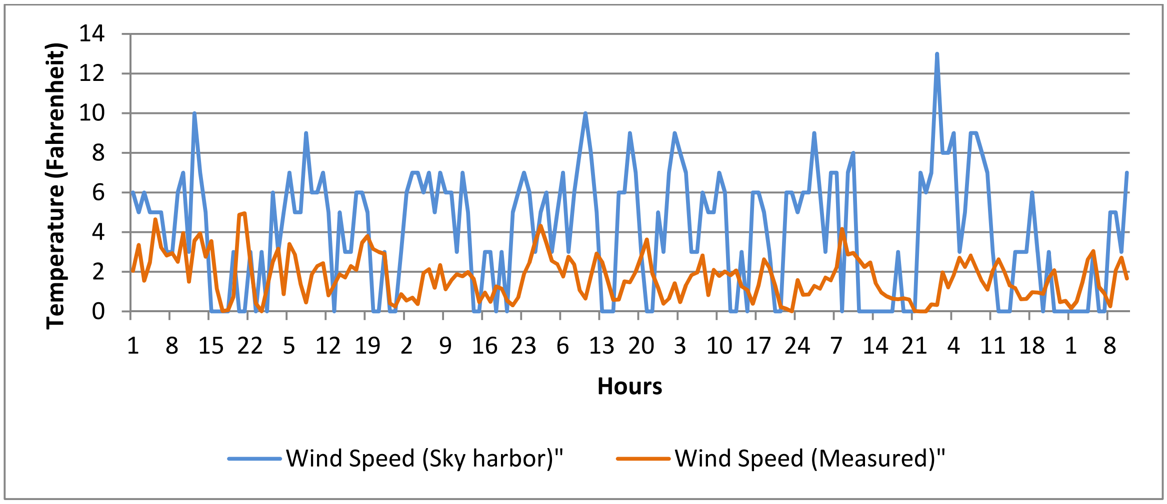

Figure 15: Comparison of Measured and NOAA data for Wind speed

The ambient air temperature and the relative humidity graphs indicated that the measured data is very consistent with the sky harbor weather station data. However wind speed data was very different. The reason for this could be the altitude and the location of the weather station. Wind speed can vary widely with change in altitude. Also it can change is the surrounding are clear from obstruction.

On examining these graphs it was assured that the data collected is accurate with acceptable degree of difference.

eQuest Model

To understand if the roof pond system works and if yes then to what extent it is successful, we required a building to test it. In absence for any measured data for the whole year on any building, it was decided to test the pond with an eQuest model generated data. The purpose of this simulation was to gather inside air temperature of the building under given weather conditions. For the reliability of the results and availability of the building information, Professor Marlin Addison's residence was modeled. The building was a 2,500 ft^2 residence with wooden construction. Building was modeled with no cooling or heating. On simulating with phoenix weather file it produced a table for indoor air temperature which would be there for a given weather condition without cooling or heating. Considering that in actual case building would have a roof pond over it, it was modeled with no heat loss through the roof. If the heat gain through roof would have been included, it would have raised the indoor air temperature and obscured the results. The data generated from this simulation was then used to calculate the amount of heat the roof pond can remove from the space.

Thermal Model

After data collection it was important for this study to distinctly identify the contribution of conduction, convection and radiation towards total heat exchange. In other words, it was necessary to calculate the amount of heat exchanged through each mode of heat transfer. For this purpose a spreadsheet was setup. The data was collected for every minute so the data set was too big to be analyzed. Hence dataset was reduced to hourly data averaging all the 60 reading of every hour to just a single reading.

To calculate the effect of each thermodynamic component namely conduction, radiation etc, a thermal model was setup. This required thermodynamic equations to precisely calculate the total heat exchange. This model was spreadsheet based and contained heat transfer equations suitable for the project.

Using the thermal model prepared by using measured data, the temperature of the water in the pond was to be determined. For this purpose "Forward Finite Difference Method" was used. It was observed that the measured temperature of water would change when coupled with the space as it will be absorbing heat from space. Hence the measured data was to be corrected for coupling effect. For this purpose the water temperature ($T_{1measured}$) for the first hour was taken as measured and then heat transfer (Q_1) was calculated.

Step 1 : $(Q_1) = U_{slab} X (72\ ^oF – T_{1measured})$ Eq. 4

Then the resultant temperature (T_2) from the measured water temperature ($T_{1measured}$) of the pond was back calculated.

Step 2 : $T_2 = (Q_1 / M X Cp_{water}) + T_{1measured}$ Eq. 5

Using this changed water temperature the heat transfer (Q_2) for next hour was calculated.

Step 3 : $Q_{2\ =} U_{slab} X (72\ ^oF – T_2)$ Eq. 6

This process was continued to calculate corrected water temperature of both the ponds and their respective heat transfer for whole year. Appendix contains the data used and generated by the spreadsheet.

M – mass of water in the pond

Cp_{water} – specific heat capacity of water

Q_1 – heat transfer in the first hour

Q_2 – heat transfer in the second hour

$T_{1measured}$ – Measured water temperature at first hour

T_2 – the calculated value of water temperature for the next hour

U_{slab} – Conductance of the 4” concrete slab

Statistics Model

As a supplement to the thermal model a statistics model was also built to extrapolate the temperature of water for the whole year. For this purpose regression technique was used.

First the whole year’s data was collected from NOAA’s website collected by Sky Harbor International airport weather station. This data was then cleaned and put into a table. Using regression technique an equation was derived to explain the relation between pond water temperature and weather data collected during the experiment. This equation was then used to calculate the temperature of water in the pond for the whole year. The details of this analysis are explained in the appendix 1.

Equations and calculations

eQuest Model

The specification of the building which was modeled to find the cooling load is as follows

- Location (Weather): Phoenix 2008
- Analysis Year = 2012
- Bldg Type = "Multi-Family Mid-Rise", 2,500 sqft, one story
- Floor-to-Floor Height = 8ft, Flr-to-Clg Ht. = 8 ft.
- Footprint Shape = Custom
- Zoning = 2 zones, i.e., Zone 1 = conditioned area; Zone 2= garage

Window

- dimensions and approximate locations as noted on plan
- Window head height = 7'-0" for all, horizontal blinds (light color, IAC = 0.7)
- Single pane, clear, aluminum fame, slider window, 1" frame width

Door

- front exterior: solid wood panel door; Interior garage door: 1-3/4" flush wood
- front exterior: solid wood panel door; Interior garage door: 1-3/4" flush wood
- Rear exterior: sgl pane glass panel with 4" wide x 1-3/4"solid wood frame

Exterior wall construction

- North wall
  - street (north) façade: 2"x4" wood frame
  - nominal R-11 batt insulation with 4" face brick exterior finish
  - ½" sheetrock interior finish

- All other facades
  - 2"x6" wood frame, 16" o.c

    - nominal R-19 batt insulation with 1” stucco exterior finish
    - ½” sheetrock interior finish

Ceiling and roof construction

- No false ceiling below the slab
- 4 inch thick flat concrete slab roof

Slab-on-Grade construction

- 6” slab, carpeted with rubber pad, no perimeter insulation Infiltration: 0.30 air changes per hour (ACH)

Internal Loads

- Lighting
    - conditioned areas: 3.58 kW installed, 3.45 kW coincident peak
    - unconditioned areas: 0.12 kW installed, 0.012 kW coincident peak
    - outdoor areas: 0.416 kW installed, 0.316 kW coincident peak
- Appliances
    - cond. areas: 14.0 kW installed, 4.2 kW coincident peak (46% sens; 10% latent)
    - cond. areas: 14.0 kW installed, 4.2 kW coincident peak (46% sens; 10% latent)
- Occupancy
    - 3 occupants, 250 Btu/hr sensible, 200 Btu/hr latent
    - Occ, lights & equip schedules: limited week day occupancy

HVAC System

- 3 ton packaged variable-volume/variable temp (PVVT), elec heat, ducted return
- 75F clg setpoint, 71F htg setpoint, 60F clg supply T, 95F htg supply T
- SEER=15.0, EER=11.5 1
- 1,200 supply cfm, 0.0% OA, 1.5” total static pressure
- std efficiency fan motor with VSD, indoor fan mode = intermittent
- supply duct UA = 110, return duct UA = 60

- cooling available Apr21 – Oct 31
- Exhaust fans: bathroom (80 cfm) + kitchen (60 cfm) +clothes dryer (150 cfm) = 290 cfm total exhaust flow

Adjacent fences or buildings

- two Building Shades (or Fixed Shades)
- approximate dimensions for both: 50 ft wide (long) and 10 ft high
- running parallel to the east and west sides of the house, ~15 ft away
- Starting ~10 ft north of the north façade of the house (and running 50 ft south).

Back patio cover

- one Building Shade to represent the cover over the back patio

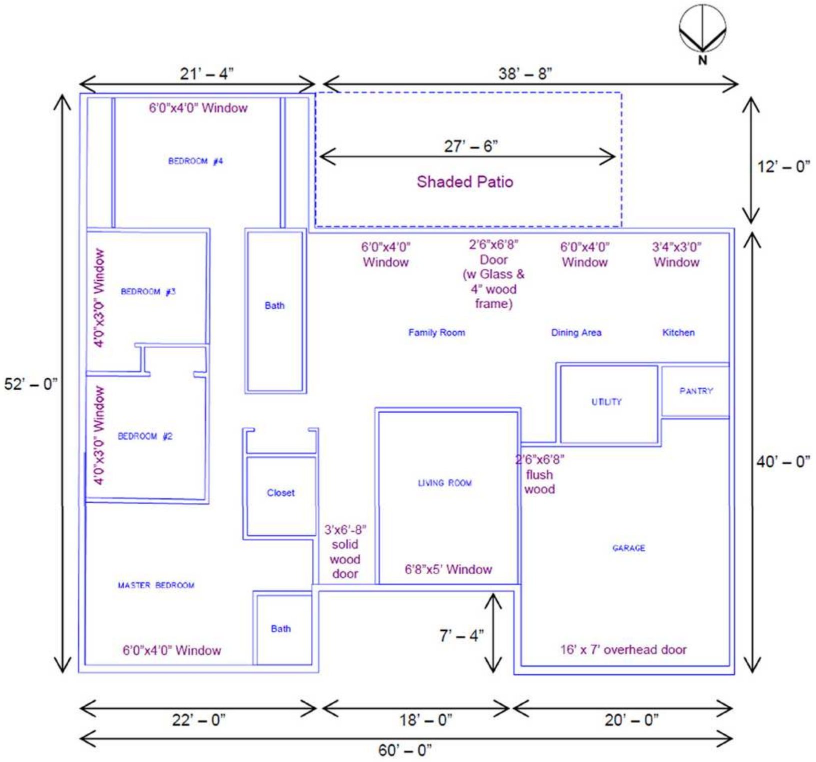

Figure 16: Typical residential building floor plan

Thermal model

Inputs	Value
Mass of water	235.7 lb
Heat capacity of moist air (Cp)	0.24 Btu/lb F
Heat capacity of water (Cp)	1 Btu/lb F
Emissivity of water + tank%	0.7
Transmissivity of water % (3 inch)	98
Stefan Boltzman constant (σ)	1.714E-09 Btu/hr ft^2 R^4
Transmissivity of glazing (Polyethylene for long-wave)	0.8
Transmissivity of glazing (Polyethylene for short-wave)	0.75
Emissivity of polyethylene for long wave	0.15
Emissivity of insulation board	0.75
U value of insulation	0.14 Btu/hr ft^2 °F
Area of insulation in contact with water	19.3 ft^2
Area of tank	15.11 ft^2
U value of 4 inch slab	0.8 Btu/hr ft^2 °F
Desired room temperature	72 °F
Area of building	2500 ft^2

Table 1 : Thermal Model inputs and assumptions

The Total Heat Transfer ($\mathbf{Q_{Total}}$) in the roof pond system when in stagnation condition is given by

Total Heat Transfer = Convection + Solar Heat Gain + Conduction – Radiation – Evaporation

$\mathbf{Q_{Total} = Q_{conv} + Q_{solar} + Q_{cond} - Q_{rad} - Q_{evap}}$ (Martin, 1988) Eq. 7

Radiative Cooling

Dew point temperature (T_{dp}) calculated by equation below was used to calculate Emissivity of sky (ε_{sky}) which was then used to compute sky temperature (T_{sky}).

$$\mathbf{T_{dp}\ (^{o}F) = \{(T_{air} - 32)/1.8\} - 14.55 + 0.114\{(T_{air} - 32)/1.8\}} \qquad \text{Eq. 8}$$

T_{air} – Ambient air temperature

$$\mathbf{\varepsilon_{sky} = 0.741 + 0.0062 \times T_{dp}(^{o}C)} \quad \text{(Berdahl, 1982)} \qquad \text{Eq. 9}$$

$$\mathbf{T_{sky}(^{o}F) : \varepsilon_{sky} = (T_{sky} / T_{air})^{4}} \quad \text{(Martin, 1988)} \qquad \text{Eq. 10}$$

Exposed Pond

Amount of heat leaving the water in the form of long wave radiation is given by:

$$\mathbf{Q_{rad} = Area\ \varepsilon_r \sigma (T_{water}^{4} - T_{sky}^{4})} \qquad \text{Eq. 11}$$

ε_r - emissivity of a radiator

σ – Stefan Boltzmann constant (0.1714×10^{-8} BTU hr^{-1} ft^{-2} R^{-4})

Covered Pond

The heat exchange for a covered pond is given by

$$\mathbf{Q_{rad} = t_g \varepsilon_r \sigma [T^{4}_{water} - T^{4}_{sky}] + \varepsilon_g \varepsilon_r \sigma [T^{4}_{water} - T^{4}_{g}] + h_{ra} [T_{water} - T_{air}] + h_{rg} [T_{water} - T_{g}]}$$

(Martin, 1988) Eq. 12

Q_{rad} – heat transfer by radiation by cover pond

h_{ra} - heat transfer coefficient for convection from water to air = h_c (Convection has been calculated separately)

h_{rg} - heat transfer coefficient for convection from radiator to glazing – this is negligible as water is far from the glazing and there is free movement of air between them.

t_g – Transmissivity of glazing (polyethylene)

ε_r – Emissivity of radiator (water)

ε_g – Emissivity of glazing (polyethylene)

T_g – Temperature of glazing (polyethylene)

Convective Cooling

Heat loss from water to the ambient air due to convection is given by:

$\mathbf{Q_{conv} = h_c (T_{air} - T_{water})}$ (Dr Bing Chen R. G.) Eq. 13

h_c – Heat transfer coefficient for convection heat loss which is given by equation below.

$\mathbf{hc = 0.6+3.5(V)^{0.5}\ \ W/(m^2K)}$ (Givoni, 1994) Eq. 14

Solar Heat Gain

The transmissivity of water was calculated as explained below

$\mathbf{t=10^{-\alpha l}}$ (Beer-Lambert Law) Eq. 15

t – Transmissivity of light through a substance

ɑ - Absorption coefficient of a substance (cm^{-1}) = 10^{-3} cm-1 (Chaplin)

l – Distance the light travel through the material

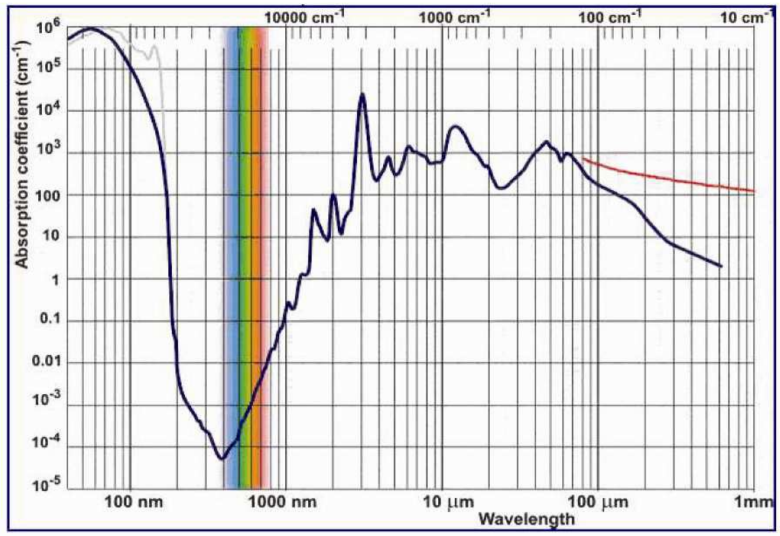

Figure 17: Absorption Coefficient of Water (Chaplin)

t = 0.98 (calculated from Beer-Lambert Law)

Transmissivity of 3 inch deep water = 0.98

Emissivity of 3 in water = 0.02

Emissivity of insulation = 0.75

Let total radiation be y

Emissivity of the pond = 0.02y + 0.98y X 0.75 + 0.98y X 0.25 X 0.02

= 0.7599y Eq. 16

Exposed Pond

Direct heat gain by the pond water due to solar radiation can be calculated as

$$\mathbf{q_{solar} = \alpha_{water} \text{ X Irradiance X Area of pond}} \qquad \text{Eq. 17}$$

α_{water} – Absorptivity of water + Absorptivity of pond

Irradiance – total radiative heat flux per ft^2

Covered Pond

Direct heat gain by the pond water due to solar radiation can be calculated as

$$\mathbf{q_{solar} = \alpha_{water} \text{ X } (t_g \text{ X Irradiance X Area of pond})} \qquad \text{Eq. 18}$$

α_{water} – Absorptivity of water + Absorptivity of pond

Irradiance – total radiative heat flux per ft^2

Conduction

$$\mathbf{Q_{cond} = U\ A\ \Delta T} \qquad \text{Eq. 19}$$

U – Conductance of the 4″ thick slab = 0.8

A – Area of the roof

ΔT – Temperature difference between pond water and indoor air.

$$\mathbf{Q_{total} = MC_p\, dt_{water}/dt} \qquad \text{Eq. 20}$$

$$\mathbf{dt_{water}/dt = \{T_{water}(t) - T_{water}(t+1)\}/Time} \qquad \text{Eq. 21}$$

Chapter 4

ANALYSIS

After collecting the data a brief analysis was conducted to examine the results and trend in the data. This was also done like a feasibility study to know if it's worth explore into this research any further. For this purpose a few graphs were drawn to quickly deduce some indications of the probable result of the research.

It was expected that the water temperature in the covered pond will be lower as it absorbs less heat from the solar gain. Also the effect of convection is less on covered pond as the polyethylene block the wind.

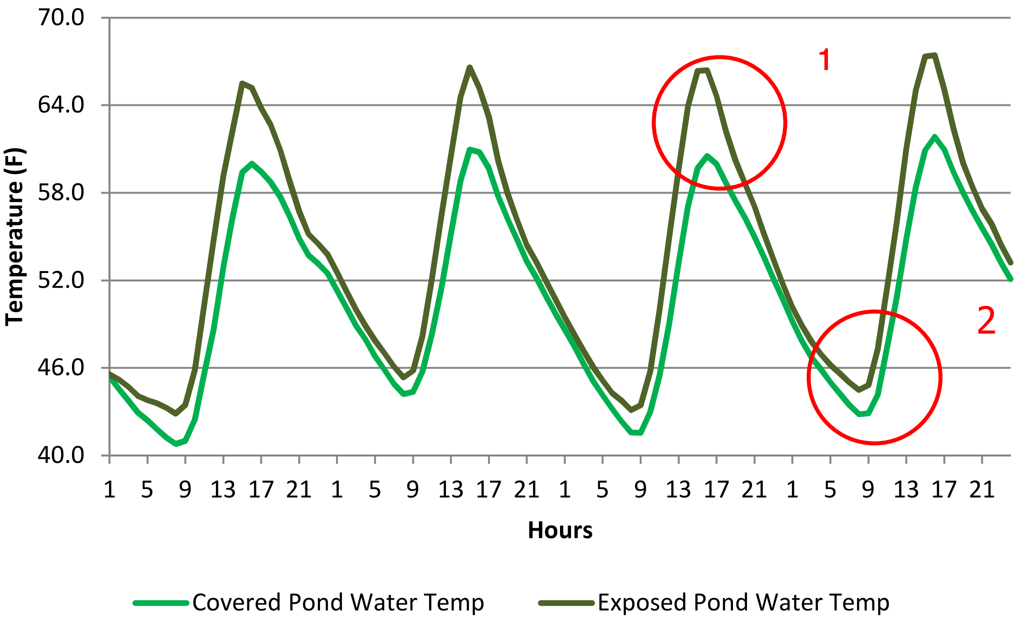

Figure 18: Comparison of Water Temperatures in both the ponds

The Figure 18 depicts that covered pond water cools to lower temperatures. Also it can be seen that exposed pond has much more variation in temperature of water as compared to the covered pond. This is usually undesirable as the aim of cooling techniques is to maintain the indoor temperature with minimum variations. Another important observation is that although temperature difference between the 2 ponds is not much at the night time but it's much more pronounced during the afternoon. Lower temperature means more heat can be removed from the space when it's most needed. Even if pond does not successfully fulfill all the cooling needs, it can certainly dampen the peak load.

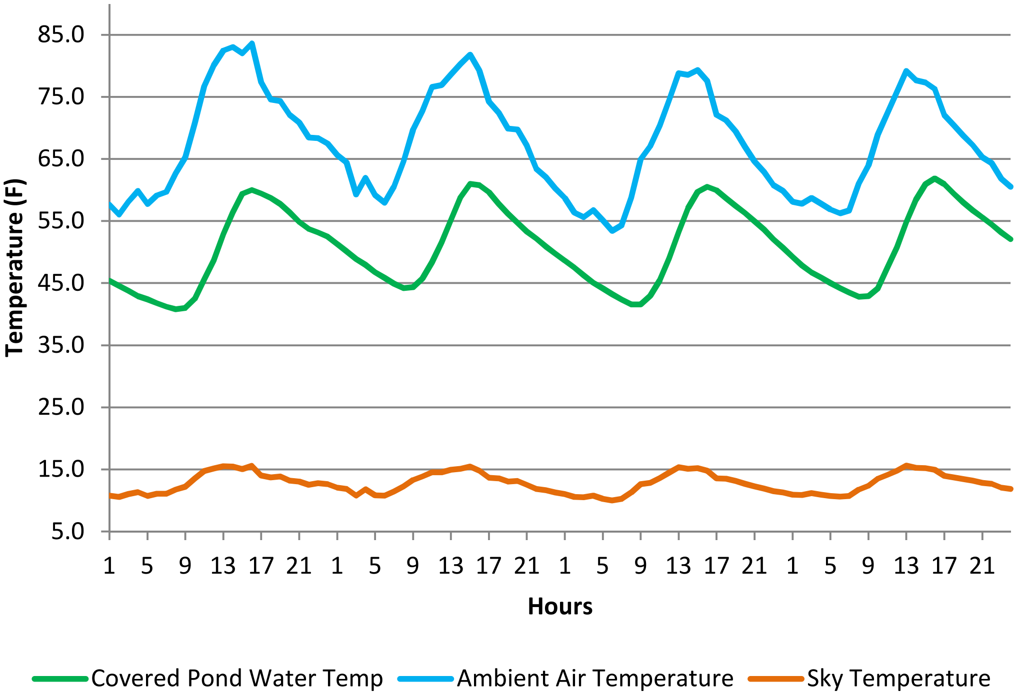

Figure 19: Comparison water, ambient air and sky temperatures

Figure 19 is a comparison of water air and sky temperature. The temperature of air is always higher than that of water. This means that convective heat gains will occur. Hence it's a good idea to reduce convection in order to achieve lower water temperatures.

The sky temperature is very low as compared to water temperature. So the is vast potential for radiative cooling in this particular geographical region. Also it's worth noting that sky temperature is much lower than water temperature even during the day time. This means that if we could device a band filter which can block the sun rays, water can still lose heat to the sky by radiation.

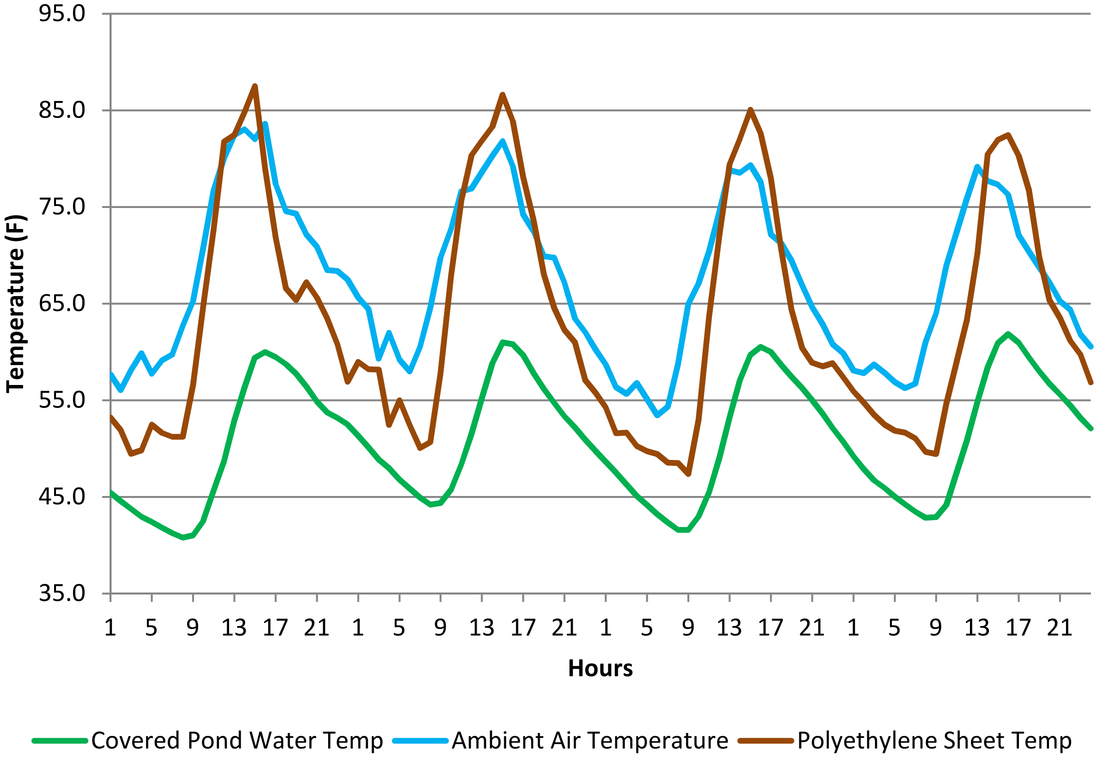

Figure 20: comparison of water, ambient air and polyethylene sheet temperatures

A very interesting observation in the Figure 20 is that polyethylene sheet temperature is higher in the afternoon. Polyethylene sheet being very thin have a very low heat capacity so it should be at ambient air temperature at all times. But this is not the case because it is absorbing heat from solar radiation in the afternoon and heating up in the process.

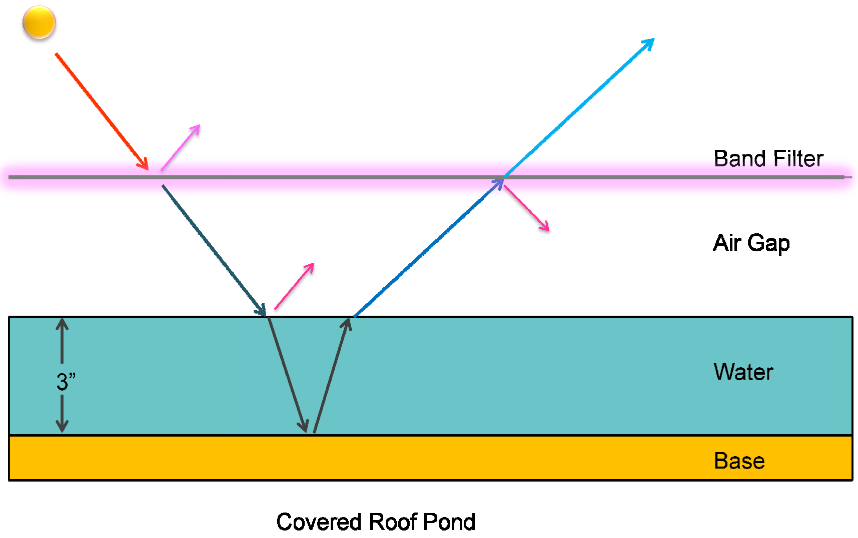

Figure 21 : Behavior of band filter in presence of solar radiation

After passing through the band filter rays hit the water surface. Surface has low reflectivity and most of the radiation enters water. Water has high transmissivity and varies with depth. 3 inches of water allows almost all the rays to pass through it. As the rays hit the base the rays are being absorbed. The heat absorbed by the base is then absorbed by the water raising its temperature in the process. Some of the radiation is reflected back from the base and escapes the pond.

Also as soon the Sun sets, polyethylene sheet rapidly looses heat and cool down to lower temperature then ambient air. Radiative cooling works together in this process. As soon as direct heat gain stops ambient air cools the sheet to ambient air temperature. Because polyethylene sheet is not 100% transparent to long-wave radiation, it also loses heat and cools down in the process. During the day time sheet temperature is much higher than the water temperature so it also radiates towards water and a small fraction of heat is transferred from sheet to the water through radiation.

To check the validity of the thermal model, it was compared with the heat balance results. For both the ponds the model predicted very accurate numbers of heat transfer. Even though the model was a close match but it failed to predict the sudden sharp variations in the heat balance.

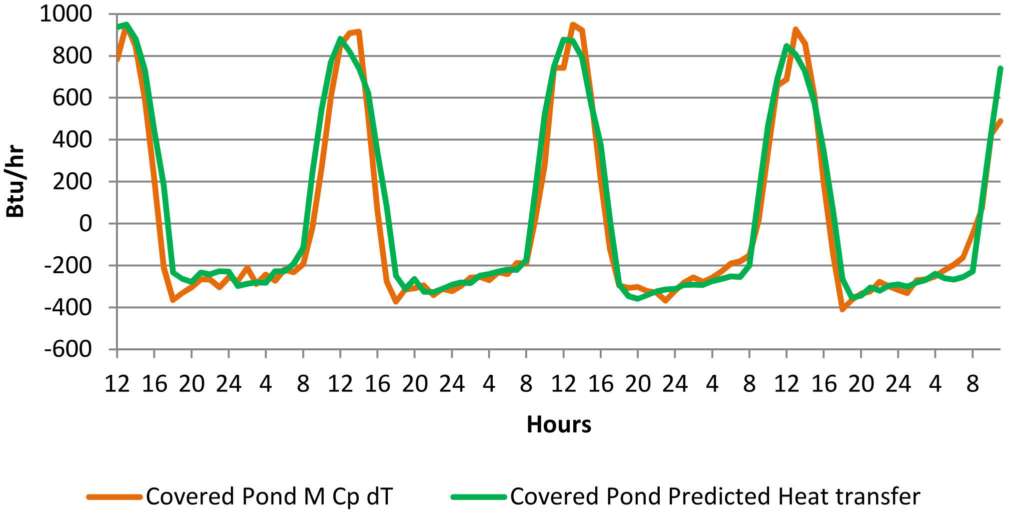

Figure 22: Comparison of predicted heat transfer and M Cp dT of covered pond

In both covered and exposed ponds the sudden changes remained unexplained. This could be error in the measurements or due to misbehaving of a sensor.

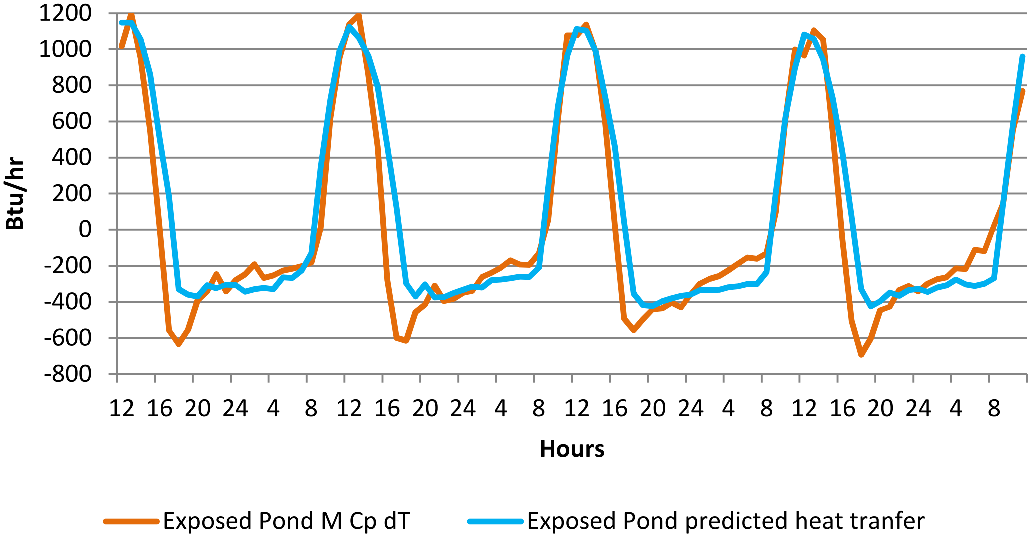

Figure 23: Comparison of predicted heat transfer and M Cp dT of Exposed pond

As expected the total heat exchange for the covered pond was lower which indicates that there will be lesser variation in water temperature.

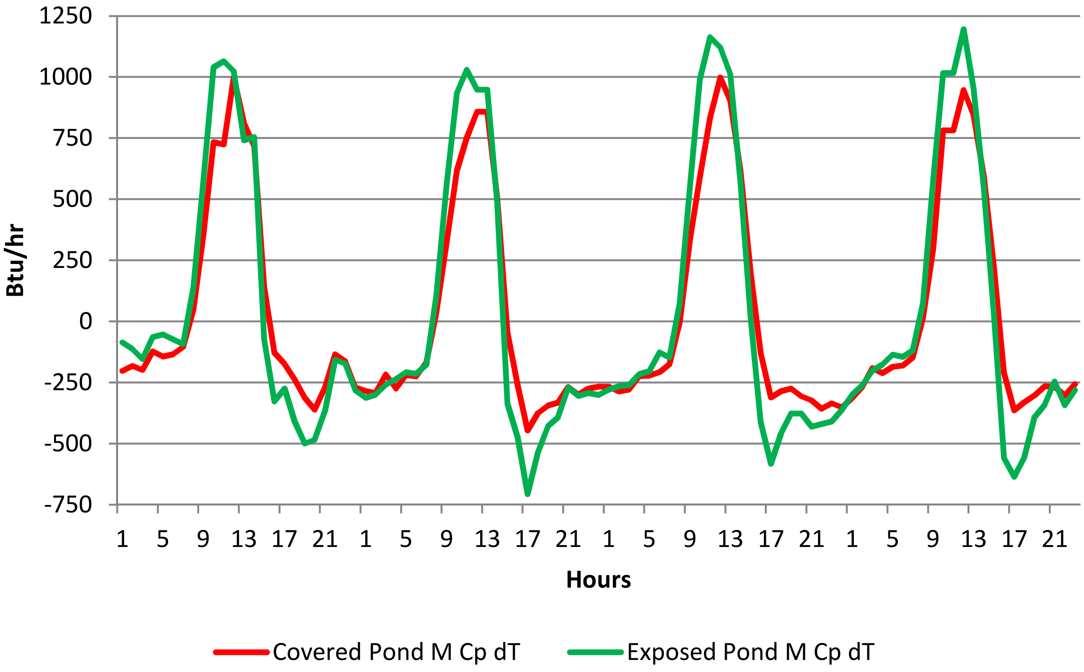

Figure 24: Comparison of M Cp dT of ponds

Although the covered pond water does not give off more energy than exposed one during the night time but it also does not absorb as much energy as the exposed one during the day time.

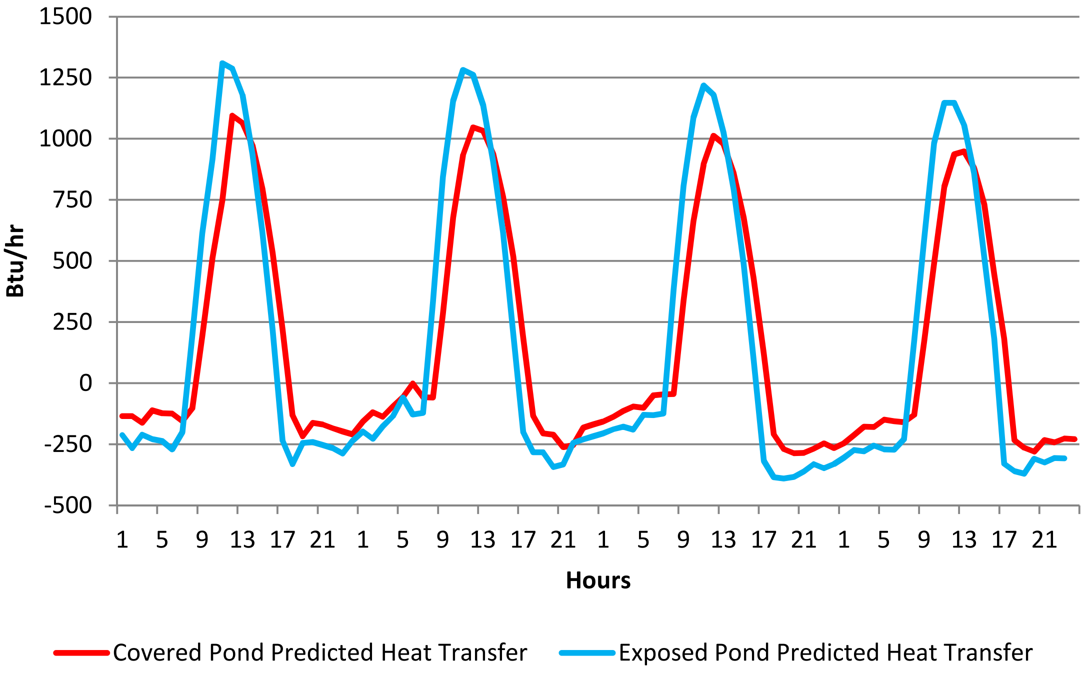

Figure 25: Comparison of Predicted Heat Transfer

This phenomenon can be seen clearly in Figure 25. It is beneficial to use the polyethylene cover as it saves energy in the afternoon and can still do almost equally good at night compared to exposed pond.

The spreadsheet based thermal model provides information about each mode of heat transfer distinctly. Figure 26 is a comparison of solar heat gain per hour by each pond. The covered pond gains less heat then the exposed one. The reason for this is that polyethylene is not completely transparent to short-wave radiations.

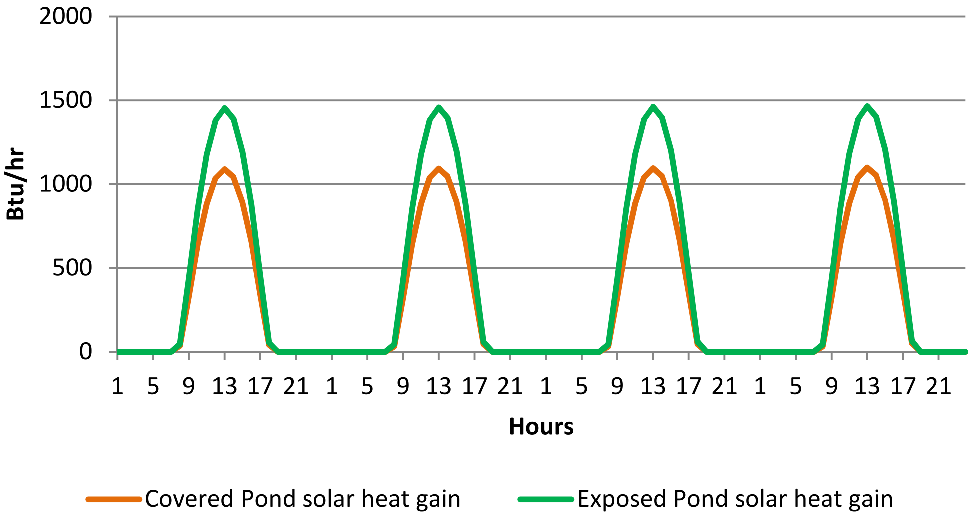

Figure 26: Comparison of solar heat gain

By calibration of the thermal model with heat balance equation M.Cp.dT the transmissivity of the polyethylene sheet was determined to be 0.75. This suggest that only 75% of the short wave radiation reaches the water whereas in case of exposed pond all the radiation hits the water surface directly due to absence of any barrier. This should be noted that polyethylene sheet has very low reflectivity hence it absorbs 25% of the short wave radiations falling on it. This raises its temperature and it stats radiating towards the water. Although theoretically this should change the temperature of water but due to small difference in the temperature of water and the sheet this effect is very small. Also the thermal mass of the polyethylene is very small compared to the water in the pond thus making this radiative heat exchange negligible.

The ponds were made up of polystyrene insulation boards with U value of 0.14 hr ft^2 ^oF/Btu so it blocked large part of the possible conduction. Still the insulation was not infinite so there was bound to be some conduction happening. Also ponds had joints which could be a path for heat to crawl into the ponds.

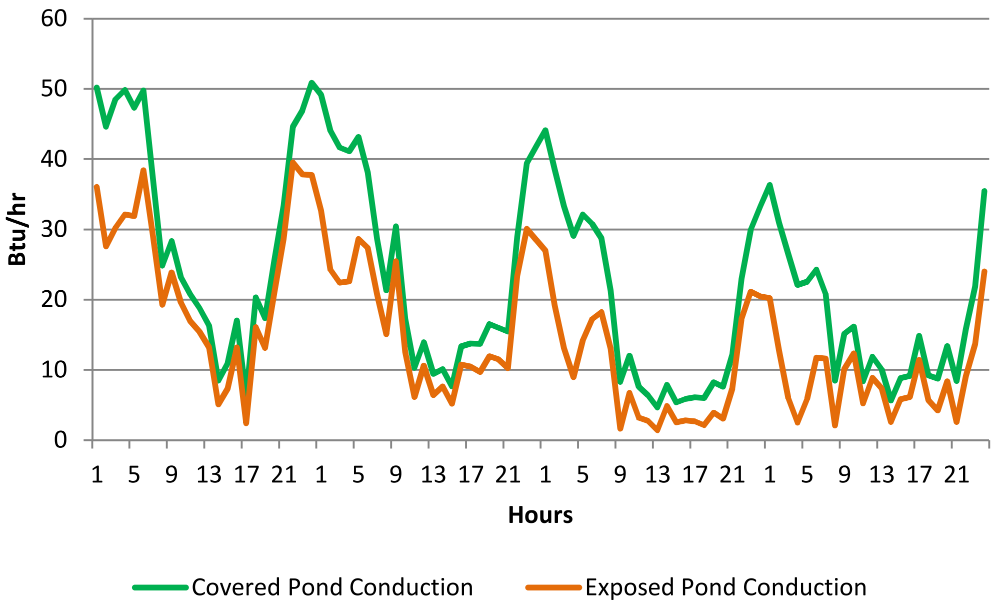

Figure 27: Comparison of conduction heat transfer

The trend shown in Figure 27 can be explained by difference in water temperature. As the temperature of water in the covered pond was lower than the temperature of water in the exposed pond and ambient air temperature being constant, covered pond observed bigger heat gain. This was calculated assuming that the ponds are identical in geometry, size and material.

By calibration of the thermal model with heat balance equation M.Cp.dT the transmissivity of the polyethylene sheet was determined to be 0.8. this means covered pond can use only 80% of the radiative cooling available. On the other hand exposed pond does not have any barrier between water surface and the sky hence it can lose more heat and cool down further.

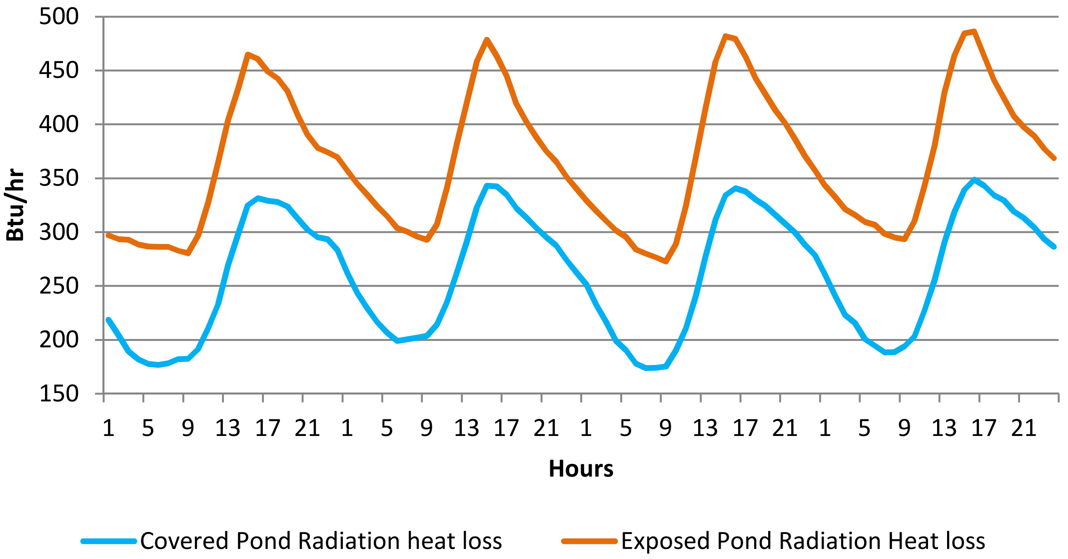

Figure 28: Comparison of radiation heat loss

The variation in heat transfer through radiation is greater in exposed pond. This can be traced back to the variation in temperature on the ponds. The sky temperature being same for both the ponds variation in their respective water temperature affects the heat transfer process.

For this study the convection of both the tank was assumed to be the same as the covered tank had ample gap between sheet and water for air to pass through freely. For this reason the convective heat gain only depends on the temperature of water and not on velocity of air.

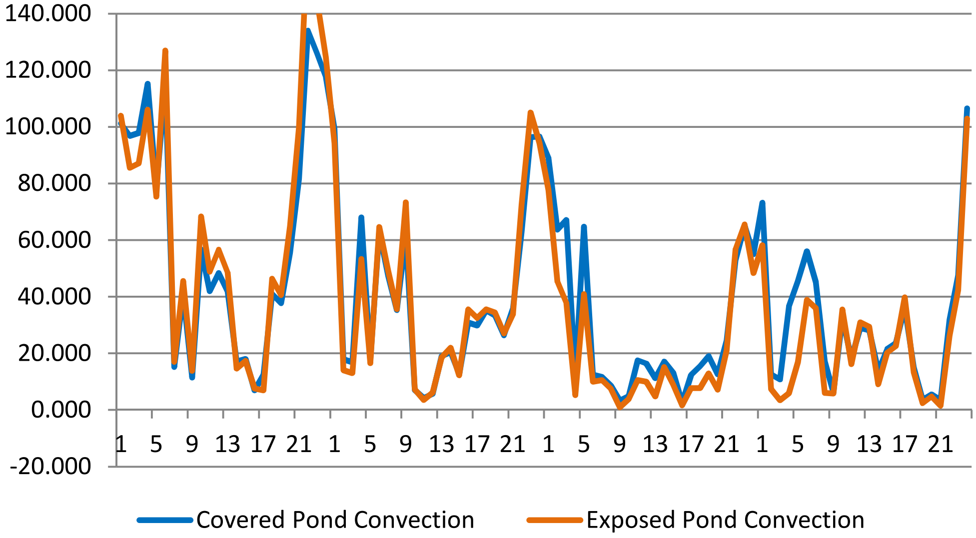

Figure 29: Comparison of convection heat exchange

The convection barrier has its trade-off. If sheet temperature drops below the dew-point temperature, dew can form on the sheet. Because water has high emissivity in the long-wave spectrum, it can block the radiative heat exchange completely stopping the cooling process. To avoid this, a small air gap is recommended to allow the moisture to escape.

Chapter 5

RESULTS

This study reveals that a roof pond which is covered by 50 μm thick polyethylene sheet performance better than an exposed roof pond. Polyethylene sheet band filter reduces the solar heat gain and helps in achieving lower water temperatures. It also eliminates the need for covering the roof ponds during the day time.

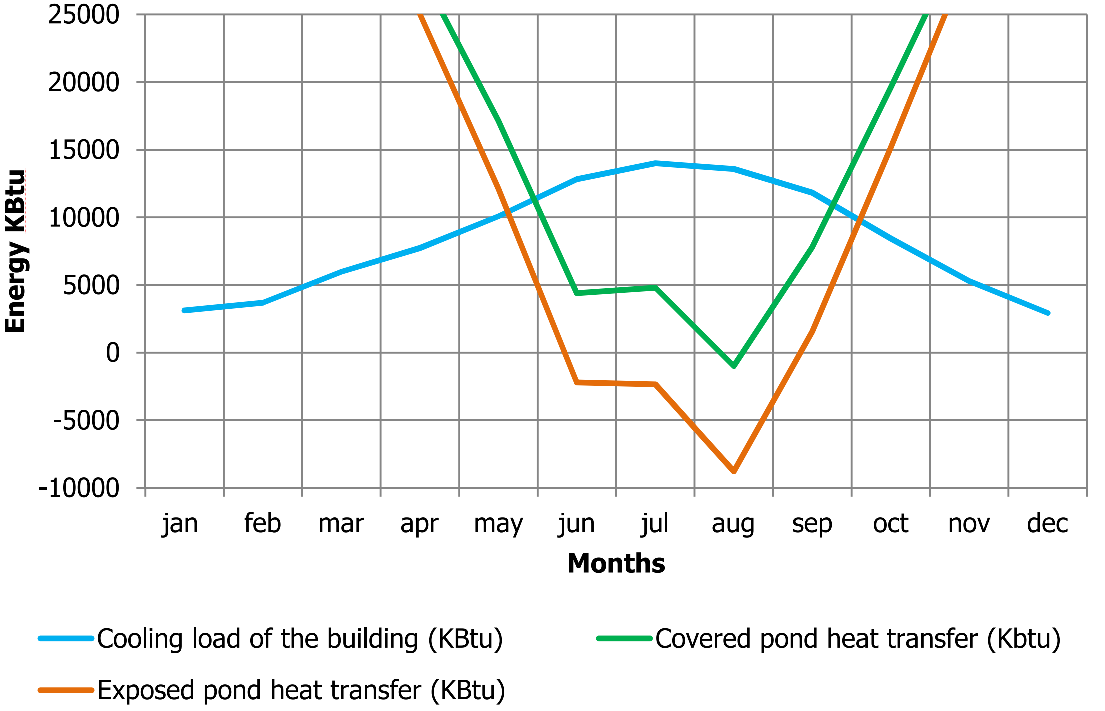

Figure 30 : Comparison of performances of both the ponds with building cooling load

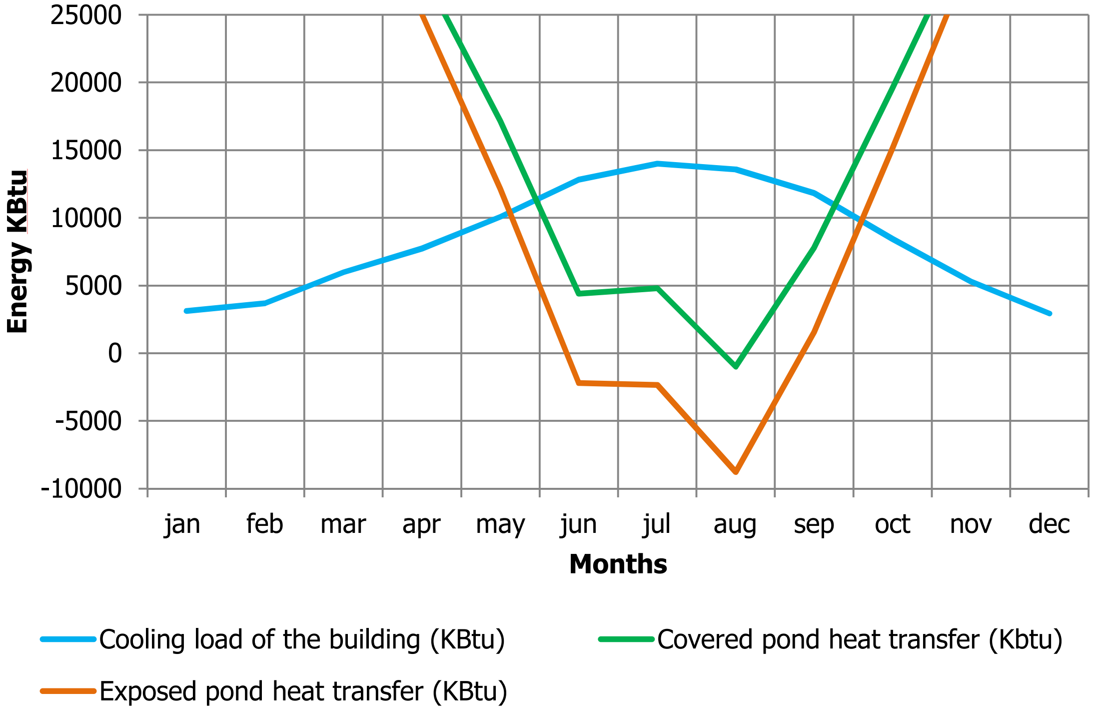

Figure **30** shows a comparison of the cooling requirements of the typical house, and performance of both the roof ponds. When the roof ponds heat transfer lines crosses the cooling load curve, these are the points in time when roof ponds can take care of all the cooling loads of the building. When these lines are above the cooling load curve, it means that water in the ponds is too cold hence it absorbs too much heat from the space. In order to maintain 72 °F indoor temperature HVAC system will have to supply heat to compensate for this excessive heat loss. This will increase the energy consumption hence it is not useful to use rood pond at this time.

When the roof pond heat transfer lines are below the cooling load curve but above the zero mark it depicts savings. It can be seen that covered pond line stays between the cooling load curve and zero mark for most times of the summer. On the other hand the exposed pond line dips deep into the negative side. Reaching towards negative sides means that pond is actually not saving any energy. Instead HVAC system will have to work harder to main the desired temperature during this period.

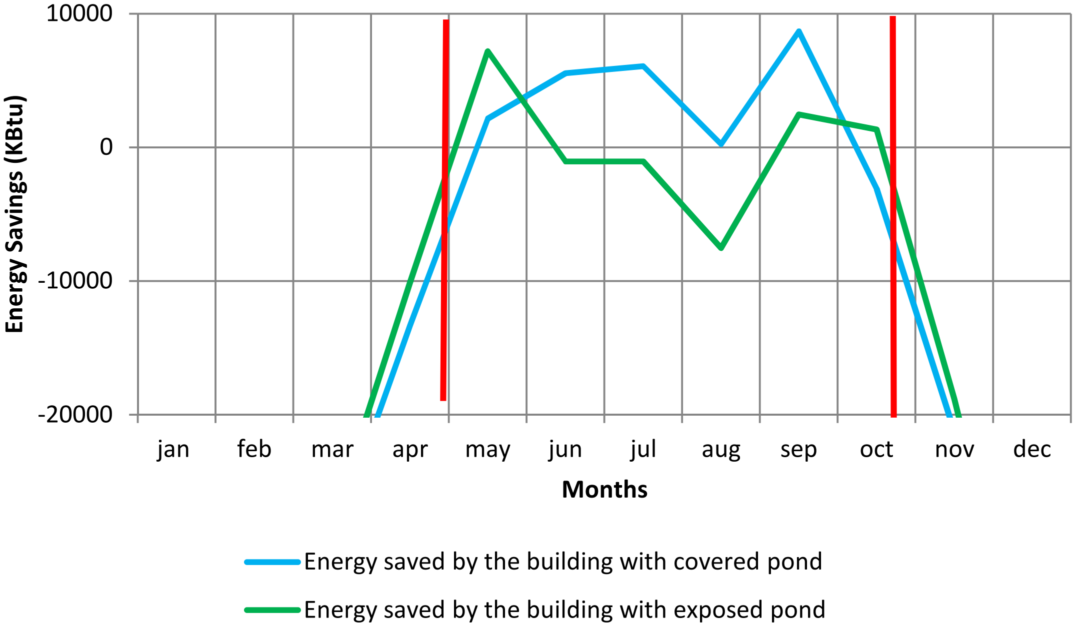

Figure 31 : Energy savings comparison

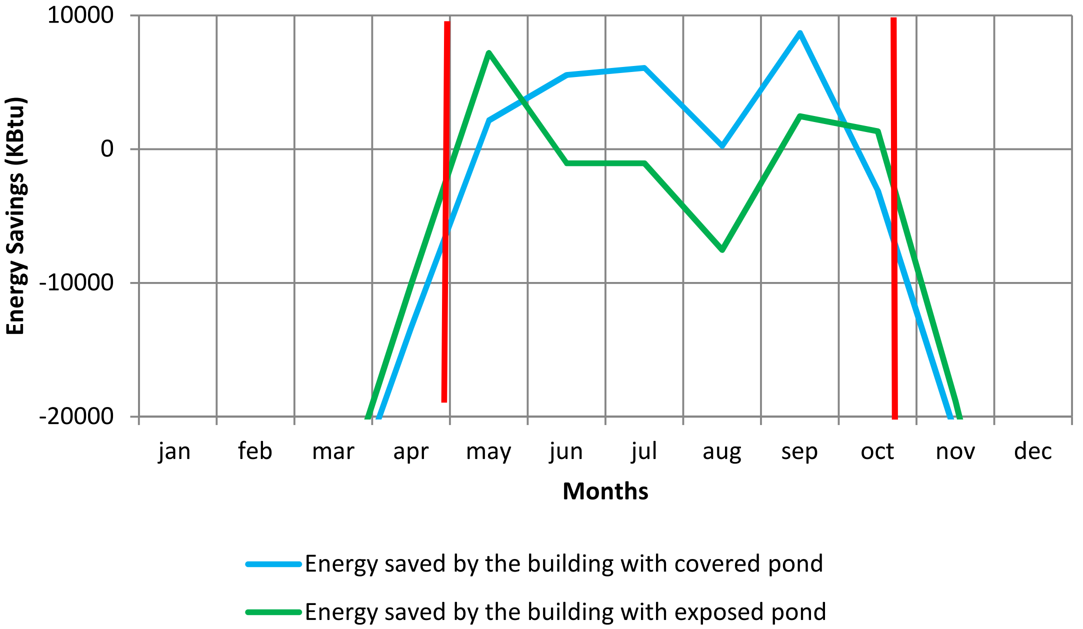

Figure **31** suggest that covered pond can save energy for the months of May to July and Sept. During the month of Aug, high humidity diminishes the radiative cooling process and performance of the rood pond is affected. At the same time the exposed pond water temperature is not cool enough to provide any cooling to the building During June to Aug. it is useful only in the months of May, Sept and Oct. Another important observation is that exposed tank starts providing cooling earlier then the exposed pond. it also proves to be useful till mid Oct whereas the covered pond fails about 1 week earlier.

	Covered Pond	**Exposed**
Total energy required (Kbtu)	48,727 (May to July & Sept)	30,326 (May, Sept & Oct)
Cooling Energy supplied (Kbtu)	22,455	10,974
Cooling season Savings %	**46.1 %**	**36.2 %**
Annual Savings	**22.5**	**11**

Table 2 : Results

The results indicate that covered pond is useful for more months of the year and saves about 46% of the total energy required to cool the building for those months. On the other hand exposed pond is not useful for most part of the summer hence it saves only 36% of the cooling energy needed for those months. Results suggest that covered pond is much more effective than the exposed pond. By using the exposed roof pond 11% of the total cooling energy can be saved annually, whereas by using the covered pond one can save 22.5% of the energy required to cool a building annually.

Conclusion

This study highlights the effectiveness of roof pond in saving energy in single story residential buildings. The Roof ponds covered with Band filters like polyethylene can save considerably more amount of energy for a Phoenix like climate. Based on the experiment designed for this study a 50 μm polyethylene covered roof pond can save up to 46% energy in the cooling season whereas exposed pond could only save 36%. This proves that band filter can make a roof pond 10% more effective. Also covered pond could be used for 4 months of the cooling season whereas exposed pond could only be helpful for 3 months. Exposed pond gets too hot during the summer months and becomes unsuitable for cooling whereas the covered pond provides cooling throughout the summer and saves much more energy. Exposed pond can start providing cooling early in the year and can keep providing cooling till late summer.

Future works

In future more detail study can be conducted carefully studying the convection and evaporation phenomenon in the covered roof ponds. The study should look into the effect of these modes of heat transfer on the performance of roof pond. Another study can look into a hybrid system which can use both covered and exposed pond techniques so that ponds can be useful for longer time during the cooling season. Better band filters can also be developed for the purpose of increasing the effectiveness of roof ponds. Different techniques oh heat transfer between the pond and the building should be developed to reduce the energy losses. Band filters should also be experimented with other kind of roof ponds like light weight metallic radiator etc.

REFERENCES

Ahmad Hamza H, A. H. (1996). *Effect of aging, thickness and color of both the radiative properties of polyethylene films and performance of the nocturnal cooling unit.* Pergomon.

Berdahl, P. &. (1982). *Thermal radiance and clear skies.*

Chaplin, M. (n.d.). *Water structures and science*. Retrieved from http://www.lsbu.ac.uk/water/vibrat.html

Dr Bing Chen, R. G. (n.d.). *Modeling of the radiation, convective and evaporative heat trasfer mechanism of the nebraska modified roof pond for the determination of cooling performance curves.*

Eleni Anastasia Dimitriadou, D. A. (n.d.). *Experimental Assessment and Thermal Characterization of ETFE Foil.*

Evyatar Erell*, Y. E. (1999). *Radiative cooling of buildings with flat-plate solar collectors.* Pergamon.

Givoni, B. (1994). *Passive and low energy cooling of building.* New York : Van Nostrand Reinhold.

Harris Poirazis, M. K. (2009). *ENERGY MODELLING OF ETFE MEMBRANES IN BUILDING APPLICATIONS.* London: Eleventh International IBPSA Conference.

Kreider, C. &. (2010).

Luciuk, M. (n.d.). *NIGHT RADIATIVE COOLING - The effect of clouds and relative humidity.*

Mahan, J. R. (2002). *Radiation Heat Transfer: A Statistical Approach.* New York: John Wiley & Sons.

Martin, M. (1988). Radiative Cooling. In J. Cook, *Passive Cooling.* London: MIT Press Cambridge, Massachissetts.

MASATO TAZAWA, P. J. (1997). *NEWMATERIAL DESIGN WITH V1−xWxO2 FILM FOR SKY RADIATOR.* Pergamon.

McGraw-Hill Science & Technology Encyclopedia. (2005).
Prapapong Vangtook, S. C. (2005). *Application of radiant cooling as a passive cooling option in hot humid climate.* Elsevier.

S.N. Bathgate, S. (2006). *A robustconvectioncovermaterialforselectiveradiative.* Sydney.

Sakkal, F. (2011). *EXPERIMENTAL TEST FACILITY FOR SELECTIVE RADIATIVE COOLING SURFACES.* Lawrence Berkeley National Laboratory.

Torbj6rn M.J. Nilsson, G. A. (n.d.). *Radiative cooling during the day: simulations and experiments on pigmented polyethylene cover foils.* ELSEVIER.

TorbjOrn M. J. Nilsson, G. A. (n.d.). *A solar reflecting material for radiative cooling applications: ZnS pigmented polyethylene.*

William P. Marlatt, K. A. (1984). *Roof Pond Systems.*

Y. ETZION, E. E. (1991). *Thermal Storage Mass in Radiative.* Pergamon.

APPENDIX A

STATISTICS MODEL

The results of a regression model are represented below. This was done to find the relation of water temperature in the pond with the weather data.

Regression results for Covered Pond are as follows

Regression Statistics	
Multiple R	0.839
R Square	0.705
Adjusted R Square	0.698
Standard Error	3.357
Observations	179

ANOVA

	df	*SS*	*MS*	*F*	*Sig F*
Regression	4	4680.968	1170.242	103.817	0.000
Residual	174	1961.353	11.272		
Total	178	6642.321			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-11.382	6.439	-1.768	0.079	24.091	1.327	-24.091	1.327
Ambient air temp	0.977	0.078	12.579	0.000	0.823	1.130	0.823	1.130
Wind Speed	-1.146	0.243	-4.714	0.000	-1.626	0.666	-1.626	-0.666
Relative Humidity %	0.073	0.040	1.827	0.069	-0.006	0.152	-0.006	0.152
Total Radiation (Btu/hr sqft)	-0.014	0.001	10.212	0.000	-0.017	0.012	-0.017	-0.012

Table 3: Regression model summary for Polyethylene Covered Pond

The resultant equation can be written as:

Covered pond water temp = -11.38 + 0.98 X Ambient air temp - 1.15 X wind speed + 0.07 X RH - 0.01 X total radiation Eq. 22

Regression results for Exposed Pond are as follows

Regression Statistics	
Multiple R	0.862
R Square	0.743
Adjusted R Square	0.737
Standard Error	3.776
Observations	179

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	7181.190	1795.298	125.942	0.000
Residual	174	2480.370	14.255		
Total	178	9661.561			

	Coefficien	*Standar*	*t Stat*	*P-*	*Lower*	*Uppe*	*Lower*	*Upper*

	ts	d Error		value	95%	r 95%	95.0 %	95.0%
Intercept	-18.975	7.241	-2.620	0.010	-33.267	-4.684	-33.267	-4.684
Ambiant air temperature	1.114	0.087	12.764	0.000	0.942	1.287	0.942	1.287
Wind Speed	-1.259	0.273	-4.604	0.000	-1.799	-0.719	-1.799	-0.719
Relative Humidity %	0.092	0.045	2.041	0.043	0.003	0.181	0.003	0.181
Total Radiation (Btu/hr sqft)	-0.011	0.002	-6.910	0.000	-0.014	-0.008	-0.014	-0.008

Table 4: Regression model summery for Exposed Pond

The resultant equation can be written as:

Exposed water temp = -18.975 + 1.114 X ambient air temp - 1.259 wind speed + 0.092 X RH - 0.010 X total radiation Eq. 23

Similar to the Thermal model, the Forward Finite Differential Method was used to calculate the corrected water temperatures and heat transfer. Total heat transfer was then computed.

APPENDIX B

LIST OF EQUATIONS

$1 = \alpha + \rho + \tau$ Eq. 1

$q_{rad} = \sigma T_b^4$ Eq. 2

$R_{emit} = \sigma \times E_r \times T_r^4$ Eq 3

Step 1 : $(Q_1) = U_{slab} \times (72\ ^{o}F - T_{1measured})$ Eq. 4

Step 2 : $T_2 = (Q_1 / M \times Cp_{water}) + T_{1measured}$ Eq. 5

Step 3 : $Q_2 = U_{slab} \times (72\ ^{o}F - T_2)$ Eq. 6

$Q_{Total} = Q_{conv} + Q_{solar} + Q_{cond} - Q_{rad} - Q_{evap}$ (Martin, 1988) Eq. 7

$T_{dp}\ (^{o}F) = \{(T_{air} - 32)/1.8\} - 14.55 + 0.114\{(T_{air} - 32)/1.8\}$ Eq. 8

$\varepsilon_{sky} = 0.741 + 0.0062 \times T_{dp}(^{o}C)$ (Berdahl, 1982) Eq. 9

$T_{sky}(^{o}F) : \varepsilon_{sky} = (T_{sky} / T_{air})^4$ (Martin, 1988) Eq. 10

$Q_{rad} = \text{Area}\ \varepsilon_r \sigma (T_{water}^4 - T_{sky}^4)$ Eq. 11

$Q_{rad} = t_g \varepsilon_r \sigma [T^4_{water} - T^4_{sky}] + \varepsilon_g \varepsilon_r \sigma [T^4_{water} - T^4_g] + h_{ra} [T_{water} - T_{air}] + h_{rg}[T_{water} - T_g]$

(Martin, 1988) Eq. 12

$Q_{conv} = h_c (T_{air} - T_{water})$ (Dr Bing Chen R. G.) Eq. 13

$hc = 0.6 + 3.5(V)^{0.5}\ W/(m^2K)$ (Givoni, 1994) Eq. 14

$t = 10^{-\alpha l}$ (Beer-Lambert Law) Eq. 15

$q_{solar} = \alpha_{water} \times \text{Irradiance} \times \text{Area of pond}$ Eq. 17

$q_{solar} = \alpha_{water} \times (t_g \times \text{Irradiance} \times \text{Area of pond})$ Eq. 18

$Q_{cond} = U A \Delta T$ Eq. 19

$Q_{total} = MC_p\, dt_{water}/dt$ Eq. 20

$dt_{water}/dt = \{T_{water}(t) - T_{water}(t+1)\}/\text{Time}$ Eq. 21

Covered pond water temp = -11.38 + 0.98 X Ambient air temp - 1.15 X wind speed + 0.07 X RH - 0.01 X total radiation Eq. 22

Exposed water temp = -18.975 + 1.114 X ambient air temp - 1.259 wind speed + 0.092 X RH - 0.010 X total radiation Eq. 23

APPENDIX C

MEASURED DATA

Date	Time	Covered pond water Temp	PE Sheet Temp	Exposed pond water Temp	Ambiant air temperature	Wind Speed	RH %	Total Radiation (Btu/hr sqft)
27-Nov	1	45.4	53.2	45.6	57.7	2.05	41.7	0
27-Nov	2	44.5	51.9	45.2	56.1	3.36	47.1	0
27-Nov	3	43.8	49.5	44.7	58.1	1.55	47.0	0
27-Nov	4	42.9	49.8	44.1	59.8	2.49	43.5	0
27-Nov	5	42.4	52.5	43.8	57.7	4.65	38.3	0
27-Nov	6	41.8	51.6	43.6	59.1	3.22	39.6	0
27-Nov	7	41.2	51.2	43.3	59.7	2.82	35.7	0
27-Nov	8	40.8	51.2	42.9	62.7	2.93	35.4	14.264925
27-Nov	9	41.0	56.6	43.5	65.2	2.51	32.0	57.23581
27-Nov	10	42.5	64.8	45.9	70.8	3.95	32.4	94.923389
27-Nov	11	45.6	72.6	50.3	76.7	1.50	27.1	122.7488
27-Nov	12	48.7	81.7	54.8	80.1	3.57	20.7	138.95093
27-Nov	13	52.9	82.4	59.2	82.4	3.94	18.7	142.29703
27-Nov	14	56.4	84.8	62.3	83.0	2.76	16.9	132.61097
27-Nov	15	59.4	87.5	65.5	82.0	3.55	15.4	110.5972
27-Nov	16	60.0	79.0	65.2	83.6	1.15	16.4	77.664591
27-Nov	17	59.5	71.8	63.8	77.4	0.03	15.9	36.454808
27-Nov	18	58.7	66.6	62.6	74.6	0.07	19.8	2.1133222
27-Nov	19	57.7	65.4	60.9	74.3	0.74	22.3	0
27-Nov	20	56.4	67.2	58.8	72.1	4.87	20.7	0
27-Nov	21	54.9	65.6	56.7	70.9	4.96	22.6	0
27-Nov	22	53.7	63.5	55.2	68.5	2.45	23.5	0
27-Nov	23	53.2	60.8	54.5	68.4	0.41	28.5	0
27-Nov	24	52.5	56.9	53.8	67.5	0.00	29.5	0
28-Nov	1	51.3	59.0	52.6	65.6	1.19	26.7	0
28-Nov	2	50.1	58.2	51.2	64.4	2.50	28.3	0
28-Nov	3	48.9	58.2	50.0	59.3	3.16	30.1	0
28-Nov	4	47.9	52.4	48.9	62.0	0.87	41.3	0
28-Nov	5	46.8	55.0	47.9	59.2	3.41	32.9	0
28-Nov	6	45.9	52.4	47.0	58.0	2.87	38.6	0
28-Nov	7	44.9	50.0	46.1	60.5	1.38	41.1	0
28-Nov	8	44.2	50.6	45.3	64.6	0.45	37.1	13.736594
28-Nov	9	44.4	57.8	45.8	69.7	1.88	32.3	56.531369

28-Nov	10	45.7	67.9	48.2	72.7	2.29	28.7	94.218948
28-Nov	11	48.4	75.6	52.1	76.6	2.44	24.6	122.04436
28-Nov	12	51.5	80.4	56.5	76.9	0.82	22.9	138.24649
28-Nov	13	55.2	81.8	60.5	78.6	1.3	23.2	141.7687
28-Nov	14	58.8	83.3	64.6	80.3	1.87	19.8	132.08264
28-Nov	15	61.0	86.6	66.6	81.8	1.71	19.4	110.24497
28-Nov	16	60.8	83.9	65.2	79.2	2.30	19.3	77.488481
28-Nov	17	59.7	78.1	63.2	74.2	2.10	20.2	36.278698
28-Nov	18	57.8	73.6	60.2	72.5	3.48	24.3	2.1133222
28-Nov	19	56.2	68.0	57.9	69.9	3.81	26.1	0
28-Nov	20	54.7	64.5	56.1	69.8	3.16	29.1	0
28-Nov	21	53.3	62.3	54.4	67.2	3.00	29.3	0
28-Nov	22	52.2	61.0	53.3	63.4	2.90	33.9	0
28-Nov	23	50.9	57.1	52.0	62.1	0.40	36.4	0
28-Nov	24	49.7	55.8	50.7	60.3	0.25	38.3	0
29-Nov	1	48.6	54.3	49.5	58.7	0.88	42.2	0
29-Nov	2	47.5	51.6	48.3	56.3	0.55	44.4	0
29-Nov	3	46.3	51.6	47.2	55.7	0.70	47.6	0
29-Nov	4	45.1	50.3	46.1	56.8	0.38	47.8	0
29-Nov	5	44.1	49.7	45.1	55.1	1.95	43.8	0
29-Nov	6	43.2	49.4	44.3	53.4	2.13	48.9	0
29-Nov	7	42.3	48.5	43.7	54.3	1.19	50.5	0
29-Nov	8	41.6	48.5	43.1	58.8	2.34	50.1	13.208264
29-Nov	9	41.6	47.4	43.4	64.9	1.12	44.5	55.826928
29-Nov	10	43.0	53.0	45.8	67.1	1.56	36.1	93.514508
29-Nov	11	45.5	63.7	50.0	70.4	1.88	34.6	121.33992
29-Nov	12	49.0	72.0	54.9	74.5	1.78	31.9	137.71816
29-Nov	13	53.2	79.4	59.7	78.8	1.98	28.5	141.24037
29-Nov	14	57.1	82.0	63.9	78.5	1.64	25.3	131.73042
29-Nov	15	59.7	85.0	66.4	79.3	0.48	24.5	109.89275
29-Nov	16	60.5	82.6	66.4	77.6	0.96	24.2	77.13626
29-Nov	17	60.0	77.9	64.6	72.1	0.49	25.7	36.102588
29-Nov	18	58.7	70.6	62.2	71.2	1.27	29.1	2.1133222
29-Nov	19	57.4	64.4	60.2	69.5	1.16	29.9	0
29-Nov	20	56.3	60.4	58.6	67.0	0.56	32.9	0
29-Nov	21	55.0	58.9	57.0	64.6	0.31	36.8	0
29-Nov	22	53.6	58.5	55.2	62.9	0.71	37.9	0
29-Nov	23	52.1	58.8	53.4	60.8	1.89	40.8	0
29-Nov	24	50.7	57.4	51.7	59.8	2.47	41.3	0
30-Nov	1	49.2	55.9	50.2	58.1	3.52	42.3	0

30-Nov	2	47.9	54.7	48.9	57.8	4.33	43.9	0
30-Nov	3	46.7	53.5	47.8	58.7	3.46	46.1	0
30-Nov	4	45.9	52.5	46.9	57.8	2.55	45.2	0
30-Nov	5	45.0	51.8	46.2	56.9	2.39	46.0	0
30-Nov	6	44.2	51.6	45.6	56.3	1.76	46.6	0
30-Nov	7	43.5	51.1	45.0	56.7	2.76	46.5	0
30-Nov	8	42.8	49.7	44.5	61.0	2.36	47.4	12.679933
30-Nov	9	42.9	49.4	44.8	64.0	1.07	44.1	55.122487
30-Nov	10	44.2	54.6	47.3	68.9	0.65	41.7	92.810067
30-Nov	11	47.5	59.0	51.6	72.4	1.8	35.8	120.81159
30-Nov	12	50.8	63.3	55.9	75.8	2.91	31.9	137.01372
30-Nov	13	54.8	70.2	61.0	79.2	2.51	31.0	140.71204
30-Nov	14	58.4	80.4	65.0	77.7	1.59	32.1	131.20209
30-Nov	15	60.9	81.9	67.3	77.3	0.59	32.5	109.54053
30-Nov	16	61.8	82.4	67.4	76.3	0.60	32.9	76.96015
30-Nov	17	60.9	80.3	65.1	72.1	1.51	33.8	35.926477
30-Nov	18	59.4	76.7	62.4	70.4	1.47	37.4	2.1133222
30-Nov	19	58.0	69.8	60.0	68.8	2.01	41.5	0
30-Nov	20	56.7	65.3	58.3	67.2	2.75	44.6	0
30-Nov	21	55.6	63.5	56.9	65.3	3.62	47.8	0
30-Nov	22	54.5	61.1	55.9	64.3	1.92	50.5	0
30-Nov	23	53.2	59.7	54.4	61.8	1.20	51.2	0
30-Nov	24	52.1	56.8	53.2	60.5	0.39	56.0	0
1-Dec	1	50.9	56.5	52.2	58.7	0.66	58.7	0
1-Dec	2	50.0	56.0	51.3	58.3	1.43	60.5	0
1-Dec	3	48.8	54.1	50.2	57.3	0.48	57.3	0
1-Dec	4	47.8	53.8	49.1	55.9	1.33	58.6	0
1-Dec	5	46.6	52.6	48.2	55.4	1.83	60.0	0
1-Dec	6	45.7	52.5	47.2	54.4	1.96	60.7	0
1-Dec	7	44.7	51.2	46.4	55.3	2.83	62.0	0
1-Dec	8	43.9	49.9	45.6	60.3	0.83	60.9	12.151603
1-Dec	9	43.8	49.4	45.7	64.5	2.11	53.3	54.418047
1-Dec	10	45.0	48.2	48.3	66.9	1.79	47.2	92.105626
1-Dec	11	47.6	54.4	52.3	72.1	2.01	45.4	120.10715
1-Dec	12	51.2	65.0	57.1	74.3	1.82	38.7	136.48539
1-Dec	13	55.0	72.9	62.2	78.1	2.07	34.2	140.18371
1-Dec	14	58.9	77.4	65.9	76.4	1.26	31.0	130.84987
1-Dec	15	61.1	81.9	67.8	75.7	1.09	31.5	109.18831
1-Dec	16	61.3	82.1	66.6	76.0	0.39	32.8	76.78404
1-Dec	17	60.2	79.9	64.1	70.9	1.33	33.7	35.750367

1-Dec	18	58.6	75.1	61.5	68.7	2.64	40.9	2.1133222
1-Dec	19	57.3	70.2	59.5	67.9	2.19	43.5	0
1-Dec	20	56.0	64.4	57.8	66.4	1.29	45.5	0
1-Dec	21	54.7	59.1	56.5	63.9	0.23	48.3	0
1-Dec	22	53.3	57.3	54.8	60.9	0.13	47.8	0
1-Dec	23	52.0	56.2	53.1	60.0	0.00	51.2	0
1-Dec	24	50.6	57.1	51.7	59.3	1.59	50.1	0
2-Dec	1	49.3	55.2	50.2	58.9	0.85	53.1	0
2-Dec	2	48.2	53.6	49.1	57.6	0.86	53.6	0
2-Dec	3	47.2	52.4	48.1	56.1	1.29	53.8	0
2-Dec	4	46.0	52.1	47.2	55.2	1.15	56.0	0
2-Dec	5	45.0	51.6	46.5	52.9	1.71	58.8	0
2-Dec	6	44.0	50.8	45.7	54.0	1.57	60.6	0
2-Dec	7	43.2	50.4	44.8	55.9	2.21	57.3	0
2-Dec	8	42.4	49.3	44.3	59.2	4.16	53.4	11.623272
2-Dec	9	42.5	48.0	44.5	63.4	2.88	50.6	53.713606
2-Dec	10	43.7	49.5	47.1	67.0	2.96	44.3	91.401185
2-Dec	11	46.8	51.8	51.7	71.0	2.6	38.7	119.4027
2-Dec	12	50.0	54.1	56.2	75.0	2.24	33.6	135.95706
2-Dec	13	54.0	64.5	61.0	76.4	2.47	33.1	139.65538
2-Dec	14	57.9	70.9	65.2	77.8	1.43	33.1	130.49765
2-Dec	15	60.5	78.8	67.7	78.1	0.97	32.1	109.0122
2-Dec	16	61.3	81.3	67.8	78.5	0.77	30.6	76.43182
2-Dec	17	60.8	82.7	65.8	71.9	0.65	30.4	35.574257
2-Dec	18	59.6	80.8	63.4	69.8	0.61	36.0	1.937212
2-Dec	19	58.3	76.7	61.3	67.4	0.67	37.9	0
2-Dec	20	57.0	70.6	59.4	66.5	0.60	42.2	0
2-Dec	21	55.6	63.5	57.6	64.1	0.03	44.2	0
2-Dec	22	54.2	60.3	55.8	60.9	0.01	47.8	0
2-Dec	23	52.7	58.0	54.0	60.7	0.01	52.7	0
2-Dec	24	51.3	56.5	52.5	59.3	0.36	53.1	0
3-Dec	1	50.1	56.0	51.2	59.8	0.33	53.5	0
3-Dec	2	49.1	55.8	50.1	57.2	1.96	49.6	0
3-Dec	3	47.9	54.5	49.0	56.0	1.22	57.2	0
3-Dec	4	46.8	53.9	48.0	56.5	1.83	57.2	0
3-Dec	5	45.8	53.9	47.2	56.3	2.71	55.5	0
3-Dec	6	45.0	52.7	46.6	55.5	2.24	56.1	0
3-Dec	7	44.3	51.7	45.9	56.3	2.83	57.2	0
3-Dec	8	43.6	51.5	45.3	61.0	2.19	56.6	11.271052
3-Dec	9	43.7	50.4	45.8	63.3	1.53	49.0	53.009165

3-Dec	10	45.1	49.7	48.3	68.6	1.10	45.3	90.696745
3-Dec	11	47.9	49.8	52.6	69.2	2.07	39.8	118.87437
3-Dec	12	50.8	55.7	56.7	74.9	2.63	38.3	135.42873
3-Dec	13	54.8	64.7	61.4	77.2	2.05	34.5	139.30316
3-Dec	14	58.4	72.1	65.8	77.5	1.32	34.3	130.14543
3-Dec	15	61.0	74.7	68.1	77.8	1.18	34.7	108.65998
3-Dec	16	61.8	81.4	67.9	74.2	0.62	33.6	76.43182
3-Dec	17	61.2	83.0	65.7	71.8	0.64	36.5	35.574257
3-Dec	18	59.5	81.0	62.8	69.8	0.97	39.6	1.937212
3-Dec	19	57.9	77.0	60.2	67.7	0.95	42.9	0
3-Dec	20	56.5	69.4	58.3	65.1	0.89	45.6	0
3-Dec	21	55.1	65.8	56.5	64.7	1.68	48.8	0
3-Dec	22	54.0	63.0	55.1	63.1	2.09	49.6	0
3-Dec	23	52.7	59.4	53.8	60.4	0.48	51.3	0
3-Dec	24	51.4	57.9	52.3	59.7	0.54	55.1	0
4-Dec	1	49.9	56.0	51.1	58.3	0.17	55.0	0
4-Dec	2	48.8	55.5	49.9	57.5	0.50	56.7	0
4-Dec	3	47.7	55.3	48.8	56.5	1.47	59.1	0
4-Dec	4	46.6	54.4	47.9	56.1	2.63	60.2	0
4-Dec	5	45.7	53.6	46.9	55.1	3.04	63.3	0
4-Dec	6	44.8	51.4	46.5	57.6	1.23	63.1	0
4-Dec	7	44.2	50.7	46.0	58.0	0.91	58.6	0
4-Dec	8	44.0	49.8	46.1	59.6	0.26	57.5	10.742721
4-Dec	9	44.3	50.3	46.7	63.6	2.05	56.1	52.304725
4-Dec	10	46.1	51.8	49.0	66.5	2.72	49.4	90.168414
4-Dec	11	48.1	51.7	52.3	51.1	1.66	45.6	118.34604

APPENDIX D

THERMAL MODEL

(PE) Qrad	(PE) Qconv	(PE) Qcond	(PE) Qsolar	(EX) Qrad	(EX) Qconv	(EX) Qcond	(EX) Qsolar	Emissivity (εsky)	Tsky(F)
218.63	9.61	23.71	0.00	296.92	13.46	23.25	0.00	0.77	10.38
204.06	43.14	26.09	0.00	293.51	57.29	24.25	0.00	0.77	10.38
189.37	8.08	19.93	0.00	292.95	10.02	17.31	0.00	0.77	9.86
181.97	48.31	22.25	0.00	288.50	59.26	19.11	0.00	0.76	9.64
177.70	34.60	20.92	0.00	286.73	40.40	17.10	0.00	0.76	9.54
176.65	32.81	19.84	0.00	286.50	35.36	14.97	0.00	0.76	9.29
178.27	6.44	15.89	0.00	286.45	5.97	10.31	0.00	0.76	8.91
182.21	28.29	17.11	33.53	282.83	26.91	11.39	44.71	0.76	8.91
182.35	13.41	33.08	326.93	280.29	15.24	26.32	435.91	0.75	9.97
191.43	18.46	45.53	639.89	296.58	20.94	36.17	853.19	0.73	10.81
211.06	22.80	56.25	881.60	327.53	25.08	43.30	1175.46	0.74	12.26
233.21	223.24	69.83	1035.28	364.80	241.60	52.90	1380.38	0.71	13.16
269.42	178.29	66.41	1089.77	403.84	188.70	49.20	1453.03	0.71	13.74
297.50	167.61	62.43	1040.87	432.44	176.61	46.05	1387.83	0.72	14.20
324.94	170.66	56.81	892.77	464.97	171.61	39.99	1190.36	0.72	14.31
331.57	154.18	55.15	655.26	460.75	163.10	40.84	873.68	0.72	14.44
329.06	153.61	51.13	345.09	448.96	168.01	39.15	460.13	0.72	14.08
328.00	113.11	42.13	41.91	442.52	120.15	31.33	55.89	0.72	13.35
323.82	76.01	31.10	0.00	430.64	77.92	22.32	0.00	0.73	12.57
312.54	112.68	37.51	0.00	408.30	132.72	30.93	0.00	0.72	12.67
302.09	97.23	36.22	0.00	390.13	119.16	31.07	0.00	0.73	12.34
295.24	79.83	31.09	0.00	378.11	99.41	27.10	0.00	0.73	11.88
293.60	69.70	27.14	0.00	374.27	85.92	23.42	0.00	0.73	11.52
283.50	51.06	23.52	0.00	369.52	61.82	19.93	0.00	0.73	11.19
262.04	75.61	29.45	0.00	357.02	95.37	26.00	0.00	0.73	11.29
243.66	91.64	32.78	0.00	344.83	118.45	29.66	0.00	0.72	11.19
229.62	61.90	30.69	0.00	334.64	79.66	27.64	0.00	0.73	10.92

216.60	89.20	33.23	0.00	324.12	117.62	30.67	0.00	0.73	10.92
206.48	109.56	39.19	0.00	314.62	144.49	36.18	0.00	0.72	10.92
199.01	151.09	47.26	0.00	303.67	201.50	44.12	0.00	0.72	11.26
200.67	104.32	38.86	0.00	300.38	136.52	35.60	0.00	0.72	10.57
202.00	76.59	35.28	32.13	295.80	99.67	32.14	42.85	0.72	10.25
203.85	112.41	48.61	325.53	292.95	147.51	44.66	434.05	0.72	11.19
214.16	190.44	61.39	639.89	307.12	242.25	54.66	853.19	0.72	12.28
234.56	220.21	65.21	882.99	340.59	264.21	54.76	1177.32	0.72	12.89
261.62	209.14	61.93	1036.68	381.60	232.75	48.24	1382.24	0.71	13.16
290.67	172.47	57.41	1092.56	419.60	183.08	42.66	1456.75	0.71	13.51
323.28	164.09	52.90	1045.06	458.63	164.32	37.08	1393.42	0.71	13.85
343.14	158.94	49.72	896.96	478.42	156.12	34.18	1195.95	0.71	14.08
342.58	150.92	50.24	659.45	463.38	163.57	38.12	879.27	0.71	14.08
334.79	122.70	47.79	350.68	445.00	139.93	38.15	467.58	0.71	13.74
321.87	102.59	41.98	44.71	418.89	123.55	35.39	59.61	0.72	13.12
313.39	75.34	32.58	0.00	402.27	92.07	27.87	0.00	0.72	12.28
303.87	65.50	28.33	0.00	387.95	81.26	24.60	0.00	0.72	11.77
295.37	9.71	23.95	0.00	375.13	12.11	20.91	0.00	0.73	11.29
287.68	9.86	24.32	0.00	365.24	12.35	21.32	0.00	0.73	11.11
274.11	61.67	30.58	0.00	351.25	79.61	27.63	0.00	0.73	11.29
262.62	62.58	31.02	0.00	340.27	81.54	28.30	0.00	0.73	11.15
251.72	63.31	31.39	0.00	329.41	83.72	29.06	0.00	0.73	10.96
232.70	64.03	31.74	0.00	319.57	85.14	29.55	0.00	0.73	10.77
216.62	70.19	32.34	0.00	310.33	92.69	29.89	0.00	0.73	10.59
199.10	71.27	32.83	0.00	301.36	93.58	30.17	0.00	0.73	10.40
190.40	60.36	29.93	0.00	295.43	78.32	27.18	0.00	0.73	10.05
178.06	88.57	40.80	0.00	283.90	117.31	37.83	0.00	0.72	10.51
173.92	87.86	40.47	0.00	280.06	113.34	36.55	0.00	0.73	10.36
174.25	61.20	37.01	32.13	276.64	77.39	32.76	42.85	0.73	10.05
175.31	136.48	50.84	325.53	272.63	175.17	45.67	434.05	0.73	10.96
190.14	155.6	57.97	639.8	288.79	192.7	50.27	853.1	0.73	11.70

	2		9		7		9		
210.43	159.45	62.10	884.39	323.78	182.37	49.72	1179.19	0.73	12.34
240.44	155.37	57.88	1039.47	368.89	159.66	41.63	1385.96	0.73	12.74
277.79	113.22	48.97	1095.36	415.37	103.33	31.28	1460.48	0.73	12.90
311.60	82.99	41.15	1047.86	458.41	63.97	22.20	1397.14	0.73	13.06
334.06	74.02	36.70	901.16	481.85	52.83	18.33	1201.54	0.73	13.29
340.67	66.01	39.91	665.04	479.33	56.07	23.73	886.72	0.73	13.67
337.65	63.94	38.66	354.87	462.75	60.93	25.79	473.17	0.73	13.44
330.20	47.17	28.52	46.11	442.77	44.44	18.81	61.47	0.74	12.70
324.47	34.44	20.82	0.00	428.02	30.99	13.12	0.00	0.74	12.03
316.08	8.63	21.28	0.00	413.21	8.55	14.77	0.00	0.74	11.84
307.61	6.72	16.59	0.00	400.88	6.31	10.89	0.00	0.74	11.35
299.39	20.00	12.09	0.00	386.18	18.07	7.65	0.00	0.75	10.89
288.11	29.34	13.52	0.00	370.38	30.39	9.80	0.00	0.75	10.66
278.64	3.71	9.15	0.00	357.21	3.66	6.32	0.00	0.75	10.15
260.73	4.26	10.52	0.00	343.44	4.50	7.78	0.00	0.76	10.02
241.58	18.90	11.43	0.00	332.93	20.18	8.54	0.00	0.75	9.79
223.07	28.65	17.32	0.00	321.34	33.91	14.35	0.00	0.75	9.92
215.70	23.22	14.04	0.00	316.18	26.44	11.19	0.00	0.75	9.54
200.83	35.84	16.51	0.00	309.49	41.08	13.25	0.00	0.74	9.49
194.64	26.57	13.17	0.00	306.82	26.86	9.32	0.00	0.74	9.12
188.34	8.43	20.79	0.00	298.33	9.57	16.53	0.00	0.74	9.49
188.75	8.01	19.76	32.13	295.02	8.78	15.15	42.85	0.74	9.31
194.05	11.29	27.84	325.53	293.35	13.06	22.55	434.05	0.75	9.92
203.11	15.46	38.14	639.89	310.05	17.09	29.51	853.19	0.74	10.79
226.93	97.40	48.29	885.79	342.40	106.38	36.92	1181.05	0.74	11.98
255.51	101.19	50.17	1040.87	380.29	103.90	36.06	1387.83	0.73	12.57
290.89	96.82	44.60	1098.15	429.66	85.53	27.58	1464.20	0.72	12.82
318.85	97.87	48.52	1052.05	463.92	87.11	30.23	1402.73	0.73	13.82
339.35	115.25	49.84	905.35	484.49	106.13	32.13	1207.13	0.72	14.32
348.75	78.25	47.32	669.23	486.29	75.35	31.89	892.31	0.72	14.20
343.02	115.0	49.77	360.4	463.24	126.9	38.42	480.6	0.71	13.94

	9		6		3		2		
334.13	15.19	37.48	48.90	440.86	16.97	29.31	65.20	0.72	13.21
329.54	41.04	24.81	0.00	424.06	45.55	19.28	0.00	0.73	12.23
318.95	11.49	28.36	0.00	407.64	13.82	23.87	0.00	0.73	12.17
312.87	56.67	23.19	0.00	397.06	68.39	19.59	0.00	0.73	11.65
304.55	41.94	20.79	0.00	389.39	48.84	16.95	0.00	0.73	11.29
293.70	48.33	18.82	0.00	377.48	56.62	15.44	0.00	0.73	10.96
286.49	41.86	16.30	0.00	368.60	48.44	13.21	0.00	0.73	10.59
323.24	17.06	8.46	0.00	362.97	14.63	5.08	0.00	0.74	9.97
315.49	18.06	10.92	0.00	355.05	17.31	7.33	0.00	0.74	9.97
304.46	6.91	17.05	0.00	343.52	7.65	13.21	0.00	0.73	10.05
300.61	12.31	6.10	0.00	339.37	6.90	2.40	0.00	0.74	9.22
287.91	40.99	20.32	0.00	326.63	46.34	16.08	0.00	0.72	9.69
282.30	37.71	17.37	0.00	320.73	40.62	13.10	0.00	0.72	9.32
272.63	55.56	25.59	0.00	310.93	65.03	20.97	0.00	0.71	9.55
263.63	81.56	33.37	32.13	300.97	99.91	28.62	42.85	0.71	9.91
258.56	133.96	44.59	325.53	295.84	169.56	39.51	434.05	0.71	10.65
265.80	126.02	46.94	641.29	317.55	145.06	37.82	855.05	0.71	11.04
282.16	117.59	50.85	887.18	349.62	124.57	37.71	1182.91	0.72	11.94
310.27	99.19	49.18	1043.66	393.57	94.17	32.68	1391.55	0.72	12.44
341.87	17.86	44.07	1100.95	441.94	14.07	24.29	1467.93	0.72	12.82
373.65	16.88	41.64	1056.24	476.24	12.99	22.43	1408.32	0.72	13.35
392.79	67.98	41.11	909.54	495.63	53.37	22.59	1212.72	0.71	13.51
394.51	17.49	43.15	674.82	482.26	16.56	28.60	899.76	0.71	13.62
385.39	63.01	38.10	364.65	457.57	64.58	27.34	486.20	0.72	13.35
375.71	47.41	28.67	51.69	436.45	49.04	20.76	68.93	0.73	12.57
367.58	35.24	21.31	0.00	421.51	35.63	15.08	0.00	0.73	11.93
354.73	61.36	30.42	0.00	402.32	73.32	25.45	0.00	0.72	12.11
349.17	7.02	17.32	0.00	396.10	7.26	12.54	0.00	0.73	11.19
339.92	4.17	10.29	0.00	383.92	3.56	6.14	0.00	0.74	10.60
328.54	5.64	13.92	0.00	368.16	6.15	10.62	0.00	0.74	10.56
319.72	18.99	9.42	0.00	357.58	18.53	6.43	0.00	0.74	10.05
310.22	20.42	10.12	0.00	345.41	21.99	7.63	0.00	0.74	9.82
303.10	12.60	7.62	0.00	337.56	12.26	5.19	0.00	0.74	9.44
292.96	30.88	13.36	0.00	326.75	35.47	10.74	0.00	0.74	9.60

284.60	29.86	13.76	0.00	319.94	32.41	10.45	0.00	0.74	9.37
277.50	35.20	13.71	0.00	314.63	35.50	9.68	0.00	0.73	9.17
269.21	33.35	16.53	0.00	307.29	34.40	11.94	0.00	0.73	9.13
263.61	26.41	15.97	0.00	300.87	27.07	11.46	0.00	0.73	8.95
257.97	35.70	15.44	32.13	297.02	33.80	10.23	42.85	0.73	8.78
253.38	62.80	28.93	325.53	292.33	72.51	23.38	434.05	0.73	9.69
257.41	96.39	39.44	642.68	309.09	105.06	30.09	856.91	0.74	10.66
279.56	96.62	41.78	888.58	347.41	94.23	28.53	1184.78	0.73	11.38
302.44	89.01	44.13	1046.46	387.20	77.70	26.96	1395.28	0.73	12.06
336.37	63.74	38.54	1105.14	434.32	45.32	19.18	1473.52	0.72	12.28
368.99	67.15	33.29	1060.43	474.92	37.81	13.12	1413.91	0.72	12.67
391.15	11.78	29.07	915.13	500.20	5.20	8.98	1220.17	0.72	12.82
397.58	64.79	32.12	679.01	499.02	40.96	14.21	905.35	0.72	13.12
394.22	12.48	30.79	370.24	478.63	9.97	17.22	493.66	0.72	12.89
384.97	11.65	28.74	54.49	456.77	10.55	18.21	72.65	0.72	12.52
375.93	8.63	21.29	0.00	438.48	7.53	13.00	0.00	0.73	12.06
369.82	3.36	8.28	0.00	426.23	0.94	1.62	0.00	0.74	11.15
357.81	4.88	12.03	0.00	407.81	3.89	6.72	0.00	0.74	11.12
348.80	17.54	7.59	0.00	394.82	10.50	3.18	0.00	0.74	10.56
337.06	16.37	6.37	0.00	379.26	9.93	2.71	0.00	0.74	10.23
326.95	11.27	4.61	0.00	366.66	4.80	1.38	0.00	0.75	9.92
316.92	17.12	7.89	0.00	354.67	15.14	4.88	0.00	0.75	9.87
310.13	13.11	5.36	0.00	346.73	8.92	2.55	0.00	0.74	9.44
300.59	2.37	5.86	0.00	337.01	1.62	2.79	0.00	0.75	9.35
292.66	12.31	6.10	0.00	329.62	7.68	2.66	0.00	0.74	9.12
285.58	15.44	6.01	0.00	323.41	7.77	2.12	0.00	0.74	8.94
279.01	19.05	8.24	0.00	317.55	12.92	3.91	0.00	0.74	8.90
273.74	12.53	7.58	0.00	312.52	7.17	3.04	0.00	0.74	8.71
267.74	24.42	12.11	32.13	306.53	21.10	7.32	42.85	0.73	8.82
263.66	53.05	22.94	325.53	304.55	56.87	17.22	434.05	0.74	9.60
271.18	65.07	29.97	642.68	323.21	65.49	21.12	856.91	0.74	10.37
290.52	55.08	33.31	889.98	358.66	48.36	20.47	1186.64	0.74	11.08
312.47	73.25	36.32	1049.25	395.20	58.23	20.21	1399.00	0.72	11.60

345.70	12.57	31.00	1107.93	441.02	7.41	12.80	1477.24	0.72	11.82
376.11	10.73	26.47	1064.62	484.56	3.48	6.00	1419.50	0.72	12.21
398.85	36.54	22.09	919.32	507.52	5.87	2.48	1225.76	0.72	12.36
405.72	45.44	22.53	684.60	504.02	16.84	5.85	912.80	0.72	12.52
399.41	56.11	24.26	375.83	480.69	38.84	11.76	501.11	0.72	12.59
386.43	45.09	20.77	57.28	453.62	35.97	11.60	76.38	0.72	12.11
377.99	17.10	8.48	0.00	434.34	6.05	2.10	0.00	0.73	11.19
364.09	6.13	15.13	0.00	413.65	5.84	10.09	0.00	0.73	11.38
352.96	32.57	16.15	0.00	396.86	35.53	12.33	0.00	0.73	11.19
346.71	18.15	8.36	0.00	387.93	16.21	5.23	0.00	0.74	10.50
336.34	28.98	11.86	0.00	375.88	31.02	8.88	0.00	0.73	10.36
327.67	28.12	10.06	0.00	365.58	29.43	7.37	0.00	0.72	9.84
319.19	13.83	5.66	0.00	357.90	9.07	2.60	0.00	0.71	9.22
310.15	21.54	8.82	0.00	347.69	20.31	5.82	0.00	0.70	9.08
300.97	23.52	9.16	0.00	337.54	22.54	6.15	0.00	0.71	9.01
290.59	36.31	14.86	0.00	327.28	39.81	11.40	0.00	0.71	9.22
285.43	15.19	9.18	0.00	322.07	13.40	5.67	0.00	0.71	8.75
279.12	3.53	8.72	0.00	318.48	2.44	4.21	0.00	0.72	8.64
272.52	5.42	13.37	0.00	312.71	4.84	8.35	0.00	0.72	8.78
272.73	3.40	8.40	32.13	315.95	1.49	2.57	42.85	0.72	8.47
271.52	31.90	15.82	325.53	317.21	26.18	9.09	434.05	0.73	9.10
282.77	47.47	21.87	644.08	334.44	42.42	13.68	858.78	0.72	9.76
294.36	106.49	35.45	892.77	358.37	102.94	23.99	1190.36	0.71	10.76