2009

Empirically derived formulas to predict indoor maximum, average, and minimum temperatures in roofpond buildings using minimum climatic information

Ibrahim Kivarkis Kako
University of Nevada Las Vegas

EMPIRICALLY DERIVED FORMULAS TO PREDICT INDOOR MAXIMUM, AVERAGE, AND MINIMUM TEMPERATURES IN ROOFPOND BUILDINGS USING MINIMUM CLIMATIC INFORMATION

by

Ibrahim Kivarkis Kako

Bachelor of Science in Architecture
University of Nevada, Las Vegas
2006

A thesis submitted in partial fulfillment of
the requirements for the

Master of Architecture Degree
School of Architecture
College of Fine Arts

Graduate College
University of Nevada, Las Vegas
December 2009

THE GRADUATE COLLEGE

We recommend that the thesis prepared under our supervision by

Ibrahim Kivarkis Kako

entitled

Empirically Derived Formulas to Predict Indoor Maximum, Average, and Minimum Temperatures in Roofpond Buildings Using Minimum Climatic Information

be accepted in partial fulfillment of the requirements for the degree of

Master of Architecture
School of Architecture

Alfredo Fernandez-Gonzalez, Committee Chair

Robert Dorgan, Committee Member

Daniel Ortega, Committee Member

Robert Boehm, Graduate Faculty Representative

Ronald Smith, Ph. D., Vice President for Research and Graduate Studies
and Dean of the Graduate College

December 2009

ABSTRACT

Empirically Derived Formulas to Predict Indoor Maximum, Average, and Minimum Temperatures in Roofpond Buildings Using Minimum Climatic Information

By

Ibrahim Kivarkis Kako

Alfredo Fernández-González, Examination Committee Chair
Associate Professor of Architecture
University of Nevada, Las Vegas

This thesis introduces an empirically developed formula to predict the comfort conditions and thermal performance of a Skytherm™ Southwest Roofpond placed over a light-weight un-insulated structure built at the School of Architecture at the University of Nevada, Las Vegas.

The predictive formula introduced in this study may be used in different parts of the world (particularly developing nations where insulation and air-conditioning are rarely used) to predict the performance of a Skytherm™ Southwest Roofpond using minimal climate data.

The data collected in the experimental setup at the Natural Energies Advanced Technologies Laboratory included outside and inside temperatures of various surfaces of two different test cells built on the site (i.e. a Skytherm™ Southwest Roofpond test cell and a control room). For the purposes of this thesis, only outdoor climatic data and indoor air and ceiling temperatures were used to analyze the performance of the system. The period covered by this study was October of 2004 through September of 2006 and March of 2009 through October of 2009.

The predictive formula developed in this study may be used along with similarly developed formulas to identify and suggest the most appropriate locations for the installation of the roofpond system.

ACKNOWLEDGEMENTS

Foremost, I want to express my deepest gratitude and sincere appreciation to Professor Alfredo Fernández-González. I am very grateful for the last five years that I have been giving the opportunity by Professor Fernández-González to be part of Natural Advanced Technologies Laboratory (NEAT) team at the UNLV School of Architecture to serve under his guidance, expertise, foresight, and his long patience in trusting and believing in me. Word can't describe my appreciation for Professor Fernández-González for his contributions and hard work to complete this thesis.

I would also like to express my gratitude and appreciation to Dr. Baruch Givoni for his contributions in development of the predicting formulas for all the passive solar system strategies and the powerful knowledge that I have gain from studying his work.

I would also like to thank Mr. Harold Hay for his conurbation and invention of the roofpond system that I believe it will change our future.

A special thanks for Daniel Overbey for inspiring me to finish my work and looking up to him for gaudiness. Also special thanks for Ahmet Ugursal for his hard work here at UNLV during the development of the roofpond project here at UNLV School of Architecture.

Finally, I would like to extend my gratitude to all my friends and classmate that have been involved in one way or another in the development of this thesis and the encouragement that all of you have given me thank you.

DEDICATION

TO MY FATHER: KIVARKIS ORAHAM KAKO (1945-1995) R.I.P

I dedicate this thesis to my beloved father whom I have always wished to be alive to this day to see my accomplishment. Thank you for making me who I am, I love you dad!

TO MY MOTHER: JULIETTE MARBINA

I dedicate this thesis to my loving, grateful mother I have. For all the unconditional love you have giving me all my life with all the support and encouragement you have brought to my life, thank you mom and I love you!

TO MY SISTERS: SCARLET KAKO AND SUHA KAKO

This thesis is dedicated to my wonderful sisters, Scarlet and Suha, who have made me to be the person I am today. You have been with me every step of the way, through good times and bad. Thank you for all the unconditional love, guidance, and support that you have always given me, helping me to succeed and giving me the confidence that I am capable of doing anything I put my mind to. Thank you for everything. I love you!

TO MY GRANDPARENTS: MARBINA MARBINA AND MARGO MARBINA

Finally, I would like to dedicate this thesis to my grandparents for the opportunity that they gave me and my family thank you and I love you!

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CHAPTER 1

INTRODUCTION

Issues our Society is Facing

Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (Bruntland, 1987). Sustainability is more than a compromise, it can also be determined as a natural approach to maintain ecological processes and functions, which, in turn will help to balance different ecosystems. Sustainability represents many professions such as science, chemistry, engineering and architecture, to name a few, working together to make sure our planet is in constant balance. These scientists and scholars research new methods of creating products that are cleaner and more environmentally friendly for humans. Architecture is deeply involved with sustainability due to the fact that 35 percent of the energy is traditionally consumed by buildings (Reynolds, 2001) and more recent data put together by Edward Mazria for Architecture 2030 shows that building energy consumption has gone up to 48 percent (Mazria),(Fig. 1.1). The United States is experiencing an intense growth, as seen in the development of cities through upward construction and urban sprawl, for example. But this intensive growth has also brought about many negative, albeit unintended, consequences such as deforestation, land degradation, and shortage of water. Sustainable architecture focuses on issues that concern with the environment, such as improving the design and construction of building. Sustainable architecture also trains architects to tackle issues that are critical in the designing of buildings, communities and cities.

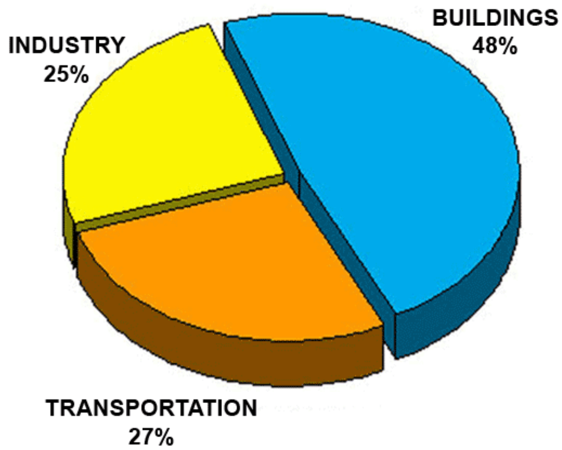


Figure 1.1 US Energy Consumption
(Source: Architecutre2030.com)

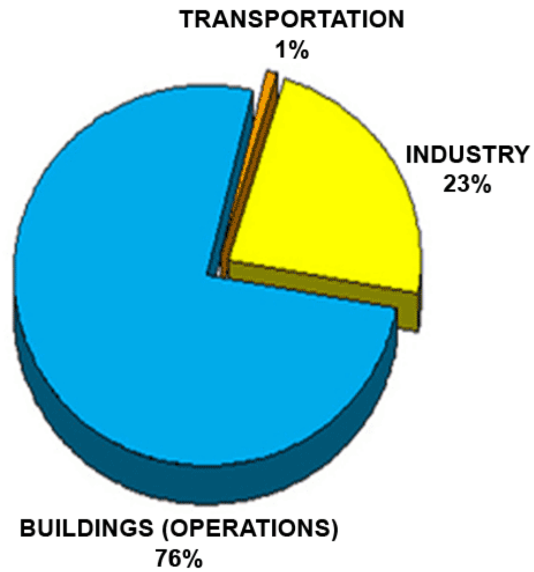


Figure 1.2 US Electricity Consumption
(Source: Architecutre2030.com)

Buildings need energy to function and provide comfort to their users. In today's urban environment buildings function to provide comfort at the expense of our environment. The source of most of the energy comes mainly from fossil fuels such as oil, gas, and coal (Smith, 2001). While these natural resources provide great source of energy, human use of these non-renewable materials has contributed to the current climatic changes of the planet. The burning of fossil fuels adds more carbon to the atmosphere and creates a greenhouse effect, which warms the earth's surface (Smith, 2001). By burning fossil fuels, humans alter the natural carbon cycle by adding 6 billion tons of carbon to the earth's atmosphere per year (Smith, 2001) (Fig. 1.3). Sustainable architecture offers a new way in which humans construct their built environment; a clean built environment in which buildings contribute to the regeneration of our planet Earth.

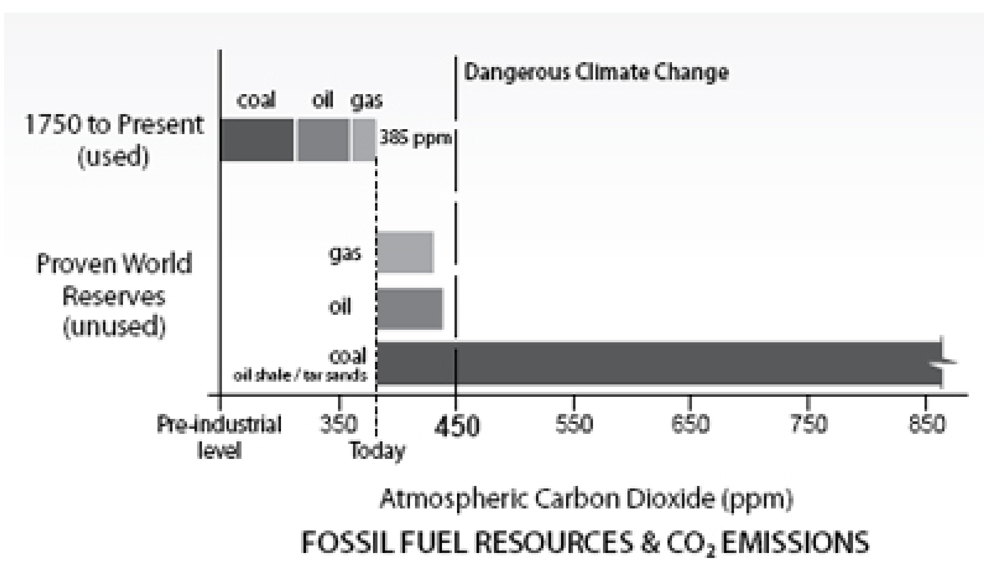


Figure 1.3 Fossil Fuel Resources & CO_2 Emissions
(Source: Architecutre2030.com)

Architects have come to the conclusion that most of the energy used by buildings goes to cooling and heating purposes (Fig. 1.2). Mechanical cooling and heating units use billions of kilowatts of energy to maintain comfortable indoor temperatures. Since the Industrial Revolution and well into the second half of the 20^{th} century, architecture was not as concerned with the consumption of energy because energy was cheap and believe to be abundant (Maiellaro, 2002). As a result of this thinking, designs did not need to meet any simple environmental basics such as shading, natural ventilation, heat storage, and other principles that have been used for thousands of years (Gissen, 2003). Even though buildings have evolved to become better spaces, buildings still function with technology that was conceived forty years ago. For example, air conditioning and heating units still run on the same principle since it was invented in early 20^{th} century (Maiellaro, 2002). With the rise of environmental awareness and the human impact on our environment, which includes our dependence on non-renewable energy sources frequently located outside of our national borders, architects and other building professionals in the US and elsewhere have realized that we must design structures that are less dependent on fossil fuels.

The first priority is to design and build buildings that are energy efficient. There are many different ways to address the issue of buildings depending on fossil fuels, for example designing buildings that use a renewable source of energy, such as the solar energy. Solar energy is an abundant source that architects have omitted from their designs due to several reasons such as high cost and material availability. For example, photovoltaic panels are a great way to collect solar energy and convert it to electrical energy. Even though there is the technological infrastructure available, today only a very small percentage of buildings use such technology due to its high cost. Researchers have demonstrated, however, that despite the high initial cost of these technologies, passive solar heating works and is cost effective in the long run (Balcomb 1992).

Nature offers an immense variety of resources for architects to manipulate and integrate within the buildings. Renewable natural resources such as sun, wind, and light are currently not being utilized fully by architects. With advent of the air conditioning, architects were able to design buildings which did not take into consideration important factors such as site orientation and materials used, for instance.

One of the main challenges of sustainability is that our society does not have the mindset to think about our environment when consuming energy. The first step towards a sustainable world is to teach our generation that our energy choices have direct consequences on our environment. We can choose to burn coal until the last ton is extracted, or we can choose to harness energy from the sun and convert it into clean electrical energy. If given the opportunity, we can choose to recycle the solid waste and treat gray water in our homes.

Sustainable architecture is one of the many professions that can contribute towards a more sustainable world. Humans can live more environmentally conscious lives in harmony with nature, but at the moment there are other capitalistic interests in our society that have not let this new age to evolve. Our planet is run by capitalist corporations whose financial interests take into consideration neither the environment nor the human beings. Fortunately, enough people are being more conscious about our environment and are developing measures to address these critical issues; engineers, chemists, scientists and architects, among many others, are inventing new ways to live healthier and "lighter" (environmentally speaking) on our planet. Our environment is the responsibility of all humans and both the wealthy and the poor nations need to show their commitment to improve the lives of all while conserving our environment for the generations to come. The technologies and resources are available for us to either destroy or to help improve our environment. Sustainable architecture is just one way in which architects can contribute to the improvement of the environment using different technologies and methods available in today's world.

Sustainable architecture should be taken more into consideration by the new age architects; buildings that are built sustainable will provide a sense of comfort and be more energy efficient. When we talk about sustainable architecture, we refer to the new way of designing buildings in which the building itself is not only energy efficient but it is also more adaptable and responsive to its respective region. A society is considered sustainable when its members' needs are fulfilled without compromising the needs of the generations to come. In such environment, people reuse, preserve and restore conscious of the benefits that can derive in present and future. As Lechner explains in his book "heating, cooling, and lighting: a design is sustainable when architects try to apply the four R’s into their design, Reuse, Recycle, Reduce, and Regenerate.” (Lechner 2001, p. 13)

With the term Reuse, we refer to the event of utilizing something again and again, maintaining its integrity in structure and material; there is no destruction and reproduction. When a building is reused, its shell usually remains intact or it is partially renovated, in order to better its habitability. Factors such as natural lighting, efficient cooling and heating systems are kept in consideration in the renovation process, and the building becomes more suitable for new use, without wasting any materials. In the event of Recycling instead, the actual structural elements are deconstructed and they become reusable individually as building materials, such as concrete, wood, steel, etc. Such materials would require a great amount of energy if they had to be produced from scratch.

Furthermore, Reduce is another important factor of sustainable design. The key is in reducing the amount of energy needed for the functioning and life of the building through cooling, heating and lighting the space with natural and more conservative strategies. Last but not least, Regenerative design is the ultimate option for a more environmental architecture; through regeneration, the building becomes a machine able to maintain itself collaborating with nature in the creation of an environment that continuously regenerates without the use of new resources. This option represents a step beyond sustainability and it is not yet accepted by society because of its controversial philosophy of creating life from waste.

Therefore, Reducing remains the ultimate answer to sustainable architecture in its capability to incorporate factors so important such as lighting, cooling and heating at the very early stages of the design of a building.

Upon the above mentioned factors depends the life of a building, its inhabitants and the surroundings. Lighting can be both artificial and natural. Artificial lighting can create great dramatic special experiences with its multifaceted properties in color, ambiance and direction and this is definitely a plus if we strictly think about design features. In actuality, artificial lighting requires the extensive use of energy and, in addition, it heats up the building. The heat generated from artificial lighting can actually be beneficial if used wisely during the cold periods of the year. Therefore, the use of artificial lighting does not need to be avoided but it has to integrate the use of natural lighting resources.

This is when the importance of sun orientation and its radiated light comes into play. In order to get the best lighting, most of the building windows have to face north because the sun is angled in a way that only indirect light is radiated at such orientation. Although, using proper shading devices blocking the south lighting, which is the direct light and the strongest in heating qualities, can bring a good source of lighting into the space when used efficiently. “For most climates and many building types, day lighting can save energy. For example, a typical office building in southern California can reduce its energy consumption 20 percent by using day lighting”(Lechner 2001, p 46).

Cooling is another key element in this equation. The rule of thumb for proper cooling is to shade before you cool; as Lechner states, “shading is the key strategy of achieving thermal comfort” (Lechner 2001, p 207). Orientation is critical when designing shading devices; for example, horizontal overhangs over windows located on the south side are very effective during the summer. These devices block direct sun light from coming into the building but simultaneously allow diffuse light to reach the building openings. Assuming that shading is appropriately used, cooling is then the next step. Depending on the location of the site, a building can be cooled with many different sustainable strategies.

For example, Las Vegas, NV is located in a region with limitless methods that can be used to create a very comfort place yet have minimal effect on the climate and the environment. This means that its climate “is characterized by extremely hot and dry summers and moderately cold winters. The skies are clear most of the year…;” (Lechner 2001, p.102). In order to cool a building in such climate different strategies can be used, such as thermal mass, stack ventilation, evaporative cooling, roofpond, and others.

Thermal mass consists of a thick massive separation between outside and inside, which can be made of water, concrete, adobe, rammed earth, or other vernacular materials. This wall structure blocks the sun radiation from penetrating the building and heating up the interior spaces. Stack ventilation is a method through which the hot air present in a room is attracted toward the ceiling and outside of the building. This event is possible with the use of a metallic surface above the ceiling structure which, when heated up, sucks the warm air out of the room.

Evaporative cooling is another very effective strategy. In dry climates the evaporation of water is used to cool the ambient. In his book, Ed Melet classifies evaporative cooling into two main categories: “direct evaporation and indirect evaporative cooling. In direct evaporation, water is sprayed into the air entering the building. This lowers the air’s temperature but raises its humidity.” (Melet 1999, p. 115). On the other hand, in indirect evaporative cooling, the evaporation cools either the building or the incoming air without changing the level of indoor humidity, for example the use of a roofpond system.

Additionally, heating is another factor that influences the amount of energy used in a building. In heating strategies, insulation is the most used method. Through insulation, the air is trapped inside the walls of the structure; there are no gaps for the cold air to enter and the warm air to exit the space. As Elizabeth Wilhide suggests in her book, “ideally, that heating, as well the domestic power supply, should come from a renewable source, such as wind, wave, tidal, or solar energy” (Wilhide 2003, p.32). Such methods are very effective in dry and hot climates such as the one in Las Vegas and surroundings, but every region has different strategies that can be combined to both cool and heat buildings without the waste of energy.

These are the foundations for Sustainable Architecture and all of them represent great ideas and solutions, but they will only remain as such unless architects and designers decide to take a more aggressive approach to the issue of environmental degradation and begin to apply these rules to their creations.

There are many reasons why sustainable architecture is not accepted in our society, such as cost, psychological issues, and the fact that architects are not responsive to the matter.

First of all, the cost of building materials used in sustainable design is still very high on the market, due to the fact that not many manufactures are yet producing such materials and if they are it is just on an experimental level. Therefore, since the industry offer is not wide spread, the price is considerably high.

In regards to psychological factors, people have always seen and thought of sustainable architecture as the creation of spaces that are uncomfortable and unpleasant, believing that they would lose the commodities such as air conditioning and heating. Architects, on the other hand, do not actively respond to the issue. This is due to their lack of knowledge in the subject which keeps them from being able to design using sustainable methods. Additionally, the thirst for money and fame takes over their reason for designing. As Stanley Port states, “most architects believe that the solutions are known and straightforward, and that their implementation requires only an act or will and the commitment of a few extra dollars” (Port 1989, p. 83). This leads the architects to rely on mechanical systems to maintain the comfort of the building, using great amounts of energy at the expense of the environment.

Finally, a change in the attitude with which architects approach design and sustainability is at the base of the possible solution. Architecture shapes spaces, but more importantly it affects people and feelings. Ultimately, what will influence society perception of sustainable architecture is in the hands of architects and their will to better our environment and create spaces that will provide a better sense of comfort and be more energy efficient.

With this in mind, both our present generation and the ones to come will benefit from such approaches and our environment will be more sound and stable. Herein lay the foundation for Sustainable Architecture.

Roofpond Fundamentals

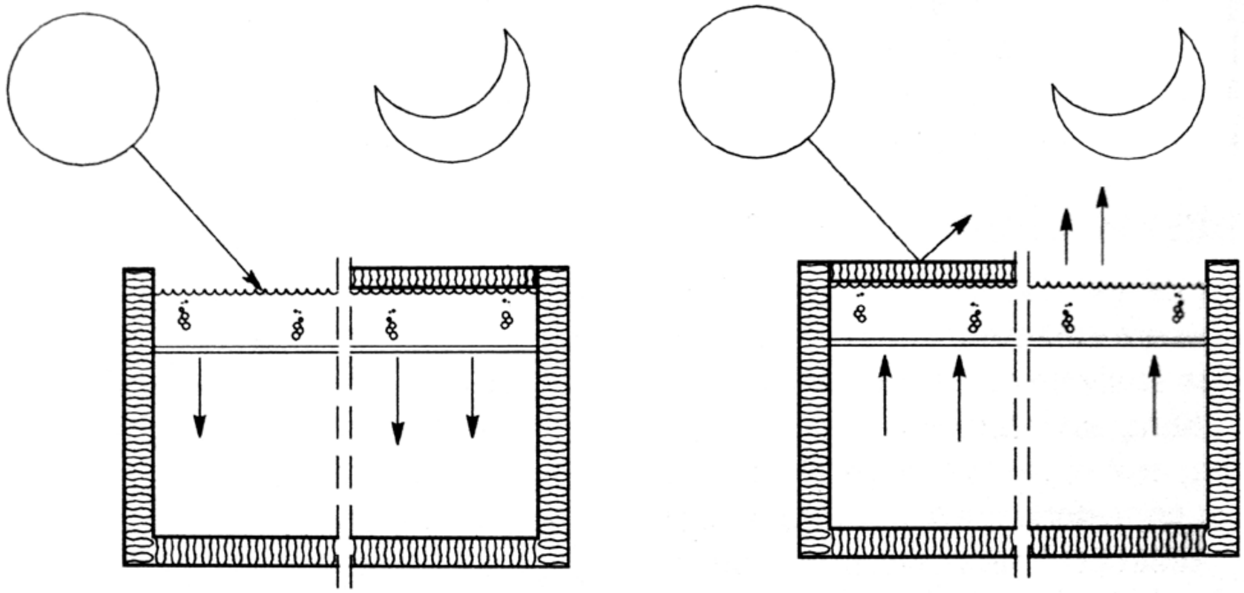
The experimental results obtained from the research project investigating the heating and cooling potential of roofpond in Las Vegas and the Southwest climates. In the experiment the control test cell and the roofpond test cell were extensively monitored to better understand the role that each of the roofpond components (the water bag and the movable insulation) play role in the heat transfer process between the experiment and the surroundings. As the roofpond strategy is known it's the one of the only passive strategy that works for cooling and heating because it mimics the ways in which nature tempers and controls the earth's climate. Therefore, the roofpond can be categorized as a two operational system one," Heating Mode" for the cold seasons, and one for "Cooling Mode" for the hot seasons.

Roofpond Heating Mode

The roofpond in its heating mode (Fig. 1.4a), solar radiation heats a body of water covering the roof. If there isn't enough solar radiation during the day, movable insulation will covers the body of water acting much in the same way as a cloud cover that minimizes the radiation losses to the sky. Similarly, at night the movable insulation helps minimize heat losses so that the energy collected during the day remains in the water bag so that it can be radiated to the space below the roofpond (Brown and DeKay 2000; Haggard et al. 1975; Hay 1984; Overbey 2007).

Roofpond Cooling Mode

In its cooling mode (Fig. 1.4b), the movable insulation covers the water bag during the daytime to avoid undesirable solar gains. At night, the roofpond will act just the opposite mimicking exactly how nature does it planet atmosphere will re-radiate the heat back to the space. Therefore, the roofpond radiates the heat to the sky that was absorbed and accumulated from the inside of the space during the daytime (Brown and DeKay 2000; Haggard et al. 1975; Hay 1984; Overbey 2007).



(a) (b)

Figure 1.4 Diagrammatic Section of a Roofpond Under
(a) Heating Mode and (b) Cooling Mode
(Source: Ramsey et al. 2000 / Overbey 2007)

Purpose of the Research

The purpose of this research is to develop predicting formulas for the roofpond to examine its performance in different parts of Nevada and the southwest region of the United States and its climates. The outcomes of this research will also be viable for other parts of the United States and even other parts of the world. The research will look at different formulas that already have been used to predict other passive heating and cooling systems such as direct gain, sunspace, trombe-wall, water-wall and roofpond. In addition, other roofpond predicting formulas will be developed from the data collected from the two test cells at the NEAT Lab at UNLV. The data have been collected from the research in two phases: in the first phase, the test cell walls were left without insulation, and in the second phase the test cells were equipped with 2 inches aluminum sheeted rigid insulation with 1.5 inches air gap on both sides of the rigid insulation. Different part of Nevada (cities and towns) will be selected to test each formula with the local climate to come up with the ideal roofpond system that will fit the area and the climate for the best performance. The research will conclude with a discussion on the future use of the predicting formulas for the roofpond and how these could be used throughout the different parts of the world and in all the different climates zones.

CHAPTER 2

LITERATURE REVIEW

Roofpond Brief History

The concept of the "roofpond" system has been used throughout the past two centuries. As mentioned in the Department of Energy (DOE) Roof Pond Systems Report "many 19th century structures exist that incorporated it, such as Colonel Joshua Yong's "Sebastopol House" built in the 1850 in Seguin, Texas" (Marlatt et al., p. 2-1).

According to Harold R. Hay, inventor of the roofpond system, the present energy and pollution crises necessitates the development of practical methods for heating and cooling buildings (Hay, p.3). While Hay's statement is relevant today, he stated this back in the 1970s, anticipating the same problem we are still facing over thirty years later today. We have advanced building technologies over the past three decades, yet our buildings use more energy per dwelling in spite of being more efficient. It is clear that we are in desperate need of action to better the way in which we heat and cool our buildings. The roof pond concept has been the only passive system that can be used to heat and cool buildings. The roof pond is an excellent system because it not only heats passively in winter but can also give effective passive cooling in the summer" (Lechner, p.166). "In many respects thermal storage roofs (roofponds) are similar to thermal storage walls: the collector and heat storage are part of the same unit" (Balcomb et al., p. C4-194).

Roofpond Types and Uses

Different types of roofpond have been developed to achieve the maximum performance level in different climatic regions. However, all the different roofpond types have the same fundamental principles yet they differ in the configuration of the roof assemblies to accommodate climatic locations and reach the highest performance level possible for passively heating and cooling. As mentioned by Marlatt a roofpond can be classified in three different system types Dry, Wet, and Open:

- Dry roof pond: a roof pond system in which the water is contained in plastic bags, and no water is exposed to the environment. This type of roof pond may or may not be glazed and is adaptable to both heating and cooling applications.
- Wet roof pond: a roof pond system in which water is contained in bags which are flooded or sprayed so that the surfaces of the bags are wetted. This type of roof pond is used only for cooling purposes, but may be adaptable for heating if the water is covering the surface is drained.
- Open roof pond: a roof pond system in which the water is not contained in bags but exists as an open pool within the boundaries of the roof parapet. This type of roof pond is used only for cooling applications. (Marlatt et al., p. 1-3).

The three characteristic of the roofpond system can be configured structurally in two different ways. The configurations are based on the construction methods to accommodate the climatic location. Therefore, the roofpond can be configured as a two operational system one, for warmer climate which it’s called the “Southwest Application” (Fig. 2.1) and one used for the colder climate which it’s called “North Application” (Fig. 2.2). The roofpond Southwest application is usually constructed with a flat roof with the water bags placed on top of the roof. The water bags are covered by movable insulation. The roofpond North application follows the same principles as the Southwest yet the only different is the water bag is house within the attic area with the glazing on the south side of the sloping roof for the solar radiation exposure requirement. As stated in the Marlatt Report:

- Exposed roof pond: A roof pond system in which the movable insulating panels are the only barrier between the pond and the environment, this configuration is used in both heating and cooling application. Any one of the three types of roof ponds mentioned above may be employed with this configuration.
- Enclosed roof pond: A roof pond system that is totally enclosed in an attic space with a clerestory-type roof, in which the clerestory is a permanent barrier between the ponds and the environments, this configuration is mainly used in applications where heating loads predominate and primarily dry roof ponds are employed. (Marlatt et al., p. 1-3).

There are several other types of roofs that use water to passively heat or cool the space under it; however, they are not related to the roofpond systems described. As explained in greater details in the US Department of Energy (DOE) Roof Pond Systems Report there are other roof system types that uses water for heating and cooling such as: “The Energy Roof, Skybird, Cool pool, Water-retaining roof, trickle roof, and Intermittent Water Spray” (Marlatt et al., p. 1-5, 6), which are not covered in this thesis.

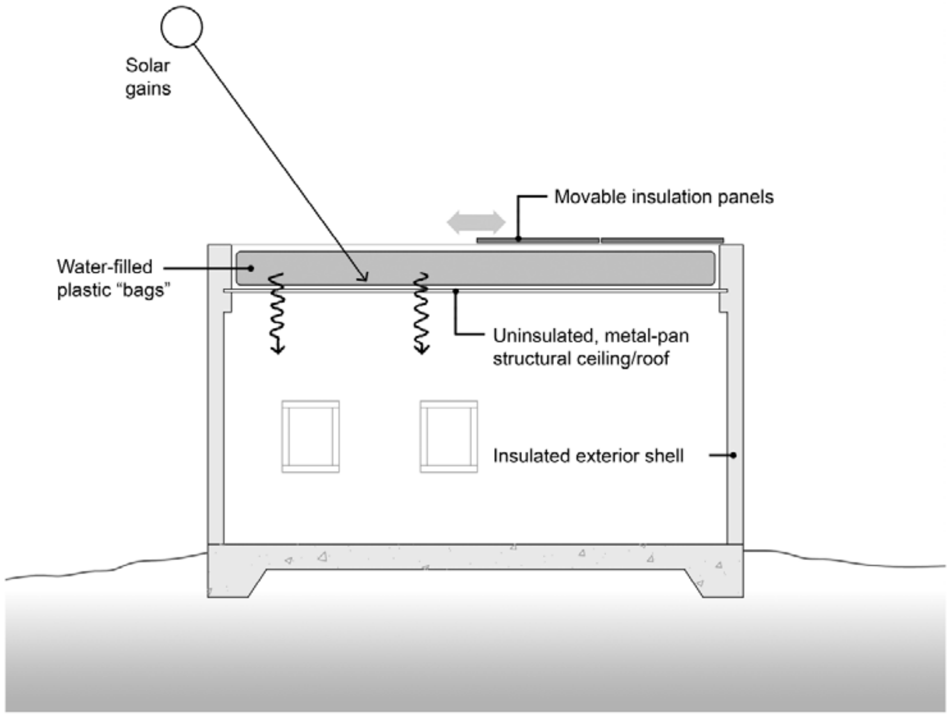


Figure 2.1 Diagrammatic Section of a Roofpond System
(Southwest Application)
Illustration by Daniel J. Overbey

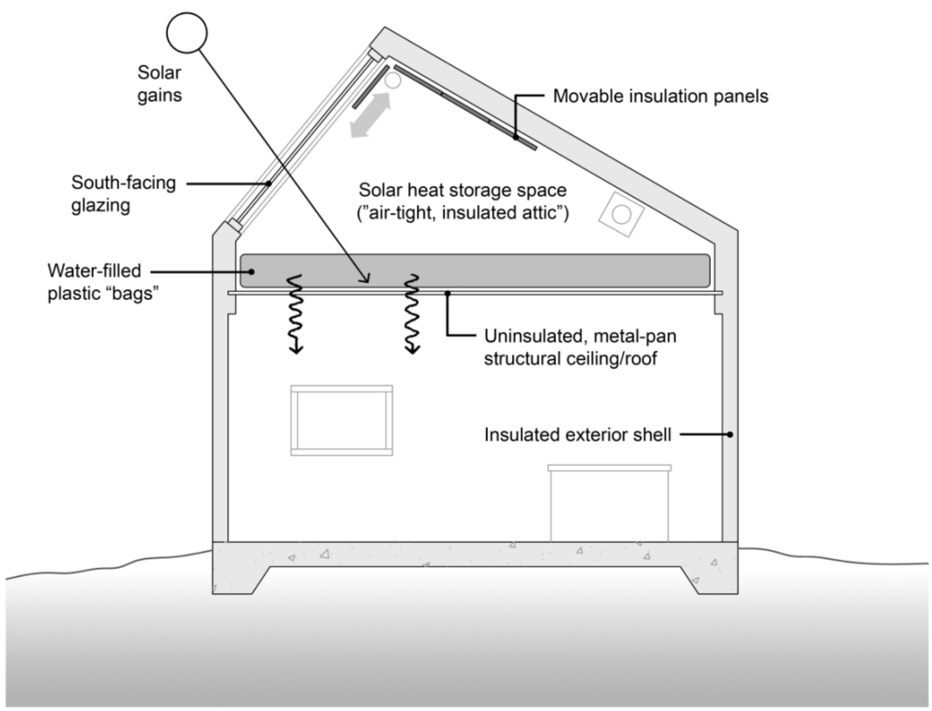


Figure 2.2 Diagrammatic Section of a Roofpond System
(North Application)
Illustration by Daniel J. Overbey

Roofpond Implementation

Over the past four decades, the few buildings with roofpond were built in the U.S in spite of the effectiveness the system. Several examples will be presented to show how well roofponds have performed for heating and cooling in different climates and regions. As Marlatt mentioned "Results have shown that this system, with minor modification discovered through this evaluation, is workable from an architectural, a thermal, an economic, and an occupancy standpoints at the present time, and that this system could play an important role in energy conservation in the United States without further prototype development" (p. 2-2).

The information provided below about the roofpond prototypes are described in greater detail in the US Department of Energy (DOE) Roof Pond Systems Report. A summary for each of the prototypes reported in Marlat 1984 and Fernandez Overbey 2007 is provided below.

Phoenix Prototype

In 1967 through 1968 the Phoenix prototype was constructed by Harold R. Hay and John E. Yellott at Arizona State University in Phoenix, AZ (Fig. 2.3). The Phoenix prototype was a 120 ft^2 test-cell structure, and was the first evaluation of the "southwest" roofpond system application. The result of a full year of monitoring the prototype indicated that the building performance without supplementary heating and cooling was excellent, maintaining the air temperature inside the building between 68 ºF to 82 ºF where the outdoor ambient air temperature spanned from subfreezing to over 110 ºF (Fig. 2.4), (Hay 1984, 1989; Marlatt 1984; Givoni 1994; Fernandez Overbey 2007).

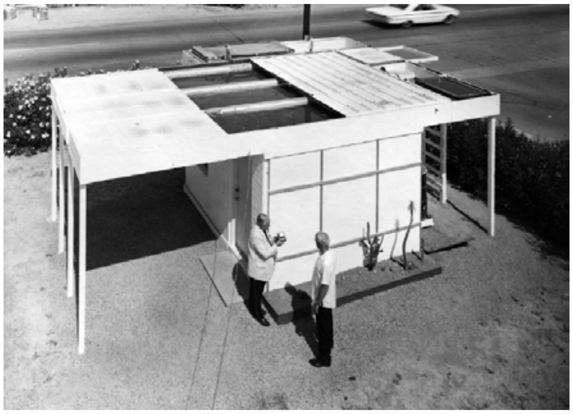


Figure 2.3 Harold Hay and John Yellott standing before the Phoenix prototype
(Source: Hay and Yellott, 1968)

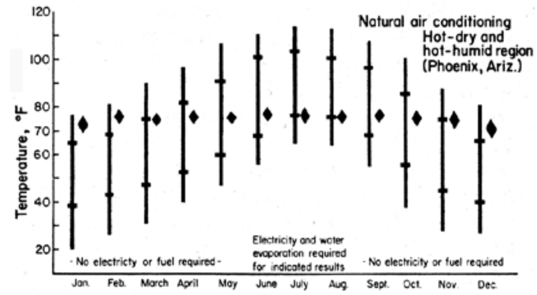


Figure 2.4 Thermal performance data of the Phoenix prototype
(Source: Hay and Yellott, 1968)

Atascadero House

As described by Overbey "The 100% Natural thermal comfort provided by the Phoenix prototype was later confirmed by the Atascadero House (Fig. 2.5), built in 1973 (Haggard et al. 1975; Hay 1989)" (p.57). This project was constructed and evaluated by the California Polytechnic State University for its performance. However, in the Marlatt Report majority of the evaluation was for its heating performance due to the climatic location of the house where the temperatures are extreme in the winter season and are in the comfort level in the summer season. As mentioned by Givoni "So, in practice, just the thermal mass of the water and the walls, even if insulated by fixed insulation, could maintain a comfortable indoor temperature most of the time under the climatic conditions of the site" (p. 103). During the cooling season where electricity was not used at all the system performance averaged 72 ºF all of the summer season. Also in the winter, for the heating seasoned "supplemental space heating" was not used to achieve indoor temperature between 66 and 74 ºF (Fig. 2.6), (Marlatt 1984; Givoni 1994)

Figure 2.5 The Atascadero residence
(Photograph: John Reynolds)

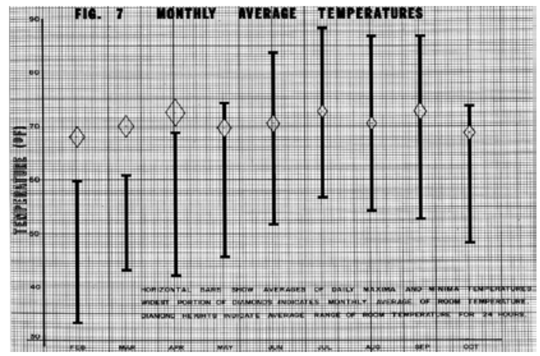


Figure 2.6 Year long record of internal temperatures versus outdoor conditions at the Atascadero residence
(source: Haggard, et al., 1975)

<u>Pala Passive Solar Project</u>

The Pala Passive Solar Project consisted of eight side-by-side test cell. Seven of the test cell incorporated different passive heating and cooling strategies: roofpond (Fig. 2.7), direct gain, clerestory direct gain, high-mass concrete walls, trombe-wall, water wall, and sun space. However, the eighth cell was constructed to be the "conventional" cell to serve as a comparison to the other seven cells (Clinton 1984; San Diego Gas & Electric and Southern California Gas Company 1981). The project data was collected and monitored starting from early 1981 and ran through middle of 1984. The project concluded and verified the effectiveness of such systems to be used in mild climate such as Pala, CA would reduce the heating and cooling cost by up to 50 to 75 % annually (Fig. 2.8), (Clinton 1984; Overbey 2007).

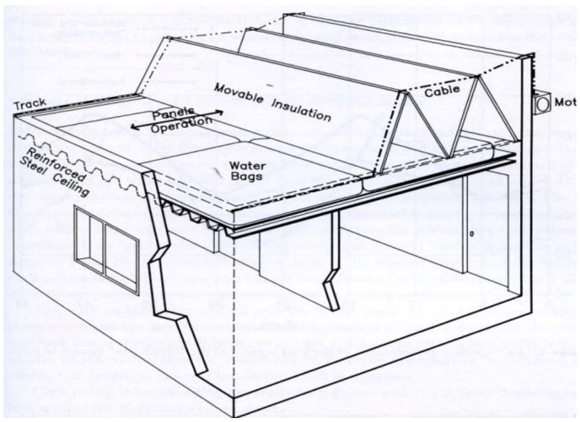


Figure 2.7 The Pala Version of the "skytherm" system
(source Givoni 1994)

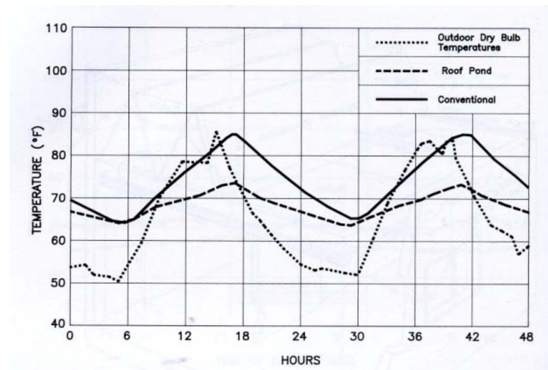


Figure 2.8 Cooling Performance of the Pala version of the "Skytherm" system
(source: Givoni 1994)

Ball State University Passive Solar Project

In 2002 a similar project to Pala Passive solar Project was conducted at Ball State University in Muncie, Indiana (Fig. 2.9) with multiple test cells looking at different strategies such as direct gain, trombe-wall, water-wall, sunspace, and roofpond; however, this project only looked at the effectiveness of the system in heating due to the nature of the cold climate of Muncie, IN. The north application of the roofpond was used in this project due to the annual snow fall in this region. Where, north application it differs from the typical flat roofpond is the water bag (thermal mass) is located under the pitched roof housed within the attic where the south facing side of the roof is equipped with clerestory and an operative garage door is also housed within the attic act as a movable insulation and block the clerestory when needed. The project's results concluded that all systems where effective for heating with the roofpond being the most effective during prolonged overcast periods typical of many winter locations in the continental U.S as stated by Fernandez-Gonzalez "given the experimental results obtained in the first phase of this research project, it would be fair to say that the thermal stability of the RP [Roofpond] can be compared with that of a mechanically air-conditioned building" (p.592). Also the result of this project concluded the combination of the roofpond system and one of the passive systems mentioned above would serve at its highest performance needed in such climate zone (Fig. 2.10), (Fernandez-Gonzalez, 2007).

Figure 2.9 View of the six test cells from the east during the second phase
(Source: UNLV NEAT Lab)

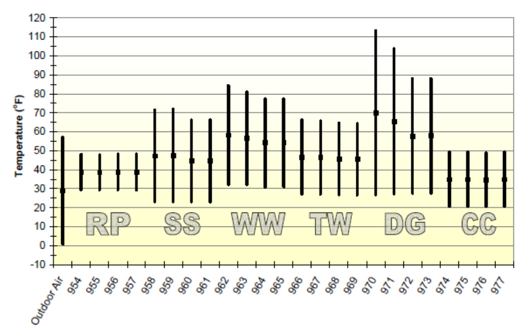


Figure 2.10 Extreme and mean conditions found during the 60-day study
(Source: UNLV Neat Lab)

Roofpond Issues

The performance results for the roofpond system are when compared to other passive strategies and it has proven over the years to have the biggest advantages over the other systems due to its high mass heating and cooling capabilities. However, the roofpond system had struggled with many issues on the operational and standardization side of the system hindering its common uses. One of the major problems the roofpond system encountered over the years was the movable insulation operation. As stated by Givioni “the Main problem encountered with the various variations of the Skytherm system [Roofpond system] seems to concern the movable insulation” (p. 107). Also stated by Clinton “uncertain reliability of operation of the movable insulation” (Clinton 1984; Givoni 1994). However, Professor Alfredo Fernandez-Gonzalez while teaching at Ball State University during his research in 2002, he introduced the use of insulated garage door in place of the movable insulation due to the low cost of the product, its availability of different component with options for modification to fit the need of the system requirement, and the reliability of the technology due to its massive use in almost every house hold.

Description of Predicting Formulas

A generalized mathematical model for predicting indoor temperature can be developed using either the climatic data or the thermal properties of the building (Givoni 1999). Givoni has developed simple experimental predictive formulas to measure indoor maximum, average and minimum temperature based on the climatic data measured extensively in Pala, southern California. He demonstrated that indoor maximum and daily average temperatures of any unoccupied and specific building type can be predicted on the basis of only the daily outdoor temperatures (Givoni 1994). Givoni tested different numbers of climatic parameters in the derivation of a set of predictive formulas and found adding daily solar energy data did not add greatly to the prediction accuracy. In fact, the most important climatic parameter in predicting the indoor maximum, under various conditions (shading, ventilation, envelope color), was found to be the outdoor daily average temperature (Givoni 2004). Givoni further evaluated the agreement between the measured and the computed temperatures with the various climatic parameters used in the derivation by statistical correlation (Fig. 2.11). Using the outdoor temperatures alone resulted in a correlation of 0.9674 while adding the solar radiation date established a correlation of 0.9760 (Givoni 2004).

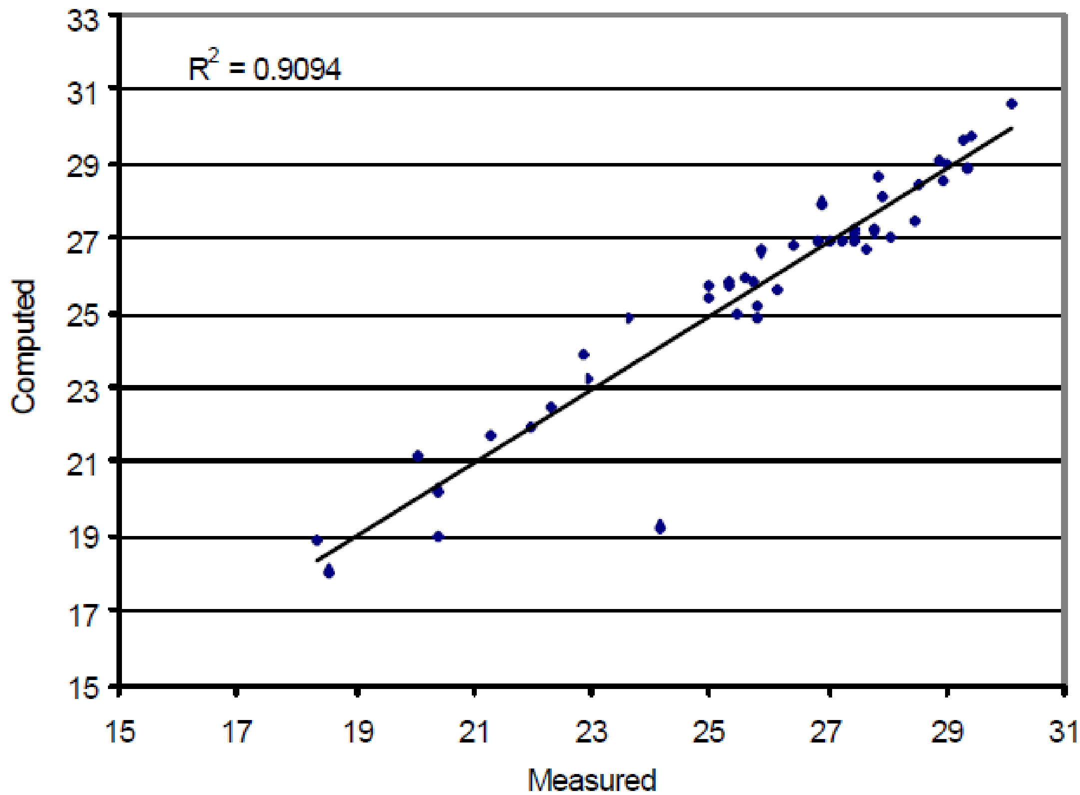


Figure 2.11 Correlation between measured and computed indoors average temperatures
(Source:Givoni, Vecchia 2001)

Vecchia used the same methodology, prescribed by Givoni, to predict indoor maximum, average and minimum temperatures recognizing that incorporating the solar radiation can slightly improve the prediction of indoor maximum temperature while incorporating the diurnal swings slightly improved the prediction of indoor minimum (Givoni, Vecchia 2001). He further validated the formulas he derived by collecting data for another extended period of time from the same buildings and putting the data in the formulas.

Givoni also used the observation of the experimental research to develop the methodology for formula to predict indoor maximum (Givoni 1994):

1. The climatic parameter best correlated with the indoor maximum is the outdoors average.
2. Under steady climate conditions, when the outdoor average is about constant, the elevation of the indoor maximum above the outdoor average depends on the thermal mass of the buildings.
3. Under dynamic climate, when outdoor average rises or falls, the indoor maximum of the high-mass building changes at a rate about one half of the change in the outdoor average. The rate of the low-mass buildings maximum is about 0.8 of the change in the outdoor average

The observations were expressed mathematically in the general form of the predictive formula (Givoni 1994):

$$Tmax = GTavg + DelT + K^*(Tavg - GTavg)$$

Tmax =	Indoor maximum temperature in a particular day
GTavg =	Grand average of the outdoor temperature
DelT =	Average elevation of the indoor maximum above the outdoor average (Fig. 2.12)
Tavg =	Outdoor temperature average in a particular day
K =	Ratio of the rates of daily changes of the indoor maximum to the rate of change of the outdoor average, depending on the mass level (Fig. 2.12)

	The k Variable
Low-Mass Buildings	k=0.8
High-Mass Buildings	k=0.5

	The DelT Variable (C)		*The DelT Variable (F)*	
Conditions	*Low-Mass*	*High-Mass*	*Low-Mass*	*High-Mass*
Windows Unshaded No Night Ventilation	12	8	22	14
Windows Shaded No Night Ventilation	10	6	18	11
Windows Shaded Night Ventilation Low Speed	9	3	16	6
Windows Shaded Night Ventilation Mid Speed	8	3	15	5
Windows Shaded Night Ventilation High Speed	8	2	14	4
High-Mass, Shaded, White color Natural Ventilation (Israeli study)		1		2

Figure 2.12 Experimentally Derived Values of The K and DelT Variables (source: Givoni 1994)

Givoni develop another methodology to predict the indoor daily maximum, average, and minimum which excludes the thermal properties of a building “DelT, and K” (Givoni 2004) (Fig. 2.13, 2.14, and 2.15). In developing the formulas for predicting the indoor temperature as Givoni stated “functions of the outdoors’ climatic conditions, it is necessary to find out what parameter of the outdoor climate could best serve as a basis for prediction. It is performed visually by plotting the indoor parameter of interest over the background of the outdoor daily maximum, average and minimum temperatures to observe the fine details of their relationship” (Fernandez-Gonzalez, Givoni 2007) (Fig. 2.13). Therefore, the relationship then can be analyzed to find similarity in patterns demonstrated by different temperature data set. Once a given pattern is observed, it is relatively simple to express it in a formula (Fig. 2.14). Hence, the general suggestion is, "if experimental data on the outdoor and indoor conditions, measures over several weeks, are available, it is possible to predict the performance of that building in conditions different from the climate under which the original data was collected" (Givoni 2004) (Fig. 2.15).

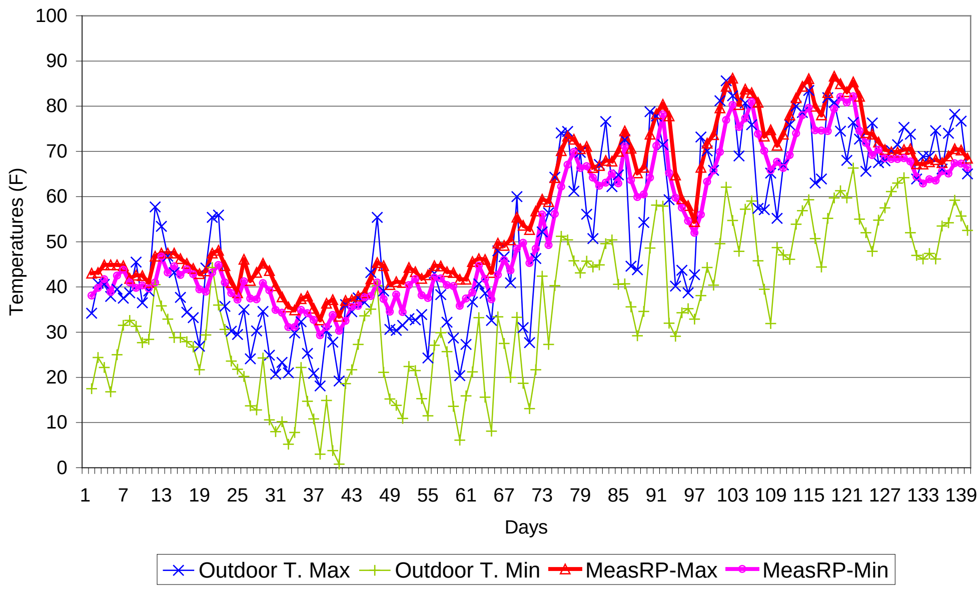


Figure 2.13 Maximum and minimum temperatures in the Roofpond cell, over the background of the corresponding outdoor temperatures. (Fernandez-Gonzalez, Givoni 2007)

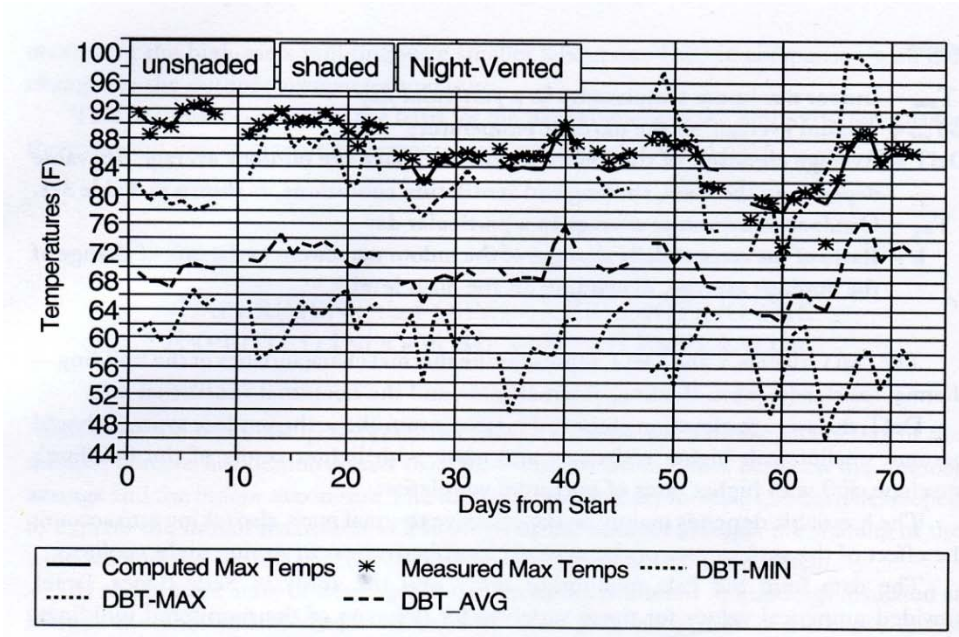


Figure 2.14 Measured and calculated indoor maximum temperatures of the low-mass building, together with the maxima, minima, and averages of the outdoor temperature
(Source: Givoni 1994)

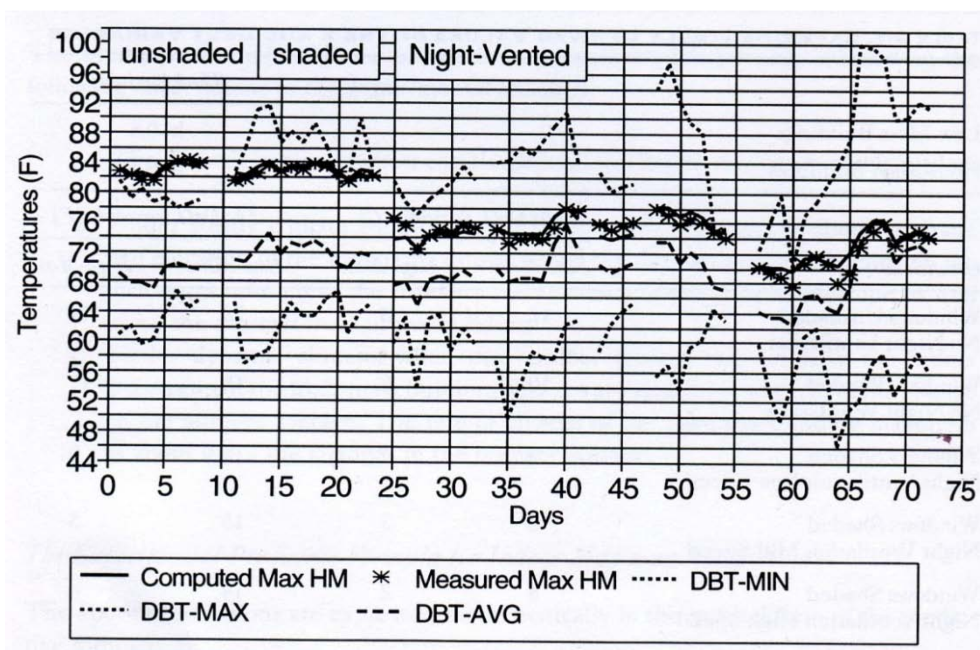


Figure 2.15 Measured and calculated indoor maximum temperatures of the high-mass building, together with the maxima, minima, and averages of the outdoor air temperature
(source: Givoni 1994)

Implementation of Predicting Formulas

The importance predicting formulas has brought to the table many opportunities in establishing an overall framework that will help to designing of building without leaving room for errors. However, one should understand how valuable it is to have information such as indoor temperature and a performance of different system implementation in passive heating and cooling in such early stage of planning and designing. As Givoni and Vecchi has described:

> When the day to day indoor daily minimum and maximum temperatures are known it is possible to reconstruct an approximate hourly pattern of the indoor temperatures during a given period. This information would be sufficient for evaluating the expected comfort conditions of persons living in un-conditioned buildings under given climatic conditions. Furthermore, once the indoor hourly temperature patterns are reconstructed, and when the upper and the lower boundaries of the comfort zone for a given regions are specified, it would be possible to estimate the number of hours in which operation air conditioning would be needed or probable (Givoni, Vecchi 2001).

Also these formulas can be very useful for locations where climatic information are limited to just the daily temperatures. As mentioned by Fernandez-Gonzalez, and Givoni "in many Developing Countries available climatic information for their different districts is very scarce, often limited only to air temperature" (Fernandez-Gonzalez, Givoni 2007). Furthermore, one can use such information generated by the predicting formulas and really develop an understanding of how different systems can work effectively and if modifications are needed to enhance the system and reach it maximum best performance possible in such locations. As Fernandez-Gonzalez, Givoni, talks about developing formulas to be used to predicted indoor temperature for buildings using different passive systems with an objective of having the minimum required data analysis for the climate information to enables the use of such thing in different climatic circumstances (Fernandez-Gonzalez, Givoni 2007) (Fig. 2.16). Further information can be found in greater detail describing the procedure of developing such formulas in and its uses Givoni 1994; 1999; and 2004.

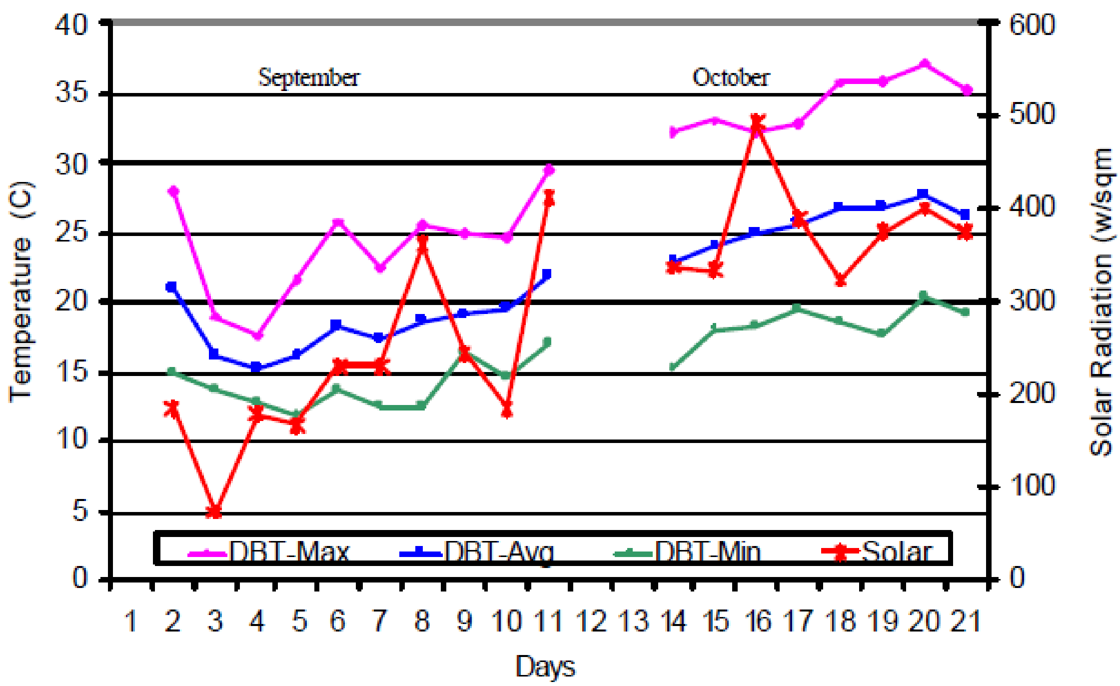


Figure 2.16 Maximum, average and minimum temperatures and solar radiation (Source: Givoni, Vecchi 2001)

Examples of Predicting Formulas

1. Prediction of thermal performance of occupied houses (Givoni, Vecchi 2001):

The indoor maximum temperature (Fig. 2.17)

*Tmax = 1.0894 * Avg DBT + 4.4*

*Maximum = 1.0894 * Avg DBT + 0.0018 * Solar + 3.8*

The indoor average temperature (Fig. 2.18)

*Average = 0.9887 * DBT + 0.0009 * Solar + 2.9*

The indoor minimum temperature (Fig. 2.19)

*Minima = DBT – 0.2 * (Tmax - Tmin) + 0.15 (DBT – G_DBT) + 2.3*

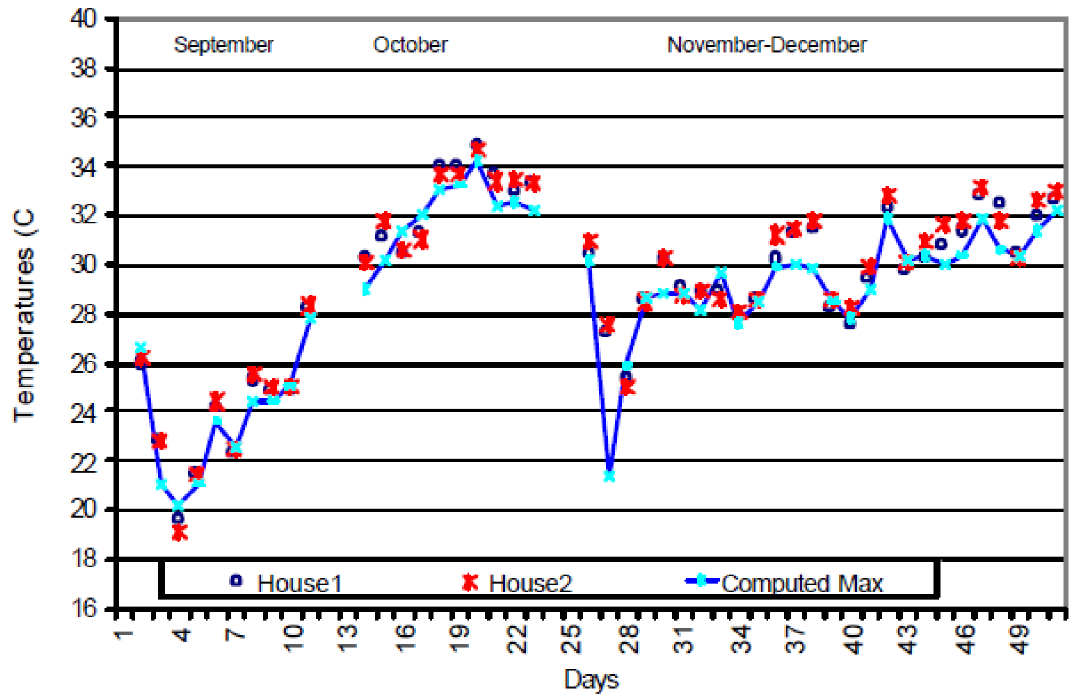


Figure 2.17 Measured and computed indoors maximum temperatures (Source: Givoni, Vecchi 2001)

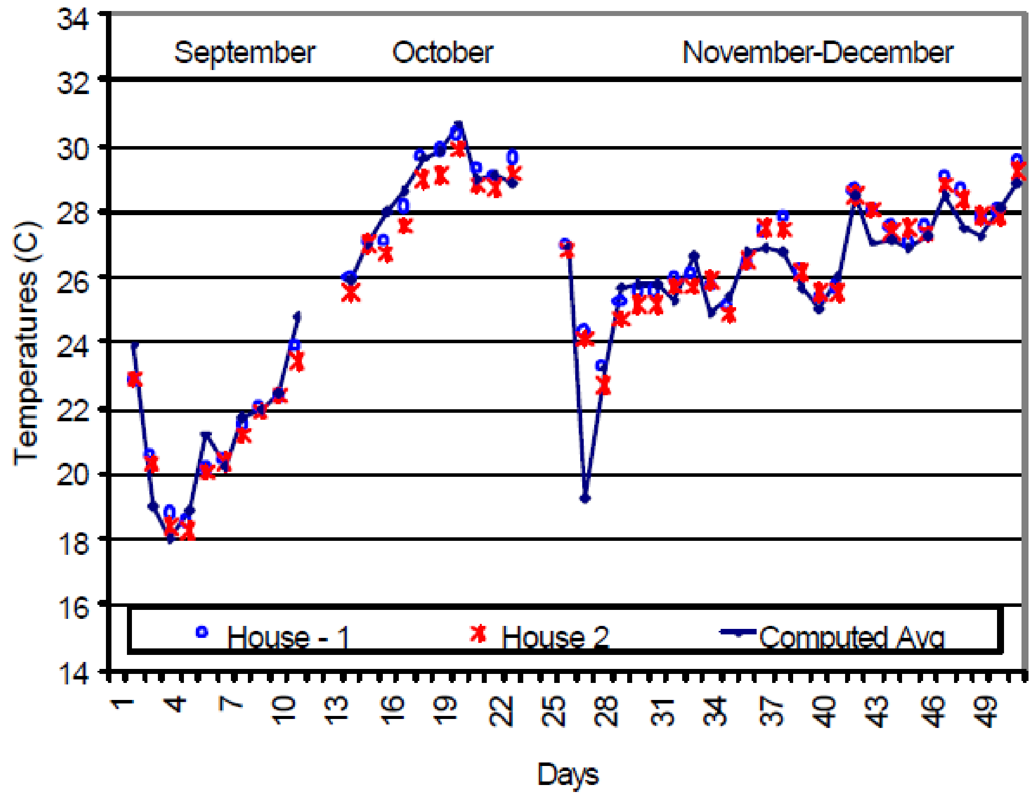


Figure 2.18 Measured and computed indoors average temperatures
(Source: Givoni, Vecchi 2001)

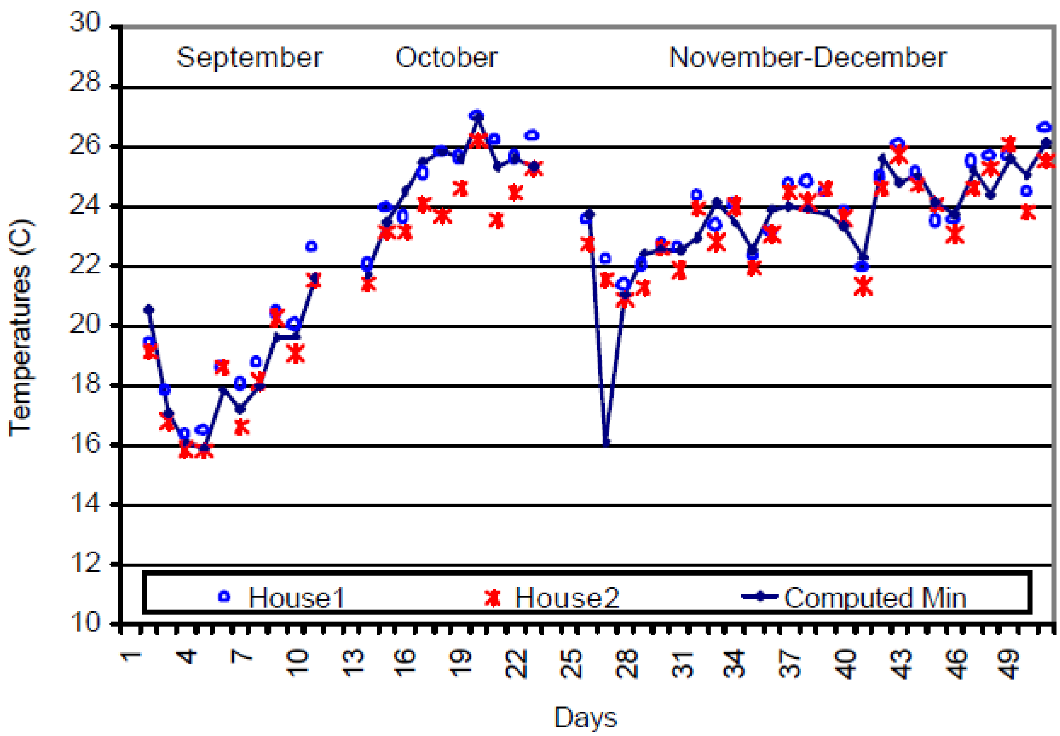


Figure 2.19 Measured and computed indoors minimum temperatures
(Source: Givoni, Vecchi 2001)

2. Prediction of indoor temperatures (Givoni, Kruger 2003):

The indoor maximum temperature (Fig. 2.20)

$$T(in)max = GTmax + 0.6 + 0.69(Tmax - GTmax)$$

The indoor average temperature

$$T(in)avg = GTavg + 4.1 - 0.067 \times GTavg + 0.74(Tavg - GTavg)$$

The indoor minimum temperature (Fig. 2.20)

$$T(in)min = GTmin + 5.4 - 0.116 \times GTmin + 0.75(Tmin - GTmin) + 0.1374(Tavg(n-1) - Tmin)$$

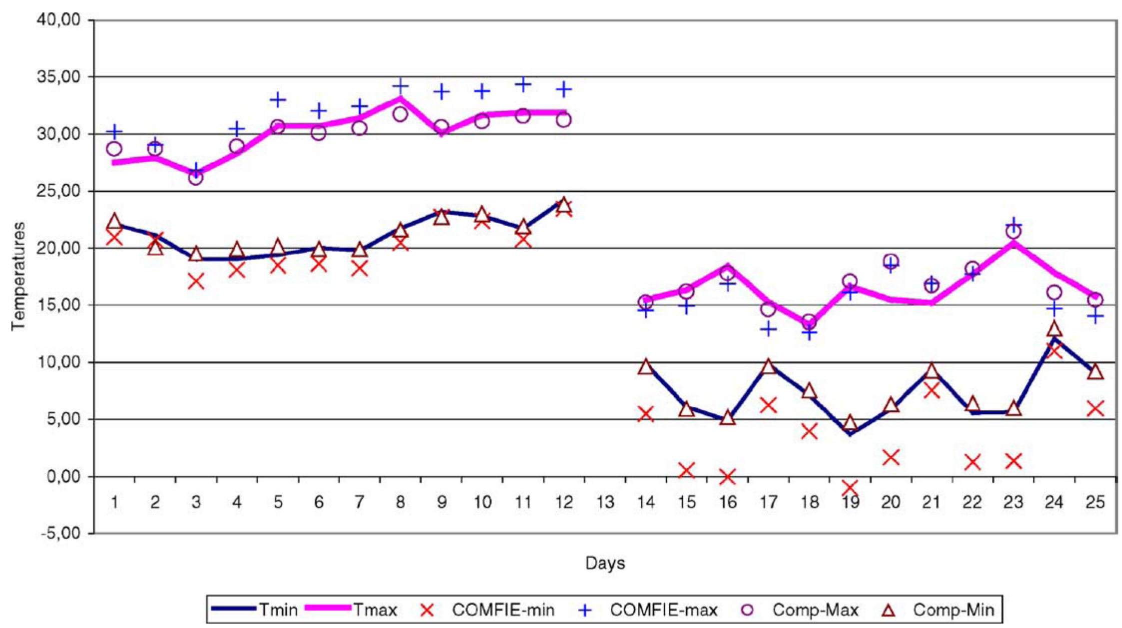


Figure 2.20 Indoor minimum and maximum temperatures in the Kurten house. Comparisons between measured, simulated and computed data (Source: Givoni, Kruger 2003)

3. Prediction of indoor temperatures (Givoni 2004):

The indoor maximum temperature (Fig. 2.21)

*Tin (max) = GTavg + (2.7 + 0.1637 * GTavg) + 0.0859 * (Tmax –Tmin - 1.2) + 1.156 * (Tavg - GTavg)*

The indoor minimum temperature (Fig. 2.21)

*Tin (min) = GTmin + (0.9 + 0.2547 * GTmin) + (0.149 * (Tmax – Tmin) - 2) + 0.808 * (Tmin - GTmin)*

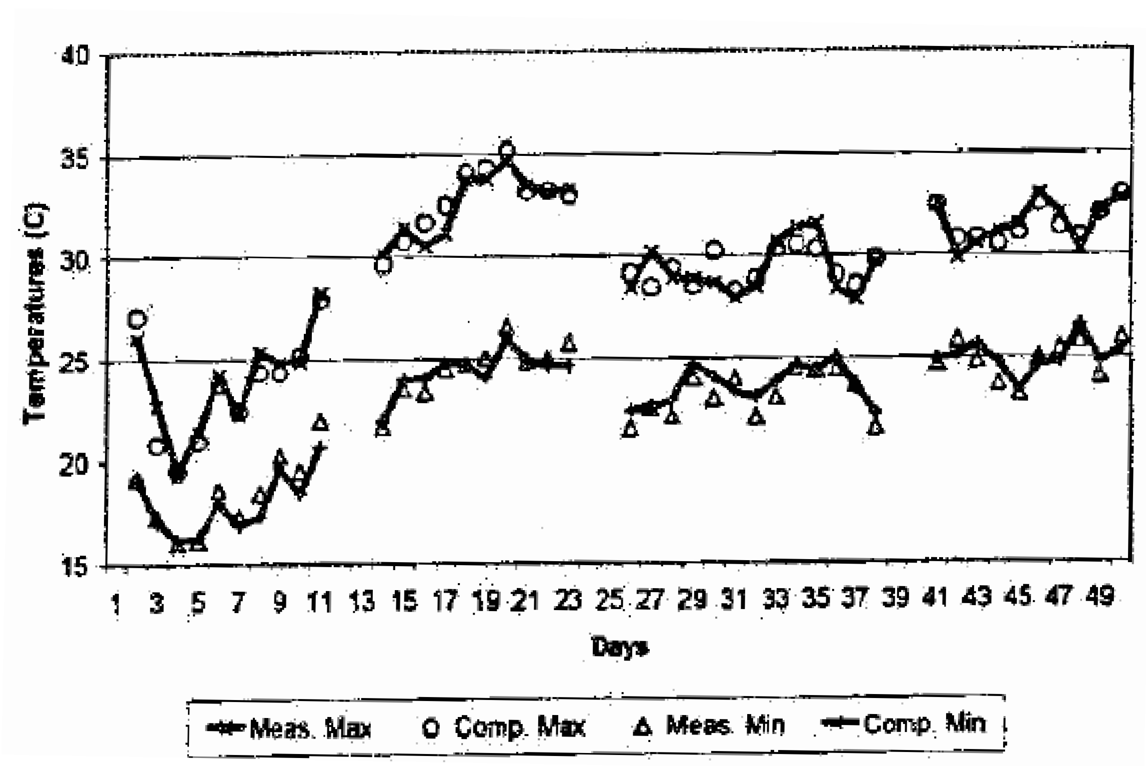


Figure 2.21 Measured and computed maximum and minimum temperatures (Source: Givoni 2004)

4. Prediction of indoor temperatures (Fernandez-Gonzalez, Givoni 2007):

The indoor maximum temperature (Fig. 2.22)

*Maximum = 11.4 + 0.0275*Tmax + 0.3608*GTavg +*

*0.5121*RunAvg + 0.0018*RunSolar + 0.0663*(Tmax - Tmin);*

The indoor average temperature

*Average = 11.06 + 0.3505*GTavg + 0.5509*RunTavg +*

*0.0016*RunSolar - 0.0044*(Tmax - Tmin);*

The indoor minimum temperature

*Minimum = 12.39 + 0.9885*Tmin + 0.5058*(Tmax(n-1) -*

Tmin)

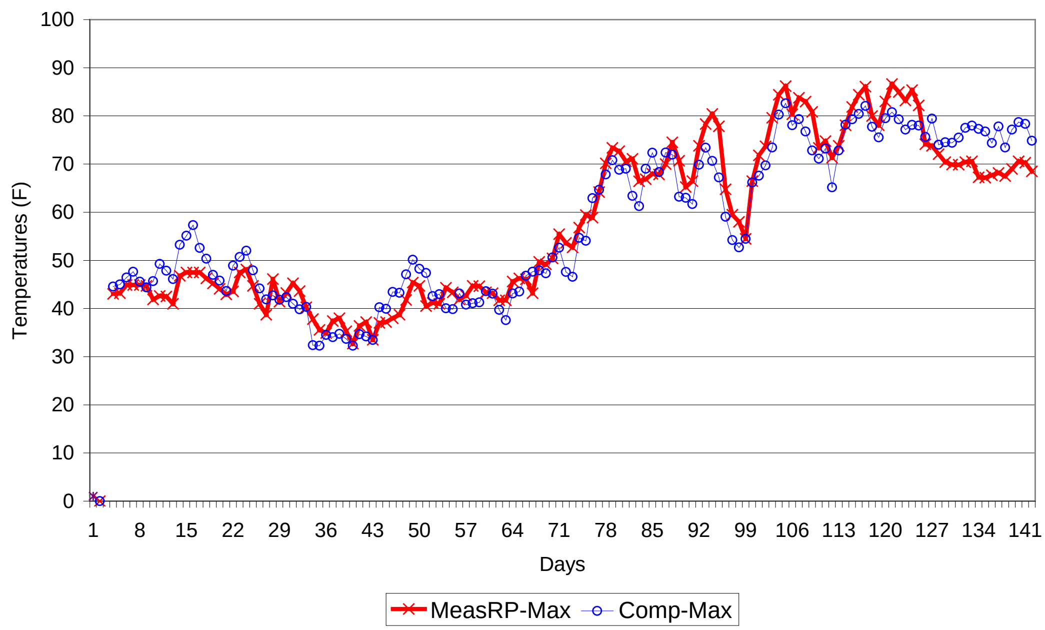


Figure 2.22 Measured and computed indoor maximum and minimum temperatures of test cell
with Roofpond system (°F)
(Source: Fernandez-Gonzalez, Givoni 2007)

CHAPTER 3

METHODOLOGY

Development of the Predicting Roofpond Formulas

This chapter will describe how each of the formulas are developed based on what have been learned from the literature review in the previous chapter and the data collected and analyzed at the UNLV School of Architecture test-cell. Multiple formulas will be developed to predict the performance of the roofpond in Nevada and the west coast region of the United States. Also the finding of this thesis will be applicable for further research in the future based on the formulas generated by pervious work and this thesis to accomplish a simulation of the maximum performance of the roofpond using the predicting formulas.

The research started when the data of the roofpond test-cell (RP) and the controlled test-cell (CC) was monitored, collected, and analyzed in the period of 2004 through 2006 (first phase) and May of 2009 through October of 2009 (second phase). The only importance why the data was collected during the both phases of the research stated above was to see how the test-cell would perform without (first phase) and with (second phase) wall insulation. The data was collected for every five minutes and was analyzed on a weekly bases due to understand the performance of the two test-cells and to catch any multifunction of the equipments, this will provide the research with the most accurate data possible and also one can understand the performance of the test-cells on a weekly bases.

Therefore, after the weekly data was analyzed by taking the collected data, that consist of every five minutes intervals and averaging it to hourly averages to be organized based on a twenty four hours day for example from 12:00 AM to 11:00 PM. That said now the weekly data consist of seven days with average indoor hourly temperature for the two test-cells. Thereafter, the weekly data was compiled together to establish continues hourly averaged data for all the days were collected and the hourly data from the weather station also was included side-by-side at this point to establish the connection between the indoor and the outdoor temperatures. Furthermore, the data was analyzed by using pivot-tables to accurately establish daily average, maximum, and minimum temperatures for the particular day is being analyzed. At this point of the research all of the data (indoor and outdoor) is compiled in one spread-sheet showing daily maximum, average, and minimum of all the data. See Figures 3.1 and 3.2 showing data plotted in a chart for the first phase of the research and also understanding the data visually by the pattern generated by the chart. Also the Figures 3.3 and 3.4 showing exactly the same thing describe above; however, the charts is only during second phase of the projects.

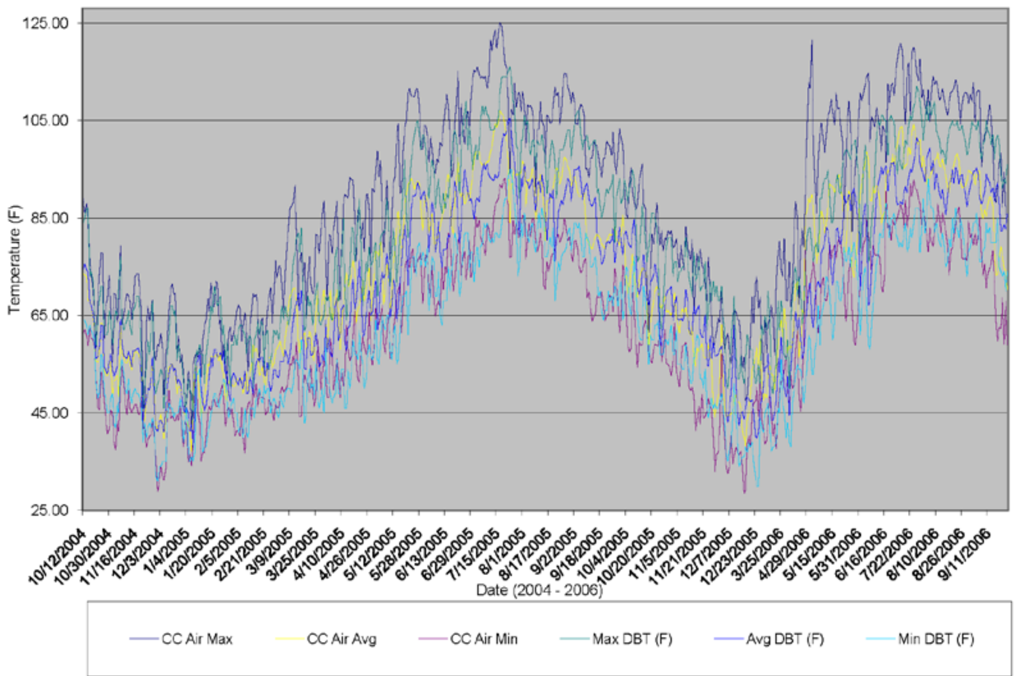


Figure 3.1 Maximum, average, and minimum of the control test-cell (CC) measured air temperatures and the outdoor dry bulb temperatures for first phase 2004-2006

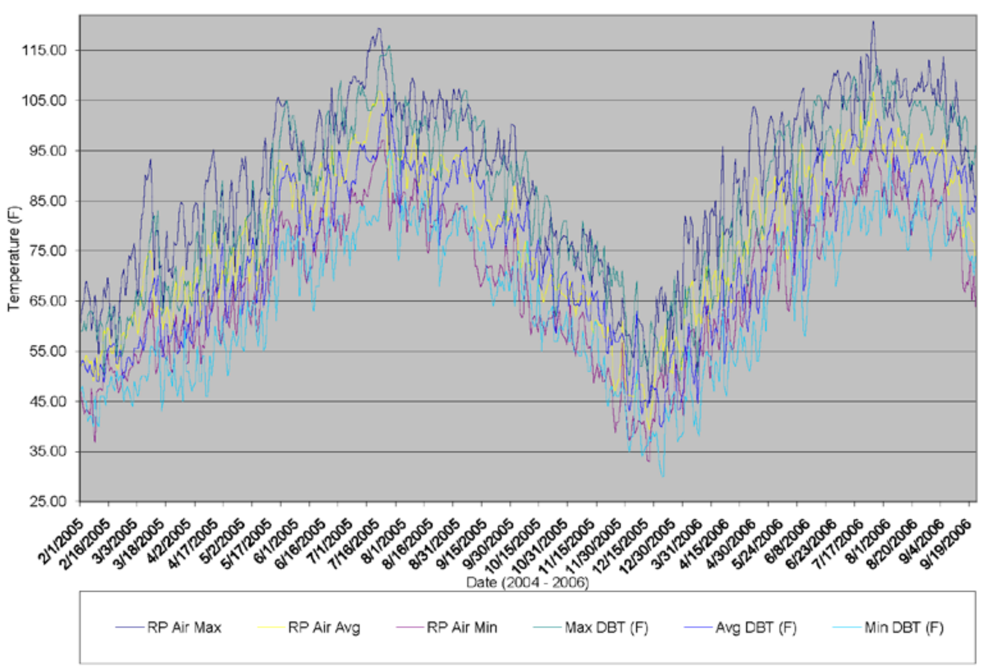


Figure 3.2 Maximum, average, and minimum of the roopond test-cell (RP) measured air temperatures and the outdoor dry bulb temperatures for first phase 2004-2006

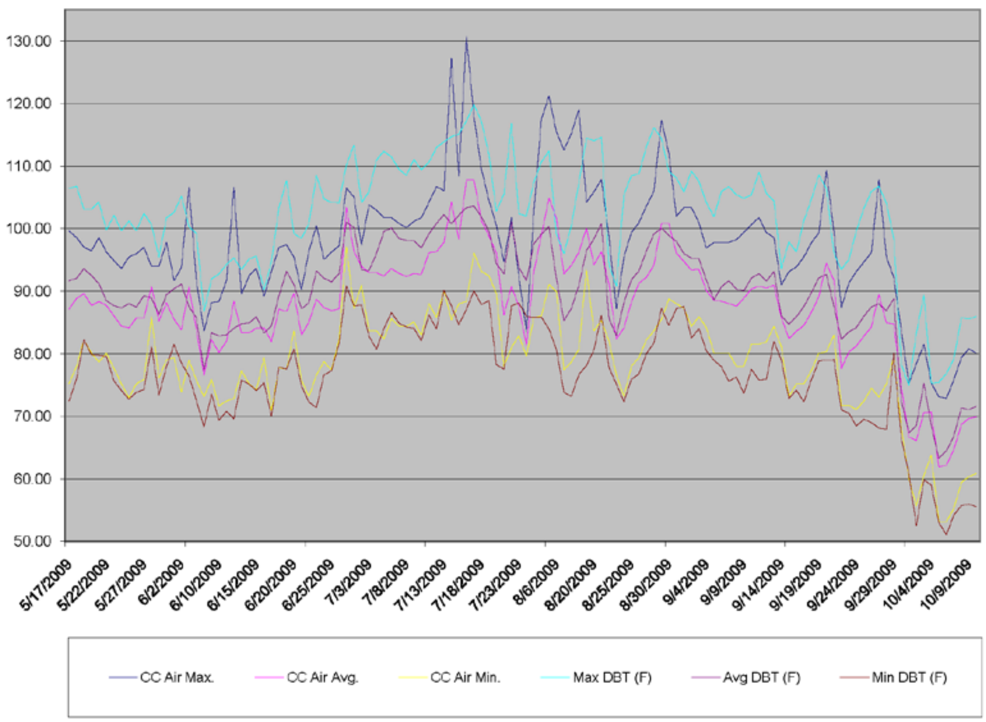


Figure 3.3 Maximum, average, and minimum of the control test-cell (CC) measured air temperatures and the outdoor dry bulb temperatures for second phase summer 2009

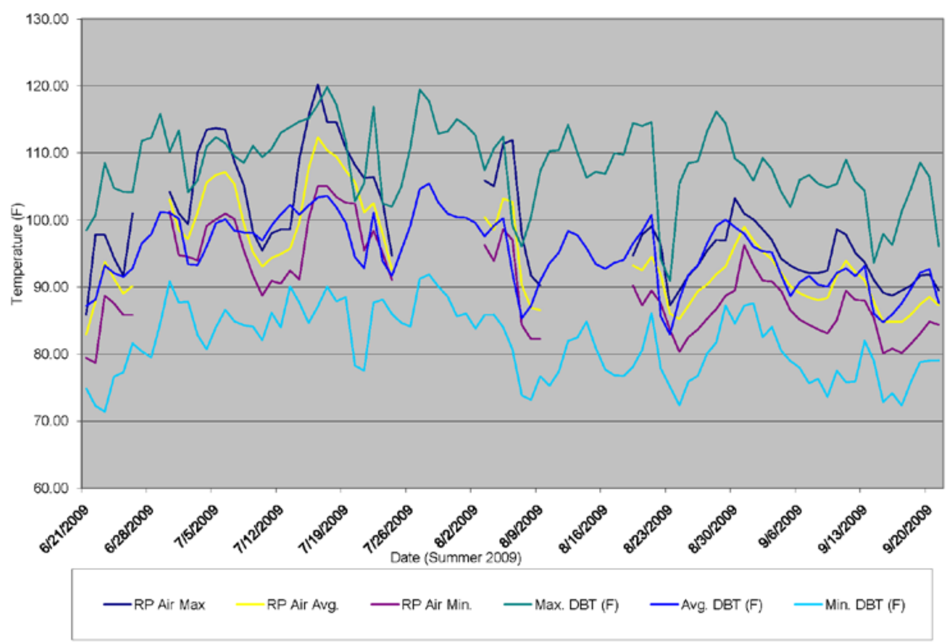


Figure 3.4 Maximum, average, and minimum of the roofpond test-cell (RP) measured air temperatures and the outdoor dry bulb temperatures for second phase summer 2009

At this point the data is organized in a fashion that each of the three values (average, maximum, and minimum) are put side-by-side in columns for example: dry bulb temperature has three column showing the three values this is done to all the values included in the pivot-table (Fig. 3.1, 3.2, 3.3, and 3.4). Thereafter, a correlation analysis is applied to the data to see if there is a strong correlation between each of the element; however, if a strong correlation is first found between indoor temperatures and the outdoor average the data is suitable to be used in generating predictive formulas. As you add additional climatic variable the predicted temperature becomes much more accurate. The next step a Regression process is applied to the whole data where regression can be described as a method of determining relationships among different data in order to predict future result. Examples of correlation analysis are provided in form of chart, each represented the linear relation between maximum, average, and minimum for the measured indoor air temperature and the computed indoor air temperature (see Figures 3.5, 3.6, and 3.7).

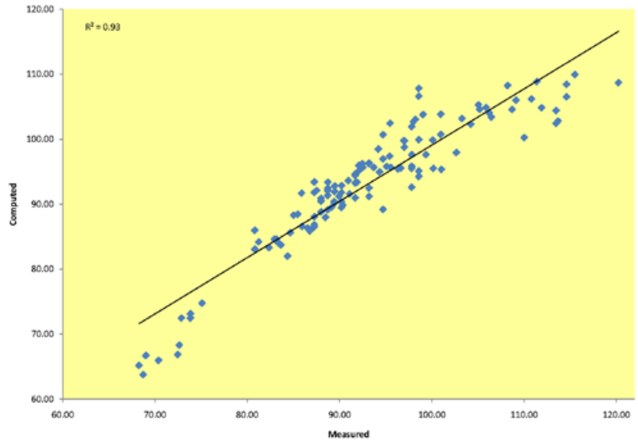


Figure 3.5 Example of correlation between the maximum measured temperatures and the predictive formula maximum computed temperatures

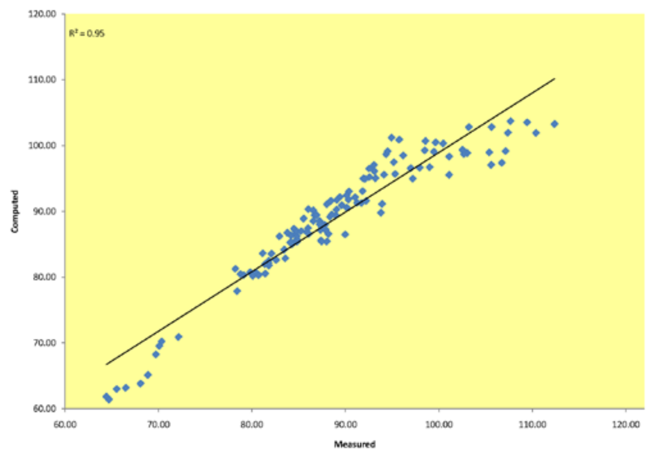


Figure 3.6 Example of correlation between the average measured temperatures and the predictive formula average computed temperatures

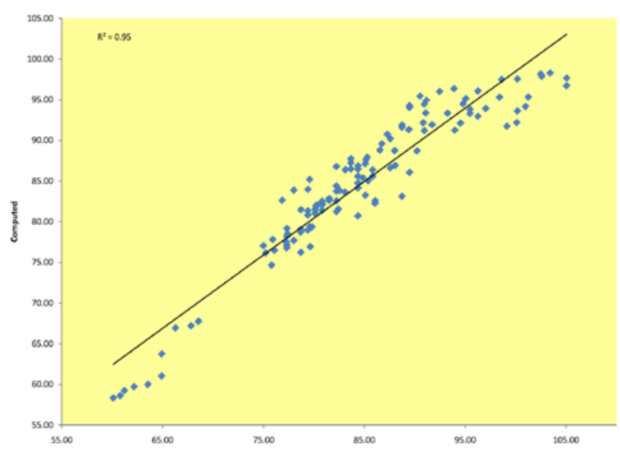


Figure 3.7 Example of correlation between the minimum measured temperatures and the predictive formula minimum computed temperatures

At this point three groups of values are established average, maximum, and minimum each group includes sets of values representing an Intercept values (I_{avg},I_{max},I_{min}). Also from the same regression calculation a coefficient is established representing each of the elements described below for example *($Sol_{per.avg.cof}$)*, (Fig 3.8). The coefficient will be multiplied by its element and added to the others and to the intercept value of each of the three formulas presented below. All the values at this point are combined in one spread-sheet with all the elements described as (Fig. 3.9):

1. Period average of solar radiation (w/m^2) 10 days average ($Sol_{per.avg.}$): This daily period average is established by averaging the last ten days of the daily average solar radiation to that particular day.
2. Running average of solar radiation (w/m^2) 3 days average ($Sol_{run.avg.}$): Running average is established by averaging the last three days of the daily average solar radiation to that particular day.
3. Daily average solar radiation (w/m^2) ($Sol_{avg.}$): The daily averages for the solar radiation based on the weather data.
4. Period average of dry bulb temperature (ºF) 10 days average ($DBT_{per.avg.}$): This daily period average is established by averaging the last ten days of the daily average Dry Bulb Temperatures to that particular day.

5. Running average of dry bulb temperature (ºF) 3 days average ($DBT_{run.avg.}$): Running average is established by averaging the last three days of the daily average Dry Bulb Temperatures to that particular day.
6. Average dry bulb temperature (ºF) ($DBT_{avg.}$)
7. Maximum dry bulb temperature (ºF) ($DBT_{max.}$)
8. Minimum dry bulb temperature (ºF) ($DBT_{min.}$)
9. Maximum wet bulb temperature (ºF) ($WBT_{max.}$)
10. Minimum dry bulb temperature (ºF) ($WBT_{min.}$)

Roofpond (RP) Intercept and Coefficient Values 2004 - 2006			
Roofpond Test-cell Intercept Value		***Max.***	*19.50*
		Avg.	*9.07*
		Min.	*2.38*
Coefficient Elements	***Max. Coefficient***	***Avg. Coefficient***	***Min. Coefficient***
Period Avg Solar (w/m^2) 10 days	*0.00211*	*0.00264*	*0.00255*
Running Avg Solar (w/m^2) 3 days	*0.00153*	*0.00156*	*0.00152*
Daily Solar (w/m^2)	*0.00119*	*0.00013*	*-0.00062*
Period Avg DBT (F) 10 days	*0.27910*	*0.28403*	*0.30253*
Running Avg DBT (F) 3 days	*0.09285*	*0.04815*	*0.03748*
Avg DBT (F)	*0.24062*	*0.22611*	*0.24039*
Max DBT (F)	*-0.18203*	*-0.09064*	*-0.02835*
Min DBT (F)	*0.18774*	*0.19487*	*0.15265*
Max WBT Depression	*0.27429*	*0.13224*	*0.01340*
Min WBT Depression	*-0.27665*	*-0.18713*	*-0.12795*

Table 3.1 example of the roofpond variable coefficient and intercept values base on a regression calculation from the weather data.

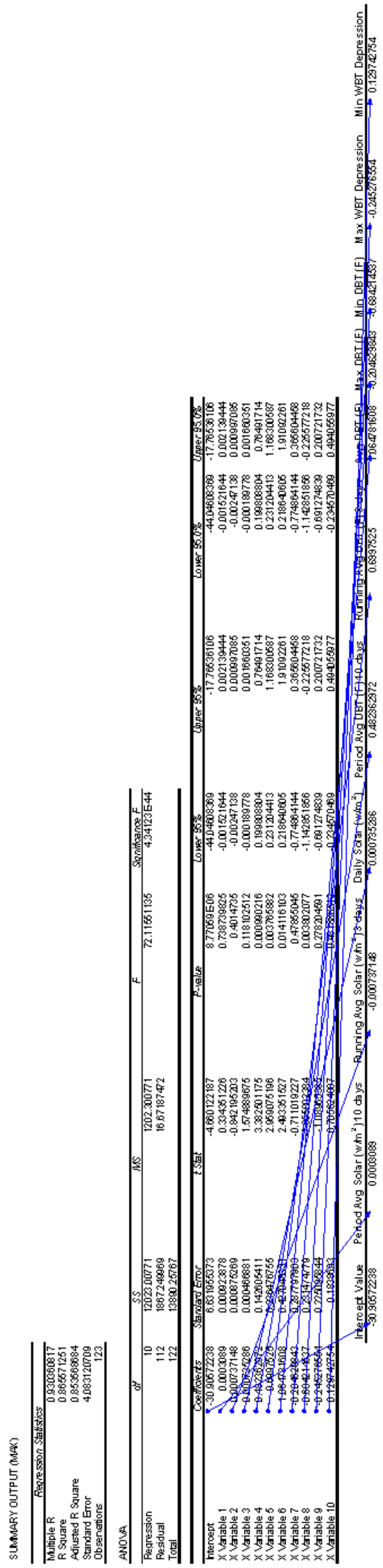


Figure 3.8 Example of regression analysis calculation generated by Excel® for each of the variable coefficient

Period Avg Solar (w/m^2) 10 days	Running Avg Solar (w/m^2) 3 days	Daily Solar (w/m^2)
8,447.96	8,447.96	8,447.96
8,412.23	8,412.23	8,376.50
8,396.54	8,396.54	8,365.17
8,375.89	8,351.87	8,313.94
8,356.51	8,319.37	8,279.00
8,371.59	8,346.63	8,446.94
8,394.81	8,420.04	8,534.18
8,222.89	8,000.18	7,019.42
8,246.85	7,997.39	8,438.57
8,288.63	8,040.88	8,664.65
8,274.96	8,471.49	8,311.24
8,180.52	8,135.98	7,432.05
8,171.21	8,005.13	8,272.09
8,216.91	8,158.37	8,770.98
8,234.91	8,500.70	8,459.02
8,166.22	8,330.00	7,759.99
8,147.66	8,189.20	8,348.58
8,277.92	8,143.52	8,321.98
7,930.76	7,212.54	4,967.05
7,814.79	6,931.32	7,504.93
7,822.45	6,953.27	8,387.82
7,801.36	7,704.63	7,221.14

Figure 3.9 Example of average calculation for period and running averages for each of the variable

After establishing all the elements above now the formula is ready to be established to generate the computed values for the three predicted indoor temperature (T_{max}, T_{avg}, and T_{min}) and the formulas are:

$$T_{max} = I_{max.} + [(Sol_{per.avg})(Sol_{per.avg.cof})] + [(Sol_{run.avg.})(Sol_{run.avg.cof})] + [(Sol_{avg.})(Sol_{avg.cof})] + [(DBT_{per.avg.})(DBT_{per.avg.cof})] + [(DBT_{run.avg.})(DBT_{run.avg.cof})] + [(DBT_{avg.})(DBT_{avg.cof})] + [(DBT_{max.})(DBT_{max.cof})] + [(DBT_{min.})(DBT_{min.cof})] + [(WBT_{max.})(WBT_{max.cof})] + [(WBT_{min.})(WBT_{min.cof})]$$

$$T_{avg} = I_{avg.} + [(Sol_{per.avg})(Sol_{per.avg.cof})] + [(Sol_{run.avg.})(Sol_{run.avg.cof})] + [(Sol_{avg.})(Sol_{avg.cof})] + [(DBT_{per.avg.})(DBT_{per.avg.cof})] + [(DBT_{run.avg.})(DBT_{run.avg.cof})] + [(DBT_{avg.})(DBT_{avg.cof})] + [(DBT_{max.})(DBT_{max.cof})] + [(DBT_{min.})(DBT_{min.cof})] + [(WBT_{max.})(WBT_{max.cof})] + [(WBT_{min.})(WBT_{min.cof})]$$

$$T_{min} = I_{min} + [(Sol_{per.avg})(Sol_{per.avg.cof})] + [(Sol_{run.avg.})(Sol_{run.avg.cof})] + [(Sol_{avg.})(Sol_{avg.cof})] + [(DBT_{per.avg.})(DBT_{per.avg.cof})] + [(DBT_{run.avg.})(DBT_{run.avg.cof})] + [(DBT_{avg.})(DBT_{avg.cof})] + [(DBT_{max.})(DBT_{max.cof})] + [(DBT_{min.})(DBT_{min.cof})] + [(WBT_{max.})(WBT_{max.cof})] + [(WBT_{min.})(WBT_{min.cof})]$$

Therefore, each of the computed value is put side-by-side to the actual measured indoor temperature to run another calculation generating correlation coefficient value that will show either be positive or negative determining the linear relation between the two to verify the accuracy of the formula. Therefore, the value calculated should be between -1 and +1, having said that if the value is closer to -1 that will mean the correlation is oppositely matched, or closer to zero that will mean there are no correlation what so ever, and the closer to +1 that will mean the correlation is very strong and the formula is near perfect. Furthermore, the complied data now consisting out of the measured data, the outdoor temperature data, and the computed data (generated by the formulas) are plotted into a chart analyzing and comparing the relationship between the patterns established by the compiled data. See figures 3.10 and 3.11 for the first phase data, and figures 3.12, and 3.13 for the second phase data.

However, different climatic variables can be added to the formulas to establish much more accuracy in predicting the indoor temperature as mentioned in the previous chapter. Therefore, looking at the examples provided in figures 3.14, 3.15, 3.17, and 3.17 showing solar radiation applied added to the data as anther variable. One can see the pattern develop in the chart where the indoor and the outdoor temperature have the same pattern as the solar radiation. Therefore, this explains how the relation between the outdoor weather and the indoor condition are consistent with each other, where weather can provide the adequate information to be used in such formulas to predict indoor conditions.

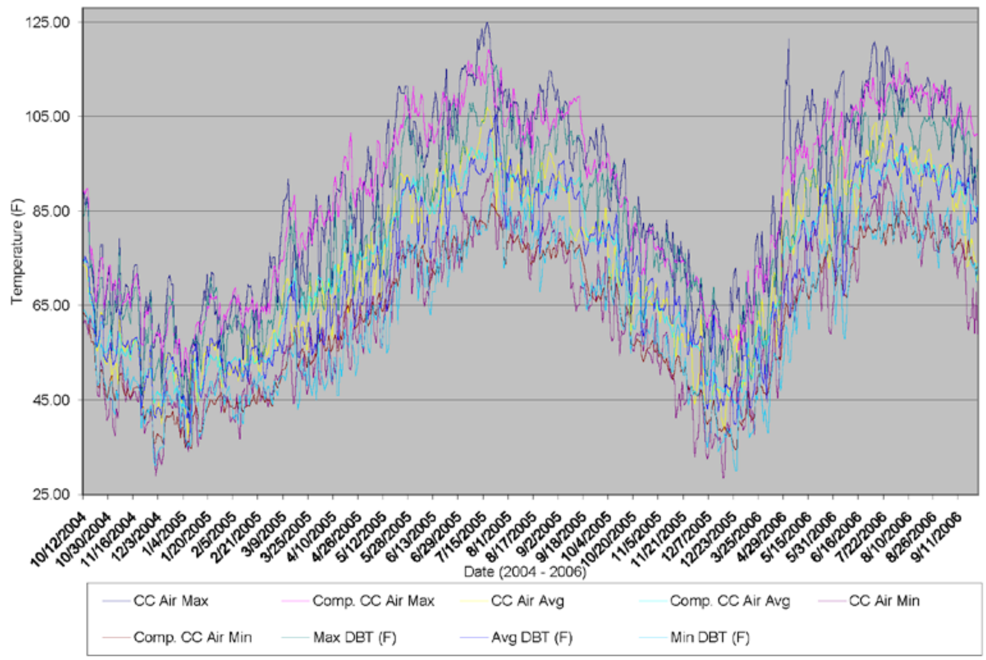


Figure 3.10 Maximum, average, and minimum of the control test-cell (CC) measured air temperatures, the outdoor dry bulb temperatures, and computed indoor temperatures for first phase 2004-2006

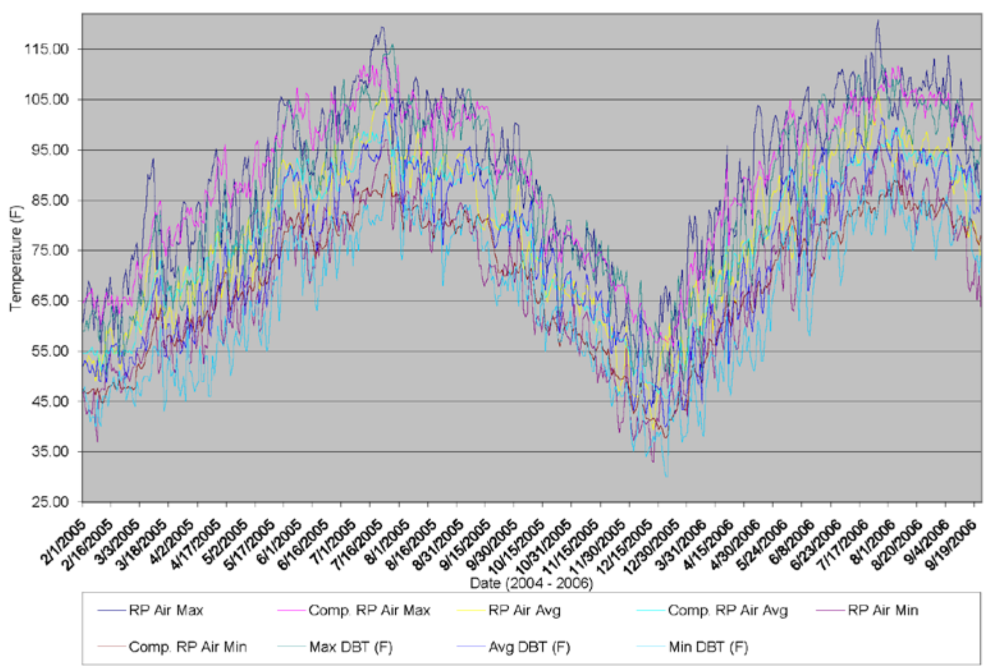


Figure 3.11 Maximum, average, and minimum of the roofpond test-cell (RP) measured indoor air temperatures, the outdoor dry bulb temperatures, and computed indoor temperatures for first phase 2004-2006

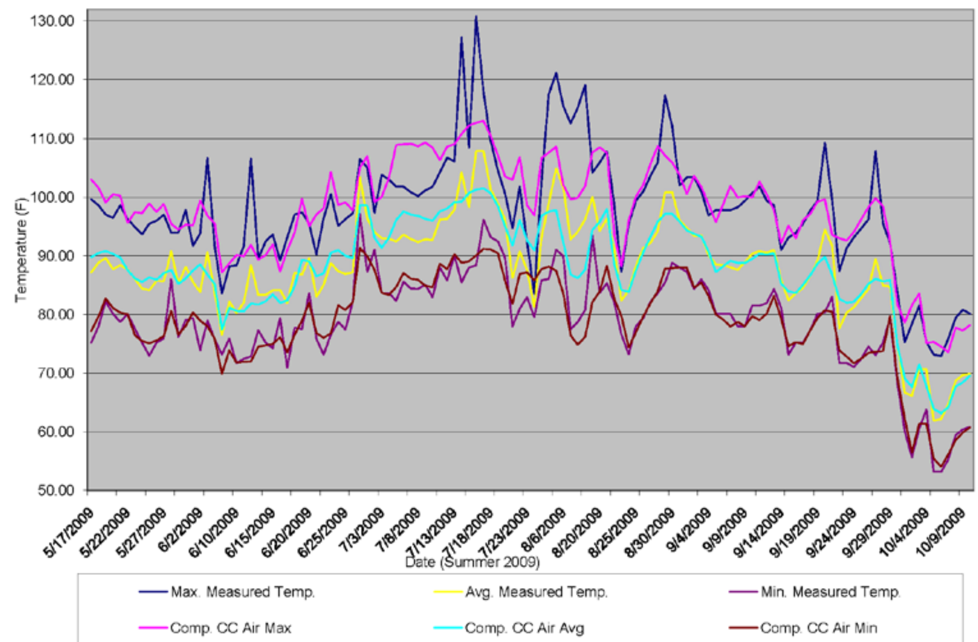


Figure 3.12 Maximum, average, and minimum of the control test-cell (CC) measured air temperatures, the outdoor dry bulb temperatures, and computed indoor temperatures for second phase summer 2009

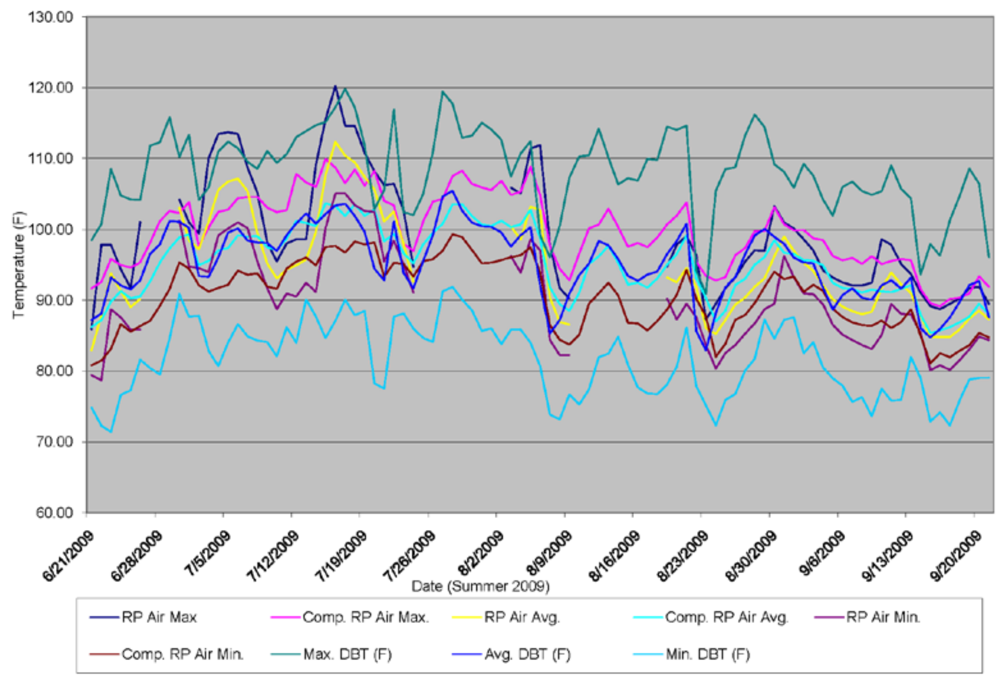


Figure 3.13 Maximum, average, and minimum of the roofpond test-cell (RP) measured indoor air temperatures, the outdoor dry bulb temperatures, and computed indoor temperatures for second phase summer 2009

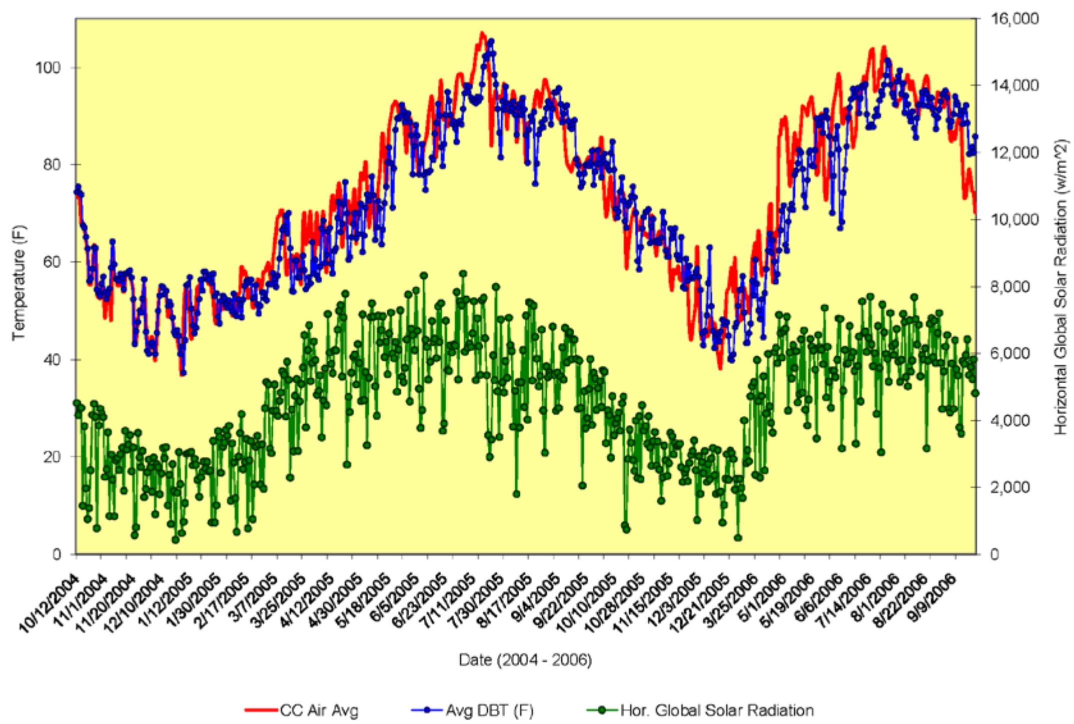


Figure 3.14 average of the control test-cell (CC) measured indoor air temperatures, the outdoor dry bulb temperatures, and horizontal global solar radiation for first phase 2004-2006

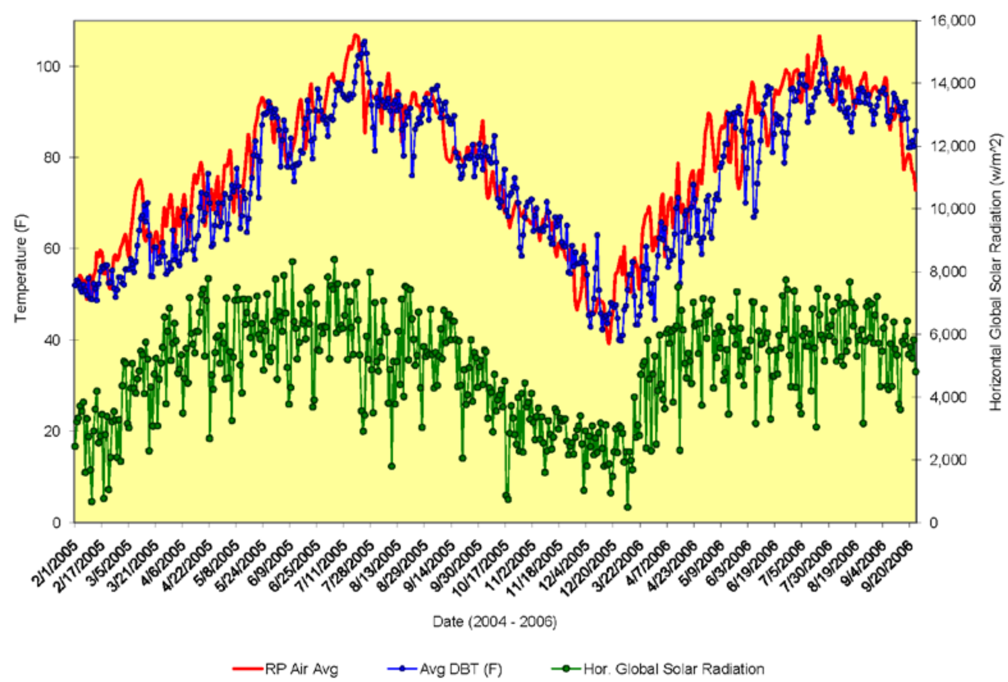


Figure 3.15 average of the roofpond test-cell (RP) measured indoor air temperatures, the outdoor dry bulb temperatures, and horizontal global solar radiation for first phase 2004-2006

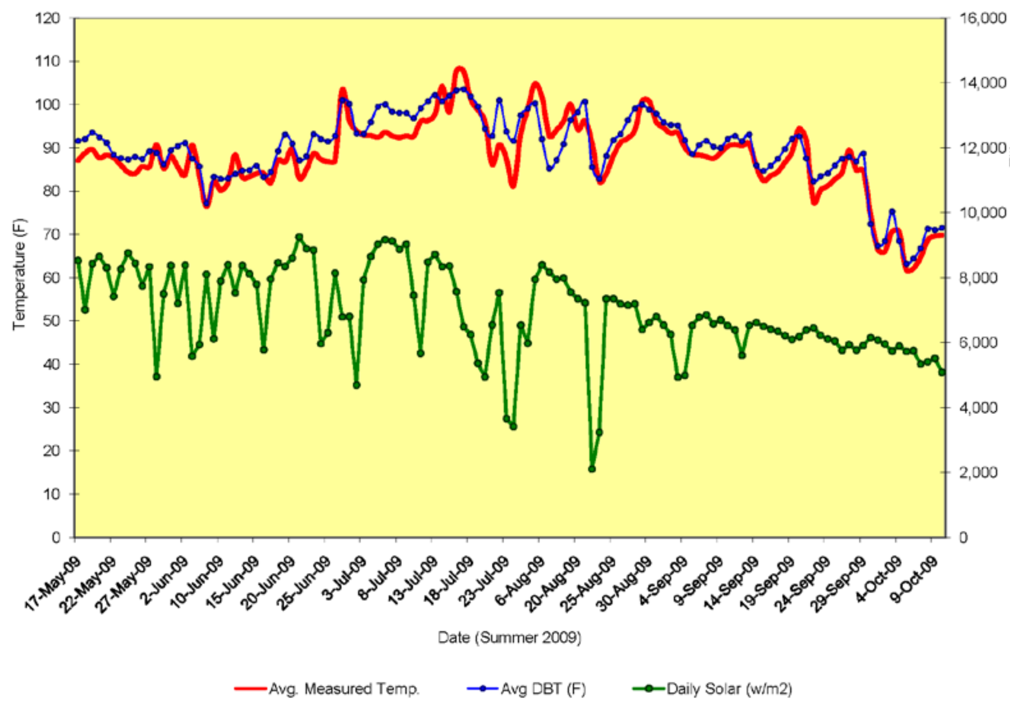


Figure 3.16 average of the control test-cell (CC) measured indoor air temperatures, the outdoor dry bulb temperatures, and horizontal global solar radiation for second phase summer 2009

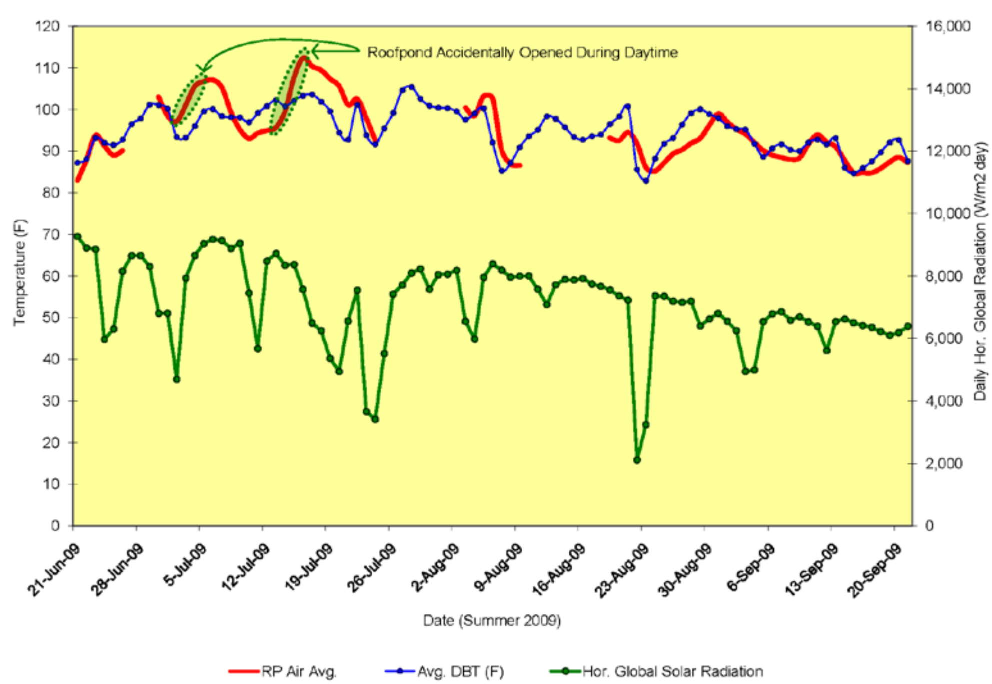


Figure 3.17 average of the roofpond test-cell (RP) measured indoor air temperatures, the outdoor dry bulb temperatures, and horizontal global solar radiation for second phase summer 2009

CHAPTER 4

FINDINGS OF THE STUDY

Purpose of the Test-cell Construction

In 2004 the Natural Energies Advanced Technologies Laboratory (NEAT Lab) at the School of Architecture at University of Nevada, Las Vegas (UNLV) has constructed two identical prototype test cell. However, one will be fitted with water bag on top the roof called "roofpond" (RP) and the other will serve as a control cell (CC) without the water bag. The two identical prototypes were built, each measuring 5 ft. wide, 8 ft. long, and 8 ft. high (finished floor to ceiling)(Fig. 4.1). The prototypes were built using wood frame construction and the same kind of insulation techniques used in residential construction (Fig. 4.3a-f)

The purpose of this experimental prototype of the roofpond system was to provide adequate research in passive solar heating and cooling performance in climate such as Las Vegas and Nevada. In addition to the research provided by building the two test cell at UNLV School of Architecture the students had the opportunity to be part of the design, construction, instrument, and monitor the performance of the test cell. The test cell were designed and constructed in a way that modification was a major part of the research to investigate the effect of different types of insulation and how it would thermal performance in passive buildings. Students being involved in this process will give them the opportunity and the experience of design and construction process needed to do such thing in the real world, as well as learning the process of communication in the design and construction field requires one to understand the importance of construction drawings as a vehicle to communicate ideas and information required for the building to be constructed (Fig.1.5a-d).

The data for the experiment was collected in two phases, first phase the test-cells were monitored and analyzed without having any type of insulation within the wall cavities as illustrated in figure 4.1 and the data was collected from 2004 through 2006. However, identical modifications were done to the two test-cells, a 2” thick aluminum facing rigid insulation with 1.5” air gap on both side of the insulation was added, also, each of the test cell got two 4” opening fitted with air fan to vent the test-cells for five minutes each hour as illustrated in figure 4.2.

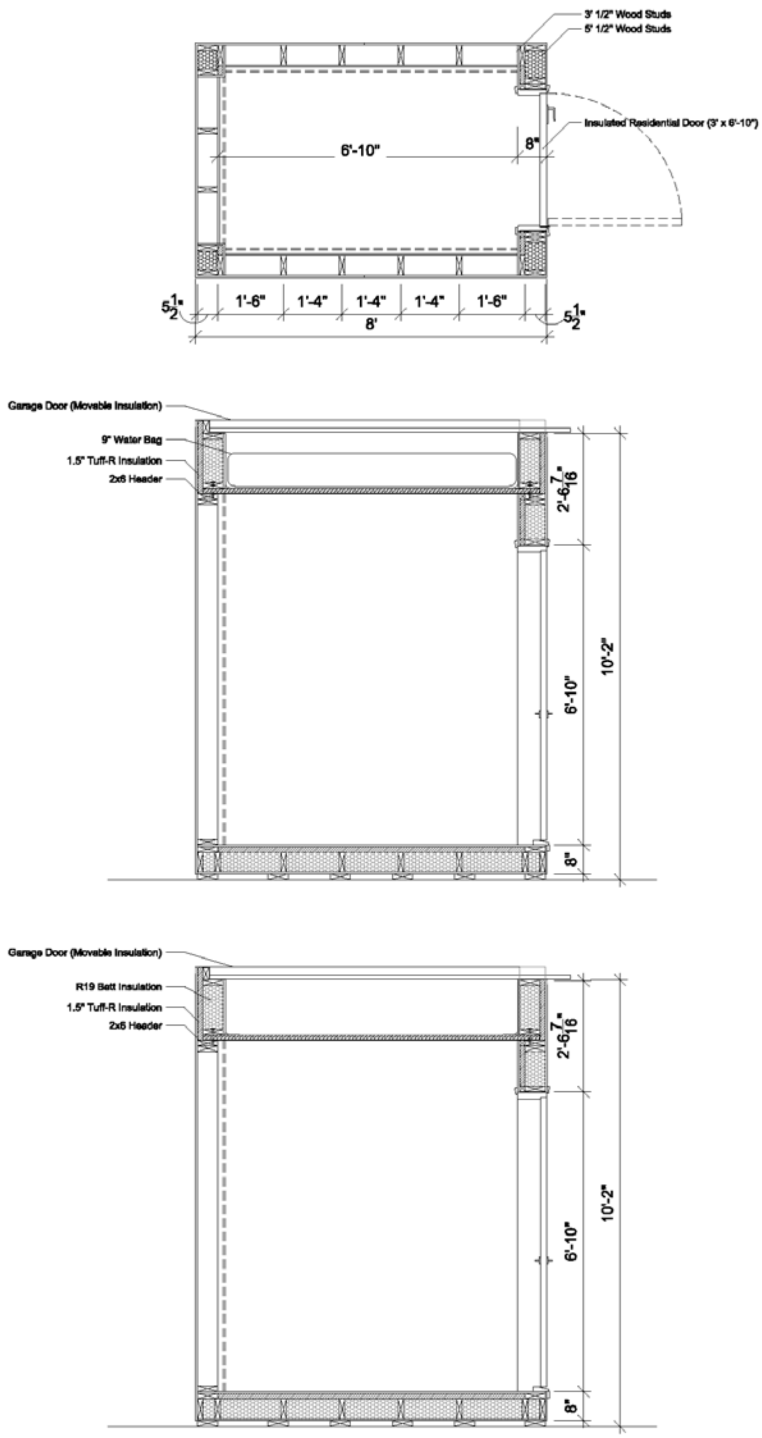


Figure: 4.1 Construction drawing of the UNLV Test-cells first phase (without wall insulation and ventilation)
(Source: UNLV NEAT Lab)

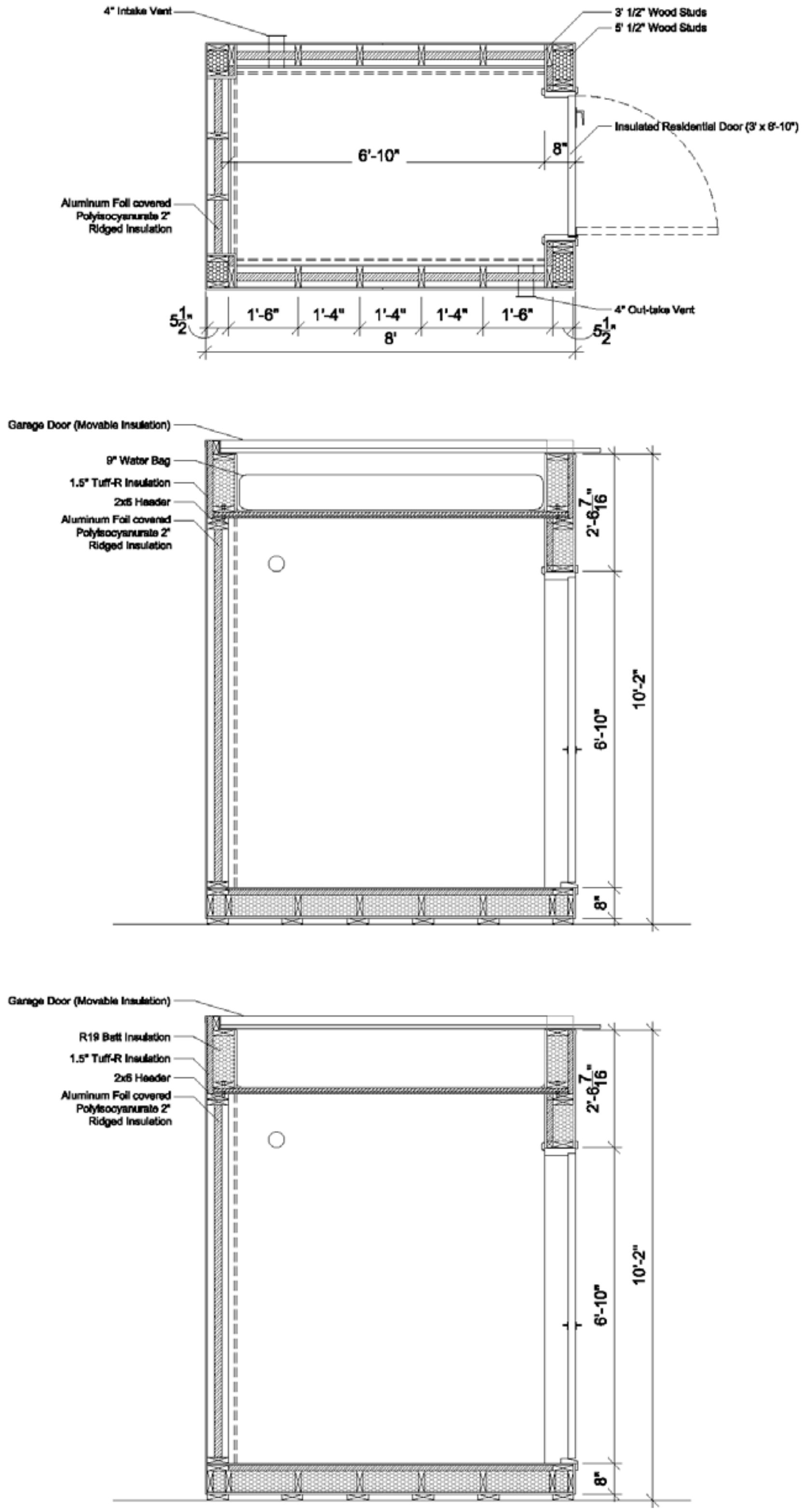


Figure: 4.2 Construction drawing of the UNLV Test-cells second phase (wall insulation and ventilation added)
(Source: UNLV NEAT Lab)

U-Value for the North, South, and West Walls

Wall Element	R-value insulated cavity	R-value studs, plates, headers
Outside air surface 7.5 MPH wind	0.25	0.25
Plywood 1/2"	0.62	0.62
1-3/4" Air space with aluminum foil on one side	3.99	3.99
2" Ridged insulation	9.8	
1-3/4" Air space with aluminum foil on one side	3.99	3.99
Wood stud 2" X 6"		5.5
Plywood 1/2"	0.62	0.62
Inside air surface	0.68	0.68
	R = 19.95 ft².°F.h/Btu	R = 15.65 ft².°F.h/Btu

U-value = 0.0536 h/Btu.ft².°F

Table 4.1 The wall elements R-Values and the U-Value for the north, south, and the west wall

U-Value for the East Wall

Wall Element	R-value insulated cavity	R-value studs, plates, headers
Outside air surface 7.5 MPH wind	0.25	0.25
Plywood 1/2"	0.62	0.62
5-1/2" insulation	19	
Tuff R-insulation 1-1/2"	7.5	3.99
Wood stud 2" X 6"		5.5
Plywood 1/2"	0.62	0.62
Inside air surface	0.68	0.68
	R = 28.67 ft².°F.h/Btu	R = 7.67 ft².°F.h/Btu

U-value = 0.2011 h/Btu.ft².°F

Table 4.2 The wall elements R-Values and the U-Value for the east wall

Figure 4.3a The construction team working on the floor-frame. (Source: UNLV NEAT Lab)

Figure 4.3b Students insulating the floor of both prototypes. (Source: UNLV NEAT Lab)

Figure 4.3c The construction team framing the walls. (Source: UNLV NEAT Lab)

Figure 4.3d The construction team sheathing the prototype. (Source: UNLV NEAT Lab)

Figure 4.3e Prototypes at the end of the first day. (Source: UNLV NEAT Lab)

Figure 4.3f Prototypes completed and operational. (Source: UNLV NEAT Lab)

Description of Roofpond Predicting Formulas

There are two set of predicting formulas resulting from the study, the first phase of the research which took place during 2004 through 2006 and the second phase which took place during summer of 2009. During the first phase as mentioned in the previous chapters both of the test-cells were un-insulated to show the effect of the thermal mass (water bag) on the indoor temperature. However, the formulas generated for this phase will explore the effect of a roofpond system performance to predicted indoor temperature for different location within the western region of the United States. Since the only available data for the second phase was analyzed during the summer of 2009 the result will only go over the cooling effect of the roofpond system performance for the specific location selected in the first phase as mentioned above. Also it's important to keep in mind that the second phase of the research are the same two test-cells used in the first phase with the modification of adding insulation to the rooms.

There are three formulas established based on the research outcome for maximum, average, and minimum predictive indoor temperatures. Each of the formula being used for both the phases and each of the phases, the formula is applied twice one for the Roofpond test-cell (RP) and one for the Control test-cell (CC). With all the formulas corresponding to each of the climatic variable describe in chapter three. However, when more climatic variables are added to the formulas the more of accuracy the predictive indoor temperature are.

First Phase

Control Test-cell (CC)

The first step as described in chapter three was to gather all the weather data and the measured data and analyzed side-by-side. As shown in figure 4.1 for the control test-cell (CC) configuration the result where gathered and plotted in a chart to study the relation between the outdoor and indoor temperature (Fig. 4.4). Therefore, the data was ran through a correlation based on Givoni's method as described in the earlier chapters (see figures 4.5, 4.6, and 4.7). Furthermore, based on the correlation between the two a regression calculation was conducted to generate all the coefficient values for all the variables required to establish the formulas. The formulas generated for the control test-cell for the maximum, average, and minimum predictive indoor temperature are:

Maximum: with correlation coefficient at 94% with the measured data (Fig. 4.8)

$$T_{max.} = 12.07 + [(Sol_{per.avg})(0.003)] + [(Sol_{run.avg.})(0.0015)] + [(Sol_{avg.})(0.0012)] + [(DBT_{per.avg.})(0.3)] + [(DBT_{run.avg.})(0.07)] + [(DBT_{avg.})(-0.14)] + [(DBT_{max.})(0.42)] + [(DBT_{min.})(0.0052)]$$

Average: with correlation coefficient at 95% with the measured data (Fig. 4.9)

$$T_{avg.} = 6.29 + [(Sol_{per.avg})(0.0033)] + [(Sol_{run.avg.})(0.0011)] + [(Sol_{avg.})(0.00017)] + [(DBT_{per.avg.})(0.25)] + [(DBT_{run.avg.})(0.01)] + [(DBT_{avg.})(-0.14)] + [(DBT_{max.})(0.21)] + [(DBT_{min.})(0.32)]$$

Minimum: with correlation coefficient at 93% with the measured data (Fig. 4.10)

$$T_{min.} = 2.86 + [(Sol_{per.avg})(0.0032)] + [(Sol_{run.avg.})(0.00076)] + [(Sol_{avg.})(-0.00063)] + [(DBT_{per.avg.})(0.26)] + [(DBT_{run.avg.})(0.018)] + [(DBT_{avg.})(-0.16)] + [(DBT_{max.})(0.074)] + [(DBT_{min.})(0.49)]$$

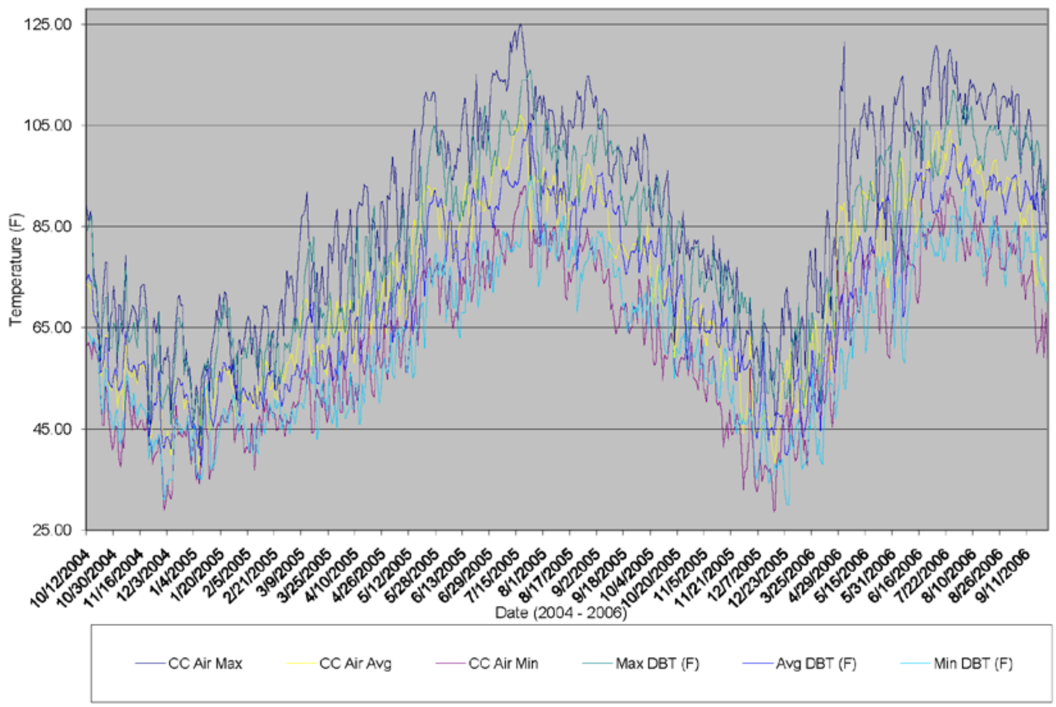


Figure 4.4 Maximum, average, and minimum of the control test-cell (CC) measured indoor temperatures and the outdoor dry bulb temperatures for first phase 2004-2006

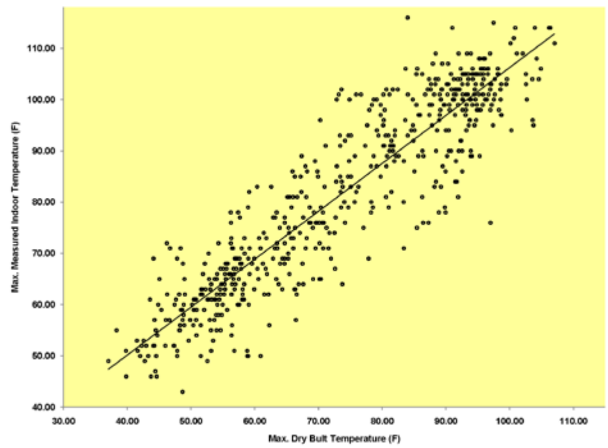


Figure 4.5 Control test-cell (CC) maximum measured indoor temperatures and the outdoor dry bulb temperatures correlation

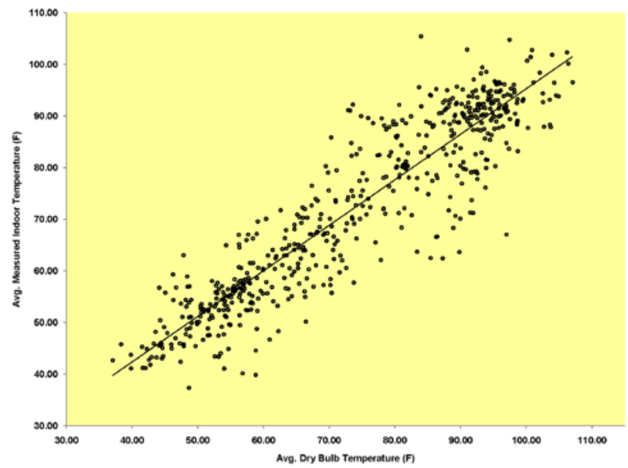


Figure 4.6 Control test-cell (CC) average measured indoor temperatures and the outdoor dry bulb temperatures correlation

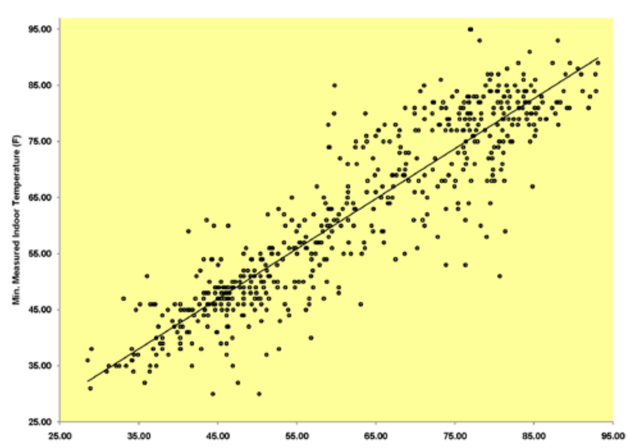


Figure 4.7 Control test-cell (CC) minimum measured indoor temperatures and the outdoor dry bulb temperatures correlation

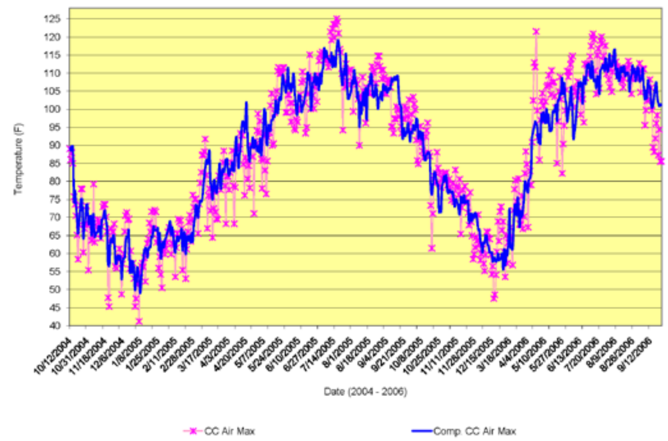


Figure 4.8 Measured and computed maximum temperatures for control test-cell (CC) during 2004-2006

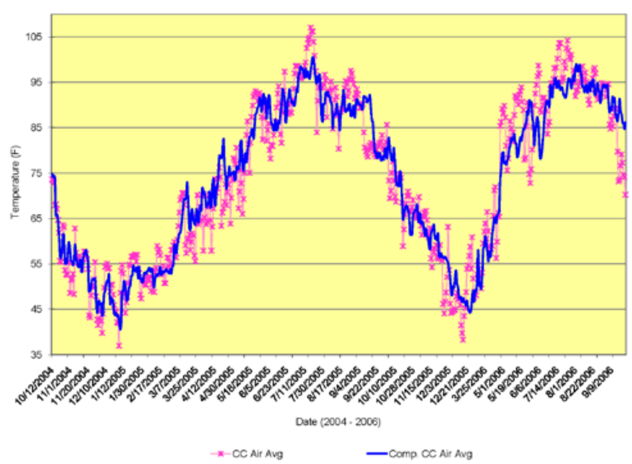


Figure 4.9 Measured and computed average temperatures for control test-cell (CC) during 2004-2006

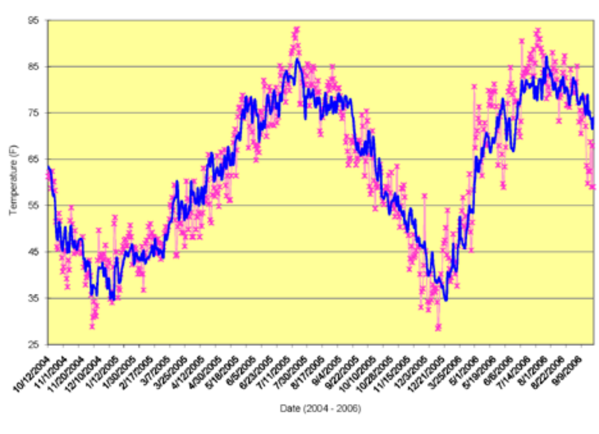


Figure 4.10 Measured and computed minimum temperatures for control test-cell (CC) during 2004-2006

Roofpond Test-cell (RP)

The same procedures were taken as the control test-cell by gathering all the weather data and the measured data and analyzed side-by-side. As shown in figure 4.1 for the roofpond test-cell (RP) configuration the result where gathered and plotted in a chart to study the relation between the outdoor and indoor temperature (Fig. 4.11). Therefore, the data was ran through a correlation based on Givoni's method (see figures 4.12, 4.13, and 4.14). Furthermore, based on the correlation between the two a regression calculation was conducted to generate all the coefficient values for all the variables required to establish the formulas. The formulas generated for the roofpond test-cell for the maximum, average, and minimum predictive indoor temperature are:

Maximum: with correlation coefficient at 93% with the measured data (Fig. 4.15)

$$T_{max.} = 19.5 + [(Sol_{per.avg})(0.0021)] + [(Sol_{run.avg.})(0.0015)] + [(Sol_{avg.})(0.0011)] + [(DBT_{per.avg.})(0.27)] + [(DBT_{run.avg.})(0.09)] + [(DBT_{avg.})(0.24)] + [(DBT_{max.})(-0.18)] + [(DBT_{min.})(0.18)] + [(WBT_{max.})(0.27)] + [(WBT_{min.})(-0.28)]$$

Average: with correlation coefficient at 94% with the measured data (Fig. 4.16)

$$T_{avg.} = 9.07 + [(Sol_{per.avg})(0.0026)] + [(Sol_{run.avg.})(0.0015)] + [(Sol_{avg.})(0.00012)] + [(DBT_{per.avg.})(0.28)] + [(DBT_{run.avg.})(0.05)] + [(DBT_{avg.})(0.23)] + [(DBT_{max.})(-0.09)] + [(DBT_{min.})(0.19)] + [(WBT_{max.})(0.13)] + [(WBT_{min.})(-0.19)]$$

Minimum: with correlation coefficient at 93% with the measured data (Fig. 4.17)

$$T_{min.} = 2.38 + [(Sol_{per.avg})(0.003)] + [(Sol_{run.avg.})(0.0015)] + [(Sol_{avg.})(-0.0006)] + [(DBT_{per.avg.})(0.30)] + [(DBT_{run.avg.})(0.037)] + [(DBT_{avg.})(0.24)] + [(DBT_{max.})(-0.3)] + [(DBT_{min.})(0.15)] + [(WBT_{max.})(0.013)] + [(WBT_{min.})(-0.13)]$$

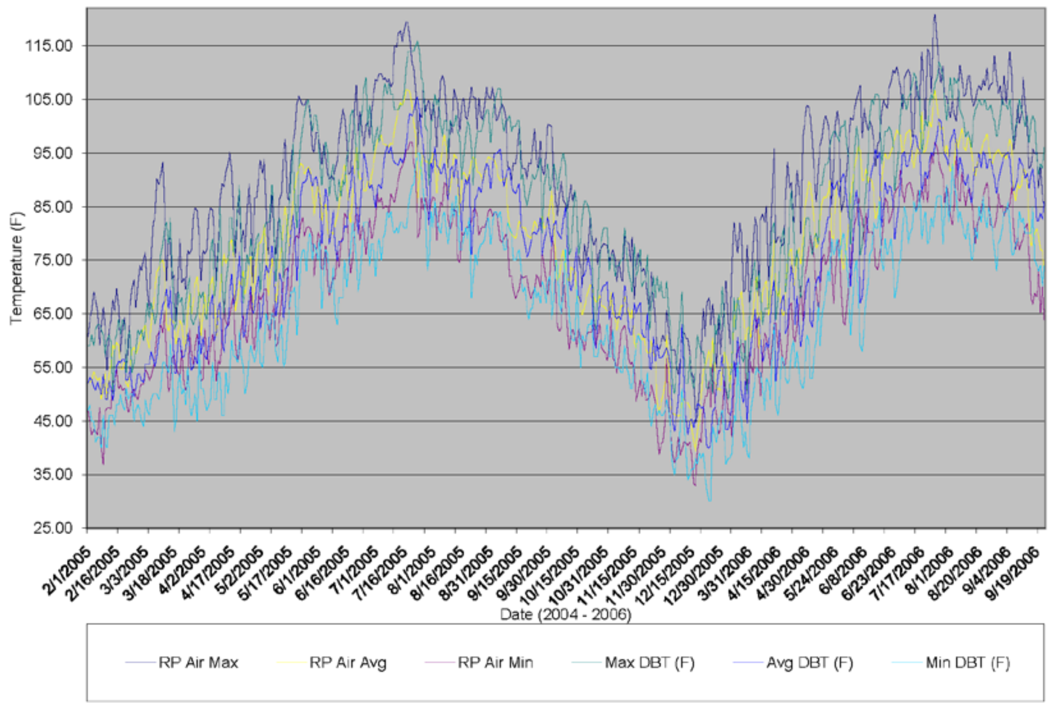


Figure 4.11 Maximum, average, and minimum of the roopond test-cell (RP) measured indoor temperatures and the outdoor dry bulb temperatures for first phase 2004-2006

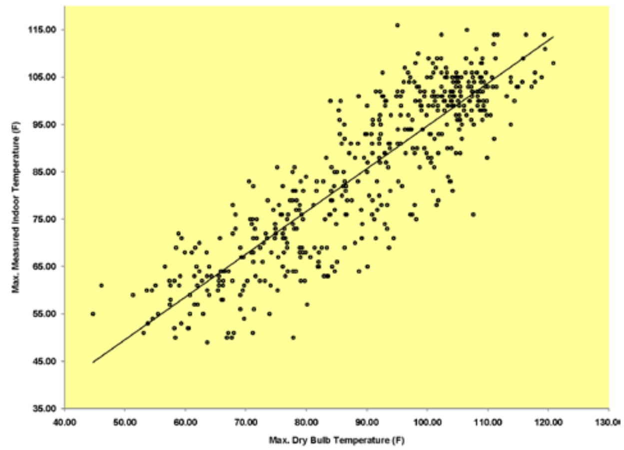


Figure 4.12 Roofpond test-cell (RP) maximum measured indoor temperatures and the outdoor dry bulb temperatures correlation

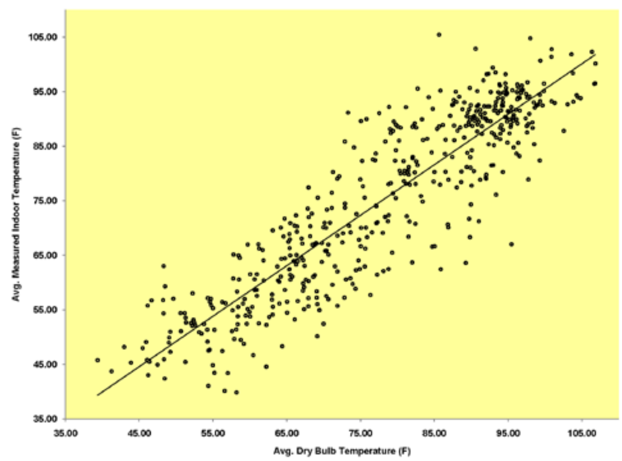


Figure 4.13 Roofpond test-cell (RP) average measured indoor temperatures and the outdoor dry bulb temperatures correlation

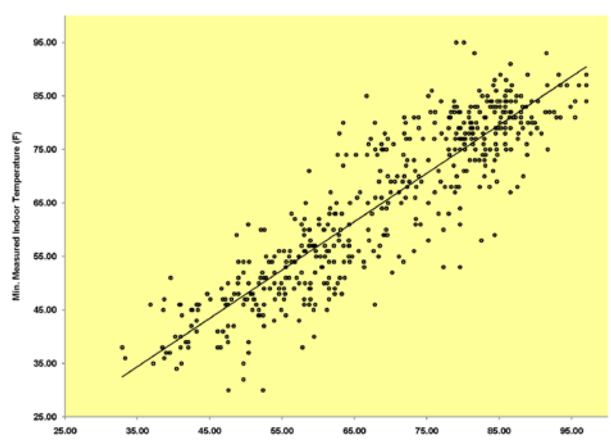


Figure 4.14 Roofpond test-cell (RP) minimum measured indoor temperatures and the outdoor dry bulb temperatures correlation

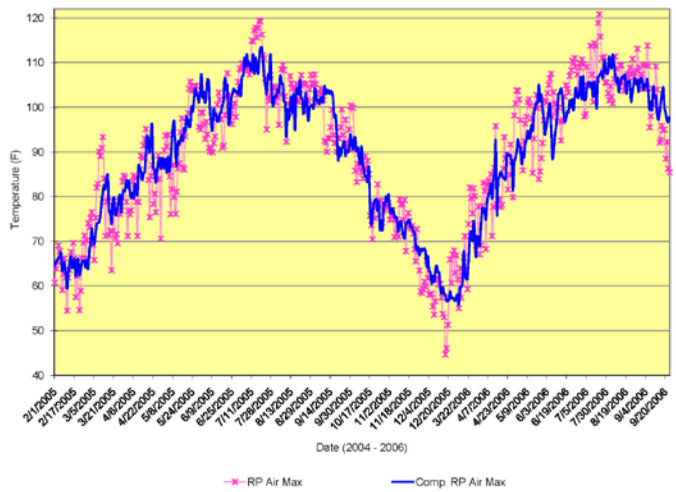


Figure 4.15 Measured and computed maximum temperatures for Roofpond test-cell (RP) during 2004-2006

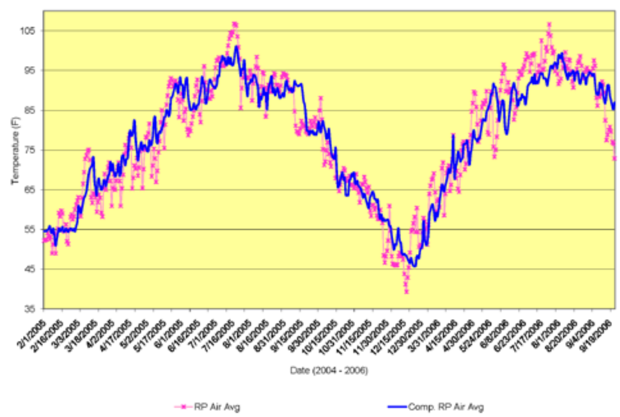


Figure 4.16 Measured and computed average temperatures for Roofpond test-cell (RP) during 2004-2006

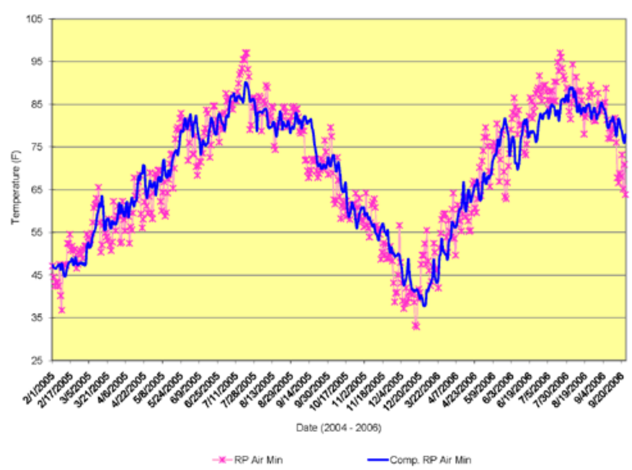


Figure 4.17 Measured and computed minimum temperatures for Roofpond test-cell (RP) during 2004-2006

Second Phase

Control Test-cell (CC)

Again as described in chapter three the first step is to gather all the weather data and the measured data and analyzed side-by-side. As shown in figure 4.2 for the control test-cell (CC) configurations for the second phase the result where gathered and plotted in a chart to study the relation between the outdoor and indoor temperature (Fig. 4.18). Therefore, the data was ran through a correlation based on Givoni's correlation method (see figures 4.19, 4.20, and 4.21). Furthermore, based on the correlation between the two a regression calculation was conducted to generate all the coefficient values for all the variables required to establish the formulas. The formulas generated for the roofpond test-cell for the maximum, average, and minimum predictive indoor temperature are:

Maximum: with correlation coefficient at 85% with the measured data (Fig. 4.22)

$$T_{max.} = -4.55 + [(Sol_{per.avg})(-0.0002)] + [(Sol_{run.avg.})(0.0009)] + [(Sol_{avg.})(-0.0002)] + [(DBT_{per.avg.})(0.31)] + [(DBT_{run.avg.})(0.4)] + [(DBT_{avg.})(0.42)] + [(DBT_{max.})(0.11)] + [(DBT_{min.})(-0.31)] + [(WBT_{max.})(0.3)] + [(WBT_{min.})(-0.1)]$$

Average: with correlation coefficient at 94% with the measured data (Fig. 4.23)

$$T_{avg.} = -4.28 + [(Sol_{per.avg})(-0.00012)] + [(Sol_{run.avg.})(0.00036)] + [(Sol_{avg.})(0.0004)] + [(DBT_{per.avg.})(0.032)] + [(DBT_{run.avg.})(0.45)] + [(DBT_{avg.})(0.68)] + [(DBT_{max.})(-0.0007)] + [(DBT_{min.})(-0.17)] + [(WBT_{max.})(-0.05)] + [(WBT_{min.})(0.06)]$$

Minimum: with correlation coefficient at 96% with the measured data (Fig. 4.24)

$$T_{min.} = -2.13 + [(Sol_{per.avg})(0.0004)] + [(Sol_{run.avg.})(-0.00034)] + [(Sol_{avg.})(-0.00032)] + [(DBT_{per.avg.})(-0.07)] + [(DBT_{run.avg.})(0.42)] + [(DBT_{avg.})(0.54)] + [(DBT_{max.})(-0.06)] + [(DBT_{min.})(0.18)] + [(WBT_{max.})(-0.19)] + [(WBT_{min.})(0.13)]$$

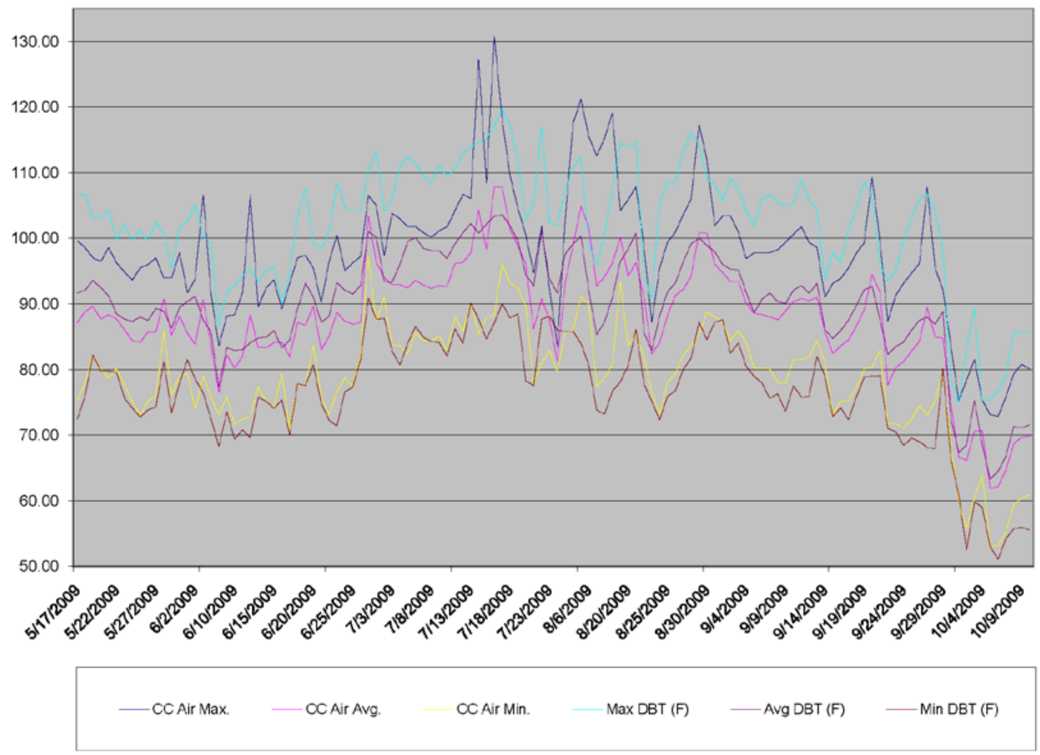


Figure 4.18 Maximum, average, and minimum of the control test-cell (CC) measured air temperatures and the outdoor dry bulb temperatures for second phase summer 2009

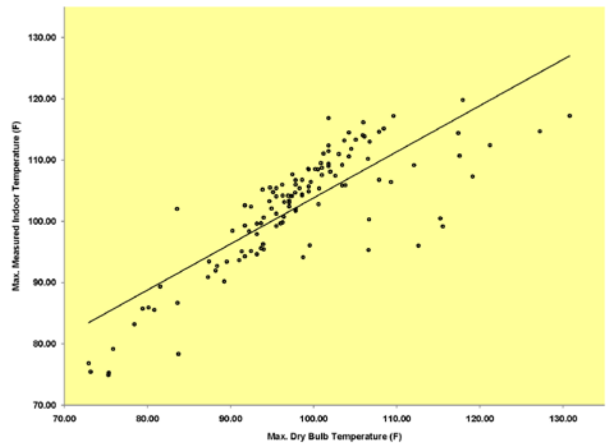


Figure 4.19 Control test-cell (CC) maximum measured indoor temperatures and the outdoor dry bulb temperatures correlation

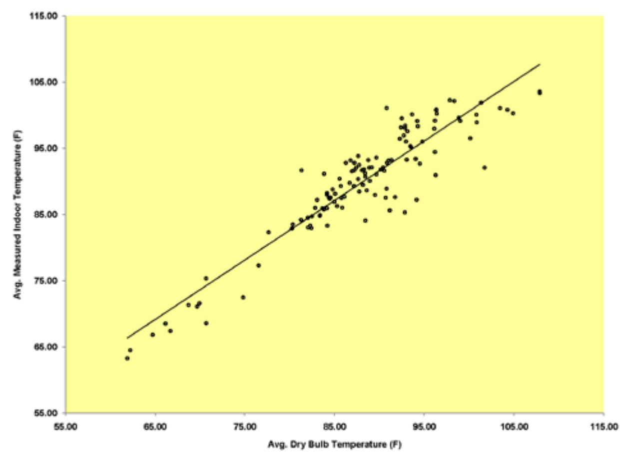


Figure 4.20 Control test-cell (CC) average measured indoor temperatures and the outdoor dry bulb temperatures correlation

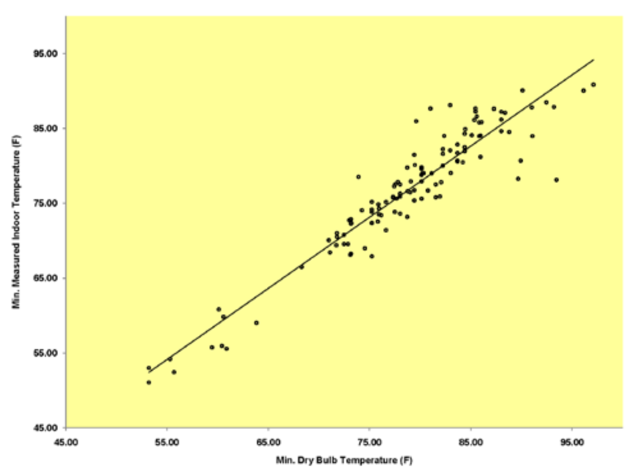


Figure 4.21 Control test-cell (CC) minimum measured indoor temperatures and the outdoor dry bulb temperatures correlation

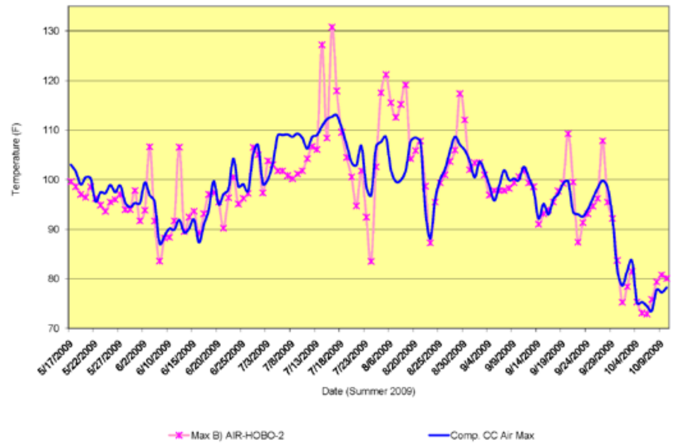


Figure 4.22 Measured and computed maximum temperatures for control test-cell (CC) during summer 2009

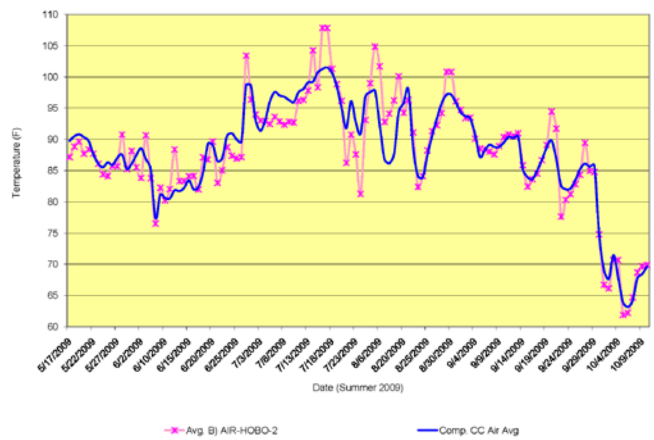


Figure 4.23 Measured and computed average temperatures for control test-cell (CC) during summer 2009

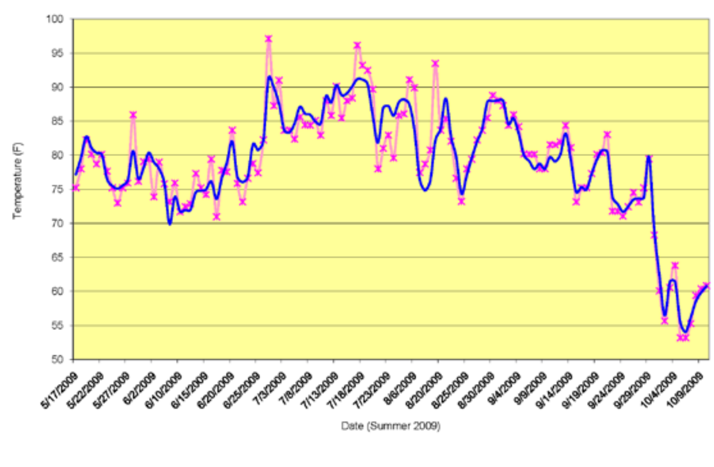


Figure 4.24 Measured and computed mimimum temperatures for control test-cell (CC) during summer 2009

Roofpond Test-cell (RP)

The same procedures were taken by gathering all the weather data and the measured data and analyzed side-by-side. As shown in figure 4.2 for the roofpond test-cell (RP) configuration the result where gathered and plotted in a chart to study the relation between the outdoor and indoor temperature (Fig. 4.25). Therefore, the data was ran through a correlation based on Givoni's method (see figures 4.26, 4.27, and 4.28). Furthermore, based on the correlation between the two a regression calculation was conducted to generate all the coefficient values for all the variables required to establish the formulas. The formulas generated for the roofpond test-cell for the maximum, average, and minimum predictive indoor temperature are:

Maximum: with correlation coefficient at 93% with the measured data (Fig. 4.29)

$$T_{max.} = -30.9 + [(Sol_{per.avg})(0.0003)] + [(Sol_{run.avg.})(-0.00074)] + [(Sol_{avg.})(0.00074)] + [(DBT_{per.avg.})(0.48)] + [(DBT_{run.avg.})(0.7)] + [(DBT_{avg.})(1.06)] + [(DBT_{max.})(-0.2)] + [(DBT_{min.})(-0.68)] + [(WBT_{max.})(-0.25)] + [(WBT_{min.})(0.13)]$$

Average: with correlation coefficient at 95% with the measured data (Fig. 4.30)

$$T_{avg.} = -26.6 + [(Sol_{per.avg})(-0.00021)] + [(Sol_{run.avg.})(0.000009)] + [(Sol_{avg.})(0.0002)] + [(DBT_{per.avg.})(0.45)] + [(DBT_{run.avg.})(0.5)] + [(DBT_{avg.})(0.97)] + [(DBT_{max.})(-0.14)] + [(DBT_{min.})(-0.43)] + [(WBT_{max.})(-0.31)] + [(WBT_{min.})(0.11)]$$

Minimum: with correlation coefficient at 95% with the measured data (Fig. 4.31)

$T_{min.} = -22.24 + [(Sol_{per.avg})(-0.0005)] + [(Sol_{run.avg.})(-0.0000024)] + [(Sol_{avg.})(-0.0000033)] + [(DBT_{per.avg.})(0.47)] + [(DBT_{run.avg.})(0.29)] + [(DBT_{avg.})(1.03)] + [(DBT_{max.})(-0.23)] + [(DBT_{min.})(-0.2)] + [(WBT_{max.})(-0.33)] + [(WBT_{min.})(0.09)]$

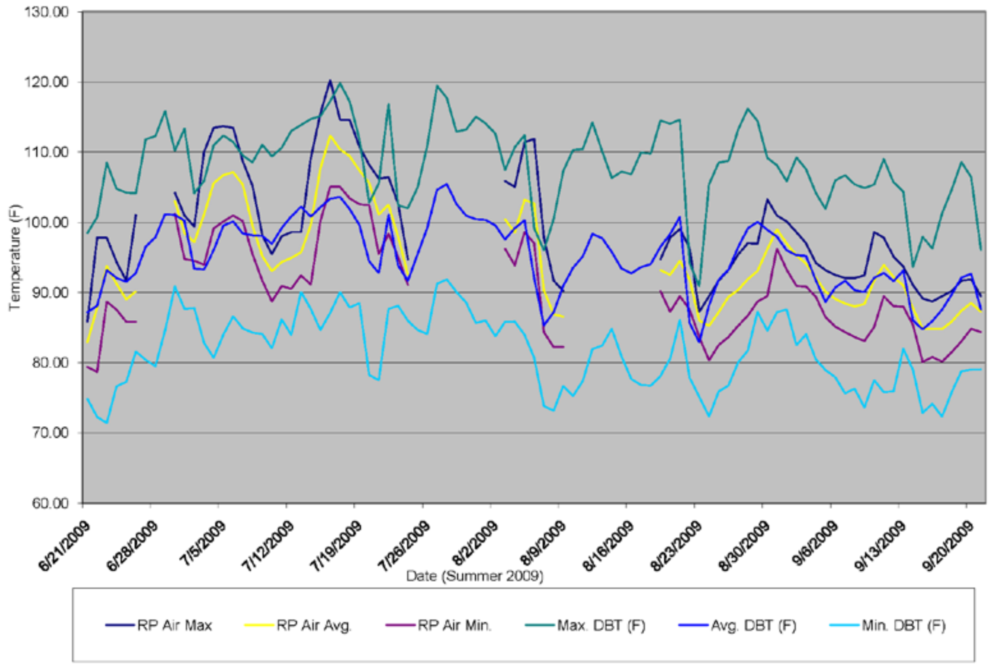


Figure 4.25 Maximum, average, and minimum of the roofpond test-cell (RP) measured air temperatures and the outdoor dry bulb temperatures for second phase summer 2009

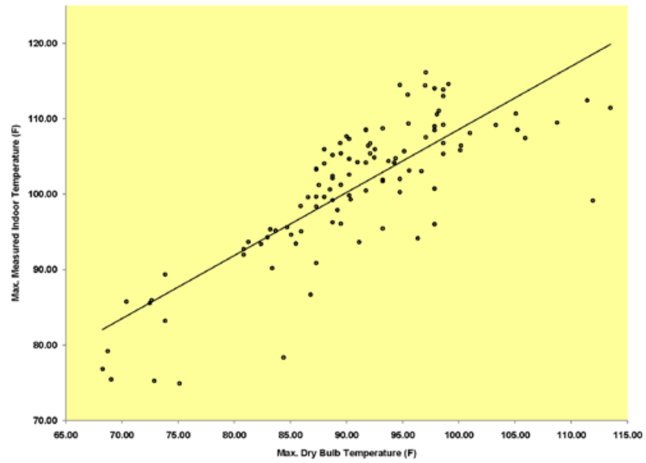


Figure 4.26 Roofpond test-cell (RP) maximum measured indoor temperatures and the outdoor dry bulb temperatures correlation

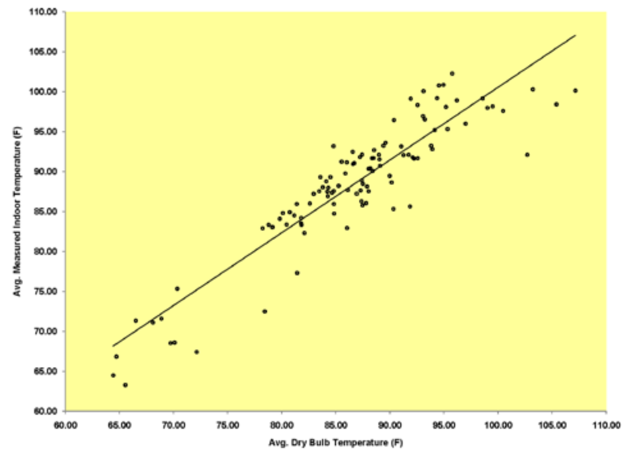


Figure 4.27 Roofpond test-cell (RP) average measured indoor temperatures and the outdoor dry bulb temperatures correlation

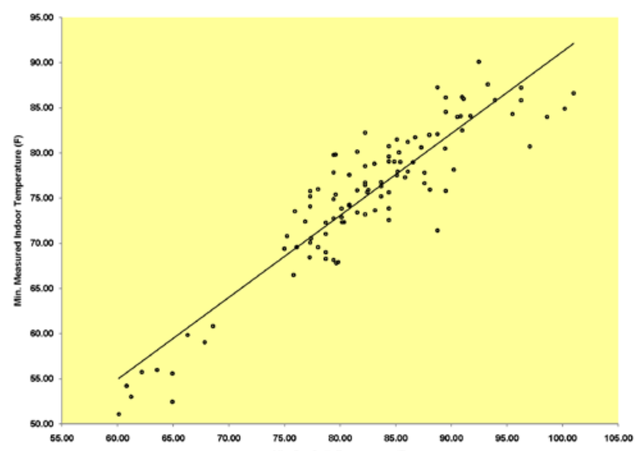


Figure 4.28 Roofpond test-cell (RP) minimum measured indoor temperatures and the outdoor dry bulb temperatures correlation

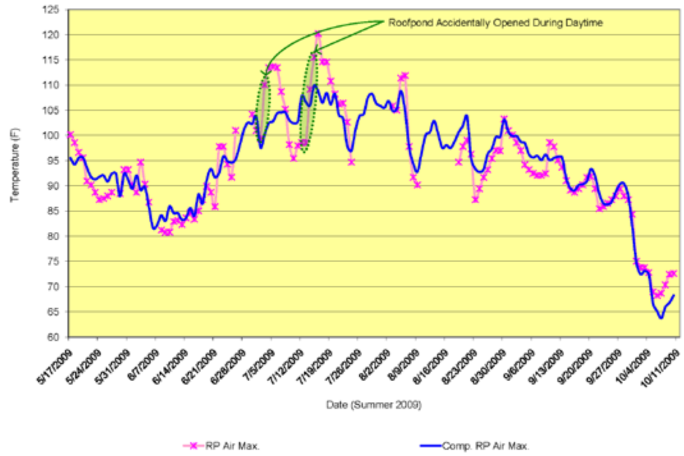


Figure 4.29 Measured and computed maximum temperatures for Roofpond test-cell (RP) during summer 2009

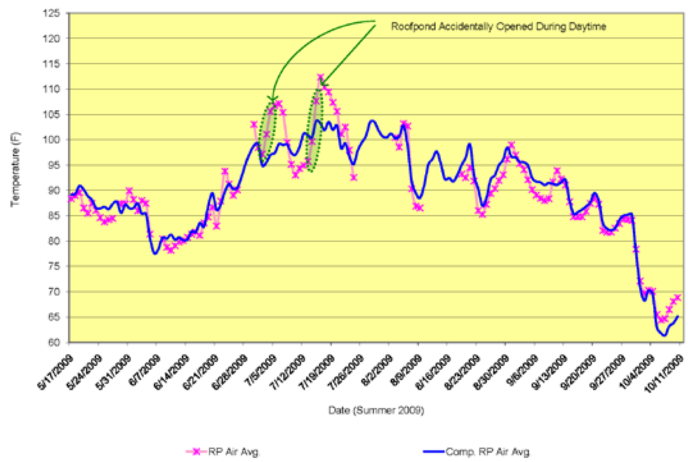


Figure 4.30 Measured and computed average temperatures for Roofpond test-cell (RP) during summer 2009

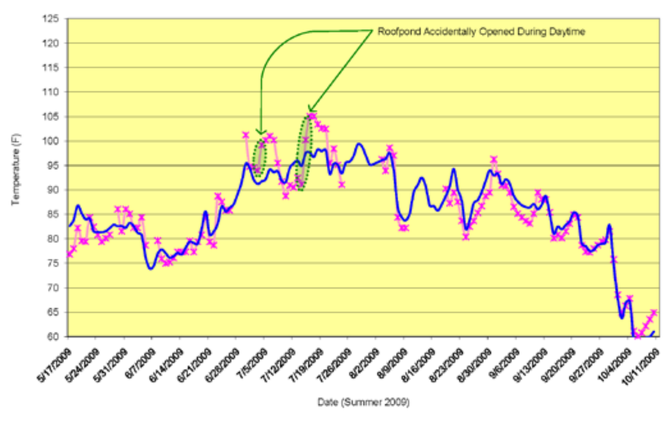


Figure 4.31 Measured and computed minimum temperatures for Roofpond test-cell (RP) during summer 2009

Each of the charts presented above is showing the relation between the measured indoor temperature and the computed indoor temperature generated by the formulas presented in this chapter. However, the correlation between the two presents a pattern that the formulas could predicate the indoor temperature based on the minimum climatic variables. Therefore, based on the information provided by the formulas one can start looking at how a roofpond can perform in such climate in the early stages of design. With this kind of information a model can be developed to look at different options that will help the end result to establish the best possible performance needed for the particular project. As designers we are always looking for ways and methods to study and understand the outcomes; therefore, these formulas are an important tool that can be use for such thing. Especially at times like this when the planet is facing crises and action must be taken quick with result that will help us overcome the future and its problems.

CHAPTER 5

CONCLUSION

Applying Predicting Formulas To Las Vegas Climate

Based on the result of predictive formulas developed by this research, Las Vegas is one of the cities will be analyzed and a model will be created to understand the effectiveness of the roofpond in such climate. The first phase of the research, when both the formulas for the roofpond test-cell (RP) and the control test-cell are analyzed based on the "Typical Meteorological Year "(TMY) data for Las Vegas. A comparison is created to understand the performance of the two rooms (Fig. 5.1). However, the outcomes shows as presented in figure 5.1 the roofpond test-cell's performance based on the maximums and minimums indoor temperatures is about 5 to 6 ºF less than the control test-cell, also the minimums are about 5 to 6 ºF higher than the control test-cell. Therefore, choosing the roofpond over the conventional methods which most buildings are done this way; by using roofpond is in fact a better performance and in the long run it will reduce the cost of operation and maintenance of the building due to passive heating and cooling verse mechanically doing so.

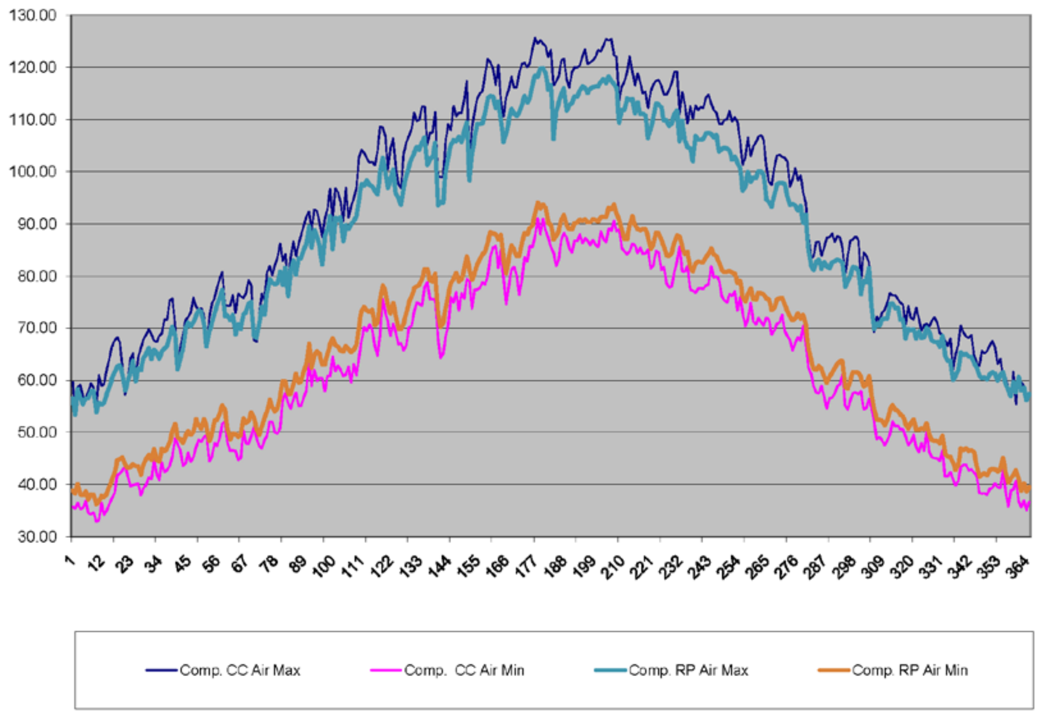


Figure 5.1 Computed indoor temperature for the control test-cell (CC) and the roopond test-cell for Las Vegas TMY based on the predictive formulas

Since the second phase of the research data was collected during the summer; therefore, the predictive formulas were applied to the cooling season performance only. The result from the formulas gives a very clear statement when the computed maximum, average, and minimum indoor temperatures where plotted with the average dry bulb temperature for the Las Vegas TMY climate data. As shown in figure 5.2, the chart explains how the computed maximum indoor temperatures are slightly higher than the average dry bulb temperatures and at time during the cooling season the computed maximum temperatures are even lower than the average outdoor dry bulb temperature. Furthermore, the result shows that the roofpond system performance for Las Vegas climate is an excellent choice for cooling strategy where one can have up to 10 ºF difference between the indoors and outdoors as an result by just using the roofpond as cooling method.

From the outcome of the predictive formulas for the roofpond (RP) and the control (CC) test-cells for the second phase were set side-by-side for performance comparison with outdoor temperatures (Fig. 5.3). The result shows there is a big swing between the maximum and minimum outdoor temperatures where it can be over 20 ºF of difference. Where, looking at the control test-cell (CC) it shows between 15 to 20 ºF of swings between the maximum and minimum temperatures. However, the roorpond shows only 5 to 10 ºF which explains how roofpond is a reliable system to be used for cooling for its consistency in maintaining the temperature at a constant level throughout the day and night (Fig. 5.3). See figures 5.4 through 5.9 for the correlation comparison of the result for the Las Vegas cooling season based on the predictive formulas.

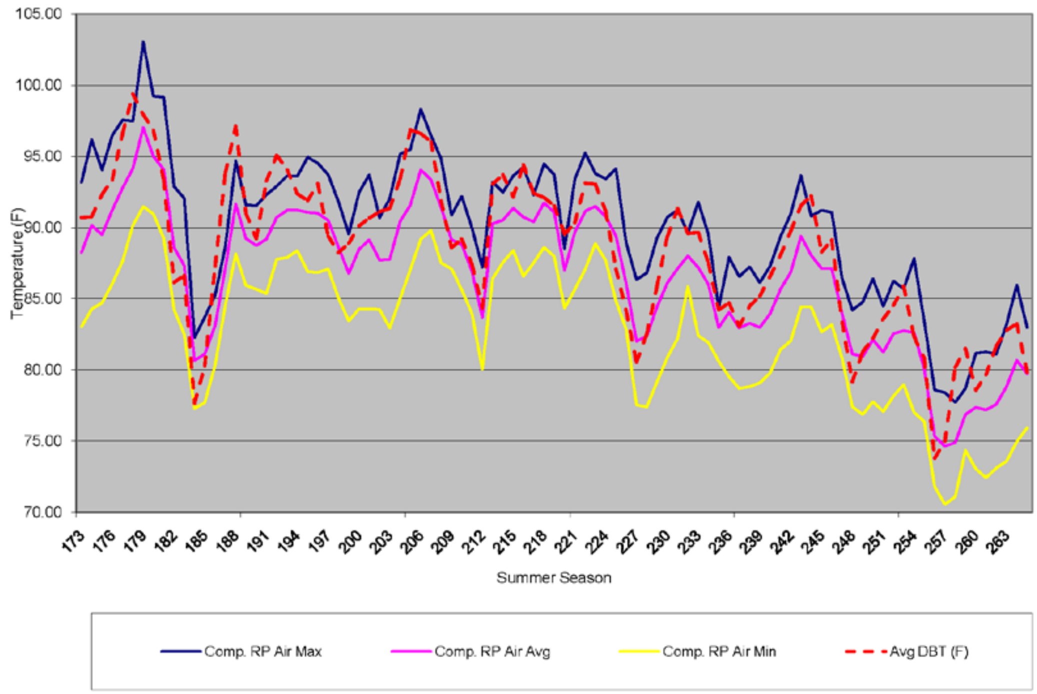


Figure 5.2 Computed maximum, average, and minimum indoor temperature for the roofpond test-cell (RP) and average dry bulb temperature for Las Vegas TMY based on the second phase predictive formulas

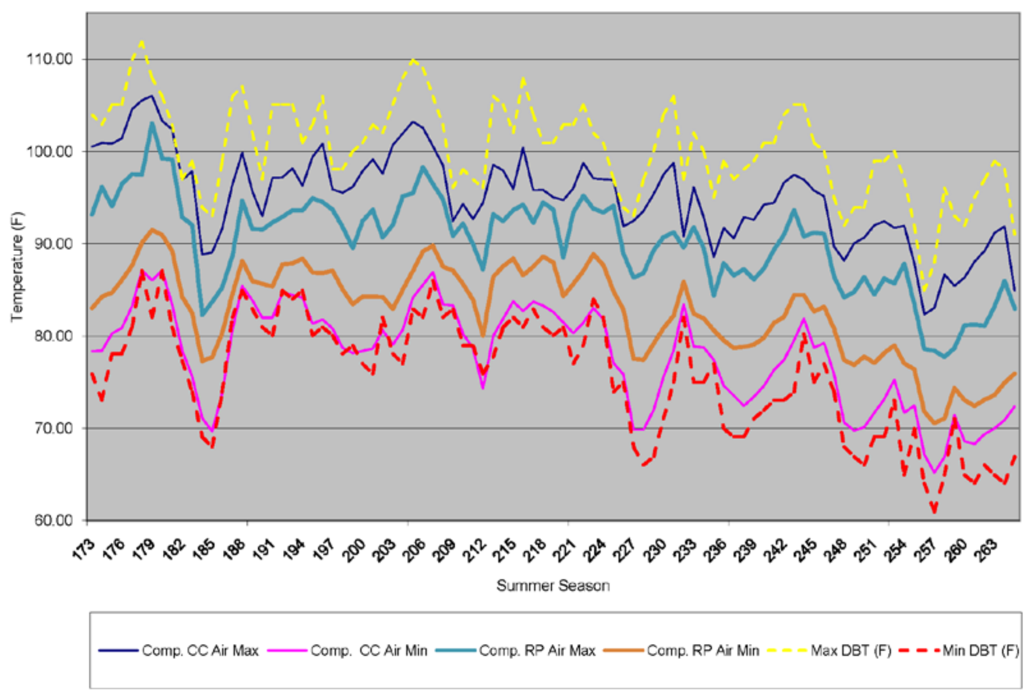


Figure 5.3 Computed maximum and minimum indoor temperature for the control test-cell (CC), roofpond test-cell (RP) and dry bulb temperature for Las Vegas TMY based on the second phase predictive formulas

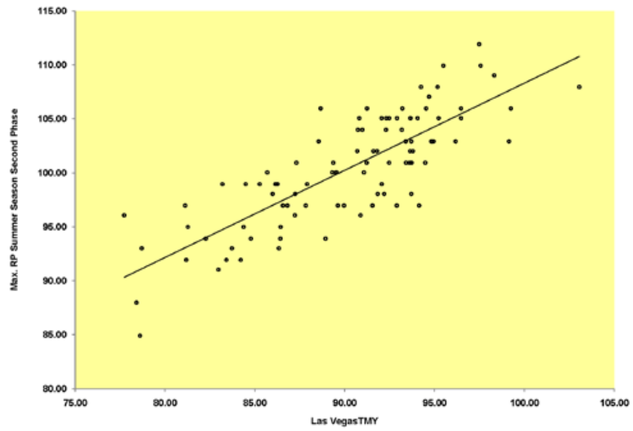


Figure 5.4 Correlation between the computed roofpond maximum predicted indoor temperature and the maximum outdoor temperature of Las Vegas TMY for the cooling season

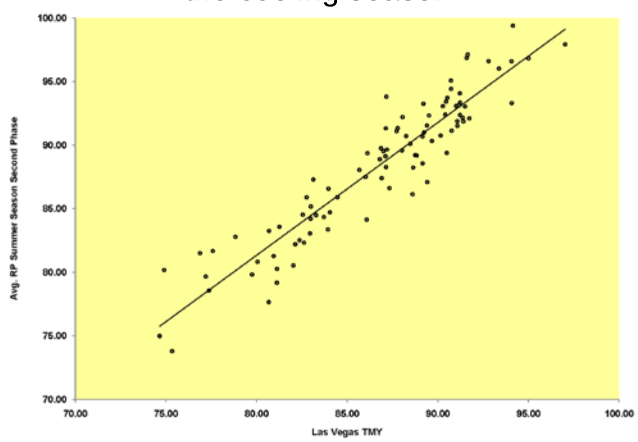


Figure 5.5 Correlation between the computed roofpond average predicted indoor temperature and the average outdoor temperature of Las Vegas TMY for the cooling season

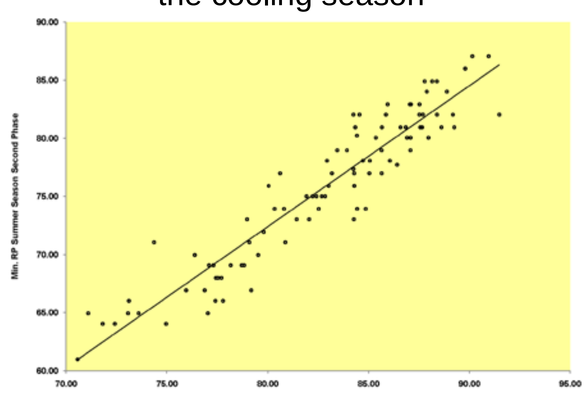


Figure 5.6 Correlation between the computed roofpond minimum predicted indoor temperature and the minimum outdoor temperature of Las Vegas TMY for the cooling season

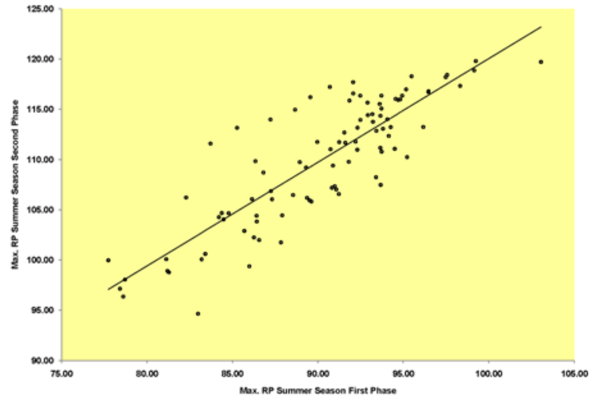


Figure 5.7 Correlation between the computed roofpond maximum predicted indoor temperature for the first phase and the second phase based on Las Vegas TMY for the cooling season

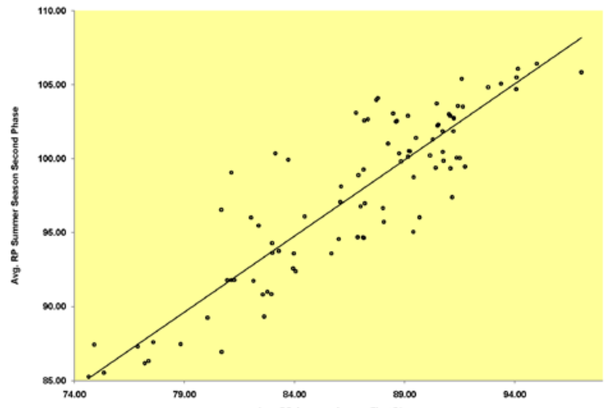


Figure 5.8 Correlation between the computed roofpond average predicted indoor temperature for the first phase and the second phase based on Las Vegas TMY for the cooling season

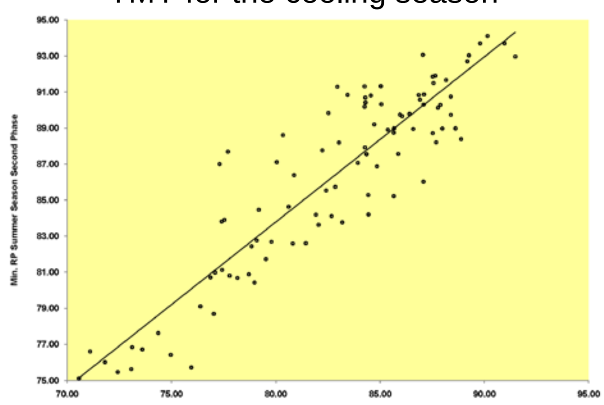


Figure 5.9 Correlation between the computed roofpond minimum predicted indoor temperature for the first phase and the second phase based on Las Vegas TMY for the cooling season

Recommendations for Further Study

The formulas generated by this study can be further developed to become a tool that can be used for the schematic stage of a design process. The tool can consist of a developed software that contain basic weather data from different city around the world that one can easily see the outcomes of a roofpond system performance in that particular city or climate region. This will tool could be further develop to combine other passive design strategies to show the use of individual system or combination of different systems to achieve the highest performance possible for passively heating and cooling.

APPENDIX 1

RENO, NV RESULT

The result for the performance of roofpond based on the predicting formulas generated by this thesis:

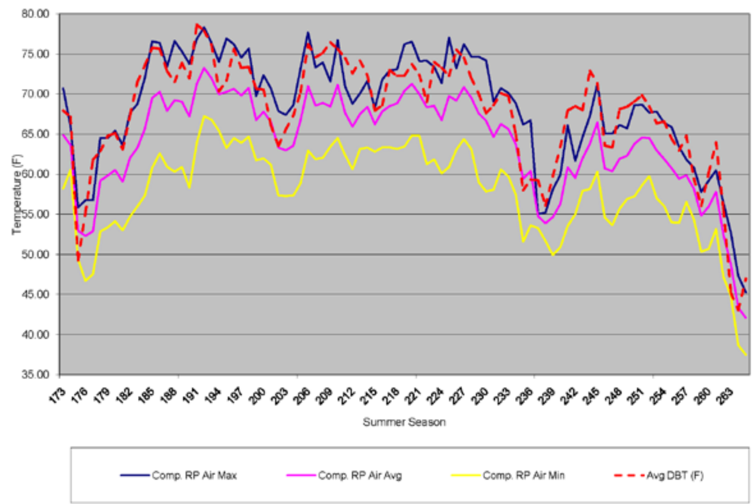


Figure A1.1 Computed maximum, average, and minimum indoor temperature for the roofpond test-cell (RP) and average dry bulb temperature for Reno TMY based on the second phase predictive formulas

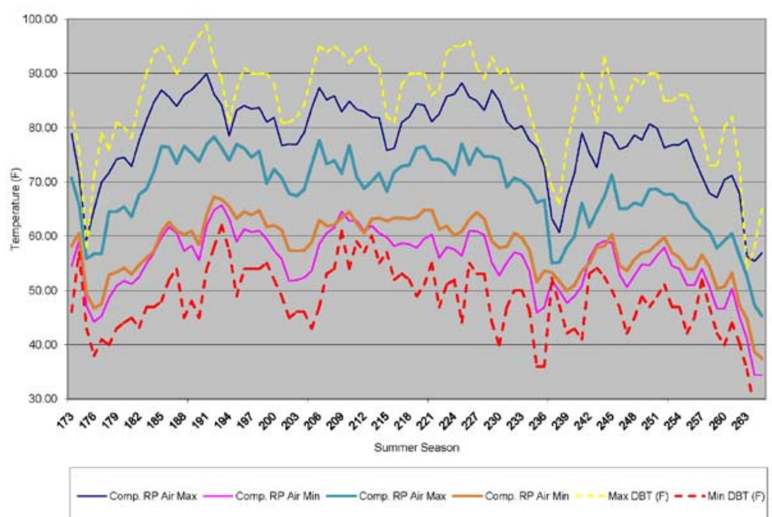


Figure A1.2 Computed maximum and minimum indoor temperature for the control test-cell (CC), roofpond test-cell (RP) and dry bulb temperature for Reno TMY based on the second phase predictive formulas

APPENDIX 2

ELY, NV RESULT

The result for the performance of roofpond based on the predicting formulas generated by this thesis:

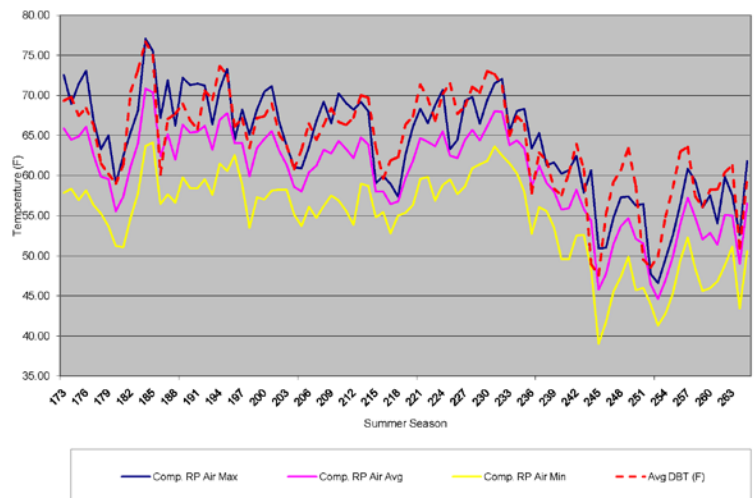


Figure A2.1 Computed maximum, average, and minimum indoor temperature for the roofpond test-cell (RP) and average dry bulb temperature for Ely TMY based on the second phase predictive formulas

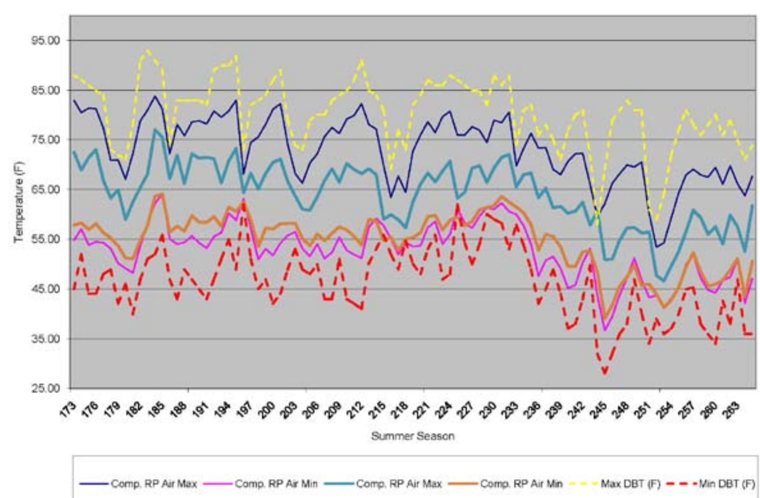


Figure A2.2 Computed maximum and minimum indoor temperature for the control test-cell (CC), roofpond test-cell (RP) and dry bulb temperature for Ely TMY based on the second phase predictive formulas

APPENDIX 3

TONOPAH, NV RESULT

The result for the performance of roofpond based on the predicting formulas generated by this thesis:

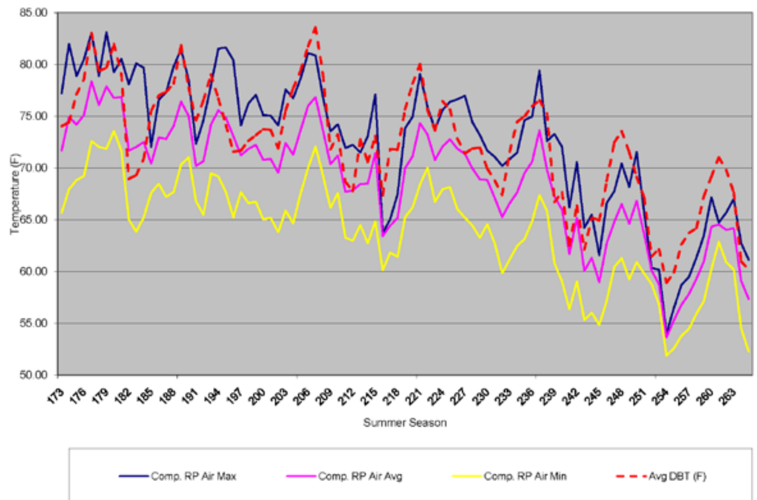


Figure A3.1 Computed maximum, average, and minimum indoor temperature for the roofpond test-cell (RP) and average dry bulb temperature for Tonopah TMY based on the second phase predictive formulas

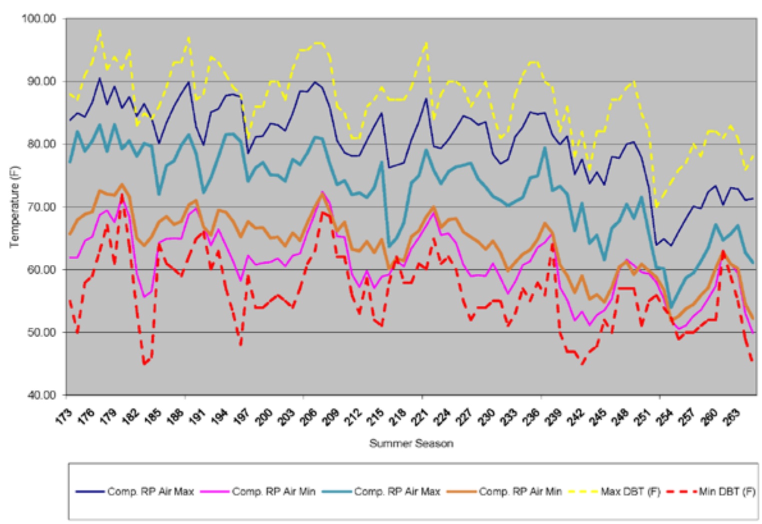


Figure A3.2 Computed maximum and minimum indoor temperature for the control test-cell (CC), roofpond test-cell (RP) and dry bulb temperature for Tonopah TMY based on the second phase predictive formulas

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VITA

Graduate College
University of Nevada, Las Vegas

Ibrahim Kivarkis Kako

Degrees: Bachelor of Science in Architecture, 2006
University of Nevada, Las Vegas

Special Honors: Top of the Class with Honors in Architecture - Fielden Medal Award.

Thesis Title: Empirically Derived Formulas to Predict Indoor Maximum, Average, and Minimum Temperatures in Roofpond Buildings Using Minimum Climatic Information

Thesis Examination Committee:
Chairperson, Alfredo Fernandez-Gonzalez, M. Arch.
Committee Member, Robert Dorgan, M. Arch.
Committee Member, Daniel Ortega, M.L.A.
Graduate Faculty Representative, Robert Boehm, Ph. D.