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Building Integrated Aquaculture

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BUILDING INTEGRATED AQUACULTURE

A Thesis Presented

by

ERIK A. WOODIN

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Building Integrated Aquaculture

A Thesis Presented

By

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DEDICATION

To my beautiful lady, for her love and support

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I would like to thank my team of advisors, David Damery, Andy Danylchuk, and James Webb, whose knowledge and help made this thesis possible. I’d also like to thank Craig Hollingsworth, Paul Fisette, and Simi Hoque for their resources, ideas, and guidance in this research.

ABSTRACT

BUILDING INTEGRATED AQUACULTURE

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Directed by: Professor David Damery

Exploratory research into a fresh concept, building integrated aquaculture, has found new information on the topic. Motives indicating building integrated aquaculture is important for sustainable development were identified. A review of the literature found relatively little in the way of experiments, aquaculture operations, and case studies which documented or demonstrated a deep understanding of the interactions between building and aquaculture systems. A simple experiment was conducted observing thermal energy and moisture interactions in simulated aquaculture facilities, some with tank covers and insulation. Two different retrofit programs were developed in a case study of building integrated aquaculture for an existing structure on the campus of the University of Massachusetts.

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CHAPTER 1

INTRODUCTION

It is becoming increasingly difficult to satisfy the global demand for fish with harvests from natural fisheries. Rapid human population growth has encouraged overfishing and pollution which reduce the productive capacity of natural fisheries. The increasing demand for fish may best be answered by increasing aquaculture instead of intensifying fishing activities (FAO 2010). Slowly but surely, modern technology has allowed fishers to pull larger harvests from more and more natural fisheries. Half of the world's fisheries are fully exploited and another quarter is overfished, depleted, or in recovery from depletion (FAO 2010). When fisheries are at or over their limit to support harvest, it drives the market value of fish up and intensifies competition amongst fishers. There are significant efforts to manage many fisheries, but management is difficult and costly and may deliver limited results.

The cost and challenge of maintaining healthy fisheries is increasing and many consumers have become more aware of the almost unavoidable and irreconcilable damages some commercial fishing practices inflict on the environment. The perceived value of cultured species of fish when compared with their wild caught counterparts has grown. This is largely due to the growing concern for the environment damaged by commercial fishing, damages which aquaculture, for the most part, avoids. However, the choice for these consumers selecting wild vs. caught fish is not easy, as aquaculture has its own host of environmental concerns. Amongst these are the high embodied energy of aquaculture products and the impact of waste by products.

Many tons of fish are produced each year in aquaculture facilities around the world, reducing the strain on natural fisheries while generating a profit for the aquaculture business owners (FAO 2010). Facilities with large containers located near or in a source of the required water and in a climate well suited to the needs of the target species have a competitive advantage. Operations like this aim to exploit economies of scale, maximizing the volume of water cultivating fish but also benefit from the hospitable environment. Many facilities must limit the volume of water used for cultivation because the host environment places restrictions on them, like building dimensions, waste treatment capacity, and availability of water.

Generally speaking, cultivation costs increase as the production location and conditions become more removed from the cultivated species' ideal habitat. Truly efficient cultivation requires a host environment which can continuously provide the conditions necessary for healthy growth of the target aquaculture species. From a systems perspective, most efficient production happens when the necessary conditions are available close to where the demand for cultured fish is located. However, a multitude of commercial aquaculture facilities are far removed from the most intensive markets that they serve (Wurts 2000). Most markets are in climates which don't well enough resemble the climate of target aquaculture species ideal habitat. This difference precludes the use of inexpensive outdoor aquaculture near or within these markets.

Without the appropriate climate, costs and considerations for aquaculture production can be overwhelming. Aquaculture facilities in temperate regions would require substantial host structures to maintain the proper conditions for cultivating popular species. Fish require water in a specific temperature range with the appropriate gas and chemical compositions as part of their cultivation. Recreating ideal growth conditions for warm or cold water species in a temperate climate often requires mechanical systems and a structure that can be expensive to purchase and operate. These costly considerations all contribute to current conditions which make globally distributed aquaculture products more common than locally distributed products.

Climate conditions are not the only barriers for localized aquaculture production. Consider that an urban setting may have higher rent costs, difficult building codes, existing structures of concrete and steel, a lack of wetlands, no local water supply, and a host of other potentially costly problems. Aquaculture facilities in areas which are rural and within a hospitable climate often can avoid these additional expenses, but typically incur the additional cost of exporting goods to distant markets. Through the marvel of modern technology and transportation, consumers in many affluent areas enjoy culinary delicacies made with aquaculture products grown quite literally on the other side of the planet.

The relatively common practice of exporting aquaculture products from remote locations with preferable conditions to distant markets has some noticeable shortcomings (Wurst 2000). This aquaculture production model supports fish harvest which in turn reduces pressure on fisheries and avoids damage to fragile marine habitats, but it can also increase the embodied energy of fish when compared to their wild caught counterparts (Folke & Kautsky 1992). The environmentally concerned consumer is often required to choose between the lesser of two evils when shopping for fish, either one which is harvested in a fashion which may be detrimental to the species natural habitat and another which is transported a very long distance by the force of combusted fossil fuel. These consumers also must consider that many traditional aquaculture practices have a negative environmental impact at multiple spatial scales. In general, people are becoming increasingly aware of their role in the food system. More people prefer to buy food that is locally grown, organic, or provides some other environmental or social benefit. These consumers provide a loyal clientele for more than four thousand farms in North America involved in community supported agriculture (Local Harvest 2011).

From a commercial standpoint, additional costs associated with transportation and production may force many aquaculture endeavors to raise their product prices when fuel prices increase. Wild caught fish which compete with aquaculture produced fish are sometimes shipped to distant markets as well. However, fishing from natural stocks avoids some of the costs associated with cultivating the species. This challenging economic situation is detrimental to the success of more sustainable food systems through aquaculture. In spite of a growing preference among consumers for environmentally friendly goods, the most price competitive product often will attract a larger market share than its competitors.

The practice of producing aquaculture products for shipment to distant consumers is not sustainable in the long term. Perhaps the embodied energy and resulting cost increase can be reduced by focusing on a local scale production model. This practice would avoid the environmental damages associated with commercial fishing while avoiding the extra embodied energy accrued from long distance transportation. Smaller scale production may also make the environmental damages from aquaculture more manageable and less severe. For some communities which are located in the ideal clime and have aquaculture producers, this model of a local sustainable food system could be more easily implemented. However, as pointed out earlier, many millions of dollars of fish products are exported to distant continents every year (FAO 2010). Local aquaculture production sufficient to meet the demand for fish in an area which is temperate, arid, and/or urban would need to overcome significant logistical barriers in order to be successful.

As the market for local scale aquaculture becomes more removed from ideal conditions, more inputs and resources become necessary. One option to manage the additional requirements for successful aquaculture in less than ideal climates is through conserving energy and innovative facility design. Hosting intensive aquaculture in the built environment can prove a daunting task for even the most qualified facility designers. Aquaculture has a large impact on building humidity and indoor air quality, most especially in temperate climates. High moisture levels can degrade materials in the built environment and create hospitable conditions for bacteria and mold growth.

The building system is radically impacted by and connected to the aquaculture system which it houses and vice versa. A facility design which does not accommodate the needs of the aquaculture system can cause failures in either or both of the systems. On the other side of the coin, aquaculture practices which do not aim to minimize the strain put on the building system can lead to failure in either or both of the systems. Successfully designing a building system which is complimentary or integrated with the aquaculture system poses many challenges.

Without integrated system design, indoor aquaculture operations far removed from the cultured species habitat are exposed to rising energy prices and increasing the embodied energy of their product (Odum 1988, Vassalo et al. 2007). This, unfortunately, can cost these operations the advantage over their competitors which ship their products long distances. It is possible that this barrier to widespread local aquaculture can be managed with energy conserving building design. However, such an approach may forego the exploitation of possible synergies which exist between the systems and new practices and technologies may be overlooked.

A new holistic design approach for aquaculture facilities needs to be developed to help make local scale production a reality in areas which are inhospitable to traditional aquaculture practices. This new approach would aim to provide a facility well suited to the needs of the aquaculture system, which would in turn minimize the strain put on the building system. Underlying the whole design process would be a focus on capturing synergies and minimizing required energy input. The term used to describe this new approach and whole system thinking is building integrated aquaculture (Danylchuk 2010). This new concept merges ideas explored in both building integrated agriculture (Caplow 2010) and solar aquaculture (Zweig et al. 1981, Barnhart 2006, Fuller 2006).

In this exploratory research, an experiment is conducted observing the temperature and relative humidity in a simulated aquaculture facility. In addition, two options for retrofitting a structure to host aquaculture are developed in a design case study. Building integrated aquaculture could not be found amongst available publications, but there is research which highlights the importance of studying the aforementioned problems (Wurts 2000, FAO 2010) and some which supports the ideas in this research (Zweig et al. 1981, Barnhart 2006, Fuller 2006, Caplow 2010). Experiments which document the interaction between building and aquaculture systems do not yet exist, highlighting the need for research into this area. This research will help form a foundation for a new way of thinking in aquaculture design and may provide useful insight for future research into better practices and technologies for aquaculture.

CHAPTER 2

RESEARCHING BUILDING INTEGRATED AQUACULTURE

Overview

Designing a building integrated aquaculture system is a complex task. There are many problems that arise when the needs of an aquaculture system and a building system both need to be met in a single structure. To prepare for these challenges, both systems need to be understood so important issues can be anticipated and researched. Information useful for successfully integrating these systems is not collected in a single text or publication, but is found amongst a myriad of scientific fields. The frameworks of very different disciplines must be merged as well as ideas. In this overview of some of the relevant literature, topics related to occupant health, energy conservation, and waste treatment in the building integrated aquaculture system are reviewed.

Ventilation

Mold and moisture sources should be considered throughout the construction and operation of any structure (Pinckney 2009). In a building integrated aquaculture system, there are many significant and uncommon sources of moisture throughout the structure. The control and management of moisture is paramount if the building integrated aquaculture system is to be successful. Data and research related to the ventilation of aquaculture facilities found during this review was very limited, despite its great importance. This may be another indication of the importance of developing a building system approach for aquaculture design.

One model of two aquaculture facilities in temperate Australia was found which considered the relationship between humidity, interior and exterior temperature (Fuller 2006). The research employed a hypothetical model to determine the energy saving impact that solar direct hot water systems of varying capacity might have when integrated with an aquaculture system. This study pointed out that the common remedy for excessive condensation, increasing ventilation, will increase the energy load of the system. In addition to supporting the integration of solar direct hot water with aquaculture, Fuller concluded that both ventilation and covered tanks can limit conditions which are conducive to condensation. In a building integrated aquaculture system, it is advisable to have both features in place.

Occupant Health

Ventilation must be effective and responsive to changing conditions in order to maintain a healthy indoor environment well-suited for the production of food products. Mold and moisture sources should be considered throughout the construction and operation of any structure (Pinckney 2009). Building systems that fail to control the abundance and flow of moisture in the indoor environment can put the health and productivity of the occupants at risk (Meklin et al. 2005, Mendell et al. 2006, Loftness et al. 2007, Pinckney 2009).

The occupants of a structure have a significant impact on the quality indoor air, in terms of their behavior and building management practices (Loftness et al. 2007). One study found that infrequent cleaning of heating, ventilation, and air conditioning components and past water damage in basements were strongly associated with lower respiratory symptoms (Mendell et al. 2006). This study also found a strong association between mucous membrane symptoms and infrequent mechanical system cleaning as well as past water damage in any mechanical room. Other research has shown that moisture damaged schools have lowered airborne microbial concentrations and reported instances of respiratory symptoms by fixing moisture damage in the structure (Meklin et al. 2005). This information suggests that indoor aquaculture facilities which have existing moisture damage should consider repairs if they are concerned for the health of their employees.

Energy Efficiency

Focusing on energy efficiency can help meet the sustainable goals of the building integrated aquaculture system. There are a number of ways to reduce the consumption of energy in the building system (Johnston & Gibson 2008). Using higher efficiency lights, heating, ventilation, and air conditioning systems is a simple solution, but often expensive. Less heating or cooling energy will be lost with a complete and robust thermal envelope made of material with a low overall heat transfer coefficient, or u value. Also, in some circumstances it is possible to use passive features like biological shading or thermal mass to reduce overall energy requirements of the structure (Fernandez-Gonzalez 2006).

Passive Heating

There are a variety of passive solar heating strategies of various cost and design which can be used to offset the heating needs of a structure in the winter time (Fernandez-Gonzalez 2006). Generally, the more successful strategies aim to store solar energy within a material with high thermal mass like concrete or water. The New Alchemy Institute successfully designed aquaculture systems in Massachusetts that captured and retained solar energy, in a system they call solar pond aquaculture (Zweig et al. 1981). Solar pond efficiency is boosted when the water is exposed to the sun in a greenhouse and integrated with a solar direct hot water collector (Fuller 2006).

On-site Energy

Producing energy on-site has been an increasingly popular choice in green building. This solution approaches the building energy demand problem from the supply side, instead of the demand. In terms of sustainable development, this is a great choice as most of the means of on-site production are considered to produce clean energy. Common choices for onsite electricity production include photovoltaic panels and wind turbines, technologies which have both grown in popularity and efficiency (Gross et al.

2003). Gross et al. concluded that photovoltaic technologies would grow more in efficiency than wind turbines in the next twenty years, but both technologies could be competitive with fossil fuel alternatives.

Material Selection

Careful consideration will have to be taken while selecting materials for a building integrated aquaculture facility. Materials which balance the needs of the structure with the interests of the environment must be used. Where possible, materials should be selected which are sustainably, locally, and/or responsibly produced. The production, delivery, installation, and disposal of construction materials all may produce negative impacts on the environment. Recent research efforts have been made to develop methods of quantifying and mitigating these and other impacts which occur throughout the building's life cycle (Gangolells et al. 2009).

Moisture is the pressing concern when designing or retrofitting a structure to host aquaculture and its effect on building materials must be taken into consideration. There are some interior finishing materials with some useful moisture buffering capacity, like common drywall gypsum board. These building materials can absorb and release moisture offering support to ventilation systems in stabilizing the relative humidity of the indoor environment (Rode & Grau 2008). However, these materials may not be the best option for moisture intensive spaces in a building integrated aquaculture system. Uncovered tanks and other aquaculture components may evaporate enough moisture into the interior environment to saturate absorptive materials, resulting in mold and decay.

Embodied Energy

The building materials and activities associated with their manufacture, harvest, installation, and disposal all contribute to the embodied energy of the structure. Embodied energy, sometimes quantified in units of eMergy, is the total amount of solar energy required directly or indirectly to make a product (Odum 1988). In a building integrated aquaculture system, preference should also be given to recycled and bio-based materials in order to reduce and offset the embodied energy of the building. However, the structure is only one major source of eMergy in the building integrated aquaculture system.

Intensive recirculating aquaculture production can require a significant amount of eMergy. The water used is laden with fish effluents which increases the total eMergy of the system. A study of three different aquatic ecosystems found that, on average, the two manmade ponds used for purifying sewage had twenty and thirty times the eMergy density, eMergy per liter, than the natural pond (Bastianoni & Marchettini 1996). Another study found that some aquaculture operations rely heavily on non-renewable energy sources and are characterized by high eMergy (Vassallo et al. 2007).

Waste

Managing waste streams is fundamental to the sustainable goals of building integrated aquaculture. The concentrated waste from the fish can be poisonous to the system and the local environment if not carefully managed (Folke & Kautsky 1991). Fortunately, recirculating aquaculture system makes use of some of the fish effluent by products. The aquatic plants being grown feed on the liquid and microscopic wastes of the fish. The heavy particulate waste from the fish can be filtered out of solution and used to increase the yield of agricultural products like bell peppers (Palada et al. 1999). The effluents can also be very useful as a fertilizer for the production of hay (Valencia et al. 2001).

Sanitation

Producing healthy, food quality aquaculture and agriculture products will require an easily maintainable sanitary environment. Sources of biological and chemical contamination must be anticipated. Means of detection and response should be included in a building integrated aquaculture system. Keeping the facility free of contamination will require a combination of mechanical and biological filters for the water moving through the system. Summerfelt and Penne showed the advantage of using sedimentation filters in conjunction with a drum filter to improve the effectiveness of the mechanical filtration (Summerfelt and Penne 2005).

An intensive aquaculture system will require an efficient and cost effective biological filter. The biological filter plays an important role in the removal of excess fluid effluent and carbon dioxide from the water of the recirculating aquaculture system. There is a spectrum of performance in a variety of designs amongst the commercially available biological filters (Guerdat et al 2009). These filters will not protect the system from all biological contaminants. The structure should include features which prevent the invasion of unwanted species like birds, frogs, rodents, and insects.

CHAPTER 3

DESIGN EFFECTS ON EXPERIMENTAL CONFIGURATIONS

Overview

One of the first steps in designing successful building integrated aquaculture is to evaluate the impact facility design features have on water and interior air temperature as well as relative humidity. It is difficult to find two or more aquaculture facilities that are similar and useful for testing variables in an experiment. Managing temperature and humidity remains one of the largest barriers for developing and designing building integrated aquaculture. In this experiment, we measure the effect of insulation and tank covers have on temperature and relative humidity in a simulated indoor aquaculture environment. Important questions are asked and answered from these observations including:

- Does the presence of water in a simulated facility improve indoor temperature stability?
- Do microalgae impact the solar absorption of the water?
- Are tank covers an effective way to control relative humidity inside the simulated facility?

- Where does insulation, either on the tank or the structure, most improve indoor temperature stability?

Background

Water can be a multipurpose tool within the building integrated aquaculture system. The water provides a growth medium for the fish and aquatic plants but can also be managed to reduce the overall energy load (Wolfe & Zweig 1977, Zweig et al. 1981, Barnhart 2006, Fuller 2006). Exploiting the solar radiation capture potential of the water and biomass in an aquaculture system has been shown to be beneficial to some aquaculture facilities. The New Alchemy Institute provided some of the earliest research along these lines which is the foundation of building integrated aquaculture.

This group explored the concept of solar aquaculture for twenty years on Cape Cod, Massachusetts. Solar aquaculture uses the thermal mass in an aquaculture system to store solar energy and warm the enclosing greenhouse overnight. Their experimental unit within the greenhouse was referred to as a solar pond, an aquaculture system enclosed within a clear fiberglass cylinder five feet in diameter and five feet tall. Years of meticulous measurement and observation of cause and effect reactions ultimately yielded some very complex models of the processes within the solar pond aquaculture system (Wolfe & Zweig 1977, Zweig et al. 1981, Barnhart 2006).

The ideas of the New Alchemy Institute have been expanded by other research that shows solar pond thermal capture is boosted when a solar direct hot water collector is integrated with the system (Fuller 2006). This research included a model of an aquaculture facility in a temperate climate, including in its variables humidity, interior and exterior temperature. The study pointed out that the common remedy for excessive condensation, increasing ventilation, will increase the energy load of the system. The results show that both ventilation and covered tanks can limit conditions which are conducive to condensation (Fuller 2006).

Theory

Any structure which hosts an aquaculture system will be interacting with both it and the surrounding environment simultaneously. The forces of convection, conduction, radiation, and evaporation carry moisture and thermal energy between the building and aquaculture systems. Water has much more thermal mass than air, so it is possible structures which contain water filled aquaculture systems will have more temperature stability than those which do not. Many aquaculture systems are in greenhouses and can directly collect solar energy. Darker materials are known to absorb more solar energy and many life forms, like fish and algae, are of darker shades and suspended in the water of the aquaculture system. The water in an aquaculture system may be warmer than clean water with similar solar exposure.

Low to moderate levels of relative humidity are important to maintain healthy air quality in any structure. In an aquaculture facility, moisture is delivered to the interior air by evaporation from the water in the aquaculture system. The rate at which the transfer occurs is largely driven by exposed water surface and interior air flow over it. Aquaculture systems which limit exposed water surface through tank covers or other means may contribute less moisture to the indoor air than systems which do not.

Whenever there is less or more thermal energy than desired for the water and interior air, mechanical systems will have to correct it. Thermal energy will be constantly passing between the water in the system, the interior air, and the external environment through conduction. Properly installed insulation is an effective way to limit conduction through a surface and reduce strain on mechanical systems. However, insulation can be installed on the tank, the cover, the facility, or any combination of the three. It is not yet established which insulation strategy works best for a given aquaculture facility.

Null Hypotheses

1. The standard deviation of the air temperature in simulated facilities with water is the same as those without.
2. The average temperature of air in simulated facilities with algae is the same as those without.
3. The average temperature of water in simulated facilities with algae is the same as those without.
4. The average relative humidity in simulated facilities with covers is the same as those without.
5. The standard deviation of air temperature in simulated facilities with insulation is the same as those without.
6. The standard deviation of water temperature in simulated facilities with insulation is the same as those without.

Methods and Materials

In this experiment, glass tanks in a temperature controlled lab are used to simulate simplified, identical aquaculture facilities (Figures 1 & 2). The experiment was simple in design and required a short list of materials (Table 1). Temperature and relative humidity were the dependent variables observed. The simulated facilities were limited in their representation of actual aquaculture facilities. However, the major interactions between the simulated aquaculture system and the simulated building system should resemble the system interactions occurring within actual facilities. The goal of this experiment was to observe the interactions between building and aquaculture systems. Further, we aim to identify design strategies, like insulation and tank covers, to help passively manage temperature and relative humidity in aquaculture facilities.

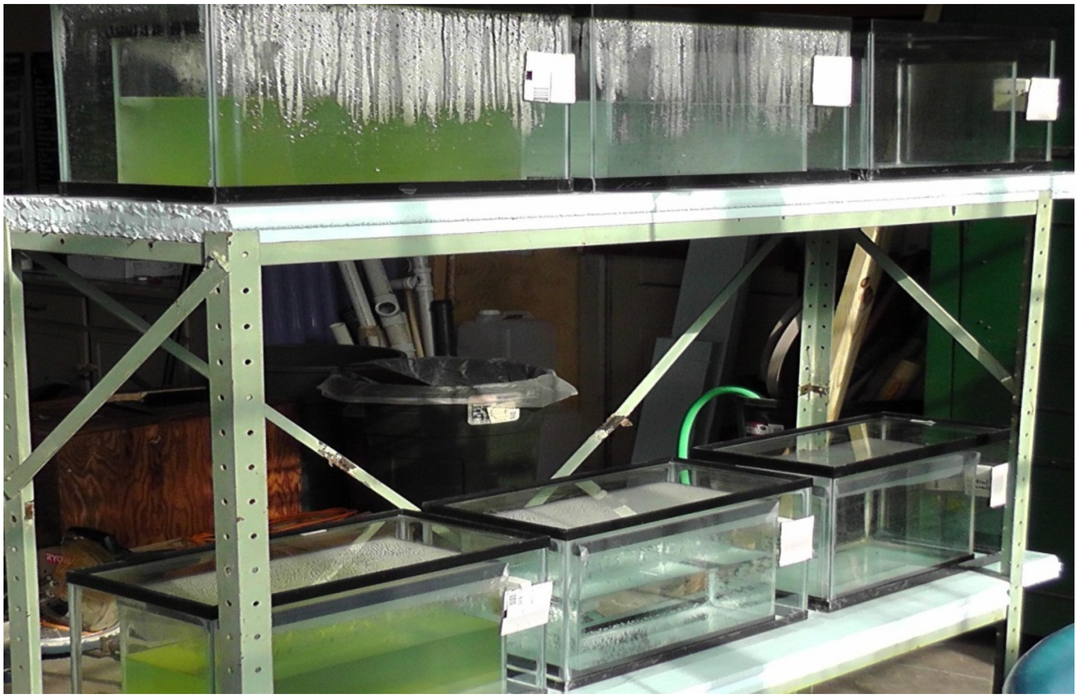

Figure 1: Experimental Setup Phase 1

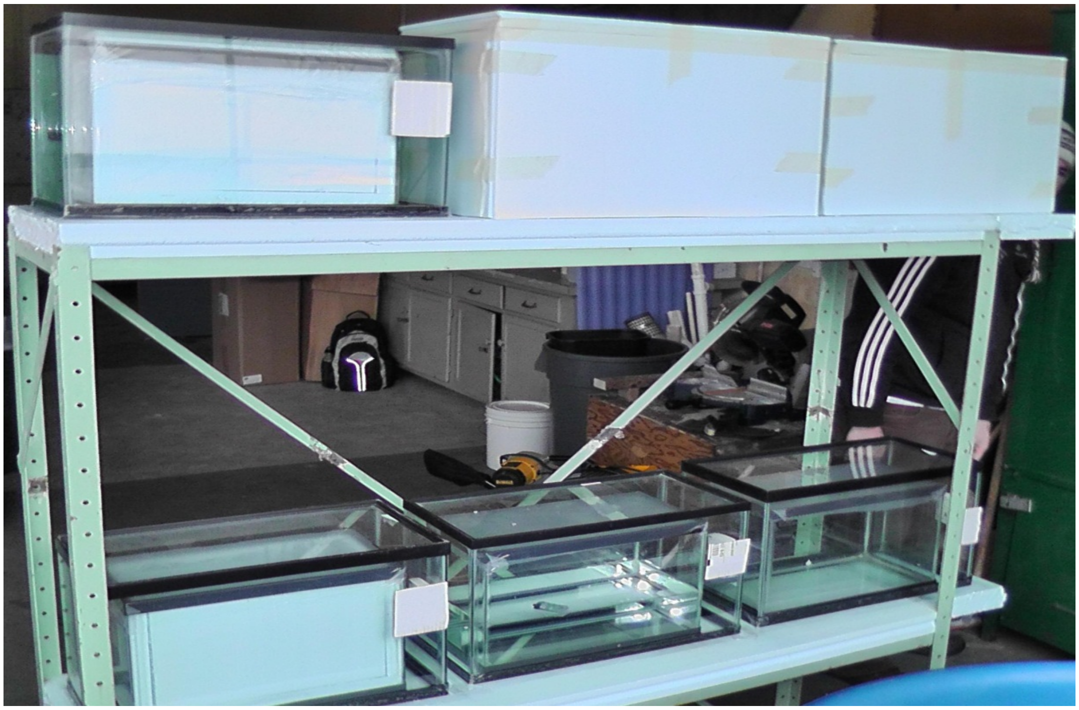

Figure 2: Experimental Setup Phase 2

Table 1: Materials Required

Materials	Amount
Translucent 10 gallon tank (L51cm x W26.5cm x 32cm)	6
Translucent 5 gallon tank (L41cm x W21cm x 26.5cm)	6
Submersible thermal data logger (HOBO-1) Model number: UA-002-64 Temperature resolution: 0.10°C at 25°C	5
Temperature and humidity data loggers (HOBO-2) Model number: U12-011 Temperature resolution: 0.03°C at 25°C Relative humidity resolution: 0.03% RH	7
Solar radiation shield (3" x 3" cardboard)	6
Extruded Polystyrene insulation (2″ x 2′ x 8′)	2
Extruded Polystyrene insulation (1″ x 2′ x 8′)	2
Packaging tape (clear)	NA
Construction/painter’s tape	NA
Waterproof construction adhesive	NA
Poly vapor barrier (3mm)	NA
Water bleach solution (500 ppm)	NA
Water w/green microalgae (Secchi disc ~13cm)	NA

The experiment was conducted in a large enclosed lab, on a shelf located approximately three meters from a very large South facing window (Figure 3). Temperature and humidity data for the lab space was recorded for the duration of both phases of the experiment. Six enclosed volumes were created by placing a ten gallon tank upside down over a five gallon tank, creating an enclosed volume of air with a small tank inside. These six volumes were arranged on the shelf so that each received approximately the same amount of sunlight every day. Temperature of the water and air within these volumes was measured and recorded by wireless data loggers every minute for ten days.

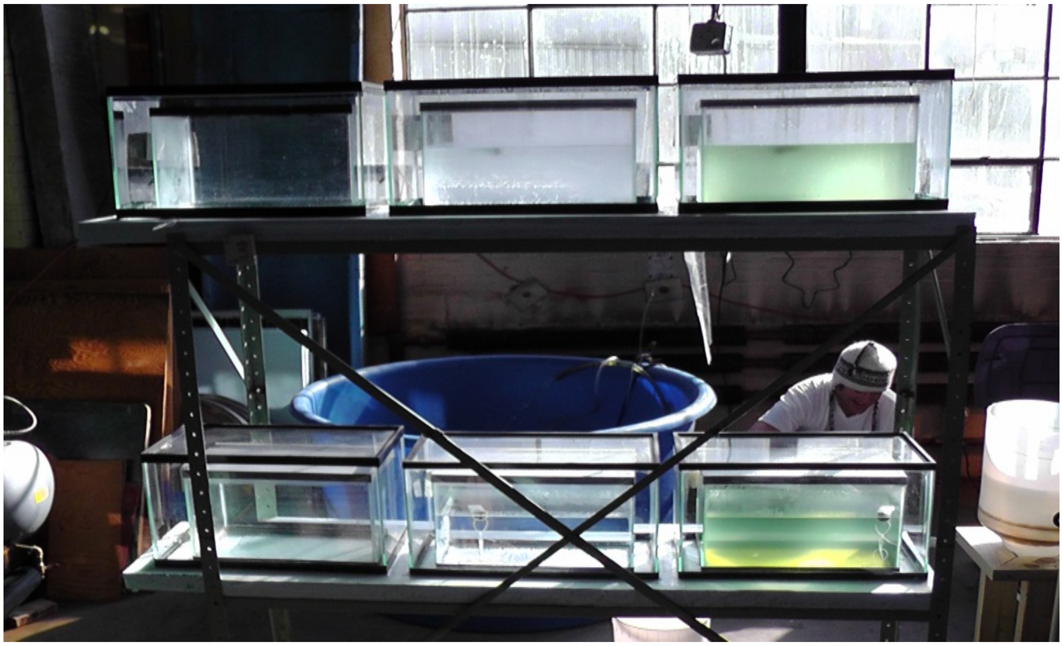

Figure 3: Phase 1 Setup in Lab

Actual facilities will have energy losses from conduction and air leakage into the external environment, but measuring these variables is not in the scope of this experiment. Insulation and air sealing were used to limit the interference of these variables on the experiment (Figure 4). Significant thermal energy losses from the simulated facilities through conduction to the metal shelf were limited by lining the shelf with insulation, 2” of extruded polystyrene. Air exchange between the lab and the enclosed volumes was minimized by sealing the edge of the

10 gallon tanks to the rigid insulation with clear packaging tape. The tanks remained adhered to the insulation and undisturbed for the duration of each experimental phase.

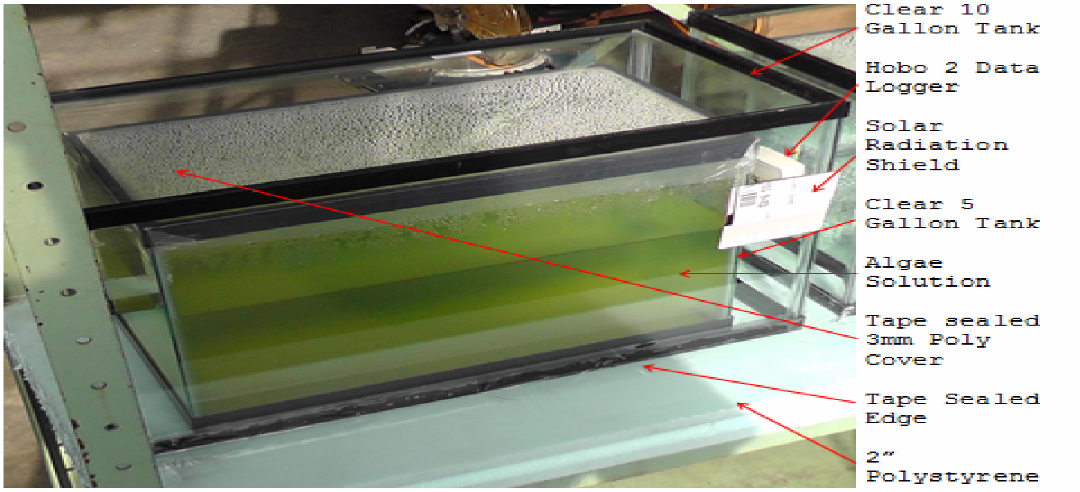

Figure 4: Experimental Unit – Simulated Facility

The experimental unit for each phase included everything within the simulated facility, an overturned 10 gallon tank. The enclosed 5 gallon tank represented the aquaculture grow-out tank within the simulated facility. In the first phase of the experiment, two of the five gallon tanks contained water bleach solution, two contained water algae solution, and two were controls with no solution added (Table 2). For each pair, one was covered by 3mm poly vapor barrier secured around the top of the 5 gallon tank with clear packaging tape. The microalgae used were of a mixed variety of green species. When harvested for this experiment, a Secchi disc vanished at about thirteen centimeters.

The entire experiment was conducted in Amherst, Massachusetts, between the fourth of February and the seventh of March, 2011. The first phase of the experiment, conducted between the fourth and fourteenth of February, simulated greenhouse facilities exclusively, as they are a relatively common form of indoor aquaculture. Data was collected in this phase to determine whether covering tanks improved relative humidity, whether the air temperature was stabilized by the presence of the water, and if the presence of microalgae increased air and water temperature.

Table 2: Matrix of Experimental Units – Phase 1

Phase 1 Experimental Unit	**Water**	**Algae**	**Cover**	**Control**
A				X
B	X			
C	X	X		
A.1			X	X
B.1	X		X	
C.1	X	X	X	

A – Empty
B – Water
C – Water & Algae
A.1 – Empty w/Cover
B.1 – Water w/Cover
C.1 – Water & Algae w/Cover

A third pair of tanks held only air and acted as controls in the first phase of the experiment. In 5 gallon tanks containing solutions, three gallons of liquids were used. Submersible thermal data loggers (HOBO-1) were left floating on the water’s surface within each of these tanks. Cardboard solar radiation shields were affixed to the exterior of the southern glass face of each 10 gallon tank to protect the temperature and humidity data loggers from direct solar radiation. One temperature and humidity data logger (HOBO-2) was affixed to the inside surface of each 10 gallon tank using a Velcro fastener included with the device. Another data logger was secured to the shaded side of the metal shelf to record the temperature and humidity of the lab.

The second phase of the experiment was inspired by the insulation theory that low U-value materials slow conduction and improve thermal stability. In this final phase, we tried to determine where insulation, extruded polystyrene, could be installed to achieve air and water temperature stability. Independent variables in this phase of the experiment included insulated tanks, insulated facilities, and insulated tank covers. All of the enclosed 5 gallon tanks contain three gallons of water bleach solution, except for one control containing only air. All of the 5 gallon tanks were tightly covered with 3mm poly sealed to the exterior tank edges with clear packaging tape.

Insulated tank covers were made with pieces cut from 1″ extruded polystyrene rigid insulation. The covers are held firmly in place by 3mm poly vapor barrier stretched over the cover and taped to the 5 gallon tank (Figure 5). Insulated tanks are simulated by lining the interior surface of the four walls and bottom of 5 gallon tanks with 1″ rigid insulation. The insulation fits snugly and is not adhered to the tank, but the seams between pieces are sealed with a water proof construction adhesive (Figure 6).

Figure 5: Insulated Tank and Insulated Tank Cover

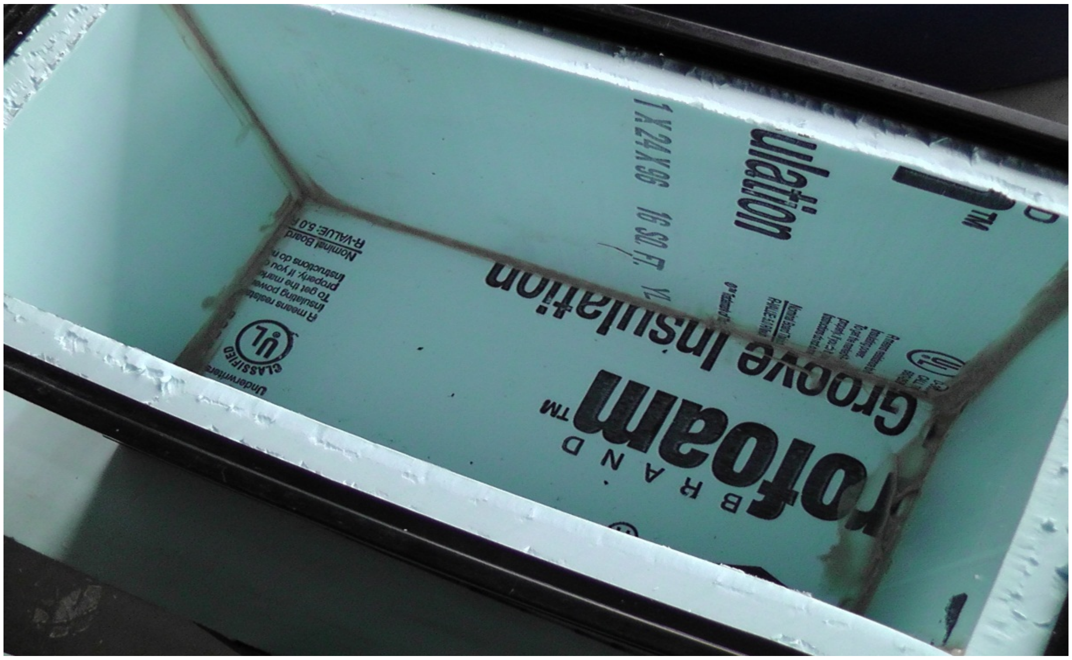

Figure 6: Interior of Insulated Tank

A similar approach was used to simulate insulated facilities shielded from sunlight. Pieces were cut from 1” rigid insulation to create a tightly fitting sheath of insulation that completely covers the exterior of a 10 gallon tank. Each piece was adhered to adjacent pieces with inexpensive construction tape (Figure 7). The completed assembly was carefully slid over the 10 gallon tank, creating a tight fit between the thermal envelope and the simulated facility. The tanks with them were sealed with clear packaging tape prior to installing the thermal envelope, negating the need for additional air sealing.

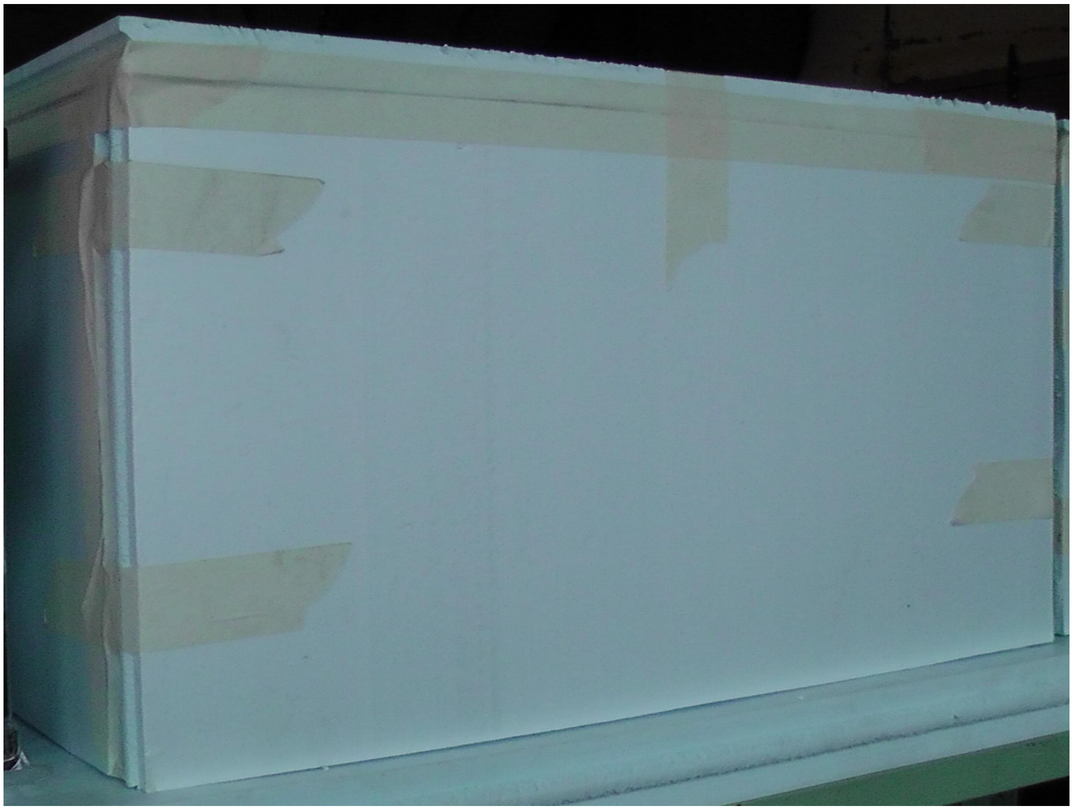

Figure 7: Thermal Envelope On Simulated Facility

These insulated components were used to create six simulated facilities for the second phase of the experiment (Table 3). The controls in this phase simulated a greenhouse and a greenhouse with an aquaculture system. Two additional greenhouse simulations were tested, one with an insulated tank covered with 3mm poly and the other with an insulated tank with an insulated cover. The last pair simulated completely insulated facilities, one with an insulated tank with an insulated cover and the other with a tank covered only with 3mm poly.

Table 3: Matrix of Experimental Units – Phase 2

Phase 2 Exp. Unit	**Water**	**Cover**	**Cover Insulation**	**Tank Insulation**	**Thermal Envelope**
D		X			
E	X	X			
F	X	X		X	
G	X	X			X
H	X	X	X	X	
I	X	X	X	X	X

D – Empty w/Cover
E – Water w/Cover
F – Water w/Cover & Tank Insulation
G – Water w/Cover & Thermal Envelope Insulation
H – Water w/Cover, Cover Insulation & Tank Insulation
I – Water w/Cover, Cover Insulation, Tank Insulation & Thermal Envelope Insulation

Data was recorded in phase two of this experiment in the same way as the first phase. In 5 gallon tanks containing bleach solution, three gallons were used. Submersible thermal data loggers (HOBO-1) were left floating on the surface of the water within each of these tanks. Cardboard solar radiation shields were affixed to the exterior of the glass face of each greenhouse simulation to protect the data loggers from direct solar radiation, but were unnecessary on the facilities with thermal envelopes. One temperature and humidity data logger (HOBO-2) was affixed to the interior surface of the South facing wall of each facility simulation using a Velcro fastener which was included with the device.

In each experimental phase, temperature and data was logged every minute over the course of ten days creating 14,400 data points for each dependent variable monitored in each simulated facility. The first day of data was omitted to allow for acclimation of the experimental units to the test conditions. The data was imported into Microsoft Excel for data summary and analysis. The daily mean and standard deviation of the air temperature, water temperature, and relative humidity was computed for each of the experimental treatments. Null hypotheses were tested by either comparing means in daily temperature/humidity (N=9) or means in the standard deviation of daily temperature. Comparisons of standard deviation were used as a measure of temperature stability/instability. All treatments were compared using t-tests (paired, two tail). Twenty four hour diurnal temperature and relative humidity profiles were included to further support the statistical comparisons.

Results

All null hypotheses in this experiment were refuted by the data collected. Mean temperature and humidity data, diurnal temperature variability data, and relevant statistical comparisons for phase 1 are provided in Tables 4, 5, 6 and 7, respectively. Hypothesis 1 was to determine whether the presence of water in the simulated facilities improved indoor air temperature stability. Air temperature in facilities containing water was significantly ($p < 0.01$) more stable than facilities without water. The conclusion that the presence of water stabilizes air temperature is further reinforced by an analysis of a graph of air temperature means by minute (Figure 8).

Table 4: Mean (± SD) of Dependent Variables – Phase 1

Mean ± SD	A	B	C	A.1	B.1	C.1
Air Temp °C	19.6 ± 4.2	19.6 ± 3.0	19.8 ± 3.1	18.7 ± 4.0	19.0 ± 3.3	19.3 ± 3.2
Water Temp °C	NA ± NA	20.1 ± 2.2	20.7 ± 2.5	NA ± NA	20.3 ± 2.4	20.7 ± 2.5
Rel. Hum. %	24.4 ± 3.5	97.4 ± 3.5	98.5 ± 2.3	24.9 ± 3.0	38.8 ± 3.3	35.7 ± 3.0

Table 5: Diurnal Air Temperature Variability – Phase 1

Air Temp °C	**A**	**B**	**C**	**A.1**	**B.1**	**C.1**
Avg. Daily SD	4.2	3.0	3.1	4.0	3.3	3.2
Variability of SD	2.5	1.8	1.9	2.5	2.0	2.0

Table 6: Diurnal Water Temperature Variability - Phase 1

Water Temp °C	**A**	**B**	**C**	**A.1**	**B.1**	**C.1**
Avg. Daily SD	NA	2.2	2.5	NA	2.4	2.5
Variability of SD	NA	1.5	1.7	NA	1.7	1.8

Table 7: Paired Two Tail T-Tests - Phase 1

Hypothesis	**Sig. Value**	**Comparison**	**P-Value***
1	Std. Dev.	A->B	0.0019
1	Std. Dev.	A->C	0.0016
1	Std. Dev.	A.1->B.1	0.0010
1	Std. Dev.	A.1->C.1	0.0010
2	Mean	B->C	0.0317
2	Mean	B.1->C.1	0.0019
3	Mean	B->C	0.0008
3	Mean	B.1->C.1	0.0009
4	Mean	B->B.1	P<0.0001
4	Mean	C->C.1	P<0.0001
*N=9			

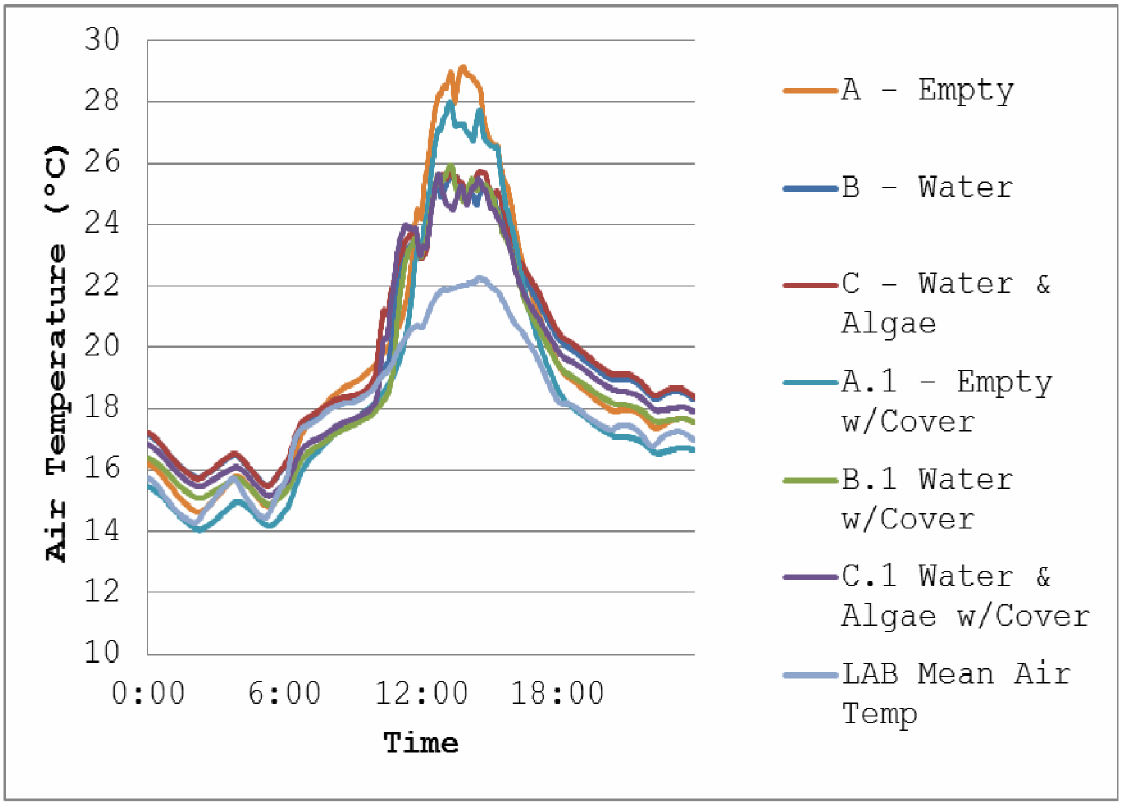

Figure 8: Diurnal Patterns in Mean Air Temperature

Phase 1

This graph clearly shows the empty facilities as having higher average midday air temperature and lower average evening air temperature. Simulated facilities with covered aquaculture tanks also did not have a large difference in average daytime air temperature from their uncovered counterparts. However, simulated facilities with uncovered aquaculture tanks did have higher average overnight air temperature.

Hypothesis 2 was to determine whether the presence of microalgae in the water increased the temperature of the air inside the simulated facilities exposed to the sun. Air temperature within the simulated facilities with microalgae was significantly different from those without (P=0.0317 & P=0.0019). Both covered and uncovered algae treatments had higher average air temperature than their clean water counterparts. Uncovered algae and water had an average air temperature of 19.8°C and uncovered water had an average air temperature of 19.6°C. The covered algae and water had an average air temperature of 19.3°C and the covered water had an average air temperature of 19°C.

The third null hypothesis was also investigating the impact of the presence of dense microalgae in aquaculture facilities open to solar radiation. Hypothesis 3 was to determine if the water temperature in simulated facilities with microalgae was significantly different from those without. Tests of both covered and uncovered algae treatments were significantly different from those without (P<0.001). Both samples with algae also had higher average water temperature than their uncovered counterparts. Uncovered algae and water had an average water temperature of 20.7°C and uncovered water had an average water temperature of 20.1°C. The covered algae and water had an average water temperature of 20.7°C and the covered water had an average water temperature of 20.3°C. This conclusion is also reinforced by a graph of water temperature means by minute (Figure 9).

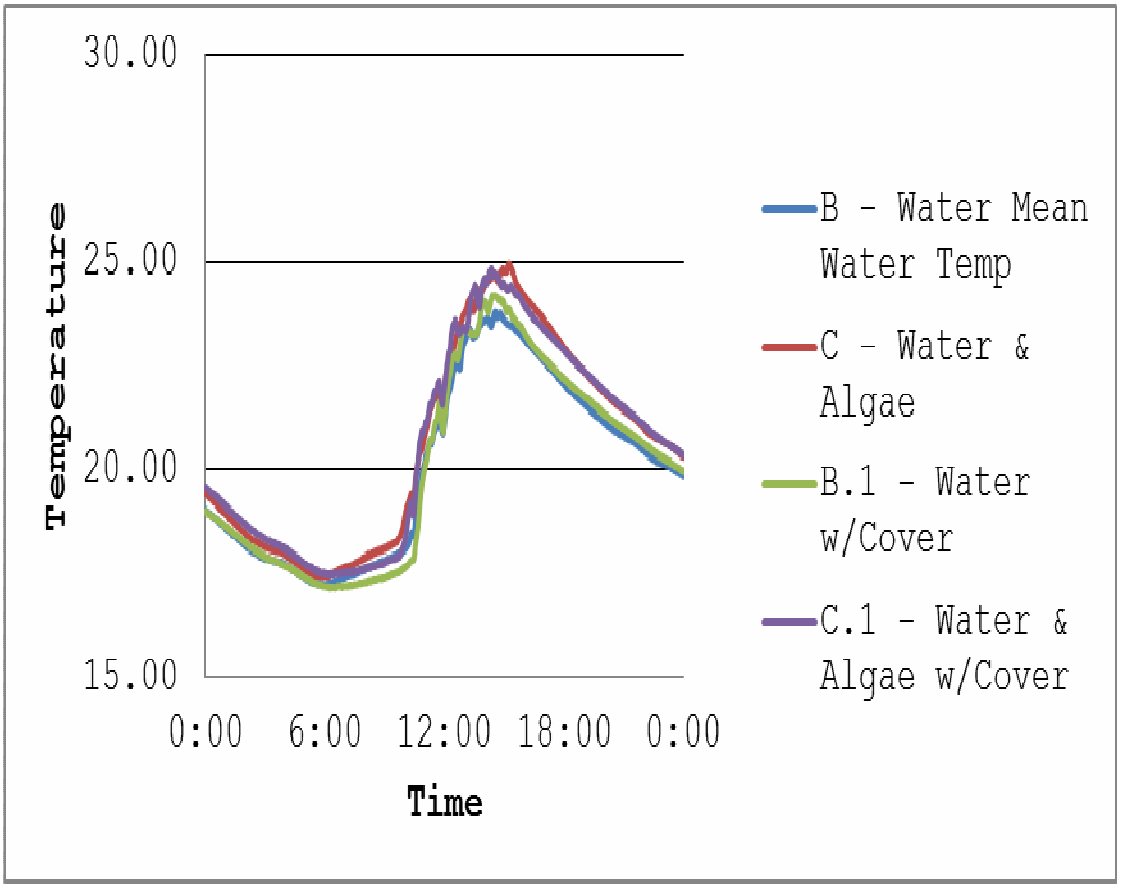

Figure 9: Diurnal Patterns in Mean Water Temperature Phase 1

The fourth and last null hypothesis explored in the first phase was to determine if the relative humidity in simulated facilities with tank covers was the same as those without. Tests of the average daily relative humidity found simulated facilities with tank covers were significantly different from those without (P<0.0001). The average relative humidity in simulated facilities with covers was much less than those without. Uncovered water and uncovered water with algae had average relative humidity of 97.4% and 98.5% respectively, while their covered counterparts had average relative humidity of only 38.8% and 35.7%. A graph of relative humidity means by minute reveals very strong evidence which supports the use of covers as an effective means of evaporation control (Figure 10). It was these findings which promoted the use of covers on all treatments in the second phase, and they were again effective at controlling relative humidity (Figure 11).

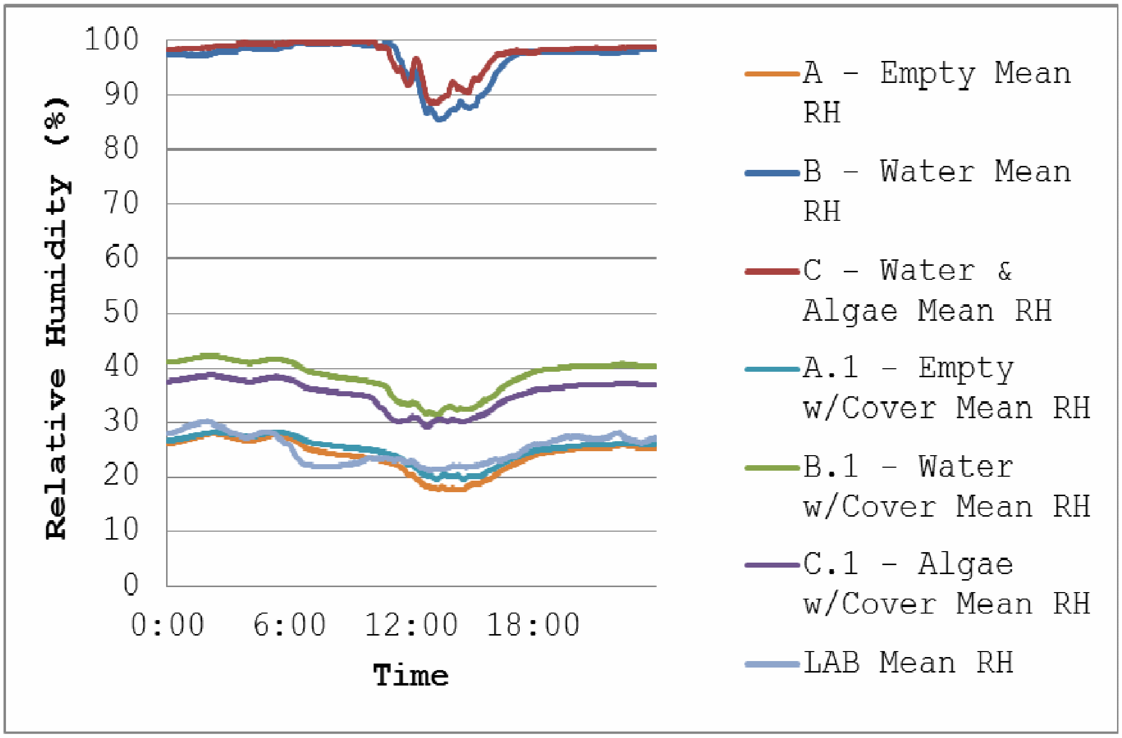

Figure 10: Diurnal Patterns in Mean Relative Humidity Phase 1

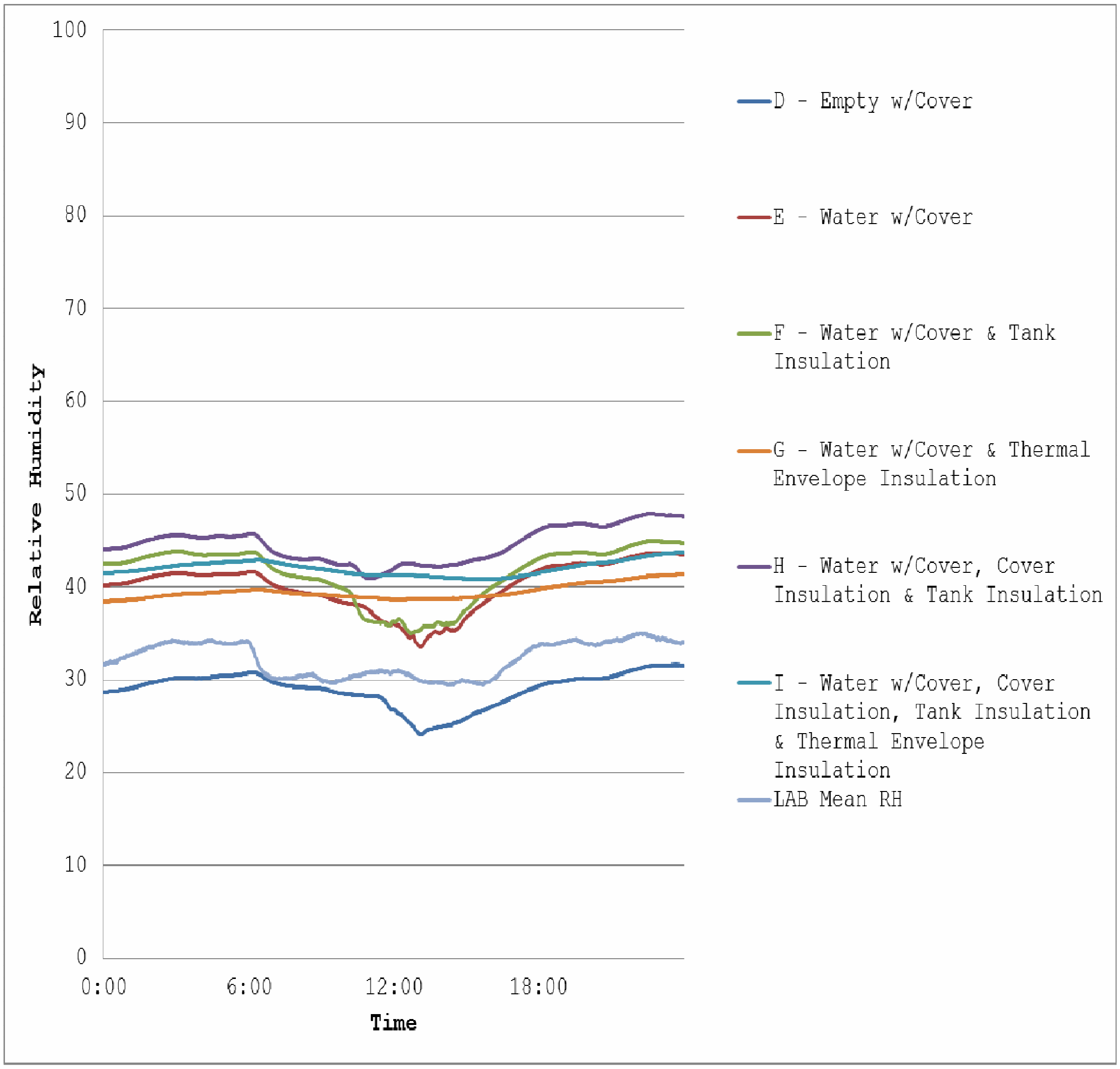

Figure 11: Diurnal Patterns in Mean Relative Humidity

Phase 2

Mean temperature and humidity data, diurnal temperature variability data, and relevant statistical comparisons for phase 2 are provided in Tables 8, 9, 10, 11, & 12 respectively. The second phase of the experiment tested the fifth null hypothesis, that simulated facilities with insulation treatments would have the same air temperature standard deviation. The standard deviation of air temperature in simulated facilities was significantly different from those without (P<0.01) excluding facility H which had an insulated tank and insulated cover (P=0.08). Simulated facility F, with tank insulation only, had higher air temperature standard deviation than all other treatments and controls, 3.7. All of the other simulated facilities with insulation treatments, G, H, and I, had lower air temperature standard deviation than the controls without insulation.

Table 8: Mean (± SD) of Dependent Variables – Phase 2

Mean ± SD	D	E	F	G	H	I
Air Temp °C	17.8 ± 3.6	18.2 ± 3.3	18.0 ± 3.7	17.4 ± 1.1	17.7 ± 2.5	17.3 ± 1.3
Water Temp °C	NA ± NA	19.3 ± 2.5	19.3 ± 1.8	17.4 ± 0.7	17.7 ± 0.7	16.8 ± 0.4
Rel. Hum. %	29.0 ± 3.7	40.5 ± 3.7	41.3 ± 4.2	39.9 ± 2.2	45.4 ± 2.9	42.1 ± 2.6

Table 9: Diurnal Air Temperature Variability – Phase 2

Air Temp °C	**D**	**E**	**F**	**G**	**H**	**I**
Avg. Daily SD	3.6	3.3	3.7	1.1	2.5	1.3
Variability of SD	2.3	2.2	2.5	0.5	1.3	0.7

Table 10: Diurnal Water Temperature Variability - Phase 2

Water Temp °C	**D**	**E**	**F**	**G**	**H**	**I**
Avg. Daily SD	2.5	1.8	0.7	0.7	0.4	0.0
Variability of SD	1.9	1.4	0.3	0.3	0.2	0.0

Table 11: Air Temp SD T-Tests P-Values - Phase 2

N=9	**D**	**E**	**F**	**G**	**H**	**I**
D	X	0.0092	0.3285	0.0038	0.0270	0.0048
E		X	0.0050	0.0063	0.0836	0.0091
F			X	0.0058	0.0410	0.0078
G				X	0.0014	0.0151
H					X	0.0011
I						X

Table 12: Water Temp SD T-Tests P-Values - Phase 2

N=9	**D**	**E**	**F**	**G**	**H**	**I**
D	X	X	X	X	X	X
E	X	X	0.0095	0.0165	0.0135	0.0103
F	X		X	0.0295	0.0225	0.0141
G	X			X	0.6660	0.0011
H	X				X	0.0017
I	X					X

The sixth and final hypothesis was to determine if simulated facilities with insulation treatments have different air temperature standard deviation. The standard deviation of air temperature within simulated facilities with insulation treatments was significantly different from those without (P<0.02). Despite the tank insulation, simulated facility F behaved very much like the water with cover control (Figures 12 & 13). All facilities with insulation treatments, F,G,H & I, had lower water temperature standard deviations than the one without, E. Simulated facility F had nearly double the water temperature standard deviation of the other facilities with insulation treatments. According to the data, the most stable water and air temperature as well as relative humidity was delivered by the simulated facility with a covered water tank and a thermal envelope.

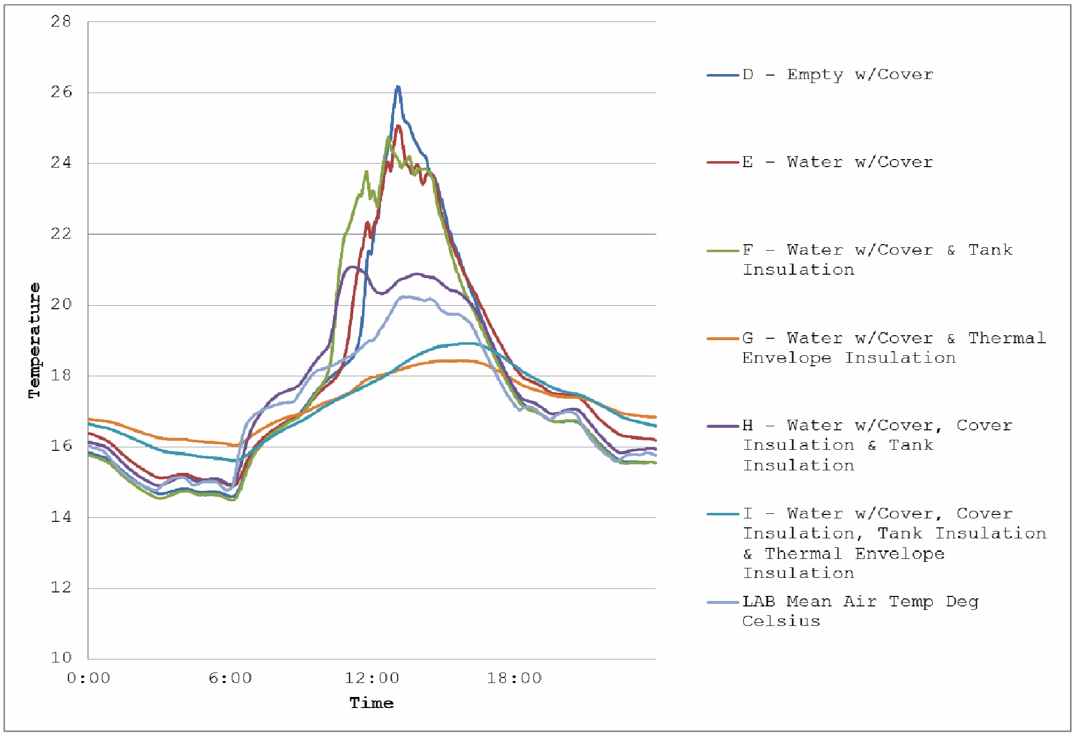

Figure 12: Diurnal Patterns in Air Temperature

Phase 2

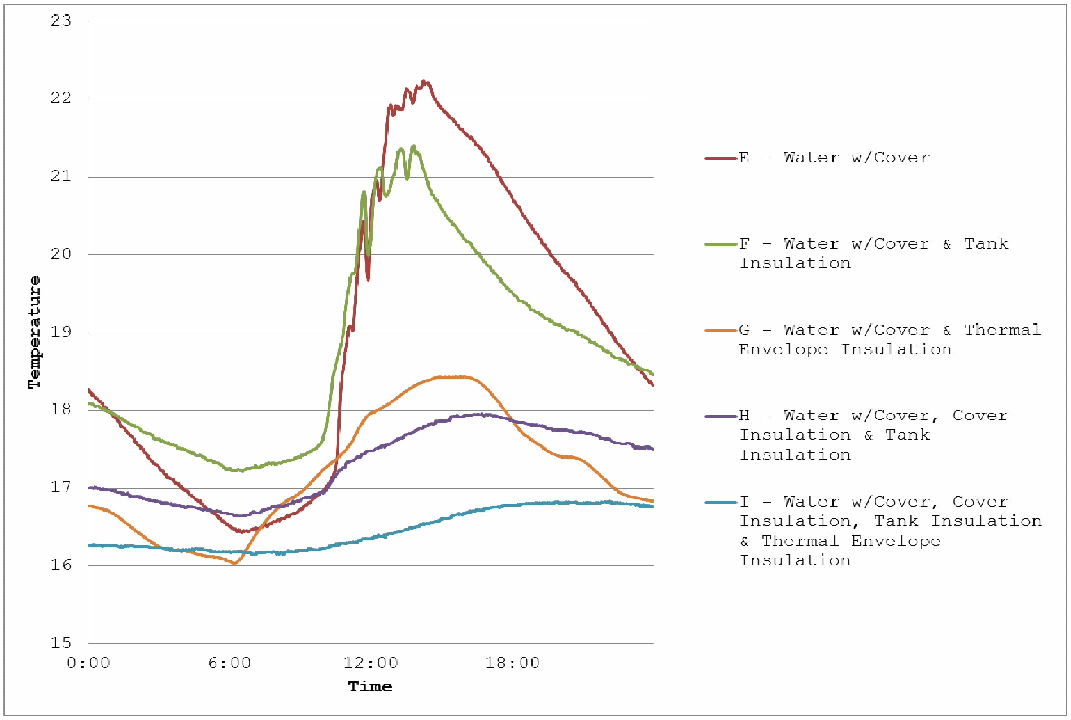

Figure 13: Diurnal Patterns in Mean Water Temperature

Phase 2

Conclusion

The data collected during phase one delivered three conclusions important to the further development of building integrated aquaculture. First, our findings show that the water in the aquaculture system is useful as a thermal mass feature which can stabilize the temperature of the interior air throughout the diurnal cycle, as was observed also by the New Alchemy Institute. Secondly, it was shown that microalgae increase the solar absorption of the water and will be observable through higher average air and water temperatures. The final conclusion from the first phase strongly endorses the use of covered tanks to control relative humidity in the interior air passively. This conclusion agrees with those inferred from the hypothetical models of Fuller in 2006.

According to the phase 2 data, it was concluded that the most stable water and air temperature as well as relative humidity was delivered by the simulated facility with a covered tank and a complete thermal envelope. This highlights the need for aquaculture system designers to consider the role of the host structure in the success of the system. It was observed that insulating the tank limited the ability of the water to stabilize the interior air temperature, but operations whose desired water temperature is not the same as the desired air temperature.

The findings from this research are considered and discussed in a broader perspective in the last chapter of this thesis. Further research should investigate the impact of water as a function of the interior volume, as this research only considered 30% water by volume. Larger simulated facilities with more realistic features should also be considered for future research as well as more replications with longer sample durations. Finally, it may be beneficial to repeat this experiment in an outdoor environment, not within a temperature controlled lab space.

CHAPTER 4

DESIGN CASE STUDY: RETROFITTING THE ANIMAL HOUSE

Overview

To advance the concept of building integrated aquaculture, many design factors must be considered. There are few, if any, successful examples of building integrated aquaculture facilities. A new holistic design approach for successfully merging building and aquaculture systems is explored through this case study. Successful design should incorporate the components of a recirculating aquaculture system into a building system to mutually gain efficiency in both systems while minimizing strain on their supporting mechanical systems. Experts from the fields of aquaculture and building science have worked collaboratively with a designer to produce two building integrated aquaculture retrofit programs for a small, simple structure in temperate Western Massachusetts.

Two programs were developed as options for the structure's retrofit. Both programs are designed to minimize strain on mechanical systems with effective thermal envelopes and passive moisture control features. Energy modeling and mechanical equipment selection are not in the scope of this research but certainly are important in the development of building integrated aquaculture. All graphical depictions of the existing structure and retrofit programs were created using the building information modeling software program Revit Architecture, from Autodesk.

Background

The programs developed in this case study are for the retrofit of an existing structure on the campus of The University of Massachusetts. The building is located in Amherst, Massachusetts 42° 22' 31" N / 72° 31' 11" W. It is a single level building with walls measuring 40′ x 44′, exterior dimensions (Figures 14 & 15). The exterior walls extend into the earth as foundation walls and are constructed of 16″ x 12″ x 12″ concrete masonry units. There is no additional finish material on either the interior or exterior of the walls. The floor is poured concrete which is slightly tapered to meet six floor drains in the center of six equally sized divisions of the room. The drains evacuate to a leach field to the North of the structure. The ceiling is primer painted plywood attached to spanning members of fink trusses spaced 24″ on center.

The structure is currently being used for long term storage and is rarely visited.

Figure 14: Exterior of Existing Structure

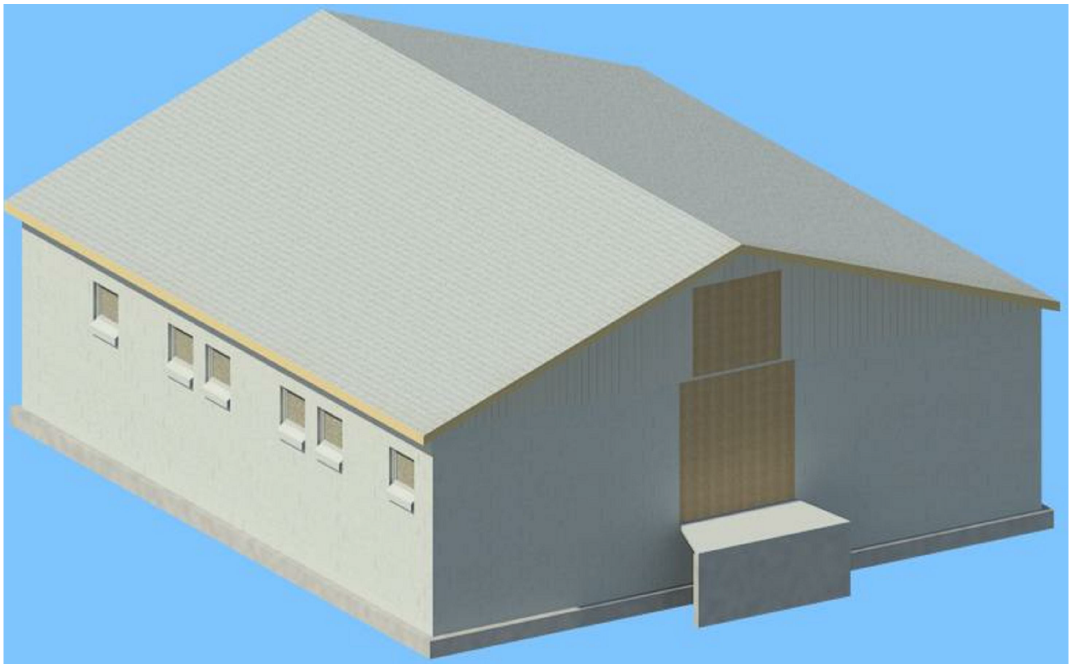

Figure 15: BIM Graphic of Existing Structure

There is evidence of past modification by aquaculture researchers trying to control heat and humidity problems in this space. They added insulated partition walls, extra insulation in the attic, and also air conditioned the partitioned space (Figure 16). This and other observed conditions strongly suggest that the structure is not be able to maintain a suitable indoor environment for intensive aquaculture production without modification to the building system.

Figure 16: Partitioned Space in Existing Structure

Intent of this section

A conceptual design process has been undertaken to consider the design challenges presented by building integrated aquaculture. Three major challenges that must be addressed during the design process have been included in this research. One challenge for the design team was to minimize energy inputs for the system in temperate western Massachusetts, as energy is costly. Another challenge was to maximize fish production for a given space, because buildings are costly to construct and maintain. The final challenge considered during the design process was finding passive design features which could help control relative humidity. Humidity control is of primary concern in building integrated aquaculture, as high humidity levels are detrimental to building durability and indoor air quality. Choices made to address one of these challenges impact the other challenges, as all three are interrelated.

Program description

The first program demonstrates an application of adaptive reuse, the process of adapting old structures for purposes other than those initially intended. The existing structure is repurposed to serve as a recirculating aquaculture facility. The primary goal of this program was to address the three design goals within the context of retrofitting a building (Table 11). The target production for the aquaculture system in this program is about 20,000 kilograms of tilapia annually. The adaptive reuse approach used in this program required the original thermal envelope to remain intact. The building's thermal envelope was reinforced above grade to meet or beat the standard of the 2009 International Energy Conservation Code. Further, waterproof materials and insulated tank containers are used to passively control airborne moisture in the structure.

Table 13: Goals and Constraints – Program 1

Goals	Constraints
Effective thermal envelope	2009 IECC, Original envelope remains intact, Cannot alter or cover slab
Adaptive reuse	All existing structural features remain intact
Meets target production	~20,000 Kg of tilapia annually
Moisture resistant	Passive features only

The second program was designed for the purpose of demonstrating new ideas for building integrated aquaculture. The main goal of this program was to alter the existing structure to provide the means to exploit synergies between the systems and provide better solutions to the design challenges (Table 12). The facility was expanded out of the footprint of the original structure because new spaces were necessary to capture synergies between building and aquaculture systems. The new spaces were also necessary to meet the aquaculture production requirements for this program, about 32,000 kilograms of tilapia annually. The existing concrete walls and floors remain intact, but the original structure has been altered significantly. The 2009 International Energy Conservation Code was once again used to provide minimum insulation requirements for the thermal envelope. Both waterproof and moisture buffering materials, like drywall, were used in addition to the insulated tank containers as passive airborne moisture control features.

Table 14: Goals and Constraints – Program 2

Goals	Constraints
Effective thermal envelope	2009 IECC, Cannot alter or cover slab
Expand structure to capture solar energy in the system	Cannot block drive, Only 1 additional level, Original concrete remains intact
Meets target production	~32,000 Kg of tilapia annually
Moisture resistant	Passive features only
Optimize for system synergies	Must have space for occupants

Design Process

A simple design process was used to generate the building information models presented in this research. As-planned construction drawings of the structure to be retrofitted were provided by the University of Massachusetts (Figures 17 & 18). These drawings were then checked for accuracy against the actual structure through a series of site visits. The drawings were then digitized into Revit Architecture, creating a building model of the structure in its current state. This model was then used as a starting template for both programs designed in this research.

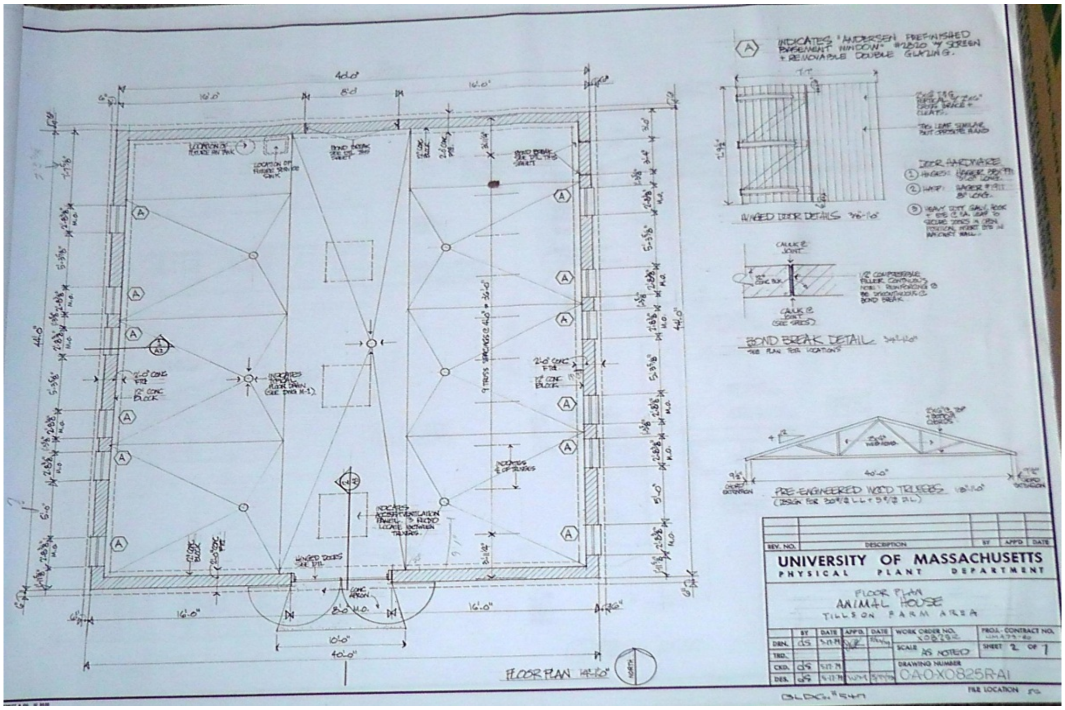

Figure 17: Construction Document – Floor Plan

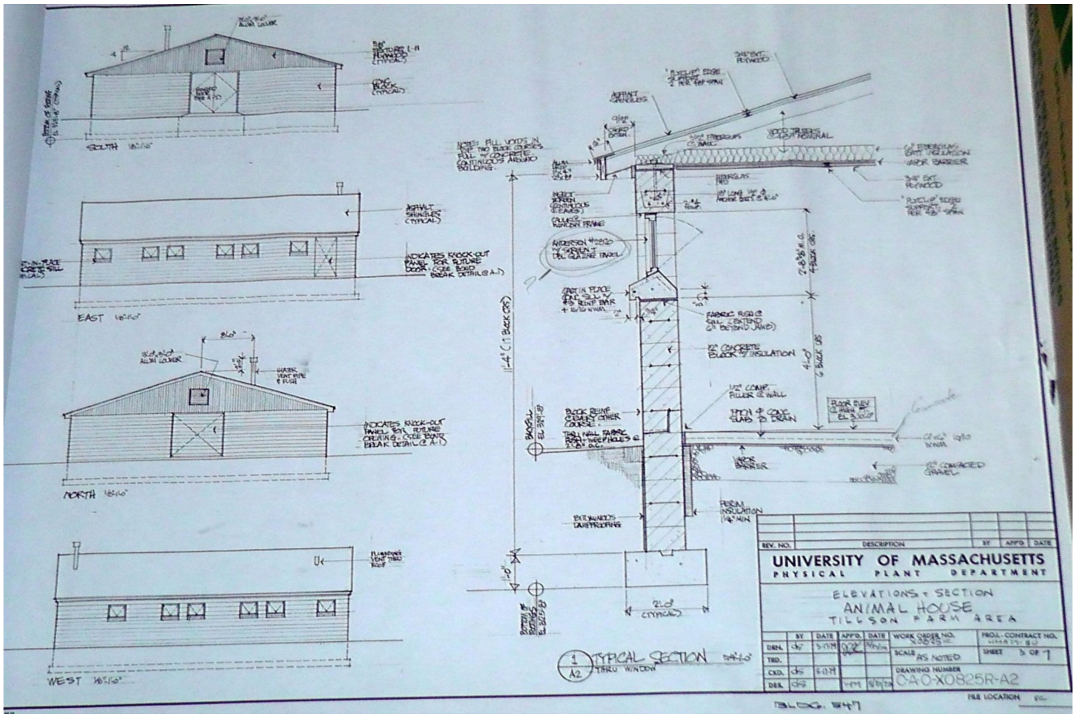

Figure 18: Construction Document – Profiles and Section

The process used to generate the design modifications for each program was a simple design spiral. Decisions for the design modifications were guided by periodic consultation and review by building and aquaculture system experts. A series of informal interviews on the topic of aquaculture design and operation were conducted with Dr. James Webb. The aquaculture system in each program was incorporated into the building information model from a short equipment list and target production rate which he provided (Tables 13 & 14). It was estimated that each tank could produce about 2,000 kilograms of tilapia every year.

Table 15: Aquaculture Equipment List - Program 1

Shown in BIM	Space Provided	Location
Culturing Tanks	-	Main room
	Sump	Main room
	Pumps	Main room
	Drum filter	Main room
	Swirl separator	Main room
	Biofilter	Partitioned space
	Aquaponic beds	Partitioned space
	Piping	Throughout

Table 16: Aquaculture Equipment List - Program 2

Shown in BIM	Space Provided	Location
Culturing Tanks	-	First Level
Sump	-	Greenhouse
Pumps	-	Greenhouse
Biofilter	-	Greenhouse
Aquaponic beds	-	Greenhouse
Header Tanks	-	Second Level
SDHW Panels	-	Roof
	Drum filter	First Level
	Swirl separator	First Level
	Piping	Throughout

The envelope for each program was designed to meet or beat the 2009 IECC standard while also satisfying other requirements for the structure. The 2009 IECC prescribes minimum R-values for all surfaces of the thermal envelope according to the climate zone in which the structure resides (IECC 2009). For climate zone five, R-38 is prescribed for the ceiling and R-20 for the walls. The insulation material chosen for the envelope had to be compatible with the goals of the program. Ideally, insulation materials would come from sustainable sources but would also be also resistant to moisture damage.

Spray-on soy based closed cell foam insulation, a moisture damage resistant material, was used in areas where the threat from airborne moisture and liquid water were most severe. This material has a relatively high R-value, reducing the intrusion of the walls into the culturing space. In addition, it seals against air and moisture penetration providing additional protection from moisture for degradable building materials. In the attics of both programs as well as the exterior walls of the second program, cellulose insulation is used. Cellulose is made from recycled newspaper and boric acid. It has a number of desirable qualities, such as fire resistance, deterring pests, and being unharmed by occasional moisture exposure.

Program 1 Results

The first program meets its goals within the constraints outlined. Most of the expenditures for this program will be for insulation. The original structure remains entirely intact and the five out of six surfaces of the thermal envelope were reinforced (Figure 19). Walls were insulated with soy-based spray-on insulating foam, which doubles as a vapor barrier. The attic is further insulated with loose-filled cellulose insulation. Special care must be taken when air sealing the interior ceiling to prevent air and moisture leakage into the attic. Virtually none of the existing structural elements have to be removed for this program.

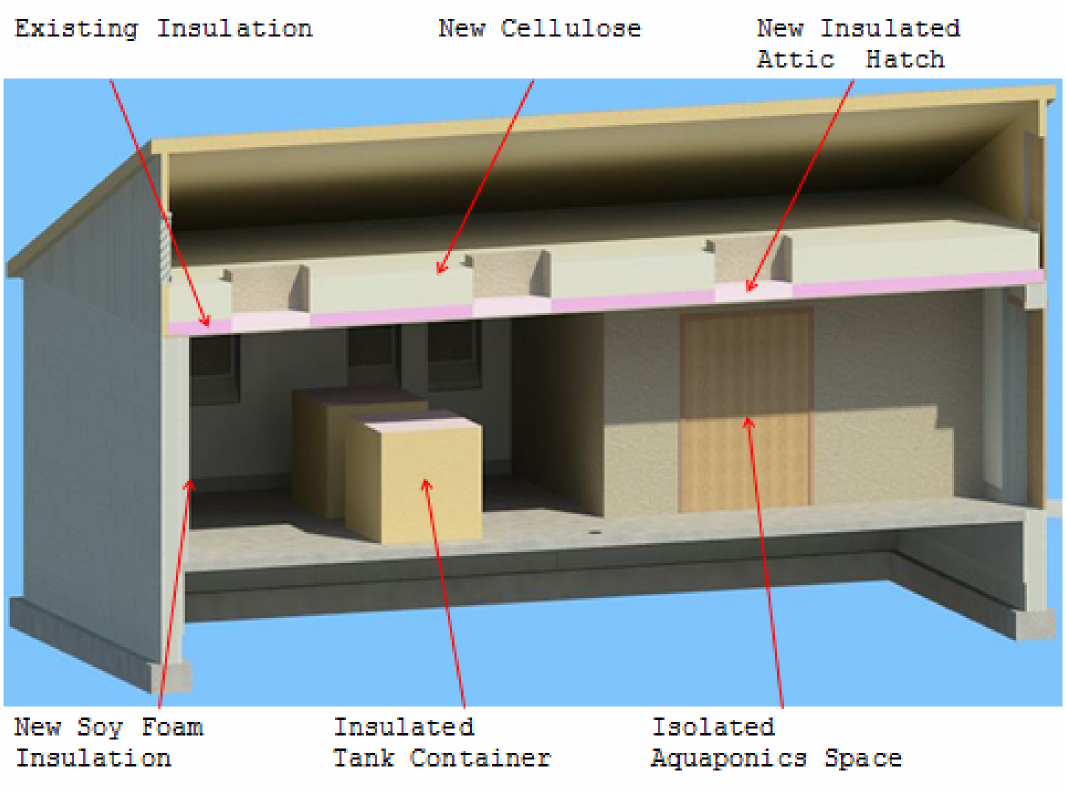

Figure 19: New Insulation Features – Program 1

Aquaculture System

A recirculating aquaculture system is intended for this structure in both programs. The first program's aquaculture system must be adapted to the constraints of the original structure. There are only two spaces in the structure to position all the necessary components of the system. The larger space contains all the large fish culturing tanks. The smaller space is where aquaponic plants will be cultivated under artificial lights. Both of these spaces will require their own set of properly sized mechanical systems to adjust temperature and ventilation.

The original structure needs the modifications in this program to provide a suitable environment for the aquaculture system. Without the complete thermal envelope provided in this retrofit, heat from the water in the system will be lost rapidly and may result in unhealthy indoor air, moisture damage, and mold. Even the new soffits help the structure become a better host for recirculating aquaculture. They are part of a series of barriers which prevent the entry of invasive species like rodents which could contaminate the system.

Insulated Covered Tanks

The results found in chapter three have shown that insulated covered tanks can help control indoor relative humidity. Specifically, this thermal isolation strategy prevents moisture evaporation to the interior environment and encourages temperature stability in both the water and air. In addition, insulated tanks provide more stability in temperature for both the water and interior air. However, there exist management requirements which cannot be satisfied without full access to the culturing tanks.

It is a common practice of successful aquaculturists to observe their fish on a continuous basis. Tank covers would interfere with this practice and become a problem. Building integrated aquaculture has a great need for an effective and low cost energy saving tank container which doesn't noticeably impair the activities of the aquaculture managers. Specifically for this case study, an insulated tank container was designed using AutoCAD 2011 (Figure 20).

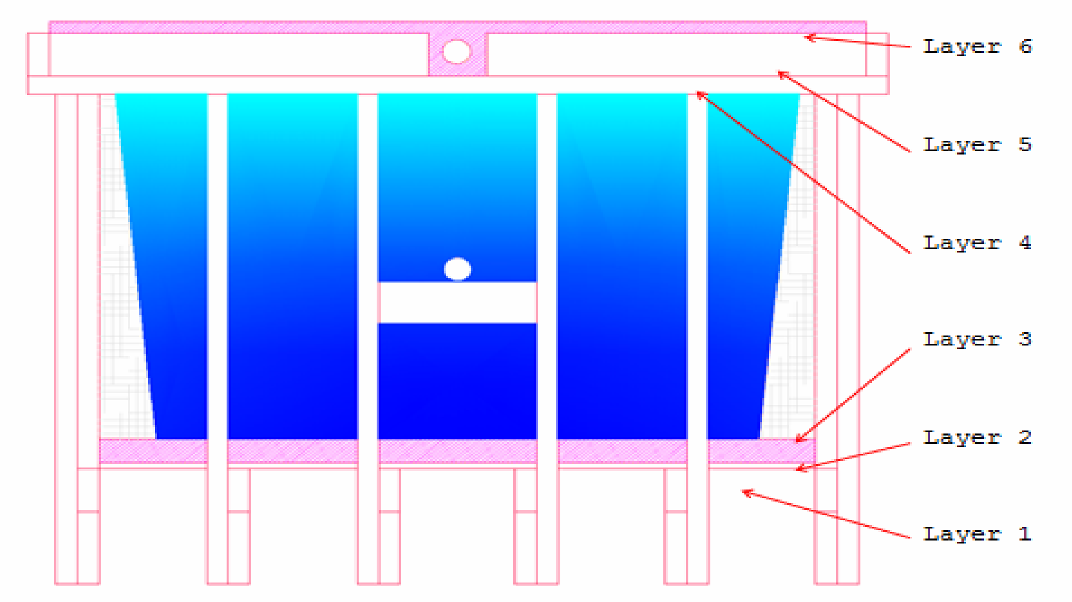

Figure 20: Insulated Tank Container – Profile 1

The designed container encloses a cylindrical plastic aquaculture tank with approximately one cubic meter of volume. The tank shown within the designed container is 30” tall, with a slight taper on its vertical wall so it measures 48” across the top and 42” across the bottom. There are six different horizontal layers in the container’s assembly (Figures 21, 22, 23, 24, 25 & 26). It is possible that these tank containers could reduce the energy requirements for both building and aquaculture systems and still satisfy the management requirement for the production of healthy fish.

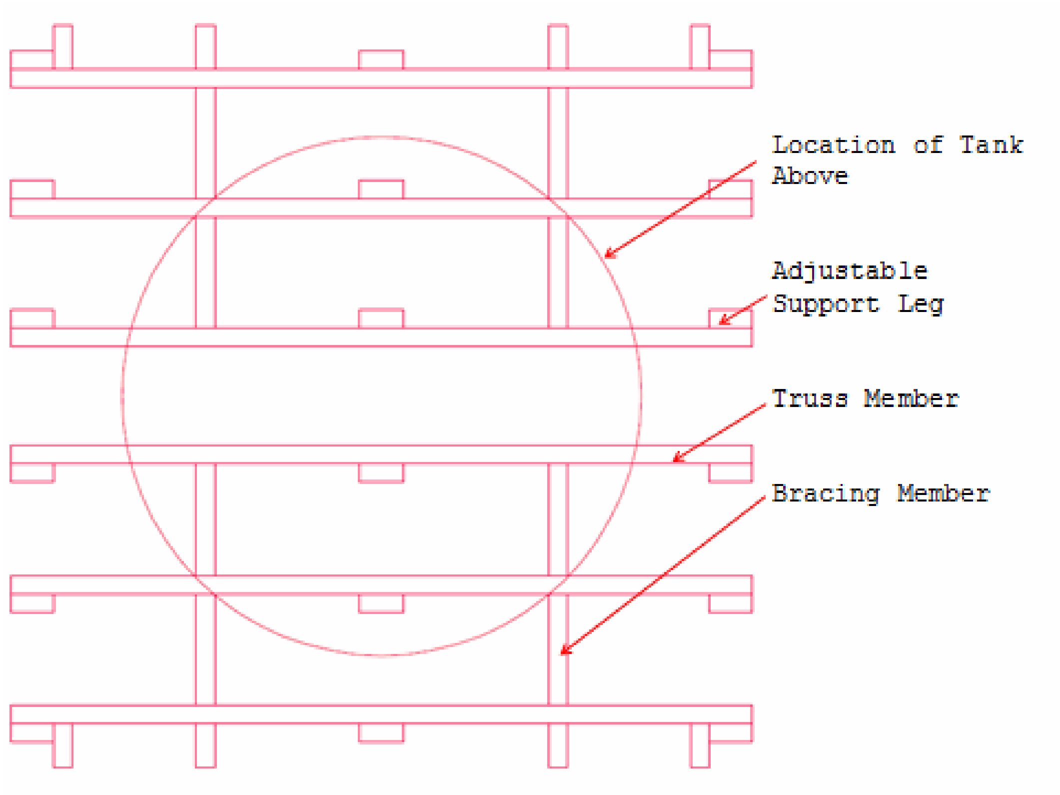

Figure 21: Insulated Tank Container – Layer 1

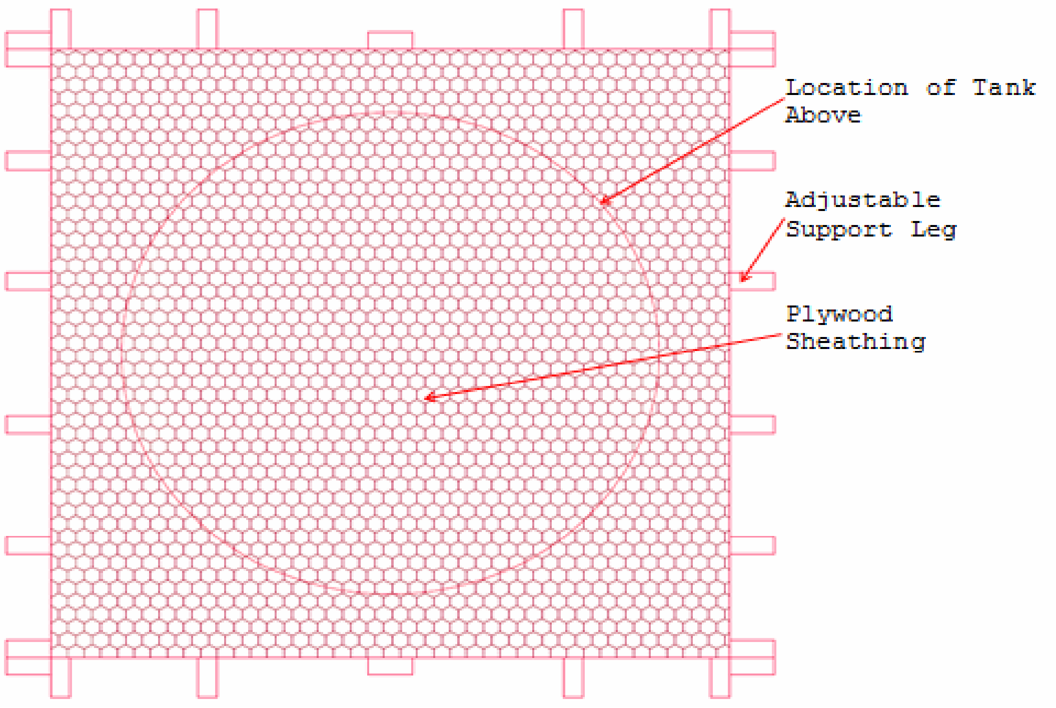

Figure 22: Insulated Tank Container - Layer 2

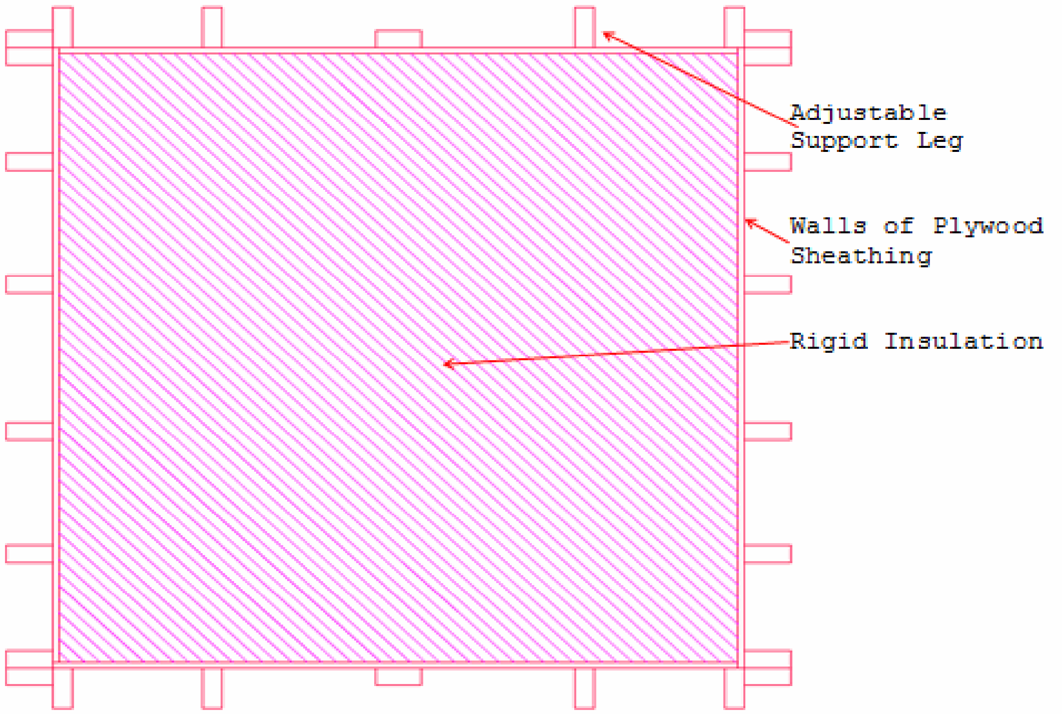

Figure 23: Insulated Tank Container - Layer 3

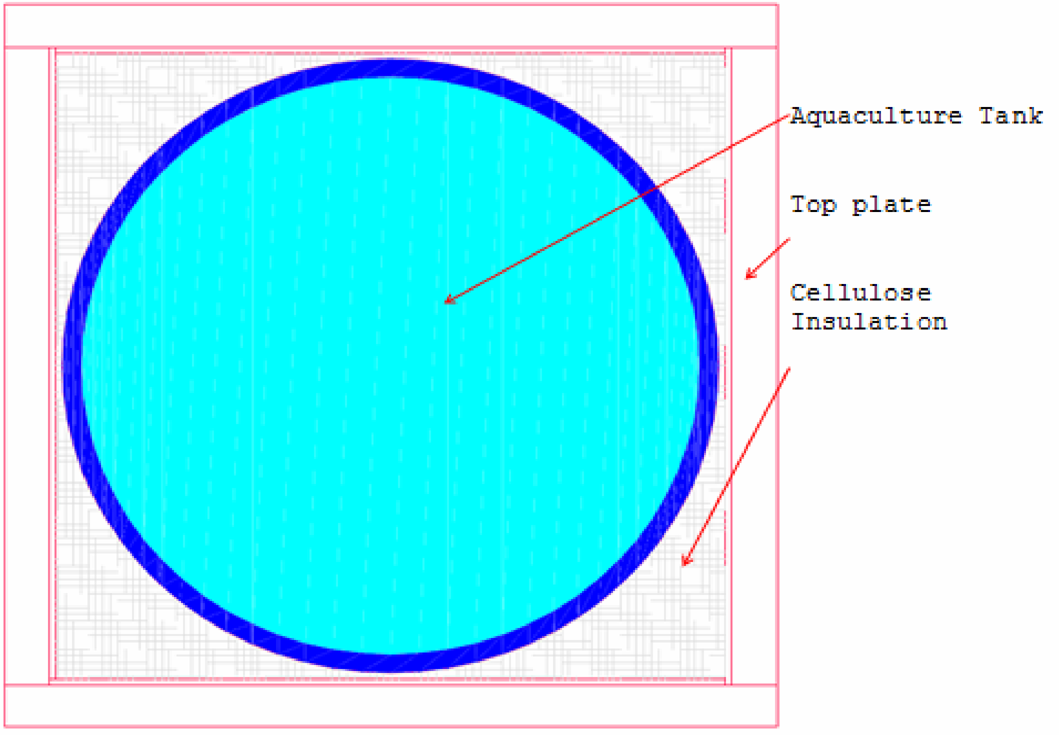

Figure 24: Insulated Tank Container – Layer 4

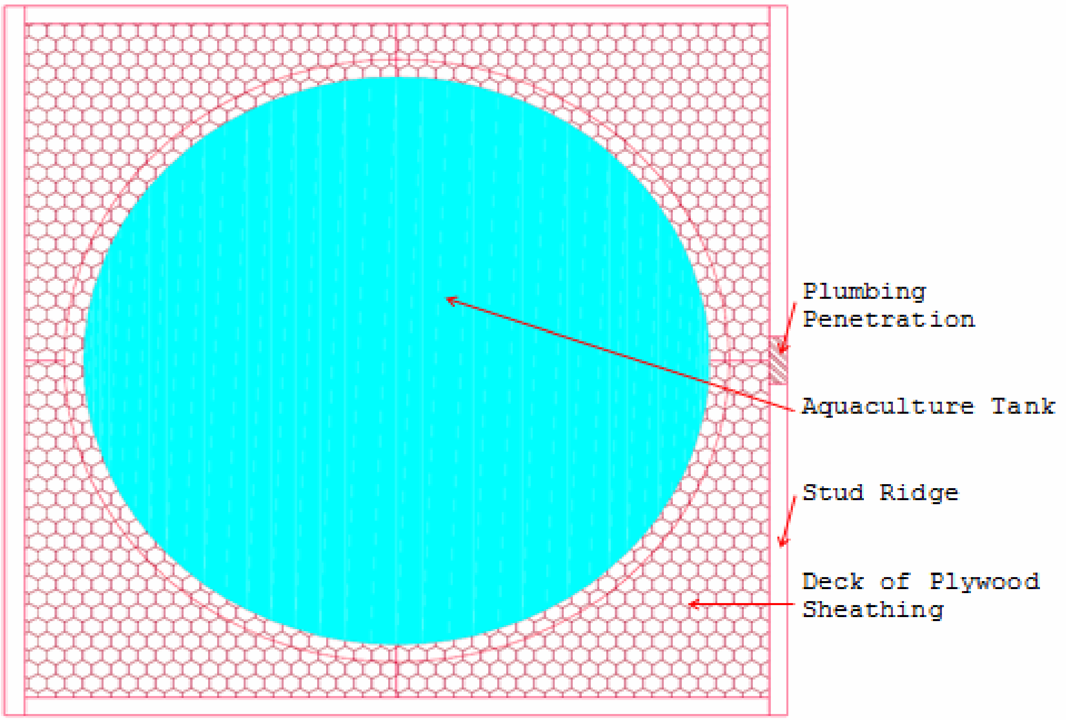

Figure 25: Insulated Tank Container – Layer 5

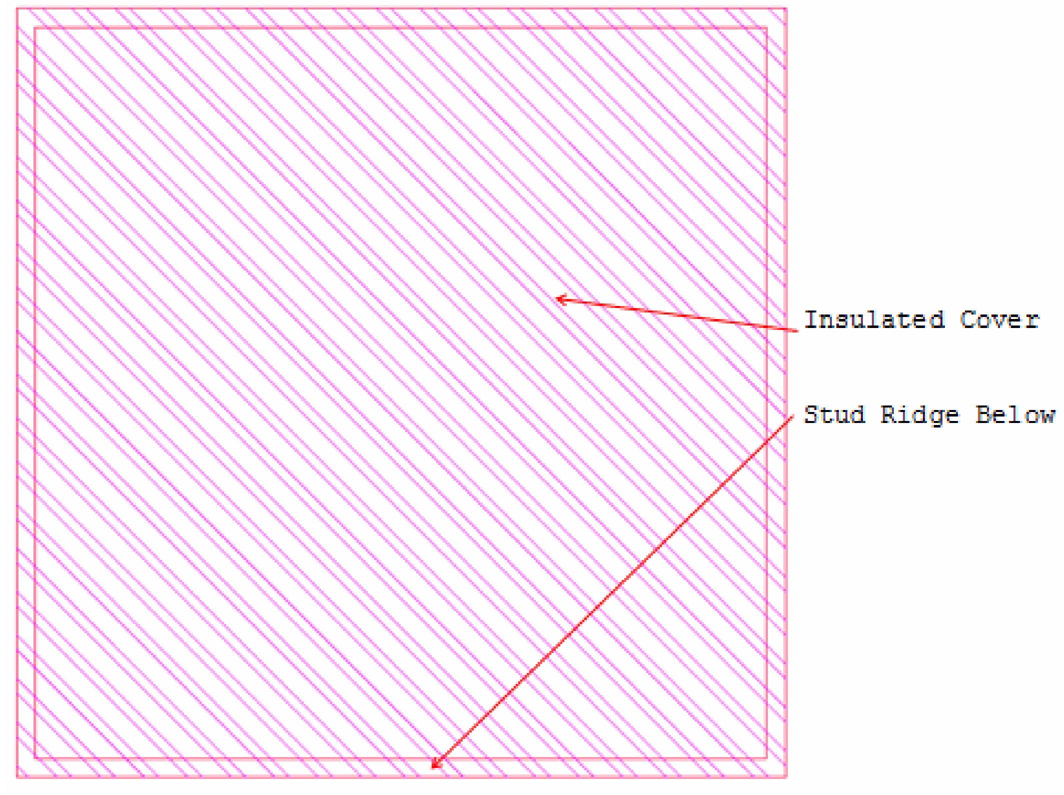

Figure 26: Insulated Tank Container - Layer 6

These containers have many features which meet the needs of the aquaculture management team. Ample room is provided beneath the tank for piping and the legs can be easily raised or lowered for a desired water pressure. There is a complete thermal envelope around the tank made of rigid insulation and blown in cellulose. There are no thermal bridges connecting the thermal mass of the water to the interior air of the facility. Wood is a sturdy base for fasteners and is available all around the tank for securing plumbing or electrical components. Also, plumbing penetrations can be easily installed in the rigid insulation cover.

The insulated covers are made of three lightweight, easily removed, and replaceable pieces of extruded polystyrene rigid insulation. Foil faced polyisocyanurate was specifically not used as it is more delicate and tends to crumble, which reduces its useful life and may contaminate the culturing tank below. Management practices for the facility should include habitual removal of the tank covers upon arriving to the site and returning them when leaving. The covers must be safely stored during working hours, perhaps affixed to the side of the tank container or overhead. This new practice would involve additional time and training when compared to traditional practices. However, insulated tank containers could significantly reduce the load on heating, ventilation, and air conditioning systems.

There are limitations to the container's design. First of all, the tank itself is limited in size and the container should be scaled up for larger tanks. Secondly, the lack of a vertical window limits the ability of the management to assess what is happening in the water column. Finally, the tank covers are made of a material which may be damaged by the activities of the fish or people managing the system.

Fish Culturing Space

The large floor space in the structure is where the fish in the recirculating aquaculture system will be cultivated (Figure 27). Moisture control is a primary design consideration, especially in this room. Fortunately, the space comes equipped with a series of floor drains. The new interior walls and ceiling are finished with a thin sheet of plastic. This finish material can be thoroughly cleaned, sealed tightly, and has ample resistance to airborne moisture. The seam where the walls meet the floor is further protected from water by a protective rubber strip adhered to the lower 6” of the interior walls. This precaution is in the event of a massive bulk transfer of water, perhaps from the sump or tanks, which temporarily overwhelms the floor drains.

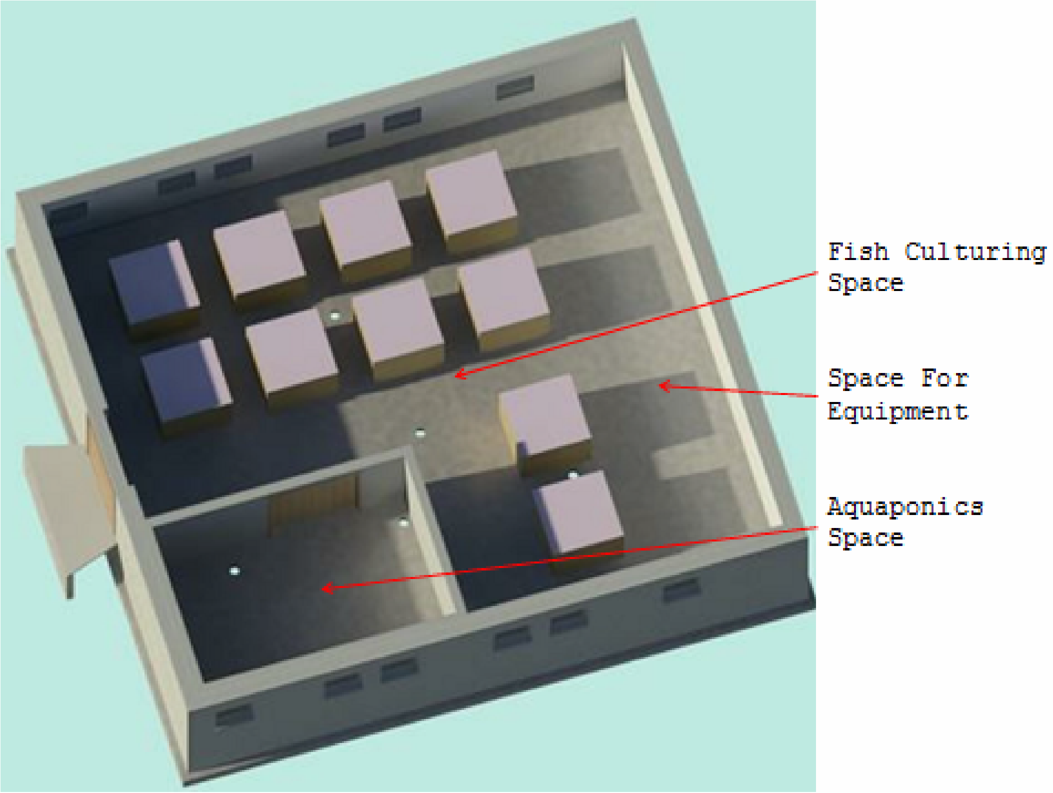

Figure 27: First Level - Program 1

The aquaculture setup is conducive to the research that will be conducted in this room, in that it provides multiple identical culturing tanks. In the first program, ten tanks can fit in the space. This is enough to meet the production goal of 20,000 kilograms of tilapia produced each year while still allowing room for the activities of the aquaculture managers. Space for tanks is limited by the need for additional aquaculture equipment including the sump reservoir, pumps, and solid waste filtration. Pumps will be a source of waste heat energy that will have to be anticipated and compensated mechanically in this room. It may be possible to include a heat exchanger in the aquaculture system to capture some of the thermal energy wasted in the water.

The equipment needed to remove the solid wastes from the water in the recirculating system will occupy much of the vacant space in the room. In this system, it is likely two different solid waste separators will be used. One will be a sedimentation filter, like a triple stand pipe or swirl separator, which reduces the velocity of the water to allow heavy particulate to settle out of solution (Webb 2011). In addition to this, a mechanical drum filter will be employed. This device removes solids by directing the water flow through a cylindrical screen that sifts the particulate out of the water. This advanced mechanical filter has automated mechanisms which clean the screen and directs the captured effluent out of the aquaculture system.

Aquaponics Space

Aquaponic plant production is important in a recirculating aquaculture system as it removes some of the fish effluents and produces a profitable by product, like basil or lettuce. Aquaponics in the first program are in the small partitioned space, but could still produce a respectable quantity of leafy produce if provided enough light. This isolated space is not only for aquaponics production but also is the ideal location for biological filtering and degassing of the water. In fact, by hosting these activities in the same place a valuable synergy can be exploited.

Isolating these activities in the smaller space limits the potential of cross contamination between fish culturing tanks and aquaponic plant beds. The aquaponics room will have much higher ventilation needs because of the evaporation associated with degassing the water and aquaponic plant production. Fortunately, this space can have more air changes without impacting occupant comfort in the larger space. This small space can be filled with growing plants if tall, vertical aquaponics elements are used. Plants could then be arranged around a central light source for more efficient capture of light.

In this isolated space, plant production can be boosted by the higher carbon dioxide levels resulting from the degassing of the water in the aquaculture system. Also, the large amounts of moisture released into the air through the biological filtering and degassing activities produces a humid environment in which most aquaponics plants can thrive. Unfortunately, allowing high levels of carbon dioxide and humidity can be detrimental to human occupants. If this synergy is to be captured, the air in the aquaponics space will have to be isolated and carefully controlled. If possible, a supplemental ventilation system should be used as a safety precaution when the room is occupied.

Program 2 Results

There are less physical restraints in the second program which transforms the structure to demonstrate the concepts of building integrated aquaculture (Figure 28). The existing roof was removed to add an additional level to the structure. New spaces were also created by extending the building's footprint to the South and West. The modifications in this program allowed each space in the structure to be specialized to its purpose within the building integrated aquaculture system. In addition, this program has space and components which would allow the water in the system to be moved from outside the thermal envelope to within, and vice versa, to accommodate changes in the external environment.

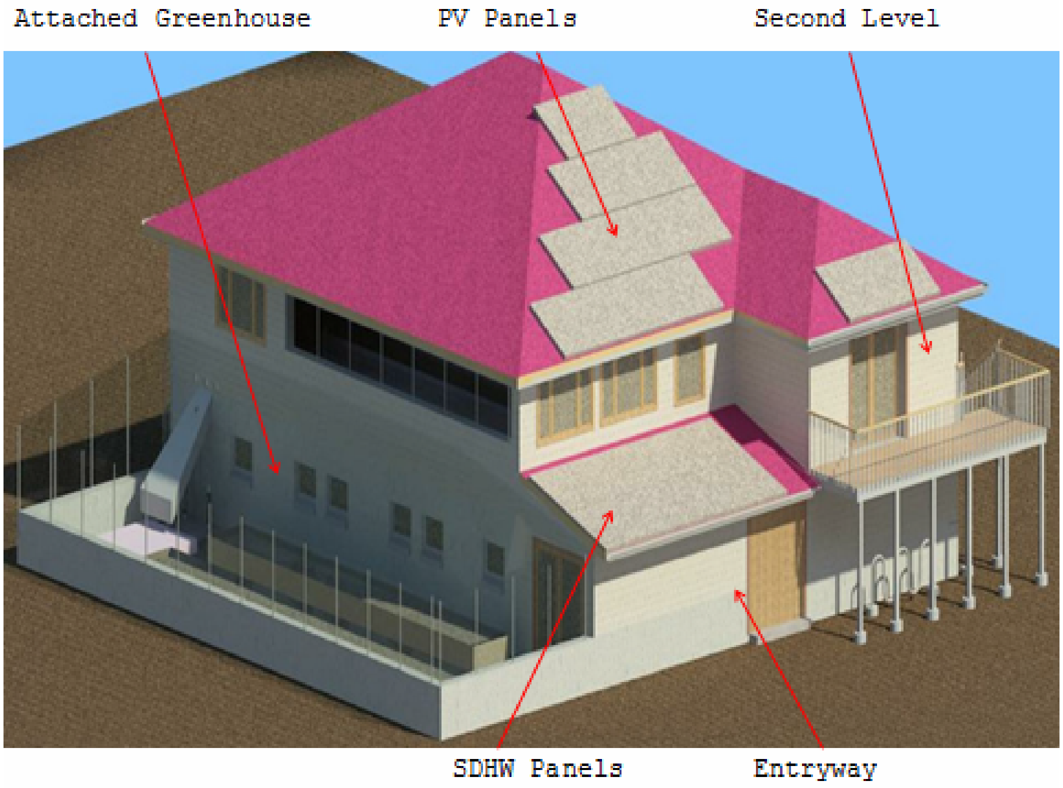

Figure 28: Exterior Perspective – Program 2

Aquaculture System

While similar to the one in the first program, the recirculating aquaculture system employed in the second program has more components and a productive capacity of about 32,000 kilograms of tilapia each year. An additional six tanks are used for the culturing of fish. The aquaponics space was moved to a new attached greenhouse with significantly more space. The new aquaculture system also includes large header tanks on the second floor. This new feature is integrated with a roof mounted solar direct hot water system. There are a number of synergies in this program between the aquaculture system and the building system which boost the efficiency of both. These synergies are grouped and discussed by the space in which they occur.

First Level Culturing Space

Fish culturing tanks dominate the fish culturing space on the first level (Figure 29). The aquaponics space is moved out of the original structure’s footprint. Removing this activity and the partition walls which separate it from the larger space creates more room for tanks in the fish culturing space. Also removed from this space are the sump reservoir and pumps for the aquaculture system. There is a new space added between the old southern wall and the new southern wall. It can be used as dry storage, further freeing up space for tanks, equipment and management activities on the first level.

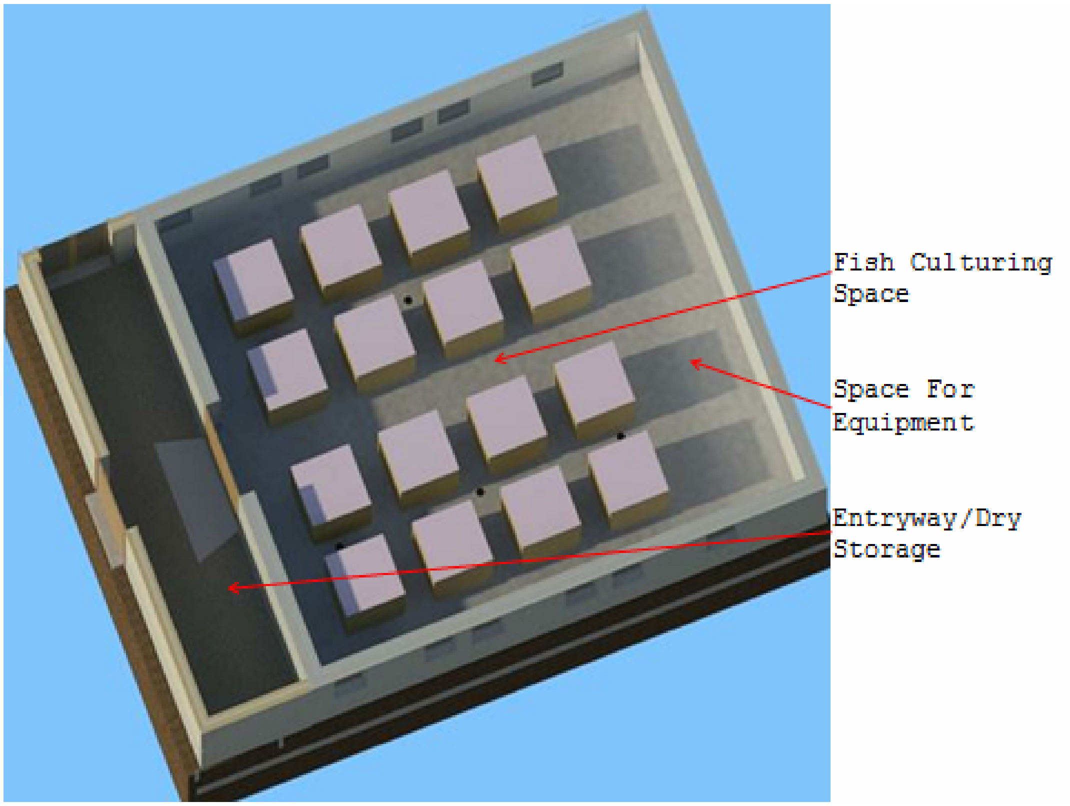

Figure 29: First Level - Program 2

The waste stream from the solid waste removal is plumbed directly to the attached greenhouse. The solid waste from fish is rich in nitrogen and other organic materials which plants consume. It can be used to fertilize plants in the greenhouse or on the second level which are not incorporated into the recirculating aquaculture system. The fish effluents can also be distributed to farms to support local agriculture.

The temperature of the water in the aquaculture system will have a significant influence on the air temperature in the structure. The largest volume of water in the system is in the many insulated tanks on the first level. Its thermal mass is held at a constant temperature by heating units. This mass may help reduce fluctuations in air temperature for the interior space. A similar benefit may be extended to the second level above, whose floor conducts the thermal energy up from the air below.

First Level Greenhouse

The aquaponics have been moved into an attached greenhouse with a lot of space (Figure 30). The greenhouse is a much easier place to grow plants with aquaponics, except during the coldest months of the year. Lighting expenses are reduced from the previous program as plants grown under natural sunlight have little, if any, need for artificial light. Environmentally responsive management practices could employ the significant amount of thermal mass in the features of the greenhouse as a means to offset heating and cooling needs of the structure.

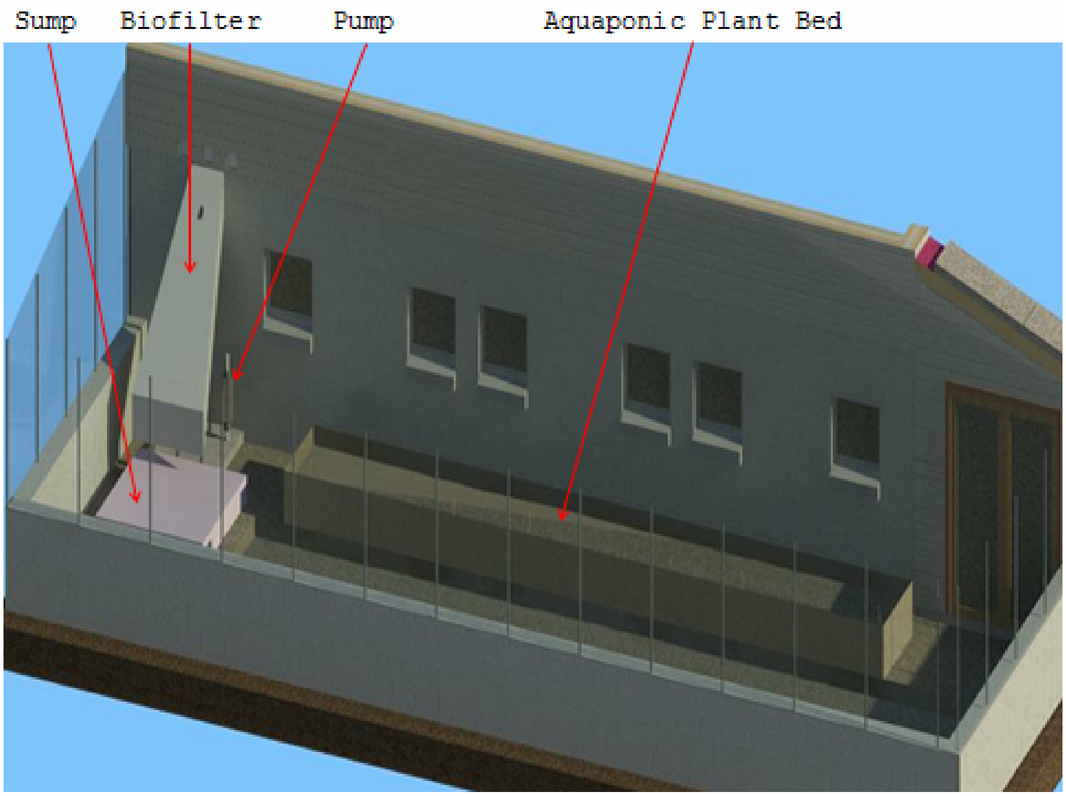

Figure 30: Attached Greenhouse – Program 2

Much more natural light and air ventilation is available in the attached greenhouse for the cultivation of plants. The sun provides a stable source of light for the plants and is immune to occasional power outages. In addition, the greenhouse has far more potential for natural ventilation through open windows, further reducing the energy needs of the aquaponics system. During cold winter months, these advantages which come at little cost are lost and it may be best to halt produce production until the next growing season begins.

The energy requirements of the greenhouse can be reduced if use and management of the space is responsive to the external environment. The natural environment in this temperate climate tends to be too cold and has too little sunlight during the winter. To avoid using expensive heat and light sources, the greenhouse could remain dormant for the coldest months. Without plants to absorb the radiance, more sunlight will reach the structure and thermal mass features in the greenhouse. The attached greenhouse will function as a solar space, trapping against the Western wall a pocket of air which absorbs thermal energy from the sun and the structure. Parts of the thermal envelope which are exposed to the trapped bubble of warmer air will lose less heat through conduction than if they were exposed to the cold winter air.

In the summer, the attached greenhouse can also be managed to reduce the cooling load of the structure. Windows can be opened on the top and bottom of the glass enclosure to create a cooling convective loop of air in the space. Tall plants can be grown along the Western wall in the aquaponics system to provide temporary biological shading for the structure. When at peak production in the summer, the foliage cover from all the plants in the greenhouse will provide shade to many of the other thermal mass features of the greenhouse as well.

The greenhouse contains a number of significant thermal mass features. The temperature of the greenhouse will probably be most stabilized by thermal mass of the water in the aquaculture components, like the sump reservoir and the aquaponics beds. The Western wall inside the attached greenhouse is made of concrete masonry units which also have high thermal mass. The material chosen for the floor, 1” gravel, has a number of desirable attributes. Not only is it an inexpensive material with high thermal mass, but it also has excellent drainage and can be easily modified to fit various aquaculture or aquaponic components.

Second Level

The second level is designed for the comfort of human occupants engaged in research. It is divided into two main rooms as well as a bathroom and vestibule for the main entrance (Figure 31). The main room is a lab space, accessible by exterior stairs in the north and south. This space is largely intended for activities auxiliary to aquaculture and aquaponic production. The other room is dominated by a pair of the largest water containing vessels in the aquaculture system, the header tanks.

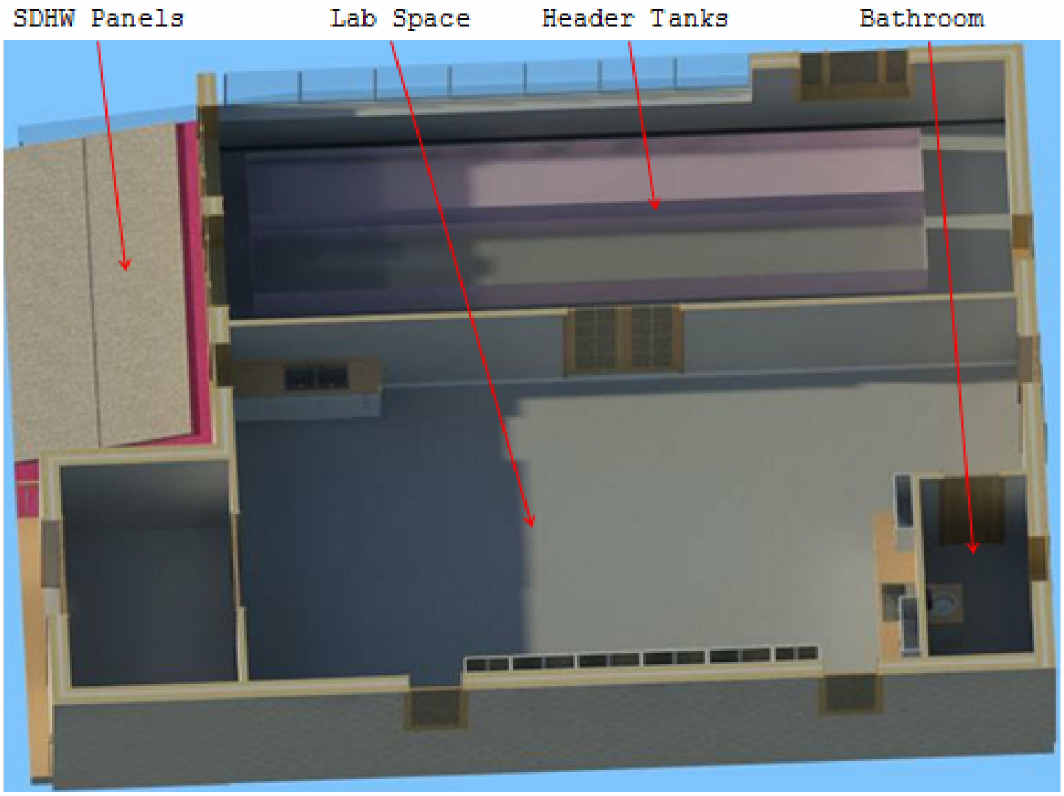

Figure 31: Second Level - Program 2

The lab is an ideal space for conducting research and educating visitors about building integrated aquaculture. To meet the changing needs of the University of Massachusetts, the lab was designed to be a very open and versatile space. Cabinets, countertops, and sinks, have been included around the room's perimeter to avoid interfering with the openness of the room. These conditions should provide an excellent working environment for the occupants and be a comfortable space for visitors to the building integrated aquaculture system.

The room to the West of the lab is filled with the header tanks of the recirculating aquaculture system. These tanks perform a number of vital functions for the building integrated aquaculture system. Foremost amongst these, the header tanks deliver water at a very consistent rate of flow to the culturing tanks and the aquaponics below. These header tanks are also a critical part of the collection of solar thermal energy in the water of the system. One of the tanks is located in front of the windows of the western wall, allowing them to collect solar radiation directly. Immersed in the other tank is the heat exchanger for the array of solar direct hot water collectors on the roof.

Discussion

The first design challenge, minimizing energy inputs, was addressed in three ways in this case study, capturing solar energy, using energy conservative construction materials and providing a strong thermal envelope. Amongst the most significant energy consumers in the building integrated aquaculture system is the heating and cooling system. To reduce strain on these systems, robust thermal envelopes were included in both retrofit programs. The insulation standard used, the 2009 IECC, prescribed thick layers of insulation because maintaining interior air and water temperature in temperate Western Massachusetts is particularly challenging. Aquaculturists interested in operating a facility in temperate areas should strongly consider following an established energy efficiency standard, like the International Energy Conservation Code.

A couple of methods for passively controlling moisture in a building integrated aquaculture system were used in the programs described above. Both included covered tanks, which would stop evaporative moisture at its major source in the structure. This is a departure from traditional indoor aquaculture practices, but was deemed necessary to accomplish the goals of building integrated aquaculture. In short, aquaculturists should be considering techniques like this to stop moisture at the source before it becomes a problem for the host structure and ultimately the aquaculture system.

All interior surfaces of the fish culturing space could be subject to intense moisture pressure and occasional splashing. This is why all surfaces in this space need to be made of waterproof and/or moisture damage resistant materials, like plastic or concrete, and sealed continuously along all the seams. Finally, where multiple spaces are available in a single facility, it is best to strategically place the components of the building integrated aquaculture system to isolate moisture sources and ventilate them naturally through windows.

The final challenge addressed in this case study was to achieve a target fish production rate for each program using a defined list of equipment. The amount of fish produced is ultimately limited by the volume of water in which they are cultured. In theory, the systems in each program could achieve their respective production rate. However, it is possible that, given another set of goals and equipment, either program could have a higher productive capacity. More research needs to be conducted to determine the optimum volume of fish culturing water in a given space. Building integrated aquaculture needs to be a profitable venture if it is to continuously support local food systems.

CHAPTER 5

DISCUSSION AND CONCLUSION

Discussion

Building integrated aquaculture is a very broad topic encompassing a number of disciplines. A number of synergies and areas of mutual concern for both building and aquaculture systems were identified in this exploratory research (Figure 32). This research has shed some light on some of the key issues pertaining to the design of such systems and the interaction of the separate components. There is still much to be explored in building integrated aquaculture which was not addressed in this research. These topics include but are not limited to comparative life cycle analysis, renewable energy system integration, and aquaculture management implications.

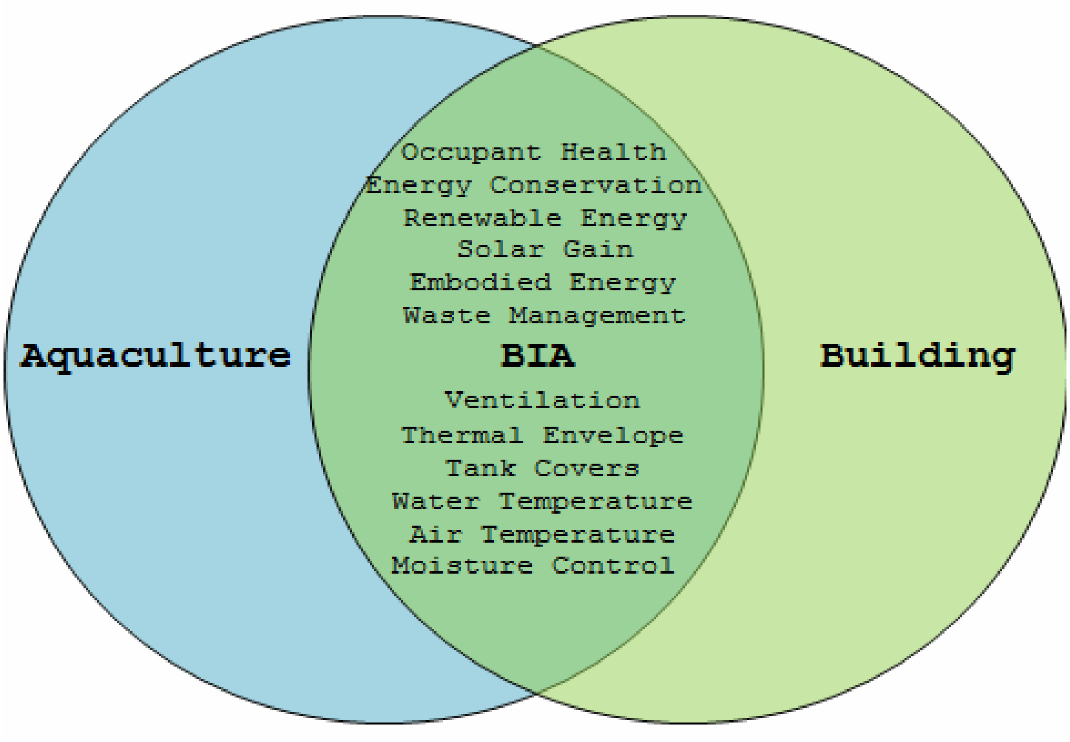

Figure 32: Important Building Integrated Aquaculture Considerations

The findings and methods of this research are of value to aquaculturists, designers, and architects participating in the development of local scale aquaculture facilities. Aquaculturists should consider the fundamental changes to common practices supported in this research, such as using tank covers and isolating activities which could be detrimental to the building system. They should develop this research further by designing and testing tank containers which are conducive to the needs of aquaculture management. Designers and architects creating host structures for aquaculture should consider using the thermal mass in the aquaculture system and including a robust thermal envelope, both can help lower the energy load of the structure and improve temperature stability (Figure 33). These experts could build upon this research by developing a set of models to understand the movement of energy between systems and perhaps use these equations to establish an energy efficient standard for indoor aquaculture facilities. Further, designers and architects should conduct many case studies collaboratively with aquaculturists. More case studies applying building integrated aquaculture concepts are needed as one is simply not sufficient for demonstrating the many possible faces of this new concept

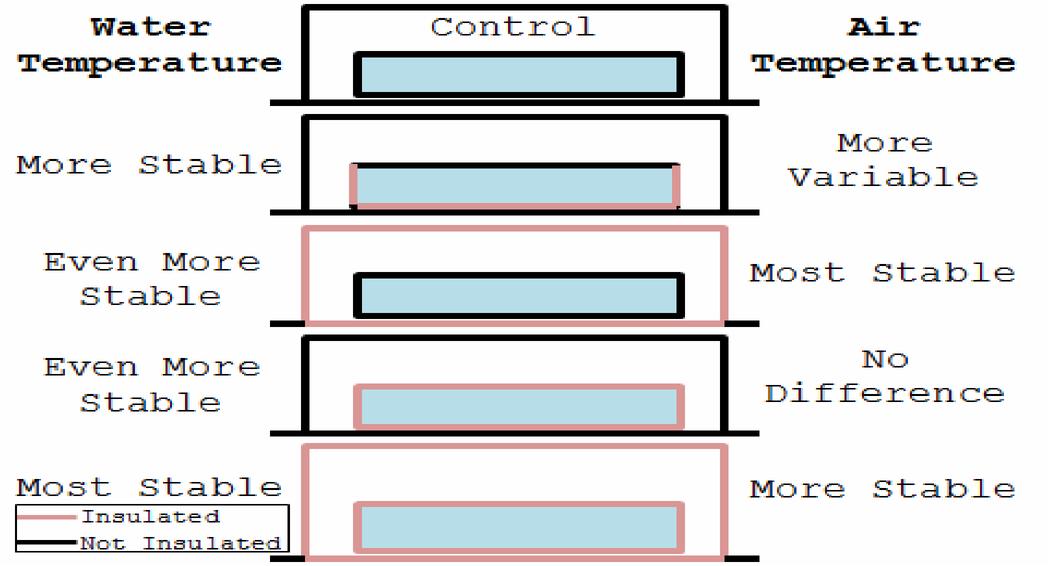

Figure 33: Insulation Effects on Air and Water Temperature

There is still much to learn about the complex interactions between the systems, but this research has pointed to some which have synergistic potential. Employing the thermal mass of the water in the aquaculture system for storing energy from the sun was very strongly endorsed. It was also strongly suggested that system designers isolate moisture intensive activities, aquaponics, and off gassing in areas where natural ventilation and aggressive mechanical ventilation could be used without impairing occupant comfort. There are many other synergies that need to be explored within building integrated aquaculture, such as biological shading and the use and reclamation of system wastes and carbon dioxide gas.

Conclusion

Building integrated aquaculture is an exciting new concept with the potential to radically change local food systems for the better. The practices and ideas explored in this avenue of research are particularly useful for the development of aquaculture operations in temperate, urban, or otherwise inhospitable environments. Researching this topic is the best way to bring this idea into fruition. It was found that there is great potential for synergies between building and aquaculture systems, but failure to consider the needs of both systems simultaneously during design could plant seeds of failure. The main challenges to the implementation and development of building integrated aquaculture are energy conservative temperature and relative humidity control, as well as spreading these concepts to aquaculturists and fish consumers alike.

Bibliography

Barnhart, E. (2006). A Primer on Solar Aquaculture. http://www.thegreencenter.net/pdf/solaraqua.pdf

Bastianoni, S., & Marchettine, N. (1997). Emergy/exergy ratio as a measure of the level of organization of systems. *Ecological Modeling, 99*, 33-40.

Caplow, T.Building integrated agriculture: Philosophy and practice. *Urban Futures 2030 Urban Development and Urban Lifestyles of the Future, 5*, 5/1/2011.

Danylchuk, A. (2010). In Woodin E. (Ed.), *Conversation about building integrated aquaculture*

FAO. (2010). *The state of world fisheries and aquaculture 2010.* Rome:

Fernández-González, A. (2007). Analysis of the thermal performance and comfort conditions produced by five different passive solar heating strategies in the united states midwest. *Solar Energy, 81*(5), 581-593. doi:DOI: 10.1016/j.solener.2006.09.010

Folke, C., & Kautsky, N. (1992). Aquaculture with its environment: Prospects for sustainability. *Ocean & Coastal Management, 17*, 5-24.

Fuller, R. J. (2007). Solar heating systems for recirculation aquaculture. *Aquacultural Engineering, 36*(3), 250-260. doi:DOI: 10.1016/j.aquaeng.2006.12.005

ICC. (2009). *2009 international energy conservation code.* U.S.A.: International Code Council.

Gangolells, M., Casals, M., Gassó, S., Forcada, N., Roca, X., & Fuertes, A. (2009). A methodology for predicting the severity of environmental impacts related to the construction process of residential buildings.*Building and Environment, 44*(3), 558-571. doi:DOI: 10.1016/j.buildenv.2008.05.001

Gross, R., Leach, M., & Bauen, A. (2003). Progress in renewable energy. *Environment International, 29*(1), 105-122. doi:DOI: 10.1016/S0160-4120(02)00130-7

Guerdat, T. C., Losordo, T. M., Classen, J. J., Osborne, J. A., & DeLong, D. P. (2010). An evaluation of commercially available biological filters for recirculating aquaculture systems. *Aquacultural Engineering, 42*(1), 38-49. doi:DOI: 10.1016/j.aquaeng.2009.10.002

Johnston, D., & Gibson, S. (2008). *Green From The Ground Up: Sustainable, Healthy, and Energy-Efficient Home Construction.* Newtown, CT: The Taunton Press.

Local harvest. (2011). Retrieved 4/1, 2011, from http://www.localharvest.org/csa/

Loftness, V., Hakkinen, B., Adan, O., & Nevalainen, A. (2007). Elements that contribute to healthy building design. *Environmental Health Perspectives, 115*(6), pp. 965-970.

Meklin, T., Potus, T., Pekkanen, J., Hyvärinen, A., Hirvonen, M. -., & Nevalainen, A. (2005). Effects of moisture-damage repairs on microbial exposure and symptoms in schoolchildren.*15*, 47.

Mendell, M. J., Cozen, M., Lei-Gomez, Q., Brightman, H. S., Erdmann, C. A., Girman, J. R., & Womble, S. E. (2006). Indicators of moisture and ventilation system contamination in U.S. office buildings as risk factors for respiratory and mucous membrane symptoms: Analyses of the EPA BASE data. *Journal of Occupational and Environmental Hygiene, 3*(5), 225.

Odum, H. T. (1988). *Energy, environment and public policy.* No. 95).United Nations Environment Programme.

Palada, M., Cole, W., & Crossman S. (1999) Influence of Effluents from Intensive Aquaculture and Sludge on Growth and Yield of Bell Peppers. *"Journal of Sustainable Aquaculture,"* 14(4)

Pinckney, C. D. (2009). KEEP MOISTURE OUT of your buildings. *Buildings, 103*(3), 42-45.

Rode, C., & Grau, K. (2008). *Moisture buffering and its consequence in whole building hygrothermal modeling.(technical report)*

Summerfelt, R. C., & Penne, C. R. (2005). Solids removal in a recirculating aquaculture system where the majority of flow bypasses the microscreen filter. *Aquacultural Engineering, 33*(3), 214-224. doi:DOI: 10.1016/j.aquaeng.2005.02.003

Valencia, E., Adjei, M., & Martin, J. (2001) Aquaculture Effluent as a Water and Nutrient Source For Hay Production in the Seasonally Dry Tropics. "*Communications in Soil Science and Plant Analysis,*" 32(7&8)

Vassallo, P., Bastianoni, S., Beiso, I., Ridolfi, R., & Fabiano, M. (2007). Emergy analysis for the environmental sustainability of an inshore fish farming system. *Ecological Indicators,* 7, 290-298. doi:10.1016/j.ecolind.2006.02.003

Webb, J. (2011). In Woodin E. (Ed.), *Conversation about aquaculture practices*

Wolfe, J., & Zweig, R. (1977). Summary of Fish Culture Techniques in Solar-Algae Ponds. "*Journal of the New Alchemists,*" 6, 97-99 http://www.thegreencenter.net/pdf/j6ponds.pdf

Wurts, W. (2000). Sustainable Aquaculture in the Twenty-First Century. "*Reviews in Fisheries Science,*" 8(2), 141-150

Zweig, R., Todd, J., Wolfe, J., Angevine, R., Doolittle, A., & Engstrom, D. (1981). *Solar Aquaculture: Perspectives in Renewable, Resource-Based Fish Production.* A Report to the National Science Foundation