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The Vertical Farming Façade Project

Summary of Research Performed August 2012 – July 2013

And Proposal for Future Work

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ABSTRACT

This report covers research performed from August 2012 through August 2013 in order to determine the viability of implementing commercial "vertical farming" systems in urban buildings. The concept developed for this research centers around a double-skin façade filled with plants, henceforth referred to as a Vertical Farming Façade (VFF). In order to explore this issue, a vertical aquaponic system and corresponding single-metering calorimeter (henceforth referred to collectively as the "Alpha Box") was constructed. Data was actively collected over a three-month period from March-May 2013 in order to come to a general understanding of how a typical VFF would perform, using R-Value and solar heat gain coefficient (SHGC) as performance metrics.

Figure 1: The Alpha Box Test Chamber

Preliminary results obtained from the Alpha Box system are promising. When the vertical farming system was introduced to the test fenestration system, SHGC was reduced by an average of 70%. The aquaponic system also improved the fenestration's R-Value by 13%. While these results were marred by testing procedure inadequacies, the VFF concept has shown enough promise that further research has been proposed to build upon the work outlined in this report. That research will attempt to develop more accurate and complete data in order to come to a more complete understanding of how alterations in VFF designs affect performance as a fenestration system (as defined by changes in R-Value, SHGC, VT, and VOC-reduction).

This future research will be continued through a minimum of April 2014. This document is meant to serve as both a summary of previous results and as a blueprint for continued work.

INTRODUCTION: WHY VERTICAL FARMING MATTERS

The concept of vertical farming was first developed by Dickson Despommier, an ecologist and Professor of Public Health at Columbia University. While our research attempts to build on Dr. Despommier's work, it is unique in that it focuses on integrating farming into buildings designed for other purposes, e.g. commercial office buildings. This distinction was made because of the belief that synergies between the two building components (e.g. increased worker productivity related to air quality improvements) could make such a design more economically viable than a building designated solely for food production.

The benefits of farming vertically in an urban environment are numerous:

- Improved Building Performance: Double skin façades improve building Insulation and temperature regulation, provide shading and reduce solar radiation, increase acoustic insulation, and protect the building from the outdoor environment. Placing plants within such a façade is likely to improve all of these characteristics, while adding the important benefit of improved interior air quality. Determining to what extent these performance characteristics are improved with a vertical farming façade is the primary goal of this research.

- Reduced Reliance on Fossil Fuels: In our current industrial agricultural system, the average calorie of food requires ten calories of oil to be produced. This energy consumption comes in the form of transportation, pesticides and herbicides, food processing, and packaging. Farming locally and indoors drastically reduces transportation requirements, negates the need for pesticides and herbicides, and encourages the consumption of unprocessed produce. This reduced need for pesticides and fertilizers also makes farming organically viable in a vertical system.

- Reduced Water Consumption: Indoor farming operations are generally capable of achieving drastic water savings in comparison with traditional farming methods. This is significant considering that approximately 70% of the world's fresh water withdrawals go to crop irrigation.

- Aesthetic Benefits: Plants look good, and they make people feel good. One recent study reported that putting plants in a work environment increased worker productivity by up to 12% while reducing reported stress levels and sick days taken. An aesthetically pleasing façade can also be used as a marketing point for architects and building owners alike.

- Reduced Land Use: Because vertical farms are indoors, climate can be controlled to enable food production 365 days/year. Food production can also be stacked, further reducing the area required to feed a community. As worldwide populations increase and arable land areas vanish due to mismanagement, the importance of space-efficient food production will become a major political issue.

- Building Community: Culture is often built around food. A local source of fresh food in a crowded urban setting can serve as communal gathering location, an information source, and more. The Grow Haus in Denver is an excellent example of an urban farming outfit that has benefited and transformed its surrounding community.

- Increased Food Security: The reduction in land required for farming enables a community to grow food dependably, without relying upon outside assistance. Indoor farms are also buffered from natural disasters, e.g. heat wave or drought.

Recently, as vertical farming has gained traction in the architectural engineering industry, a multitude of potential designs for vertical farm façades have been developed (many examples can be found on Dickson Despommier's website, verticalfarm.com). Unfortunately, while these designs are visually striking, they rely on surprisingly little real data to determine building performance. Our research attempts to find how well a typical vertical farm façade design performs in order to allow architects to make educated decisions about whether a VFF is practical in their project, as well as what design specifications should be used for optimal performance.

INITIAL RESEARCH (AUGUST 2012-DECEMBER 2012)

The Fall 2012 semester was spent researching several topics related to the design of a successful vertical farming system. Different farming systems, lighting strategies, plant requirements, materials options, and economic factors were all covered in order to come to a basic understanding of what a “typical” VFF might look like. This information was used in the design of the Alpha Box during the Spring 2013 semester.

Note: Much of this section has been adapted directly from reports written between September and December 2012 by Michael Gartman, Matthew Kincaid, and Brian Carpenter.

POTENTIAL FARMING SYSTEMS

Vertical farming systems do not lend themselves particularly well to soil-based farming. Soil is heavy, is a relatively inefficient medium for nutrient transport, and can cause drainage problems when used in a confined space. There are numerous benefits associated with growing food in the substrate it was designed to live in, but unfortunately taking advantage of these benefits within a closed environment can be an extremely complicated and difficult task.

Hydroponics has steadily grown in popularity as an alternative to traditional soil-based farming over the last several decades. At their core, hydroponic systems consist of a soilless growing medium and a method of delivering nutrient-rich water directly to plant roots. While the most basic hydroponic systems rely solely on capillary action to provide plants with their essential nutrients, an ever-increasing number of more complex nutrient delivery systems have been recently developed, including (but not limited to) Nutrient Film Technique, Deep Water Culture beds, Aeroponics/Fogponics, Bubbleponics, Continuous Flow Solution Cultures, and Flood-and-Drain Systems. While these system types are all unique, they also all rely on the same basic concept: that plant growth is proportional to the ease with which nutrients are supplied. By removing soil from the growing environment, highly concentrated and specialized nutrient solutions can be delivered directly to plant roots, allowing plants to focus all energy on aboveground growth. This difference generally leads to faster plant harvesting times, higher maximal planting densities, and higher plant production.

Unfortunately, while hydroponic systems represent a major modern innovation in agriculture, all of these systems contain inherent flaws. One flaw in particular makes these systems difficult to rationalize on a commercial scale: cost. Disregarding installation costs (which are significant themselves), the cost of the nutrients needed to maintain these systems can be astonishing. One hydroponic farmer consulted for this research reported that he spends several thousand dollars on nutrients each year for his family-sized system, making the food he grows more expensive to produce than it costs at his local supermarket. Expense isn’t the only problem- these nutrients are frequently petroleum-based or extracted from sensitive ecosystems, and can become so toxic in higher concentrations that frequent water discharges are required to keep plants alive.

Fortunately, there is an alternative to hydroponics: aquaponics. Aquaponic nutrient delivery systems can take the form of many of the systems mentioned above, with one major difference: the nutrients are provided in the form of fish waste. These systems, first researched by Dr. James Rakocy at the University of Virgin Islands, combine the flawed concepts of hydroponics and aquaculture (intensive fish farming) into a nearly closed-loop system. Instead of constantly buying man-made nutrients, plants are fed by fish waste. Instead of fish requiring constant filtration and water exchanges to survive, water is filtered inexpensively and naturally by the soilless growing medium and plant roots. Some aquaponic proponents claim that commercial aquaponic systems can be run more cheaply than hydroponic or aquaculture systems alone, with the revenue stream of both.

AQUAPONIC SYSTEMS

While aquaponic systems can theoretically be modeled using any of the hydroponic nutrient delivery systems mentioned above, high solids concentrations make more complex systems (i.e. Aeroponics or Fogponics) unreasonable. Instead, aquaponic systems are almost exclusively grouped into three major design categories: Nutrient Film Technique (NFT), Deep Water Culture (DWC), and media-based systems.

In NFT systems, nutrient-rich water is pumped through small gutters in a thin film, giving it direct access to plant roots in a highly controlled environment. Because of the high solids content of aquaponic water, this water must be pre-filtered (sometimes in a conjoined media-based system) before traveling across plant roots. Lettuce (a major cash crop) thrives in an NFT system, and these systems are significantly lighter than DWC or media-based systems. However, because of the delicacy of NFT systems, they are not suitable for heavier plants or plants with large root systems. This constraint ruled out the use of an NFT system for the purposes of this research. Exploring the use of these systems could prove valuable in subsequent research endeavors.

Figure 2: A Typical Commercial-Scale NFT Aquaponics System

While not feasible on a family-scale, commercial aquaponic outfits use DWC systems almost exclusively. These systems consist of large troughs of nutrient rich water, with plants suspended on the water surface by floating “rafts” (frequently consisting of Styrofoam sheets). While these systems still require pre-filtration and are significantly heavier than NFT systems, they are simpler, easier to maintain, and more universal in application. Unfortunately, DWC systems do not lend themselves to VFF applications for obvious reasons. However, if a media-based VFF system is relied upon for water filtration, a conjoined DWC of NFT system could easily be installed on building rooftops in order to substantially increase food production.

Figure 3: A Typical Commercial-Scale DWC Aquaponic System

Smaller-scale aquaponic systems are almost exclusively media-based systems due to their relative simplicity. Media-based systems can be built exclusively from materials available from a local hardware store. More importantly, the tasks of water filtration and nutrient delivery are performed in the same location. This isn't possible in NFT or DWC systems because nitrifying bacteria, the organisms that convert ammonia (i.e. toxic fish waste) into nitrate (non-toxic and easily-absorbed plant food) require a submerged porous medium to colonize. Similar mediums are also required for solids removal, which can clog and damage system components if not adequately removed. Media-based systems negate the need for a train of water filtration chambers, greatly simplifying the overall system.

Media-based systems do have two major drawbacks: First, nutrient delivery is less efficient in these systems (though still significantly more efficient than soil), so plant density and overall production is decreased. This was determined not to be a major detractor when applied to VFF systems, as marginally increased plant spacing allows for greater light penetration and should reduce the need for interior lighting. Second, plant extraction is significantly more difficult in media-based systems- roots grip rather well to the soilless media, making it unfeasible to produce plants with a high turnover rate (e.g. lettuces). This problem was highlighted in initial Alpha Box testing, when replacing dead or harvested plants was revealed to be the single most intensive system maintenance requirement. While this is a significant problem, considering lettuce's status as a cash crop, it can be reduced or negated by employing longer-lived or perennial plants. These plants are more desirable in a VFF application because their larger size is likely to lead to increased insulation, shading, and VOC-reduction. As mentioned above, the potential also exists to produce mass quantities of lettuce in a connected rooftop NFT- or DWC-style system while taking advantage of a VFF component to filter system water and produce perennial plant species.

Figure 4: A Typical Family-Scale Media-Based Aquaponic System

For the purposes of Alpha Box research, a media-based aquaponic system was chosen for its relative simplicity and impressive performance characteristics. Lettuce plants were employed in the system to verify the harvesting challenges reported, though all other plants used were longer-lived.

PLANT ANALYSIS

In order to come to an understanding of what a "typical" VFF system could look like, it was vital to come to an understanding of which plants could perform well in a VFF application. While none of the researchers involved in this project had a background in horticulture, common-sense knowledge and basic research into favorable growing conditions managed to yield a list of 30 plant species which are suited for an aquaponic application, could handle the growing conditions expected in a VFF system, and either have a significant value as produce or provided some other major benefit to the system (e.g. excellent VOC-harnessing capabilities).

GENERAL REQUIREMENTS

The requirements of a plant for successful propagation vary extensively between plants- some plants simply cannot survive in conditions where another plant may thrive. Despite this unavoidable fact, it was desirable for this project to come to a generalized list of plant requirements for use in designing a farming system. These requirements dictated much of the system design- an analysis of plant lighting requirements, for example, quickly revealed that artificial lighting was to be avoided at all costs.

LIGHTING

"Almost every indoor greenhouse I've seen has failed because of the amount of electricity needed to provide light to the plants"

–Avery Ellis, owner and founder of Integrated Aquaponics

While light requirements vary widely between plants, there is an apparent illuminance threshold of approximately 5,000 fc (half the intensity of full sunlight). Beyond this point, additional light can actually inhibit growth and damage foliage on many plants. Minimum lighting requirements vary much more widely between plant species, an important note for this project. Some shade-loving plants will burn if exposed to direct sunlight for too long, others (e.g. lettuce) use prolonged light exposure as a signal to "bolt", going to seed and losing much of their flavor. Anyone who's tasted a bolted lettuce leaf will attest that plants are virtually worthless if they bolt before being harvested.

As a general rule, most plants grown commercially in the United States thrive in illuminance levels of 1,000-4,000 fc. There are some notable exceptions, including strawberries (requiring a minimum of only 30 fc) and most air-purifying houseplants. Plants also have specific tolerance ranges for their daily lighting duration- the vast majority of plants grow best in 12-16 hours of light each day.

The majority of artificial lighting guides suggest striving for a light output of 15-30 W/ft^2 to reach the illuminance levels required for adequate plant growth, depending on the lighting type and the distance between lighting source and plants. This leads to a *minimum* annual electricity cost of $6.50/ft^2 (assuming average 2013 US electricity prices) simply for lighting the plants. This doesn't incorporate the added cost of lighting installation, nor the incompatibility between lighting levels required for plants and those for human comfort. Simply put, a vertical farming system designed to use artificial light is destined to fail.

WATER

One of the major benefits in an aquaponic system is the simplicity with which it manages individual plants' water needs. In traditional soil systems, watering requirements vary by orders of magnitude- some plants need to be watered heavily multiple times each day, others prefer to be watered once/month. In vertical aquaponic systems, plant roots are never fully submerged nor fully dry. The constant flow of water allows plants to siphon off water as it is needed, allowing a water-intensive plant to be planted within inches of a desert species and negating the need to compartmentalize watering systems.

Exact water consumption rates for aquaponic systems vary widely with climate- because the water in aquaponic systems is recycled and reused, evaporation overtakes plants' consumption as the determining factor in this number. Regardless, aquaponic systems are reported to use 10-20% of the water required by traditional soil-based systems, so water consumption should rarely prove to be a major cost.

One complexity of aquaponic systems is their requirement for a tank of water to be present in the system (for a fish habitat). This is unlike soil-based systems, where water can be siphoned from a nearby source as needed by plants. The water volume needed for an aquaponic system is determined once the system size has been determined, with water volume being 50-100% of the media bed. This water volume needs to be run through the system at an exchange rate of 100% per hour in order to provide adequate water filtration for fish.

SOIL DEPTH AND VOLUME

Aquaponic proponents report being able to situate plants approximately twice as densely as in traditional soil systems. This improvement is due to the way nutrients are delivered to plants in aquaponic and hydroponic systems- in both, water delivers nutrients directly to the base of the plant. While plants in soil need to send roots deep into soil to mine for nutrients, plants in aquaponic systems can focus on aboveground growth.

Soil volume requirements vary widely between plants, but the requirements most commercially grown species are well known. These requirements can be easily used to determine the relative space required in an aquaponic system.

It is worth noting that some aquaponic designs utilize virtually zero soil volume, instead allowing a very shallow channel of nutrient-rich water to be guided directly through plant roots. This method is known as the Nutrient Film Technique, or NFT. While NFT systems are nearly unparalleled as a low-weight farming system, they can only support the smallest of plants (e.g. lettuces) and are significantly more complex to build and maintain than media bed systems. While we rejected NFT systems in our design of the Alpha Box for these reasons, they may be worth reconsidering in future work.

MINERAL NUTRIENTS

All plants require three primary macronutrients to survive- Nitrogen, Phosphorus, and Potassium (frequently referred to collectively as NPK). Plants also require a multitude of secondary macronutrients and micronutrients to remain healthy and maintain sufficient yields. Generally 12 of these additional nutrients are recognized as essential for plant success (not including Oxygen and Carbon, which are absorbed from the air), although the degree to which each secondary nutrient is required varies significantly by plant species.

Properly managed aquaponic systems generally provide plants with adequate amounts of 12 of the 15 essential plant nutrients. For optimal plant performance, however, three nutrients need to be supplemented: Calcium, Potassium, and Iron. These supplements don’t generally represent a major cost in aquaponic systems, but correctly administering these supplements without adequate monitoring equipment does create an added difficulty for residential-sized systems. Fortunately many plants, especially non-fruiting plants (e.g. lettuce or basil), can survive without supplements. While it was decided that supplements would not be administered in the Alpha Box for simplicity’s sake, future research should further explore the use of these supplements in order to come to an accurate understanding of a VFF’s optimal production capacity.

CLIMATE

While there is a wide variation of climate preference between plants, the vast majority of commercially grown plants perform well within the range of human comfort, i.e. 68-75^{o} F and 40-60% relative humidity. This indicates that a simple climate management strategy in a vertical farming system would be to open the façade to the indoors, allowing plants and humans to coexist in the same climate.

There are, unfortunately, some complications with this idea. Most notably, plant transpiration can quickly raise the relative humidity in a closed space to over 90%. This could prove to be beneficial in arid climates, where a building could theoretically negate the need for air humidification by employing a vertical farming system, but in humid environments complex ventilation strategies would be required to properly manage a vertical farming system.

PLANT RECOMMENDATIONS

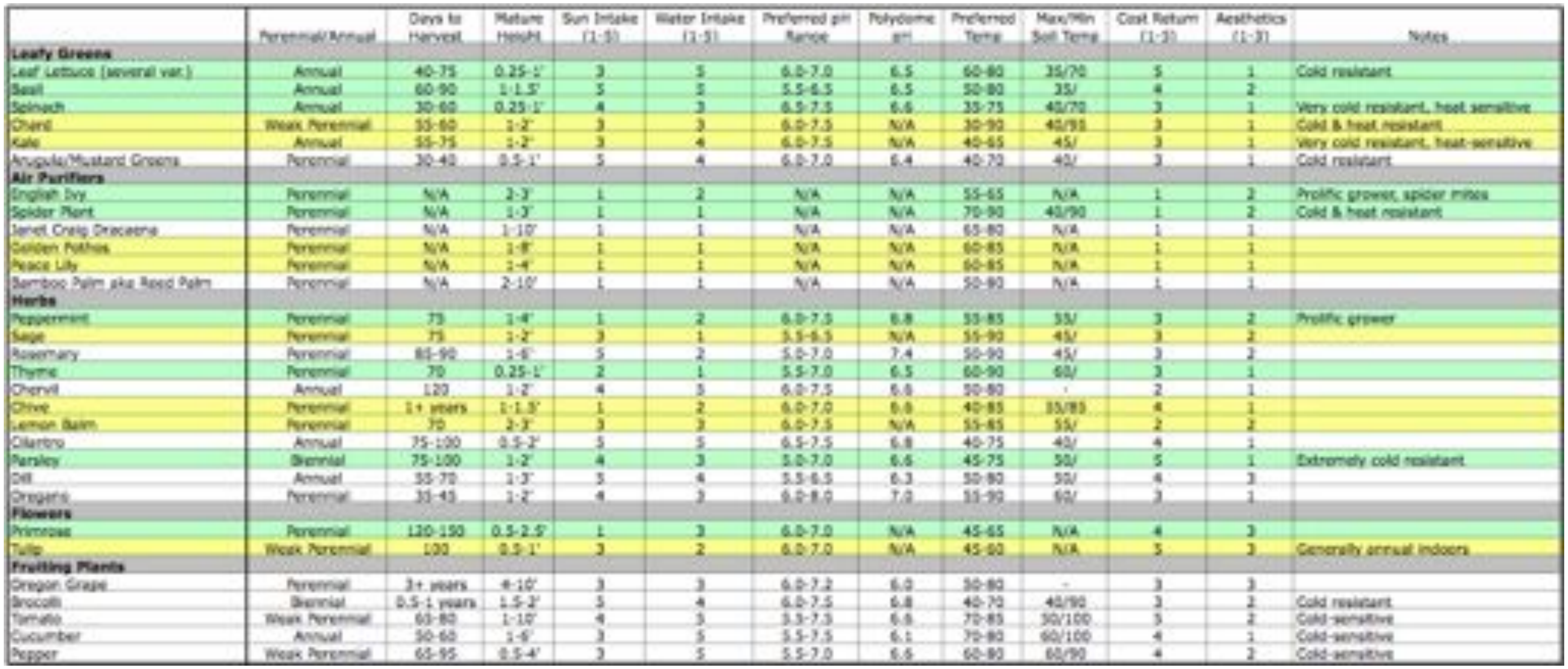
After looking at an extensive list of possible plant species covering over 300 common plant varieties, potential species were split into seven distinct categories: herbs, leafy greens, flowers, root vegetables, vine plants, fruiting plants, and air quality plants. Not all of these plant categories were used in the final list of plant recommendations- they primarily served as a paradigm to aid in the group's understanding and as a starting point for further refinement. The plant categories established, with a list of attributes and possible species, are available in Appendix 1.

The culmination of the outlined plant species research was a list of recommended plant species to be employed in an indoor vertical farming environment. Each plant was chosen for its performance across a wide range of variables: water and light requirements, size, preferred pH levels, days to harvest, etc.

The plant list is provided below. Relative levels of recommendation are denoted by row color:

- Green: highly recommended (9 plants)
- Yellow: recommended (8 plants)
- White: other possible options (13 plants)

These recommendations were provided using base assumptions concerning the design of our vertical system. While it was unlikely that initial tests will be able to accommodate more than the nine most highly recommended plants, others were provided in case of a significant design change or the failure of a “highly recommended” plant during prototype testing. This did in fact happen when an English Ivy plant died during the first month of testing; that plant was replaced with rosemary.



	Perennial/Annual	Days to Harvest	Mature Height	Sun Intake (1-5)	Water Intake (1-5)	Preferred pH Range	Polydome pH	Preferred Temp	Max/Min Soil Temp	Cost Return (1-5)	Aesthetics (1-3)	Notes
Leafy Greens												
Leaf Lettuce (several var.)	Annual	40-75	0.25-1'	3	5	6.0-7.0	6.5	60-80	35/70	5	1	Cold resistant
Basil	Annual	60-90	1-1.5'	5	5	5.5-6.5	6.5	50-80	35/	4	2	
Spinach	Annual	30-60	0.25-1'	4	3	6.5-7.5	6.6	35-75	40/70	3	1	Very cold resistant, heat sensitive
Chard	Weak Perennial	55-60	1-2'	3	3	6.0-7.5	N/A	30-90	40/95	3	1	Cold & heat resistant
Kale	Annual	55-75	1-2'	3	4	6.0-7.5	N/A	40-65	45/	3	1	Very cold resistant, heat-sensitive
Arugula/Mustard Greens	Perennial	30-40	0.5-1'	5	4	6.0-7.0	6.4	40-70	40/	3	1	Cold resistant
Air Purifiers												
English Ivy	Perennial	N/A	2-3'	1	2	N/A	N/A	55-65	N/A	1	2	Prolific grower, spider mites
Spider Plant	Perennial	N/A	1-3'	1	1	N/A	N/A	70-90	40/90	1	2	Cold & heat resistant
Janet Craig Dracaena	Perennial	N/A	1-10'	1	1	N/A	N/A	65-80	N/A	1	1	
Golden Pothos	Perennial	N/A	1-8'	1	1	N/A	N/A	60-85	N/A	1	1	
Peace Lily	Perennial	N/A	1-4'	1	1	N/A	N/A	60-85	N/A	1	1	
Bamboo Palm aka Reed Palm	Perennial	N/A	2-10'	1	1	N/A	N/A	50-80	N/A	1	1	
Herbs												
Peppermint	Perennial	75	1-4'	1	2	6.0-7.5	6.8	55-85	55/	3	2	Prolific grower
Sage	Perennial	75	1-2'	3	1	5.5-6.5	N/A	55-90	45/	3	2	
Rosemary	Perennial	85-90	1-6'	5	2	5.0-7.0	7.4	50-90	45/	3	2	
Thyme	Perennial	70	0.25-1'	2	1	5.5-7.0	6.5	60-90	60/	3	1	
Chervil	Annual	120	1-2'	4	5	6.0-7.5	6.6	50-80	-	2	1	
Chive	Perennial	1+ years	1-1.5'	1	2	6.0-7.0	6.0	40-85	35/85	4	1	
Lemon Balm	Perennial	70	2-3'	3	3	6.0-7.5	N/A	55-85	55/	2	2	
Cilantro	Annual	75-100	0.5-2'	5	5	6.5-7.5	6.8	40-75	40/	4	1	
Parsley	Biennial	75-100	1-2'	4	3	5.0-7.0	6.6	45-75	50/	5	1	Extremely cold resistant
Dill	Annual	55-70	1-3'	5	4	5.5-6.5	6.3	50-90	50/	4	3	
Oregano	Perennial	35-45	1-2'	4	3	6.0-8.0	7.0	55-90	60/	3	1	
Flowers												
Primrose	Perennial	120-150	0.5-2.5'	1	3	6.0-7.0	N/A	45-65	N/A	4	3	
Tulip	Weak Perennial	100	0.5-1'	3	2	6.0-7.0	N/A	45-60	N/A	5	3	Generally annual indoors
Fruiting Plants												
Oregon Grape	Perennial	3+ years	4-10'	3	3	6.0-7.2	6.0	50-80	-	3	3	
Brocolli	Biennial	0.5-1 years	1.5-2'	5	4	6.0-7.5	6.8	40-70	40/90	3	2	Cold resistant
Tomato	Weak Perennial	65-80	1-10'	4	5	5.5-7.5	6.6	70-85	50/100	3	2	Cold-sensitive
Cucumber	Annual	50-60	1-6'	3	5	5.5-7.5	6.1	70-80	60/100	4	1	Cold-sensitive
Pepper	Weak Perennial	65-95	0.5-4'	3	5	5.5-7.0	6.6	60-80	60/90	4	2	Cold-sensitive

Table 1: Preliminary Plant List

While little has been done to measure the quantitative impacts of establishing plant diversity within a vertical farm, it is possible that the *number* of species selected is nearly as important as the varieties chosen to the success of a vertical farm. While increasing diversity may slightly reduce the profitability of a commercial system, this diversity has been shown to promote wellness within plants (via numerous symbiotic relationships), increases the overall stability of the system and is a safeguard against catastrophic system failure in the case of disease or pest outbreak.

LIGHTING ANALYSIS

DAYLIGHTING

A daylighting analysis was performed in order to predict the amount of light that could be expected to fall upon the plants in a “bookshelf style” VFF system. This analysis was performed before the determination of an optimal design style, but the bookshelf design was determined to be a worst-case scenario from an interior illuminance standpoint. This analysis determined that even a bookshelf design provided adequate interior lighting. A detailed summary of this analysis, performed by Matt Kincaid, is available in Appendix 2.

Future work will work to accurately determine expected interior illuminance levels through experimental methods.

LIGHT SHELVES

An analysis was performed to determine both the optimal light shelf design to be implemented in a VFF system and the optimal height to place such a light shelf. This analysis showed that a light shelf with variable interior and exterior components placed seven feet from the ground (assuming standard floor height specifications) provided the most energy savings. A detailed summary of this analysis, performed by Brian Carpenter, is available in Appendix 3.

Utilizing light shelving within a VFF system was abandoned for three reasons: First, testing such a design was determined to be cost-prohibitive and outside the scope of this research. Second, the depth of a double-skin façade was found to have a negative impact on the overall value of light shelving. Choosing to design a VFF spanning multiple stories was determined to be a more cost effective method for increasing the light available to the building interior. Finally, determining a way to fit both vertical farming components and light shelving into the same space was a challenge we were not able to adequately solve, especially when so many of the VFF’s proposed design variables remained unknown.

Once an adequate computer model is created to analyze the performance characteristics of a vertical farming façade, it may be worthwhile to revisit the value of incorporating light shelves into the façade. This analysis should be much simpler and more accurate once an adequate VFF computer model is established.

VENTILATION AND THERMAL ANALYSIS

Prior to the development of a prototype, preliminary heat gain analysis was required to develop a rough estimate of ventilation requirements and HVAC loads associated with the addition of a vertical farm façade. A common ventilation heuristic used in green houses is 40 ACH. This ventilation rate was used as the basis for modeling the interior temperature of the plant cavity. The primary concern was that the plant cavity would become too warm during the day to sustain plant life, and supplemental cooling would have to be integrated in the design. A detailed summary of this analysis is available in Appendix 4.

Under the assumptions made, the VFF cavity experienced a theoretical temperature range of 53-76^{o}F. This temperature range is well within the requirements for most all plant species, and indicates that far lower ventilation standards may be sufficient for a VFF space.

GLAZING ANALYSIS

One of the initial problems considered was the design parameters and requirements for the fenestration of a potential vertical farm design. Indoor crop growth systems that rely heavily on electric lighting require far more electrical energy than systems that rely solely on day lighting. Up to 90% of the energy costs associated with hydroponic systems result from electric lighting, which could easily cancel any environmental gains achieved from urban farming. For this reason it is desirable to select a fenestration that would allow enough daylighting for crop growth and minimize the need for supplemental electric lighting. This, coupled with a sound optical design to bring light into the plants will achieve a low energy design.

With these considerations in mind, many fenestration materials were researched to determine one that is most suitable for this application. The design process is discussed at length in the glazing report in Appendix 5. This decision-making process resulted in the selection of conventional, double-pane glass windows as the primary fenestration, coupled with aerogel panels to separate the crops from the occupied portion of the space. This strikes a suitable balance between the desires for a high visual transmittance from the exterior fenestration, and good thermal performance to keep the building well insulated. The double pane glass provides more than enough illuminance for plant growth on a south-facing window while the aerogel panel keeps the sunlight from overheating the space.

Using an Aerogel panel as an interior barrier during Alpha Box testing was determined to be cost-prohibitive. However, future testing may use such a panel in order to verify the benefits described within the Glazing Report.

PRELIMINARY ECONOMIC ANALYSIS

Another important attribute of vertical farming is its potential as a profitable business endeavor. It was of interest to determine whether the revenue yielded from indoor crop growth could be competitive with revenue generated from traditional urban building uses, such as retail and residential leasing. To this end, research was done to determine the amount of revenue potential for various crops on a per square foot basis. This information was compared to the revenue potential on real-estate investments for office and real estate space. A summary of this analysis is available in Appendix 6.

The key finding of this analysis was that dedicated vertical farming structures are not a profitable endeavor with current crop prices, in high-density urban markets. For high-density urban areas, investors will see a greater return if real estate is purposed as office space, retail space, or residential dwellings. In coming years, increasing scarcity of fossil fuels will almost certainly raise transportation costs for traditionally farmed crops. When this happens, crop prices will rise and the revenue potential for a dedicated vertical framing structure will increase accordingly. However, current economic conditions indicate that a vertical farming design that is integrated with a traditional office or retail building is the more practical option. This is one of the key benefits associated with the façade design developed during this project. By integrating the design with an existing wall, building owners can continue to lease space to tenants while the revenue seen from crops will serve as a supplement.

It is important to note that no considerations were made with regard to the operating or start-up costs associated with a vertical farming system. There were many details associated with these costs that put them outside the scope of the current research. This research determines only whether the revenue associated with vertical farming is comparable to that of traditional real estate, while a cost-analysis remains to be done.

THE ALPHA BOX (JANUARY 2013-MAY 2013)

DESIGN DEVELOPMENT

During the Spring 2013 semester, the focus of this project was shifted from conceptual research to the development of a prototype design (the Alpha Box) in order to test some of the basic assumptions made about the performance and optimal design characteristics of a VFF system.

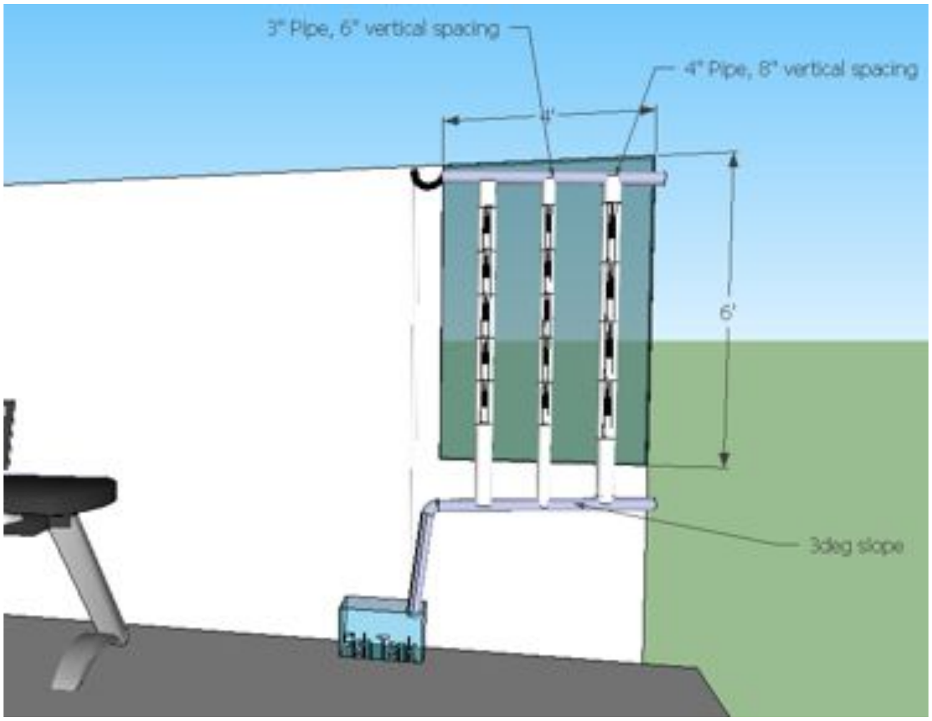


Figure 5: Initial Prototype Concept

The Alpha Box concept centered around a series of vertically oriented PVC pipes with plants installed at regular intervals. These vertically oriented pipes were chosen over a series of horizontal pipes because such a design was believed to be easier to connect and more stable (a major requirement for media-based systems). Horizontal tubing designs do lend themselves well to NFT applications, but this was outside the scope of our research.

The final Alpha Box prototype consisted of a 3’ wide x 6’ tall x 1.5’ deep cavity built out of a clear plexiglass frame and an outer panel made of Starphire clear glass. This model was manufactured by Slade Glass Co.

The prototype frame was filled with two 4”-diameter PVC pipes. One PVC pipe incorporated a plant spacing of six inches, while the other pope spaced plants at 9” (in order to determine which spacing specification was superior for plant growth. Plants were oriented facing in four different directions- NE, NW, SE, and SW (in order to determine which orientation was superior for plant growth). These tubes were both connected to a 10-gallon aquarium filled with common Goldfish and Red Minnows by a series of PVC pipes and clear vinyl tubing.

The single metering chamber itself was built out of 2x4 plank framing, filled in with R-13 rigid insulation, covered by 1/4” exterior-grade particleboard sheeting, and sealed with insulative foam and latex caulking. The VFF prototype protruded from the testing chamber by approximately four inches in order to simulate the wall thickness of a typical residential building.

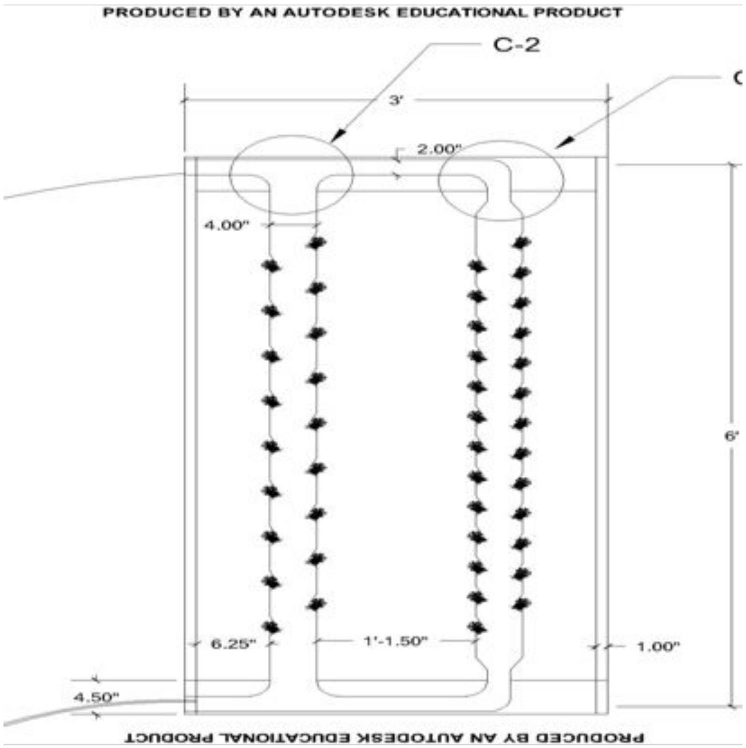


Figure 6: Final Prototype Design

TESTING ENERGY PERFORMANCE

Subsequent to the development of a prototype, it was of interest to observe potential benefits of adding plants to the window cavity. Typical metrics used to compare windows are the R-Value, the solar heat gain coefficient (SHGC) and the visual transmittance (VT). Because the plants provide significant shading, theoretically, the SHGC and VT should be greatly reduced with the introduction of agriculture. Additionally, by adding an extra barrier between the interior and exterior of the space, there is potential for improvement to the R-value as well. Because the visual properties are so vastly altered by the addition of plants, it was deemed inappropriate to compare VT values between the vertical farm and traditional windows. Therefore, performance analysis was done to estimate R-value and SHGC improvements only.

THERMAL RESISTANCE (R-VALUE) TESTING

To estimate the R-value of the window, a "single-metering chamber" was utilized to measure heat flow both with and without the addition of plants. Tests were performed both with and without plants in the cavity, to estimate the performance improvement. Tests were performed at night to eliminate effects of solar radiation. The basic steps of the procedure are summarized below.

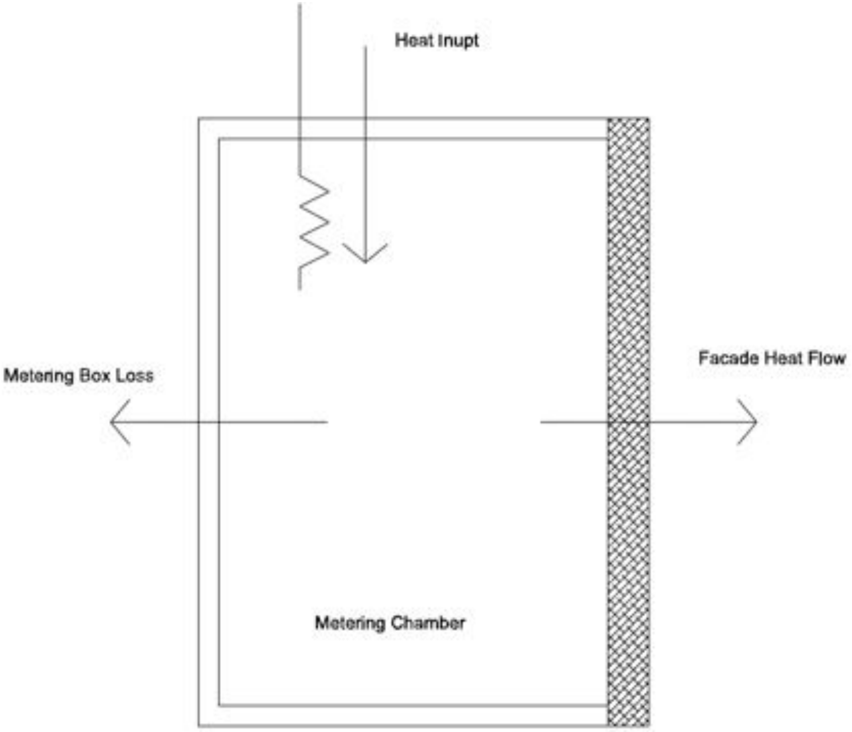


Figure 7: The Basic Concept Behind the Alpha Box

Equipment Used

- Electric resistance heater with oscillating fan. (Lasko 16 in. 1500- Watt Oscillating Ceramic Tower heater)
- In-line ampere meter to estimate heat input of heater.
- Fluke infra-red thermometer to measure temperature of surfaces. Calibrated for emissivity of .95
- Standard duct tape used to seal cracks in structure to minimized effects of infiltration.
- Test chamber box. Constructed of R-13 rigid insulation and 2x4 framing .The box was sealed with particleboard siding. The structure was estimated to have an overall R-value of $12.25\ \frac{hr\cdot ft^2\cdot {}^\circ F}{BTU}$ with the thermal bridging of the 2x4's taken into account.

Data Collection Procedure

- Turn-on heater to 75% power and seal the chamber.
- Allow 30 minutes for box to reach equilibrium.
- Measure electrical current supplying heating using an amp meter.
- Take exterior surface temperature measurements at the test points shown in Figure 8[1].
- Remove door and take interior surface temperature at the points show in Figure 8.
- Remove plants from the cavity and repeat the steps described above.

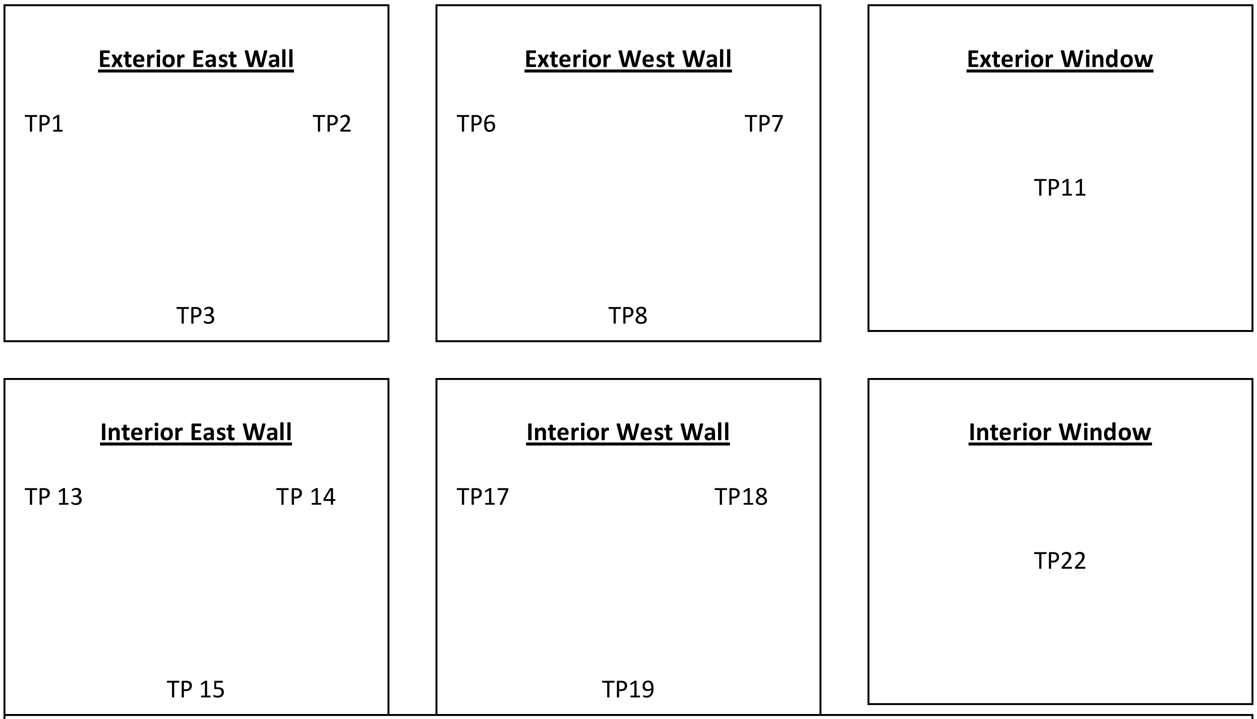


Figure 8: Exterior and Interior Temperature Measurement Points

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[1] Because the temperatures were measured using an infrared meter, white masking tape was placed on all the test points to ensure uniform emissivity.

SOLAR ENERGY TRANSMITTANCE (SHGC) TESTING

It was of additional interest to quantify the reduction of solar heat gain with the addition of plants. The plants and piping systems essentially act as a solar shield, similar to conventional blinds or curtains, and block solar radiation from heating the space. Additionally, the grow media used in the pipes serves as a thermal mass to potentially reduce peak heating and cooling loads in a space. In order to help quantify these potential benefits, the improvement to the solar heat-gain coefficient (SHGC) was measured.

Equipment Used

- Same testing chamber used for R-Value measurement (described in previous section).
- Pyrometer to measure incident solar radiation on exterior and entering solar radiation on the interior.
- Fluke multimeter to measure voltage across pyrometer leads.

Data Collection Procedure

- Incident solar irradiance was measured at the test points shown in Figure 9.
- Incident solar irradiance was measured at parallel interior points with the interior Plexiglas pane removed.
- Tests were performed during cloudy sky, and clear sky conditions, at different times of day.

Exterior Window Face

TP1	TP2	TP3
TP4	TP5	TP6

Interior Window Face

TP24	TP25	TP26
TP27	TP28	TP29

Figure 9: Solar Irradiance Measurement Points

RESULTS AND ANALYSIS

THERMAL RESISTANCE (R-VALUE) RESULTS

Subsequent to the collection of surface temperature measurements, it was possible to use an energy balance to estimate the thermal conductance of the window panel. By conservation of energy,

$$Q_{heater} + Q_{box} + Q_{window} = 0$$

where

$$Q_{box} = k_{box} * A_{box} * (T_{ext,wall} - T_{int,wall})$$

$$and$$

$$Q_{window} = k_{window} * A_{window} * (T_{ext,win} - T_{int,win})$$

It was then possible to solve the above expressions for the unknown parameter of k_{window}.

Test	May 4th, 2013, With Plants	May 4th, 2013, W/O Plants	May 14th, 2013, With Plants	May 14th, 2013, W/O Plants
Heat Input (BTU/hr)	4381.01	4667.62	2620.42	
Avg. Exterior Wall Temp. (F)	48.85	48.73	66.0	
Avg. Interior Wall Temp. (F)	82.5	75.0	99.6	
Avg. Exterior Window Temp. (F)	56.5	60.0	74.25	
Avg. Interior Window Temp. (F)	82.0	85.0	104.25	
Calculated R-value $(\frac{hr*ft^2*°F}{BTU})$	0.1705	0.1534	0.357	.3086
Percent improvement with plants.	11.1%	-	15.1%	-

Table 2: Thermal Resistance Testing Summary

As shown in Table 2, the resistance of the window was improved with the addition of plants to the cavity. The calculated R-values were quite low for a few reasons. To establish a base line for the benefits of plants, a very low performance glass (R=.98 $\frac{hr \cdot ft^2 \cdot °F}{BTU}$) was used as the exterior window. This glass was selected for it's high visual transmittance, to allow for design iterations with different films, rather than for its thermal performance. The overall thermal performance could easily be improved with a higher performing window (such as a double-pane window) in future designs, with the benefits of the plants still being preserved.

The low calculated R-values are also indicative of the limitations of the testing equipment. The data for the R-value calculations were collected outdoors, in variable climate and wind conditions, which is far from the ideal conditions that could be established in a laboratory. Because factors such as, exterior wind, test chamber infiltration, flanking loss around window, and convection within the chamber could not be easily quantified or controlled, the above calculations are likely to contain error. However, it is still apparent that there is benefit to the R-value from adding plants. Development of a more sophisticated test technique, under more controlled conditions would very likely confirm this, as well as give a more precise R-value of the system over all.

SOLAR ENERGY TRANSMITTANCE (SHGC) RESULTS

Subsequent to the collection of solar irradiance data, the SHGC was determined as

$$SHGC = \frac{Q_{Sol,interior}}{Q_{Sol,Exterior}}$$

Test Date	May 4th, 2013	May 17th, 2013
Sky Condition	Patchy Cloud Cover	Clear
Average Exterior Irradiance (W/m^2)	239	220
Average Interior Irradiance (W/m^2)	59.2	66.2
SHGC with plants	.248	.30
SHGC w/o plants[2]	.90	.90
Percent improvement with plants.	72.4%	66.7%

Table 3: Solar Energy Transmittance Testing Summary

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[2] SHGC of window without plants was obtained from glass manufacturer's cut sheet.

PLANT AND FISH PERFORMANCE

Though some plants fared better than others, the majority of the species specified in this research performed rather poorly within the Alpha Box. This performance was primarily due to inherent failures in the Alpha Box's design. While the testing chamber did allow us to accurately measure the R-Value of our prototype, it was simply too small and too rudimentary to effectively control its own interior climate. Plants frequently experienced temperatures more than 50^{o} F hotter than those outside; in the spring temperatures inside the Alpha Box reached 100^{o} F with snow still on the ground inches away. These temperatures caused several plants, including all lettuce and basil, to bolt far before becoming fully grown. All but three plants survived the heat (one parsley and two English ivy plants died), but none fared as well as expected.

While plants started to be seriously affected by the Alpha Box's interior temperatures starting in March, the fish used fared well until the start of summer. In May, however, fish began to die at a rapidly increasing rate. At the time this report was written, during the hottest month of the year, fish were dying at a rate of approximately one per day (a 10% daily population turnover). These deaths stunt aquaponic system performance, as decaying fish carcasses release levels of ammonia in the water that kill off nitrifying bacteria and prevent them from supplying plants with the nutrients they need to grow. The occurrence of this phenomenon was confirmed by the slowed plant growth observed in June and July, when growth rates are generally at their peak.

Unfortunately, the poor performance of the Alpha Box's flora and fauna likely had a substantial negative effect on the prototype design's observed thermal performance. The vast majority of plants were not nearly as large as expected at the time testing for R-Value and SHGC was performed, meaning that the majority of the benefit noted was likely provided by the aquaponic structure and not the plants themselves. However, if framing and small plants alone led to an improvement in both R-Value and SHGC, it can be inferred that larger plants would only add to this benefit.

There were two plant species which performed relatively well inside the Alpha Box: rosemary, peppermint, and spider plant. This selection reveals a few things:

1. Temperature was, in fact, the leading cause of plant failure. These three plant species were the most heat-tolerant of the nine employed in the Alpha Box.

2. Sunlight may not be as significant of a limiting factor in vertical farming systems as was once thought. Rosemary is considered to be a sunlight-demanding herb, which is why it was originally excluded from the Alpha Box plant list. If it can grow well in a vertical farming application, it's likely that other sun-loving plants (e.g. arugula or broccoli) can perform better than originally assumed.

3. 9" plant spacing appeared to show a measurable benefit over 6" spacing. The rosemary and mint, the two largest and fastest-growing plants currently living in the Alpha Box, were both situated in the western pipe with a plant spacing of 9" (as opposed to the eastern pipe, spaced at 6"). Unfortunately, this was not a large enough sample size to definitively correlate this increased plant growth to greater plant spacing.

FUTURE WORK: THE BETA WALL

The research outlined in this report will be continued through the 2013-2014 academic year. Year Two of this research will build upon the lessons learned during the operation of the Alpha Box, revising design failures and inefficiencies, building upon demonstrated design strengths, and diversifying procedures in order to come to a more complete understanding of how the design variables inherent in a vertical aquaponic façade affect the overall performance of the façade as a building fenestration system.

CHANGES TO DESIGN AND TESTING METHODOLOGY

While the “Beta Wall” will be relatively similar to the Alpha Box in terms of the farming system implemented, it will be designed specifically in order to analyze as many different design variables as possible. The primary design flaw inherent in the Alpha Box was the fixed pipeline system. The Beta Wall will negate this flaw by taking advantage of an innovative and impressively simple design characteristic developed by Jay McClellan in order to make each vertical tube completely removable opening the door to use an unlimited number of tubes with an unlimited number of design differences.

In addition to this design change, a much larger scale will be used in the Beta Wall. While the length of each vertical tube will remain similar in order to accommodate insulation testing (which will take place within the Alpha Box), the horizontal length of the testing area will increase from 3’ to 10-16’ (space permitting). This will allow for more accurate testing results and more variability in design variable inputs. The increased system volume will also create a far more stable biological climate within the aquaponic system. This stability was something that was truly lacking in the Alpha Box, as proven by the fish population turnover rate (over 10% per day at its peak). Most commercial aquaponic websites recommend using at least 250 gallons of water for optimal stability- while the Beta Wall will only use 40-75 gallons, it will be far more stable than the 10-gallon system implemented in the Alpha Wall. This will allow for the use of Tilapia in the Beta Wall system, adding a potential revenue stream to monitor during testing.

The types of plants used in the Beta Wall system will also be modified to reflect the findings of Alpha Wall testing:

- No lettuces will be used. While lettuce is perhaps the most economically viable plant to grow aquaponically, commercial aquaponic outfits almost exclusively grow lettuce in NFT (Nutrient Film Technique) or DWC (Deep Water Culture) systems. This is due to the fact that lettuce plants have an extremely fast harvesting rate, and media-based systems make frequent plant extraction and re-planting difficult.
- More sun-loving plants will be tested, in accordance with the unexpectedly high performance of Rosemary (a sun-loving herb) during Alpha Box testing.

Finally, and perhaps most notably, the Beta Wall will be run in a far different environment than the Alpha Box. Rather than building a fully-enclosed calorimeter around the test specimen (as was done with the Alpha Box), the Beta Wall will be run inside a climate-controlled greenhouse on CU grounds. This change is significant for two reasons: first, it makes testing the wall and changing design variables immeasurably easier than it was within the cramped confines of the Alpha Box. Second, and more importantly, it allows for the plants being grown in our system to live in conditions favorable to them. As discussed previously, the design of the Alpha Box led to very unsatisfactory swings in temperature, with interior temperatures frequently reaching over 120^{o} F. While most plants were able to survive in these conditions, growth was severely stunted, leading to a façade that was both unpleasant in appearance and dissimilar to the design this research is attempting to build toward in the first place. While operating inside a greenhouse does have its disadvantages (most notably reduced lighting levels), plants are expected to perform at a much higher level.

OBJECTIVES FOR FUTURE RESEARCH

The primary objective of the Beta Wall will be to come to an in-depth understanding of the performance characteristics of a vertically oriented and media-based aquaponic farming fenestration system. A number of design input variables (listed below) will be manipulated in order to analyze their effect on the overall performance of the fenestration system, using regression analysis in order to determine how dependent each "output variable" (performance characteristic) is upon each "input variable" (design characteristic). This analysis will lead to the creation of an analytical model that can be plugged into existing architectural design software in order to help building designers determine the feasibility of implementing an aquaponic system in a building façade.

In addition to this primary research scope, some time may be spent determining the optimal performance of a more complex (nutrient supplements, worms, pH buffers, different plants for different seasons, etc.) and properly managed (climate controlled, constant fish pop, algae managed, sump tank) aquaponic VFF system. To this end nutrient supplements, composting worms, pH buffers, climate controls, increased fish populations, sump tanks, and/or algae-minimizing components may be incorporated into the Beta Wall design. Several reports have already been written concerning the production capacities of well-maintained aquaponic systems however, so this aspect of research may be ignored.

Once an analytical model for VFF design and performance characteristics is developed, an overall economic analysis will be performed for a number of different possible VFF applications, i.e. different climates and building specifications, to determine when and where a VFF system could add a tangible economic benefit. Without a substantial economic benefit, of course, VFF systems will never be implemented. Results will also be compared with drastically different methods of incorporating plants into urban environments that have been proposed by other research endeavors (e.g. living walls, rooftop production, and hydroponic/soil designs) in order to determine whether these options might provide more of an economic benefit than the proposed VFF system. An analysis of the possible production capacity of an integrated VFF-rooftop system, as proposed earlier in this report, will also be performed.

Time permitting, an initial feasibility study will be performed to determine how well a VFF system could be combined with other modern sustainability technologies. Graywater harvesting, solar PV, and geothermal systems in particular appear as though they could work very well when incorporated into a VFF system.

COLLABORATORS AND RELATED RESEARCH

Marc Prades performed his own research on the viability of vertical farming systems, using the thermal performance results determined in the Alpha Box to model and analyze the performance of commercial-scale systems. His thesis was titled something.

Brian Carpenter provided research support during the Fall 2012 semester. Brian's research focused primarily on

Casey Martin and **Josh Young**, two high school students, worked in parallel with this project. They built a small "Living Wall" system in order to determine the VOC-harnessing ability of some of the plants used in the Alpha Box.

Tamzida Khan provided support in rendering architectural-grade renderings of possible commercial-scale vertical systems, using the specifications of the Alpha Box design.

Avery Ellis, owner and founder of Integrated Aquaponics, provided invaluable consulting and advice during the research and development phase of this project.

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